

Shattered pellet injection studies at the tokamak ASDEX Upgrade

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SPI - an artist's impression

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Short abstract

Nuclear fusion reactors based on the tokamak concept are prone to plasma-terminating disruptions, which are a major concern for the machine protection. The improvement of the shattered pellet injection (SPI) technique – used for disruption mitigation – is of highest priority. In this thesis, I discuss the SPI experiments at the tokamak ASDEX Upgrade, which were designed to optimise the injection geometry and pellet parameters for the highest possible mitigation efficiency.

Kurzzusammenfassung

Kernfusionsreaktoren basierend auf dem Tokamak-Konzept sind anfällig für Disruptionen, welche den Plasma-Einschluss beenden und eine große Sorge für den Zustand der Maschine darstellen. Eine Verbesserung der shattered pellet injection (SPI) Methode ist von höchster Priorität, welche die Auswirkungen von Disruptionen reduziert. In meiner Arbeit diskutiere ich die SPI-Experimente am Tokamak ASDEX Upgrade, welche konzipiert wurden um die Injektionsgeometrie und Pellet-Parameter zu optimieren.

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Publications

First authored papers

- [A] P. Heinrich, G. Papp, J. Artola, M. Bernert, P. de Marné, M. Dibon, R. Dux, T. Eberl, J. Hobirk, S. Jachmich, M. Lehnen, T. Peherstorfer, N. Schwarz, U. Sheikh, B. Sieglin, J. Svoboda, the ASDEX Upgrade Team, and the EUROfusion Tokamak Exploitation Team. Radiated energy fraction of SPI-induced disruptions at ASDEX Upgrade. *Nuclear Fusion*, **65** (5):056036 (2025).
- [B] P. Heinrich, G. Papp, P. de Marné, M. Dibon, S. Jachmich, M. Lehnen, T. Peherstorfer, I. Vinyar, and the ASDEX Upgrade Team. Recipes for pellet generation and launching in the ASDEX Upgrade SPI. *Fusion Engineering and Design*, **206**:114576 (2024).

Co-authored papers

- [C] A. Patel *et al.* Modelling of shattered pellet injection experiments on the ASDEX Upgrade tokamak. *Nuclear Fusion*, accepted paper (2025), <https://doi.org/10.1088/1741-4326/ade890>.
Contribution: preparation & execution of experiments, formal analysis – measurements, methodology – discussions about implementations, writing – review & editing
- [D] P. Haldestam *et al.* Reduced kinetic modelling of shattered pellet injection in ASDEX Upgrade. *Journal of Plasma Physics*, accepted paper (2025), <https://doi.org/10.48550/arXiv.2412.17995>.
Contribution: preparation & execution of experiments, formal analysis – measurements, methodology – discussions about implementations, writing – review & editing
- [E] G. Bodner *et al.* Multi-device analysis of energy loss duration and pellet penetration with implications for shattered pellet injection in ITER. *Nuclear Fusion*, **65** (6):066010 (2025).
Contribution: preparation & execution of experiments, formal analysis – measurements, methodology – discussions about implementations, writing – review & editing
- [F] E. Joffrin *et al.* Overview of the EUROfusion Tokamak Exploitation programme in support of ITER and DEMO. *Nuclear Fusion*, **64** (11):112019 (2024).
Contribution: participated in the JET SPI experiments in 2022 and 2024
- [G] H. Zohm and the ASDEX Upgrade Team. Overview of ASDEX Upgrade results in view of ITER and DEMO. *Nuclear Fusion*, **64** (11):112001 (2024).
Contribution: part of the ASDEX Upgrade team, writing – review & editing
- [H] S. J. Lee *et al.* Peridynamic modelling of cryogenic deuterium pellet fragmentation for shattered pellet injection in tokamaks. *Nuclear Fusion*, **64** (10):106023 (2024).
Contribution: provided laboratory data, writing – review & editing
- [I] J. Illerhaus *et al.* Status of the Deep Learning-Based Shattered Pellet Injection Shard Tracking at ASDEX Upgrade. *Journal of Fusion Energy*, **43**:14 (2024).
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- [J] Á. Kovács *et al.* Acceleration of cryogenic pellets for Shattered Pellet Injection. *Fusion Engineering and Design*, **202:114303** (2024).
Contribution: provided laboratory data
- [K] N. Schwarz *et al.* The mechanism of the global vertical force reduction in disruptions mitigated by massive material injection. *Nuclear Fusion*, **63 (12):126016** (2023).
Contribution: preparation & execution of experiments, formal analysis – measurements, methodology – discussions about implementations, writing – review & editing
- [L] M. Dibon *et al.* Design of the shattered pellet injection system for ASDEX Upgrade. *Review of Scientific Instruments*, **94 (4):043504** (2023).
Contribution: provided laboratory data, preparation & execution of experiments, formal analysis – measurements, methodology – discussions about implementations, writing – review & editing

Co-author papers in preparation

- [M] O. Vallhagen *et al.* Simulation of Shattered Pellet Injections with Plasmoid Drifts in ASDEX Upgrade and ITER. *Plasma Physics and Controlled Fusion*, submitted (2025),
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- [N] W. Tang *et al.* Non-linear shattered pellet injection modelling in ASDEX Upgrade. *Nuclear Fusion*, submitted (2025),
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- [I] **ORAL** P. Halldestam *et al.* Modelling of shattered pellet injection in ASDEX Upgrade with DREAM. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #198*, Lausanne, Switzerland (2025)
- [II] **ORAL** J. Chlum *et al.* 3D radiation forward modeling of SPI mitigated disruptions at AUG using Emis3D. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #193*, Lausanne, Switzerland (2025)
- [III] **ORAL** O. Ficker *et al.* SPI mitigation of disrupting, unhealthy plasmas in JET and AUG. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #189*, Lausanne, Switzerland (2025)
- [IV] **ORAL** W. Tang *et al.* Non-linear MHD modelling of shattered pellet injection in ASDEX Upgrade. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #176*, Lausanne, Switzerland (2025)
- [V] **ORAL** A. Patel *et al.* Simulating shattered pellet injections with the INDEX code. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #175*, Lausanne, Switzerland (2025)
- [VI] **ORAL** P. Heinrich *et al.* Current status of the SPI studies at ASDEX Upgrade. *Joint Runaway Electron Modelling (REM) and WPTE RT03 Analysis meeting #163*, Lausanne, Switzerland (2025)

- [VII] **INVITED** W. Tang *et al.* Non-linear shattered pellet injection simulations based on ASDEX Upgrade experiments. [8th AAPPs-DPP](#), Malacca, Malaysia (2024), [inproceedings](#) and [slides](#) available at the EUROfusion pinboard
- [VIII] **INVITED** P. Heinrich *et al.* Overview of shattered pellet injection studies at ASDEX Upgrade. [66th APS-DPP](#), Atlanta, USA (2024)
- [IX] **ORAL** U. Sheikh *et al.* Thermal Quench Dynamics of Single Shattered Pellet Injections on JET. [66th APS-DPP](#), Atlanta, USA (2024)
- [X] **INVITED** P. Heinrich *et al.* Overview of the ASDEX Upgrade shattered pellet injection studies. [3rd TM Disruptions and Their Mitigation](#), IO headquarters, France (2024)
- [XI] **ORAL** P. Heinrich *et al.* Shattered pellet injection experiments performed at ASDEX Upgrade. *DPG-Frühjahrstagung P 9.2*, Greifswald, Germany (2024)
- [XII] **ORAL** A. Patel *et al.* Modelling of shattered pellet injection experiments with the INDEX code. *ITPA MHD, Disruptions & Control Topical Group*, online, (2024)
- [XIII] **ORAL** O. Vallhagen *et al.* From injection to deposition – capturing the drift of ablated pellet material in a tokamak. *50th EPS conference O2.305*, Salamanca, Spain (2024)
- [XIV] F. Lengyel *et al.* Plasma radiation characteristics of SPI mitigated disruptions in ASDEX Upgrade. *50th EPS conference P5.041*, Salamanca, Spain (2024)
- [XV] P. Haldestam *et al.* Reduced fluid modelling of shattered pellet injection in ASDEX Upgrade. *50th EPS conference P5.085*, Salamanca, Spain (2024)
- [XVI] **ORAL** S. Jachmich *et al.* Validation of ITER disruption mitigation physics on JET and ASDEX-Upgrade. *50th EPS conference I.303*, Salamanca, Spain (2024)
- [XVII] **ORAL** P. Haldestam *et al.* Modelling Shattered Pellet Injection in ASDEX Upgrade with DREAM. *Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting #136*, Lausanne, Switzerland (2024)
- [XVIII] **ORAL** A. Patel *et al.* Modelling of shattered pellet injection experiments on the ASDEX Upgrade tokamak. *Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting #130*, Lausanne, Switzerland (2024)
- [XIX] **ORAL** O. Vallhagen *et al.* Increasing the Physics Fidelity of SPI Simulations With the DREAM Code. *Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting #106*, Lausanne, Switzerland (2024)
- [XX] **ORAL** F. Lengyel *et al.* Plasma radiation analysis of AUG SPI experiments. *Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting #100*, Lausanne, Switzerland (2024)
- [XXI] P. Heinrich *et al.* Analysis of shattered pellet injection experiments at ASDEX Upgrade. *49th EPS conference Tu.MCF54*, Bordeaux, France (2023)
- [XXII] **ORAL** S. Jachmich *et al.* Shattered Pellet Injection experiments at ASDEX-Upgrade for design optimisation of the ITER Disruption Mitigation System. *49th EPS conference O2.103*, Bordeaux, France (2023)

- [XXIII] **ORAL** G. Bodner *et al.* Multi-device analysis of thermal quench duration induced by mixed neon/deuterium shattered pellet injection. *65th APS-DPP BP11.096*, Denver, USA (2023)
- [XXIV] **ORAL** W. Tang *et al.* Nonlinear shattered pellet injection simulations on AUG using JOREK. *10th REM #91*, Garching, Germany (2023)
- [XXV] **ORAL** N. Schwarz *et al.* The mechanism of vertical force reduction in mitigated disruptions. *10th REM #78*, Garching, Germany (2023)
- [XXVI] **ORAL** P. Heinrich *et al.* Radiation characteristics of the SPI experiments at ASDEX Upgrade. *10th REM #67*, Garching, Germany (2023)
- [XXVII] **ORAL** N. Schwarz *et al.* Mechanisms of the global force reduction in disruptions - Experimental validation of mitigated and unmitigated VDEs with the MHD code JOREK. IAEA Fusion Energy Conference (FEC) *TH/8-6*, London, United Kingdom (2023)
- [XXVIII] **INVITED** N. Schwarz *et al.* Mechanism for the reduction of the global vertical force in mitigated disruptions. *TSDW*, Princeton, USA (2023)
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- [XXXI] **ORAL** G. Papp *et al.* ASDEX Upgrade Shattered Pellet Injector. *9th REM #55*, Garching, Germany (2022)
- [XXXII] **ORAL** T. Peherstorfer *et al.* Comparison of modeled and experimental SPI fragment sprays for 4 mm pure Ne pellets. *9th REM #52*, Garching, Germany (2022)
- [XXXIII] **ORAL** P. Heinrich *et al.* Status of the shattered pellet injector at ASDEX Upgrade. *9th REM #32*, Garching, Germany (2022)
- [XXXIV] **ORAL** J. Illerhaus *et al.* Machine Learning Applications in Control at ASDEX Upgrade. *86. Jahrestagung der DPG und DPG-Frühjahrstagung der Sektion Materie und Kosmos (SMuK) P12.29*, Dresden, Germany (2022)
- [XXXV] **ORAL** P. Heinrich *et al.* ASDEX Upgrade shattered pellet injection experiments. *86. Jahrestagung der DPG und DPG-Frühjahrstagung der Sektion Materie und Kosmos (SMuK) P11.45*, Dresden, Germany (2022)
- [XXXVI] **ORAL** G. Papp *et al.* ASDEX Upgrade SPI Experiments – The effect of shatter head geometry on SPI performance. *42nd Meeting of the ITPA Topical Group on MHD, Disruption and Control*, online, (2021)

Chapter 1

Motivation behind this project

In the recent years, nuclear fusion has gained a large attention of the media and politics: significant milestones had been reached at the Joint European Torus (JET) [2, 3] and National Ignition Facility (NIF) [4, 5]. At the same time, more and more start-ups are entering the fusion business [6]. In the center of the attention is the multi-national experimental reactor ITER with more than 30 participating nations, currently being assembled in Cadarache, France [7]. The Latin word “iter” is translated to “way” or “path” and is chosen as ITER is paving the path towards a clean, base-load energy source. It should demonstrate a fusion gain of $Q = 10$ – which means $10\times$ more thermal energy released than injected by the heating systems into the plasma [8–12] – and enables essential reactor relevant studies.

While ITER is currently in the assembly phase, enabling research is still necessary for further design of components and operation. One of these active research fields is disruption mitigation. Disruptions are undesirable events terminating the operation of the device and can result in large heat loads and forces on the structure, posing a significant threat to the machine integrity and operation [13–19]. Due to recent advancements in discharge control and disruption forecasting, it is expected (and also required) that disruptions in the full-performance operation of ITER are rare events [20–23]. Even though disruptions may be the rare exceptions, a reliable disruption mitigation system (DMS) is indispensable [11, 24]. One simplified analogy that I like to draw at conferences is that

“the DMS is the ‘air-bag’ system of fusion experiments and reactors”.

To ensure machine protection, it was decided in 2019 to apply the shattered pellet injection (SPI) technology for the disruption mitigation in ITER [10]: In our case, a frozen hydrogenic pellet, admixed with neon, is launched with velocities in the range of 70–800 m/s towards the plasma. Less than half a meter away from the plasma surface, the guiding tube has a miter bend and the pellet is shattered inside this “shatter head” increasing the surface to volume ratio of the frozen pellet material. The goal is to convert the potentially harmful plasma energy into isotropic radiation, mitigating the effects of the disruption. In simple words, one may compare this technique to

“shooting with a hydrogen/neon ice shotgun into plasmas, mitigating the effects of the worst case scenario of fusion experiments and power plants”.

However, while phrasing it like this may make the whole endeavor sound like a trivial task, the processes from pellet generation, launching, and shattering required to conceptualise & build many “first of a kind” experiments. The concept of the shattered pellet injection was first tested at the tokamak DIII-D in 2009 [25, 26]. After the decision of the ITER organization (IO) in 2019, many more machines deployed SPI systems, such as JET [26], KSTAR [27, 28], ASDEX Upgrade [29, 30], HL-2A [31], J-TEXT [32, 33],

and EAST [34–36]. Each of these experiments help to study certain aspects of shattered pellet injections: for example the two toroidally separated SPI locations at KSTAR allow to investigate the toroidal asymmetries and the role of synchronised injections [27, 28], while injections into JET illustrate the effectiveness of SPI in large devices [37–40].

In a multi-million euro project, a highly flexible SPI system was built for the tokamak ASDEX Upgrade (AUG) to provide dedicated design input for the ITER DMS that no other system could deliver. The outstanding feature of our SPI system is the unique opportunity to study the effects of varied fragment size & velocity distributions independently as well as the effect of pellet compositions on the SPI-induced disruptions. To help deliver the critical input needed for the ITER DMS design, AUG also received a major SPI-related diagnostic upgrade in preparation of the experiments. With this, AUG has the world-wide best diagnostic setup to assess toroidal asymmetries of the radiated powers for different injection & pellet parameters.

This project consists of more than just building and testing a machine protection system: it involved months of laboratory commissioning (papers B [30] and L [29]), during which a versatile pellet fragmentation database was created, vital for validation of pellet generation, launching and shattering codes [41–45] (papers H [46], I [47], and J [48]). Based on around 1300 launched pellets, three final candidates of the shatter head geometries were selected for their first experimental campaign at ASDEX Upgrade in 2022.

The project also includes three direct modelling efforts at the Max Planck Institute for Plasma Physics (IPP) (papers C [49], D [50], and N [51]) accompanying the experiments. Hereby, the experimental results are indispensable for benchmarking these codes, allowing to extrapolate to ITER-relevant plasmas. On the other hand, these codes allow us to investigate phenomena, that are otherwise difficult or even impossible to assess in the experiment. All of this with the goal of preparing a solid basis for the DMS of ITER and future fusion power plants (papers A [52], K [53], and M [54]). Besides the physics understanding, the data collected also contributes to multi-machine studies, extrapolating to ITER parameter spaces (paper E [55]).

Given the strict timeline of ITER with the final design review in 2024 [56, 57], a significant fraction ($\approx 22\%$ [58]) of the AUG machine time was assigned to the SPI project in 2022 before a planned two year break for machine upgrades.

My contributions to this project include the commissioning of the system, preparation & execution of the experiments, and subsequent analysis of experimental results. By executing some of the experiments as the scientific coordinator and the involvement in different international projects, I contributed to building a solid basis for the ITER DMS design with us all having one shared goal in mind:

TUTEM MONSTRAT ITER.

(He shows the protected way.)

In the following chapters, I present my results of this more than three year long journey.

Outline of this thesis

In chapter 2 I introduce the topic of this thesis: disruption mitigation via shattered pellet injections. First, a brief introduction to nuclear fusion and the tokamak concept is provided. I discuss the chain of events of disruptions, certain phenomena that can occur, and their potential harm to the device. The disruption mitigation strategies via material injection are introduced with focus on the main topic of this thesis – the SPI. Hereby, I provide a short overview of the relevant physics basis and strategies, experiments & modelling, and the ITER disruption mitigation system.

The main research objectives and experiment phases of the ASDEX Upgrade SPI system are introduced with a brief summary of the results and references to the according chapters in my thesis. The first of these research phases I contributed to was the laboratory phase of the SPI system, which I discuss in detail in chapter 3.

In chapter 3 I introduce our SPI system with focus on the laboratory commissioning phase. It covers a description of the main components of the system during the laboratory commissioning as well as the integration of the system into the environment of AUG. I discuss the pellet desublimation process and potential quality issues that can arise, together with our counter-measures. An important task during the laboratory phase was to develop pellet launching recipes, for which I developed a metric to predict the pellet detachment state. The shattering process is discussed, which includes the comparison of the different shatter head geometries, relevant for the interpretation of the experiments performed at ASDEX Upgrade in chapters 5 and 6.

In chapter 4 the experimental setup of the AUG experiments and plasma target scenarios are discussed. I provide a brief overview on the tokamak ASDEX Upgrade and the discharge control system. The diagnostics that will be covered in this thesis are described with strong focus on the main diagnostic for this thesis – the foil bolometers – and the calculation of the radiated energies. I provide an overview on the different plasma scenarios used in the 2022 experiments. The main scenario – the 1.8 T H-mode used for the SPI experiments is discussed in more detail, which I focus on in the analysis in the chapters 5 and 6.

In chapter 5 I present the different phases of the SPI induced disruptions as well as the change in disruption behavior with increasing neon content in the pellets. The effect of the SPI parameters on this disruption evolution is discussed for which the material assimilation is an important parameter.

While I already connect the different disruption phases to peaks in the radiated power, I focus on the analysis of the radiation characteristics in chapter 6.

In chapter 6 my radiation analysis is discussed with the radiated energy fraction and radiation asymmetries as the main focus. In the context of this thesis, I refer with the term “radiation” mainly to non-ionizing radiation. I present the derivation of f_{rad} and the experimental values of the 2022 campaign. The influence of the shattering parameters (i.e. fragment size & velocity) are discussed with the help of a heuristic fit function. I describe the radiation asymmetries qualitatively before showing quantitative assessments via the toroidal peaking factor (TPF). Hereby, also the effect of the shattering parameters

is discussed. The toroidal asymmetries during the phases of the main fragment arrival and vertical displacement event (VDE) are provided, before I compare of the results of the 2022 experiments with results from AUG SPI modelling (INDEX, DREAM, and JOEREK).

In chapter 7 I summarise this thesis including my contributions to successful experiments in 2022.

As the experiments with the SPI system will continue in the 2025 experimental campaign, I also want to provide a brief outlook at the end.

Chapter 2

Introduction

2.1 Nuclear fusion & the tokamak concept

Nuclear fusion describes the process of fusing light nuclei into heavier ones, typically releasing large amounts of binding energy in the process [59, 60].

The reactants most commonly envisioned for the power generation of future fusion reactors are deuterium (D_2 or D) and tritium (T_2 or T). These are the heavy isotopes of hydrogen, where the most frequently appearing isotope with a single proton in the nucleus is referred to as protium (H_2 or H). The D–T reaction is typically selected as the maximum fusion cross section at reactor relevant plasma temperature (T) around 10–20 keV (≈ 115 –230 mio. °C) is orders of magnitude higher compared to other reactants, e.g. D–D or D– ^3He [60]. During the D–T fusion process, a helium nucleus and a neutron are produced, while about 17.6 MeV of binding energy is released [59, 60]. Determined by their mass ratios, the helium nucleus carries around 3.52 MeV, the neutron 14.06 MeV [59, 60].

ITER and AUG are both based on the tokamak principle. The acronym comes from the Russian expression for *toroidal chamber with magnetic coils* (tokamak), describing a concept for the magnetic confinement of the plasma [59, 61]. To provide a stable confinement, nested flux surfaces of twisted field lines are required [59, 61]. The toroidal magnetic field (B_{tor}) component (definition of the direction in figure 2.01) is externally generated by the toroidal field coils, while the poloidal magnetic field (B_{pol}) component is generated in the tokamak concept by driving a toroidal plasma current (I_p). Additional poloidal field and shaping coils are used to control the plasma position and shape [62–64]. The plasma current is induced in the plasma by the central solenoid via the transformer principle (inductive current drive) [59, 61]. The downside of this approach is the inherently pulsed nature of tokamaks and current driven instabilities [61]. Each of these experimental runs or pulses is referred to as a “discharge” or “shot” (operational days are often referred to as “shot days”). However, it had been shown, that a large fraction of non-inductive current drive is possible [65], which is an active area of research [66, 67]. The induced current in the plasma will also heat it via the Ohmic heating (plasmas with only Ohmic heating are also referred to as “Ohmic” discharges). While it may sound unintuitive at first – based on our every-day-life experiences with electricity & conductors – the plasma resistivity (η) decreases proportional to $T^{-3/2}$ [60, 68]. As a consequence, Ohmic heating becomes ineffective at temperatures above a few keVs, thus additional heating sources are necessary to further increase the plasma temperature beyond 1–3 keV [69, 70]. The neutral beam injection (NBI) method relies on energetic neutrals injected from the plasma periphery [71, 72]. They are ionised in the core and loose their energy via collisions [71]. In electron cyclotron resonance heating (ECRH) [73] or ion cyclotron resonance heating (ICRH) [74], externally launched waves (GHz for electrons; MHz for ions) are used to heat the plasma [60]. In 1982 [76] it was observed that with increasing heating power the energy confinement suddenly increases by forming an edge pedestal and with it increasing the core plasma temperatures [77]. This regime was later called high confinement mode

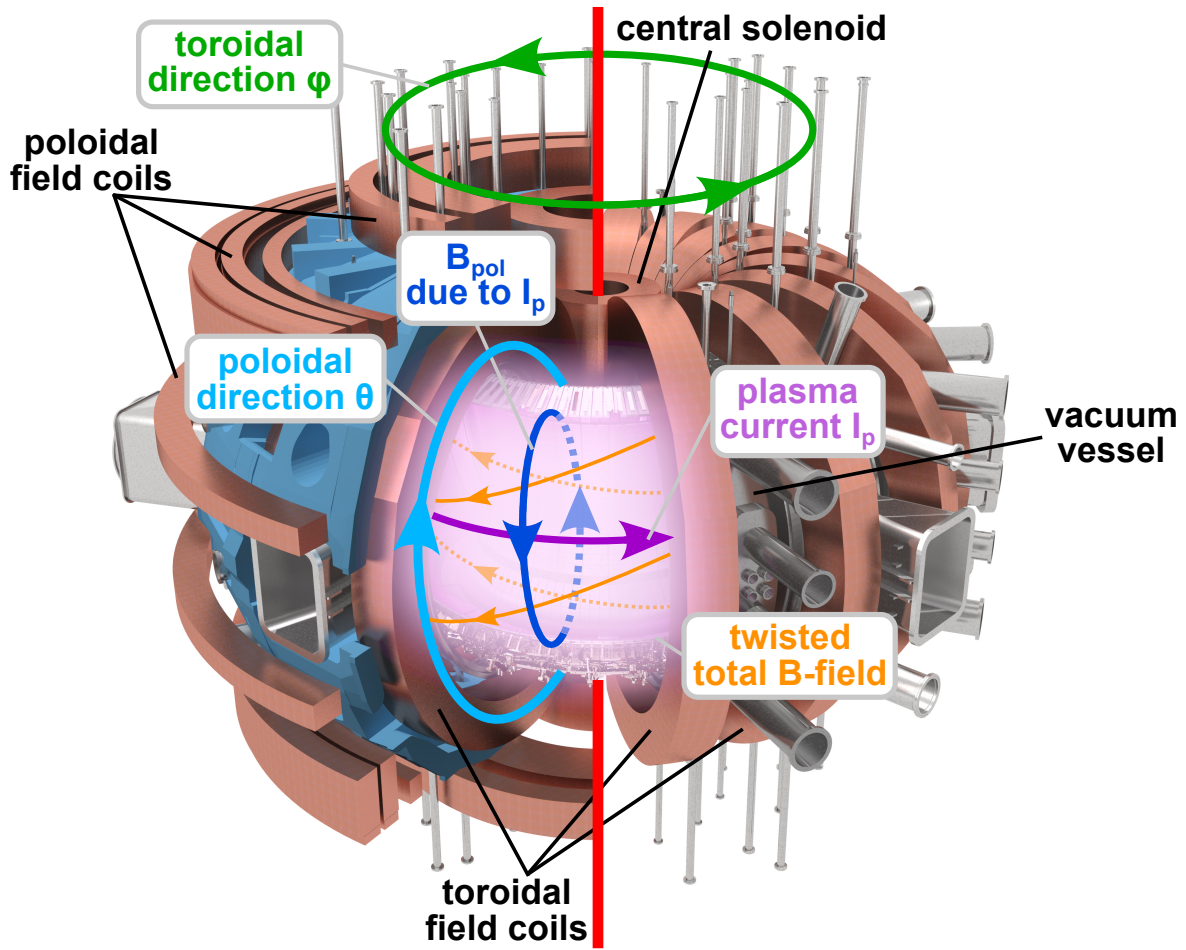


FIGURE 2.01: Cut through the individual layers of the vessel of AUG. Some of the key technical components (black) and plasma physics concepts (coloured) are illustrated. The combined images are taken from the image database of the Max Planck Institute for Plasma Physics [75].

(H-mode) in contrast to the low confinement mode (L-mode) [77–79]. Ever since, the H-mode is highly reactor relevant [79–82] and consequently the main target plasma for our SPI experiments.

In general, a high ratio of plasma pressure to magnetic pressure (β) is desirable for future fusion power plants, as it influences the viability and costs of the reactors [68, 83, 84]. In an equilibrium condition, the plasma pressure (p) has to be balanced by the magnetic pressure, thus the force balance can be expressed by $\nabla p = \mathbf{j} \times \mathbf{B}$ with the current density ($\mathbf{j}$) and magnetic field ($\mathbf{B}$) [68, 85]. On the nested flux surfaces, p is constant, consequently, the vectors of $\mathbf{j}$ and $\mathbf{B}$ lie within these surfaces and the integral over the magnetic flux vanishes [68]. Therefore, these flux surfaces can be used as a radial coordinate labelled by either the toroidal magnetic flux (Ψ_t) or poloidal magnetic flux (Ψ_p) [68]. By example using Ψ_p , the plasma normalized radius (ρ_{pol}) is frequently used to indicate the radial position inside the plasma. Here, a value of 0 is used for the plasma center (“on (the magnetic) axis”) and 1 for the separatrix – the last closed flux surface (LCFS). Using the magnetic fluxes, the plasma safety factor (q) is defined as

$$q = \frac{d\Psi_t}{d\Psi_p} \xrightarrow{R \gg a} q \approx \frac{a \cdot B_{tor}}{R \cdot B_{pol}} = \frac{\text{number of toroidal turns}}{\text{number of poloidal turns}}, \quad (2.01)$$

which is a critical factor for the plasma stability [60,68,85–87]. In the toroidally symmetric tokamak geometry with a large aspect ratio ($R \gg a$) it describes the number of toroidal turns of a field line until it will conduct exactly one poloidal turn, closing on itself [85]. For plasma stability – therefore disruption physics – low order rational surfaces within the plasma play an important role [68,85,86]. Rational flux surfaces are defined by a rational value of q , thus can be expressed by

$$q = \frac{m}{n} \quad m, n \in \mathbb{Z}. \quad (2.02)$$

Hereby, low order rational surfaces (small values of m, n) are most relevant, as a low number of toroidal and poloidal turns are necessary until the field line closes in on itself and instabilities can grow rapidly due to the short connection lengths [85, 88, 89]. Due to stability considerations, the values of the q -profile typically vary between $q_0 \gtrsim 1$ (internal kink/sawtooth instabilities [90–92]) in the plasma core and 3–4 (external kink instabilities/infernal modes [93, 94]) in the edge region [68]. Therefore, the $q = 2$ rational surface is typically present inside the plasma, playing a special role in the context of disruptions [68, 86]. Here, large perturbations, e.g. by injected material during disruption mitigation, can cause strong magneto-hydrodynamic (MHD) instabilities which may lead to a disruption. For this reason, a strong drop of plasma temperature within the $q = 2$ rational surface is used in the papers C [49] and E [55] to indicate the onset of the thermal quench (TQ). As the q -value at the separatrix diverges, the plasma safety factor at the edge (q_{edge}) is often experimentally described with the plasma safety factor at $\rho_{\text{pol}} = 0.95$ (q_{95}).

2.2 Disruptions in tokamaks

While the plasma current creates the poloidal magnetic field component – necessary to ensure the confinement of the plasma – it makes the plasma prone to so-called disruptions [8, 17, 95–97]. A major disruption [98] comes with the sudden loss of the confinement of the plasma. If not mitigated, this can lead to large mechanical forces [13–16], high heat loads on the plasma facing components (PFCs) [17–19] and can generate a runaway electron (RE) beam with the risk of causing strongly localised heat loads [99–101]. Therefore, reliable disruption mitigation techniques are required, which often involves the injection of elements with high nuclear charge number (Z) (neon in our case). These impurities radiate strongly, hence spreading the thermal loads over a larger area compared to unmitigated disruptions, described in more detail in section 2.3. The potential causes of disruptions are numerous [102, 103] with the three main stability limits being the current, density and pressure limits, respectively [104].

In the following, I will introduce the different phases of disruptions. Note, that the chain of events also depends on the cause of the disruption and mitigation strategies, hence the exact dynamics might vary. I will discuss the specific disruption phases of the SPI induced disruptions in more detail in section 5.1.

Figure 2.02 shows the different phases of a disruption. In our example, the disruption is initiated by shattered pellet injection of a 100% neon (Ne) pellet. As the material enters the plasma from the outside, a first decrease in thermal energy (W_{th}) and with it a drop in the plasma current can be observed. This phase is denoted as the pre-thermal quench (pre-TQ) phase. As the name suggests, this phase ends with the onset of the thermal quench (TQ), where the plasma temperature rapidly drops, plasma resistivity

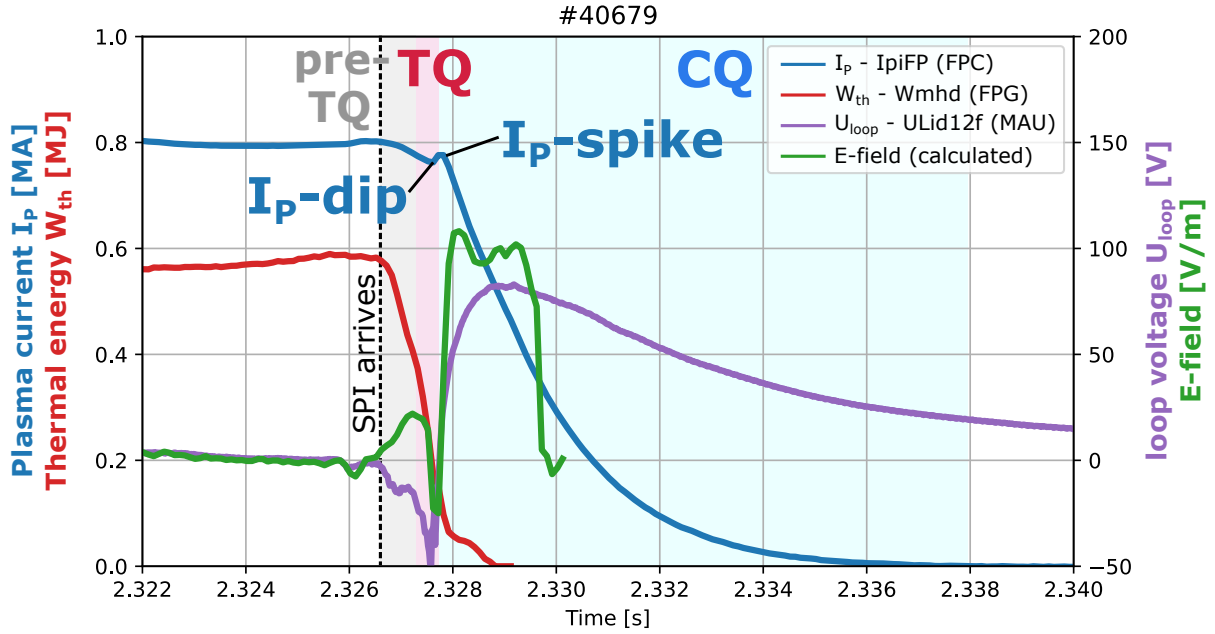


FIGURE 2.02: Disruption phases for a 100% neon SPI with plasma current (I_p), thermal energy (W_{th}), loop voltage (U_{loop}) and core electric field (E-field). The electric field is calculated following G. Pautasso *et al.* [105]. As the fragments enter the plasma at $t = 2.3266$ s ($t_{SPI-trigger} = 2.30$ s), the thermal energy is reduced during the pre-thermal quench (pre-TQ) phase and with it a small drop in the plasma current is observed. During the TQ, the thermal energy rapidly drops even further and the magnetic field lines become stochastic. The IP-spike forms due to conservation of helicity and the plasma current decays exponentially during the current quench (CQ) afterwards.

increases, and a stochastisation of the magnetic field lines due to reconnection takes place [106–108]. Note, that the final stochastisation event – included in the term “thermal quench” in the context of this thesis – is recently also separately referred to as the global reconnection event (GRE) in the literature [109] (see also paper E [55]). The flattening of the plasma current profile during the TQ causes the characteristic plasma current spike (IP-spike) as the conservation of helicity requires an increase in the total plasma current to counteract these changes [110, 111]. This IP-spike can be up to 10% of the initial plasma current [96, 98, 111] and depends on the change of the plasma current profile [96, 111–113]. Consequently, the quantity and kind of material added to the plasma (e.g. impurities for disruption mitigation) affects the changes of η and with it the properties of the IP-spike (i.e. the height and width) [107, 111, 114].

The timing of the TQ can be determined in various ways described in paper E [55] – e.g. by electron temperature measurements via electron cyclotron emission (ECE) or observation of radiation spikes in the soft X-ray (SXR) range. However, when large amounts of material are injected into the plasma – our SPI-pellets have $\approx 100\times$ more particles (i.e. $\approx 1.5 \times 10^{22}$ D₂ molecules) than the pre-injection plasma – the ECE measurements frequently go into density cut-off [115, 116]. For our typical magnetic fields strengths of 1.8 T (on axis) in the SPI experiments in 2022, the cut-off frequencies are in the order of $\approx 6.3 \times 10^{19}$ [m³] (calculation in the appendix A.1), which is typically exceeded in the pre-TQ phase (compare figures 4.07b – II and 4.08b – II). Therefore, due to its simplicity,

the minimum in the plasma current before the IP-spike (IP-dip) [117] is used frequently as a first approximation of the TQ onset time (t_{TQ}) and will be also used throughout this thesis.

In the cold and resistive post-TQ plasma, the plasma current is decaying over time, which is referred to as the current quench (CQ). In an ideal case, this decay would continue until the plasma current has reached zero. Hereby, the initial decay rate of the plasma current after the IP-spike depends on the plasma inductance and resistivity of the post-TQ plasma [118–120]. As the resistivity strongly depends on the temperature ($\propto T^{-3/2}$ [60, 68]), the early CQ decay rate (i.e. $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) is sometimes used as a proxy for the assimilation of the material during the SPI: higher amounts of assimilated impurities (neon in our case) inside the plasma will lead to a colder plasma temperature, higher resistivity and ultimately to a faster CQ and smaller IP-spike [119–121].

However, the plasma current does not necessarily decay to zero during the CQ: a beam of so-called “runaway electrons” (RE) can form, which may carry a large fraction of the initial plasma current [122–126], indicated in figure 2.03. The friction force on the electrons

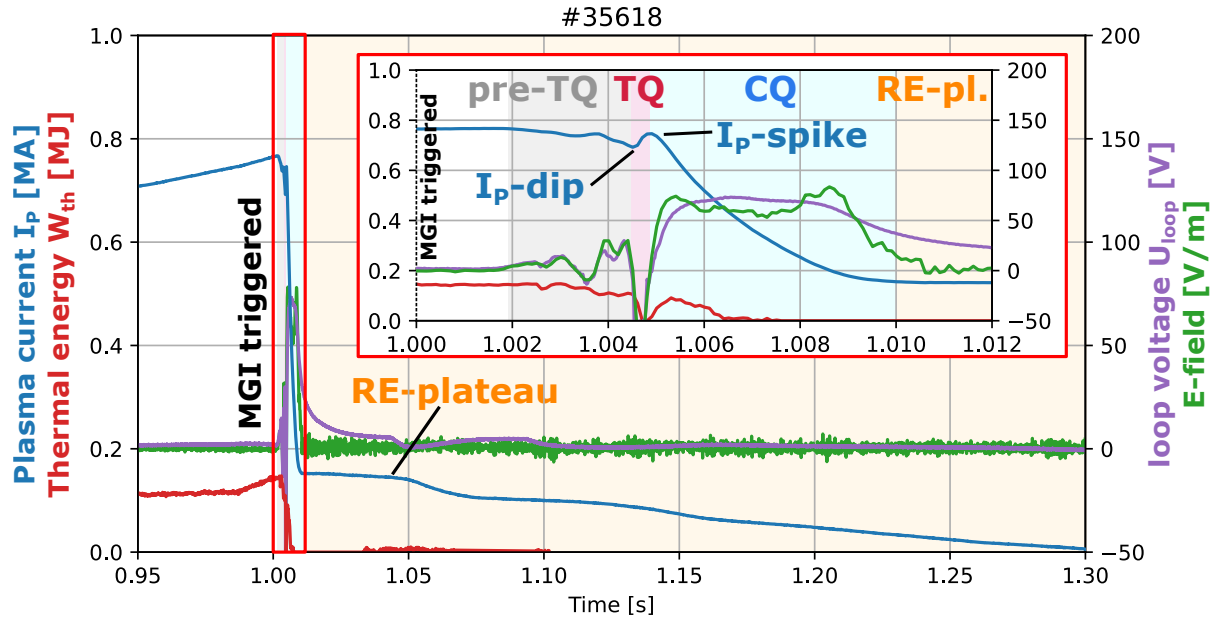


FIGURE 2.03: Disruption phases for an 100% argon MGI with the same signals as shown in figure 2.02. The MGI-valve is triggered at $t_{\text{MGI-trigger}} = 1.0$ s and is opened within 2 ms [127]. This discharge setup is designed to study REs [105, 128–130]. A RE-beam forms, carrying $\approx 25\%$ of the initial I_p in the beginning of the RE-plateau phase.

inside the plasma is a non-monotonic function of the electron momentum (p_e). Electric fields above the critical electric field (E_{crit}) accelerate electrons with p_e above a critical momentum (p_{crit}) to relativistic energies: the “runaway process” [125, 126]. Since large electric fields are present during the CQ (see figures 2.02 and 2.03), disruptions come with an increased risk of generating REs. This becomes even more dangerous, as the initial seed electrons can collide with other electrons from the thermal bulk, generating even more REs in the process [126, 131–133]. Via this so-called “avalanche process”, even tiny amounts of initial seed runaway electrons (in the order of $\approx 10^{-8}$ A and less [131]) can evolve into a multi-megaampere REs-beam in large devices such as ITER [126, 131–133]. As there

will always be sources of seed REs, especially in the presence of activated wall materials, strategies to suppress RE-beam formation and their mitigation are essential [126, 131–133]. One concern about these RE-beams is their interaction with the surrounding structures: if a RE-beam hits the PFCs, high & localised heat loads can lead to strong melting effects [99–101, 134, 135]. Depending on the wall material [12], these electrons can also penetrate deeply into the wall, depositing their energy further inwards and might even cause damage to the cooling pipes behind the wall elements [24, 136, 137]. As the acceleration of the electrons is a critical phase, increasing the free electron density (n_e) in the plasma core before the onset of the TQ is one attempt to suppress the generation of RE-beams, as $E_{\text{crit}} \propto n_e$ [125, 126, 132, 138]. While impurities with high-Z in the core could provide a large amount of electrons, their larger number of potentially still bound electrons may even worsen the situation [132, 139–144]. In fact, injections of high-Z impurities – like argon – via massive gas injection (MGI) are routinely used at AUG to generate strong RE-beams for dedicated studies [105, 128–130, 145–147]. Consequently, it is rather envisioned to increase the core densities by injection of hydrogenic material (see section 2.3).

If a RE-beam were to emerge in an ITER disruption, the position control of the beam is essential to avoid the RE–wall–impact before mitigation measures had been applied [148]. However, maintaining plasma position control long enough during a disruption is a difficult task. Especially, shaped tokamak plasmas are vertically unstable and require an active position control of the plasma [149, 150]. The vertical elongation of these plasmas – favorable for confinement, hence highly reactor relevant – is generated by a quadrupole moment produced by the poloidal field/shaping coils [149–151]. For a vertical displacement from the plasma rest position, this field can accelerate the plasma further in the direction of the displacement [151]. During this so-called vertical displacement event (VDE) the vertical position control (z-position) of a plasma is lost [16, 53, 151, 152]. If not happened before, the plasma will start to disrupt once it comes into contact with the wall. A “hot VDE” describes an unmitigated VDE, which can lead to strong heat loads and vessel forces [53, 151]. They may appear if the plasma position control fails in an unpredicted event and disruption mitigation is not on time. If the mitigation takes place early enough during or even before the VDE, the heat loads and vessel forces can be reduced significantly [53, 151] turning it into a so-called “cold VDE” [16].

The CQ induces a vertical shift of the plasma which can overwhelm the capabilities of the vertical position control. Following this, the VDE-motion will be accelerated during the CQ [151, 153, 154] and can even become a function of I_p [155]. Consequently, in most disruptions [102], plasmas will become vertically unstable at some point and hit the PFCs before the plasma current has fully decayed [154]. Hereby, the vertical displacement for cold VDEs – as they appear after disruption mitigation actions – tends to be towards the active X-point [150, 156], whereas for hot VDEs the direction of the movement depends strongly on the evolution of the disruption [157].

Part of the initial plasma current is located in the previous scrape-off layer (SOL) plasma, closing the current loop through the conducting structures around the plasma [53, 151, 152]. This is referred to as the halo current (I_{halo}), which can cause high electro-magnetic (EM) forces on the structure [53, 151]. These currents can be measured inside the conducting components around the plasma [158] (see “shunt current measurements” in section 4.1). Hereby, disruptions with lower post-TQ plasma temperatures (cold VDEs), thus shorter CQ durations, tend to show lower halo currents and consequent vessel forces [53, 151]. Additionally, they will exhibit less asymmetries compared to hot VDEs [53, 151]. These

cold VDEs or radiation dominated disruptions require impurities in the plasma as observed for mitigated plasmas via impurity injection [16, 151]. Therefore, the typical disruption mitigation techniques aimed to reduce the thermal loads – as they will be introduced in section 2.3 – will also mitigate the effects of the VDEs. This also explains why we observe higher (toroidal) asymmetries, heat loads and vessel forces for non- or poorly mitigated VDEs during our SPI studies (i.e. 100% D₂ pellets or low neon doping) compared to injections with a high neon fraction. This is discussed in detail in [paper K](#) [53] as well as in the chapters 5 and 6.

Energy balance during disruptions

The plasma energy can be split into a magnetic energy (W_{mag}) and thermal energy (W_{th}) component. During a disruption, the pre-disruption energy $W_{\text{mag}} + W_{\text{th}}$ is released. The energy balance during a disruption

$$W_{\text{mag}} + W_{\text{th}} \implies W_{\text{c}} (+W_{\text{RE}}) + W_{\text{rad}} + W_{\text{con}} \quad (2.03)$$

is illustrated in figure 2.04 and the individual terms explained in the following.

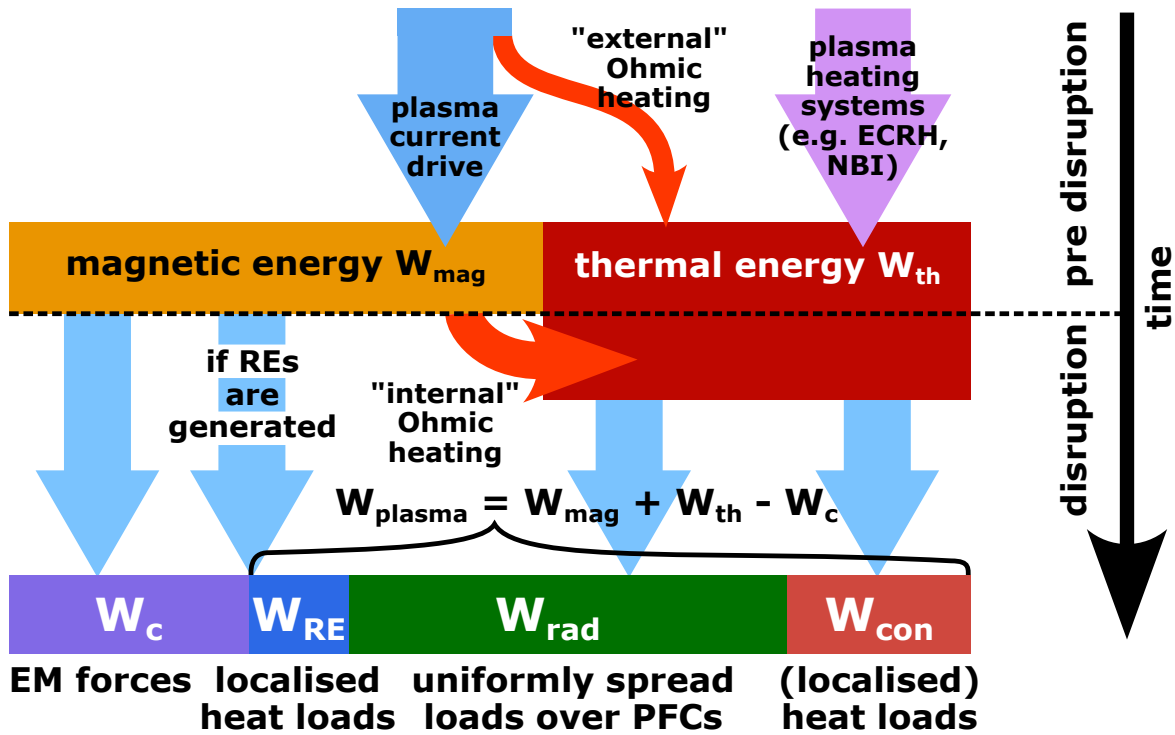


FIGURE 2.04: Energy balance during the disruption. The pre-disruption energy $W_{\text{mag}} + W_{\text{th}}$ is converted into $W_{\text{c}} (+W_{\text{RE}}) + W_{\text{rad}} + W_{\text{con}}$. As the radiated energy (W_{rad}) spreads the heat loads uniformly over the PFCs, disruption mitigation aims to increase the fraction of W_{rad} as much as possible (within certain boundary conditions). Adapted figure published in [paper A](#) [52].

Over the course of the disruption, W_{mag} can either be coupled into the surrounding structure, converted into W_{RE} or internally converted via Ohmic heating into W_{th} . The latter happens mainly in the cold, post-TQ plasma during the CQ [159] also shown in [paper N](#) [51]. Part of the thermal energy will be radiated during this process – strongly

depending on the available impurity content in the plasma – and the remaining energy will be conducted/convected to the PFCs [19, 24, 160, 161]. As the coupled energy (W_c) can lead to strong EM forces and W_{RE} as well as W_{con} can lead to surface melting of the PFCs, it is desirable to maximise the radiated energy (W_{rad}) within given boundary conditions (such as e.g. not generating strong RE-beams). Following the formula by M. Lehnen *et al.* [19, 160] and U. Sheikh *et al.* [162], the radiated energy fraction (f_{rad}) is defined as

$$f_{rad} = \frac{W_{rad}}{W_{plasma}} = \frac{W_{rad}}{W_{mag} + W_{th} - W_c}, \quad (2.04)$$

with the energy dissipated in the plasma (W_{plasma}) defined as [160]

$$W_{plasma} = W_{mag} + W_{th} - W_c. \quad (2.05)$$

For my radiation analysis in chapter 6, I expand this formula by an additional term that arises due to external heating during the disruption (see equation (6.01)). The radiated energy fraction will be one of the crucial metrics by which we can quantitatively compare the thermal load mitigation efficiency (maximizing f_{rad} is crucial in this aspect) as discussed in section 6.1.

The radiation can come from different sources inside the plasma:

- the ablated fragment material itself – emitting line, (charge exchange) recombination radiation as well as contributing to Bremsstrahlung,
- the background plasma, where changes in the plasma parameters (e.g. density and temperature) can change the radiation characteristics, and
- additional impurities that enter the plasma during the injection/disruption process [17, 163–168].

2.3 Disruption mitigation via material injection

As the consequences of disruptions on the machines can be severe [24, 101], a reliable DMS is required in order to ensure machine protection.

At the present day, massive material injection (MMI) is the commonly used disruption mitigation technique. The material is either injected in form of gas (massive gas injection (MGI)) or solids (“killer pellets” [169], SPI, dispersive shell pellet injection [170–172], ...) but also liquid injection techniques were developed [173, 174].

ASDEX Upgrade is equipped with five MGI valves, each connected to a gas reservoir: two ex-vessel valves are integrated into the DCS for machine protection [175], while three in-vessel valves are manually filled and only used for dedicated disruption experiments [127, 176]. The valves are opened within 2 ms and the gas can exit the reservoir and penetrate into the plasma [127]. More technical details are available in the thesis by M. Dibon [127]. For our SPI studies, the automated disruption mitigation by the DCS is deactivated.

Shattered pellet injections

With the decision to use the SPI technology for the ITER DMS [10], this mitigation technique became one of the main fields of research within the disruption mitigation community (see “RT03” within the 2025 EUROfusion WPTE programme [177]) and is rated as “highest priority/major impact” by the IO [178]. It allows the fast delivery of material into the plasma core even for large devices and at the same time the material ablation rates can be optimised via the shattering process [117, 121].

The three main objectives of the SPI are illustrated in figure 2.05. These are: the suppression/mitigation of RE-beams, thermal load mitigation, and reduction of vessel forces.

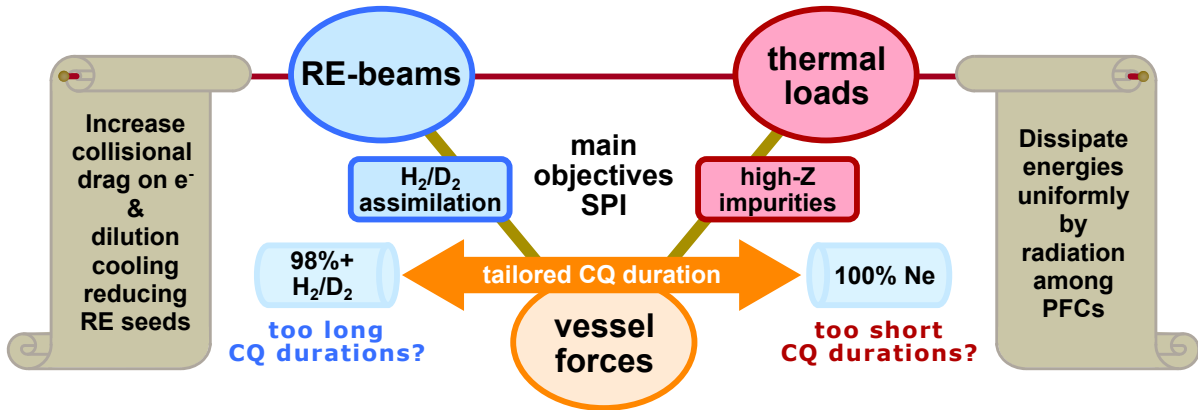


FIGURE 2.05: Three main objectives of the SPI: RE-beam suppression, thermal load mitigation, and reduction of vessel forces. The optimal disruption mitigation strategy will need to find the right balance for the assimilation of H₂ or D₂ for RE-beam suppression and high-Z impurities to dissipate the thermal loads uniformly via radiation. The consequent CQ duration will also affect the vessel forces.

To achieve these three objectives, certain sub-goals need to be reached:

- **RE-beam suppression – D₂ or H₂ assimilation:** As discussed in section 2.2, increasing the free electron density in the plasma core before the TQ will increase the collisional drag acting on the electrons [125, 126, 138]. For this, high assimilation fractions of D₂ or H₂ from the pellet material are required before the TQ onset.

Additionally, the hydrogenic pellet material leads to a slowly decreasing plasma temperature due to “dilution cooling”, reducing the risk of increased RE seed production compared to rapid cooling of the plasma [109, 131, 179, 180].

- **Heat load mitigation – radiation via high-Z impurities (Ne):** injected high-Z impurities can efficiently radiate in the core plasma. This will spread the plasma energy over a larger surface area compared to unmitigated disruptions, where most of the remaining thermal energies are lost via conduction/convection to the wall [160]. Therefore, maximizing the radiation reduces the heat loads during the disruption [109, 160].
- **Force mitigation – reduction of currents in the conducting structure:** high currents that are induced inside the conducting structures around the plasma

(i.e. eddy [181, 182] & halo currents [53, 151, 152]), can cause large forces. Short CQ durations (large, early dI_p/dt rates) can induce strong eddy currents [181, 182], while long ones pose the risk of high, asymmetric halo currents [16, 53, 151]. Therefore, the present mitigation requirements for the ITER DMS contain a CQ duration in the range of 50–150 ms [24, 183].

To achieve a reliable disruption mitigation, all of the three objectives need to be addressed. Consequently, maximizing the radiative energy losses is one aspect, however, this will have to take place within boundary conditions that are set by the ability to suppress the generation of strong RE-beams [132, 139–144], their mitigation [184], and a reduction of vessel forces [181, 182]. Within this thesis, I will focus on the analysis of these radiative losses and their “optimisation”, however, one has to keep the motto “more is not always better” in mind.

Different disruption mitigation scenarios had been developed addressing these three objectives, which are shown in figure 2.06. While for the AUG SPI system, deuterium is used, for ITER, these schemes will involve the injection of protium. This is advantageous for multiple reasons:

- the fuel-recycling plant separating D_2 and T_2 is not flooded with D_2 gas (harder to separate from tritium than protium [185]) and
- no additional fusion reactants ($D_2 + T_2$) are added.

The H_2 for the different injection schemes described in the following is simply replaced by D_2 for the experiments at ASDEX Upgrade.

- A Synchronised injection of H_2 -Ne-mixed pellets:** via the synchronised injection of multiple H_2 -Ne-mixed pellets, the material for the different aspects of the disruption mitigation are delivered simultaneously. Hereby, the synchronous injection from different toroidal locations may help to decrease toroidal asymmetries. For the experiments at AUG, synchronised injections of two pellets (via the three independent pellet guide-lines) were performed, hence this injection scheme was also often referred to as the “dual” injection scheme (in contrast to “single” injections with only one pellet).
- B Staggered injection of $H_2 + H_2$ -Ne-mixed pellets:** first, 100% H_2 pellets (or neon doped pellets to suppress the plasmoid drift – explained at the end of this section) are injected, followed by neon enriched pellets, triggering the disruption of the plasma. The hydrogen injection causes a pre-disruption dilution cooling and increases the free electron densities for RE-beam suppression, while the neon is supposed to radiate the majority of the stored energies [109, 117, 186]. While this injection scheme is more complex than the synchronised injection scheme, it can provide more time for the assimilation of the H_2 in the plasma.
- C RE-beam mitigation via H_2 pellets (“benign terminations”):** in case a RE-beam forms during the disruption, the injection of H_2 into the beam is currently investigated as a promising candidate for the RE-beam mitigation [109]. In these so-called “benign terminations” of the RE-beam [184, 187–191], the high neutral pressures after the hydrogen injection will cause a recombination of the background/companion plasma, thus a decreasing n_e . Together with a decreasing q -value in the

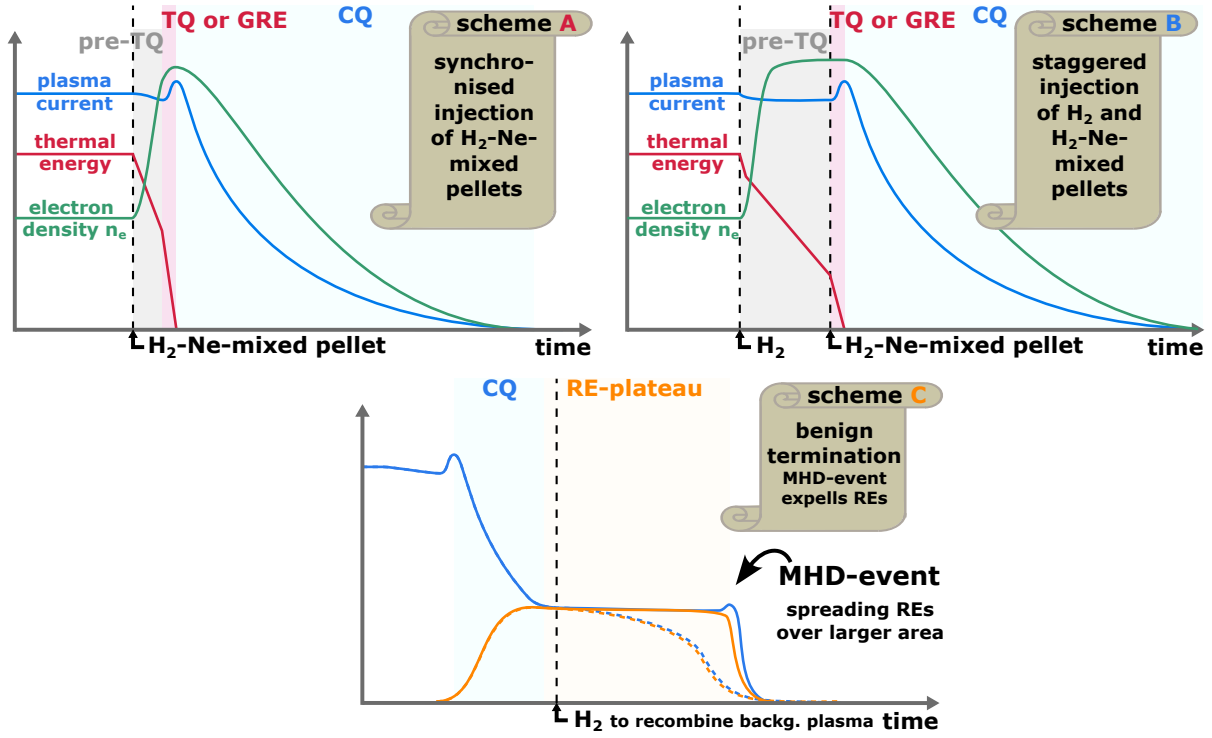


FIGURE 2.06: Injection schemes for disruption mitigation and RE-beam suppression (schemes A & B), as well as RE-beam mitigation (scheme C). Sketches adapted from M. Lehnen *et al.* [109] and experimental observations.

edge (e.g. by compressing the plasma), this will lead to the onset of strong MHD activity. This will lead to a rapid termination of the RE-beam, however, spreading the impact of the REs over a larger wetted area, thereby decreasing the localised heat loads [184, 187, 189, 190]. The hydrogen injection flushes out the high-Z impurities from the plasma, important to reduce re-avalanching at the final loss [189, 190].

In the 2022 SPI experiments at ASDEX Upgrade, the single, dual, and staggered injection schemes were tested. While the benign termination experiments are usually performed with argon (to generate REs) and deuterium MGI alone, on December 12th in 2024, we performed for the first time a 100% D₂ shattered pellet injection into the RE-beam at ASDEX Upgrade.

The ITER DMS To be able to prepare different sets of pellets for all of the above-mentioned injection schemes, the ITER disruption mitigation system will consist of 27 injectors, that are located at 4 different toroidal locations (number of injectors grouped inside one sector in brackets) [56, 186]:

- 24 (12 + 6 + 6) equatorial port injectors and
- 3 (1 + 1 + 1) upper port injectors.

At present, the ITER pellets are foreseen with the following dimensions [56, 186, 192, 193]:

$$L = 57 \text{ mm}, D = 28.5 \text{ mm}, \quad (2.06)$$

with pellet length (L) and pellet diameter (D). However, it had been reported, that these dimensions of the pellets might deliver too much material for the benign termination scheme of the RE-beam [191, 194].

Fragment ablation process Independent of the injection scheme, the deposition of the pellet material in the plasma core is indispensable for successful disruption mitigation via SPI. The assimilation of the material is set by a complex interplay of different pellet, fragmentation and plasma parameters.

Studies about the ablation processes of cryogenic material inside the tokamak environment have been conducted already over many decades as they are essential to understand the deposition of the fueling pellet material. Phenomena – such as the plasmoid drift [54, 195–197], striations [195, 198], and the rocket effect [183, 195, 199] – are observed for the small fueling pellets but also for fragments in SPI experiments. As the fragments enter the hot plasma, the outer layers of the pellet start to ablate [195]. Part of the neutral gas will quickly ionise and create a region of high β plasma around the fragments – the so-called “plasmoid” [195–197]. This region expands along the field lines and – together with the neutral gas cloud surrounding the fragment – shields the fragment against the incoming heat flux [62, 195, 196, 200, 201]. Hereby, the main driver of the parallel expansion of the plasmoid along the field lines is the pressure gradient, however, potential effects of the plasma rotation are also discussed [202, 203]. This plasmoid will experience an $\mathbf{E} \times \mathbf{B}$ -drift directed towards the low field side (LFS) [54, 195–197, 204]. The consequence will not only be that the material is deposited further outwards (towards the LFS) [195] but this plasmoid drift can also induce a rocket effect on the fragment itself [183, 195, 199]. As the plasmoid drifts towards the LFS, less shielding is provided to the side of the fragment which faces the high field side (HFS). Consequently, more material will ablate on this side, which also accelerates the fragment towards the LFS [195, 199].

In AUG, the fueling pellets are injected into the plasma from the HFS as the pellets will be pulled inwards instead of being expelled by the plasma [163, 205, 206]. For shattered pellet injections that will take place from the LFS – as foreseen in the ITER DMS strategy – a suppression of this plasmoid drift is desirable. Doping hydrogenic pellets with small amounts of neon was found to decrease the plasmoid drift effect [196, 197, 204, 207]. This can lead to increased material assimilation in the plasma [208], also observed experimentally at AUG [117, 121, 209] (see section 5.4 and paper M [54]).

While the direct deposition further inside the core region remains desirable, strong MHD mixing events may help to transport the material from the edge into the core region [51, 131, 210].

2.4 SPI modelling

The experiments are accompanied by an increased interest in modelling, often indispensable for the interpretation of the experimental results [38–40] and designing new experiments.

The prescription of the fragment size & velocity distributions is a key factor for the SPI modelling. To determine the fragment size distributions for prescribed pellet velocities, the statistical fragmentation model developed by P. Parks [211], later refined by T. Gebhart *et al.* [212], is presently the most frequently used basis for the fragment size distributions in SPI modelling. It is also the currently used model to sample the fragment

size distributions for the SPI modelling of AUG. A different approach to get fragment size distributions for given pellet parameters is via peridynamic simulations of the fragmentation process, which had been done for the AUG SPI system [41–46], discussed in [paper H](#) [46]. While the Parks model does not agree quantitatively with the experimentally observed fragment size distributions during the commissioning phase of the AUG SPI system, the peridynamic simulations show good agreement, which will be further discussed in section 3.3.

The SPI disruption experiments at AUG are accompanied and complemented by modelling with three different codes:

INDEX The disruption simulator INDEX is used for AUG to investigate pellet and fragmentation parameter effects [49, 213]. It is an axisymmetric code, solving 1D transport equations together with 2D Grad-Shafranov equilibria [49, 213]. Therefore, while being computational not very expensive, it takes into account flux surface averaged plasma quantities [49, 213].

In the following, the results from the thesis of A. Patel [214] and [paper C](#) [49] are briefly summarised. At this stage, INDEX is used within the AUG project to scan for optimal fragment size & velocity distributions, as well as neon content in the pellet to maximise the material assimilation of the pellet and thermal load mitigation. The plasma temperature at the $q = 2$ rational surface reaching 10 eV is used as a semi-empirical TQ onset criterion [215]. This is important, as it was observed, that the timing of this TQ onset has a big influence of the final ratio of assimilated pellet material. Independent on the neon content inside the pellet, with larger fragments the TQ onset condition was reached later in time and more material could be assimilated in the simulations. Faster fragments reach the core plasma earlier and also ablate more material until the TQ onset condition is met. The fragment size distributions are generated following the Parks model [211, 212]. For injections with more than 1% neon inside the pellet, a significant cold front develops. It travels inwards following the ablation front of the shards with a slight delay, causing a plasma cooling from the outside. In contrast, pellets with less than 1% neon, often causes an inside-out cooling of the plasma. At present, these simulations are carried out for the pre-TQ phase as most of the material is assimilated before the TQ.

DREAM The Disruption and Runaway Electron Analysis Model (DREAM) [216] was also used to investigate the effect of the neon content on the evolution of the disruptions and the sensitivity to fragmentation parameters for AUG. DREAM is a 1D + 2P disruption and RE code [216]. Hereby, the 2P represents the two momentum dimensions, i.e. parallel and perpendicular, in the kinetic description. The background plasma is simulated via a 1D fluid description with a flux-averaged grid [216]. It offers the possibility to describe the REs either:

- also in the fluid picture (1D, flux-averaged),
- a fluid + kinetic hybrid picture (1D + 2P, bounce-averaged) or
- fully kinetic (1D + 2P, bounce-averaged) [216].

The DREAM simulations by P. Haldestam are discussed in detail in [paper D](#) [50], summarised in the following. For the SPI simulations performed for AUG, the 1D fluid

representation for the REs is used. This treatment was selected as the exact energy distribution is not required for these studies and is well enough treated by the full fluid picture. Additionally, it is further justified as in both – simulation and experiment – the RE population is negligible.

For each simulation run, the fragment size distributions are individually, randomly sampled following the Parks model [211,212]. For each neon content in the scan, 40 different realizations of the fragmentation process – each followed by its own DREAM simulation – are sampled for the same pellet parameters to estimate the sensitivity of the disruption behavior on the probabilistic fragmentation process.

Hereby, the 1D fluid DREAM simulations match the experimental observations well: while VDEs are not modeled, the CQ durations and the radiated energy fractions from the experiments are also obtained in the simulations. Additionally, the highest sensitivity on the different fragmentation realizations is observed for the neon doped pellets with 0.17% neon concentration, which also matches the experimental observations. I will provide a more detailed discussion of the experimental values in the respective chapters 5 and 6).

JOREK 3D SPI simulations with the non-linear, extended MHD code JOREK [217] had been performed for AUG as described in paper N [51]. In the following, I will provide a brief overview on these simulations and results relevant for comparison with the experiments.

The reconstructed equilibrium [218] of the H-mode discharge #40355 from the 2022 AUG SPI experiments was used for the plasma simulations. The fragment size distributions are also generated following the Parks model [211,212].

Scans in neon content with 0, 0.12, 1, and 10% neon in the pellet, as well as fragment size & velocity distributions were performed. In all simulations, a rapid drop in W_{th} of about 50% was observed right after the first fragments reach the plasma. It is caused by convective and conductive losses after the stochastisation of magnetic field lines in the edge region of the plasma. A prompt drop in W_{th} is also observed in the experiments, however, the reduction in W_{th} in the simulation is much higher. While the maximum ablation ratio of the 0.12% Ne pellets is highest – around 20% of the neon in the pellet – the overall highest assimilated amount of neon is observed for the 10% cases. Therefore, also the earliest t_{TQ} times and shortest early CQ durations are observed for the 10% Ne pellets.

A double-peaked radiation pattern is observed during the early stage of the disruption connected to a two stage cooling phase: the first peak is connected to the fragment arrival (fast conductive/convective losses) and the second to the TQ (radiation dominated).

Across all neon fractions in the pellets, smaller fragments and also faster fragments are observed to increase the material assimilation and radiation. Hereby, the most pronounced effect is observed also for the neon doped (0.12%) pellets, matching the experimental findings. The diverging observation of the “optimal” fragment size distribution compared to the experiments (see chapters 5 and 6)) is believed to be caused by an inaccurately modeled fragment ablation process, where the plasmoid drift effect is not well captured and pellet rocket effect is not considered. Depending on the pellet parameters, similar to the INDEX simulations, a change from outside-in to inside-out cooling is observed. Finally, the radiated energy fractions are comparable to the ones that I will discuss in chapter 6 for the ASDEX Upgrade experiments in more detail.

2.5 Main research objectives of the AUG SPI system

The ASDEX Upgrade SPI system was financed by the IO to provide crucial input for the design of their DMS and mitigation strategies. A major diagnostic upgrade for AUG – specifically targeted for the SPI experiments [117, 219] – and the unique design of our system allow to address open questions that remained for the finalisation the ITER DMS design until the final design review in 2024 [56, 57]. Three central research objectives for our system were identified:

1. Investigate the effects of fragment size & velocity distributions

Our system has the unique possibility to test the effect of different fragment size and velocity distributions on the disruption: three different shatter head geometries can be installed at the same time, each attached to an independent pellet guide tube. This way, the optimal shattering geometry for the ITER DMS was determined based on the results from AUG: The current DMS design plan foresees a rectangular shattering unit with a shallow 15.5° shatter angle, aimed to produce large & fast fragments [109, 220]. This design choice was based on the optimization of material assimilation and radiation characteristics, which are discussed in the chapters 5 and 6.

2. Assess radiated energy fractions & toroidal asymmetries of the radiation

For the AUG experiments in 2022, I observed radiated energy fractions up to 85%, which are strongly increasing with increasing neon content inside the pellet. The effect of the fragment size & velocity distributions are mostly relevant for neon doped pellets ($< 1\%$ neon). The high toroidal coverage of radiation measurements (see section 4.1) creates the unique opportunity to assess the toroidal radiation asymmetries of shattered pellet injections. One initial concern for future fusion devices is the phenomenon called “flash-melting”: a concentrated source of radiation close to the PFCs (as during the “radiation flash” at fragment arrival) could lead to melting effects (especially of materials with low melting points). High (toroidal) asymmetries of the radiation at high neon content SPI (high total radiation) would therefore be a concern. However, I observed a reduction of the toroidal asymmetries (represented by the toroidal peaking factor see section 6.2) by a factor of up to $\approx 50\%$ for increasing radiated powers, reducing this concern significantly. On top of this observation, the decision to change the first wall (FW) material of ITER from beryllium to tungsten [11, 12] (which was made public after the time of my analysis) further reduces the concern about flash-melting [109]. I will discuss the results of my radiation analysis in chapter 6.

3. Test & optimise synchronised/staggered injection schemes

First synchronised (“dual”) and staggered injections had been performed in the experimental campaign 2022 and more, dedicated experiments planned for 2025. We observed, that already the injection of small amounts of neon – as used to suppress the plasmoid drift – significantly reduce the time between the injection and the onset of the thermal collapse. This would not leave much time for the material assimilation of the hydrogenic pellet (to suppress the generation of REs) and would also require a precisely timed injection of the subsequent neon-enriched pellet(s) for thermal load and EM-force mitigation. The timescales of these injections are discussed in chapter 5.

To achieve these three research objectives, the experiments with the AUG SPI system can be divided in three dedicated phases:

- **Laboratory commissioning phase:** The SPI system was installed on a support structure in a dedicated testing laboratory at IPP. The system was attached to a test chamber and the fragment distributions were recorded with a ultra-highspeed camera. During this phase, around 1100 fragmentation videos were recorded to analyse the fragmentation process. At the same time, pellet desublimation and launching recipes were developed (see chapter 5).
- **Pellet launching into the empty tokamak vessel:** After the transfer of the system from the laboratory to AUG, we were allowed to inject pellets into the empty vessel of AUG on non-shot days. For these tests, only the pellet integrity camera and no fragmentation camera was available. The fast cameras installed for the plasma experiments could not record the fragmentation of the pellet due to missing illumination in the empty vessel amongst other reasons. The pellet tests were used to refine recipes (see chapter 5) and test the planned pellet launching recipes for the upcoming experiments to ensure successful injections.
- **Plasma experiments:** On the days of the plasma experiments, UHS cameras observe the pellet injection into the plasma (see chapters 5 and 6). For the experiments, mainly well tested pellet recipes were used. However, if changes in the injection plan were required, my simplified pellet detachment model (see section 3.2) allowed me to extrapolate new pellet launching recipes on the spot.

Chapter 3

The shattered pellet injection system of ASDEX Upgrade

Timeline of the experiments & my contributions My thesis work started with the extended laboratory commissioning phase of our SPI system that took place between end of May and October 2021. The injector built by PELIN LLC arrived at the IPP late April, was assembled in May and the first pellet launched on the May, 26th [221]. The tests and operations involved a small team of five people, with always at least two people operating the system and cameras. After the first commissioning of the system, the main objective during the laboratory phase was to record enough shattering videos for a detailed analysis of fragment size and velocity distributions and to develop pellet freezing and launching recipes. I created a graphical user interface (GUI) to manage the camera recordings, search through & analyse the pellet data base, as well as predicting pellet velocities & generating recipe look-up tables. We optimised the illumination setup for the fragmentation analysis with the UHS camera, that was performed by T. Peherstorfer during the laboratory testings. In total we had recorded around 1100 shattering videos before the system was transferred to ASDEX Upgrade between October and November, where no shattering videos could be recorded anymore (more details in section 3.2). During this laboratory phase, my main tasks involved the recording of the UHS videos for various shatter geometries, stable pellet recipe development and investigation of the different pellet quality aspects. The first pellet launched into the empty vessel of AUG was pellet identification number (pellet ID) #1391 on November 5th and the first piggy-back plasma injections on December 14th (pellet IDs #1409 – #1413) into the discharges #39888 – #39895. We used the injections into the empty vessel on non-shot days to refine and prepare the pellet launching recipes for the upcoming experiments. During the experiments, I operated the UHS cameras almost in full-time and developed new pellet launching recipes if changes in original experiment program were required on the shot day. With the experience after being involved in most of the around 2000 pellet launchings, extrapolating to new pellet recipes was possible for me within seconds to a few minutes. This was only possible with the knowledge about the pellet detachment regimes for which I developed a simple model. In June 2022, I was leading the SPI experiments as the scientific coordinator.

In this chapter I will provide an overview on the AUG SPI system, which will start with a description of the main components of the system. The results and parts of the text/figures in this chapter were also published in [paper B \[30\]](#).

3.1 Main components of the system

Within this section the main components of the SPI system are introduced as depicted in figure 3.01 – from gas mixing and pellet creation, to pellet launching and shattering. A more technical description of the components is given in [paper L \[29\]](#).

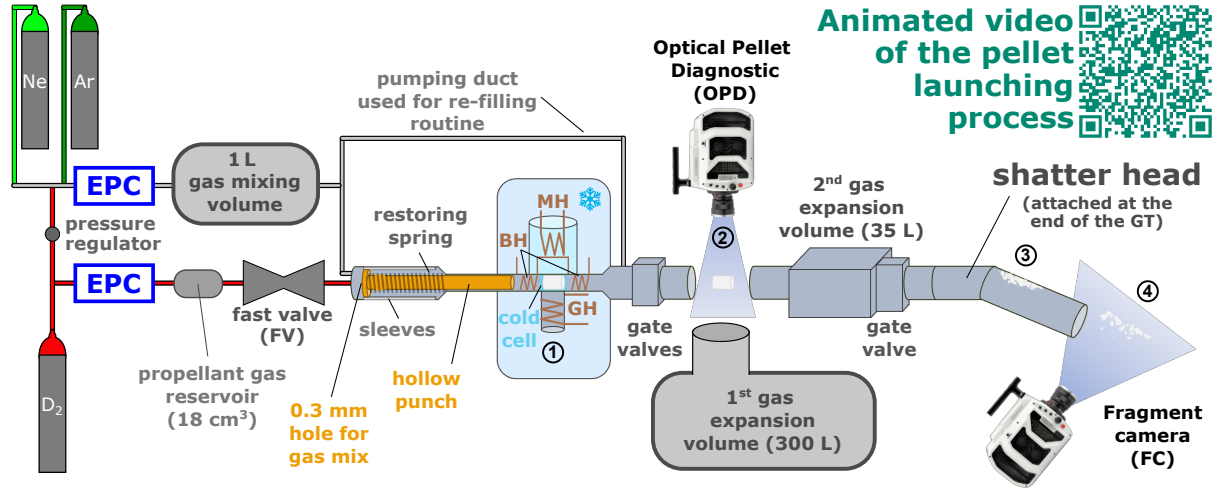


FIGURE 3.01: Sketch for one of the three independent injection lines of the SPI system with its main components in the laboratory environment. An animated video is available following the QR code [222] or online material of [paper B \[30\]](#). The individual components are introduced in this section. Note, that the fragment camera was only available during the laboratory commissioning phase. The steps (1) – (4) depict the timeline of the pellet: desublimation, observation in the OPD, shattering, and the observation in the fragment camera. The image of the Phantom v2012 UHS cameras are taken from [223] with their permission.

Gas handling system The gas supply system for the AUG SPI system was designed for using protium/deuterium, neon, and argon (see figure 3.01). With the decision of the IO to use only protium and neon for their DMS, the pellet generation and shattering characterisation was only performed for 100%-D₂, 100%-Ne and deuterium-neon mixed pellets in the laboratory phase (section 3.2 and section 3.3). The possibility to generate argon pellets might be useful for future RE studies, as the RE-beam is routinely created via argon MGI at AUG [105, 128], thus argon pellets could potentially be used to generate REs.

Pellet gas mixing volumes Before the pellet creation, the corresponding 1 L pellet gas mixing volume (GMV) is filled with the desired gas mix (one volume for each guide line). Hereby, the electronic pressure controller (EPC) can control the pressure inside the GMV with a minimum of 17.5 mbar for each gas species [224]. The minimum neon pellet mixtures we directly created contained 1.25% Ne and 98.75% D₂ inside the GMV. Hereby, the GMV is filled with 25 mbar neon gas first and afterwards deuterium is added until the total maximum pressure of 2 bar in the GMV is reached. The pellet mixture is indicated via the partial pressure ratio of neon/deuterium inside the GMV (25 mbar/2000 mbar = 1.25% Ne). We assume, that the pellet composition will reflect the partial pressure ratio

parameter	neon	source	D ₂	source
molar mass ($M_{\text{neon/D2}}$) in [g/mol]	20.18	[225]	4.03	[226]
frozen mass density ($\rho_{\text{neon/D2}}$) in [g/cm ³]	1.43	[227]	0.20	[227, 228]
Avogadro number (N_A)	$6.022 \cdot 10^{23}$			

TABLE 3.01: Parameters necessary for the calculation of N_{neon} . A slightly higher value of $\rho_{\text{neon}} = 1.44$ [g/cm³] than used is published by T. Gebhart *et al.* [228].

of the gas mix with deuterium being a molecular gas. To refer to the amount of neon inside the pellet, often the percentage of neon in the pellet (f_{neon}) is used: a pellet created from a gas mix with 1.25% Ne and 98.75% D₂, is referred to as a “1.25% Ne pellet” in this thesis. The estimated number of neon atoms (N_{neon}) is calculated as

$$N_{\text{neon}} = N_A \cdot f_{\text{neon}} \cdot \rho_{\text{neon}} \cdot (V_{\text{pellet}} \cdot 10^6) / M_{\text{neon}} \quad (3.01)$$

with the estimated pellet volume (V_{pellet}) in [m³] ($\rightarrow 10^6$ for conversion to [cm³])

$$V_{\text{pellet}} = \pi \cdot (0.5 \cdot D)^2 \cdot L, \quad (3.02)$$

the Avogadro number (N_A), neon mass density (ρ_{neon}), and molar mass of neon (M_{neon}) as given in table 3.01. The respective values for deuterium are used to calculate the number of D₂ molecules with $f_{\text{D}_2} = 1.0 - f_{\text{neon}}$.

The GMV is usually filled to 2 bar (2 barL), which is enough to generate 2–3 full-size pellet with 8 mm diameters (8 mm) or around 6 full-size pellet with 4 mm diameters (4 mm) before the need of re-filling the GMV.

For the SPI experiments in the 2022 campaign of AUG, pellets with a very low neon doping (down to 0.085% Ne) were requested. As the system was not designed for this, a mix of this low neon content requires multi-step mixing, using the following procedure: the GMV was filled with a 1.25% Ne mixture, usually half of the gas mix (could be also a different ratio) is pumped away and the remaining part is diluted with deuterium. It is assumed, that this way, a 0.625% Ne mixture is created. For further dilution, this step is repeated, until the desired gas mix is achieved. It is possible to create pellets from the gas inside the mixing volume before half-emptying (step-wise pellet generation) and thereby wasting less gas in the process.

Fast valves Each of the three injection lines is equipped with its individual fast valve (FV). The FVs have a 18 cm³ internal reservoir which allows up to 50 bar of propellant pressure [29], hence separate the high pressure propellant gas from the barrels. When the pellets should be launched a trigger signal is sent to the FVs, which will open for a predefined time to release the high pressure propellant gas before being closed again. This opening-closing cycle is automated with a high precision and reliability, with our default setting of 2 ms opening time. This gas will first push forward the hollow punch and afterwards enter the barrels inside the barrel and cut-outs in the punch. More details can be found in [paper L](#) [29] and [paper B](#) [30].

The hollow punch To assist the pellet detachment from the cold cell, a hollow punch is used. After triggering the FV, the high pressure propellant gas will push the piston

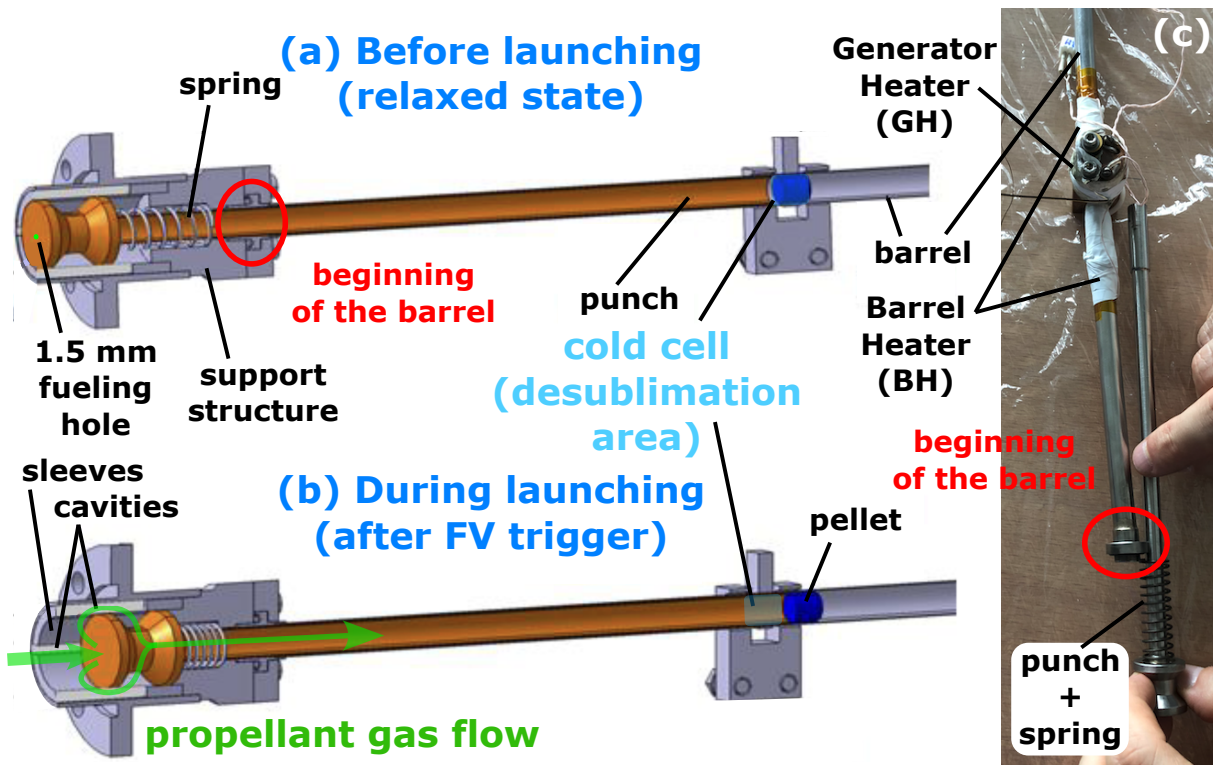


FIGURE 3.02: The hollow punch system of the AUG SPI system. CAD drawing taken from [229]. In (a) the hollow punch location during the pellet generation is shown. When the pellets are launched, the propellant gas will push forward the hollow punch as illustrated in (b) assisting the pellet detachment in the right pressure range. An image of the punch and barrel (without the support structure in between) is shown in (c).

at the back of the punch against a spring. This spring has two purposes: Avoid strong metal-to-metal contact of the piston with the connecting structure around the barrel entrance (compare figure 3.02) and also to restore the original punch position after the punch action.

With sufficient propellant pressure, the punch is pushed forward enough to reach into the cold cell. While the punch moves forward, the propellant gas can now enter through cavities inside the sleeves into the hollow punch through a small hole on the side of the piston (see figure 3.02(a)). As the pressure peak of the propellant gas ceases, the spring restores the original punch position.

The original spring set allowed the punches to significantly assist the pellet detachment down to propellant pressures of around 6 bar. In order to achieve lower pellet velocities (compare section 3.2), lower propellant pressures are desirable. A softer spring set can be installed allowing punch action down to around 4 bar. However, this softer spring set restricts the propellant gas pressures to a lower range to avoid the hard metal-to-metal contact (see figure 3.02(b)).

Depending on the propellant pressure, spring set, and pellet composition, the hollow punch will either cut into the outer layers of the pellet ice or completely cut out the pellet if the propellant pressure is sufficient [30].

With the hollow punch design employed at AUG, almost all pellets survive the impact with the punch. Therefore, we observed only a single-digit count of completely shattered pellets during the laboratory testing and only a small fraction of broken pellets (almost

no broken pellets during the 2022 experimental campaign, see appendix A.7). Hereby, “broken pellets” refers to pellets that were broken into at least two larger parts as observed by the optical pellet diagnostic (OPD), before the actual shattering process in the shatter head. More details on the pellet detachment are given in section 3.2.

Barrels and guide tubes The SPI system at AUG is a three-barrel-system with individual flight or guide tubes (GTs) which allows generating and injecting up to three pellets simultaneously. While the three FVs and cold cells are positioned in a row, the GTs have a triangular layout (compare figures 3.03 and 3.04). Consequently, slightly bent barrels were designed, connecting a specific FV-GT-pair, while the slight bending is preserving the integrity of the pellet. These barrels come with different diameters to enable different pellet diameters. The mapping between the different FVs and GTs via the barrels (Bs) (B1–B8) is given in the appendix A.2. Each barrel has its own set of barrel heaters (BHs) already attached to it which are used to generate shortened pellets.

The injector and heating coils The heart of the system is the injector built by Pelin LLC for which the CAD drawing and a picture is shown in figure 3.03. The three

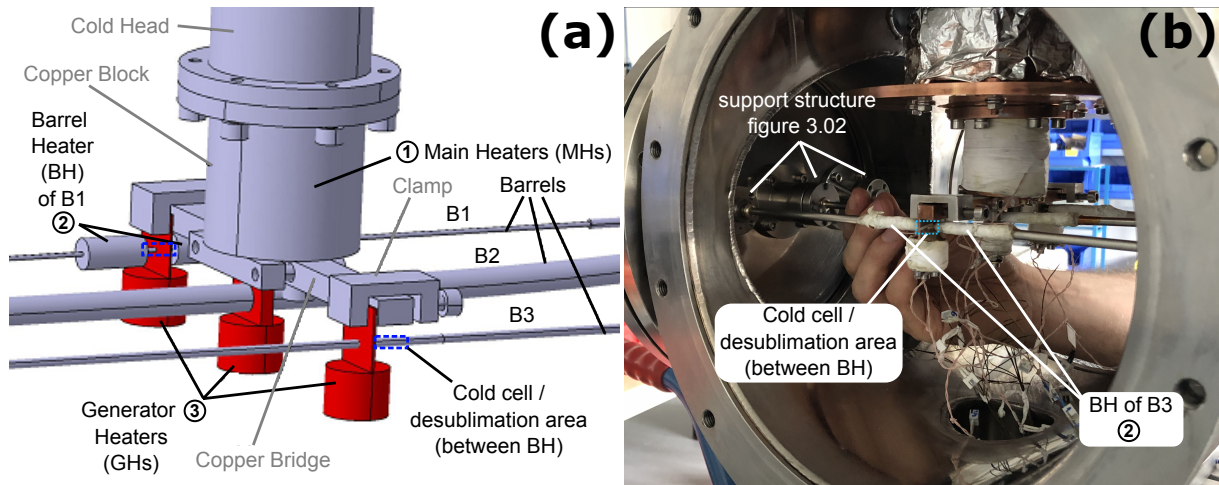


FIGURE 3.03: Most relevant parts of the injector of the SPI system build by Pelin LLC. The CAD drawing in (a), created by I. Vinyar, is published in [paper B \[30\]](#).

barrels are attached to the cold head via a copper bridge, clamps and a layer of indium is applied to improve thermal conduction. This will create a cold cell inside the barrels in which the pellets will form (section 3.2). Each of the barrels has its own BH (2) and generator heater (GH) (3), which are used to control the temperature gradients inside the cold cell. While the BHs are used to generate shortened pellets and the GHs to bias the temperature of each individual cold cell, the main heaters (MHs) (1) are used to bias the overall temperature in all three barrels. Hereby, the BHs and MHs are kept active during the entire desublimation process and the GHs were only activated before launching to assist the pellet detachment (see “GHR” in section 3.2).

Gate valves In each injection line, gate valves are located in two positions to confine the gas in certain parts of the system: A first set of three gate valves is located between each barrel and GT. It is closed during the generation process in order to confine the gas

inside the barrels. After the generation process is finished, the gate valve is opened to allow for efficient pumping and the pellet to exit the barrel through the open gate valve. A second, single, large gate valve is located further downstream (behind a second expansion volume) to detach the SPI system from the part of the GTs that is inside the AUG vacuum vessel (see figure 3.07(b)). This gate valve ensures, that the SPI system does not accidentally pollute AUG.

Residual gas removal Behind the first set of gate valves, the first expansion volume is located (see figure 3.04). The pellet will fly through a gap in the GT, where it is also observed by the OPD camera. Via this gap, the residual gas of the desublimation process and also the propellant gas accompanying the pellet after launching can expand into the dedicated 300 L expansion volume, where it is pumped away [29]. The second, smaller expansion volume (35 L) is connected to a second gap in the GTs from the torus gate valve [29] (see figure 3.07(b)). Hereby, $\approx 99.96\%$ of the propellant gas is removed [29]. At each of these gaps, the diameter of the subsequent GT-part is increasing to reduce the chance of the pellet hitting the edge of the tube (compare figure 3.15(a)).

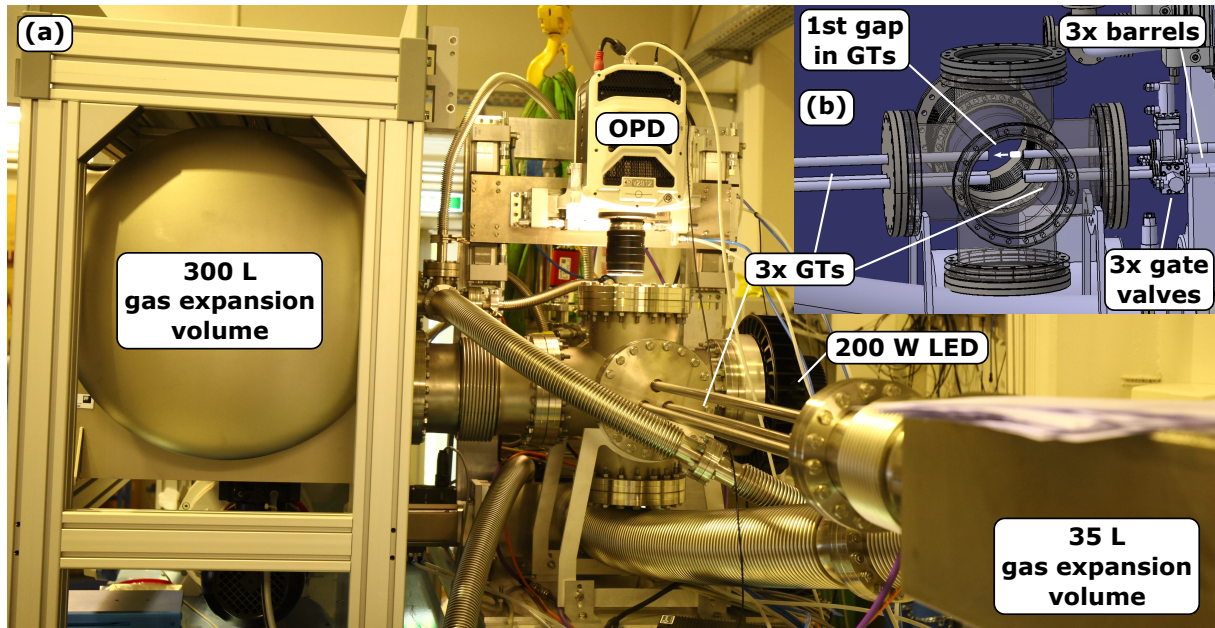


FIGURE 3.04: Picture of the OPD during the laboratory commissioning phase observing the pellets in-flight in (a). The double cross structure allows to mount the camera, 200 W LED, and the connection to the large 300 L expansion volume around the first gap in the GTs. The CAD drawing in (b) shows the double cross structure with the first gap in the GTs, where the pellets are observed and the propellant gas is removed. Picture taken by G. Papp and CAD drawing by M. Dibon is published in [paper L \[29\]](#).

Optical pellet diagnostic In the first pumping gap the optical pellet diagnostic (OPD) is located as shown in figure 3.04. During the laboratory experiments, a Phantom UHS v2012 camera was mounted on an actuator to control the camera's position. For the experiments at AUG, instead of the camera, only the lens and an image guide are connected to the actuator and the camera is located in a nearby shielding box connected via the

image guide. The maximum achievable time resolution of the UHS camera depends on the spatial dimensions of the recordings. The cropped view on a single GT allows for frame rates of up to around 110,000 frames per second, while in case of a synchronised/staggered injection – where multiple GTs are observed simultaneously – frame rates up to 45,000 frames per second are possible. The illumination for the camera is created by a 200 W LED array located at the side of the system. The camera is recording continuously (buffering duration depends on resolution) and with the trigger of the FV the buffered recording is saved. Afterwards, an analysis tool is run to assess the pre-shattering pellet velocity (v_{pellet}), size, and potential rotation angle developed by T. Peherstorfer [230].

This camera proved itself very useful throughout the commissioning of the system and the laboratory experiments. Not only as a video is often easier to interpret but was also essential to analyse the pellet quality and resolve initial alignment issues of the barrels with respect to (w.r.t.) the GTs. As the illumination is coming from the side (apparent from the top in the videos), the light is scattered from the pellet into the camera. This way, the recordings look similar to what a pellet would look like in ambient light illumination of a room in contrast to other illumination settings which look more like a shadowgraph image as used in the Center for Energy Research (CER) (compare section 3.2).

Shatter heads The shatter heads are attached at the end of the GTs via threads and can easily be exchanged. However, this requires physical access to the end of the guide tubes which is only possible in the laboratory environment and during the vacuum vessel opening of AUG between experimental campaigns.

The shatter heads have a miter bend and the pellets shatter as they hit the inner surface of the shatter head after the bend (see figure 3.05). Hereby, shatter heads with a circular cross section are referred to as “circular” and “rectangular” for a rectangular cross section, respectively. In total, 11 different geometries, as shown in table 3.02, were tested during the laboratory phase. The default shatter head length after the miter bend (L_{head}) of 78 cm was selected to ensure that the pellet will hit the inner surface of the shatter head completely for all of the available shatter angles (compare figure 3.05(a)). Based on early observations during the commissioning phase, new shatter heads were manufactured to explore the impact of certain shatter head parameters on the resulting fragment plume:

- **12.5°, rectangular head:** at first, a rectangular version was only available for the 25° bend angle. During the commissioning, we observed that the rectangular shatter head had a more collimated fragment plume against our initial expectation following the results from T. Gebhart *et al.* [231] reporting a more collimated fragment plume for shatter heads with circular cross section and ITER-sized pellets. Shallower bend angles are beneficial to create larger fragment sizes as launching pellets below 6 bar propellant pressure becomes increasingly difficult (see section 3.2). As the circular shatter head geometry has the downside of an unknown effective shattering angle (more details in section 3.3) I suggested to build a rectangular version of the 12.5° for comparison. For the 2022 and 2025 experimental campaigns, this head was eventually installed at ASDEX Upgrade due to the ability to produce large & fast fragments reliably.
- **Shortened shatter heads:** we observed a spiral pattern of the fragment plume in some of the pellets launched into the circular shatter heads, causing a wide opening angle of the fragment plume (low collimation of fragments). In the attempt

Shatter heads							
angle	shape	D _{head}	L _{head}	#pellets (total)		#pellets (AUG)	
[°]		[mm]	[mm]	4 mm	8 mm	4 mm	8 mm
0	no head	–	–	24	18	–	–
12.5	circular	16	78	42	78	–	–
	circular	16	46	8	0	–	–
	square	21	78	105	190	25	74
	horn	21 → 46	78	11	0	–	–
15	circular	16	78	143	15	–	–
25	circular	16	78	166	75	–	–
	circular	16	46	102	153	19	46
	square	21	78	182	361	20	56
	square	21	46	27	41	–	–
30	circular	16	78	67	8	–	–
Total number of pellets				877	939	64	175
#AUG22 discharges with 4 or 8 mm injections:						57	151

TABLE 3.02: The geometry information and number of pellets for the 11 different shatter head geometries. In bold text, the shatter heads installed in the 2022 experimental campaign are highlighted. The diameter of the shatter head (D_{head}) will refer to the side-length for the rectangular/horn geometries. The shatter head length after the miter bend (L_{head}) is measured from the miter bend. The column(s) #pellets (total) shows the total number of pellets injected into the laboratory test chamber, the empty AUG vacuum vessel and AUG plasmas in 2021/22, while the column(s) #pellets (AUG) shows the subset of pellets injected into the plasmas. Out of these, 5 pellets were injected into 4 discharges during commissioning in 2021. The last row indicates the number of successful discharges with at least one pellet injected into the plasma. Due to dual and staggered injection schemes, the total number of pellets is higher than this number. Table published in [paper B \[30\]](#).

to maximise this effect, shortened versions of the circular and rectangular shatter heads were created to analyse the effect of L_{head} on the collimation of the fragments.

- **Horn geometry:** The horn geometry was built to investigate the effect of a widening shatter head geometry on the spatial fragment distribution (see figures 3.05 and 3.08).

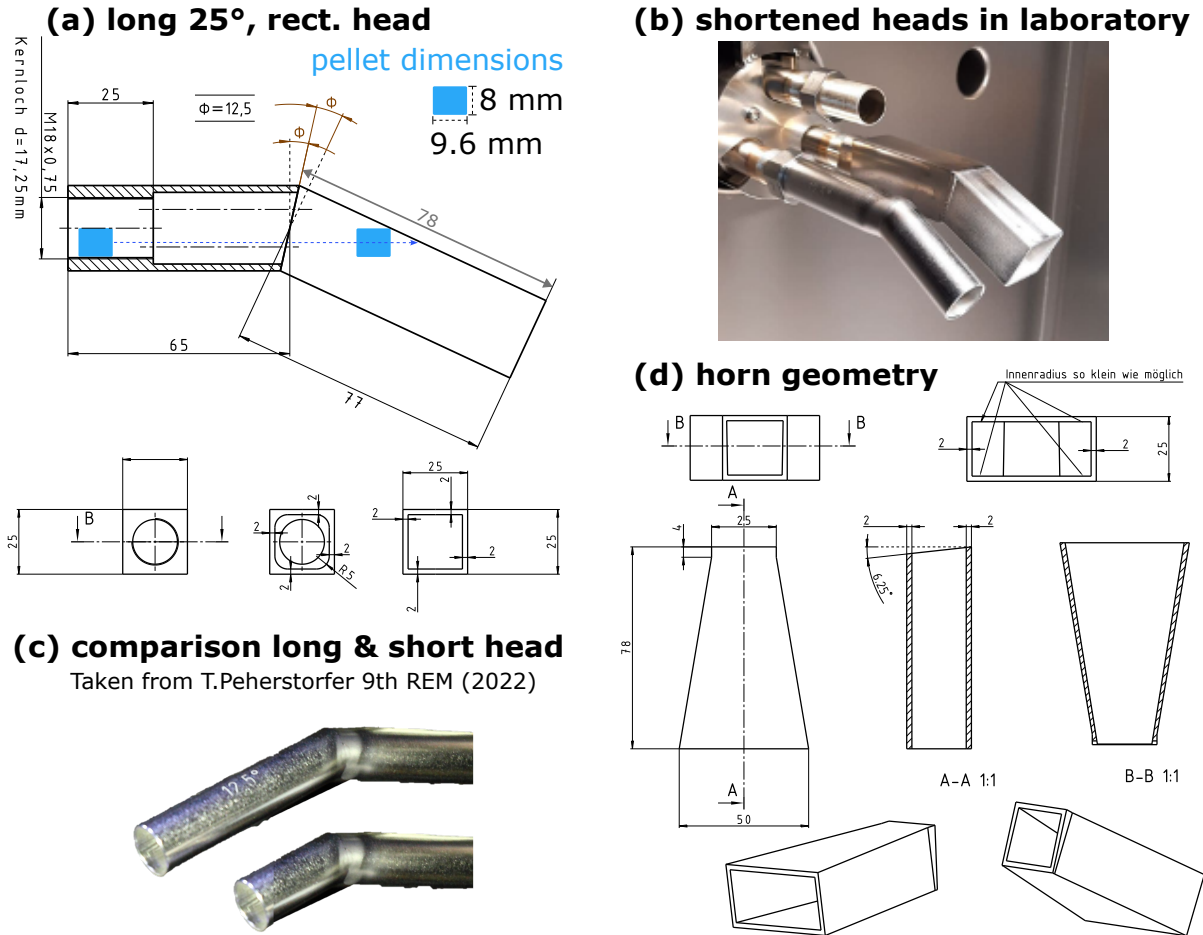


FIGURE 3.05: Excerpts of technical drawings and images of shatter heads. Into the drawing in (a), an 8 mm pellet with nominal size is added for reference. The long shatter head ($L_{\text{head}} = 78 \text{ cm}$) ensures that pellets will always hit the tube after the miter bend. In (b) an image of the shortened heads during the laboratory commissioning is provided, taken by G. Papp. A length comparison of the 12.5°, circular heads is provided in (c), taken from T. Peherstorfer [232]. In (d) the drawing of the horn geometry is provided. The technical drawings were created by M. Dibon.

A more detailed comparison of the effect of the different shatter head geometries on the fragment distributions is provided in section 3.3.

Test chamber and fragment observation camera During the laboratory phase, the SPI system was installed at the laboratory mock-up [29]. Hereby, the shutter heads were installed inside a vacuum chamber with an acrylic plexiglass door, which enabled to observe the fragment plumes with a second Phantom v2012 UHS camera – the fragment camera (FC). The FC was mounted on a support structure on guiding rails. By moving

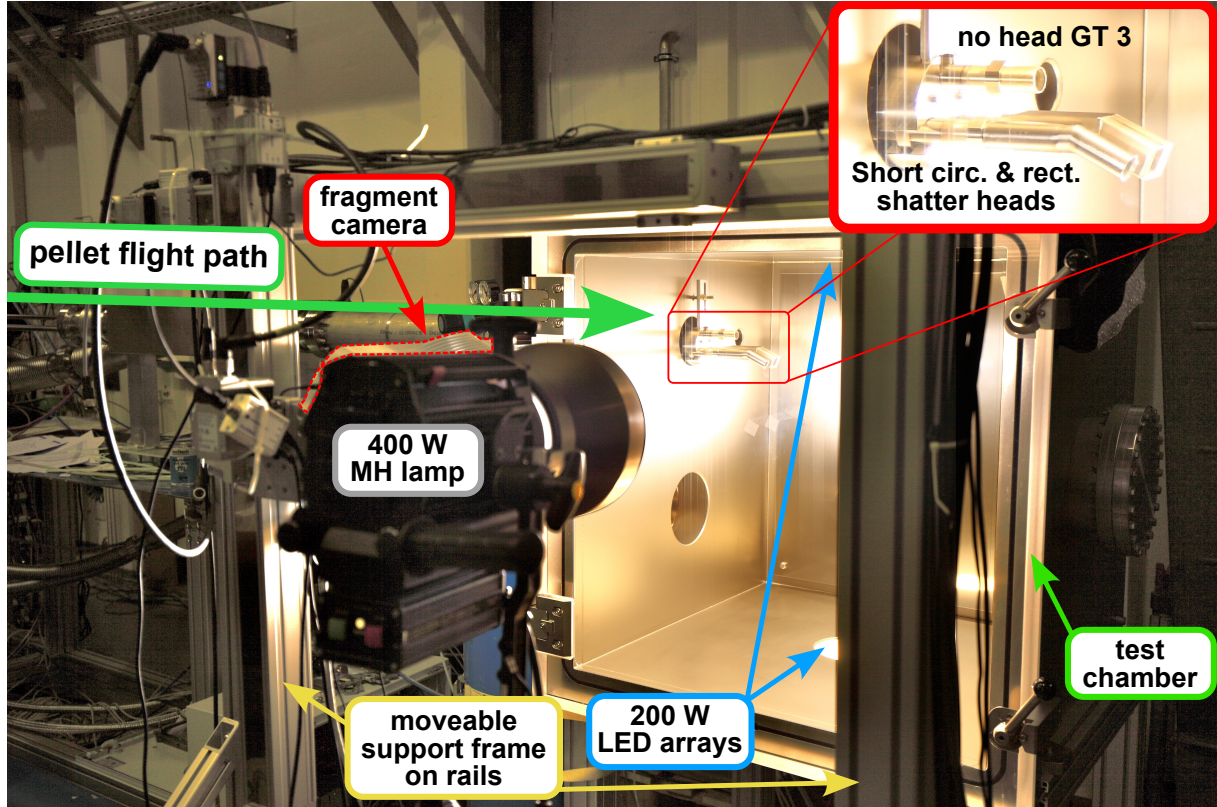


FIGURE 3.06: View on the fully illuminated test chamber with shortened rectangular and circular shutter head installed at GTs 1 and 2 (bottom two GTs). The portable 400 W metal-halide (MH) lamp partially covers the view on the camera that is mounted on the moveable support structure (dashed, red outlines). Picture taken by G. Papp.

this support structure by the distance between the two bottom shutter heads, the currently tested shutter head can be brought into focus of the camera. The camera position and rotation angle (w.r.t. the support frame) could be controlled with remote-controlled actuators. The fragment camera was rotated to the same angle as the shutter head within a precision of 1° and the center of the fragment plume (and exit of the shutter head) was chosen as the focus plane. The chamber is illuminated by another two 200 W LED arrays from the top and bottom as well as a portable 400 W metal-halide lamp [29] (shown in figure 3.06). An example of the illuminated fragments is given in figure 3.08(c). For the given cropping of the recordings to capture the fragmentation process, frame rates between 22,000 – 310,000 frames per second were achieved [29].

Integration into AUG After the last pellet test during the laboratory phase on October 13th (pellet ID #1390), the system was transferred from the laboratory to the torus hall. The SPI system is installed in sector 16 as shown in figure 3.07(a) (poloidal and

toroidal cross sections in figure 4.01 in chapter 4). The shutter heads installed for the 2022 experimental campaign are shown in figure 3.07(c) and the selection of these heads is explained in more detail in section 3.3. First successful pellet tests into the empty vessel were performed on November 5th. The UHS cameras that observe the fragments

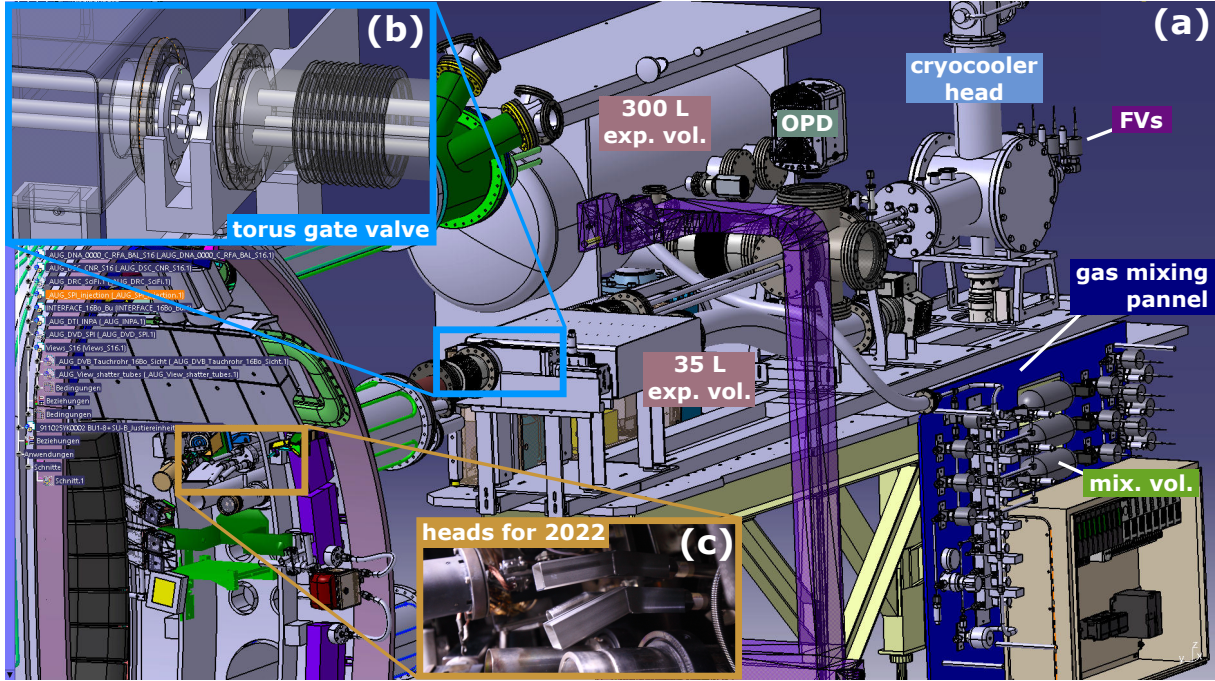


FIGURE 3.07: CAD drawing of the system at AUG. The system is located at sector 16. The torus gate valve located at the second expansion volume is shown in (b). A side-view image of the shutter heads installed for the 2022 experimental campaign is provided in (c) taken by G. Papp. The CAD images were created by M. Dibon.

entering the plasma were only operated when fragments were injected into plasmas (either dedicated glow discharges or on experimental shot days). At first, the OPD camera was mounted above the double-cross on non-shot days in the position shown in figures 3.04(a) and 3.07(a). During the shot days, the camera could only be operated from March 24th onwards as before that date, no shielding box for the camera was available to protect the camera from the magnetic field and neutrons. The camera was connected to a lens mounted on top of the double-cross via an image guide from that day onwards.

3.2 Commissioning & pellet recipe development

This section covers the description of the laboratory experiments as well as the characterisation of the pellets and the insights gained on the desublimation and detachment processes.

Pellet tests

During the laboratory experiments, the shatter heads that should be tested were attached to the lower two GTs and the camera rotated such that the fragments fly horizontally in its view (rotation angle equals miter bend angle). As changing the observation angle unfortunately required the dis-/remounting of the camera due to a technical issue with the rotation actuator, shatter heads with the same bend angle were tested at the same time. On three dedicated experimental days in the laboratory phase, the shatter heads were mounted 90° turned (pointing away from the camera) to investigate the fragment distributions in a “top-down” view (see figure 3.08(b)). Both pellets were created simultaneously (see section 3.2) and launched in sequence from the different barrels. In-between the launching, the support structure of the camera was pushed or pulled on its rails to marked positions to bring the shatter heads and fragment plumes into focus. During the laboratory testing, the main goal was to generate high quality shatter videos for analysing the fragment distributions as well as develop launching recipes.

Pellet database									
Laboratory setup					Into the empty AUG vessel				
D	L/D	Ne	speed	#pellets	D	L/D	Ne	speed	#pellets
[mm]		[%]	[m/s]		[mm]		[%]	[m/s]	
1	2–3	100	208, 233	2	4	0.5–2.3	0–100	29–758	154
4	0.5–2.3	0–100	29–758	659	8	0.4–2.0	0–100	63–622	179
8	0.4–2.0	0–100	63–622	586					
Into AUG plasmas in 2021/22									
4	1.5–1.9 [‡]	0–100	232–656	64	8	0.5–1.6	0–100	76–710	174 + 1

TABLE 3.03: Overview over launched pellets until the end of the 2022 experimental campaign (5 pellets injected for testing in 2021). The L/D of the 4 mm pellets[‡] was inferred from the matching recipes in the laboratory data, as the OPD was not available for these discharges. The “174 + 1” denotes one pellet that was accidentally desublimated (see appendix A.3). Table published in [paper B \[30\]](#).

After the system had been transferred to AUG, no fragment camera is available and the pellet testing only involves refining pellet recipes for successful detachment and launching of the pellets in preparation of the plasma experiments. An overview of the parameter ranges for the shattered pellet tests/injections is given in table 3.03 and figure 3.09. The usual L/D of the pellets without barrel heating is 1.7 (D = 4 mm) and 1.2 (D = 8 mm),

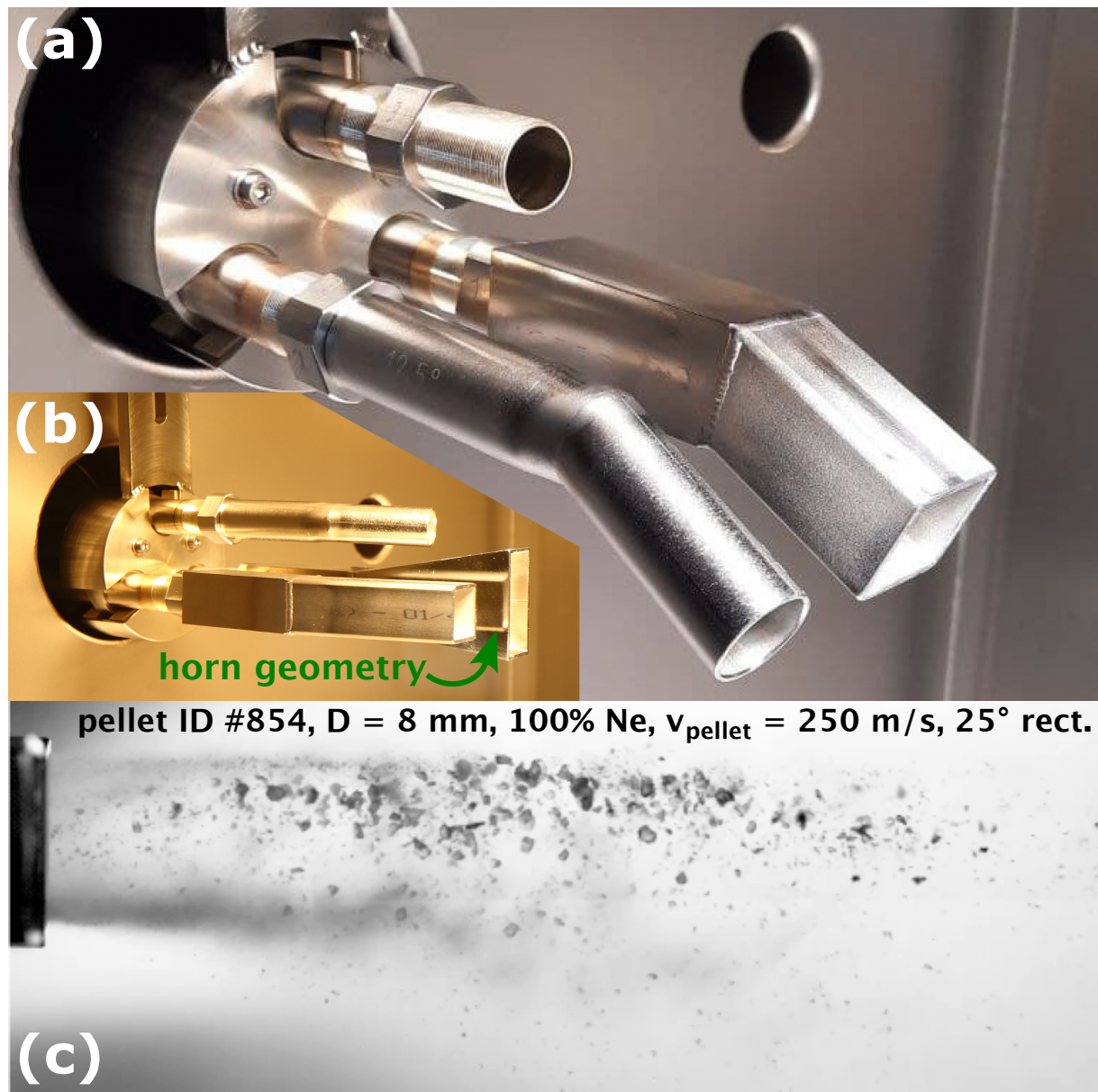


FIGURE 3.08: Shatter heads installed in the laboratory test chamber. In (a) the usual setup for the shatter heads pointing downwards, sharing the same shattering angle for the bottom two GTs (two shortened heads are shown). The turned shatter heads for the “top-down” view experiments in (b). Example for fragment plume in (c). Pictures taken by G. Papp.

respectively. However, the length might vary as it also depends on the thermal conductivity of the system after a barrel change – i.e. the full-length pellets after the transfer to AUG usually had a nominal pellet length (L_{nom}) > 10 mm. By applying different heating via the BHs, shorter pellets can be generated indicated in figure 3.09(b). We assume a low pellet velocity of 30 m/s in cases where the pellets self-released before the trigger of the FV (see figure 3.09, explained later in the text). These pellets survive the impact inside the shatter heads and the intact pellets were observed moving around at the bottom of the vacuum chamber due to the Leidenfrost effect. As the pellets release before the trigger signal is sent to the FVs and the camera, the pellets were not recorded by the OPD nor

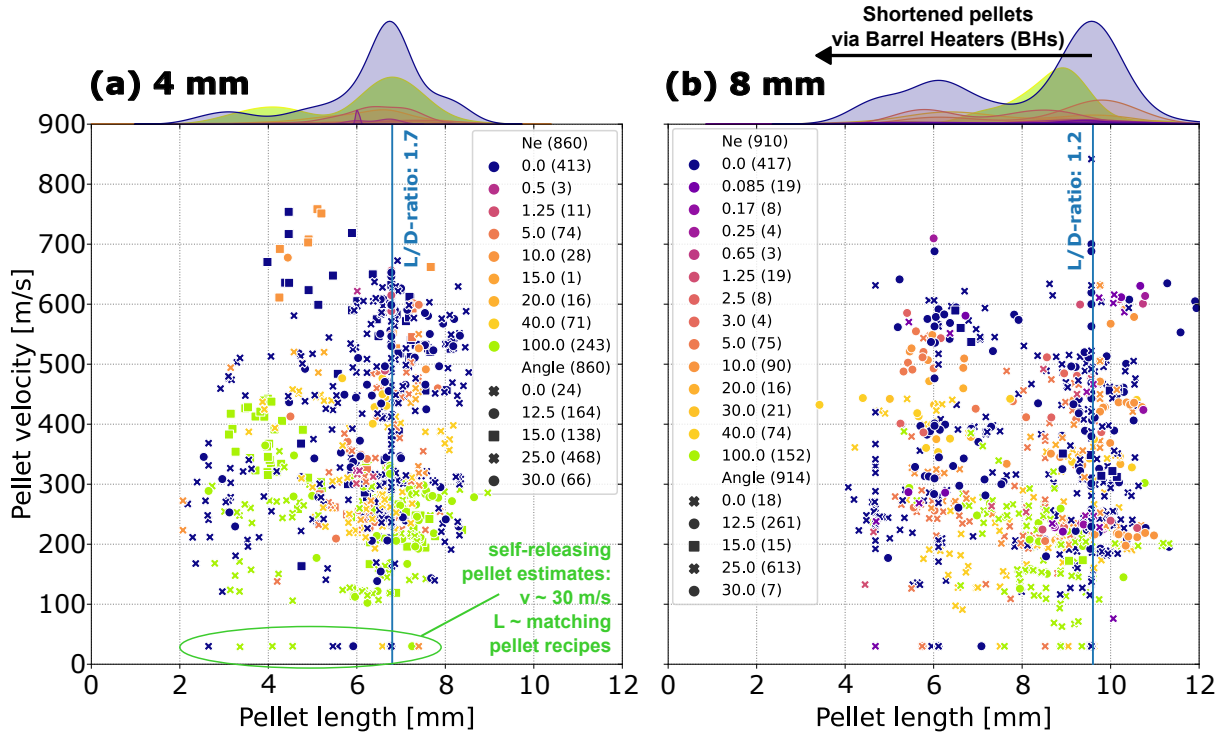


FIGURE 3.09: Overview of pre-shattering pellet velocity and length ranges for given neon content indicated by the colour-coding. The bend angle of the shatter heads into which the pellet was fired is indicated by the point types. For cases with no available OPD measurements, the pellet length and velocity was estimated from existing (similar) recipes. The pellet velocity of self-releasing pellets is estimated to 30 m/s. The nominal pellet lengths for the 4 mm and 8 mm pellets are of 6.8 mm and 9.6 mm, respectively. Figure published in [paper B \[30\]](#).

fragment camera as they arrive outside of the recorded interval. In just one single case, a the slow pellet was still barely within the recorded interval of the OPD, revealing a low velocity of 30 m/s. Hereby, we do not know about the pellet detachment conditions and also whether the pellet might still received a bit of acceleration by the propellant gas triggered most likely after the pellet self-released. The pellet length and v_{pellet} are estimated in cases where no OPD video was available. In these cases, the average of the measured length and velocity from the same or similar pellet recipe is used. While these unshattered, early pellets into plasmas are typically excluded in the analysis within this thesis, they are still useful for pellet ablation studies [198].

Pellet desublimation process

To better understand the pellet quality aspects, first the pellet desublimation process needs to be discussed. This section combines conclusions drawn from the observation of different pellet quality aspects via the OPD, discussions with the team at the CER in Budapest, and their publication on the desublimation process by T. Szepesi [233]. More details on the overall experimental setup [192, 234, 235], the pellet sublimation [233], launching & acceleration ([paper J \[48\]](#)), and shattering process of the pellets [236] are available within the publications of the CER-team. At CER, the pellet desublimation process can be observed via a camera viewing from the front (in later flight direction of the pellet) into the barrel. Hereby, the a moveable mirror in the first gap in the injection

line allows to observe the pellet during freezing, which is illuminated by a laser source from the back side [233, 234]. Fruitful discussions with the CER-team in the early laboratory stage of the AUG SPI tests helped me characterising the pellet quality aspects of our pellets and gain insights on the pellet sublimation process.

As described in section 3.1, the pellets in the AUG SPI system are generated inside the barrel (cold cell) itself. The gas mix is supplied from the GMV for a pre-defined “freezing” time (t_{freezing}) (set by the operator based on generation recipes) and afterwards the barrel and pumping ducts are pumped again. During the pellet desublimation time window, the gas mix from the GMV can enter into the barrel until the first gate valve through a 1.5 mm diameter hole the piston of the punch (see figure 3.02(b)). After some initial

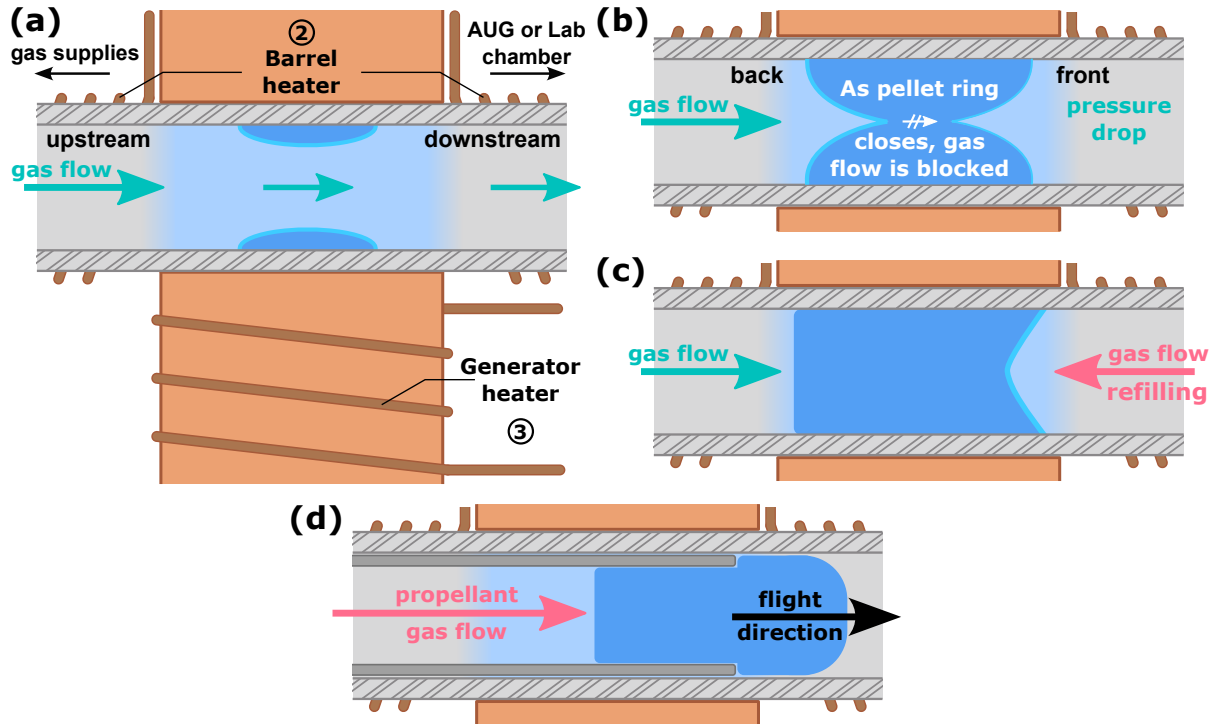


FIGURE 3.10: The pellet desublimation process. In (a) and (b) the usual pellet desublimation process is illustrated. In case the refilling criterion is reached, additional pellet material is supplied to the pellet front. In (d) the pellet launching with assistance of the hollow punch is illustrated. Figure published in [paper B \[30\]](#).

testing, a constant 100 mbar inlet pressure (p_{inlet}) was used for 100% D_2 or deuterium-neon-mix pellets, while 250 mbar was used for 100% Ne pellets. The gas mix will start desublimating at the barrel surface within the cold cell as indicated in figure 3.10(a). Firstly, a pellet ring or hollow cylinder will form, which will become narrower over time as more material is desublimated. At the blockage time (t_{blockage}), the pellet ring will close, which is detected as a pressure loss on a downstream pressure sensor as shown in figure 3.10(b). This closing time is monitored and gives first indications about the necessary generation time for a certain recipe, as the AUG SPI system does not have an in-barrel camera system. The pellet will consume the remaining gas inside the volume between the front of the pellet and first gate valve (front volume) to fill the empty cone in the front, while the pellet back is kept at a constant pressure from the upstream side. In early pellet realisations (especially for the full-sized 4 mm pellets), we observed an

empty cone at the pellet front (see figure 3.13). This indicates a lack of gas mix in the front volume, insufficient to desublimite enough material in the front cone. To ensure more symmetrical pellets a new routine had been implemented: whenever the pressure at the downstream side drops below 3 mbar before the freezing timer ends, a pumping duct re-fills new gas from the GMV into the front volume (opened for 10 seconds). This process is shown in figure 3.10(c). Since this routine was first applied for pellet ID 822, it was triggered 500 out of 1145 recorded pellets.

Without active BHs and MHs, the cold cell temperature settles around a value in the range of 5–10 K. The specific temperature depends on the thermal conductivity (changes after a barrel change) and is also different for the central and edge cold cells. For 100% Ne pellets (and some 40% Ne pellets), the MH 2 is activated, raising the temperature to a range of 10–17 K. This prevents neon to desublimite at the barrel outside the dedicated cold cell. Whenever some neon is in the pellet, the pellet needs to be heated before launching it to protect the punch from damage. This is usually done by applying a low power heating via the GHs even if not necessary to detach the pellet from the barrel. With this, the pellet ice is softened, hence reducing the stress on the punch, assuring its longevity.

Depending on the pellet diameter, composition, and heating settings, the freezing timer was set to 400–900 seconds. Whenever the pressure drop, indicating the pellet closure, was not observed repeatedly before the freezing timer had ended, the generation times were adjusted for this recipe. An overview table of the generation recipes is given in table 3.04 for 0%, 10%, and 100% Ne pellets. Since recording, a total of 118 non-closing and 1689 closing pellets were observed.

Pellet generation recipes									
Pellets with $D = 4$ mm					Pellets with $D = 8$ mm				
Ne	size	p_{inlet}	t_{blockage}	t_{freezing}	Ne	size	p_{inlet}	t_{blockage}	t_{freezing}
[%]	L/L_{nom}	[mbar]	[100 s]	[100 s]	[%]	L/L_{nom}	[mbar]	[100 s]	[100 s]
0	full	80–100	0.2–0.6	4	0	full	100	1.3–4.5	5–8
10	full	100	0.3–1.4	4	10	full	100	1.7–6	5–8
100	full	250	0.8–1.6	4	100	full	250	5–7.3	7–8
0	0.5–0.75	80–100	1.45–4 ⁺	4	0	0.5	100	5.5–8.3	9
10	0.5	100	3	4	10	0.6	100	6.7–9 ⁺	9
100	0.75	250	3.6–3.8	4	100	0.5	100	5.5–8.3	9

TABLE 3.04: Overview on pellet generation recipes for 0%, 10% and, 100% Ne pellets. The nominal pellet length (L_{nom}) from figure 3.09 is taken for the ratio of L/L_{nom} . The ⁺ indicates, that for this recipe, the absence of the pellet closure was observed for the given t_{freezing} for some pellets. Table published in [paper B \[30\]](#).

Pellet quality

The pellet qualities and characteristics depend strongly on the composition and generation conditions. In this section, some of these quality aspects and issues during the desublimation process are discussed.

For different neon percentages, the usual pellet quality is shown in figure 3.11. Hereby, the 100% D₂ and 100% Ne pellets are transparent and only the mixed pellets are opaque, see figure 3.11. Thin structures were only observed in the pellet front for the full-sized, 8 mm, 100% D₂ pellets (see figure 3.11(g)). The 5% Ne pellets are the easiest pellet mixture to work with: these are well visible within the OPD, hence a good automated tracking is possible and are easy to launch. In contrast, the 40% Ne pellets perform worst. It is suspected that the pellet ice at the front of the pellets is extremely brittle as it already shatters when the pellet is launched (independent of the punch action). The small fragments and dust (see figure 3.11(d), often made the automated tracking inaccurate or even impossible, which was worse for the 4 mm pellets. Strong heating of these pellets before launching sometimes reduced this issue, however, the 40% Ne mixtures remain unfavorable. Typically, the 8 mm pellets showed less and smaller fragments accompanying the more intact pellets after launch, indicated in figure 3.11(j).

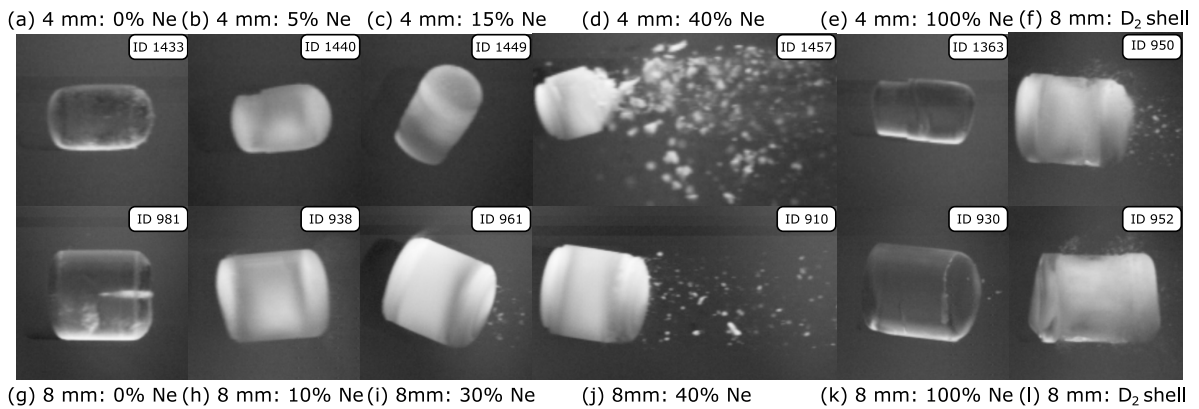


FIGURE 3.11: Pellet quality for the different pellet compositions. The 4 mm pellets are shown in the top row and the 8 mm pellets in the bottom row. In (f) and (k) 8 mm, deuterium-shell pellets are displayed. The 40% Ne pellets are difficult to handle due to strong fragmentation of the pellet front during launching. Figure published in [paper B](#) [30].

As shown in figures 3.11(c, f, h, i, j, l), the pellet tips – previous cone positions that were filled after closure of the pellet – with a different opaqueness are often visible for mixed pellets. This may indicate, that either the ice structure is different or even the composition may vary in these regions. Conceivable explanations for this may be changing generation parameters during the different phases of the desublimation or gas pressure differences for open and closed pellets. It may be these tips that are especially unstable in the 40% Ne cases.

In case of the four pellet IDs 949–952, the deuterium shell concept was tested. A thin D₂-shell is supposed to lower the temperatures needed for a successful pellet launching of Ne pellets [237]. Hereby, a 100% D₂ outer shell was created first by manually aborting the desublimation process after 45 seconds ($p_{\text{inlet}} = 100$ mbar) or 120 s ($p_{\text{inlet}} = 250$ mbar) in the stage indicated in figure 3.10(a). Afterwards, the residual gas got pumped away, the

gas in the GMV changed and a new desublimation process initiated to fill the interior of the pellet. In stage 2, a neon mixture of 57.2% and 100% were used with $t_{\text{freezing}} = 900$ s, respectively. However, these shell pellets were just meant as a proof of concept. With the hollow punch and heating coils, the AUG SPI system does not require the deuterium shells for the pellet detachment.

Pellet quality issues Under the right conditions (temperature, gas flow rate, ...), snow-like crystal layers can form, which can be encapsulated within the pellet interior or deposited loosely on the pellet surface (e.g. inside the pellet cones). When these pellets are launched, these crystals can be released from the pellets and form a dust cloud in front of the pellet, which can cause inaccurate automatic tracking. This process is indi-

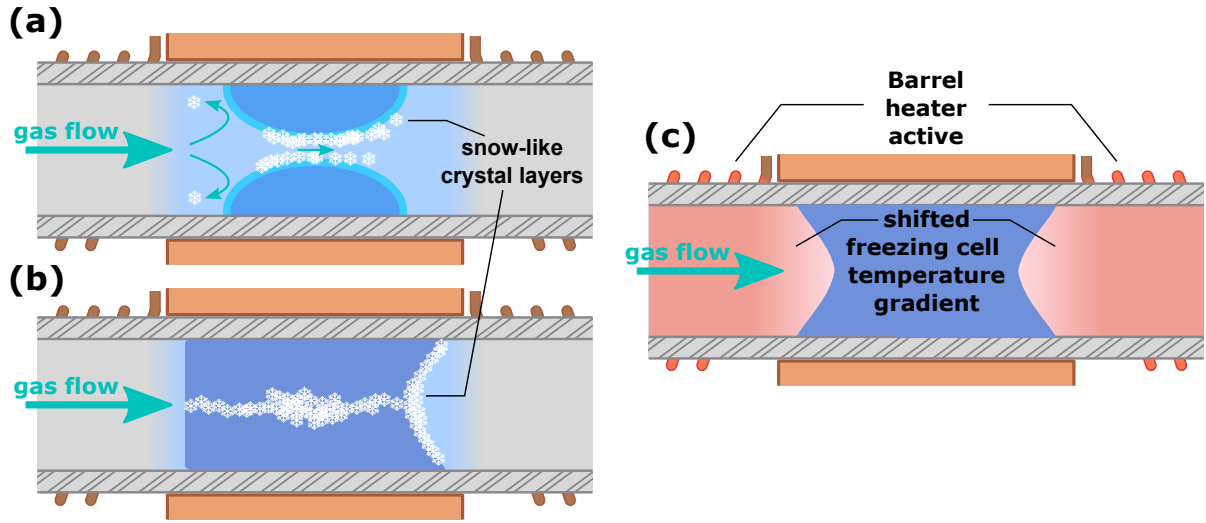


FIGURE 3.12: Issues during the pellet desublimation process. The formation of snow-like crystal layers inside the pellet and the front cone is indicated in (a) and (b). The symmetric cones caused by too high barrel heating is illustrated in (c). Figure published in [paper B \[30\]](#).

cated in figure 3.12(a, b), figure 3.13(a, b) as well as in figures 12 & 13 in the paper by T. Szepesi [233]. This process may also explain the so-called “dark-waist” observed at CER [233]: depending on the angle between pellet illumination and UHS camera, either the reflected light or the absence of light is observed. For the AUG SPI, the camera illumination is from the side (top in the videos), hence the reflected light would lead to a white appearance of the snow-like material, while at CER, with the light source opposite to the camera, it would appear black. However, recent studies about the “dark-waist” pellets indicate that the outer layers of the pellets itself have an opaque ice structure, while the interior is transparent – which was observed by broken and turned pellets [235]. This opaque ice structure might be similar to the opaque pellet tips from figure 3.11(c, f, h, i, j, l). While cones at the pellet front that remain after desublimation may indicate a lack of gas mix in the front volume, symmetric cones at the front and back of the pellet indicate too high BHs settings (see figure 3.13(d–e)) or insufficient t_{freezing} (see figure 3.13(c)). Too high heating via the BHs can shift the temperature gradient inside the cold cell too much and prevent the gas mix from desublimating onto the pellet as illustrated in figure 3.12(c). In the case displayed in figure 3.13(d) the pellet rotated during the launching process by 90°. Hereby, it is visible, that besides the desublimation at the interface between the gas mix and the cryo-cooled barrel surface, no gas was able to desublimates onto the gas-pellet

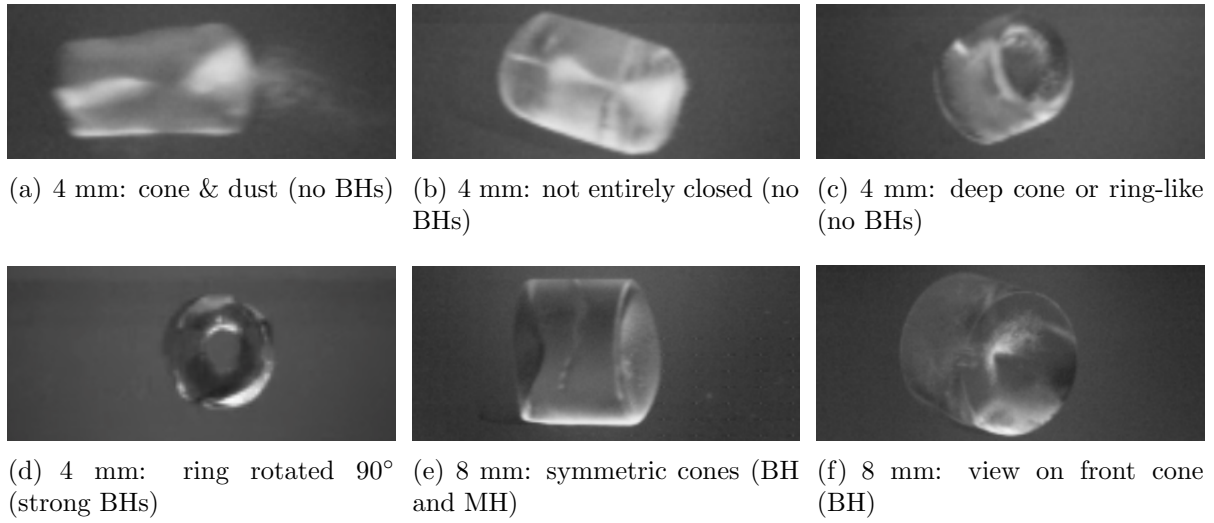


FIGURE 3.13: Pellet quality issues recorded by the OPD. Empty cones inside the pellet front can be caused by a lack of gas mix at the pellet front (before the re-filling technique was applied). Symmetric cones at the pellet front and back indicate too high applied barrel heating. Figure published in [paper B \[30\]](#).

interface most likely due to too much barrel heating. However, we managed to develop heating recipes even for higher BH-settings, in which shortened pellets with flat surfaces (no cones) were generated.

Pellet detachment and launching process

While the pellet detachment for the ITER DMS will fully rely on a carefully designed propellant gas pressure pulse to detach the pellet from the cold-cell [192], SPI systems deployed at different machines often use dedicated detachment strategies like heating coils or punch mechanisms to support the pellet detachment. The SPI system of ASDEX Upgrade was designed to ensure the detachment via the hollow punch (see section 3.1) in the range of around 6 to 50 bar propellant pressure, which results in pellet velocities of 340–800 m/s (D_2) and 170–445 m/s (Ne) (compare figure 3.16) where the punch is significantly supporting the detachment process. The pellet edge heating is only applied to pellets with high neon fractions to reduce the risk of damaging the punch at impact or D_2 pellets to reduce the likelihood of pellet breaking. Over time, we developed dedicated heating recipes to enable access to even lower launching velocities with lower propellant pressures necessary. Hereby, we achieved successful pellet launches with propellant pressures as low as 0.5 bar – at 1 bar, pellet velocities are between 160–320 m/s (D_2) and 60–120 m/s (Ne). Once a stable launching recipe was found, the high automatisation of the system with reliable hardware resulted in a reproducible pellet detachment & velocity, enabling a precise velocity prediction. However, operating below the threshold of the punch action, the operational space narrows significantly as the risk of unsuccessful pellet launches increases.

The development of launching recipes depends not only on various pellet parameters (e.g. pellet diameter, composition) and launching parameters (e.g. propellant gas pressure, individual barrel number, single vs dual/staggered injections) but also the interplay of the 8 installed heaters. Therefore, creating stable heating recipes requires a lot of experi-

ence with the system. In the beginning of the commissioning phase, recipe development required days after days of trial-&-error to develop suitable heating recipes for the low pellet velocity range. With the development of my pellet detachment model, I was able to extrapolate to un-tested pellet recipes within seconds to minutes. This also allowed me to adapt to changes in the pellet schedule in between discharges. I will discuss this model in the following.

Pellet detachment regimes

From the experience of the pellet recipe generation, I created a simplified model to describe the pellet detachment regimes, which proved itself extremely useful. Hereby, heating recipes that allow a successful pellet launching at lower propellant pressures are referred to as “increased heating (recipes)”, where the term “heating” is used as a synonym for all parameters that affect the pellet detachment. This is illustrated in figure 3.14(a)

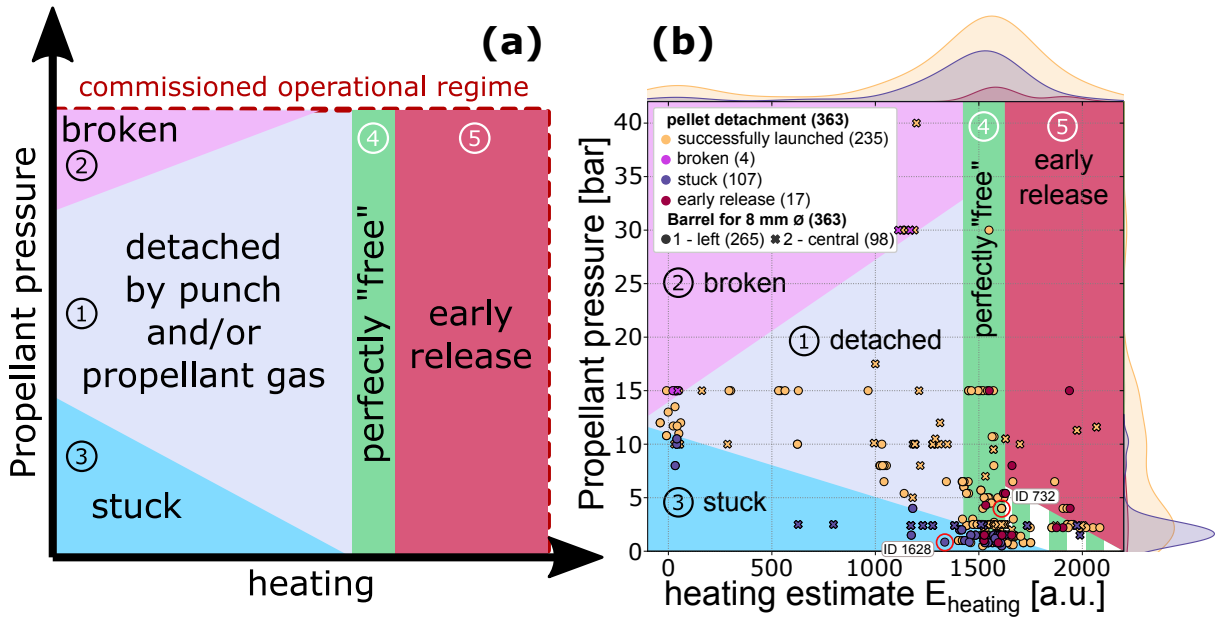


FIGURE 3.14: Sketch of the pellet detachment regimes useful for recipe development. In (a) the version used during the 2022 experiments is shown. In (b) the adapted version with the individual pellet realizations of 8 mm pellets from B1 and B2 are shown. The pellet IDs used in the example equations 3.04 and 3.05 are highlighted. Figure published in [paper B \[30\]](#).

as “heating” on the x-axis. After the conclusion of the 2022 AUG SPI experiments, I developed a heuristic metric indicated by the heating estimate (E_{heating}) in figure 3.14(b) and explained in the subsequent section. Consequently, before this metric was developed, recipe development relied purely on experience and the simplified model in figure 3.14(a) helps to inter-/extrapolate to new recipes even for changes to the schedule during the shot day itself with high reliability. With the experience of almost 2000 pellets launched by the end of the 2022 experiments, I can quickly identify in which direction to modify existing recipes for non-functioning or new recipes by identifying the pellet detachment state. These different detachment regimes, indicated by the numbers in figure 3.14, are introduced in the following:

- ① The pellet is successfully detached by the combination of the punch action, propellant gas pressure, and heating applied to the pellet.
- ② Increasing the propellant pressure, the impact force of the punch on the pellet increases. While the hollow punch design reduces the stress on the pellets as it cuts into the outer layers of the pellet, under certain conditions this can cause the pellets to break. As indicated in figure 3.15(a, b), usually the tip of the pellet will break

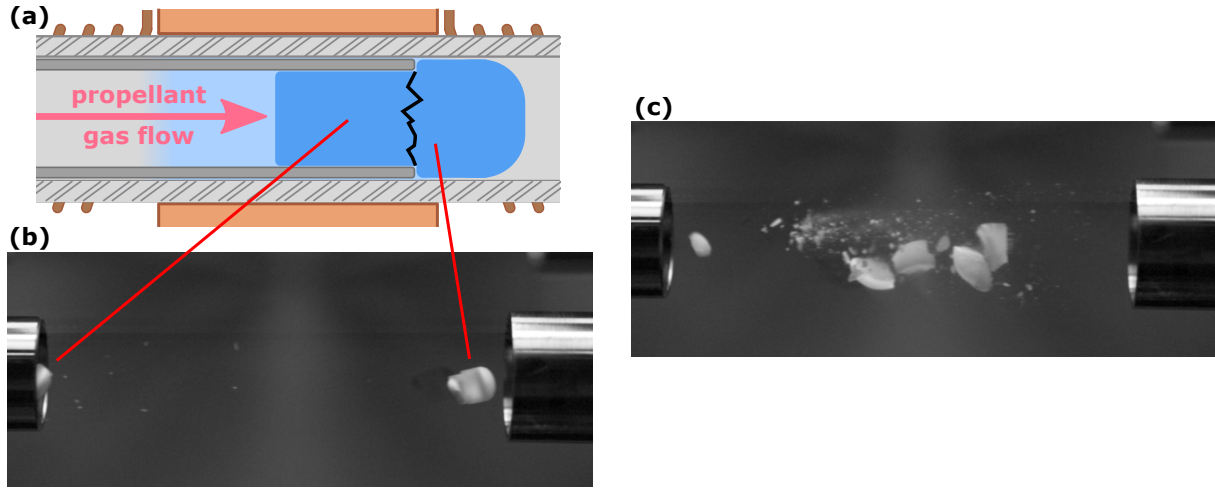


FIGURE 3.15: Punch breaking or shattering the pellet. If not sufficiently heated pellets are hit by the punch, the pellet tip can break apart illustrated in (a) and (b). In (c) a pellet completely shattered by the punch is shown. Figure published in [paper B \[30\]](#).

apart from the remainder. However, in less than a handful of pellets, the complete shattering of the pellet was observed (illustrated in figure 3.15(c)).

- ③ At low propellant pressures – where the punch action is reduced or the punch does not even reach the cold cell anymore – the pellet may be stuck inside the cold cell if the combination of propellant pressure and heating is insufficient to detach the pellet from the barrel. Experimentally this is observed as the absence of the pellet in the OPD at the expected time window and also the measured upstream pressure remains high as the pellet is blocking the propellant gas flow along the barrel.
- ④ By increasing the heating, the pellets detach more easily from the barrel, which can help to prevent the pellets from breaking or being stuck, which is interpreted as a reduced sticking force to the barrel surface. As pointed out in a discussion with the CER-team, this reduced sticking force is still observed after turning off the heaters and re-cooling of the cold cell to pre-heating values, which we did not investigate up to this point. We observed, that there seems to be a certain sweet spot, in which the sticking forces becomes low enough that even tiny amounts of propellant pressure (around 0.4 bar – without punch action) are enough to launch the pellet successfully as the pellets are detached by the heating alone. These pellets are referred to as “perfectly free” and enables pellet velocities below the originally designed parameter space where no punch action is available. These low pre-shattering pellet velocities were requested to further increase the mean fragment size. Even though launching pellets with higher propellant gas pressures in the “perfectly free” regime

is possible, we only apply these heating settings when necessary to achieve low injection velocities as this regime is extremely sensitive to various system and pellet parameters.

- ⑤ Heating the pellets beyond the “perfectly free” regime, we observe the “self-releasing” or “early” pellets. Hereby, it is suspected, that the increased cold cell temperature leads to a pressure increase on the former upstream side of the pellet due to sublimation of the pellet ice. The pressure on the upstream and downstream sides of the pellet are not equalised via the bypass to diagnose the pellet closure during generation and prevent accidentally filling this region with high pressure propellant gas. Therefore, the pressure difference can cause the pellet to launch itself before the FV is triggered and the propellant gas released. This will result in low pellet velocities and premature release times, hence the pellets typically arrive at the OPD outside the recorded time window and exit the shatter heads in one piece due to the low velocity. In one occasion (pellet ID #562), an early releasing pellet was observed by the OPD, showing a pellet velocity of around 30 m/s. For other early pellets, this velocity is used as an estimate.

As these regimes are highly sensitive to pellet and system parameters, minor changes can already have significant effects on the detachment of the pellets: While a pellet may be stuck at 16.4 seconds of a certain level of applied heating, at 16.5 seconds it may be perfectly free and at 16.6 seconds early releasing. Therefore, the development of robust heating recipes is a challenging task, which may require a lot of trial-&-error, fine tuning, and experience where the detachment model can be used for guidance. In the following, I discuss the insights gained during the recipe development.

Pellet recipes The pellet recipe development depends on many different parameters – some of which may be more intuitive others more subtle. In the following, an excerpt of parameters is provided:

Pellet specific parameters

1. Pellet diameter (4 mm or 8 mm),
2. Pellet material composition (D₂–Ne-mixture),
3. pellet length → barrel heater settings.

Launching parameters

4. Pellet velocity → Propellant pressure
5. Which of the hand-crafted barrels is used,
6. Heating recipe applied to the other cells (thermal coupling).

System parameters

7. Cold cell temperature, depending on the thermal conductivity subject to subtle changes after each barrel change (see section 3.1) or temperature hysteresis of subsequent pellet generation and launching recipes,

8. Whether the 200 W OPD camera light is switched on or off. While this light source is located about 1 m downstream of the cold cell, it was observed during plasma experiments without the camera light (before the OPD shielding box was available) that pellets remained stuck which were detached otherwise. While the thermal conductivity to the cold cell was estimated to be minor, it appears to be just enough to make the difference. After switching back on the light, the pellet recipes worked again as tested days before.

Based on the experience of different parameter effects on the detachment process I developed a simplified formula to indicate the expected detachment state for a given recipe via the heuristic heating estimate

$$E_{\text{heating}} = c_{T0} \cdot T0 + c_{MH} \cdot MH + c_{BH} \cdot BH + \left[c_{GHR} \cdot GHR \cdot c_{t(\text{heat})} \cdot \log_{10}(1 + t_{\text{heating}}) \right] + c_{dT} \cdot dT, \quad (3.03)$$

with the parameters and weighting factors (c_X) of the linear combination given in table 3.05. For the different heaters, the heater setting is given in % w.r.t. the maximum

Parameters & weighting factors for E_{heating}	
T0 with $c_{T0} = 5$	t_{heating} with $c_{t(\text{heat})} = 4$
Cell temperature at $t_{\text{end freezing}}$ [K]	GHR heat time [s]: $\log_{10}(1 + t_{\text{heating}})$
MH with $c_{MH} = 1$	dT with $c_{dT} = 100$
Heating of the MHs [0–50%]: MH = MH2 (MH1 not used)	Change in cell temperature [K]: $dT = T_{\text{end heating}} - T_{\text{end freezing}}$
BH with $c_{BH} = 50$	GHR with $c_{GHR} = 5$
Heating of the BHs [0–50%]: B1: BH = BH1 + 0.5 BH2 + 0.3 BH3 B2: BH = 0.5 BH1 + BH2 + 0.5 BH3 B3: BH = 0.3 BH1 + 0.5 BH2 + BH3	GHs heating for detachment [0–90% [‡]]: B1: GHR = GH1r + 0.4 GH2r + 0.25 GH3r B2: GHR = 0.4 GH1r + GH2r + 0.4 GH3r B3: GHR = 0.25 GH1r + 0.4 GH2r + GH3r

TABLE 3.05: Parameters and weighting factors used in equation (3.03) for the heating estimate in figure 3.14(b). The different formulas used for B1–3 to determine BH and GHR are also provided.

[‡]Early tests involved higher GHR settings. Table published in [paper B \[30\]](#).

current through the wires. To protect the thin wires of the heaters from damage, heater settings of 50% were used as the maximum value for the experiments in 2022. The heating settings for the BHs and GHs for the pellet detachment depends on the barrel the pellet is launched from. Hereby the central barrel (B2) is usually the coldest. As the GHs were used to briefly heat up the pellets before the pellet launching, this is stored as an extra value in the data base: “power setting of the GHs for pellet detachment (GHR)”. In figure 3.14(b), this heating estimate E_{heating} is given for B1 (circular point shape) and B2 (“x” point shape) for 100% D₂, 8 mm pellets. Barrel 3 is not included in the plot, as the

metric from equation (3.03) does not separate the points well and a more refined combination of parameters and weighting coefficients would be required. The colour-coding indicates the detachment state of the pellet and the detachment regimes from figure 3.14(a) indicated by the shaded areas. As indicated by the green-white striped triangle in the lower-right corner of the plot, the metric does not well describe the detachment states for the highly optimised, low velocity pellet recipes where minor parameter changes have the largest impact. In this regime, future recipe developments will require the adaptation of the weighting coefficients and/or my intuition/experience based on previous recipes. For the two pellet IDs 732 and 1628, an example of the calculated E_{heating} -value is given in the following:

- Pellet ID 1628 – B1 (GT1): stuck ③

$$\begin{aligned} E_{\text{heating}} = & 5 \cdot 12.9 \text{ [K]} + 1 \cdot 0 \text{ [%]} + 50 \cdot (9 + 0.5 \cdot 0 + 0.3 \cdot 0 \text{ [%]}) + \\ & + [5 \cdot (20 + 0.4 \cdot 0 + 0.25 \cdot 0 \text{ [%]}) \cdot 4 \cdot \log_{10}(1 + 2 \text{ [s]})] + \\ & + 100 \cdot 6.3 \text{ [K]} = 1335.35 \end{aligned} \quad (3.04)$$

- Pellet ID 732 – B1 (GT1): “perfectly free” ④

$$\begin{aligned} E_{\text{heating}} = & 5 \cdot 10.2 \text{ [K]} + 1 \cdot 0 \text{ [%]} + 50 \cdot (0 + 0.5 \cdot 0 + 0.3 \cdot 0 \text{ [%]}) + \\ & + [5 \cdot (30 + 0.4 \cdot 0 + 0.25 \cdot 0 \text{ [%]}) \cdot 4 \cdot \log_{10}(1 + 4 \text{ [s]})] + \\ & + 100 \cdot 11.4 \text{ [K]} = 1610.38 \end{aligned} \quad (3.05)$$

Pellet velocity predictions

Besides the pellet composition, the perpendicular velocity component ($v_{\perp}$) is the most important pellet parameter in order to characterise the fragmentation process which will be discussed in detail in section 3.3. Consequently, the assessment and control of v_{pellet} is crucial for the operation of SPI systems. Hereby, the pre-shattering pellet velocity depends on the propellant gas pressure, pellet length, and pellet mass density (ρ) (composition) as it is described by the ballistic formula for an ideal cylinder [238]

$$\frac{(\gamma + 1)}{2 \cdot V_{\text{max}} \cdot c_0} \cdot \frac{p_{\text{FV}}}{\rho \cdot L} = \left[\frac{\gamma - 1}{2} + \left(1 - \frac{v_{\text{pellet}}}{V_{\text{max}}} \right)^{-\frac{\gamma+1}{\gamma-1}} - \frac{\gamma + 1}{2} \left(1 - \frac{v_{\text{pellet}}}{V_{\text{max}}} \right)^{-\frac{2}{\gamma-1}} \right]. \quad (3.06)$$

Here, the maximum gas expansion rate into vacuum (V_{max}) with the speed of sound of the propellant gas (c_0) and the adiabatic index (γ) is given as $V_{\text{max}} = 2 \cdot c_0 / (\gamma - 1)$. This dependence of v_{pellet} is shown in figure 3.16(a). Different branches are visible depending on the pellet composition, hence mass for the same pellet dimensions. 100% D_2 pellets have the highest v_{pellet} for a given p_{FV} , 100% Ne the lowest, and the deuterium-neon-mixed pellets are located in-between. Vertical lines for a given neon percentage indicate pellet length scans via the BHs, resulting in varying pellet mass, hence v_{pellet} . When plotting v_{pellet} as a function of the mass density normalized propellant pressure ($p_{\text{FV}}/\rho L$) from equation (3.06), the different branches collapse into a single branch as shown in figure 3.16(b). With the help of this representation and the experience with different effects of heating recipes, the necessary p_{FV} for a desired v_{pellet} can be calculated, knowing of the pellet lengths for a given heating recipe (see figure 3.09), and the mass of the pellet via its neon content. With this, we were able to achieve pellet velocities with an accuracy

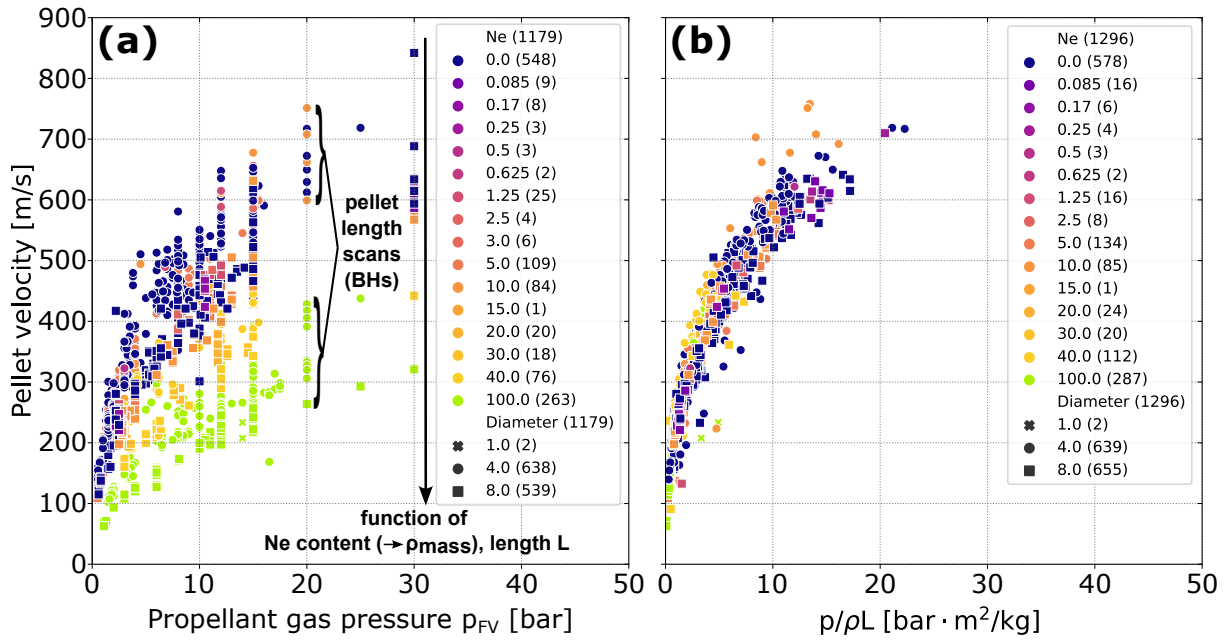


FIGURE 3.16: Pellet velocity as a function of (a) requested propellant gas pressure (FV filling pressure) and (b) $p_{FV}/\rho L$ from equation (3.06). Separate branches are visible in (a) for different pellet compositions (colour-coding). In the representation in (b) they collapse into a single branch. The 42 pellets labelled as broken are excluded from the plots. Figure published in [paper B](#) [30].

of 1 m/s w.r.t. the desired, previously unused target velocity. The two main reasons, why this is an import achievement are: the timing of diagnostic measurements (e.g. laser pulses of the Thomson measurements) and the resulting fragment size distributions which depend on $v_{\perp}$. The latter point is discussed in the following section in more detail. In addition to our velocity prediction via fitting of the experimental data, a 0D pellet acceleration model was developed by our colleagues at CER, published in [paper J](#) [48]. It takes key pellet and system parameters (e.g. D , f_{neon} , p_{FV} , FV opening time, ...) calculating v_{pellet} and predicting, whether the pellet will detach successfully or remains stuck. With this model, simulations for each pellet launched by us and the CER-team at this time were performed. The results were compared to the experimentally observed velocities with a good agreement, especially for the 8 mm pellets. Hereby, the sticking pressure of the pellets for the AUG SPI was manually set to 0 to account for the hollow punch and the relatively high launching temperatures of the cold head of more than 12 K [48].

3.3 Shattering characterisation

The main goal of the laboratory commissioning phase was to collect a large amount of shattering videos with the fragment camera in order to study the fragment size and velocity distributions. After the system had been transferred to AUG, no fragment camera was available and pellet tests were only performed to test existing/create new pellet recipes for the upcoming plasma experiments. During the laboratory commissioning phase, around 1100 shatter videos had been recorded. The fragment distributions were then analysed by T. Peherstorfer [230] with the help of tracking algorithms developed based on the `openCV` python package [239]. In traditional computer vision (CV), the detection of objects in an image is sensitive to the image quality (i.e. the contrast of the objects w.r.t. the background, noise, ...). Consequently, the illumination settings were optimised for the tracking algorithms throughout the laboratory phase. However, even for constant illumination settings, the parameters of the fragment tracking had to be adjusted constantly (e.g. due to the ratio of small fragments/dust cloud to larger fragments) to ensure good tracking results. As a consequence, the analysis was performed on a subset of the 1100 recordings. In order to analyse the remaining videos, J. Illerhaus developed a fragment detection software based on machine learning (ML) [47]. Here, the raw images from the fragment camera and boolean masks created from the labeled data by T. Peherstorfer serve as input for the neural network. It then creates the boolean masks necessary for the further analysis pipeline directly from the raw images without the need of the manual parameter adjustments in the traditional CV approach. The fragment distribution analysis performed by M. Miah with the help of the ML based approach are work in progress. The current interpretation of the AUG SPI experiments is done based on the analysis results by T. Peherstorfer.

In the following, the main results of the analysis by T. Peherstorfer about the fragment size & velocity distributions are briefly summarised. A more detailed analysis is available in his thesis [230].

Fragment velocity distributions The mean fragment velocity was found to lie in between the parallel velocity component ($v_{\parallel}$) (see figure 3.18(a)) and the pre-shattering pellet velocity (v_{pellet}), indicating an inelastic collision [230]. Consequently, the mean fragment velocity (v_{fragment}) is estimated as

$$v_{\text{fragment}} = (v_{\text{pellet}} + v_{\parallel})/2 \quad (3.07)$$

the mean of the two velocities for the AUG DREAM, and JOREK simulations (see papers D [50] and N [51]).

Fragment size distributions Within my thesis, I will use the $v_{\perp}$ as a proxy for the mean fragment size. Hereby, higher values of $v_{\perp}$ will result in an increased number of small fragments compared to lower values of $v_{\perp}$ as described in the probabilistic fragmentation model by P. Parks [211], refined by T. Gebhart *et al.* [212]. In his thesis [230], T. Peherstorfer compared – among other parameters – the expected mean fragment size from the Parks model with the observations from the shattering videos of the AUG SPI system. 1,000 Monte-Carlo simulations of the fragmentation process following the Parks model were performed for each analysed pellet realisation in the laboratory. Afterwards, the individual pellet realisations were compared to the mean of the 1,000 simulations. For

low values of $v_{\perp}$, the Parks model was significantly underestimating the number of small fragments, whereas the number was overestimated for high values. While the simulation points follow a linear trend between the mean fragment and $v_{\perp}$, an exponential behaviour was observed experimentally as illustrated in figure 4.7 in the thesis. Peridynamic simulations of the pellet fragmentation process for the AUG laboratory phase performed by S. Lee (see [paper H](#) [46] and his thesis [41]) as well as modeling via the discrete element method by P. Matura *et al.* [42, 43, 45] and S. Signetti *et al.* [44] show quantitative agreement with the fragment size distributions found by T. Peherstorfer.

Issues with $v_{\perp}$ as fragment size proxy As shown in figures 4.6 and 4.8 in the thesis by T. Peherstorfer [230], the mean fragment size ($\bar{d}_{\text{frag}}$) of the AUG SPI does not scale linearly with perpendicular velocity component. While $v_{\perp}$ is useful as a simple metric for the expected mean fragment sizes, this non-linear scaling brings in additional complexity when analysing fragment size effects on the disruptions (see sections 5.4 and 6.1). Additionally, v_{pellet} does not only influence the fragment size via $v_{\perp}$ but also the velocity distributions of the fragments. I want to illustrate this with the example of the pellet IDs #582, #657, and #625 provided in table 3.06. Hereby, the $\bar{d}_{\text{frag}}$ -values are taken from the analysis of T. Peherstorfer [230, 240].

pellet ID	shatter head	v_{pellet}	$v_{\perp}$	$\bar{d}_{\text{frag}}$	v_{fragment}	$v_{\text{fragment}}/\bar{d}_{\text{frag}}$
		[m/s]	[m/s]	[mm]	[m/s]	
#582	25°, rect.	121.4	51.1	0.48	115.7	241.0
#657	25°, rect.	244.0	102.4	0.32	232.6	726.9
#625	25°, rect.	493.5	208.1	0.22	470.4	2,137.2

TABLE 3.06: Ratio of the mean fragment size & velocity for three pellet examples. While v_{pellet} and $v_{\perp}$ follow a linear relationship, $\bar{d}_{\text{frag}}$ does not.

Consequently, whenever $v_{\perp}$ will be used as a simple indicator of the fragment size distribution, one needs to keep in mind that this is also tied to v_{fragment} . Additionally, it is important to keep in mind, that the fragmentation process follows a statistical nature, which requires an even larger number of SPI discharges to verify trends for fragment size effects.

While these constraints have to be taken into account in the analysis, I will use $v_{\perp}$, due to its simplicity, as a proxy of the fragment size throughout this thesis.

Shatter head comparison

A major objective of the laboratory experiments was to identify three shatter heads for the 2022 experimental campaign and potential candidates for future experiments at AUG. They should provide unique fragmentation characteristics on their own but also allow matching $v_{\perp}$ at different v_{pellet} to separate out fragment size & velocity effects. As discussed in section 3.1, we observe significant differences in the resulting fragments not only for variations in the shattering angles but also between shatter heads with circular

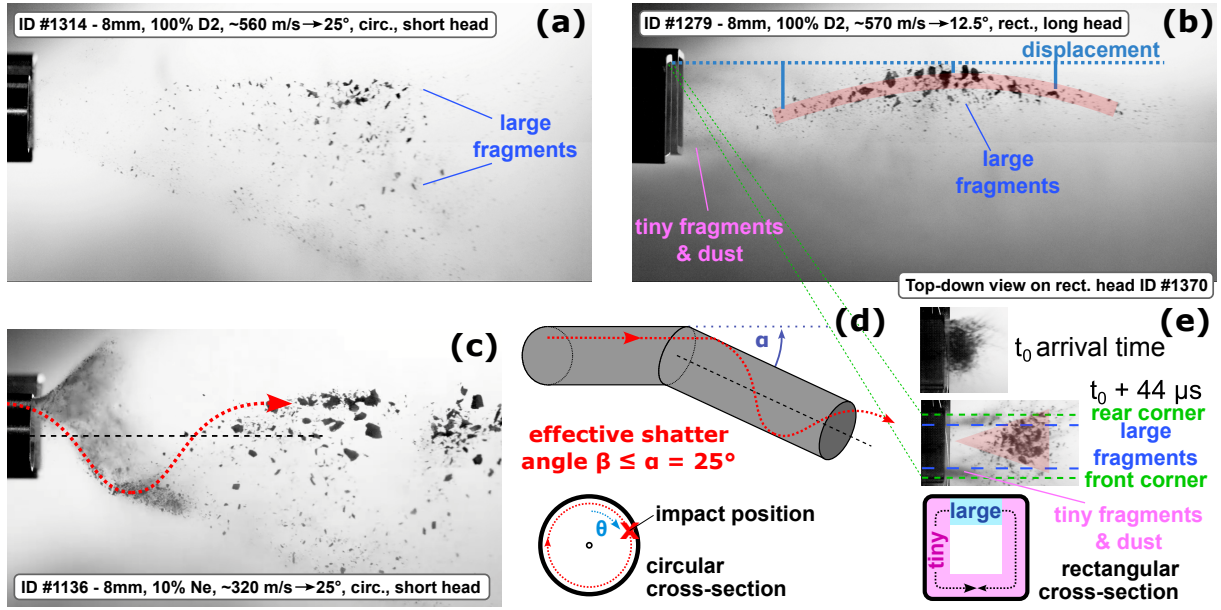


FIGURE 3.17: Comparison of circular and rectangular shatter head geometries. Overall, the rectangular shatter heads (b) have a more collimated fragment plume compared to the circular ones (a). For circular cross sections, fragments can have a spiral motion and the effective shatter angle depends on the impact position inside the head, depicted in (c, d). In contrast, for rectangular shatter heads, the large fragments exit the heads at the edge connected to the shatter plane (top corner in (b)) as illustrated in (e) and the shatter angle is equal to the miter bend angle. Figure published in [paper B \[30\]](#).

and rectangular cross section. Figure 3.17 shows a comparison of circular and rectangular shatter head geometries. Compared to the circular geometries (see figure 3.17(a, c)), the rectangular shatter head geometries (b) display more collimated fragment plumes. In the side-view (shattering plane at the top in (b)), these plumes often have a slightly arched shaped, where the smaller fragments have a higher displacement to the shattering plane compared to the larger ones. The images in figure 3.17(e) show the spatial fragment distribution for a 90° rotated, rectangular head – creating a “top-down” view (see figure 3.08(b)). Hereby, the large fragments leave the shatter head at the center of the shattering plane, while the tiny fragments and the dust are pushed towards and around the corners (larger displacement). It is expected, that this leads to an accumulation of small fragments at the corners, hence higher material density, which is visible as the darker dust clouds in figure 3.17(b, e). As the large fragments leave the shatter head along the edge of the shattering plane (top edge in b), the fragment plume appears more collimated in the side-view.

The horn geometry showed a similar distribution of the larger fragments in both the “top-down” & side view. The large fragments were still located in the central part of the horn and were not further pushed outwards compared to the rectangular geometry.

For the circular shatter head geometries, two important effects are observed:

- **Spiral motion of the fragments** – due to the circular cross section and the absence of corners where larger fragments could be stopped, fragments can form a spiral pattern (see figure 3.17(c, d)). Hereby, the angular momentum of the fragments can be induced by an off-center hit but also the gas, generated during the shattering process, pushing fragments outwards.

Therefore, the effective opening angle of the fragment plume is increased as shown in figure 3.17(c) and table 4.4 in the thesis by T. Peherstorfer [230]. Compared to rectangular geometries, this can result in a wider fragment plume width. Keep in mind that the fragment plume width will depend on the impact position, hence will have some probabilistic elements to it.

- **Variable effective shatter angle** – in a circular shatter head cross section the shattering angle depends on the impact position of the pellet inside the head. Consequently, the effective shatter angle β is $\leq$ the miter bend angle α , illustrated in figure 3.17(d). In contrast, the shattering angle is always equal to the miter bend angle for the rectangular geometries.

As a result, the fragment size distributions of the circular shatter heads show a higher variation in the data compared to the rectangular geometries as shown e.g. in figure 6.5 in the thesis by T. Peherstorfer [230]. This effect will be important for the discussion of the fragment size effect of the disruptions in chapters 5 and 6. The approximation of fragment size via $v_{\perp}$ might not be valid.

For the AUG system the rectangular shatter head seems to have a more collimated fragment plume, whereas T. Gebhart *et al.* [231] reported for their system a more collimated plume for the circular shatter head geometry. While the collimation of the fragment plume will most likely also be specific to the system, as it will depend on many different parameters (e.g. pellet dimensions, shatter head dimensions, ...), one potential explanation might also be the viewing angle of the UHS camera onto the fragment plume. For the AUG laboratory experiments a “side-view” was chosen as the default (shattering plane at the top in the videos; compare figure 3.17(b)), whereas the observations by T. Gebhart *et al.* [231] are based on a “top-down”-like view (shattering plane faces the camera; compare figure 3.17(e)). In the “top-down view” in figure 3.17(e), the fragments seem less collimated, as larger fragments are in the center and the smaller the fragments are pushed towards the corners. If compared, the images in figure 3.17(e) and figure 9 by T. Gebhart *et al.* [231] look very similar to each other. Both show a slightly triangular outline as the fragments seem to disperse over time. However, if we look at these fragments from the side-view, they are located mostly in a plane perpendicular to the camera view, hence seem more collimated and only the small fragments that are pushed around the corners are visible at the bottom half of the image in figure 3.17(b). In the case of a circular shatter head, where the fragments can rotate inside the shatter head, the “side-view” and the “top-down view” are similar.

Based on this characterization of the shatter head geometries, an informed decision on the shatter heads for the experimental campaigns at ASDEX Upgrade could be made.

Shatter head selection for the 2022 campaign Due to the upcoming decision on the shattering angle for the shatter units of the ITER DMS for the final design review in 2024 [56, 57], the most important research objective for this campaign was the assessment of the fragment size effect on the disruptions. Therefore, the following three shatter head geometries were selected (position viewed w.r.t. pellet flight direction):

- **GT 1** (bottom-left) – 25° , rectangular, long shatter head.
- **GT 2** (bottom-right) – 25° , circular, shortened shatter head.

- **GT 3** (top-central) – 12.5°, rectangular, long shatter head.

To compare the fragment plume width effect on the disruptions, a shortened, 25°, circular (maximizing the fragment plume width) and a long, 25°, rectangular shatter head (minimizing the plume width) were installed. The underlying idea of the 25° and 12.5°, rectangular shatter heads is the following: by matching the perpendicular velocity component ($v_{\perp,12.5^\circ} = v_{\perp,25^\circ}$), similar fragment size distributions are expected [211, 212] (see figure 3.18(a, b)). As the mean fragment velocity was found to depend only on v_{pellet} and $v_{\parallel}$ (see equation (3.07)) it is not affected by the choice of $v_{\perp}$. Consequently, if a pellet with double the pre-shattering pellet velocity is injected via the 12.5° head (compared to the 25° head), similar fragment size distributions are expected but with varied fragment velocity distributions.

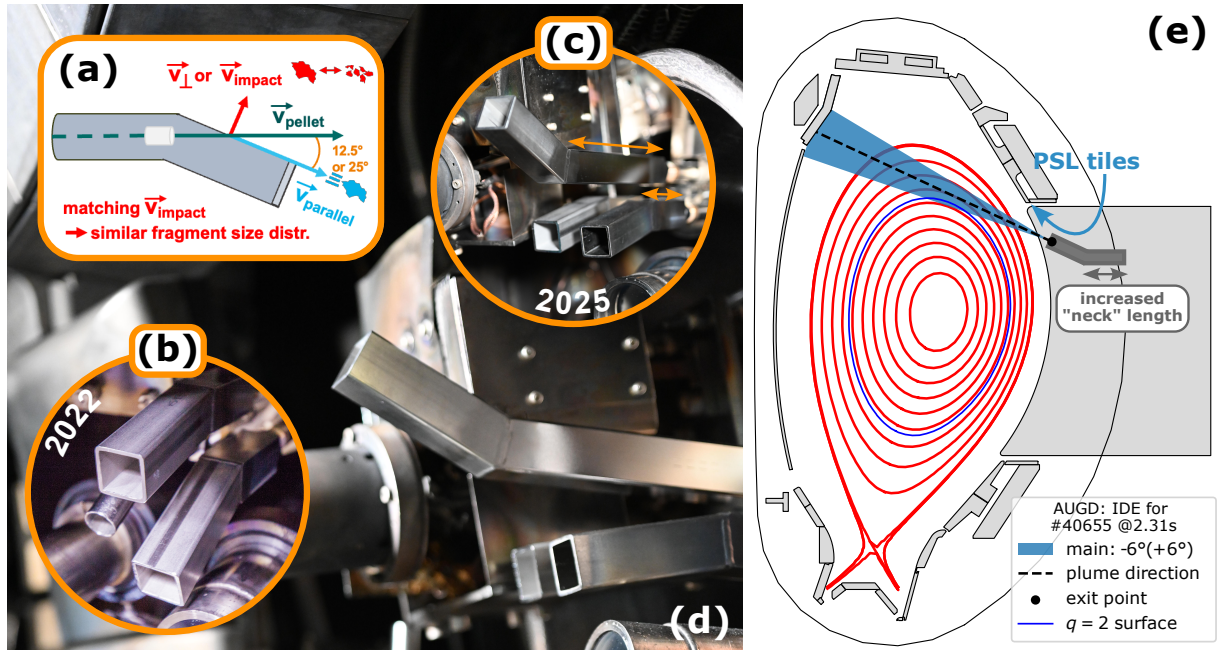


FIGURE 3.18: Shatter head geometries for the experimental campaign 2022 (b) and 2025 (c – e) at AUG. (e) The large fragments (“main”) are expected to miss the $q = 2$ intentionally. The neck length of the upwards pointing head is increased to avoid hitting the PSL tiles. The sketch in (a) illustrates the connection of $v_{\perp}$ and $v_{\parallel}$ with fragment size & velocity. The pair of 12.5° and 25°, rectangular heads from 2022 allow to separate fragment size and velocity effects. Photo in (b) taken by G. Papp and the plot in (e) created by P. Halldestam.

Shatter head selection for the 2025 campaign The main research objectives of the upcoming 2025 experimental campaign will be to study the synchronised and staggered injection schemes in more detail and investigate how precise these injections need to be without decreasing performance. Together with A. Bolland and R. Nocentini, I installed the following shatter heads for this campaign in July 2024:

- **GT 1 & 2** (bottom) – 12.5°, rectangular, long shatter head.
- **GT 3** (top-central) – 25°, rectangular, long shatter head with extended neck length pointing towards the upper divertor.

The two identical shatter heads attached to the GTs 1 and 2 are selected for the study of the synchronised and staggered injection schemes. The upwards pointing shatter head is installed to intentionally miss the $q = 2$ rational surface. This way, it is possible to study the mitigation efficiency for injections where the fragments do not cross the very core of the plasma. This is relevant in case a delayed injection into an already vertically displaced plasma would occur in ITER, especially for the upper port injectors. The neck length was increased to prevent hitting the passive stabilising loop (PSL) tiles. The hundreds of collected fragmentation videos were crucial in designing this geometry, complemented by the analysis of M. Miah with the ML model of J. Illerhaus ([paper I \[47\]](#)). The potential impact of the fragments on an AUG PSL tile were tested for us by T. Gebhart at Oak Ridge National Laboratory (ORNL) [[174](#), [231](#)]. He observed no damage to the tungsten coated tile, placed in a similar position and orientation w.r.t. the shatter head exit as it is inside AUG.

With the shatter head setups for the 2022 and 2025 experimental campaigns now introduced, I will now provide an overview on the diagnostic setup and plasma target scenarios of ASDEX Upgrade in the following chapter.

Chapter 4

Setup for the ASDEX Upgrade SPI experiments

In this chapter, I want to provide an overview of the setup for the SPI plasma experiments at ASDEX Upgrade and the diagnostics that were used throughout this thesis. Hereby, the foil bolometers will be in the focus, as the analysis of the radiated energy during the experiments was my main research topic.

The tokamak ASDEX Upgrade The tokamak ASDEX Upgrade is the successor of the Axially Symmetric Divertor Experiment (ASDEX) and is located in Garching, Germany [241–243]. It is referred to as a “medium sized tokamak with a full tungsten wall” (solid tungsten for some of the lower divertor tiles, otherwise tungsten coated graphite PFC tiles) [244–247]. AUG is divided in 16 parts (sectors) and between each sector (S) a toroidal field coil is located. The shattered pellets are injected into sector 16 (S16).

R	1.65 m	$P_{\text{Ohmic}} \leq 1 \text{ MW}$
a	0.5 m	$P_{\text{NBI}} \leq 20 \text{ MW (D}_2\text{)}$
B_{tor}	$\leq 3.1 \text{ T}$	$P_{\text{ECRH}} \leq 6 \text{ MW (140 GHz)}$
I_{p}	0.4 – 1.4 MA	$\leq 5 \text{ MW (105 GHz)}$
pulse duration	$< 10 \text{ s}$	$P_{\text{ICRH}} \leq 6 \text{ MW (30–120 Hz)}$

TABLE 4.01: Parameters of ASDEX Upgrade [242, 248, 249]: plasma major radius (R), typical plasma minor radius (a), toroidal magnetic field (B_{tor}), plasma current (I_{p}), Ohmic power (P_{Ohmic}), NBI power (P_{NBI}), ECRH power (P_{ECRH}), ICRH power (P_{ICRH}).

A poloidal and toroidal cut through the vacuum vessel of AUG is provided in figures 4.01(a) and (c), respectively. In (b), an in-vessel picture with annotations is provided, taken by G. Papp during the vessel opening in 2020. The shutter heads in the inlet-picture depict the shutter heads that were used for the 2022 experimental campaign (the heads in the large picture in (b) were replaced by the heads in the inlet before the experiments). The exit point locations of the shutter heads as well as the injection angles are provided in figure 4.01(a). The plasma equilibrium shown in figure 4.01(a) is taken from the reference discharge #41014 right before the injection ($t = 2.3 \text{ s}$) and the diagnostics are described in the following section 4.1.

The discharge control system ASDEX Upgrade is equipped with a flexible discharge control system (DCS), which allows both continuous control (e.g. feedback-control) as well as event based exception handling [175, 250, 251]. Usually certain target values (e.g. n_{e} or

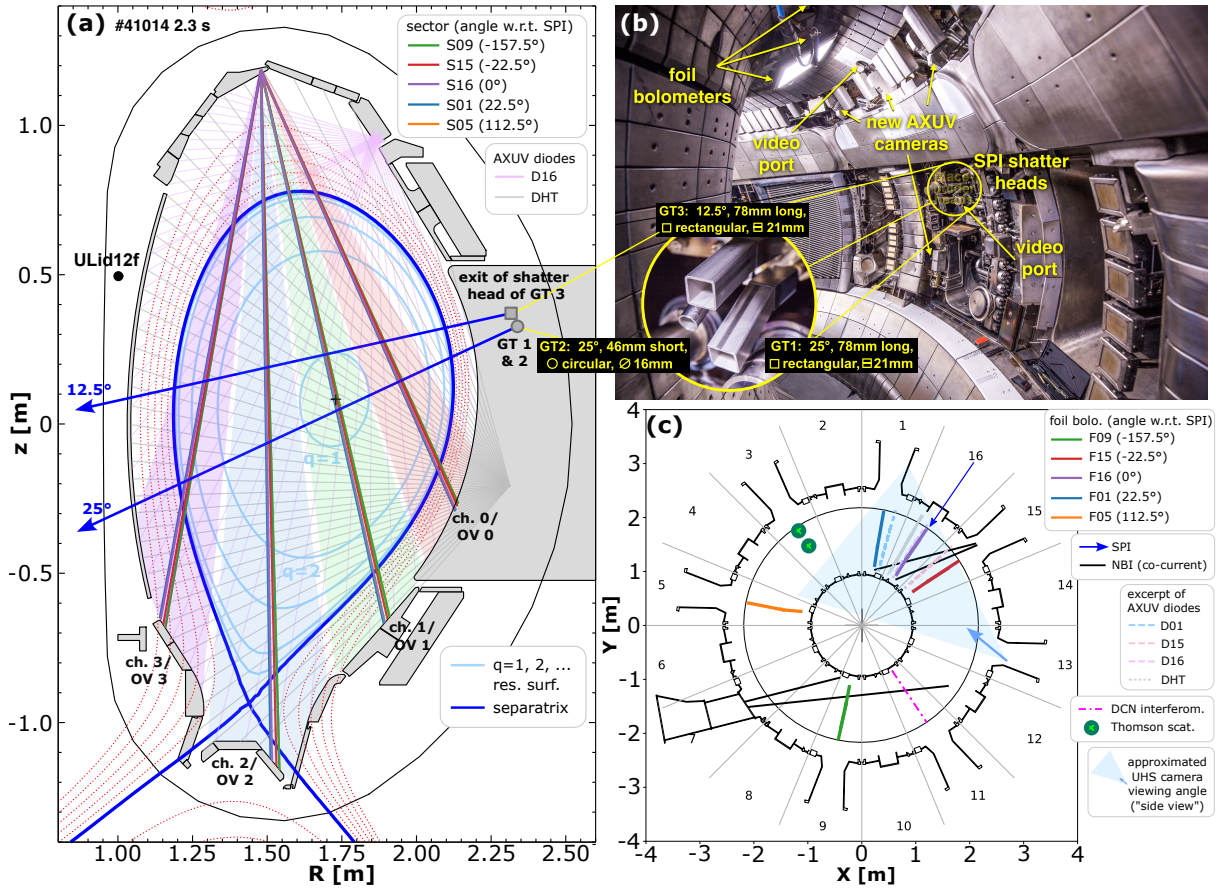


FIGURE 4.01: Poloidal (a) and toroidal (c) cross section of AUG. An in-vessel picture of sectors 15, 16, and 1 with inlet of the 2022 shatter head setup is shown (b), with both images taken by G. Papp. Only an excerpt of diagnostics/LOSs is shown (e.g. more AXUV diodes are available than depicted). Adapted figure published in [paper A \[52\]](#).

electron temperature (T_e)) are requested and the DCS can adapt for changes in these values via certain actuators (e.g. gas/pellet fueling rate, heating power, ...) [175]. However, it is also possible to disable certain feedback-control features and prescribe the actuator values directly (“feedforward”) [175]. This requires a more detailed shot planning, however, gives more direct control over the actuators, which may be necessary depending on the specific experiment requirements. As disruptions are – besides dedicated studies – not desired during normal operation, the DCS has multiple actuators to react to changes, that might cause a disruption [20, 175, 250, 251]. This requires the real-time capability of the system, which has a typical cycle-duration of 1.5 ms [20]. If not adapted/disabled before the experiment, the DCS will try to counteract plasma states that would lead to a disruption [251].

The controller for the vertical position of the plasma monitors the difference between the actual and requested vertical position, e.g. vertical position of the current centroid (Z_{curr}). In case the control deviation is above a pre-defined threshold – 7 cm is the default setting – the controller issues the notification that a VDE is detected. In this case, the system state of the VPE in the DCS (VPEState) will switch from the value 0 (no action required) into a higher state. The VPE program will try to initiate a soft landing of the discharge [252]. A maximum of three NBI sources are allowed at the beginning of the VPE. In case four

beam sources are requested for the discharge – as done in our SPI experiments – one of these beam sources is switched off. A step-wise ramp-down is pre-computed at the start of the VPE, shown in the appendix A.4. First, it will try to freeze the current plasma state (“hold state” $\text{VPEState} = 1$) and afterwards ramp down the plasma current.

If this threshold is not modified/disabled, experiments in which a threshold is (deliberately) exceeded will be eventually influenced by the action of the DCS. For the experiments in 2022, the threshold value of Z_{curr} had not been modified/disabled before the experiments: some of the discharges with 100% D₂ SPI might have been affected by the VPEState -change or even disrupted if one of the NBI sources was switched off by the DCS (also cases were observed where a NBI interlock disabled the beams). I recognised this in the analysis of the pre-TQ durations of the disruptions after the experimental campaign 2022 had already finished. Disruptions in which a change of the VPEState is triggered prior to the IP-spike (pre-IP-spike VPE) are often excluded from the analysis (see “ VPEState -change or MGI” in the appendix A.6). Note, no change in the VPEState does not automatically mean, that all NBI sources stayed active, as these sources also have their own interlock system. For the upcoming experiments in 2025, the DCS trigger conditions will be discussed in advance to avoid undesired interference with the experiments: e.g. for the first experiments on December 12th in 2024, the Z_{curr} -threshold was effectively removed by adjusting the value from 7 cm to 2 m.

4.1 Diagnostic setup used in this thesis

Radiation measurements

After the diagnostic upgrade of ASDEX Upgrade accompanying the deployment of the SPI, AUG is equipped with a multitude of bolometric lines of sight (LOSs) with good poloidal and toroidal coverage. This creates the unique opportunity to study the radiation asymmetries inside the plasma after the SPI and get a good estimate for the radiated energies derived from the foil bolometers. In the following, the foil and diode bolometers are explained as well as the technique to measure W_{rad} . A more detailed technical description of the bolometers installed at AUG is provided by M. Bernert [253, 254].

Foil bolometers

Inside the foil bolometers a thin metal foil (gold for AUG) absorbs the energy that reaches it via radiation. This will lead to a change of resistance due to an increase in temperature, from which the power deposited onto the foils can be derived. Taking the system geometry into account, the total radiated power (P_{rad}) and W_{rad} can be calculated. As the foil bolometers are intrinsically absolutely calibrated, they are a reliable diagnostic for the absolute total radiated power measurements [254]. Due to the readout methodology, an average of at least two sampled points is necessary, resulting in a maximal time resolution of 0.8 ms (1.25 kHz). These fast signals are written to the BOLZ experiment files (see table 6.01). For non-disruptive studies at AUG, the signal is averaged over more data points to reduce noise inside the signal and get a more robust measurement – written to the AUGD experiment files. While there were foil bolometers installed at AUG before, in preparation of the SPI experiments, five new absolutely calibrated, 4-channel foil bolometers were installed (see figure 4.01). They are located in five different toroidal positions: three around the SPI location (sectors 1, 16, 15), one “perpendicular” (sector 5) and one

“opposite” (sector 9) to it (see figure 4.01(c)). They all have a shared poloidal viewing geometry, where pinholes allow the illumination of four channels. Therefore, each channel (ch) has its individual observation volume (OV) (see figures 4.01(a, c) and 4.02). These OVs indicate the regions from which radiation can directly illuminate the foils through the pinhole (“full-shadow”). While the foil bolometers measure the radiation entering the pinhole from the OV and are **not** a line-integrated measurement, the definition of a central “LOS” depicted in figures 4.01 and 4.02 can be useful to indicate the viewing angles and will be frequently used throughout this thesis.

An effect of increasing neutral particle pressure on the signals of the foil bolometers had been observed for very high neutral pressures [255, 256]. While the exact effect of the neutrals on the measurements of our experiments is difficult to determine, the strong increase in neutral densities due to the injection seems to happen after the most relevant phases of the disruption as shown by pressure gauge measurements (see appendix A.8).

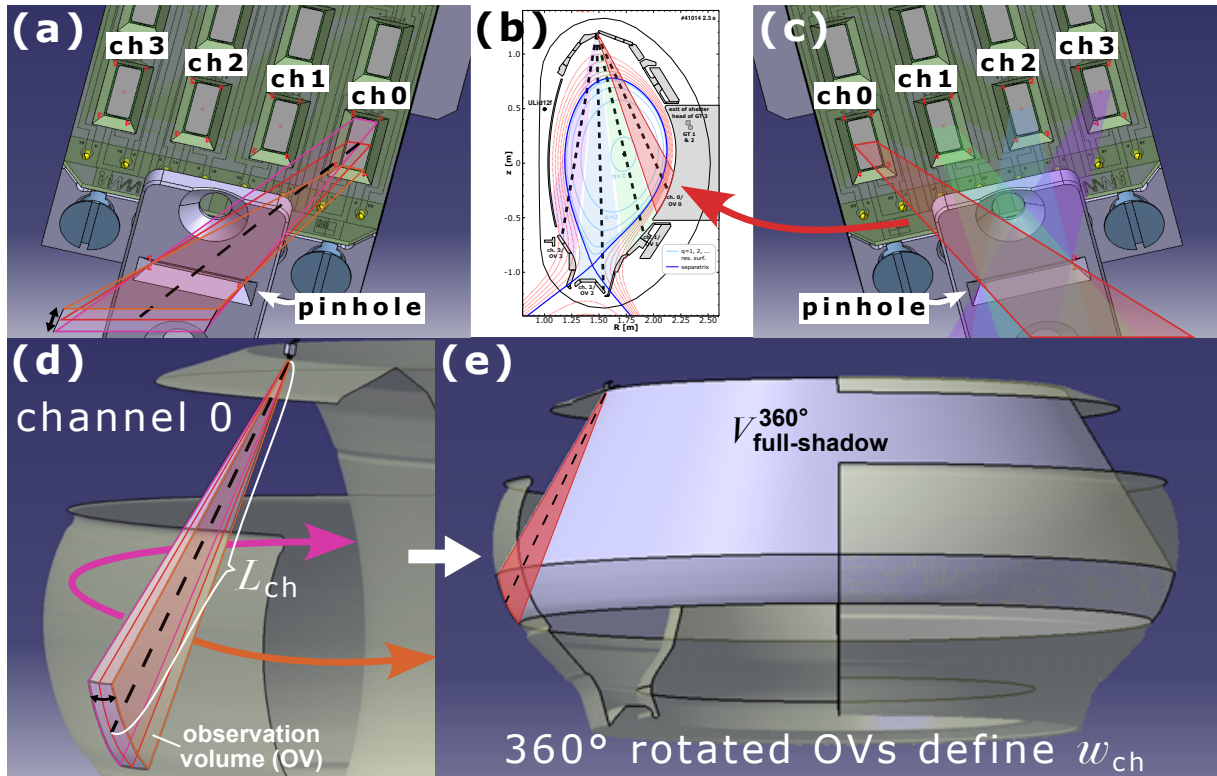


FIGURE 4.02: Channels and observation volumes (OVs) of the foil bolometers. The four observation volumes for each bolometer are created by the pinhole geometry, which illuminates one of the four foils shown in (a)–(c). The second set of foils is not illuminated and they are used as reference channels. To assess the radiated energy coming from the entire plasma ($\Phi = 360^\circ$), the OV of channel 0 in (d) is rotated by 360° around the torus, creating $V_{full-shadow}^{360^\circ}$. From this, $w_{ch=0,360^\circ}$ and $w_{ch=0,S}$ are derived (see equations (4.02) and (4.04)). The CAD drawings are created by T. Eberl.

Calculation of W_{rad} via the foil bolometers In order to estimate the radiated energy coming from the entire plasma (toroidal angle (Φ) = 360°), certain channel specific weighting factors ($w_{ch,360^\circ}$) are necessary for each channel of the foil bolometers. These factors take into account the arithmetic mean of the full- & half-shadow OVs and the chord

length (L_{ch}). As the poloidal coverage varies depending on the channel (see figures 4.01(a) and 4.02), the weighting factors are different for each channel. Following channel 0 as an example, the calculation of $w_{\text{ch},360^\circ}$ is given as

$$w_{\text{ch}=0,360^\circ} = \frac{V_{\text{full-shadow}}^{360^\circ} + V_{\text{half-shadow}}^{360^\circ}}{2} \cdot \frac{1}{L_{\text{ch}}} \quad (4.01)$$

$$= \frac{2.67 + 4.36}{2} \cdot \frac{1}{1.61} = 2.18 \quad (4.02)$$

with the full-shadow-360°-expanded Volume ($V_{\text{full-shadow}}^{360^\circ}$) and half-shadow-360°-expanded Volume ($V_{\text{half-shadow}}^{360^\circ}$). The radiated power in an individual sector ($P_{\text{rad, sector}}$) is defined as

$$P_{\text{rad, sector}} = \sum_{\text{ch}=1}^4 w_{\text{ch},\text{S}} \cdot P_{\text{ch}}, \quad (4.03)$$

with the individual sector weighting factors for each channel ($w_{\text{ch},\text{S}}$)

$$w_{\text{ch},\text{S}} = \frac{w_{\text{ch},360^\circ}}{16} \Rightarrow \begin{cases} w_{\text{ch}=0,\text{S}} = \frac{2.18}{16}, \\ w_{\text{ch}=1,\text{S}} = \frac{2.54}{16}, \\ w_{\text{ch}=2,\text{S}} = \frac{2.41}{16}, \\ w_{\text{ch}=3,\text{S}} = \frac{1.74}{16} \end{cases} \quad (4.04)$$

for channels 0–3 and radiated power of a certain channel (P_{ch}). The factors were originally derived to estimate the radiation coming from the entire plasma ($\Phi = 360^\circ$) from the measurements in one sector (similar to the idea behind the **Pradtot** measurement/algorithm frequently used at AUG [257]) with the assumption of toroidally symmetric radiation. To compare the asymmetries, one could then compare the individual estimates for the total radiated power. However, we came to the conclusion to divide the weighting factors by 16 ($\rightarrow w_{\text{ch},\text{S}}$) to assess the radiation in the particular measurement sector and for the missing sectors a linear interpolation of the data is used. As indicated in section 6.2, this method should give a good estimate for the total P_{rad} or W_{rad} as the most prominent asymmetries seem to be covered by the observation of sectors 1, 16, and 15. The radiated energy can be calculated by summing over all 16 sectors (5 measurement sectors plus 11 interpolated sectors) and integrating over the desired time window

$$W_{\text{rad}} = \int_{t_{\text{start}}}^{t_{\text{end}}} P_{\text{rad}} \, dt \quad (4.05)$$

$$= \int_{t_{\text{start}}}^{t_{\text{end}}} \sum_{\text{sector}=1}^{16} P_{\text{rad, sector}} \, dt, \quad (4.06)$$

with the integration interval start-marker (t_{start}) and integration interval end-marker (t_{end}). We assume an uncertainty of W_{rad} in the order of 20% comparing this technique to the real radiated values. For a comparison of the W_{rad} -values between different discharges (“inter-shot comparison”, see e.g. figure 6.03), we assume an uncertainty in the order of 10%.

Semi-automatic peak finding and integration algorithm To analyse the radiation characteristics of the 208 discharges from the 2022 experimental campaign, I used a semi-automatic peak finding and integration algorithm based on the `scipy.find_peaks` python package. Two examples are provided in figure 4.03 with a disruptive SPI in (a) and a non-disruptive injection in (b). In the disruptive case for the reference discharge #41014, four radiation peaks are detected. The physics interpretation of these radiation peaks is provided in chapter 5.

The plasma current is provided as a reference in figure 4.03(I). The blue/red numbers together with the bars next to them in (II), illustrate the minimum/maximum difference between the detected peaks of the five sectors in amplitude and time. In (III), the normalised time derivatives of the signals are shown. They are normalised w.r.t. the first maximum of the derivative. The dashed vertical lines indicate the suggested integration boundaries for the discharge based on each sector – the earliest and latest of these suggestions are selected as the “total integration boundaries” in (IV). They mark the positions where the derivative approaches zero before the first and after the last radiation peak, respectively. When the derivative exceeds a threshold value of -0.025 and also the average over the next 3 & 20 data points exceeds this threshold, the position is marked as a boundary-suggestion for this sector. This technique is also used to detect the end time of the CQ (t_{CQend}), which I developed initially for the transition of the CQ to the RE-plateau for previous studies [129, 130]. The 3- & 20-point averages ensure that the derivative approaches zero and not only a fluctuation in the signals or short plateau phase is detected. In (IV), the following definitions of the radiation peak values are shown:

- local maximum of P_{rad} for the Xth radiation peak in sector SY ($P_{\text{rad, X. peak}}^{\text{SY}}$):
e.g. $P_{\text{rad, 2. peak}}^{\text{S15}}$ refers to the maximum value of the 2nd radiation peak in sector 15,
- global maximum of P_{rad} in sector SY ($P_{\text{rad, max}}^{\text{SY}}$):
e.g. $P_{\text{rad, max}}^{\text{S1}}$ refers to the global maximum value across all radiation peaks in sector 1, and
- global maximum of P_{rad} for all measurement sectors ($P_{\text{rad, max}}^{\text{total}}$):
in the given example in figure 4.03(IV), the total maximum is the total maximum in sector 16 ($P_{\text{rad, max}}^{\text{S16}}$), which is the peak value of the 1. peak ($P_{\text{rad, 1. peak}}^{\text{S16}}$).

For some discharges, a symmetric bug for some of the channels appears, which complicates the peak finding process (see appendix A.5). By adjusting the peak finding parameters, I could often still obtain good results. These bugs typically do not affect the calculation of W_{rad} due to their symmetric appearance. In the rare cases the peak finding is strongly influenced by these bugs or measurements are missing/corrupted, the discharges are excluded from the dataset (see “corrupted foil bolo signals” in the subset table in the appendix A.6).

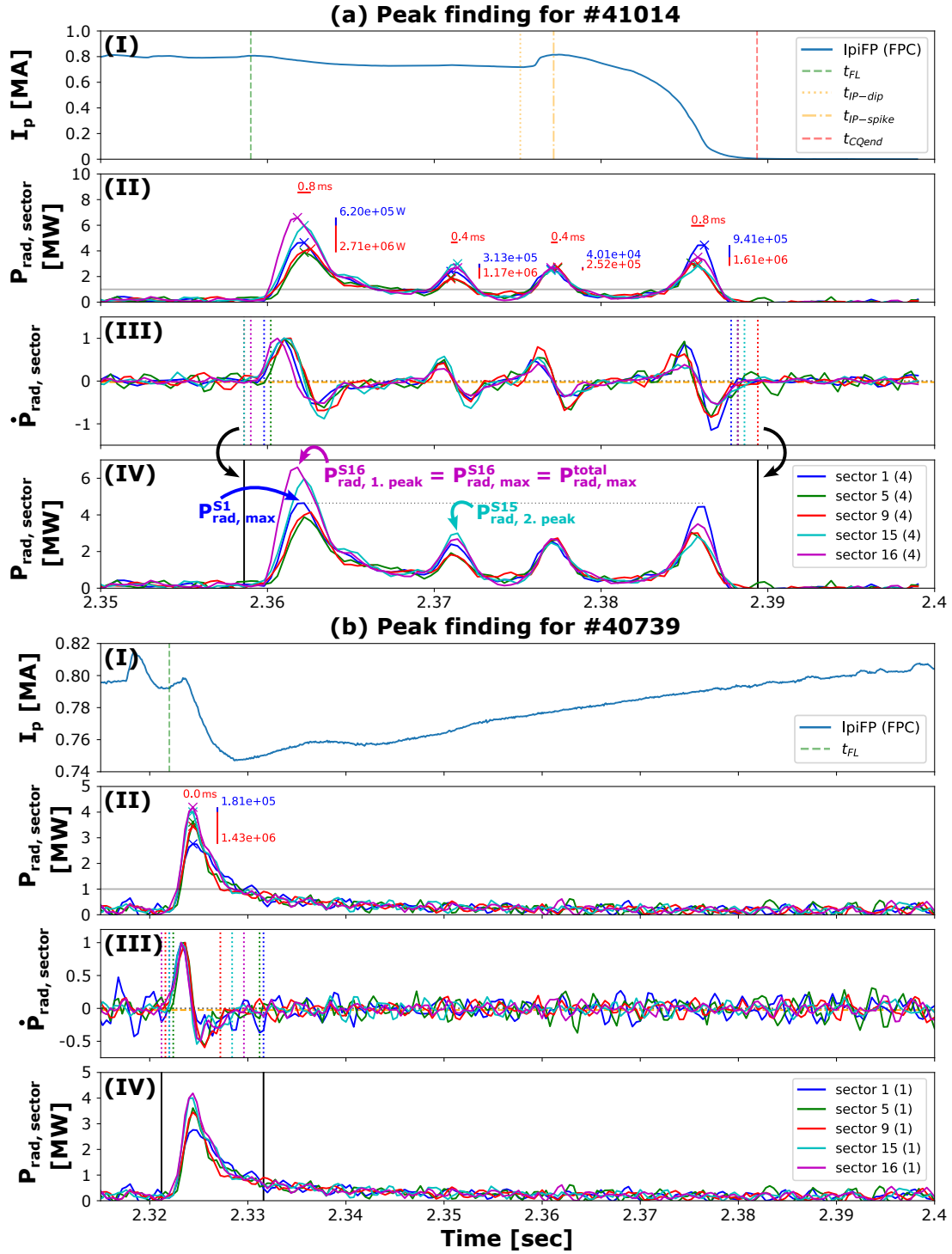


FIGURE 4.03: Examples of the semi-automated radiation peak detection. The plots show the following: (I) plasma current with time markers, (II) $P_{\text{rad, sector}}$ (see equation (4.03)) where the crosses indicate the detected peaks, blue/red bars indicate the minimal/maximal difference in time and amplitude between peaks as well as the vertical gray bar indicating the user-selected minimum threshold value, (III) time derivative of $P_{\text{rad, sector}}$ normalised w.r.t. maximum of the first peak and proposed integration borders for each sector (dashed vertical lines), (IV) $P_{\text{rad, sector}}$ with definition of peak radiated powers and black vertical lines indicate the selected total integration borders.

AXUV diodes

One downside of the foil bolometers is the comparably low time resolution, hence the limited capabilities of studying transient events such as disruptions. While the use of the Absolute eXtended UltraViolet (AXUV) diodes offers a much higher time resolution of $\Delta t = 2 \times 10^{-6}$ s (500 kHz) [254], the degradation of the AXUV diodes poses a major difficulty assessing W_{rad} . The major problem is, that the responsivity of the AXUV diodes degrades rapidly during the first 50 s of plasma operation [254]. While there are efforts to take the degrading responsivity into account for the analysis of the SPI experiments at AUG [258], generally speaking they are not well suited to measure the radiated energy. Therefore, for the work presented here, W_{rad} is derived by the foil bolometers alone, while I use the AXUV diodes only to gain more insight on the fast processes during the disruption and did not analyse them quantitatively. An excerpt of the AXUV diodes/LOSs is shown in figure 4.01 with many more being available (e.g. high poloidal coverage in S5). In addition to the vertical LOSs (D01, D15, and D16 in the respective sectors), horizontal LOSs are available in S16 (DHT) and e.g. S5. The combination of vertical and horizontal LOSs allows to track the radiation with the help of the fast AXUV diodes [258] as briefly discussed in section 6.2.

Ultra-highspeed cameras

During the plasma operation, enough light is emitted in the visible range by the plasma and fragments that the UHS cameras [259] can record the fragment arrival and disruption evolution. The emission from Balmer- α transition for deuterium (D_α) is in the visible range (≈ 656 nm [165, 260] – red). To focus on the emissions of the pellet material, D_α filters around $\lambda_0 \approx 659.8$ nm (see appendix A.9) were added for the majority of the discharges. In figure 4.04 a CAD of the views for the (a) top-down and (b) toroidal camera views is provided. This is also illustrated as a sketch in (c).

At first, only the UHS camera with the toroidal view was installed for the experiments. Due to missing shielding boxes, the “top-down view” and the OPD UHS cameras were not available for first experiments until a later time in the campaign. Detailed studies on the fragment penetration process had been performed by A. Patel [214, 265] comparing the recordings of these UHS cameras with AXUV signals. Throughout this thesis, I will use the two views from figure 4.04(a, b) of the UHS camera recordings for the analysis and illustration of the different disruption phases (see figures 5.03 and 5.04).

Shunt current measurements

ASDEX Upgrade is equipped with shunt current measurements that are distributed poloidally and toroidally [53, 151, 158]. They measure the currents that are flowing between different tiles. While they are routinely used to measure the temperature difference between the inner and outer divertor halves (T_{div}) [158, 266] via a temperature dependent sheath potential difference [60], they can be also used to infer the halo currents arising during disruptions [53, 151]. A more detailed description of this diagnostic and how this relates to the halo current is provided in section II.4 in the thesis of N. Schwarz [151].

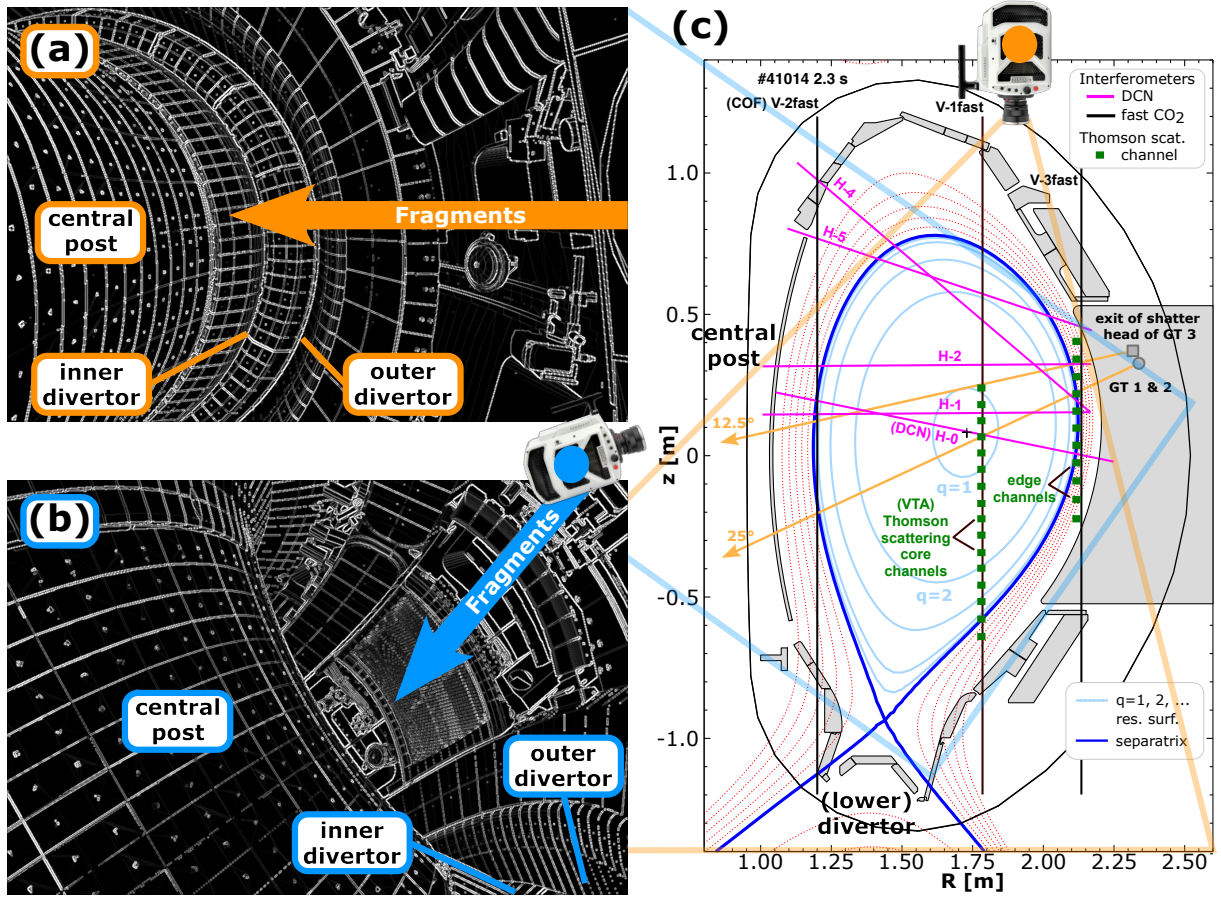


FIGURE 4.04: UHS camera views and density measurements via DCN & CO₂ interferometers, as well as Thomson scattering. The virtual views for the (a) top-down view and the (b) toroidal view are shown. These views are illustrated in (c) by light orange/blue triangular/rectangular frames, respectively. Also in (c), the LOSs for the DCN [261, 262] and CO₂ [263] laser interferometers are shown. Additionally, the channels of the core and edge vertical Thomson scattering system [264] are provided. The virtual camera views in (a, b) were generated by T. Lunt and G. Papp.

Density measurements

As one of the three main objectives of SPI is to assimilate enough pellet material to suppress the generation of REs, reliable density measurements are essential for these studies. The different laser based density measurement techniques that we used for the analysis of the SPI experiments are introduced in the following:

DCN and CO₂ laser interferometry Laser interferometry is frequently used in tokamaks for density measurements [261]. A laser is split into two beams, one goes through the plasma and the other one is used as the reference beam [60]. From the phase shift between the two beams, the plasma density can be inferred [60]. Hereby, the maxima in the interfering beams are counted that occur with every 2π phase shift, the so-called “fringes”. However, this method is susceptible to so-called “fringe jumps”: e.g. missing out on a 2π phase shift by rapidly increasing densities cause too low density measurements [261]. Especially, for strong density changes on short time scales – as in our SPI experiments – it can be difficult to obtain valid signals: an example of this is provided in figure 4.07(b – II),

where the density measurement of V-2fast (in green) does not approach zero at the end of the disruption around $t = 2.34$ s.

At present, interferometry at ASDEX Upgrade is done with DCN [261, 262] and CO₂ [263] infrared lasers. For the upcoming experimental campaign in addition a dispersion interferometer will be available that is better suited for density measurements during disruptions [267]. In figure 4.04, the LOSs used within this thesis are displayed. The signals depend on the cord length of the LOSs through the plasma. The raw signal measures the line integrated electron density ($\tilde{n}_e$) (unit: [m⁻²]) and the line averaged electron density ($\bar{n}_e$) (unit: [m⁻³]) is obtained by dividing the signal by the cord length through the plasma (which is in the order of ≈ 1 m for AUG).

Thomson scattering Another technique to determine the density and also temperature of free electrons in the plasma is via Thomson scattering [268]. For monochromatic light, the temperatures can be reconstructed by measurements of the Doppler shift, whereas the densities depend on the fraction of scattered/unscattered photons [264, 269, 270]. For the AUG SPI experiments in 2022, the Thomson scattering system [264] was used in “burst mode” [271], where short laser pulses with a time delay of < 1 ms were used to capture the fast increase of density in the plasma. Hereby, the exact timing of the lasers relative to each other can be adapted, where the time until the next cycle is determined by the 20 Hz (50 ms) repetition rate [264]. Therefore, during the disruption, usually only one well timed set of laser pulses can be used. For disruptions with long pre-TQ durations (see section 5.2), it is easier to get the timing of the laser pulses to lie within the pre-TQ. This becomes increasingly difficult for shorter pre-TQ times as the timing needs to be very precise w.r.t. the fragment arrival in the plasma.

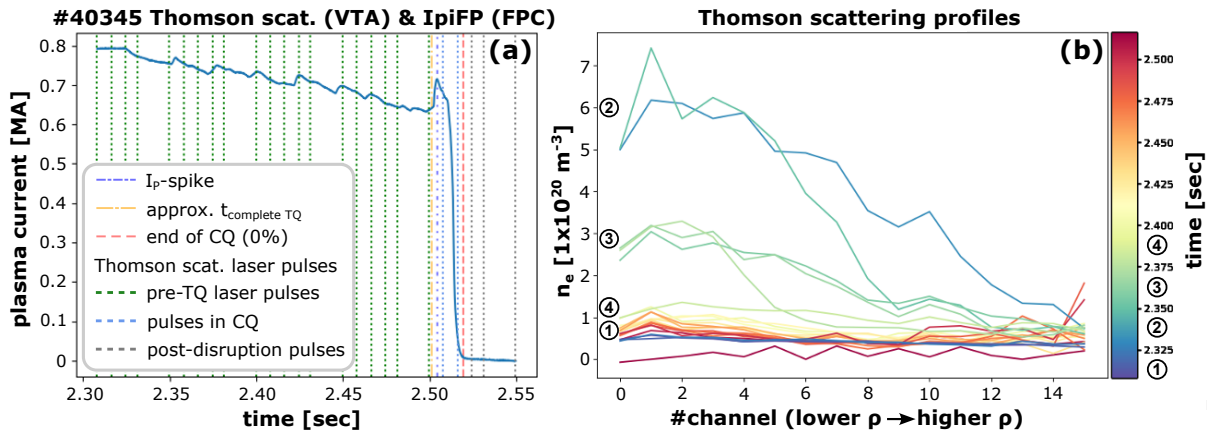


FIGURE 4.05: Thomson scattering laser pulses [264] (burst mode [271]) into Ohmic discharge #40345. During the ramp-down of the plasma current by the DCS, multiple measurement laser bursts were possible before the plasma disrupts around 2.5 seconds. In the first phase, the plasma density quickly rises, before it collapses, indicated by the electron density (n_e) profile in (b). Hereby, larger channel numbers correspond usually to larger values of ρ_{pol} , shown in figure 4.04(c).

An example of the density profiles for an Ohmic discharge #40345 are provided in figure 4.05. After the injection, the plasma current in (a) is slowly decreasing. At 2.40 s, the “plasma hold” state of the DCS is triggered. During this extended pre-disruption phase,

multiple measurement bursts were possible. Between 2.30–2.35 s (① → ②), the plasma density increases strongly, before it drops again. Here, laser pulses with a time delay of < 1 ms were used and higher channel numbers usually correspond to larger values of ρ_{pol} (see figure 4.04(c)).

4.2 Plasma scenarios for the 2022 experiments

For the experiments, multiple different plasma scenarios had been used. All of these discharges were lower single null (LSN), NBI and ECRH heated discharges, with the $\nabla B \times B$ -drift directed towards the active X-point. An overview of the plasma parameters is provided in table 4.02.

plasma scenario	SPI H-mode	Ohmic	2.5T H-mode	low T_e	High W_{plasma}
B_{tor} [T]	1.8	1.8	2.5	1.8	2.5
I_p [MA]	0.8	0.8	0.8	0.8	1.0
P_{NBI} [MW]	7.5 – 9.9	–	9.3 – 9.9	2.4	8.3 – 9.7
P_{ECRH} [MW]	2.85 – 3.2	–	2.85 – 3.0	1.6	2.05
q_{95}	< 4	< 4	> 5	< 4	≈ 4
$\tilde{n}_e$ [$\times 10^{19} \text{ m}^{-2}$]	4.5 – 6.8	3.9 – 4.5	5.5 – 6.8	5.5 – 6.1	no meas.
avg. pre-inj. W_{plasma} [MJ]	1.25 – 1.4	0.69 – 0.74	1.3 – 1.4	0.93	1.92
avg. f_{th}	0.48	0.15	0.48	0.33	0.47
#discharges	176+3	16	6	3	3+1
with (#pellets)	(204+3)	(16)	(9)	(3)	(3+1)

TABLE 4.02: Plasma parameters for the different plasma scenarios for the 2022 experimental campaign at AUG. In total, 239 pellets were injected into 208 plasmas. The “+3/+1” refers to unhealthy H-modes, where the plasma energy dropped significantly before the injection. The plasma parameters are averaged over 50 ms prior to the injection. The line integrated electron density ($\tilde{n}_e$) is provided for the LOS H1 (DCN). The calculation of thermal energy fraction (f_{th}) follows equation (4.07). Table published in [paper A](#) [52]. (subset: [full dataset](#))

The thermal energy fraction (f_{th}) [162, 272] is defined as:

$$f_{\text{th}} = \frac{W_{\text{th}}}{W_{\text{mag}} + W_{\text{th}} - W_{\text{c}}} = \frac{W_{\text{th}}}{W_{\text{plasma}}} = \frac{W_{\text{th}}}{W_{\text{con}} + W_{\text{rad}} (+ W_{\text{RE}})}, \quad (4.07)$$

averaged over 50 ms prior to the injection. Hereby, discharges with low heating powers – like the Ohmic and low T_e scenarios – have a lower thermal energy fraction. The thermal and magnetic stored energies of the different target plasmas are shown in figure 4.06. The colours indicate the different target plasmas and the point types the pellet detachment states as introduced in section 3.2. A valid pellet arrival time-marker (“time of first light”

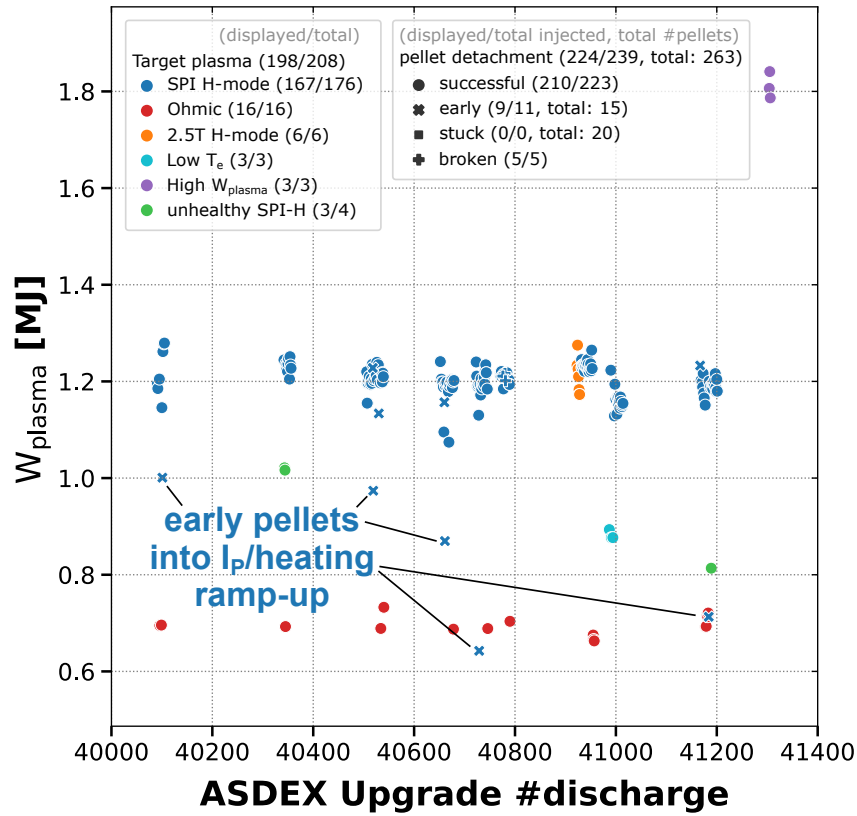


FIGURE 4.06: The energy dissipated in the plasma (W_{plasma}) for the different target plasmas of 2022 averaged over 50 ms prior to the injection. Colours represent the different target plasmas, point type indicates the pellet detachment states from section 3.2. The highlighted early pellets accidentally self-released so early, that the unshattered pellets were injected into the (heating and/or current) ramp-up phase, hence the reduced W_{plasma} -values. A minor degradation of W_{plasma} for the SPI H-mode is observed for later discharges in the campaign. (subset: [full dataset](#))

see section 5.1) was not identified for all 208 discharges. Therefore, the numbers in the brackets indicate the number of displayed discharges, total number of discharges/injections, and total number of pellets – including pellets that not arrived in the plasma as they remained stuck or released early into still closed torus gate valve (see figure 3.07(b)). Some pellets that self-released early arrived before the heating powers are fully ramped up. These pellets either arrived into the plasma current ramp-up phase or before the transition from L-mode to H-mode (L-H-transition), hence these discharges have a reduced W_{plasma} . However, some of these early pellets had been useful for pellet ablation studies performed for fueling pellets [198], as they are expected to arrive as intact pellets at the plasma surface. This assumption was also confirmed in a case where one of these intact pellets was captured by an in-vessel camera. This camera could not observe all of these early pellets, as the time resolution is much lower compared to the UHS cameras, required to reliably capture the injections. Seven 100% D_2 pellets that were originally planned as the first pellet of a staggered injection, remained stuck. The subsequent 10% Ne pellets (planned as the second injection) were treated as “single injections” for the analysis, explaining the higher number of discharges with single, 10% Ne injections (e.g. figures 6.03 and 6.06 in chapter 6).

The base scenario was a 1.8 T H-mode used for the SPI experiments (SPI H-mode) shown in figure 4.07. Towards discharges later in the campaign, a small degradation of the thermal energy leads to reduced values of W_{plasma} .

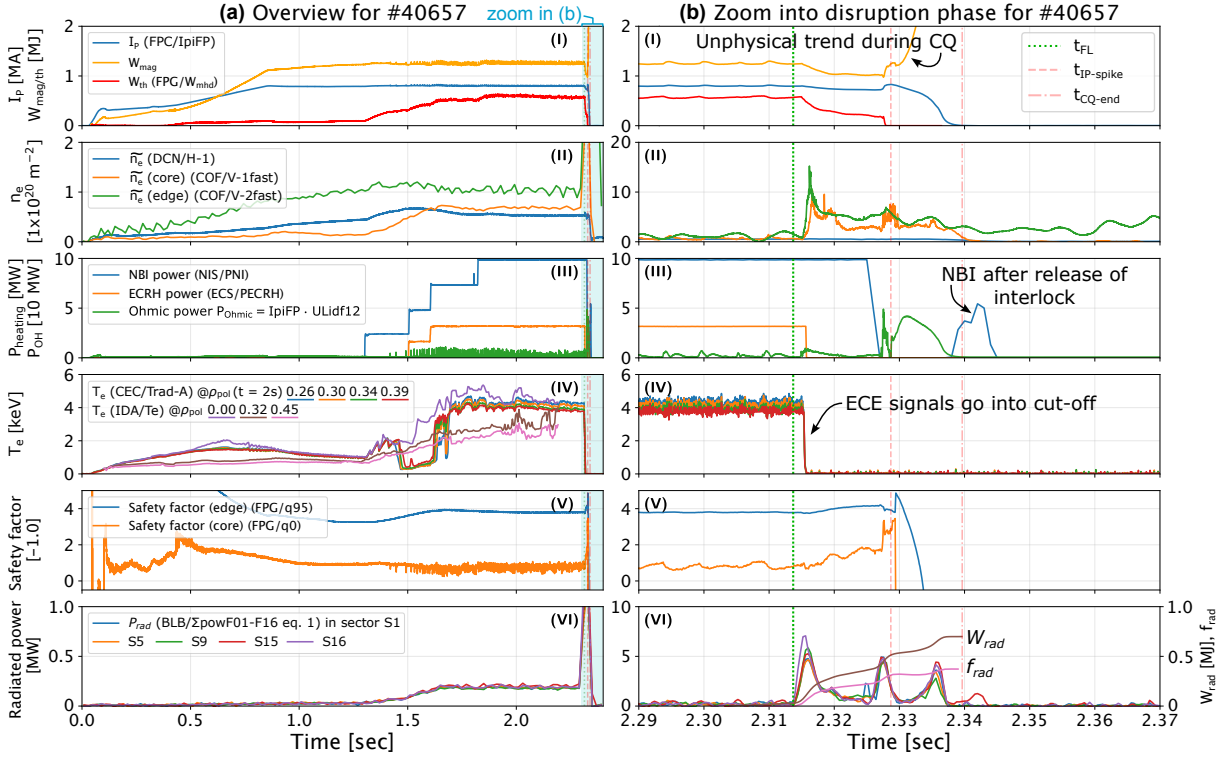


FIGURE 4.07: Scenario overview for the SPI H-mode. The entire discharge is shown in (a) and a zoom into the disruption is provided in (b). Note, different y-axis limits are selected in (II) and (IV) between (a) and (b). The following signals are shown: (I) the plasma current, stored magnetic and thermal energies, (II) line integrated electron density derived from the core LOS H-1 [261, 262] and the fast CO₂ lasers [263] are shown. The CO₂ laser signals are averaged with a rolling window of $w_{\text{avg}} = 16$ ms in (a). (III) The heating powers (P_{NBI} , P_{ECRH} , P_{Ohmic}) with the NBI interlock discussed in section 5.3, (IV) electron temperature from ECE [115] and the integrated data analysis (IDA) [273] are provided. The ECE and integrated data analysis signals in (a) are averaged with $w_{\text{avg}} = 3.2$ ms and 5 ms, respectively. Note, the ECE signals go into density cut-off [115] around ≈ 2.315 sec, hence do not show the TQ (compare W_{th} from (I)). In (V) the core and edge safety factors (q , q_{95}) and in (VI) the $P_{\text{rad, sector}}$ -values from equation (4.03) for the five measurement sectors ($w_{\text{avg}} = 20$ ms in (a)) are provided. In (VIb) also the radiated energy (W_{rad}) and radiated energy fraction (f_{rad}) are shown (see equation (6.01) in section 6.1). For this 100% D₂, 8 mm injection, three radiation peaks are visible during the main fragment arrival, TQ/IP-spike, and VDE phase – discussed in chapter 5. Figure published in paper A [52]. (subset: #40657 $\in$ 8/single/1.8H/disr/100% D₂ via 25°, circular shatter head, $v_{\text{pellet}} = 464.5$ m/s)

In total 239 pellets had been injected into 208 discharges – the number of pellets is larger than the number of discharges due to synchronised/staggered injections. The total number of performed discharges was around 240 (not counting aborted discharges). This includes discharges with no successful injection or discharge related issues (e.g. disruptions prior to the injection). The experience obtained from the extensive laboratory phase together with the pellet recipes, allowed to conduct the SPI experiments with a high rate of successful injections of 84.4% (see appendix A.7).

In order to analyse the data from the about 208 SPI discharges efficiently, certain subsets are created, which are used throughout the thesis. These subsets are provided in the appendix A.6 and will be used in figures and tables.

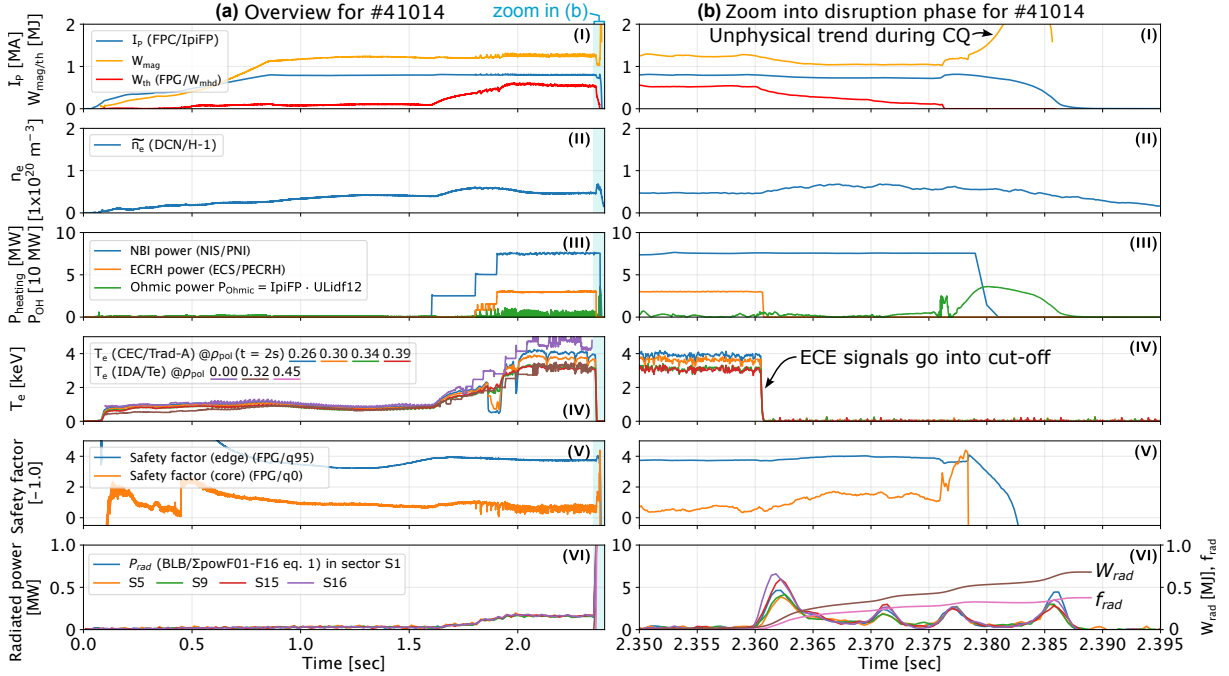


FIGURE 4.08: Scenario overview for the SPI H-mode. For the description of the different plots see caption in figure 4.07. The density measurements via the fast CO₂ lasers are not valid due to strong fringe-jumps for this discharge, hence are not displayed. (subset: #41014 $\in$ 8/single/1.8H/disr/100% D₂ via 25°, rectangular shutter head)

The discharge #41014 from figure 4.08 – injection of a single, 8 mm, 100% D₂ pellet ($\in$ 8/single/1.8H/disr/100% D₂) – is used throughout this thesis as a reference discharge as the different disruption phases with their respective radiation peaks are well visible. It was injected with a high velocity of $v_{\text{pellet}} = 466$ m/s via the 25°, rectangular shutter head, producing small fragments in the process. This discharge shows a very long pre-TQ phase of around 15 ms, which makes it a perfect study case for the different phases of the disruptions. Note, that the signals of the fast CO₂ lasers suffered from strong fringe-jumps (drifted into negative values), hence are not shown in figure 4.08(II).

After introducing the experimental and diagnostic setup, I want to discuss the different phases of the SPI-induced disruptions – and how they evolve with changing pellet parameters – in the following chapter.

Chapter 5

SPI-induced disruptions at AUG

As introduced earlier in section 2.5, three main objectives of the shattered pellet injections exist: suppressing the generation of strong RE-beams, maximizing the radiation to spread the plasma energy uniformly, while at the same time reducing the forces that arise due to the coupling to the surrounding structures. To optimise this mitigation process, many different plasma and pellet parameters are typically scanned. While for example at JET – amongst other experiments – a detailed scan in plasma energies was performed to see potential scaling effects and investigate different thermal fractions [121, 183, 274], the strong focus for the ASDEX Upgrade experiments was to utilise the unique opportunity to study the effect of varying fragment distributions. While also different plasma target scenarios were tested, most pellets were injected into the SPI H-mode – the focus of this chapter. I want to introduce the distinct disruption phases of the SPI-induced disruptions, that I observed for our experiments. Some of these phases – like the TQ or CQ – were already introduced before, but will be complemented by observations specific to our SPI-induced disruptions. As I will show over the course of this chapter, the disruptions will change their behavior as we inject more and more neon and vary the shattering parameters. This evolution of the disruption behavior ranges from non-disruptive injections, over disruptions with strong VDEs, to radiation dominated disruptions. Knowing in which stage of this evolution a certain discharge is, helps to compare the influence of the fragment distributions at the end of this chapter. Figure 5.01 depicts the evolution of the disruption behavior (plasma & shunt current at the top, $P_{\text{rad, sector}}$ at the bottom). I want to use this figure to provide a brief overview first, before I will discuss each of the depicted phenomena in more detail in the following section.

100% D₂ injections with less than 1×10^{22} deuterium molecules do not cause prompt disruptions and the DCS can bring back the discharge to the requested parameters before the injection. This will be discussed in more detail in section 5.3. Above this threshold, the injections will ultimately end up in a disruption. From left to right (figure 5.01(b) → (f)), the amount of neon that was injected is increasing. Hereby, the most prominent changes are the change in the CQ shape (convex → linear → concave) and the increasing radiated power (further details in section 5.2).

For 100% D₂ injections causing disruptions, I observed pre-TQ durations of up to 15 ms. For these disruption time scales, up to four distinct radiation peaks are observed, shown in figure 5.01(h). Each of these peaks are linked to a specific disruption phase, indicated by the coloured areas, which will be discussed in section 5.1. With increasing neon content inside the pellet, the disruption duration becomes successively shorter, which affects the presence and/or possibility to resolve each of these events.

In the following, I want to start with the individual phases during a disruption as shown in figure 5.01(h). While first radiation characteristics connected to each of these disruption phases will be described in this chapter, a more detailed analysis of the total radiated powers and asymmetries in the radiation is provided in the subsequent chapter 6.

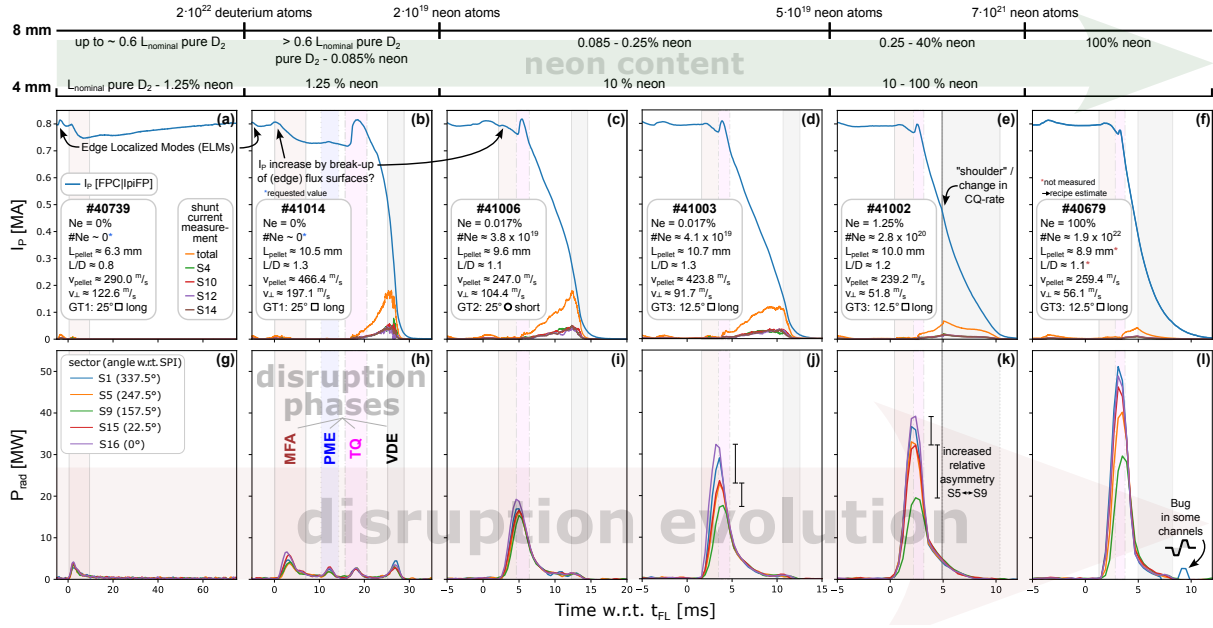


FIGURE 5.01: Overview over the evolution of disruption behaviors from 100% D₂ to 100% Ne SPI. In (a) → (f) the plasma & shunt current measurements are shown and the radiated power in an individual sector in (g) → (l). The individual disruption phases within a discharge – indicated by the coloured areas (see (h)) – are introduced in section 5.1, whereas the evolution (a) → (f) with changing neon content is discussed in section 5.2. The neon content (atoms or percentage of neon in the pellet (f_{neon})) is given for the 8 mm (top) and 4 mm (bottom) pellets at the top of the image with the tick-markers corresponding to the individual behaviors of the evolution. (subsets: analysis on [full dataset](#); depicted [4+8/single/1.8H](#))

5.1 Disruption phases

I will discuss the different phases of the SPI induced disruptions depicted in figure 5.01 in this section with the help of my reference discharge #41014 ∈ [8/single/1.8H/distr/100% D₂](#) (25°, rectangular shatter head).

First light (FL) Prior to the main fragments entering the plasma, a slight increase in the outermost LOSs (directed towards the LFS midplane) of the fast AXUV camera in sector 16 is observed. This small increase to a plateau-like level is referred to as first light (FL) (see figure 5.02) and is suspected to be caused by first tiny fragments and small amounts of gas entering the chamber followed by the rest of the fragments shortly afterwards. As the AUG SPI system removes at least 99.96% of the propellant gas before the shattering process [29, 30], this gas is generated during the shattering process. This first increase in radiation is frequently used as a first time marker – time of the FL (t_{FL}) – not only in AUG, but also in other SPI experiments, such as e.g in JET [191].

Main fragment arrival (MFA) As the main bulk of fragments starts to enter the plasma (time of the MFA (t_{MFA})) a first radiation peak is visible – which usually is the largest radiation peak (compare figures 5.01(a) and 5.07(a, e)) throughout the injection/disruption phase. This radiation peak will be also referred to as “MFA (radiation)

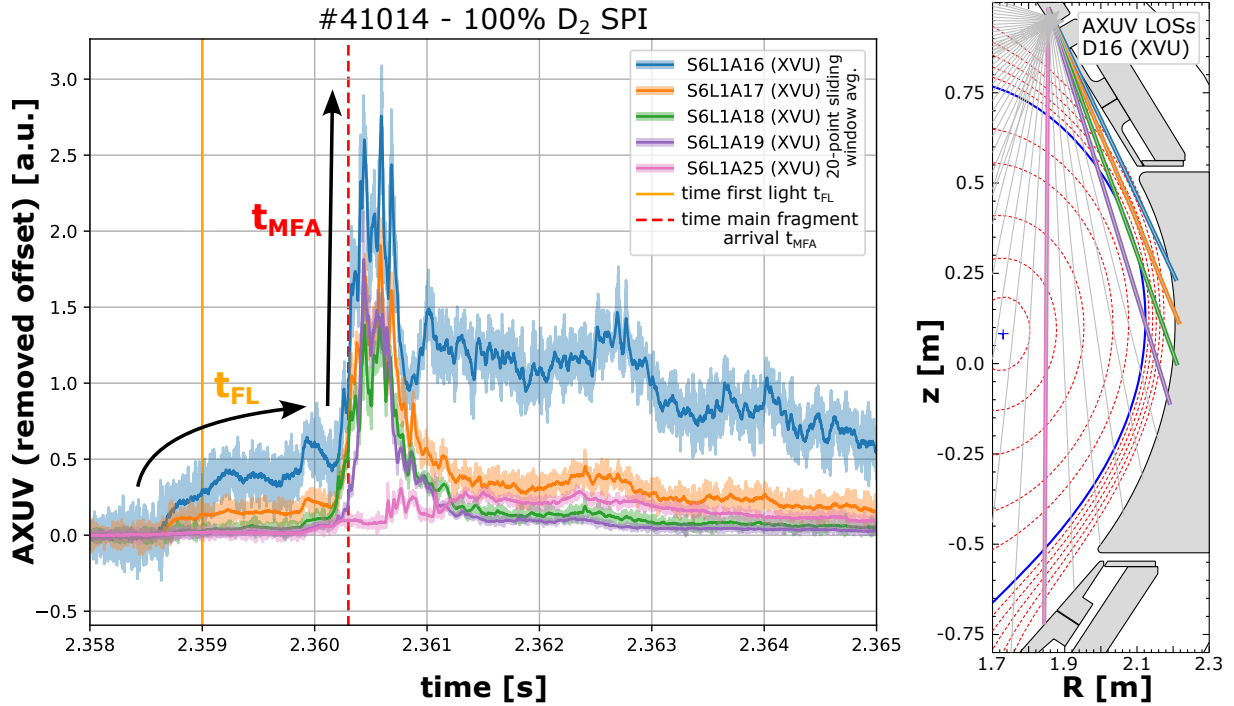


FIGURE 5.02: First increase in the edge AXUV channels to a plateau-like level is used as the first light (FL) time marker. Soon afterwards the steep increase in radiation marks the main fragment arrival (MFA). For consistency, these markers were selected manually for every discharge by J. Svoboda and U. Sheikh. (#41014 $\in$ 8/single/1.8H/dissr/100% D₂)

peak”. As the fragments are injected in sector 16, most of the time the measured radiation is highest in this sector (see figure 5.01(g–k), violet line) discussed in more detail in section 6.2. This is especially the case for 100% D₂ injections (or neon doped pellets with < 1% Ne), in which case the radiation is dominated by the foil bolometer channel 0 – directed to the LFS from which the fragments enter the plasma (more details in section 6.2). During the 2022 experiments, a fast camera located at the top of the machine was observing the fragment arrival in the plasma to study the fragment ablation process, as shown in figure 5.03. The ablated material spreads around the torus following the magnetic field lines, which is most likely also influenced by the plasma rotation. More details on this are provided in section 6.2. Around 4 ms after the MFA, a radiation pattern appears in the divertor region, visible in both fast camera recordings: the top-down view (figure 5.03(d)) and the side view (green circle in figure 5.04(5, 6)). It is likely to be identified as the pellet material re-appearing in sector 16 after spreading around the torus.

From the recording for this discharge (#41014 $\in$ 8/single/1.8H/dissr/100% D₂), it appears that the material may come from both sides (clockwise and counter-clockwise rotation) as the radiating region does not appear to rotate in only one direction indicated by the arrows. Potential aliasing effects or other factors influencing this apparent movement are not investigated further.

As the fragments enter the plasma, some of the outer flux surfaces might break-up and part of the thermal energy is lost conductively/convectively as observed in JOREK simulations described in paper N [51]. However, this fast drop in W_{th} right after the MFA is

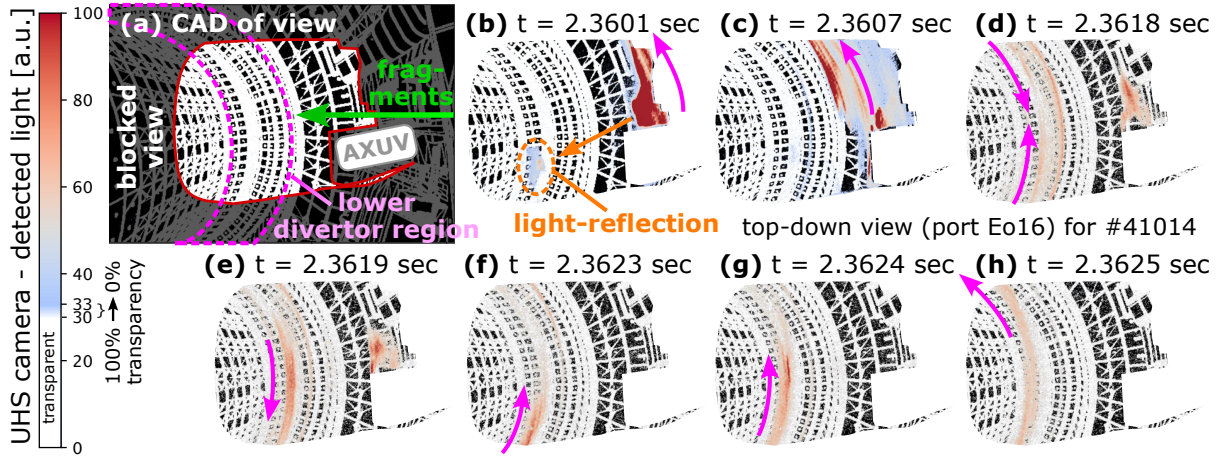


FIGURE 5.03: Top-down view on the main fragment arrival with a fast camera for discharge #41014 $\in$ 8/single/1.8H/distr/100% D₂. The colour-inverted virtual view from figure 4.04(a) is provided in the background and the UHS camera recording with transparent $\rightarrow$ blue $\rightarrow$ red intensity colour-mapping on top (transparency increasing for values below 33%, fully transparent below 30%). The view is partially blocked by components (i.e. tiles, AXUV-box) indicated by the black shaded area in (a). Only the visible area is cut out in (b)–(h). The fragments arrive at the LFS (right side) and travel towards the plasma center (towards the left). Hereby, the material spreads around the torus following the magnetic field lines and most likely also influenced by the plasma rotation as shown in (b) and (c). The potential re-appearance of the material in the divertor region is given in (d)–(h). Note, the contrast in the images (d)–(h) is increased to increase visibility of the radiation pattern in the divertor (otherwise too faint). For this specific discharge, it seems like the material is coming from both sides as it meets in S16 as indicated in (d). It rotates in clockwise direction first, followed by a counter-clockwise rotation in (f)–(h).

overestimated in the simulations compared to the experimental observations. The strong radiation during the MFA will lead to an additional loss of plasma pressure. As the position control of the DCS can not react on this timescale (< 1 ms), this loss of pressure (β) results in a movement of the plasma towards the central post (see “Rcurr” signal & circle-marker in figure 5.05(b, f)) and together with a changing value of plasma internal inductance (li), the plasma shape also changes (triangular-markers and corresponding signals in (b, c)). At the same time, a strong radiation source is visible in the UHS recordings between the upper divertor and the central post, shown in figure 5.04(7–9) labeled as “post injection”.

Plasma movement event (PME) For long pre-TQ durations, caused by 100% D₂ or neon doped pellets, in some cases a second radiation peak is observed before the TQ (see figure 5.04(10–12), 5.05(d), and 5.07). As it is accompanied by the movement (and change in shape) of the plasma, I will refer to this event as the plasma movement event (PME) and the radiation peak as the “PME (radiation) peak” throughout this thesis. During the PME, the Z_{curr} position is moving downwards (towards the active X-point) and further towards the central post as the plasma shape also changes (figure 5.05(f)). This motion is also visible in the fast camera recordings (see figure 5.04(10–12)) as the radiation pattern moves further down the central post with increasing amplitude in the visible range compared to figure 5.04(9) (applied filters see section 4.1). As the real-time

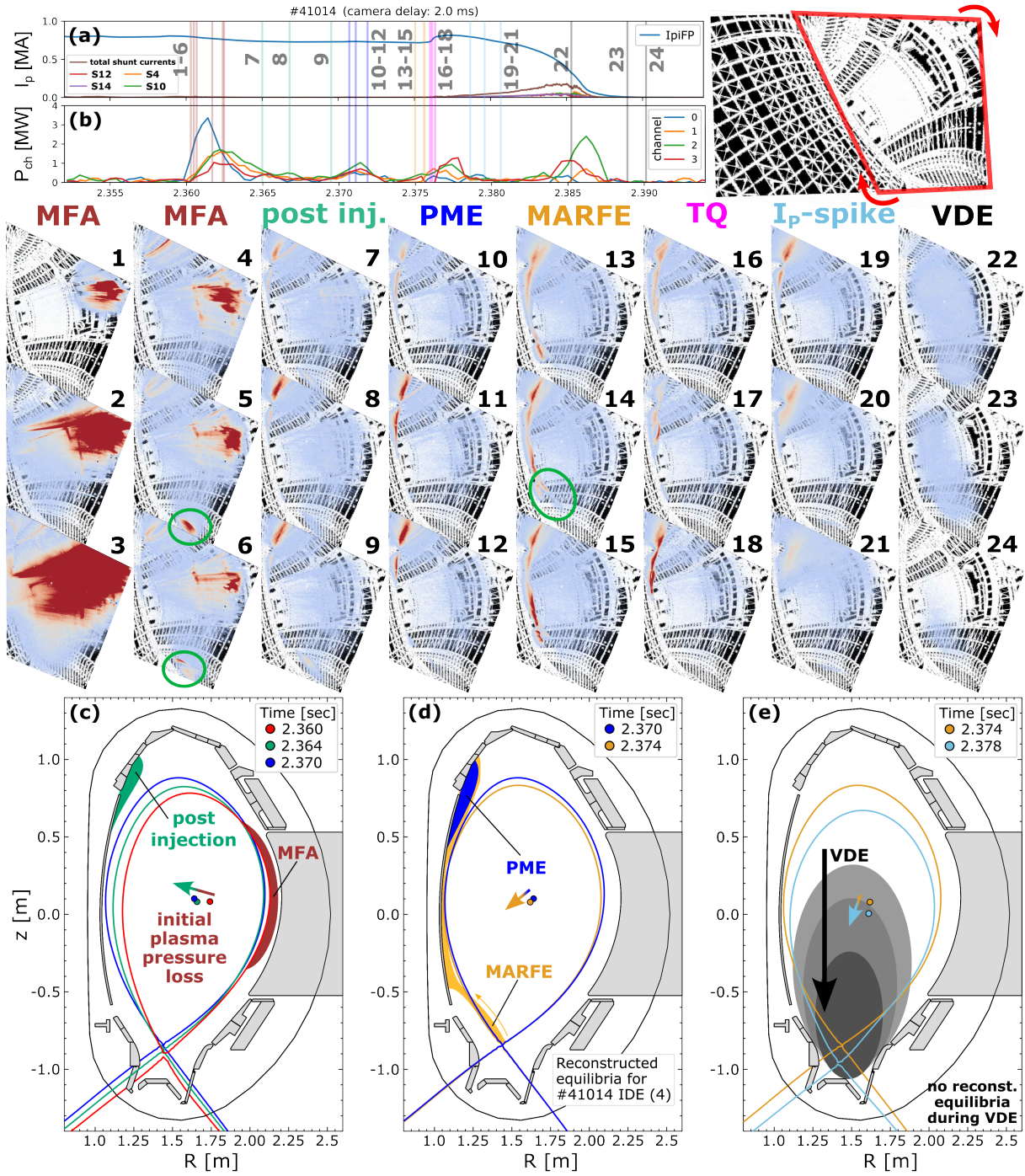


FIGURE 5.04: Images taken from the fast camera recordings of the disruption during the different disruption phases (1–24) with a transparent→blue→red intensity colour-mapping (as used in figure 5.03). The virtual view from figure 4.04(b) is provided in the background. In (a) the plasma & shunt currents, and in (b) the P_{ch} -values of S16 are shown. The regions of highest intensity for each phase are displayed in (c–e): the MFA & post injection phase in (c), the PME & MARFE in (d), and the VDE motion in (e). (#41014 $\in$ 8/single/1.8H/disr/100% D₂)

Z_{curr} reconstruction (DDS, compared to FPG shot-file) does not exceed the 7 cm threshold in this discharge (not shown in figure 5.05), the $VPEState$ remains unchanged. Only after the IP-spike had occurred, the $VPEState$ changes in (a) and a new current z -position

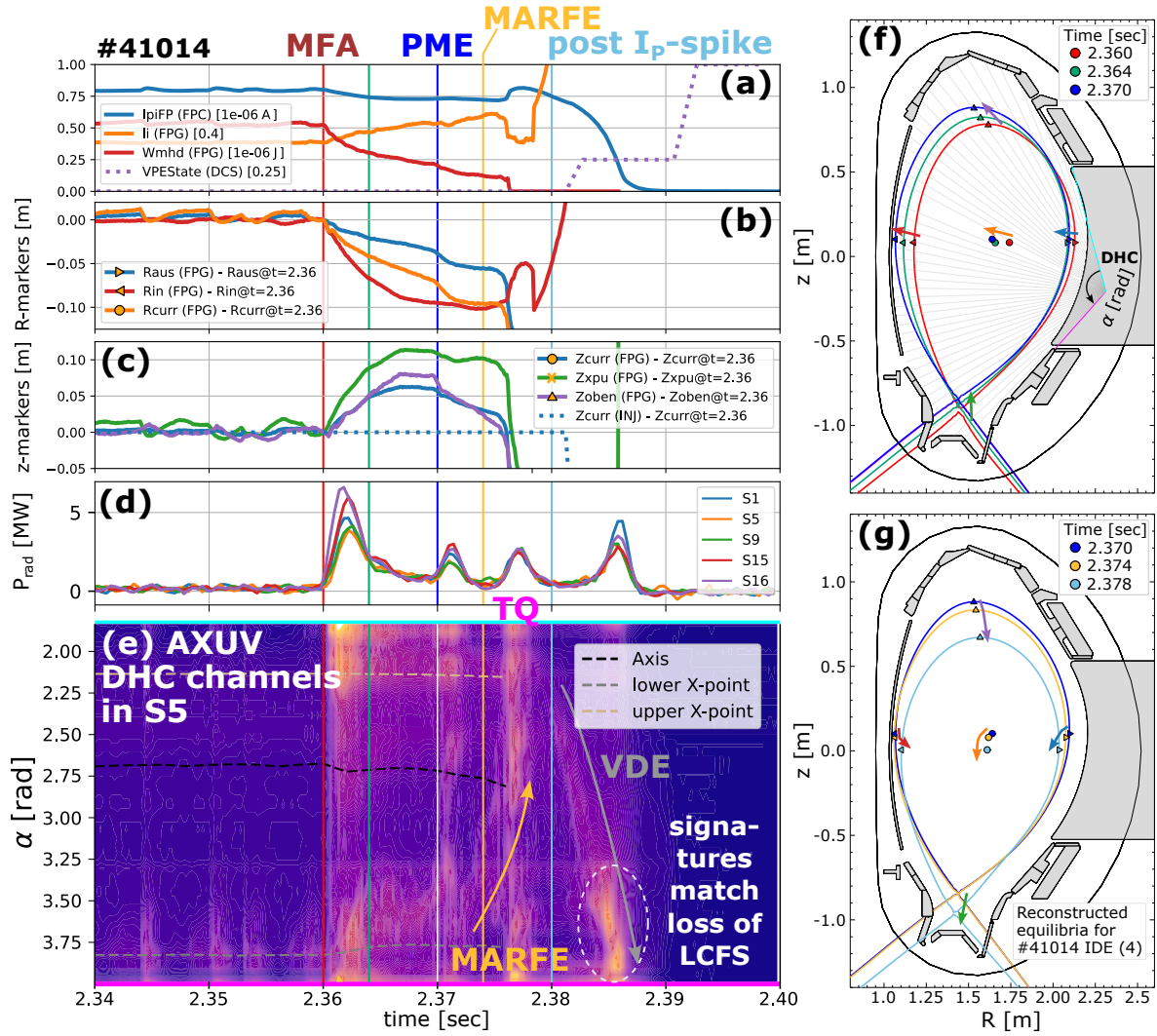


FIGURE 5.05: The plasma movement event in discharge #41014 $\in$ 8/single/1.8H/distr/100% D₂: (a) I_p , plasma internal inductance (li), W_{th} , and $VPEState$, (b) R-position markers, (c) z-position markers, (d) $P_{rad, sector}$. The arrows in (f, g) indicate the movement of the different control positions of the plasma, where the colour is the same as in (b, c). (f) Directly after the injection, the plasma moves closer to the HFS (central post) and the plasma shape changes, which can be connected to the initial pressure loss and changes in li . Note, that the DCS will also react on these changes of β & li , however, this does not involve a $VPEState$ -change. At 2.370 s (10 ms after injection), the PME takes place: (g) the movement of the Z_{curr} is now directed downwards (towards the active X-point) and further towards the HFS while the plasma shape is also slightly changing. After the IP-spike, the plasma starts to move downwards (towards active X-point) during the VDE phase. The maximum of the last radiation peak (VDE peak) in (d) appears around the time when the shunt currents drop (compare figure 5.04(a) around time frame $\approx$ 22) and the signatures match the loss of the LCFS [16]. The plot in (e) was created by F. Klossek.

($Z_{curr} - INJ$) is requested shown in (c). Consequently, this movement of the plasma during the PME is not initiated by the DCS.

There is strong evidence, that a break-up of a few central flux surfaces may cause this event. During the pre-TQ phase, li is steadily increasing. However, at the time of the

PME, a small drop in li is visible and the plasma current is increasing (better visible in figure 5.07(e)). This is accompanied by a small drop in W_{th} . These signatures are the same that we observe on a bigger scale a bit later during the TQ: here, a full stochastisation of the field lines takes place and W_{th} fully collapses.

This break-up of a few central flux surfaces during the PME will reduce the plasma pressure, hence lead to the further shift of the plasma towards the central post observed during this time [153, 157]. The thermal energy that escapes from the core plasma will then cause increased heating of the outer plasma leading to more efficient radiation of impurities in the SOL, hence the second radiation peak.

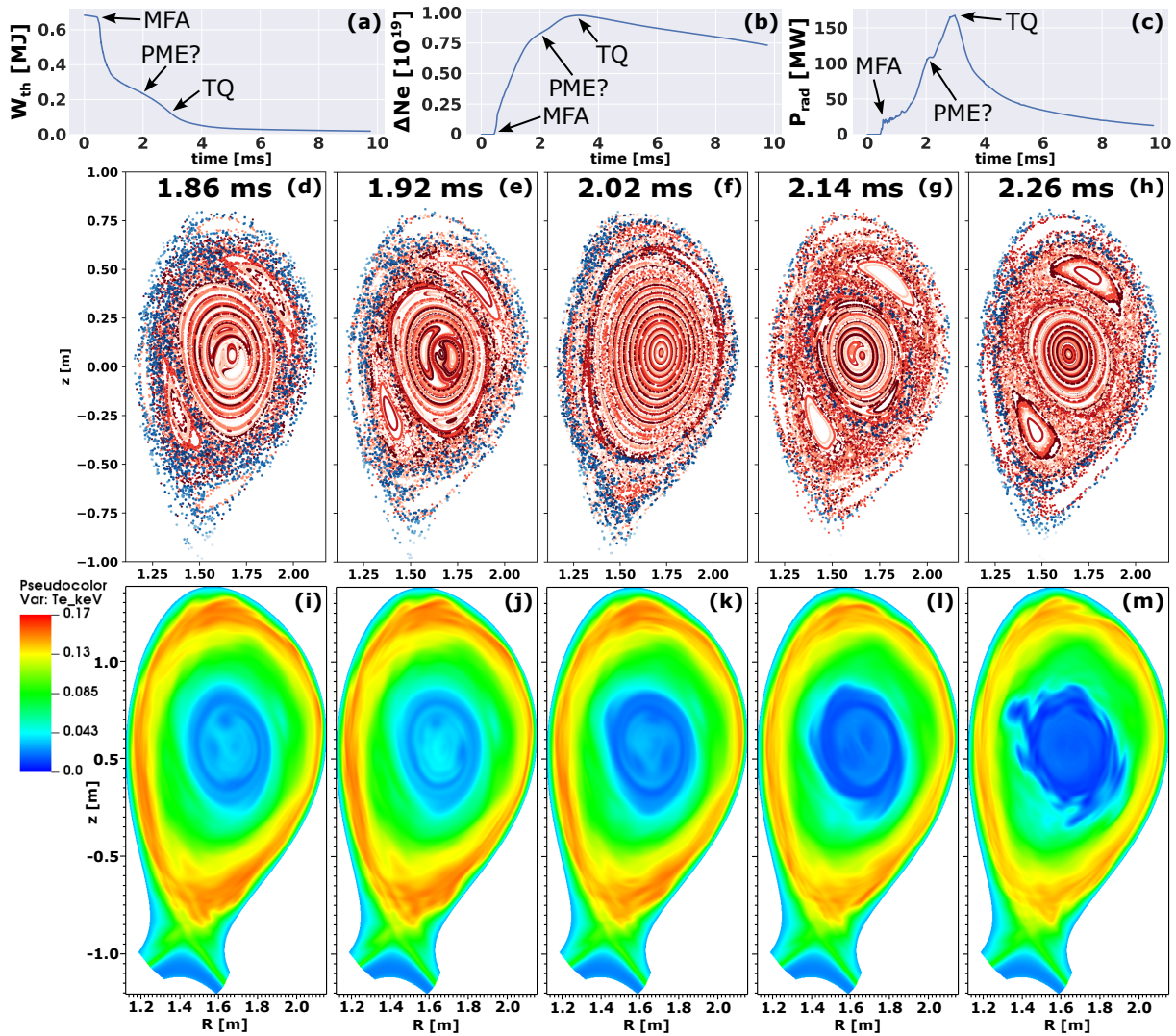


FIGURE 5.06: (1, 1) kink mode that occurs in the JOREK simulations after a $f_{neon} = 0.12\%$ Ne injection (“SF FV Ne0.12” from paper N [51]). The timing (between MFA and TQ) but also the signatures might indicate a connection to the experimentally observed PME. In (a) W_{th} , (b) neon assimilation ΔNe , and (c) P_{rad} . The Poincaré plots in (d)→(h) indicate the flux surface break-up with the T_e during the MHD activity in (i)→(m). Whether the PMEs are caused by (1, 1) kink modes requires further studies for confirmation. Conduction of the simulation and creation of the plots by W. Tang.

The exact cause of this flux surface break-up is at present not yet fully understood, however, first indications hint towards the material assimilation processes that increase the plasma density strongly around that time which induce a strong MHD activity. In the JOREK simulations for low neon contents shown in figure 3 of [paper N \[51\]](#), a small radiation peak between fragment arrival and TQ is visible. In the case of the 0.12%/1% neon cases it occurs at about 2–3 ms after the injection, while the pellet material is still being assimilated in the plasma. At this time in the simulations, a (1, 1) kink mode ($n = m = 1$, see equation (2.02)) is present in the core region, which will lead to the partial stochastisation of central flux surfaces, shown in figure 5.06 for the case “SF FV Ne0.12” from [paper N \[51\]](#). This MHD event will decrease T_e , hence the plasma pressure in the core region. At the same time, a small radiation peak is visible in (c) before the full stochastisation takes place during the TQ. This would match the experimental observation of the PME, however, as we observed this event only recently in JOREK, this connection is still to be verified.

As indicated in figure 4 in [paper C \[49\]](#), the time of the fragments reaching the core region is in the order of a few ms. The case shown in figure 4 is for a pellet with a velocity of 200 m/s, while $v_{\text{pellet}} = 466$ m/s (25° , rectangular head) for #41014, hence the fragments reach the $q = 2$ rational surface even earlier than the 2 ms. However, as shown in figure 19, the density close to the magnetic axis does not start to increase before 8 ms after fragment arrival for a 100% D₂ injection with 270 m/s. Therefore the strong increase in the central plasma density is a promising candidate for the trigger of this event.

The PME in my reference discharge #41014, takes place rather late after the fragment arrival. Earlier times of the PME – around 5 ms and earlier – are also observed. One example is discharge #40657, where the PME occurs around 5 ms (at $t = 2.32$) after the MFA (see figure 4.07(b)). It is also accompanied by an increase in the core density, further supporting this hypothesis. While $v_{\text{pellet}} = 464.5$ m/s is similar to the injection into #41014, the fragments had been injected via the 25° , circular shatter head, hence the fragment size might be larger & the fragment velocity higher, due to the variable effective shatter angle effect (discussed in section 3.3).

MARFE Directly after the PME for discharge #41014, a multifaceted asymmetric radiation from the edge (MARFE) [275] is observed to move upstream. The phenomenology of the MARFE [275–279] can be understood as a sort of radiation condensation effect: a local increase in plasma density will lead to increased radiation in that area, which in return causes an increase in plasma density to maintain the local pressure balance [277, 278]. In diverted plasmas, this region will form close to the X-point (also referred to as “X-point radiator (XPR)” [279–281]). With increasing density, the MARFE can start moving upwards along the HFS [276, 279–281]. This movement can be stopped if enough heating is supplied, bringing it back to the stationary, downstream position [280, 281]. Once the radiating region has reached a far upstream position, it moves towards the LFS and deeper into the confined region (towards the magnetic axis) triggering the consequent disruption [280, 281]. For AUG it was shown, that with the real-time actuators of the DCS, the displacement of the MARFE can be controlled and the disruption avoided [20]. The movement of the MARFE can be tracked with the help of the fast AXUV diodes as shown in figure 5.05(e) and is even visible in the fast camera recordings figure 5.04(14–16). It starts from the X-point (green circle in figure 5.04(14)) and moves to- and upwards the central post. It is only visible in a few LOSs at the same time, while the PME radiation peak shortly before was visible in all LOSs simultaneously.

TQ phase and formation of the IP-spike If the injected material is sufficient to cause a disruption, the disruption phase is initiated. The thresholds for 100% D₂ injections are discussed in section 5.3. After the TQ, the characteristic IP-spike is observed as described in section 2.2. As shown in figure 5.04(b), a third radiation peak (“TQ (radiation) peak”) is visible during this phase in the foil bolometers, which usually is toroidally symmetric. The cause of this radiation peak is most likely similar to the one suspected for the PME described above, where the stochastisation of the field lines leads to an enhanced heat transport into the SOL, thus increasing radiation. The IP-spike height and width also depends on the neon content of the injections, as this strongly affects the TQ dynamics and post-TQ resistivity. Hereby, the higher the assimilated neon content, the smaller the amplitude and the width of the IP-spike (see figure 5.01 and appendix A.10).

CQ, VDE, and final plasma loss As introduced in section 2.2, the early CQ rate can be used as a proxy for the assimilated neon in our SPI studies: higher amounts of neon – hence radiation dominated disruptions – will cause faster early CQ rates, leading to the characteristic exponential decay curve of the current (concave shape). For 4 mm pellets, I frequently observed multiple “shoulders” during the CQ, shown in the appendix A.11, which may be connected to differences in the VDE phase.

In case of injections with $f_{\text{neon}} < 0.17\%$ (CQ-shape (1) in figure 5.07), the early CQ rate is low. As introduced in section 2.2, the motion of the plasma during the VDE is accelerated throughout the CQ [151, 153, 154]. With it, $|dI_p/dt|$ will increase, creating the overall convex CQ shape as illustrated in figure 5.04(a). This vertical movement towards the lower divertor (in direction of the active X-point) is visible in the fast camera recordings shown in figure 5.04(20–24). While for the 8 mm, 100% Ne SPI (#40679) a smooth current decay is visible, a small “shoulder” in the plasma current or change in the decay rate (see figure 5.01(e) and 5.07(c)) is observed for intermediate to high neon content injections. This phenomenon is linked to the phase of the VDE where the LCFS is lost [16], and a drop in halo currents is observed in the experiments and JOREK VDE simulations [16, 53, 151]. Note, that in these investigations [16, 53, 151], VDEs are leading to a disruption – “kicking the plasma towards the divertor” in the experiments [53, 151] – instead of “natural” VDEs that occur often after the TQ in our SPI experiments. Around the loss-time of the last closed flux surface (t_{LCFS}), the maximum of the last radiation peak (“VDE peak”) is observed for injections with $f_{\text{neon}} < 0.17\%$ (CQ-shapes (1–2)), shown in figures 5.05(e), 5.07(e) and 6.13. For injections with $f_{\text{neon}} > 0.17\%$ (CQ-shapes (3–4)), a small radiation plateau is observed until t_{LCFS} , shown in 5.07(b). This evolution of the CQ-shape is described in more detail in the following.

5.2 Evolution of disruption behavior

As demonstrated in the previous section, the properties of the disruptions and even the event chain depends strongly on the amount of assimilated neon in the plasma. The figures 5.01 and 5.07 show the disruption evolution as a function of injected neon content. While the injection parameters like fragment size and velocity distributions affect the efficiency of the neon assimilation, the total amount of injected neon is the dominant parameter here. “More injected neon” or “a higher neon fraction” are used within this thesis as synonyms for a higher total amount of assimilated neon, assumed to be inside the core plasma. The effect of the injection parameters, which are especially relevant

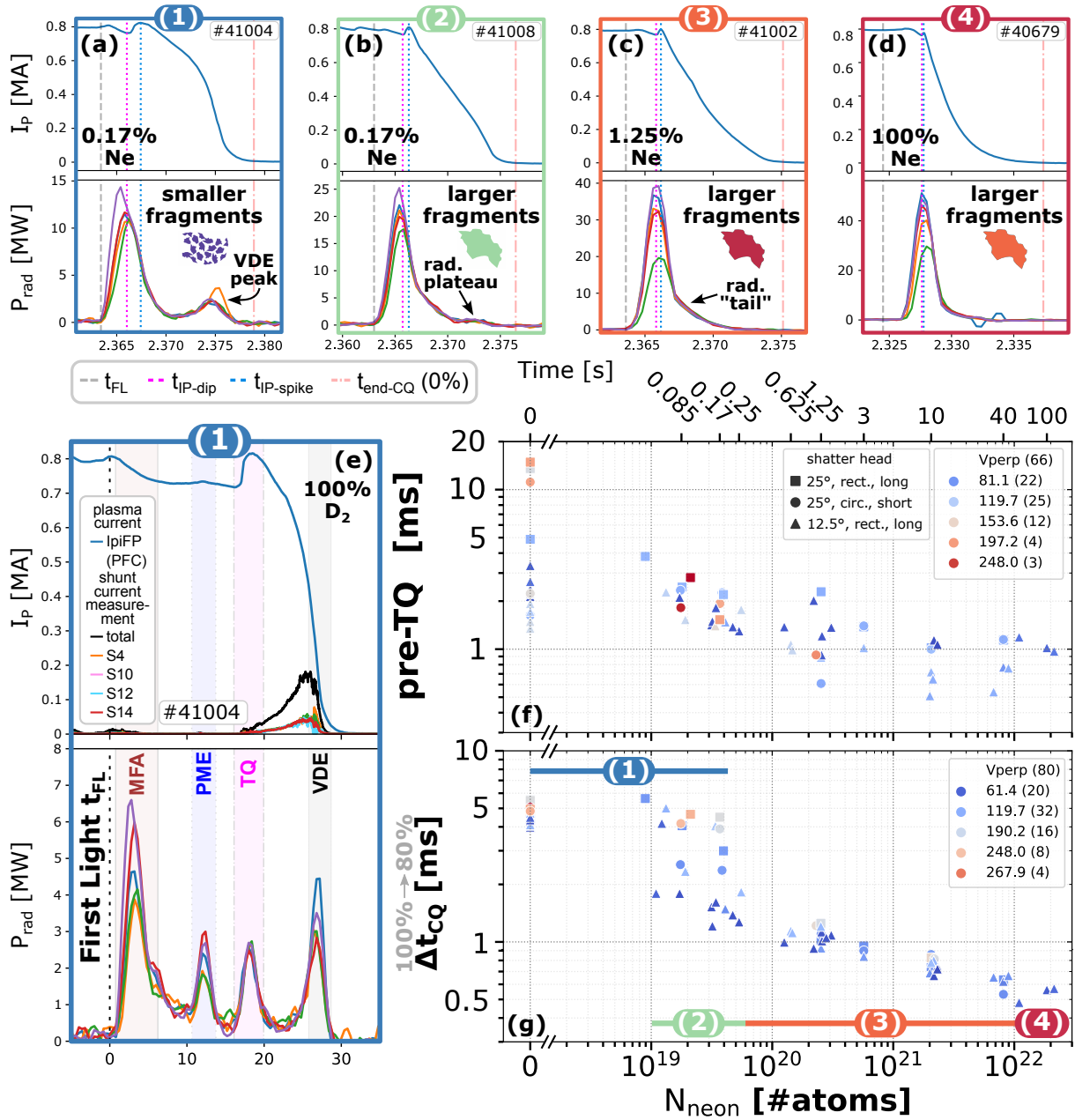


FIGURE 5.07: Evolution of the disruption dynamics with increasing amount of assimilated neon content. From (1) to (4), the amount of assimilated neon increases and a transition from convex to linear and finally concave CQ shapes is visible. At the same time, the VDE peak is reducing: first the amplitude decreases until it looks more like a radiation plateau shown in (b). Afterwards, this plateau looks more like a smooth "tail" of the single radiation peak. The disruptions in (a) and (b) share the same neon content but with varied $v_{\perp}$, hence fragment size distributions, illustrating the importance of the fragment size distributions in the transition from convex to linear CQ shape. In (f) the pre-TQ duration and in (g) the early CQ duration ($\Delta t_{CQ}^{100 \rightarrow 80}$) as a function of N_{neon} are shown. (subsets: (a–e) 8/single/1.8H/disr, (f, g) 8/single/1.8H/disr/corr)

for the disruption evolution in the low neon doping range, are discussed in section 5.4 in more detail. In the following, the disruption evolution is discussed, starting at 100% D₂ injections and ending at 100% Ne injections following the CQ-shapes from figure 5.07 (more details about the radiation characteristics are provided in chapter 6):

- (disr.) For 100% D₂ injections below 2×10^{22} deuterium atoms, the DCS-settings of AUG for the 2022 experiments can recover the discharge and bring it back to pre-injection parameters (see also section 5.3). Only a small, toroidally symmetric radiation peak is observed as the main fragments arrive.
- (1) In case of an injection of a full-length, 8 mm, 100% D₂ pellet or neon fractions up to 0.085% (8 mm) / 1.25% (4 mm), the plasma will disrupt and up to four radiation peaks can be observed in case of a long disruption time scale (see figure 5.07(e)). These radiation peaks correspond to the time windows of the MFA, PME, TQ, and VDE, respectively. For these disruptions, the CQ-shape is convex and IP-spike-amplitudes of up to 105% of the average pre-injection plasma currents ($\approx 115\%$ w.r.t. IP-dip) are observed (see appendix A.10).
 - (1–2) For increasing amount of assimilated neon, hence shorter pre-TQ durations, the radiation peaks merge – due to the restricted time resolution of the foil bolometers – and up to two radiation peaks can be observed:
MFA (+ PME) + TQ as well as a separated peak during the VDE phase (compare #41004 in figure 5.07(a)). The presence of the PME phase for these disruptions is not confirmed.
 - (2) The higher the assimilated amount of neon (compare figure 5.07(b)), the more linear the current quench becomes. At the same time, the pre-TQ duration and the amplitude of the IP-spike are further reduced (see also appendix A.10). Additionally, the second radiation peak (VDE peak) is reduced with increasing neon assimilation until it forms a radiation plateau – slightly above the pre-injection radiation level – which lasts until t_{LCFS} , when the plasma current also approaches zero.
 - (3–4) For even higher neon fractions (compare figure 5.07(c)), the CQ starts to exhibit a concave shape with a prominent shoulder as introduced in section 5.1. The radiation plateau vanishes, thus the radiation tail directly approaches zero after the single radiation peak. The prominent CQ shoulder vanishes for the 100% Ne SPI.

From 100% deuterium to 100% neon injections, the relative asymmetry of the radiation between S16 and the neighboring sectors reduces, while the asymmetry of sectors 5 and 9 increases (more details in section 6.2).

In summary, the CQ shape transitions from a convex (conduction dominated) to a linear and finally a concave shape (radiation dominated), while the four distinct radiation peaks turn into a single one and the halo currents (indicated by shunt currents in figure 5.01(a) $\rightarrow$ (f)) are reduced. A similar observation of linear (2)/concave (3–4) CQ-shapes had been related to the presence/absence of VDEs in figure 2 by Yoshino *et al.* [156], respectively. Hereby, the fast shut-down of the plasma via injection of a neon “killer-pellet” (compare (3–4)) stabilised the plasma position [156]. The reduction of the shunt currents and with it the VDE radiation peak – with the maximum at t_{LCFS} – in our experiment are in line with previous observations: increasing the amount of injected neon, the mitigation efficiency of the otherwise violent VDEs is expected to increase, causing lower

shunt currents in the process [16, 53, 151, 156]. Additionally, the amplitude of the IP-spike is also reducing with increasing neon content. The CQ shape can already be used as a first indicator of the neon assimilation and therefore quick assessment of the disruption mitigation efficiency on the shot day from the plasma current measurement alone.

SPI-induced disruption time scales at AUG

In this section, an overview of the time scales for the pre-TQ and CQ of the SPI induced disruptions at AUG is provided.

pre-TQ and CQ durations					
	$\Delta t_{\text{pre-TQ}}$	$\Delta t_{\text{CQ}}^{100 \rightarrow 0}$	$\Delta t_{\text{CQ}}^{100 \rightarrow 80}$	$\Delta t_{\text{CQ}}^{80 \rightarrow 20}$	$\Delta t_{\text{CQ}}^{90 \rightarrow 10}$
injected material	[ms]	[ms]	[ms]	[ms]	[ms]
100% D ₂	1.3 – 14.9	10.7 – 13.3	4.0 – 5.5	3.0 – 5.4	5.2 – 9.0
0.085% Ne	1.5 – 3.8	9.7 – 12.2	1.8 – 5.6	2.8 – 5.1	4.9 – 6.6
10% Ne	0.5 – 1.1	8.2 – 11.1	0.7 – 0.9	2.7 – 3.7	3.9 – 5.1
100% Ne	1.0 – 1.2	9.6 – 10.2	0.5 – 0.6	2.7 – 2.8	4.2 – 4.3

TABLE 5.01: Duration of the pre-TQ and CQ for injections with different f_{neon} taken from figure 5.07(f, g). All CQ durations are unscaled (e.g. $\Delta t_{\text{CQ}}^{80 \rightarrow 20}$ is not multiplied by 5/3). With increasing f_{neon} , the pre-TQ and CQ durations decrease. Already a minor neon doping of $f_{\text{neon}} = 0.085\%$ leads to a drastic reduction in the maximum pre-TQ duration to values below 4 ms (compare figure 5.07(f)). (subset: [8/single/1.8H/di](#)[sr](#))

With increasing neon assimilation the pre-TQ and CQ durations are decreasing, shown in figure 5.07(f, g), figure 5.08(a), and table 5.01. This reduction is a continuous process accompanied by an increase in radiation, illustrated in figure 5.08.

The pre-TQ durations ($\Delta t_{\text{pre-TQ}}$ -values) are calculated from t_{MFA} until the time of the IP-dip ($t_{\text{IP-dip}}$) (see figure 5.08(a)). Here, the time marker t_{MFA} is used – compared to the t_{FL} – as the exact timing of the MFA is easier to identify, hence more precise. In contrast, for the radiation analysis in chapter 6, the marker t_{FL} is used, which ensures to capture all the SPI induced radiation.

For 100% D₂ SPI, $\Delta t_{\text{pre-TQ}}$ varies strongly with the injection parameters, around 1–15 ms. Hereby, disruptions with long pre-TQ durations (> 10 ms) show four radiation peaks and disruptions with shorter $\Delta t_{\text{pre-TQ}}$ only show two or three radiation peaks. Doping the pellets with 0.085% Ne, to suppress the plasmoid drift, already reduces the maximum pre-TQ duration significantly (< 4 ms) also observed in other machines, e.g. JET [191]. This may be a limiting factor for the planned staggered injection scheme for ITER as it brings two problems with it: firstly, the pre-TQ durations might be too short to lead to high deuterium assimilation fractions, necessary to prevent the formation of high current RE-beams [191]. Further, these reduced pre-TQ durations may require a high precision in the timing of the injections – which is one of the main research objectives for the 2025 experimental campaign at AUG.

The values for the unscaled duration of the CQ (100% $\rightarrow$ 80%) ($\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) shown in figure 5.07(g) indicate the early CQ durations. This metric is frequently used within this thesis – compared to the often used metrics $\Delta t_{\text{CQ}}^{80 \rightarrow 20}$ and $\Delta t_{\text{CQ}}^{90 \rightarrow 10}$ – as the early CQ rate is less influenced by VDE dynamics and often provides a cleaner inter-shot comparison, observed during my studies and also frequently used by the ITER DMS team [117, 121].

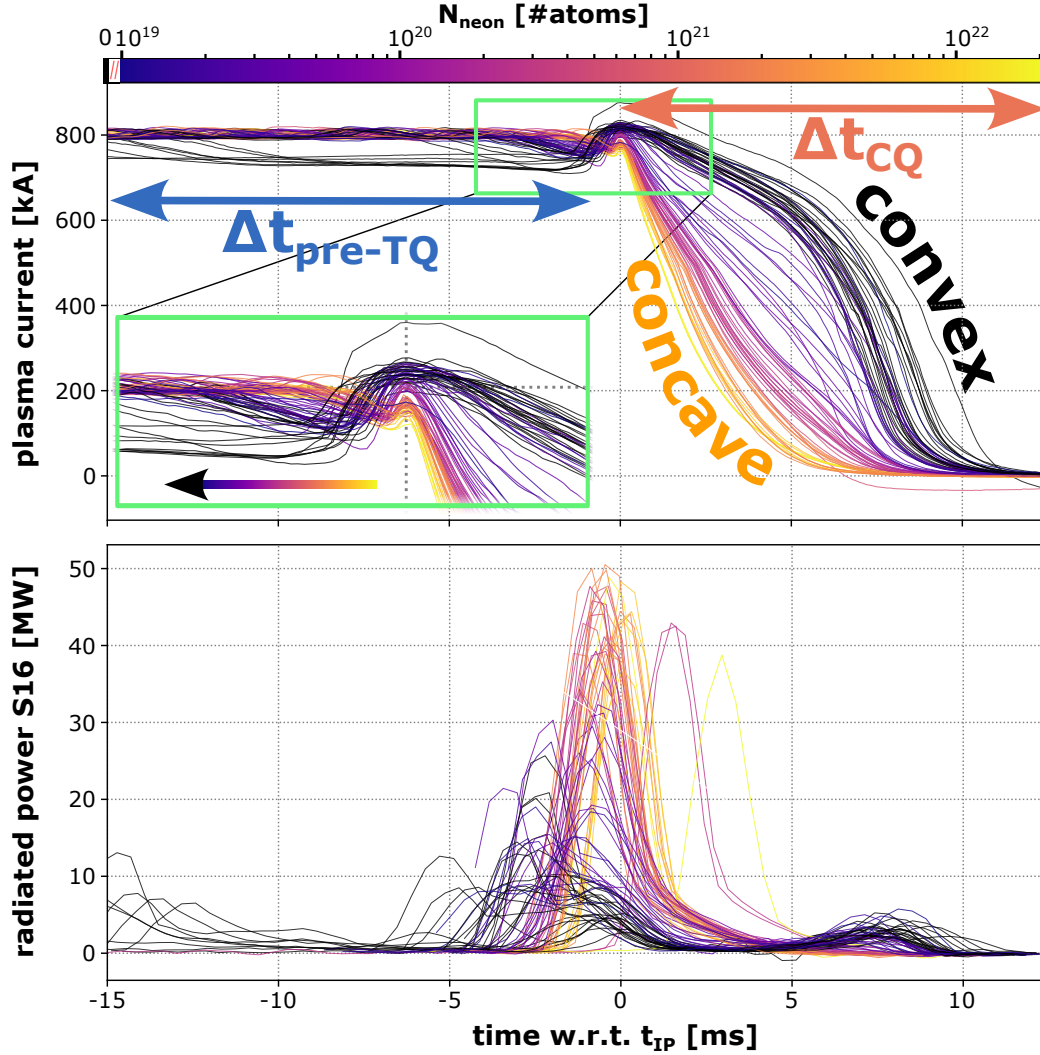


FIGURE 5.08: Continuous reduction of pre-TQ and CQ durations with increasing neon content, hence peak radiation. The (a) plasma current and (b) radiated power in S16 are shown aligned w.r.t. the IP-spike. The transition from convex to linear and finally concave CQ shapes is observed in this continuous disruption evolution. (subset: 8/single/1.8H/dissr)

5.3 Disruption thresholds

Investigations of disruptions thresholds can help to identify operational limits and validate modeling efforts. However, it is essential to include not only the apparent physical limits but also the technical realisations of the discharges. The DCS of ASDEX Upgrade has various actuators to feedback-control the discharge and bring back the plasma parameters to the desired ranges (more details in section 4). Therefore, interpretation of

the data and threshold values always have to be viewed in context of the plasma control systems. Figure 5.09 indicates the disruption threshold for 100% D₂, single injection SPI into the different SPI scenarios described in section 4.2. Hereby, only discharges that did not trigger the `VPESState` state-change of the DCS are displayed. The colour-coding in figure 5.09(a) indicates the number of estimated injected deuterium molecules and in (b) whether a discharge disrupted or could be brought back by the DCS to nominal conditions. For 100% D₂ injections with less than 1×10^{22} D₂ molecules (2×10^{22} deuterium

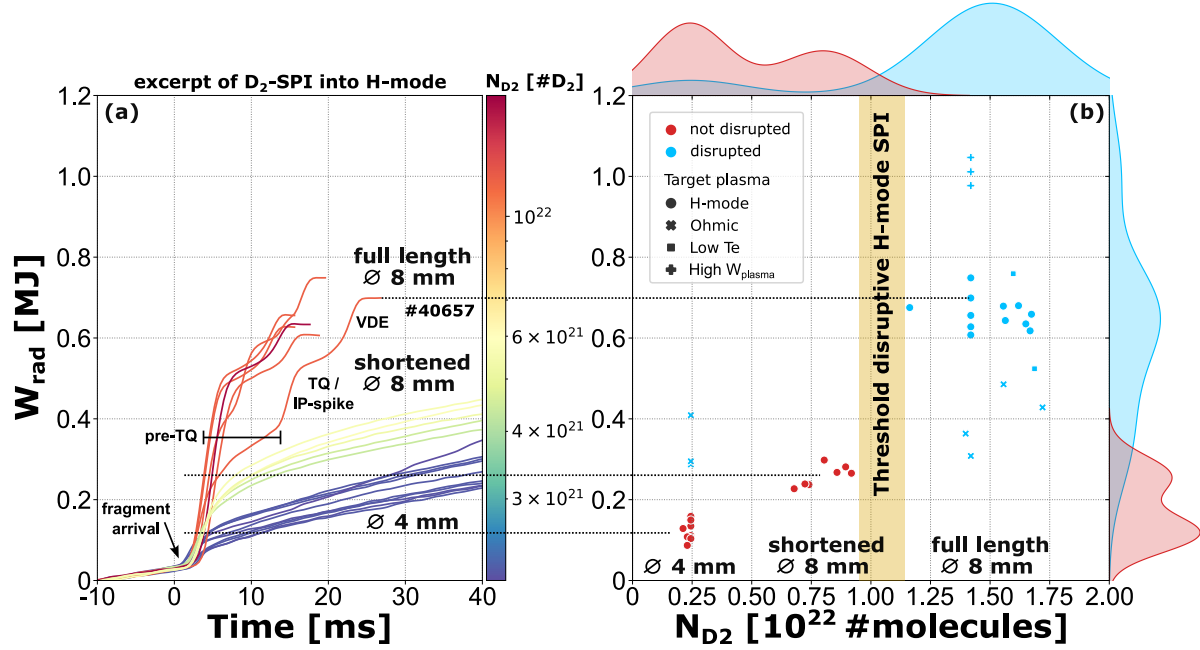


FIGURE 5.09: Deuterium threshold for disruptive SPI into the SPI H-mode. For the given DCS settings, 100% D₂ injections with more than 1×10^{22} D₂ molecules (i.e. full-sized 8 mm pellets) are not recovered and cause the SPI H-mode to disrupt. The 4 mm or half-length 8 mm pellets did not cause SPI H-mode disruptions. During the disruption, additional radiation is visible indicated by the step-wise increase W_{rad} in (a). Figure published in [paper A \[52\]](#). (subset: 4+8/single/100% D₂)

atoms) – full-size 4 mm or half-size 8 mm pellets – only the Ohmic discharges disrupted. The H-mode scenarios disrupted above this threshold for the 2022 DCS settings. This observation is in good agreement with JOREK simulations, which indicate a strong increase in MHD activity around this parameter range [282]. Scanning the amount of deuterium inside the pellets, the simulation results suggest incomplete TQes below a threshold of $(8 \pm 4) \times 10^{21}$ deuterium atoms. Note, that in the simulations the entire pellet material was injected in form of fragments. In contrast, it is expected that in the experiment some of the pellet material is converted into gas & tiny fragments during the shattering process, which may hinder the fast penetration into the core region. This effect may contribute to the factor of two difference between simulation and experiment. Additionally, the behavior of the DCS as in the experiments, is not simulated. For 100% D₂ SPI above 1×10^{22} molecules, the consequent disruptions often exhibit long pre-TQ times. Note, that the disruptions can have various underlying reasons: Besides the expected “physical” disruption causes (e.g. density limits/MARFEs, ...), often certain plasma control mechanisms can also initiate the disruption. While the trigger of the `VPESState` in the DCS

had already been discussed, other technical implementations can also cause disruptions for discharges, which might have been recovered by the DCS otherwise. One example, that I observed during the analysis was the trigger of an NBI interlock after the injection (see figure 4.07(III)). While a constant NBI beam power is still requested by the DCS, a plasma current interlock sends an off-signal to the NBI beam sources. With the release of the interlock (around 2.34 s in #40657), the NBI sources are re-activated if the DCS does still request heating power. Note, that if no valid density measurements are available or the density is below $1 \times 10^{19} \text{ m}^{-3}$, a “worst case scenario” of 100% shine-through for the heating systems is assumed. Therefore, the requested values for the heating systems are always below the material limits and the short re-activation of the NBI beams is not concerning for the machine protection, while not being desirable either.

5.4 Fragmentation parameter effect on disruptions

In this chapter, I discussed the different phases of the SPI-induced disruptions and the evolution from 100% D₂ to 100% Ne injections so far. In the big picture, it is of course not surprising, that more neon can be assimilated for a 10% Ne compared to a 0.085% Ne pellet. The more relevant investigation in this regard, is the effect of the SPI parameters (i.e. fragment distributions) on the assimilation, hence disruption behavior.

Disruption dynamics The strongest effect of the SPI parameters I observed was for the transition region between the convex $\rightarrow$ linear CQ shape ($1 \times 10^{19} - 1 \times 10^{20}$ neon atoms), shown in figure 5.07(a, b, f). The pellet in (a) was injected into the 25°, rectangular shatter head with a high velocity of $v_{\text{pellet}} = 467 \text{ m/s}$. Based on the laboratory observations (see section 3.3), this is expected to produce a large fraction of tiny fragments and dust. On the other hand, the pellet in (b) was injected into the 12.5°, rectangular head with a low velocity of $v_{\text{pellet}} = 233 \text{ m/s}$, hence expected to produce large fragments. Following the formula of equation (3.07), the mean fragment velocities of (a) 445 m/s and (b) 230 m/s are obtained.

While the small & fast fragments caused a disruption with a convex CQ shape, the large & slow fragments showed a linear CQ shape, indicating better neon assimilation. This is also quantitatively shown in figure 5.07(g), where the injections via the larger shatter angles (usually smaller fragments) show higher early CQ durations. This also matches the observation, that for this neon range, injections of larger fragments have higher resulting radiated energies, which will be discussed in more detail in chapter 6. In addition, also the DREAM simulations performed by P. Haldestam show the largest effect of the pellet/injection parameters in this range of $1 \times 10^{19} - 1 \times 10^{20}$ neon atoms, presented in paper D [50]. For neon contents above this range, I did not observe a significant trend of the fragment size distributions on the disruption behavior.

Pre-TQ durations In figure 5.10 the (a) pre-TQ and (b) CQ durations are plotted as a function of $v_{\perp}$ – proxy for the fragment size. The colour-coding indicates the N_{neon} in the pellets. Note, two deuterium and five neon pellets with reduced pellet length via the BHs are included, marked with blue outlines and a line through the middle.

The strongest effect of $v_{\perp}$ is observed for the pre-TQ of the deuterium injections: lower values of $v_{\perp}$ (larger & slower fragments) result in shorter pre-TQ durations. However, a large fraction of the D₂ injections via the 12.5°, rectangular head (and two injections via

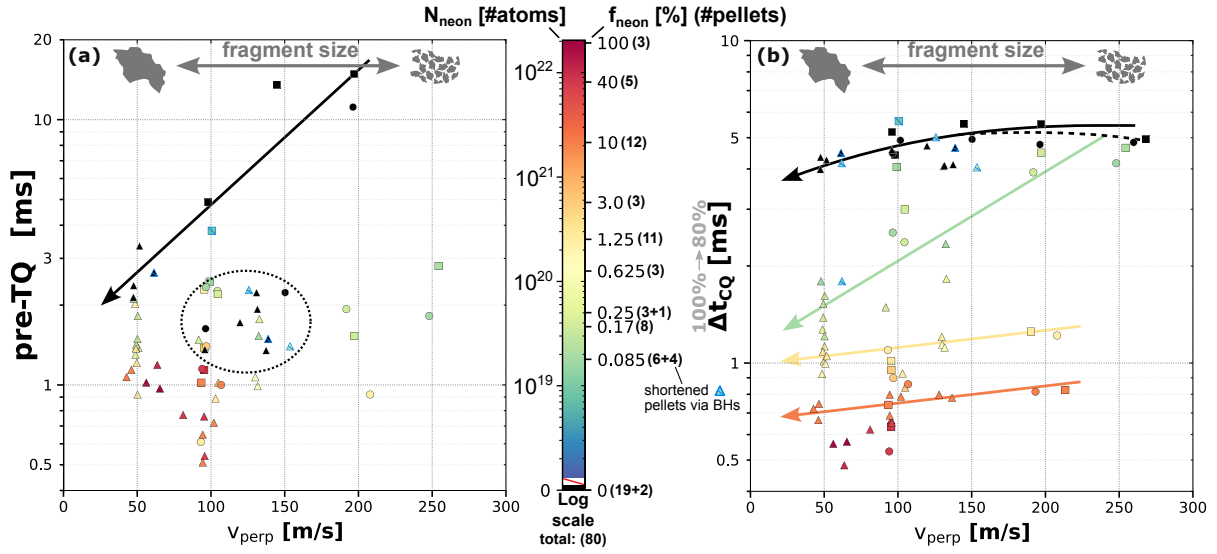


FIGURE 5.10: The (a) pre-TQ and (b) CQ durations as a function of the perpendicular velocity component. As discussed in section 3.3, $v_{\perp}$ can be used as a proxy for the fragment size, however, the mean fragment velocity also changes with $v_{\perp}$, hence both effects have to be taken into account here. While the early CQ duration ($\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) in (b) decreases with increasing $v_{\perp}$ for all f_{neon} (strongest in the range $1 \times 10^{19} - 1 \times 10^{20}$ neon atoms), a significant reduction for the pre-TQ duration in (a) is only observed for the 100% D₂ pellets. The potential effect of v_{fragment} is indicated by the dotted circle. (subset: 8/single/1.8H/distr/corr)

the 25°, circular head) show the lowest pre-TQ durations for intermediate $v_{\perp}$, marked with the dotted circle. To verify whether this trend is significant – given the probabilistic fragmentation process – may require additional investigations/experiments. If it is indeed a significant trend, it may be explained by the coupling between fragment size & velocity distributions: Higher values of $v_{\perp}$ for the same shattering angle will also mean higher fragment velocities. A more detailed discussion on this coupling is provided in section 3.3. As shown in the INDEX simulations in paper C [49], smaller and also faster fragments (scans performed separately) cause shorter pre-TQ times. On the other hand, the larger fragments cause larger total assimilation of the material due to the delayed TQ onset. For these realizations of the fragmentation process, the effect of the higher mean fragment velocity at higher $v_{\perp}$ might be the relevant factor.

Also for high neon quantities above 1×10^{21} neon atoms, higher perpendicular velocity components ($\rightarrow$ higher $v_{\text{fragment}} \rightarrow$ earlier arrival in the core) seem to reduce the pre-TQ duration. Again, whether this trend is a statistically significant trend and whether this may be caused by the decreasing fragment size or increasing mean fragment velocity is currently not confirmed. However, this would be in line with my observations of increasing radiated energy fractions for larger values of $v_{\perp}$, discussed in section 6.1.

CQ durations As the early CQ duration ($\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) depends on the assimilated neon content, we can use this dependency to estimate the effect of the fragment size distributions on the assimilation efficiency. This is especially useful, as obtaining valid density measurements in our experiments has been difficult due to technical constraints in the setup of the density measurements at AUG (see section 4.1).

As shown in figure 5.10(b), with decreasing $v_{\perp}$ (larger fragments), the early CQ duration is decreasing for all f_{neon} , also shown by S. Jachmich *et al.* in [contribution XVI](#) [121]. The largest effect is observed for the pellets with low neon doping below 1×10^{20} neon atoms. This also matches the observations for the DREAM simulations from [paper D](#) [50]. For higher neon content, the change in the CQ duration is minimal, indicating being close to some saturation threshold of the neon content inside the plasma. A saturation of the radiated energy fractions is also observed for these amounts of neon (see section 6.1). For the 100% D₂ injections at high perpendicular velocity components, the $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$ values seem to saturate or even show a potential roll-over effect, indicated in figure 5.10(b) by the black, dashed line.

Material assimilation While my main focus was the analysis of the disruption behavior and radiation, my colleague S. Jachmich analysed material assimilation in more detail. In the following, I will briefly summarise his results from contributions [XXII](#) [117] & [XVI](#) [121] as the material assimilation is important to interpret the results in this thesis. For the 100% D₂ injections, the central LOS of the fast CO₂ laser interferometer (see “V1-fast” in figure 4.04(c)) was used to assess the fraction of the assimilated to injected pellet material ($f_{\text{assimilated}}$)

$$f_{\text{assimilated}} = \Delta N_{\text{e, total}} / N_{\text{D-atoms}}. \quad (5.01)$$

An increasing $f_{\text{assimilated}}$ is observed for reduced values of $v_{\perp}$, hence for larger (& slower) fragments. By comparison of the 12.5° and 25°, rectangular shatter heads, a higher v_{fragment} for matching $v_{\perp}$ was observed to be beneficial for material assimilation. The 25°, circular shatter geometry showed often larger assimilation fractions (with large scatter of the data) compared to the 25°, rectangular counter-part. This might either indicate, that the fragment plume width increases the assimilation or the effect of the variable effective shattering angle, producing larger & faster fragments (which would match the large scatter of the data).

The same trends are also observed for D₂-Ne-mixed pellets, where the assimilated neon fraction is assessed by the early CQ duration ($\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) as shown in figure 5.10(b). This approximation is used due to difficulties in assessing the density changes directly during the short pre-TQ duration.

In the following I want to briefly summarise the main take-aways of this chapter.

- The SPI-induced disruptions can show the following phases (bold connected to a radiation peak): FL, **MFA**, **PME**, MARFE, **TQ** & **IP-spike**, CQ, **VDE**.
- During a continuous evolution, the CQ shape changes from convex → linear → concave (conduction → radiation dominated disruptions) with increasing amount of injected/assimilated neon and the number of radiation peaks are reduced from 4 → 1. The largest effects are observed in the neon doped range ($< 1 \times 10^{20}$ Ne atoms) in the experiment and DREAM simulations.
- The 12.5°, rectangular shatter head shows the highest material assimilation, however, $v_{\perp}$ & v_{fragment} are coupled, showing a potential roll-over effect.

After introducing the different disruption phases and the evolution of the disruption behavior – which depends strongly on the material assimilation – I want to discuss the results from the radiation analysis in more detail in the following.

Chapter 6

Radiation analysis

To minimise the heat loads on the PFCs it is desirable to maximise the fraction of the energy that is radiated isotropically compared to the conducted/convected thermal energies. A frequently used indicator for this is the radiated energy fraction [162, 272], introduced in the following section. Hereby, I expanded the usual definition by an additional term, that will take external heating effects after the injection into account. Afterwards, I will provide the radiated energy fractions for the 2022 experiments and discuss the effect of different shattering parameters. The 12.5°, rectangular shatter head showed the overall highest radiated energy fractions. However, while maximizing the radiation after the injection is one of the main goals, the strongly radiating region close to the PFCs – as it may appear at the fragment arrival – poses the risk of flash melting (see section 2) and a strong toroidal peaking of the radiation may be a concern. It is of particular interest to evaluate not only the total radiated energy but also its asymmetries, which is provided in section 6.2. The results and parts of the text/figures in this chapter are reported in paper A [52].

6.1 Radiated energy fraction

Definition & calculation of f_{rad}

For my radiation analysis of the 2022 experiments, I expanded the formula of the radiated energy fraction (f_{rad}) by M. Lehnen *et al.* [19, 160] and U. Sheikh *et al.* [162] in equation (2.04) by the additional excess heating (W_{heat}) term, which expresses the plasma heating after t_{FL} . Therefore, the full definition used throughout this thesis is given as

$$f_{\text{rad}} = \frac{W_{\text{rad}}}{W_{\text{plasma}} + W_{\text{heat}}} = \frac{W_{\text{rad}}}{W_{\text{mag}} + W_{\text{th}} + W_{\text{heat}} - W_{\text{c}}}. \quad (6.01)$$

In the following, the methods to derive the elements of equation 6.01 are presented.

Calculation of the radiated energy The term W_{rad} represents the radiated energy after the injection, measured by the foil bolometers. P_{rad} as described in equation (4.05) is integrated between t_{FL} and the corresponding t_{end} (see equation (6.02)). In case of a disruptive injection, the end-marker is given by the t_{CQend} . If the injection was not sufficient to cause a disruption, the end of the radiation peak(s) is used when the derivative of the signal approaches zero again, using the same algorithm as used to detect the end of the CQ from the plasma current signal [129, 130]. This t_{end} coincides roughly with the minimum of the plasma current before its recovery phase. I used my peak-finding algorithm, indicating the different time points of each radiation peak as well as automatically selecting the integration interval for each of them (see section 4.1). The last of these interval boundaries is used for the integration between t_{FL} and t_{end} . Consequently, the radiated energy is defined as

$$W_{\text{rad}} = \int_{t_{\text{FL}}}^{t_{\text{end}}} P_{\text{rad}} dt \quad (6.02)$$

$$= \int_{t_{\text{FL}}}^{t_{\text{end}}} \sum_{\text{sector}=1}^{16} P_{\text{rad, sector}} dt, \quad (6.03)$$

with $P_{\text{rad, sector}}$ as defined in equation (4.03).

Calculation of plasma stored energies To calculate W_{plasma} for equation (6.01) we need to assess the magnetic, thermal and coupled energies. For W_{th} , we directly take the reconstructed value given in table 6.01. The magnetic energy is calculated as [283, 284]

$$W_{\text{mag}} \approx 0.5 \cdot L_p \cdot I_p^2, \quad (6.04)$$

with the plasma inductance (L_p) [272, 283]

$$L_p \approx \mu_0 \cdot R \cdot [0.5 \cdot li + \ln(8R/a) - 2]. \quad (6.05)$$

The full parameter list is given in the table 6.01. The values of W_{th} and W_{mag} used in equation (6.01) are averaged over 50 ms before t_{FL} . The coupled energies to calculate W_{plasma} are estimated as described in the following.

Estimate for the coupled energy The coupled energy describes how much of the initial magnetic energy is coupled into the surrounding structure. The main sources are eddy currents induced during the TQ and halo currents that are strongly increasing towards the end of the CQ/VDE phase (see figure 5.01). While shunt current measurements in the (lower) divertor region of AUG are available to infer the halo currents (see section 4.1), this alone is not sufficient to calculate W_c nor the coupled energy fraction (f_c)

$$f_c = \frac{W_c}{W_{\text{mag}}}. \quad (6.06)$$

However, to calculate f_{rad} , it is necessary to determine W_c . Based on observations from U. Sheikh *et al.* [162] (AUG), M. Lehnen *et al.* [160] (JET) and JOREK simulations for ASDEX Upgrade VDEs by N. Schwarz [151], W_c is estimated to be 50% of the initial W_{mag} . The 2D JOREK simulations performed by N. Schwarz to assess W_c are based on a L-mode discharge [53]. The following discussion of the simulation results presented in this section is based on private communication with her and J. Artola in preparation of paper A [52], her PhD thesis [151] and publication [53]. In these simulations, different neon quantities were added as a uniform source into post-TQ plasmas, causing different CQ durations. As the neon is added after the TQ in these simulations, only the CQ phase is affected as a consequence. The magnetic energy can either be transferred to thermal energy via the internally converted Ohmic power ($P_{\text{in, Ohmic}}$) or coupled into the surrounding structure

$$W_c = W_{\text{mag}} - W_{\text{in, Ohmic}}. \quad (6.07)$$

With this setup, a lumped parameter model of the ASDEX Upgrade conductive structures can be validated as done before by M. Lehnen *et al.* [160].

term	signal	diagnostic	exp.
radiated energy (W_{rad})	calculated	equation (6.02)	
radiated power in an individual sector ($P_{\text{rad, sector}}$)	calculated	equation (4.03)	
radiated power per channel (P_{ch})	e.g. powF16:0	BLB	BOLZ
thermal energy (W_{th})	W_{mhd}	FPG	AUGD
magnetic energy (W_{mag})	calculated	equation (6.04)	
plasma inductance (L_{p})	calculated	equation (6.05)	
vacuum permeability (μ_0)	constant	$4\pi \cdot 10^{-7} \text{ NA}^{-2}$	
plasma current (I_{p})	IpiFP	FPC	AUGD
plasma internal inductance (li)	li	FPC	AUGD
plasma major radius (R)	Rcurr	FPG	AUGD
plasma minor radius (a)	ahor	FPG	AUGD
excess heating (W_{heat})	calculated	equation (6.08)	
NBI power (P_{NBI})	PNI	NIS	AUGD
ECRH power (P_{ECRH})	PECRH	ECS	AUGD
externally driven Ohmic power ($P_{\text{ex. Ohmic}}$)	calculated	equation (6.09)	
loop voltage (U_{loop})	ULid12f	MAU	AUGD
coupled energy (W_{c})	estimated	50% W_{mag} (figure 6.01)	

TABLE 6.01: Signals used throughout this thesis with their corresponding signal names, experiment descriptions (AUGD or BOLZ) and diagnostic shortcut (three-letter abbreviations). The parameter reconstruction through function parametrization (FPC/FPG) is described by Braams *et al.* [285] and McCarthy [286]. Table published in [paper A](#) [52].

Figure 6.01 shows the coupled energy fractions (using equations (6.06) and (6.07)) and radiated energy fractions [151], as well as the experimental values of f_{rad} (discussed later in section 6.1). Here, the different fractions are plotted against the duration of the CQ (Δt_{CQ}). Note, in these simulations, the plasma is not externally heated after the onset of the disruption as in the experiments (compare equation (6.08)). A direct comparison with

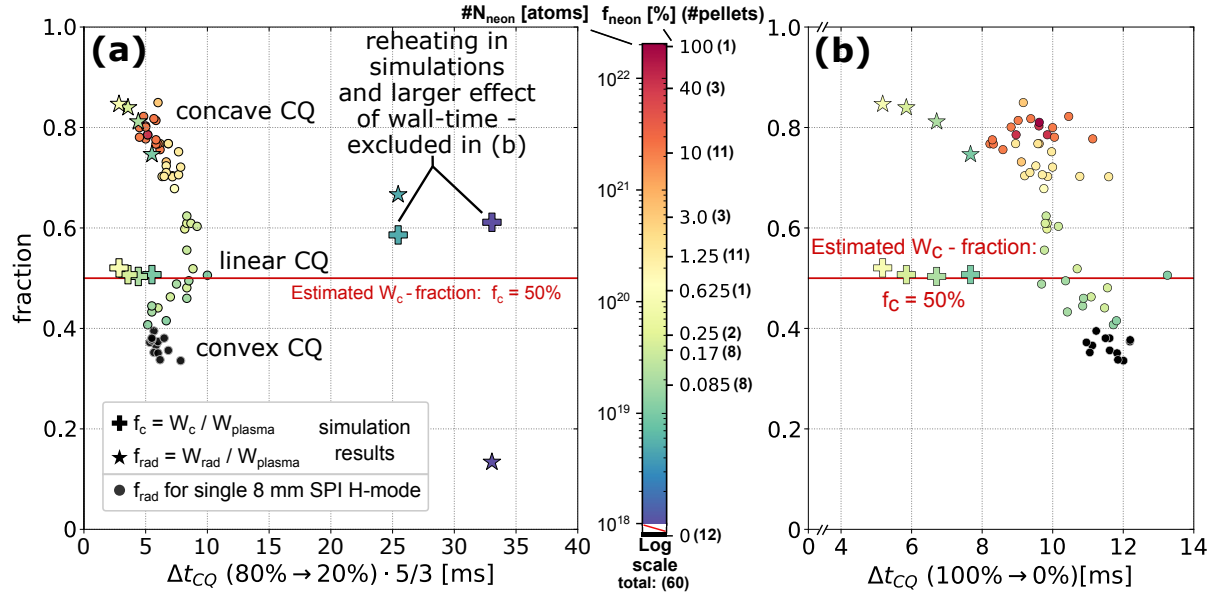


FIGURE 6.01: The coupled energy fractions and radiated energy fractions as function of (a) the scaled $\Delta t_{\text{CQ}}^{80 \rightarrow 20} \cdot 5/3$ as well as (b) the full CQ duration. The values from the 2D coupled JOREK-STARWALL mitigated L-mode VDE simulations (crosses and stars) as well as the experimental f_{rad} -values (circles) are shown. The colour-coding shows N_{neon} and inside the brackets, the number of injected pellets with a given f_{neon} of the experiments is provided. The non-monotonic behaviour of the scaled CQ durations of the experiment in (a) is caused by the transition from convex to linear CQ shapes (compare figure 5.07(h)). The two cases in which reheating occurs in the simulations ($N_{\text{neon}} = 1 - 5 \times 10^{18}$) are excluded from (b) and the calculation of W_c as they are not representative for the experiments. The figure in (b) is published in [paper A](#) [52]. (subset: 8/single/1.8H/distr)

experimental results for low neon contents ($1-5 \times 10^{18}$ neon atoms in (a)) turns out to be increasingly difficult, as these disruptions are no longer radiation dominated and reheating of the plasma occurs as shown in figure IV.25 in the thesis of N. Schwarz [151]. A detailed description of the simulation setup is provided in [paper K](#) [53]. The threshold temperature for the heat flux estimate ($T_{\text{min}, \chi_{\parallel}}$) of $T_{\text{min}, \chi_{\parallel}} = 40$ eV – indicating conduction/radiation dominated disruptions – is used for the simulations to derive f_c and f_{rad} . The exact definitions of the CQ duration displayed in figure 6.01 are explained in section 5.2. It is expected, that W_c strongly depends on the wall time for the net vessel current. Hereby, less energy is coupled into the structures in case of shorter wall times. The simulations (JOREK-STARWALL) used for this estimate of W_c by N. Schwarz [151] were performed with a wall time of about 60 ms. However, the simulations performed at this time did not represent the wall time well. A toroidal resistivity of $3 \mu\Omega\text{m}$ as in L. Giannone *et al.* [287] instead of the $0.45 \mu\Omega\text{m}$ would lead to wall times around 9 ms instead. For short CQ durations below 10 ms – as observed for high neon content SPI – the estimated $f_c = 50\%$ should remain a good approximation. For disruptions with longer CQ durations – 100% D_2 or $< 1\%$ neon doped injections – the coupled energy, hence f_{rad} , might be overestimated.

Calculation of the heating energy In the experiments we did not pre-program the heating systems (ECRH, NBI) to stop right before the injections, but instead they continue to heat the already collapsing plasma. The reason for this is threefold as we would need to

1. estimate the planned arrival times of the pellets very precisely for each discharge,
2. frequently update the discharge planning software to adjust the timings, and
3. this may make an inter-shot comparison difficult if not carefully executed.

However, at some point in time, the heating systems will switch-off automatically when some interlock-conditions are reached (e.g. plasma current interlock for the NBI) or the DCS requesting them to stop (see section 4). These interlocks were designed to prevent large amounts of power being deposited outside of the plasma. Hereby, W_{heat} represents the heating energy put into the system between first fragments arriving and shut down of the heating systems. For the scope of this thesis, all the energy is assumed to be absorbed and the heat transport is neglected.

The plasma heating after t_{FL} is given via

$$W_{\text{heat}} = \int_{t_{\text{FL}}}^{t_{\text{end}}} P_{\text{NBI}} + P_{\text{ECRH}} + P_{\text{ex. Ohmic}}, \quad (6.08)$$

where the externally driven Ohmic power ($P_{\text{ex. Ohmic}}$) describes the heating effect of the Ohmic current that is still actively induced by consuming the flux from the central solenoid given by

$$P_{\text{ex. Ohmic}} = I_{\text{p}} \cdot U_{\text{loop}}, \quad (6.09)$$

which is illustrated in figure 2.04. This term does not cover the internally converted Ohmic power ($P_{\text{in. Ohmic}}$) converting part of the pre-disruption magnetic energy into W_{th} as this is already accounted for in W_{plasma} .

Experimental values of W_{rad} and f_{rad}

With the formula from equation (6.01), I have calculated the f_{rad} -values for 197 discharges of the 2022 experiments at AUG. Figure 6.02 shows the radiated energies as a function of the energy dissipated in the plasma at t_{FL} and t_{end} , hence without and with W_{heat} , respectively. Only single injections without missing/corrupted foil bolometer channels (see sections 4.1 and A.5) are shown in the plots. As the W_{heat} term is calculated by integrating over the external heat sources (equation (6.08)), later evaluation times with respect to t_{FL} result in higher W_{heat} (until the switch-off time). Therefore, figure 6.02(a) does not include the excess heating while in (b) W_{heat} until t_{end} is included. This leads to a shift of the values to higher energies dissipated in the plasma (to the right in the plot), hence effectively reducing f_{rad} (diagonal lines in the plots). As 100% absorption of W_{heat} is assumed, the W_{rad} -values in (a) & (b) can be used as upper & lower bounds, respectively. The radiated energy fraction of non-disruptive SPI is below 30% as indicated by the shaded blue region.

In figure 6.03, the values of W_{rad} and f_{rad} (from figure 6.02(b)) are plotted as a function of N_{neon} . The colour-coding shows $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$ (colour bar in the center), pre-IP-spike VPE (magenta), and non-disruptive SPI (black). The point types indicate the different

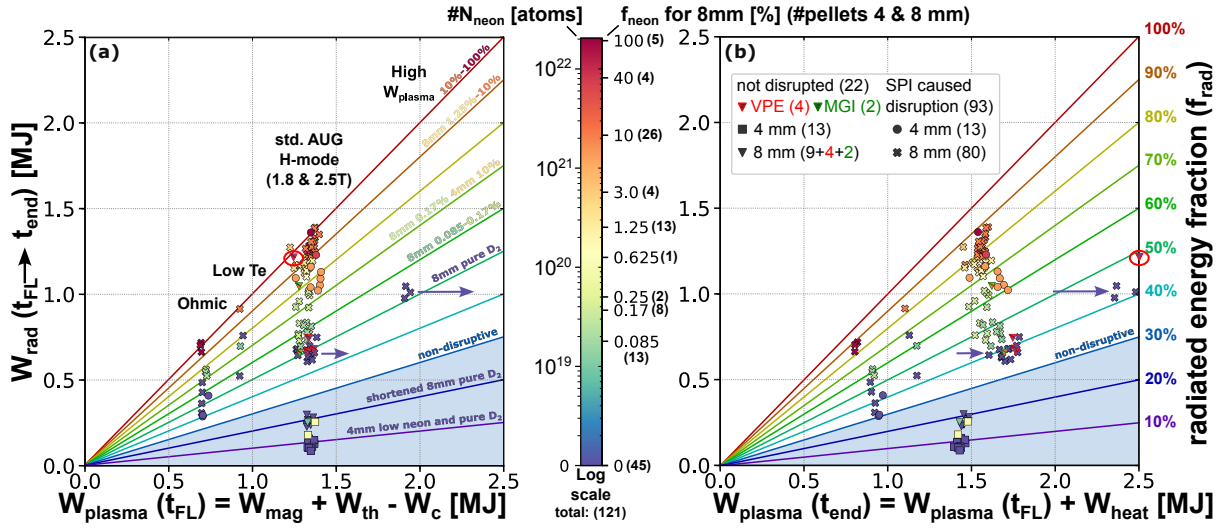


FIGURE 6.02: W_{rad} as a function of W_{plasma} (see equations 2.05 and 6.01) at (a) t_{FL} and (b) t_{end} . The markers indicate the different pellet diameter and if the plasma disrupted by the SPI. The colour bar shows N_{neon} (logarithmic scale) and the corresponding percentage of neon in the pellet for the 8 mm diameter pellets. The numbers in the brackets give the number of displayed pellets with this particular f_{neon} for 4 mm and 8 mm pellets combined. The different target plasmas from section 4.2 are indicated in (a). The coloured lines depict the different radiated energy fractions obtained for t_{FL} and t_{end} . The additional excess heating term in (b) leads to a shift of the points to higher W_{plasma} (see arrows & red circle), which also depends on the pre-TQ duration and shut-down time of the heating systems. Consequently the lower neon content SPI with longer pre-TQ are shifted further to the right. The three 100% Ne injections into Ohmic plasmas were part of (partially mitigated) VDE studies (see paper K [53]). The representation is inspired by figure 4 of M. Lehnen *et al.* [19, 160]. Figure published in paper A [52]. (subset: 4+8/single/VPE)

shatter head geometries and pellet diameters. With increasing neon content inside the pellets W_{rad} and f_{rad} are increasing and the shattering parameters only play a second order effect.

Shown in figure 6.03(b), f_{rad} saturates around 80%, matching the observation of an apparent saturation in the neon assimilation (see section 5.4). However, one has to take into account, that with the given (simplified) assumptions of the absorbed heating powers (see equation (6.08)), the plasma heating may be overestimated which may lead to lower values of f_{rad} as a consequence.

In cases of disruptive SPI, f_{rad} -values between 30% (100% D₂) and 80–85% ($> 10^{21}$ neon atoms) are observed, while non-disruptive injections showed values below 30%. These observations are in line with radiated energy fractions between 30% and 85%, reported for disruptive SPI at JET [38] and slightly higher modeling-supported values [40].

As introduced in section 5.1, the time evolution of SPI-induced disruptions can be divided into different phases, with distinct radiation characteristics and radiation peaks. Therefore, the overall value of f_{rad} depends strongly on these phases. In non-disruptive injections, only the single MFA radiation peak is visible and afterwards, the plasma recovers. If we apply the definition for f_{rad} from equation (6.01) until t_{end} , we get radiated energy fractions between around 10% (4 mm) and 20% (shortened 8 mm) for 100% D₂ pellets. However, note that in these cases, f_{rad} is **not** directly equivalent to the fraction

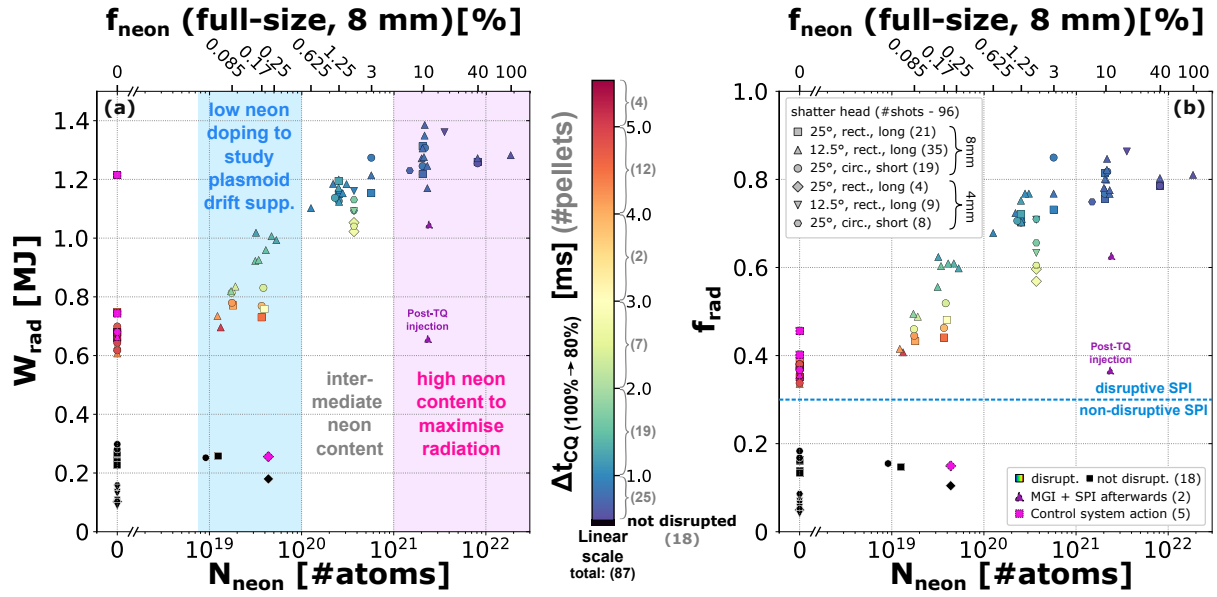


FIGURE 6.03: W_{rad} in (a) and f_{rad} (at t_{end}) in (b) as a function of N_{neon} . At the top, f_{neon} for the 8 mm pellets is given. The markers indicate the different shatter heads and pellet diameters. The colour-coding indicates the $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$ with a linear scale and non-disruptive SPI in black. The numbers in the brackets indicate the number of injections resulting in these CQ durations. Magenta points indicate cases where a DCS state-change was triggered. The two purple points (at 10% Ne) show deuterium MGI followed by 8 mm, 10% Ne SPI. Hereby, W_{rad} and f_{rad} are a strong function of the neon content and the shatter head geometry has only a second order effect. Figure published in [paper A](#) [52]. (subsets: 4+8/single/1.8H/VPE)

of the initial total plasma energy ($W_{\text{mag}} + W_{\text{th}}$) being lost. Only part of the energies dissipated in the plasma are lost during this process, hence the definition of f_{rad} – including $f_c = 50\%$ – should be interpreted with caution. As soon as the disruptive threshold is reached for 100% D_2 injections (see section 5.3), the other phases (i.e. the TQ and VDE) cause additional radiation that increases the radiated energy fractions to around $f_{\text{rad}} \approx 40\%$. This is shown by the step-wise increase of the radiated energies over the course of the disruption in figure 5.09. Consequently, higher radiated energy fractions do not automatically correspond to more benign disruptions, as thermal loads, vessel currents & forces are not directly reflected in these values. While $f_{\text{rad}} \approx 40\%$ of disruptive, 100% D_2 SPI may sound high, these disruptions in practise usually translated to high vessel forces that were noticeable even inside the control room of AUG. We expect, that these conduction dominated disruptions are closer to what may be called a “hot VDE”, as the radiation is low and strong shunt currents & vessel forces were observed, however, a full force analysis had not been performed on these discharges at present.

In two cases (violet, dashed triangles), the disruptions were triggered by 100% D_2 MGI in S4 and and mitigated by subsequent 10% Ne SPI with $v_{\text{pellet}} \approx 220$ m/s. Hereby, $\approx 0.77 \text{ bar} \cdot \text{L}$ ($\approx 78 \text{ Pa} \cdot \text{m}^3$; 6 bar filling pressure) of D_2 was injected triggering a slow disruption. The delay between MGI and SPI triggers was selected manually. For the first attempt, the SPI was triggered 10.4 ms before the in-vessel MGI valve in sector 4. This pellet arrived after the TQ, hence showed reduced radiation ($f_{\text{rad}} \approx 37\%$). In the second test, the SPI was triggered 14.4 ms prior to the MGI and arrived after the gas but before

the TQ in the plasma with higher resulting $f_{\text{rad}} \approx 63\%$. This experiment illustrates, that the delivery of the neon before the TQ is necessary for an efficient disruption mitigation.

Influence of the shattering parameters on f_{rad}

In this section, the effects of the shatter head geometry and fragment size distributions on the radiated energy fractions are discussed.

Heuristic f_{rad} fit function For a better illustration of these effects, a heuristic fit function was derived by J. Artola in preparation of [paper A \[52\]](#), which will be introduced in the following: for this purpose let us now denote

$$f_{\text{rad}} = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{thFW}}} = \frac{1}{1 + x}, \quad (6.10)$$

with the thermal energy flux to the wall (P_{thFW}) and the power fraction $x = P_{\text{thFW}}/P_{\text{rad}}$. This term scales as [\[288, 289\]](#)

$$P_{\text{thFW}} \propto n_e \cdot T_e^{3/2}, \quad (6.11)$$

with the electron density (n_e) and electron temperature (T_e). From atomic physics [\[210\]](#), the proportionality

$$P_{\text{rad}} \propto n_e \cdot n_{\text{imp}} \cdot L_{\text{rad}}(T_e), \quad (6.12)$$

is derived, with the impurity density (n_{imp}) as well as the electron temperature dependent radiation factor ($L_{\text{rad}}(T_e)$). Hereby, a coronal equilibrium for the different charge states is assumed. With this, the power fraction from equation (6.10) is inversely proportional to the impurity density

$$x \propto \frac{T_e^{3/2}}{L_{\text{rad}}(T_e)} \cdot \frac{1}{n_{\text{imp}}} = G_{\text{rad}}(T_e) \cdot \frac{1}{n_{\text{imp}}}, \quad (6.13)$$

with an electron temperature dependent pre-factor ($G_{\text{rad}}(T_e)$) containing $L_{\text{rad}}(T_e)$ and the proportionality factors. The impurity density itself depends on the number of assimilated neon atoms in the plasma ($N_{\text{assimilated neon}}$) and N_{neon} as

$$n_{\text{imp}} \propto N_{\text{assimilated neon}} = b/(1 + b/N_{\text{neon}}) \quad (6.14)$$

and inserting into equation (6.10)

$$f_{\text{rad}} = \left(1 + \frac{B \cdot G_{\text{rad}}(T_e)}{N_{\text{assimilated neon}}}\right)^{-1} = \left(1 + \frac{a \cdot (1 + b/N_{\text{neon}})}{b}\right)^{-1} \quad (6.15)$$

$$= \frac{b}{a + b + a \cdot b/N_{\text{neon}}}, \quad (6.16)$$

where the constant factor B contains all proportionality factors as well as the radiation fit parameter (a) and the assimilation fit parameter (b). With the help of these parameters, the radiated energy fraction is fitted as a function of the N_{neon} in the following section. However, note that the parameters a and b are not orthogonal to each other (see figure 6.04), hence when both parameters are fitted at the same time, a direct comparison

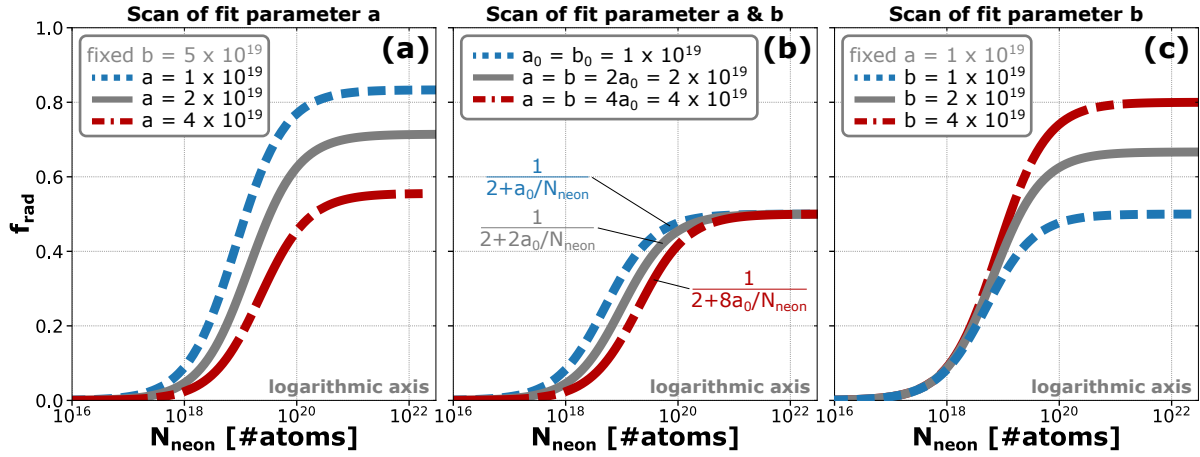


FIGURE 6.04: The f_{rad} -fitting parameters a and b do not span an orthogonal basis. Consequently, comparing certain values of b does not imply differences in $N_{\text{assimilated neon}}$ if a is not kept fixed and vice-versa. The different effect of varied fitting parameters are illustrated: (a) radiation fit parameter a , (b) $a = b$, and (c) assimilation fit parameter b .

between individual fitting parameters (i.e. assimilation parameter b) is not suggested. In other words: The parameter b does not correspond to any measurement quantity of the material assimilation directly, nor does a higher value of b in one fit indicate that the assimilation is higher compared to another fit if a is not kept fixed and vice-versa. If one of these parameters is fixed, (i.e. b in figure 6.05(a)), the other parameter may be used to indicate trends in the data.

Effect of the shatter head geometry on f_{rad}

The effect of the shatter head geometry on f_{rad} is shown in figure 6.05. Hereby, f_{rad} is plotted as a function of N_{neon} as done in figure 6.03(b), but only for 8 mm pellets that contain neon (upper-right branch). The fit function from equation (6.15) is used to illustrate the trends, and the fitting parameters a and b are given in the appendix A.12. The fitting was done with the `scipy.optimize.curve_fit` function with the error estimate `np.sqrt(np.diag(pcov))` as suggested in the `scipy` documentation [290]. In figure 6.05(a), the total fit (dashed black line denoted as $\textcircled{t}$) includes all three different shatter head geometries used in the 2022 experimental campaign (fit parameters a and b are displayed in the appendix A.12). For the individual shatter head fits, b is fixed to 6.57×10^{19} (taken from $\textcircled{t}$) and only a is fitted. The fixed parameter b now indicates the maximum possible amount of neon, that could be assimilated in the plasma independent of the shatter head geometry, as indicated by the saturation of $f_{\text{assimilated}}$ in section 5.4. This way, a indicates the “optimal” shatter head to reach this assimilation, maximising f_{rad} . This routine is applied as a and b do not span an orthogonal parameter pair (see figure 6.04). Additionally, in order to compare the shatter head geometries more quantitatively, keeping a single fit parameter unfixed may be preferable. Hereby, lower values of a result in higher f_{rad} -values, therefore are considered optimal. The largest impact of the shatter head geometry is observed for pellets with 0.17% Ne or around 4×10^{19} neon atoms (plasmoid drift suppression studies) with a difference in the order of 10–20%. This is also reproduced in the DREAM simulations, where the largest variation in f_{rad} for different

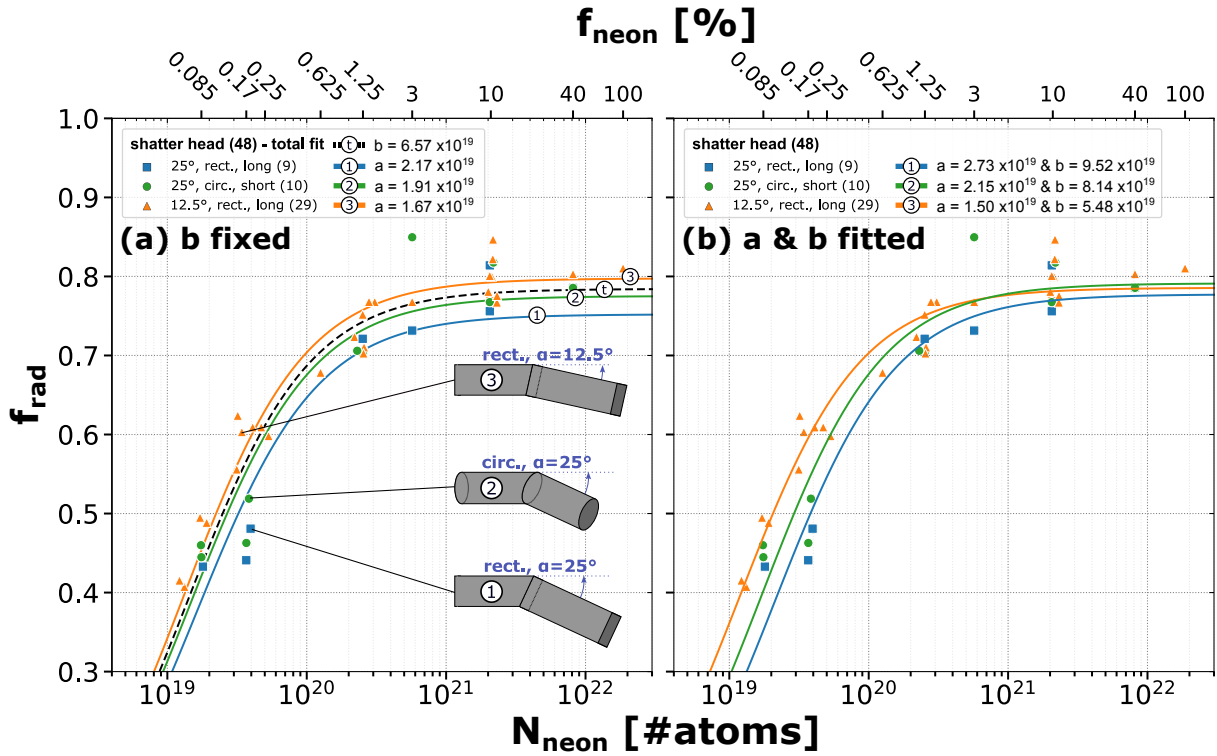


FIGURE 6.05: Effect of the shatter head geometry on the radiated energy fraction. The fitting parameters for the different heads are provided in the appendix A.12. By fixing the parameter b in (a), the fits indicate, that the 12.5°, rectangular shatter head leads to the highest overall values of f_{rad} – especially relevant for $N_{\text{neon}} < 1 \times 10^{20}$. A version without fixed fitting parameter b is provided in (b). The figure in (a) is published in [paper A \[52\]](#). (subset: 8/single/1.8H/diss for $N_{\text{neon}} > 0$)

realizations is observed for $f_{\text{neon}} = 0.17\%$ Ne (see [paper D \[50\]](#)). Additionally, in this range of f_{neon} , the strongest effects of the pellet/injection parameters are also observed on the disruption evolution, in both – experiment and DREAM (see section 5.4). The curve in figure 6.05 starts to saturate around 10% Ne injections. The aim of these high neon content injections is to maximise the radiation. For these injections, the difference between the shatter head geometries is in the order of 2–5%, hence within the estimated errors of 10% for inter-shot comparisons (see section 4.1). The 12.5°, rectangular head (large & fast fragments) shows the highest radiated energy fractions. The 25°, rectangular counter part shows the lowest f_{rad} -values and the 25°, circular shatter head (varying effective shatter angle) lies in between these two.

In summary: to maximise f_{rad} , the **12.5°, rectangular head** is found to be the “optimal” shatter head out of the three tested geometries. This is in line with the observations by S. Jachmich *et al.* [117, 121], that this head also maximises the material assimilation for D_2 and D_2 -Ne-mixed pellets (see section 5.4). For this reason, the current ITER DMS design plan foresees the shallowest possible shattering angle of their shattering unit of **15.5°**, and also uses a rectangular cross-section [109, 220].

With our “optimal” shatter head geometry in mind now, we can try to isolate out the effects of the different fragment sizes & velocities.

Fragment size effect on f_{rad} In figure 6.06, the effect of the fragment size is shown. Hereby, larger values of $v_{\perp}$ correspond to smaller fragments, as discussed in section 3.3. However, while $v_{\perp}$ is used to approximate the fragment size, it is also coupled to the mean fragment velocity. Low, medium, and large perpendicular velocity components are fitted, this time with free fitting parameters a and b , necessary to well reflect the trends within the data. The intention of these fits is **not** to draw quantitative comparisons for the different perpendicular velocity components (as a and b are both unfixed) but to illustrate the trends and guide the eye along the data points. For low neon content ($< 1.25\%$ or $\approx 2-3 \times 10^{20}$ neon atoms), lower perpendicular velocity components (larger & slower fragments) are beneficial for f_{rad} , similar to the conclusion drawn from figure 6.05(a). However, at the intermediate range of neon content (between 10^{20} and 10^{21} neon atoms), this trend might reverse: Now higher perpendicular velocity components (smaller & faster fragments) seem to have a positive effect on f_{rad} . The zoom in figure 6.06(b) shows the 10% Ne pellets (around 2×10^{21} neon atoms). It is important to mention, however, that a

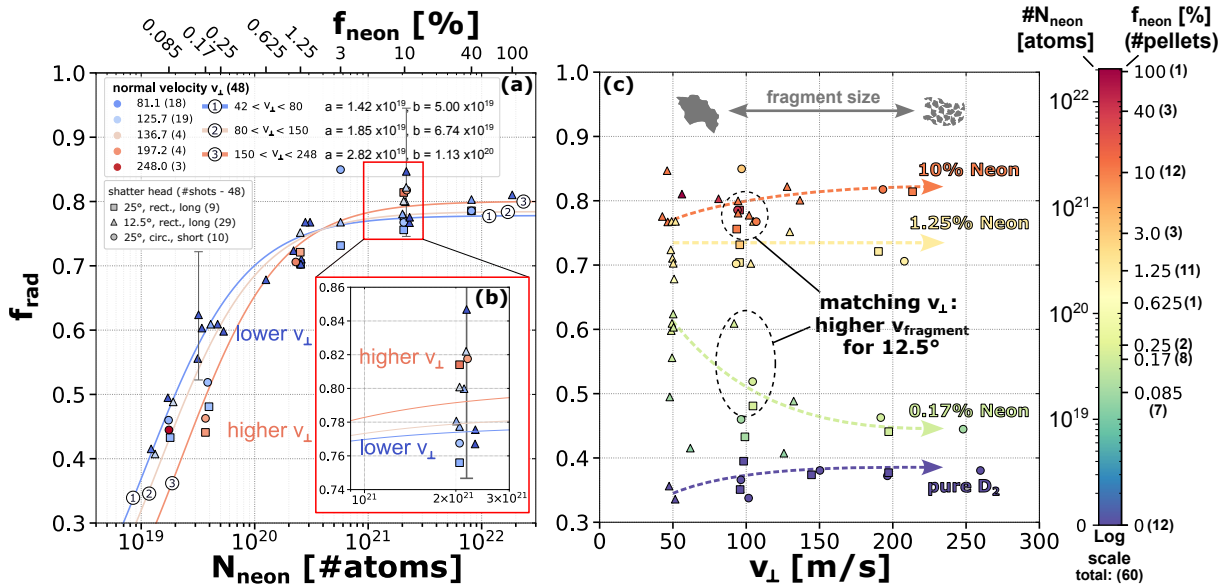


FIGURE 6.06: Influence of the fragment size (approximated by $v_{\perp}$) on f_{rad} . In (a) low, medium, and high ranges of $v_{\perp}$ are fitted with zoom on the 10% Ne pellets in (b). Similar to the fit in figure 6.05(b), the parameter b is not fixed, revealing a change in trend between low and high neon content injections. This change in trend around 1.25% Ne is also illustrated by the coloured arrows in (c), where f_{rad} is plotted as a function of $v_{\perp}$: for $f_{\text{neon}} > 1.25\%$ Ne, $f_{\text{rad}}(v_{\perp})$ might increase along $v_{\perp}$. The dashed circles are discussed in the following section about the effect of v_{fragment} on f_{rad} . Two estimated error bars with $\Delta f_{\text{rad}} \pm 10\%$ (see section 4.1) are also provided. The figure in (c) is published in [paper A](#) [52]. (subsets: (a, b) 8/single/1.8H/diss for $N_{\text{neon}} > 0$, (c) 8/single/1.8H/diss)

direct comparison is only available for the 10% Ne pellets and the difference of $\Delta f_{\text{rad}} < 10\%$ lies within the uncertainties, hence more detailed studies would be required to verify this observation. These trends are also illustrated by the arrows in figure 6.06(c), where f_{rad} is plotted as a function of $v_{\perp}$ and the colour-coding representing the neon content: for 100% D_2 and potentially the high neon content injections, higher perpendicular velocity components (smaller & faster fragments) show slightly higher radiated energy fractions, while the trend seems to be reversed for the neon doped pellets. At a neon percentage

of 1.25%, the radiated energy fraction appears to be independent of $v_{\perp}$ (compare yellow, horizontal arrow), hence this indicates the transition from low to high $v_{\perp}$ -values being optimal for f_{rad} . Therefore, this apparent shift in trend could be also explained by the increase in v_{fragment} becoming dominant in this region. Most of the injections for the $f_{\text{neon}} = 10\%$ Ne pellets had been performed with the 12.5° shatter head – due to stuck 100% D_2 pellets in the staggered injection scheme followed by 10% Ne pellets. Consequently, the effects of fragment size & velocity are difficult to disentangle without enough comparison injections via the 25° heads. The pellet/fragmentation parameters for the pellets in figure 6.06(b) are provided in the appendix A.13 sorted by highest f_{rad} -values to lowest.

Mean fragment velocity effect on f_{rad} As discussed in section 3.3, when comparing the 12.5° and 25° shatter heads for matching $v_{\perp}$, the effect of v_{fragment} can be estimated. However, the number of matching $v_{\perp}$ -values for the same neon content inside the dataset 8/single/1.8H/disr is sparse. The limited data available indicates higher radiated energy fractions for higher values of v_{fragment} , shown by the dashed ellipses in figure 6.06(c) for 0.17% and 10% neon pellets.

However, maximising f_{rad} is not the only objective of shattered pellet injections: if the toroidal peaking during the MFA is too high, flash-melting may become a concern for e.g. steel-components inside a fusion reactor. In the following, I will discuss the radiation asymmetries I observed for the 2022 experimental campaign.

6.2 Radiation asymmetries

A high toroidal peaking in the radiation may indicate a potential risk of flash-melting as introduced in section 2, as they would point towards a highly radiating but spatially confined region. If this region is too close to a PFC and the total level of radiation is high, this could lead to an overburden of the material. To assess this risk, the radiation asymmetries are an important factor. When looking at the radiation asymmetries, often two approaches are of great interest to study: Tracking the highly radiating region in space & time and also comparing the total radiated powers or energies of certain locations. In this thesis, I will focus on the relative asymmetries of certain locations (i.e. channels within one foil bolometer or toroidal sectors) with the help of the slower but absolutely calibrated foil bolometers.

Radiation tracking (in the poloidal plane) with the highly time resolved AXUV diodes had been started by J. Svoboda and myself (see section A.14) as well as conducted by F. Lengyel (see contributions XIV [258], XX [291], and [292]).

The discussion in this chapter focuses on single injections of 8 mm pellets into the SPI H-mode ($\in$ 8/single/1.8H) if not explicitly stated otherwise.

In the first section, the qualitative asymmetries within the radiation are discussed.

Qualitative radiation asymmetries

When material is injected from a dedicated location into the plasma, often a highly radiating region is formed, where the material is interacting with the background plasma. Hereby, the poloidal asymmetries describe, where this radiating region is located in the poloidal cut, its extent, and also its relative strength w.r.t. the surrounding background plasma.

As the fragments at ASDEX Upgrade are injected from the LFS midplane in sector 16, it is expected to see high radiation at the LFS at first. When the first larger fragments enter the plasma at t_{MFA} , a strong increase in the LFS channels for the foil bolometers (channel 0) and AXUV diodes is observed in sector 16 first, followed by the other channels – both poloidally and toroidally – soon afterwards (see also figure 5.04(b, 1–6)). Depending on the pellet and injection parameters, the temporal evolution and absolute values can vary significantly as indicated in figure 6.07: for the 100% D₂ injection in (a), the peak radiation measured by the LFS channel 0 of sector 16 is about twice as high as the highest radiation peak in the other channels. This indicates a large poloidal (compare blue and orange arrow in (III)) and toroidal asymmetry ((I) – (V)) of the radiation. In contrast, the radiation is poloidally & toroidally more symmetric in case of the 100% Ne injection in (b). This is also visible in the UHS camera recordings illustrated in figure 5.04: for the initial phase of 100% D₂ injections, the radiating region has a wider poloidal ex-

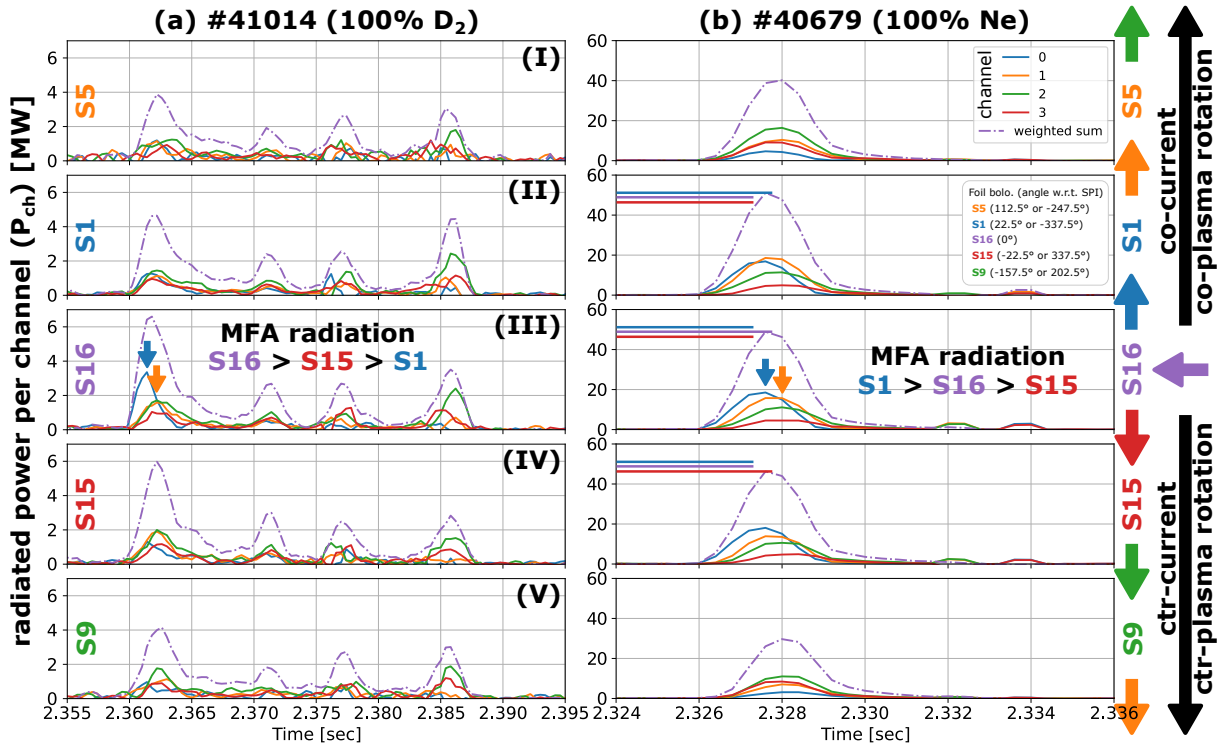


FIGURE 6.07: Asymmetry of the radiation for the different foil bolometer channels (poloidal asymmetry) and toroidal locations. Note, the lines represent the individual channels (P_{ch}), **not** the individual sectors ($P_{\text{rad, sector}}$). The total sum (violet dashed lines) for each sector (I–V) is used as $P_{\text{rad, sector}}$ throughout this thesis. Discharges with (a) 100% D₂ and (b) 100% Ne SPI are compared. For the D₂ injection, the radiation is poloidally and toroidally more asymmetric compared to the Ne injection. The poloidal asymmetry is indicated by the blue and orange arrows for channels 0 and 1 of S16 in (III), respectively. (subsets: (a, b) $\in$ 8/single/1.8H/distr)

tension (still within the LFS-channel 0) but lower toroidal extent (see following section) compared to injections with high neon content. Deuterium atoms with their single electron contribute mainly via line radiation **prior to the ionization** as their contribution to Bremsstrahlung is small. In contrast, neon can still radiate strongly while being **partially ionised** thanks to remaining bound electrons emitting line radiation but also larger contribution to Bremsstrahlung. Therefore, high emissions are observed as neon spreads around the torus, following the helical magnetic field lines. This motion of the radiation can be tracked across the different sectors with the help of the fast AXUV diodes and compared to the expected poloidal location due to the magnetic field line mapping as done in [contribution XIV](#) [258]. However, not only the neon content inside the pellet but also fragmentation parameters (i.e. fragment size & velocity) can impact the asymmetry of the injection, discussed later in this section in more detail.

Quantitative, absolute toroidal radiation asymmetries

To indicate toroidal asymmetries in the radiation between the injection location and the other sectors, the toroidal peaking factor (TPF) [293] was defined in collaboration with the ITER DMS team as

$$\text{TPF} = \frac{P_{\text{rad, max}}^{\text{total}}}{\sum_{\text{sector}=1}^{[1,5,9,15,16]} \frac{P_{\text{rad, sector}} + P_{\text{rad, sector}+1}}{2} \cdot \frac{\Delta\Phi(\text{sector, sector}+1)}{360^\circ}} \quad (6.17)$$

$$\equiv \frac{P_{\text{rad, max}}^{\text{total}}}{\sum_{\text{sector}=1}^{16} \frac{P_{\text{rad, sector}} + P_{\text{rad, sector}+1}}{16}} \quad (6.18)$$

$$= \frac{\text{“peak (max) radiation”}}{\text{“toroidal mean at time } t_{\text{max}}\text{”}} \quad (6.19)$$

with the $P_{\text{rad, max}}^{\text{total}}$ as defined in section 4.1 and the difference in toroidal angle (Φ) between the sectors. In equation (6.17), $\text{sector} \in [1, 5, 9, 15, 16]$ and $\text{sector} + 1$ refers to the next measurement sector in the list (with the next element of sector 16 is sector 1 to close the torus). This is mathematically equivalent to the expression in equation (6.18) [293], where the mean over the 16 sectors of AUG is used in the denominator as done in the calculation of W_{rad} in equation (6.02). Here, $\text{sector} \in [1, 2, \dots, 14, 15, 16]$ with linearly interpolated values of P_{rad} for non-measurement sectors.

A $\text{TPF} = 1.0$ would indicate a perfectly, toroidally symmetric emission pattern – ignoring potential sub-structures within the individual sectors. Hereby, higher values correspond to higher “toroidal peaking”. Note, the TPF is not a good measure for the “overall toroidal asymmetries” but highlights the “toroidal peaking” of a single/few toroidal sector(s) w.r.t. the others, illustrated in figure 6.10.

The TPF-values of injections into the SPI H-mode ($\in 8/\text{single}/1.8\text{H}$ for $N_{\text{neon}} > 0$) are given in figure 6.08. Overall, lower TPF-values are observed for higher neon content inside the pellets, which reduces the concern about flash-melting (see section 2.5) to occur in future fusion devices such as ITER. The foreseen tungsten FW [11, 12] and synchronised injection scheme from multiple – toroidally separated – locations [109, 294] further reduces this concern for ITER.

Dual and staggered injection schemes [109] (shown in red in figure 6.08), show similar TPF-values compared to single injections (blue). For staggered injections – where a 100% D_2 pellet was injected first followed by a deuterium-neon-mixed pellet – the neon content of the second pellet was used for the comparison. In the experimental campaign

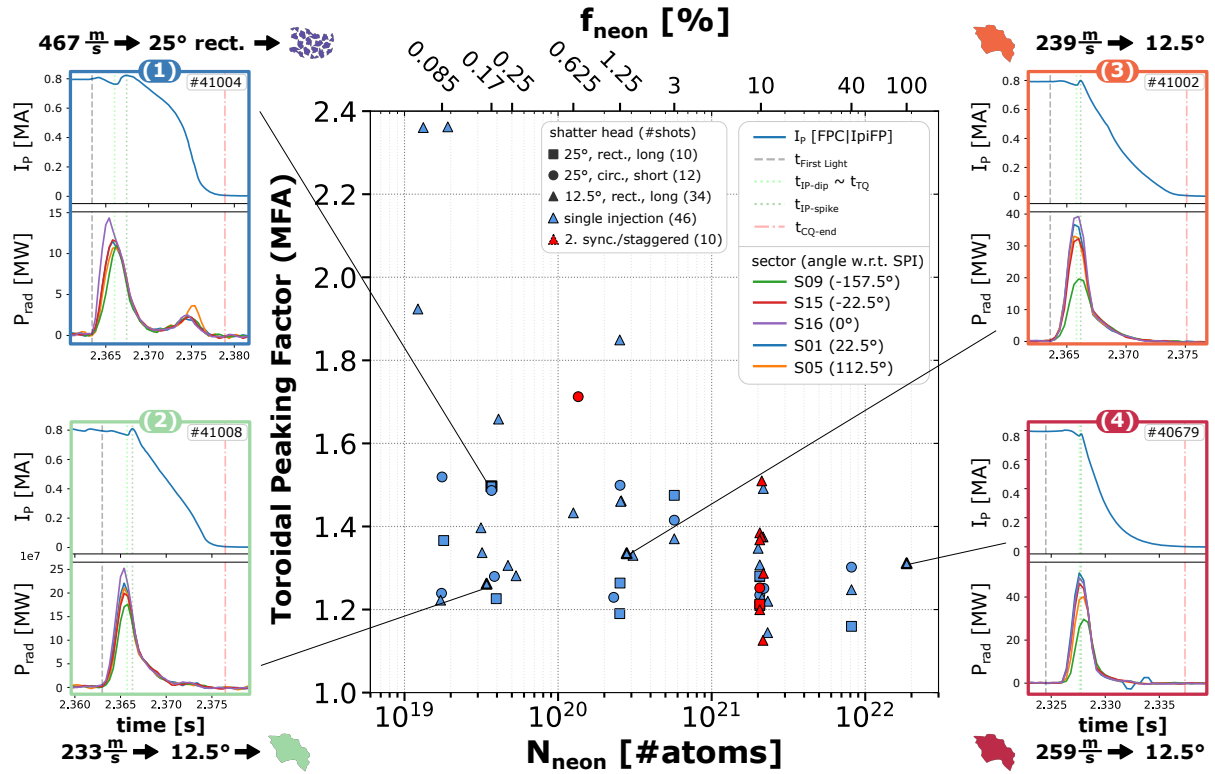


FIGURE 6.08: The TPF as a function of N_{neon} for single (blue) and sync./staggered (red), 8 mm pellets injected into the SPI H-mode. Four single injections from figure 5.07 are highlighted in the plot with the corresponding time traces of the plasma current and radiation. Overall, with increasing neon content, the TPF decreases. At low neon content – when the transition from convex to concave CQ-shapes is observed – the larger fragments from (b) lead to a lower TPF with a more benign disruption compared to (a). The discharges with sync./staggered injections have TPF-values in the range of the corresponding single injections. (subset: 8/single+dual/1.8H/VPE for $N_{\text{neon}} > 0$ and only second pellet for “dual” (synchronised/staggered) injections)

in 2022, the staggered injection scheme was mainly tested for 10% Ne (around 2×10^{21} neon atoms) for the second pellet, hence different trends compared to single injections can not be excluded.

Effect of fragmentation parameters on radiation asymmetries

The fragmentation parameters, like fragment size & velocity, show an effect on the radiation characteristics of the injections. This is not only visible in the radiated energy (and therefore radiated energy fraction) as shown in section 6.1, but also the radiation asymmetries.

The effect of the fragment size effect is indicated by the discharges #41004 in (a) and #41008 in (b) in figure 6.08. They had been used before in section 5.4 to illustrate the fragment size effect on the disruption evolution. Both injections share the same pellet composition: 0.17% or around 3×10^{19} neon atoms. In figure 6.08(a), the pellet with pre-shattering pellet velocity around 467 m/s was shattered inside the 25° rectangular shatter head expected to produce small & fast fragments. In contrast, the pellet in (b) is expected to have larger & slower fragments as it had half the pre-shattering pellet velocity and shattering angle. The larger & slower fragments in (b) lead to a disruption with higher peak radiated power, a more linear CQ (compare section 5.1) and a lower TPF-value.

Relative toroidal asymmetries

In this section, the relative toroidal asymmetry is discussed and the $P_{\text{rad, max}}^{\text{SY}}$ -values (see section 4.1) are compared. As already indicated in section 5.1, the radiation during the PME and TQ are toroidally mostly symmetric, while the radiation peaks at fragment arrival and the VDE-phase can show high toroidal asymmetries. Consequently, in the following the asymmetries for these two peaks are discussed in more detail.

Toroidal asymmetries during the main fragment arrival

In all cases illustrated in figure 6.08, the highest radiated power was observed for the first radiation peak (MFA peak)

$$P_{\text{rad, max}}^{\text{total}} = \max(P_{\text{rad, 1. peak}}^{\text{S1-16}}), \quad (6.20)$$

hence illustrating the toroidal asymmetries of the radiation during the MFA. However, in a handful of cases, higher radiation during the TQ or VDE phase were observed for Ohmic discharges, synchronised/staggered injections or discharges with pre-IP-spike VPE. The latter sometimes showed a violent VDE phase. All of these three categories are not included in the subsets displayed in the figures.

While the TPF reduces the total toroidal asymmetries to a single value, the relative asymmetry of the individual sectors might not be correctly represented by this factor. In figure 6.09, the $P_{\text{rad, 1. peak}}^{\text{S1-16}}$ -values for the first radiation peak of the different sectors are shown in (a). This first peak is equal to the MFA peak but also includes the radiation during the TQ (+ potentially PME) for high neon SPI. In (b), the minimum area that contains all the data points is given indicating the trends from the scatter plot in (a). While the trend of increasing radiated power with increased neon content in the pellet is the same for all five sectors, the peak radiated power in the opposite sector S9, is reduced by a factor of around 4/3–5/3, while for the perpendicular sector S5 is closer to the peak values of the other sectors (i.e. to S15). Therefore, the absolute asymmetry between S5 and S9 (S5/S9-asymmetry) increases with increasing neon content. When comparing this to the TPF-values from figure 6.08, it is visible, that this is not represented by the

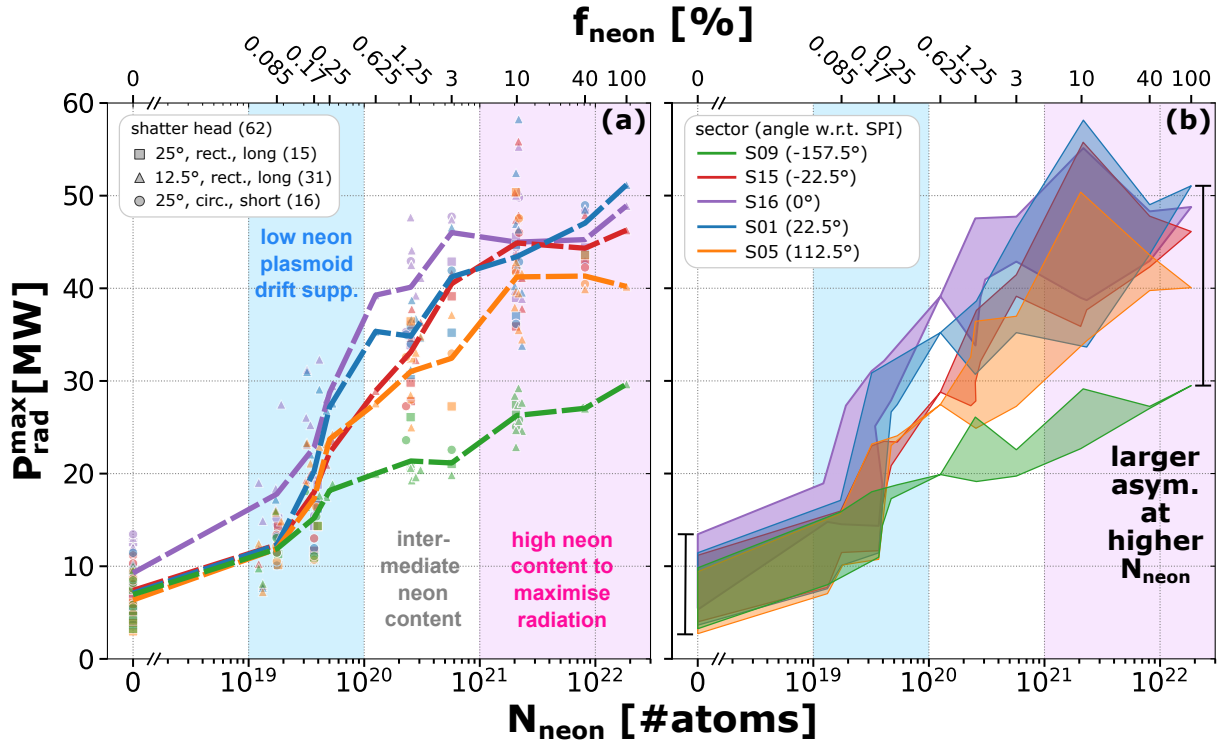


FIGURE 6.09: Peak radiated power in each sector as a function of N_{neon} . The individual peak values for each sector and discharge are provided in (a). The dashed lines connect the mean values for each f_{neon} -value from the top axis. The confining areas of the scattered data points from (a) are shown in (b). While the $P_{\text{rad}, \text{max}}^{\text{S15, S16, S1, and S5}}$ -values are comparable for high neon contents, $P_{\text{rad}, \text{max}}^{\text{S9}}$ is reduced by a factor of around 4/3–5/3. Consequently, the S5/S9-asymmetry is increasing for higher neon injections. (subset: 8/single/1.8H/VPE)

toroidal peaking factor. The large S5/S9-asymmetry seems to be compensated by the low asymmetry of the sectors S1, S5, S15 and S16 at high neon content. For low neon content and 100% D₂ pellets, the radiation in S16 is in some cases much higher compared to the neighboring sectors, which leads to a larger peak radiation value compared to the toroidal mean (see equation (6.19) and figure 6.10), therefore a large TPF-value. Hereby, the effect of a larger $P_{\text{rad}, \text{max}}^{\text{total}}$ -value of S16 on the numerator of equation (6.18) outweighs the reduced value in S9, which affects the denominator only via the mean over all sectors. Therefore, the toroidal peaking factor – as the name suggests – is well suited for investigating the peaking of a single sector compared to the remaining sectors. It is less suited for illustration of the drop in radiation in a certain sector compared to the remaining sectors shown in figure 6.10.

At low and intermediate neon content in the pellet, the highest radiation at the fragment arrival is observed in sector 16 (injection sector) as illustrated by the colour-coding in figure 6.11. However, for higher neon content, the radiation in one of the neighboring sectors (S1 or S15) and even the perpendicular S5 is often slightly higher. Note, the difference lies within the uncertainty of the measurements.

In figure 6.12, the ratio of the peak radiation in S1 and S15 are plotted as a function of (a) the neon content and (b) $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$. As these sectors are both directly neighboring the injection location, their relative asymmetry could give first indications to the preferred

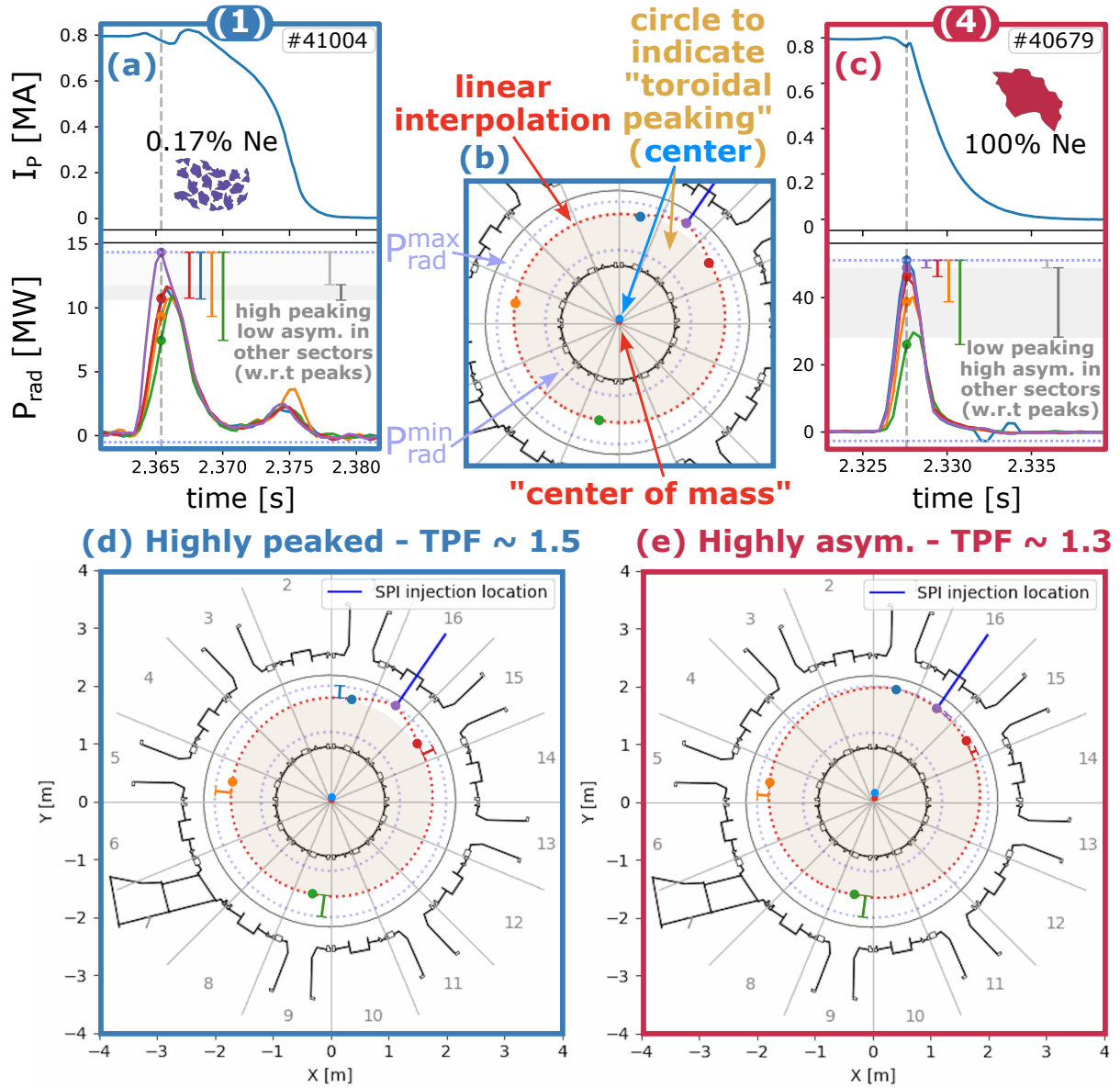


FIGURE 6.10: Representation of toroidal asymmetries and influence on the TPF-value. The illustrations in (d, e) show the $P_{rad, \text{sector}}$ -values marked with circles in (a, c) in a toroidal representation. They are evaluated at the time of $P_{rad, \text{max}}^{\text{total}}$ (dashed, vertical lines in (a, c)) for which also the TPF-values are calculated. The outer/inner dashed circles indicate the global maximum/minimum P_{rad} -values, respectively. While the TPF indicates large peaking in a single sector in (a, b, d) well, the overall toroidal asymmetries in (c, e) are not well represented. This is illustrated with the help of the circle in (d, e): the deviation of S16 from the circle surface in (d) has a larger impact on the TPF, than the larger displacement of the center in (e). The ratios of “peaking” to “asymmetries between the other sectors” for the individual peak values are indicated by the gray bars in (a, c). (subsets: (a–e) $\in$ 8/single/1.8H/dissr)

rotation direction of the radiation pattern potentially linked to the material spreading. Note, that the asymmetries depicted in these plots are within the errors of the measurements. It seems like larger (& slower) fragments cause higher radiation in S1 and smaller (& faster) fragments in S15. One potential explanation for this could be the effect of the

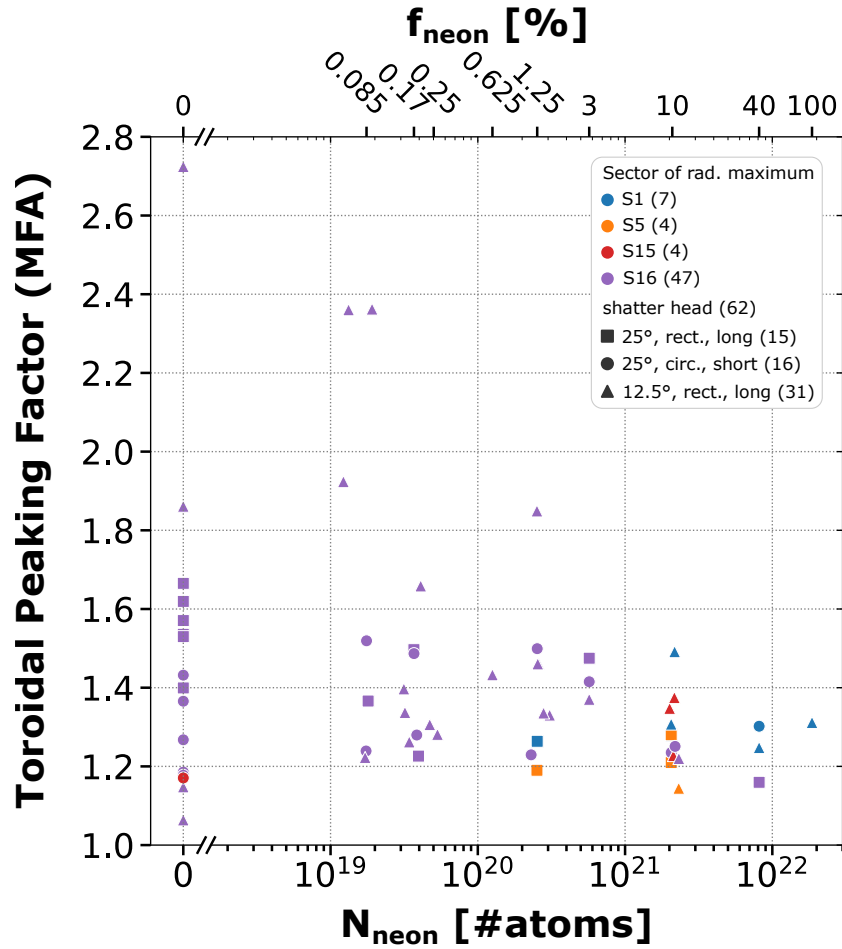


FIGURE 6.11: TPF plot from figure 6.08 (also including 100% D_2 pellets) with colour-coding indicating the sector with the highest peak radiated power during the MFA. While for low neon content the radiation in the injection sector S16 is the highest, for high neon content (around 10%), the measured radiation in the other sectors is often slightly higher but the difference is mostly within the uncertainty (see section 4.1) of the measurements. (subset: 8/single/1.8H/VPE)

sheared plasma rotation – changing direction at the separatrix [78] – which could affect the direction the fragments/ablated material is dragged along for different combinations of fragment size & velocity distributions and neon contents.

The high neon content ($\Delta t_{\text{CQ}}^{100 \rightarrow 80} < 1$ ms) but also the 100% D_2 injections ($\Delta t_{\text{CQ}}^{100 \rightarrow 80} > 4$ ms) have S1/S15-asymmetry ratios centered around 1.0 as shown in figure 6.12(b). However, for the 0.17% and 0.085% Ne pellets, a correlation between the early CQ duration and radiation asymmetry is visible. For early CQ durations with $\Delta t_{\text{CQ}}^{100 \rightarrow 80} < 2$ ms, the MFA radiation peak is higher in S1, while for durations > 2 ms it is higher in S15.

Preferred toroidal material/radiation spreading directions are also observed in experiment and simulations for MGI in EAST [295, 296], DIII-D [297, 298], and SPI in JET [39, 40, 299–301]. In the JOREK simulations for EAST, the asymmetry in the toroidal direction is connected to the strength of the electric field during the disruption [295, 296]. The electric field itself depends strongly on η and the early dI_p/dt rate during the CQ, hence is connected to the early CQ duration. Hereby, shorter quench times would result in higher E-fields and a preferred co-current propagation direction, applying the particle-

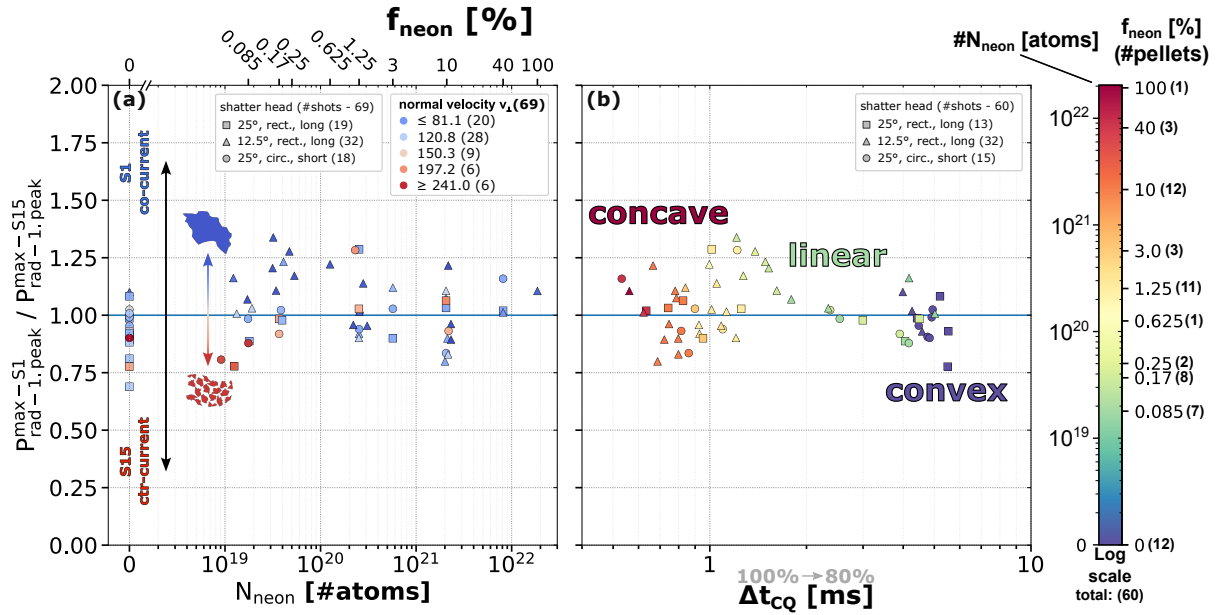


FIGURE 6.12: The asymmetry in radiated power at the main fragment arrival between sector S1 (co-current) and S15 (counter-current direction w.r.t. the injection location). The fragment size (approximated by $v_{\perp}$) seems to influence which of the two sectors shows the highest radiated power: for smaller (& faster) fragments more frequently higher radiation in S1 is observed, whereas increased radiation in S15 is shown for larger (& slower) fragments. The asymmetry as a function of the early CQ duration is shown in (b). (subsets: (a) 8/single/1.8H, (b) 8/single/1.8H/dissr)

picture for the impurities. This may be also in line with the apparent effect of the early CQ duration in the transition from convex to concave CQ-shapes in figure 6.12(b): for the linear CQ-shapes, indeed the shorter $\Delta t_{\text{CQ}}^{100 \rightarrow 80}$ durations show their maximum in the co-current direction compared to the higher durations. However, why the 100% D₂ and high neon fraction pellets do not seem to follow this trend is not yet resolved. Note, that similar observations were also made for the ASDEX Upgrade JOREK simulations described in paper N [51], where the equilibrium toroidal flow is not considered. In figure 21, the radiated power from the simulation is compared to the experimental one. During the TQ in the simulation and the MFA (+ PME) + TQ in the experiment, the radiation in S1 is the highest.

NIMROD simulations by V. Izzo *et al.* [298] suggest a “magnetic nozzle effect” causing asymmetries in the propagation direction for injections below or above the midplane, treating the impurities as a fluid that is rapidly heated to a common equilibrium temperature with the background plasma. However, due to this effect no preferred asymmetries in toroidal direction are predicted for an injection at the midplane (as in our case).

More detailed studies about this asymmetry between S1 and S15 would be necessary to verify if it is a statistically significant trend and investigate the cause of this effect. A first starting point for this may be to analyse the evolution and strength of the electric fields during the disruption in detail.

Toroidal asymmetries during the VDE-phase

As discussed in section 5.2, low neon or 100% D₂ SPI can lead to violent (poorly mitigated) VDEs. Previous studies [302, 303] indicate, that VDEs can be toroidally highly asymmetric, which can translate to large sideways forces. The toroidally distributed shunt

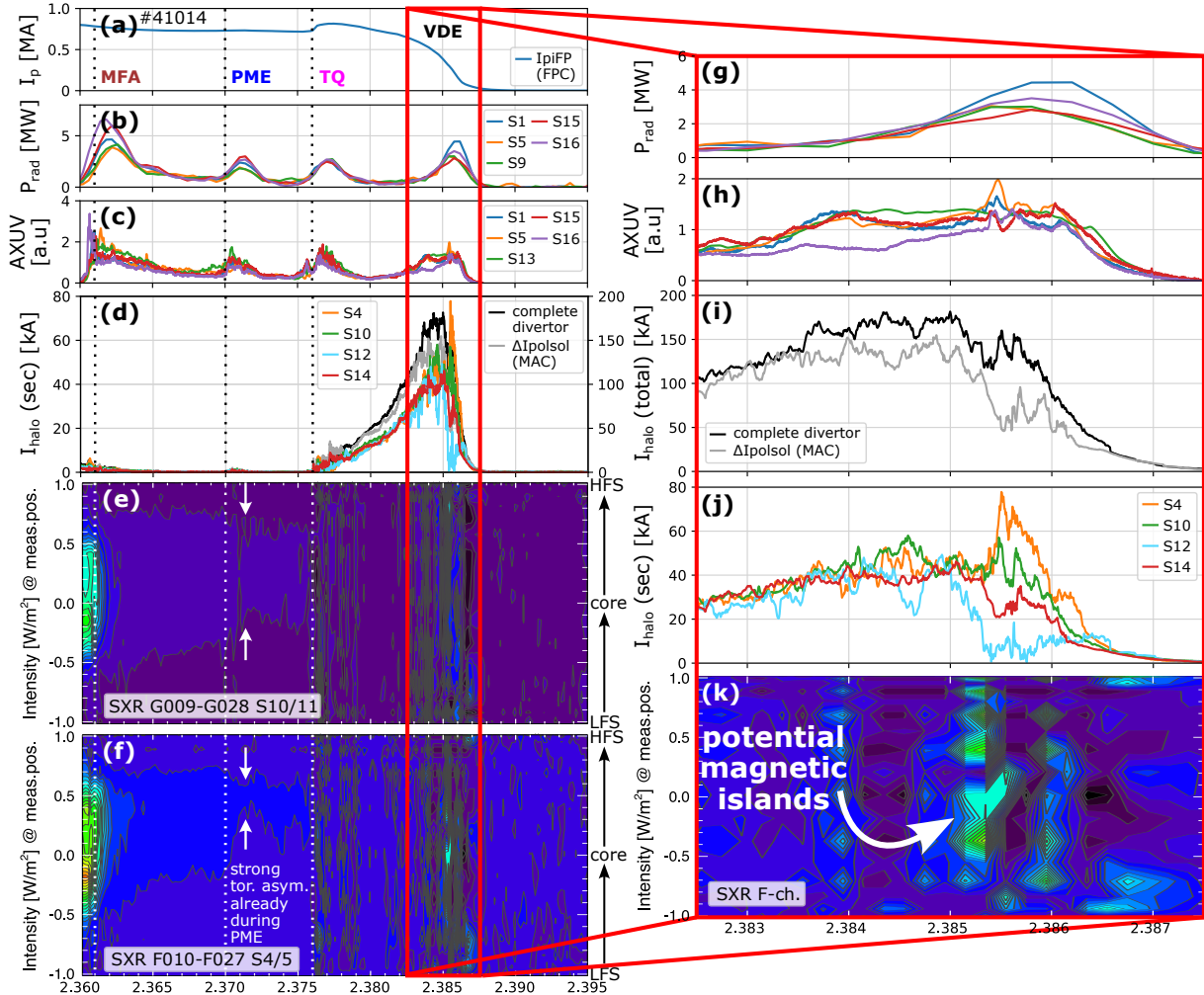


FIGURE 6.13: Asymmetries inside the plasma during the VDE-phase. In (a) plasma current, (b, g) $P_{\text{rad, sector}}$, (c, h) AXUV signals (offset removed – absolute values not comparable!), (d, i) shunt current measurements for the complete divertor, (d, j) shunt current measurements in tiles of different toroidal sectors, and (e, f, k) 2D-mappings of SXR-LOSs in different toroidal locations (see appendix A.15) are provided. As indicated by the SXR measurements in (e, f), the plasma becomes strongly asymmetric during the PME. While the TQ causes a toroidally symmetric radiation peak, the VDE-peak is toroidally asymmetric. This is also indicated by the asymmetries in the shunt current measurements from which I_{halo} is inferred. Around $t = 2.385$ s, potential magnetic islands are visible, while the toroidal asymmetries are the highest. The plots in (e, f, k) were created by M. Maraschek. (#41014 $\in$ 8/single/1.8H/disr/100% D₂)

current and SXR measurements, shown in figure 6.13, can be used as indicators for this asymmetry. During the PME, strong (toroidal) asymmetries arise inside the plasma as indicated by the SXR-LOSs in (e, f). While the radiation peak during the TQ is toroidally symmetric, the radiation during the VDE-peak is not. This matches the observation of toroidally asymmetric shunt current measurements, hence halo currents, around

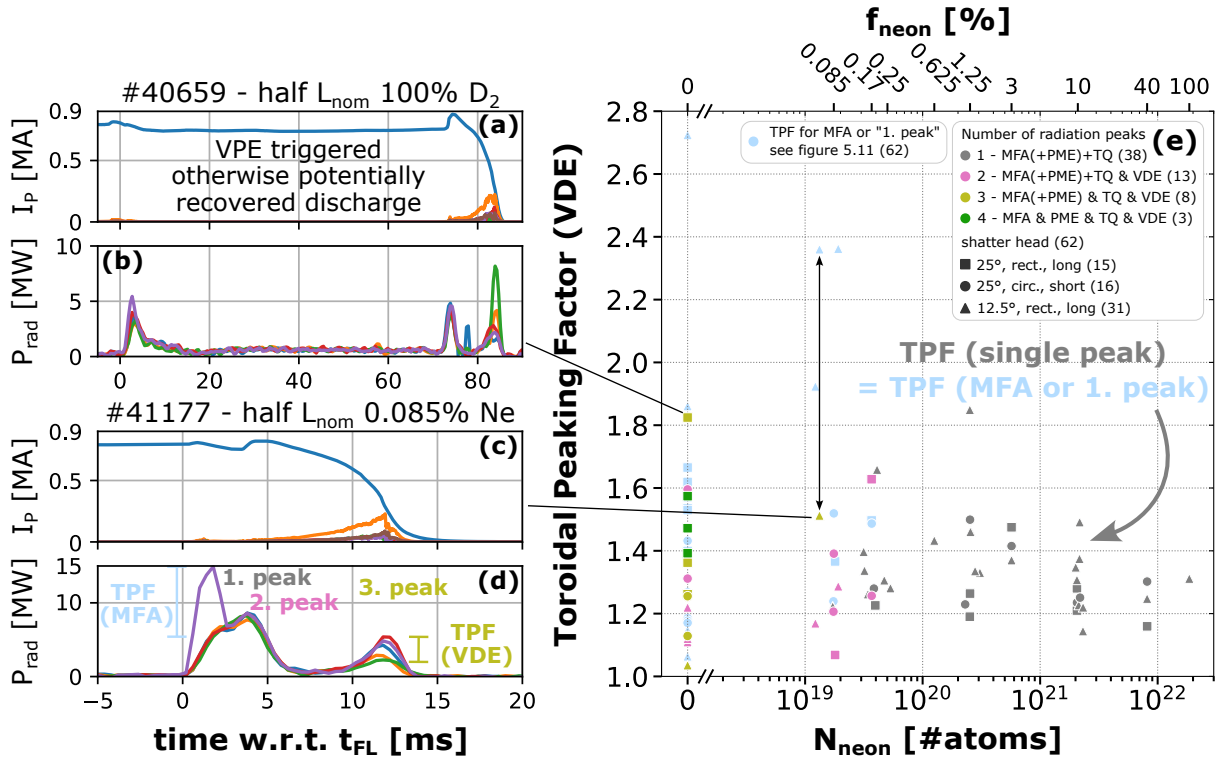


FIGURE 6.14: TPF-value calculated for the last radiation peak (VDE peak) in (e). The colour-coding shows the number of detected peaks via the semi-automatic peak finding algorithm (section 4.1). For $N_{\text{neon}} \gtrsim 4 \times 10^{19}$ (0.25% Ne), only a single radiation peak is detected (gray points), hence the TPF-value of the “last peak” equals the values from figure 6.11. The evolution of (a, c) plasma current and (b, d) radiation for the two discharges #40659 and #41177 are shown in (a)–(d). The disruption in #40659 is most likely triggered by the `VPESState` change (Z_{curr} limit) consequent switch-off of one NBI beam source. Here, the radiation during the VDE phase even exceeds the radiation during the MFA. (subset: 8/single/1.8H/VPPE)

$t = 2.385$ s. During this time, I identified structures inside the SXR measurements, that may indicate magnetic islands inside the plasma. While dedicated studies would be necessary for verification, magnetic islands are expected to appear during this phase as shown by N. Schwarz *et al.* on slide 7 of the [contribution XXVII](#) [304].

Consequently, the radiation measured by the foil bolometers also indicates toroidal asymmetries during the last radiation peak (VDE-peak) for SPI with low neon content. Figure 6.14(a) shows the TPF calculated for the last radiation peak. The colour-coding indicates the number of detected peaks by the semi-automatic peak finding algorithm introduced in section 4.1. Around $3\text{--}4 \times 10^{19}$ neon atoms, the last radiation peak is not prominent enough to be detected (see “radiation plateau” in section 5.2) and only a single radiation peak is observed for the medium to high neon content SPI (gray points for comparison which match the TPF-values from figure 6.08). Hereby, the number of peaks does not correlate to the TPF-values.

For the total toroidal asymmetry, no systematic trends (compare to figure 6.09) for the different toroidal measurement sectors are visible, as illustrated in figure 6.15.

Note, that the amplitude of the last radiation peak does not necessarily correspond directly to the severity of the VDE which is characterised by the forces and heat loads on the

PFCs. However, in general, the amplitude of the VDE-peak is decreasing with increasing neon content until only the single MFA (+ PME) + TQ radiation peak is visible. It is expected that in cases with a high VDE-peak, the plasma is still hot enough to cause a lot of radiation as the impurities from the wall-contact enter the plasma, however, a dedicated heat load analysis had not been performed to verify this assumption.

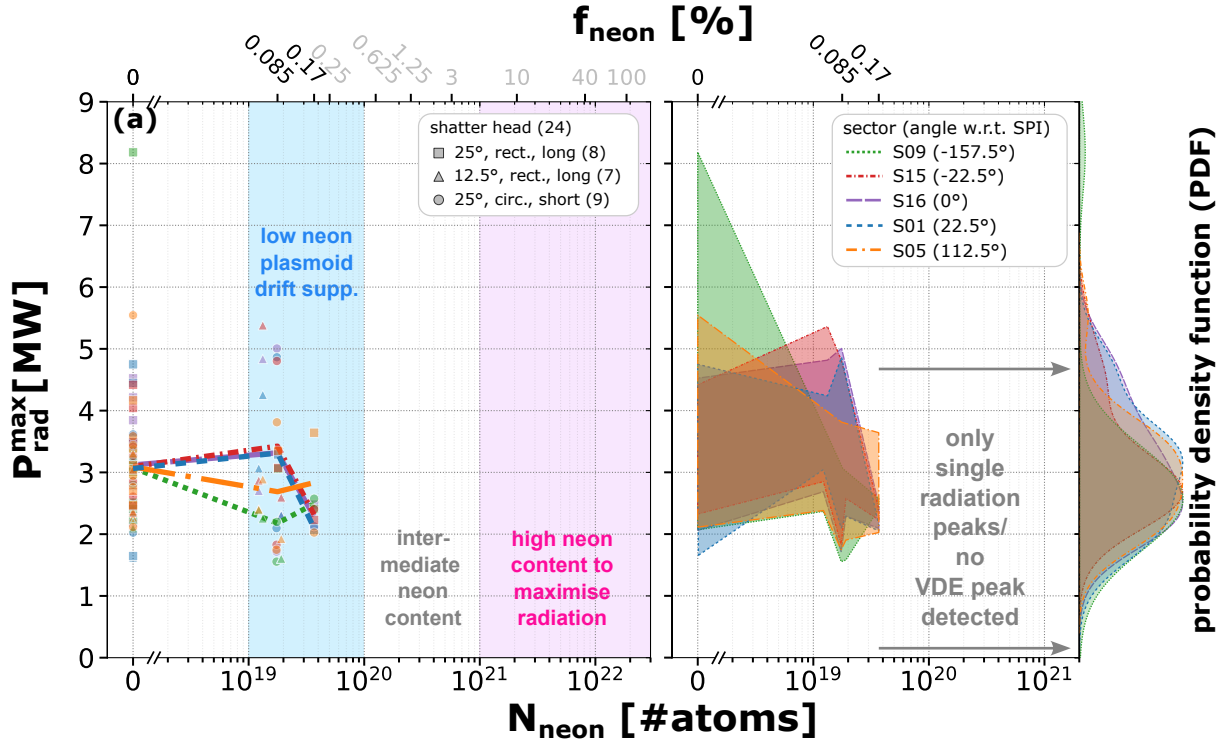


FIGURE 6.15: Peak radiated power in each sector as a function of N_{neon} for the “VDE/last peak”. The same representation is used as in figure 6.09. For pellets with $N_{\text{neon}} \approx 4 \times 10^{19}$ atoms (0.17% Ne), the VDE peak was below the detection threshold and a single radiation peak is visible (see figure 5.07). (subset: 8/single/1.8H/VPE with #peaks > 1)

6.3 Comparison of experiments with simulations

To finish this chapter, I want to provide an overview on the different effects of fragment size & velocity distributions for the different contexts.

An overview table for the experiments as well as the INDEX & JOEREK AUG SPI simulations is given in figure 6.16. Hereby, the icons of the different fragment sizes indicate the “optimum” for the given entry. While e.g. maximising f_{rad} is most relevant for pellets with a high neon fraction, also the low neon/100% D_2 injections are provided for completeness. I will focus in the following on the most relevant parts for a successful disruption mitigation which are indicated by the boxes.

As expected, maximising f_{rad} requires high neon fractions $> 1 \times 10^{21}$ Ne atoms ($f_{\text{neon}} \geq 10\%$ for 8 mm) indicated by the red box. Within the experimental uncertainties, high $v_{\perp}$ may be optimal in the experiment. Whether this is due to smaller fragment sizes or the increased v_{fragment} is at present not confirmed. However, this matches the observation in the JOEREK simulations from paper N [51], where smaller fragments were observed to increase f_{rad} .

		100% D ₂	< 1% Neon	≥ 10% Neon	V _{fragment}
goal		D ₂ assimilation for suppression of REs	plasmoid drift suppr. for higher D ₂ assim.	max. radiation for heat load mitigation	
f _{rad}	Exp.	fig. 6.06c 	fig. 6.06c 	fig. 6.06c 	fast fig. 6.06c
	INDEX				fast [C]
	JOIREK		 =  [N] no difference	 [N]	fast [N]
assimilation	Exp.	 * [XVI]	fig. 5.10b  † [XVI]	fig. 5.10b  ? † minor Δt _{CQ}	fast [XVI]
	INDEX	 [C]	unclear  ? [C]	 [C]	fast [C]
	JOIREK		 [N]	 =  [N] no difference	fast [N]

*CO₂-laser density measurements
†inferred from
Δt_{CQ} → f_{assi, neon} → f_{assi, D₂}

FIGURE 6.16: Overview of the fragment size & velocity effect on the material assimilation and f_{rad}. It follows my observations for f_{rad} (figure 6.06(c)), the material assimilation (estimated via Δt_{CQ}^{100→80} in figure 5.10(b)), and the results obtained from our team discussed in papers C [49], N [51] and contributions XXII [117], XVI [121]. (subset: comparison for 8/single/1.8H)

For the suppression of the RE-beams, a high assimilation of D₂ is required. In the experiment [117, 121] and also INDEX simulations (paper C [49]), larger fragments resulted in higher f_{assimilated} (blue box).

For the neon doped pellets – which should suppress the plasmoid drift effect – the trends are not quite clear. In the experiment, larger fragments lead to lower early CQ durations, which indicates that the neon inside the pellet is better assimilated inside the plasma. Assuming that the majority of the pellet material – the D₂ inside the pellet – will also follow this trend, lower values of v_⊥ (larger & slower) seem beneficial. However, in the JOIREK simulations, smaller fragments are observed to have an increased assimilation fraction for the 0.12% neon doping. In paper N [51], an inaccurate modeling of the plasmoid drift and rocket effect are discussed as potential reasons for this discrepancy.

Regarding the effect of v_{fragment}, the experiment and both simulation codes suggest that faster fragments are beneficial to increase material assimilation and radiated energy fractions.

Chapter 7

Summary & outlook

The shattered pellet injection technique is a promising candidate for future large fusion experiments & power plants, and will be employed for the disruption mitigation in ITER. It can quickly deliver large amounts of material to the plasma core, necessary for a reliable disruption mitigation. In this thesis, I have provided an overview on the ASDEX Upgrade SPI project (commissioning, experiments, and modelling) and discussed the SPI experiments that had been performed in 2022 in detail. I will first summarise these results before providing a brief outlook on the upcoming experimental campaign in 2025 at the end of this chapter.

The ASDEX Upgrade SPI system Our AUG SPI system was built with a high system flexibility to study the effect of varying pellet and fragmentation parameters on the disruption behavior & mitigation efficiency. The three independent cold cells and guide tubes allow the injection of multiple synchronised or staggered pellets. Additionally, it allows to also test up to three different shatter head geometries during one experimental campaign at AUG without the need of a vessel opening. The high automatisisation of the systems allows for highly reproducible pellet mixing and launching: pellets of 100% D₂ or Ne and D₂-Ne-mixtures were used in 2022 and the pellet velocities often within a few m/s to the target value were achieved.

To investigate the effect of the fragment distributions on the disruptions, we recorded about 1100 shattering videos during an extensive laboratory testing phase. We observed that for our system, the rectangular shatter head geometries have a more collimated fragment plume compared to the circular counter-part which can cause spiral patterns in the fragment plume and has a probabilistic effective shatter angle.

Analysing the 4 mm pellets from our laboratory phase, T. Peherstorfer [230] found a significant deviation of experimental fragment size distributions compared to the widely applied probabilistic shattering formula based on the Parks-model [211, 212]. However, a good agreement to peridynamic simulations was observed [41–46].

By analysing the recordings of our optical pellet diagnostic and discussions with the CER-team, we obtained valuable insights of the pellet quality aspects during the pellet generation. With this, we were able to develop pellet generation recipes that could assure high pellet quality for the experiments.

We created pellet launching recipes during the laboratory phase and on non-shot days after the system was transferred to AUG. With the help of these recipes, we could achieve a high system reliability during the 2022 experimental campaign with a rate of successfully injected pellets of 84.4% (see appendix A.7).

For this, I developed a pellet detachment model based on the experience of almost 2000 launched pellets until the end of the experiments in 2022. This model connects the different detachment states of the pellet with the propellant gas pressure used to launch the pellets and a simplified heating power indicator. With this, I was able to extrapolate to new pellet recipes within seconds to minutes even during changes in schedule on the shot

day. Thereby, I was able to shortcut days over days of trial-&-error recipe development that would be necessary otherwise.

Disruption behavior of SPI-induced disruptions The main objective of the AUG plasma experiments was to investigate the effect of different pellet and fragmentation parameters on the SPI-induced disruptions. I characterised their behavior by identifying different disruption phases. With the help of these phases, I compared the disruption evolution for changing neon content or fragment size & velocity distributions. Hereby, a continuous transition from convex $\rightarrow$ linear $\rightarrow$ concave CQ shapes with increasing assimilated neon content occurs (connected to the transition from conduction $\rightarrow$ radiation dominated disruptions). The early CQ rate ($\Delta t_{\text{CQ}}^{100 \rightarrow 80}$) before the VDE phase of the discharge is set by the amount of assimilated neon in the plasma, consequently comparing these shapes can already indicate the effectiveness in assimilating neon in the plasma.

I observed, that the disruption behavior shows the highest sensitivity to the fragmentation process in the range of minor neon doping ($< 1 \times 10^{20}$ neon atoms or $f_{\text{neon}} \leq 0.25\%$) matching the observations of DREAM modeling for the AUG SPI [50]. In the same range, also the largest effect of the fragmentation process is visible on the material assimilation with larger (& faster) fragments being optimal [117, 121] which is also reflected in shorter pre-TQ and early CQ durations. However, I identified potential roll-over effects, where the higher mean fragment velocities may dominate over smaller fragment sizes.

For 100% D₂ injections, up to four radiation peaks are visible in the foil bolometers that are connected to each of these disruption phases: the main fragment arrival (MFA), plasma movement event (PME) (break-up of flux surfaces and consequent loss of plasma pressure), TQ, and the VDE phase. With increasing neon content, the pre-TQ and CQ durations decrease. First, up to two radiation peaks are visible: MFA (+ PME) + TQ & VDE. The amplitude of the VDE peak decreases with increasing neon assimilation until only a single radiation peak remains detectable via the foil bolometers.

For 100% D₂ injections with less than 1×10^{22} D₂ molecules, the SPI H-mode scenario does not disrupt, matching the expected increased MHD activity for this parameter range [282].

Radiation analysis for the SPI-induced disruptions With the help of the foil bolometers sharing the same viewing geometry, I calculated the radiated energy fractions and toroidal radiation asymmetries. I expanded the usual definition of f_{rad} [19, 160, 162] by an additional term W_{heat} which takes into account the post-injection external heating sources. As expected, the radiated energies increase with increasing neon content in the pellets. Hereby, f_{rad} saturates at around 80% for injections with 2×10^{21} neon atoms ($f_{\text{neon}} = 10\%$ neon for 8 mm pellets), while the early pre-TQ duration continues to decrease exponentially. Non-disruptive injections had f_{rad} -values below 30%, while the radiation during the TQ + VDE phases of disruptive injections increase it to $\approx 40\%$.

With the help of a heuristic fit function for f_{rad} , developed by J. Artola, the effect of the shatter head geometry and fragment size effect is illustrated. The overall highest f_{rad} -values are observed for the **12.5°, rectangular shatter head geometry** which produces the largest & fastest fragments for a given pre-shattering pellet velocity. The largest effect of the shattering parameters are again observed for the low neon doping range ($< 1 \times 10^{20}$ neon atoms or $f_{\text{neon}} \leq 0.25\%$) as already observed for the material assimilation and disruption behavior: larger fragments seem to maximise f_{rad} . However, I observed a potential change in the $v_{\perp}$ -trends for neon contents above 1×10^{21} atoms ($f_{\text{neon}} = 10\%$ neon for 8 mm pellets). Within the uncertainties of inter-shot comparisons,

a minor increase of f_{rad} for increasing $v_{\perp}$ (smaller & faster fragments) may be indicated. Whether this could be caused by the diverging fragment size to fragment velocity effect for high values of $v_{\perp}$ or smaller fragments assimilating the neon content faster as indicated by the JOREK and INDEX simulations will require additional studies.

As the foil bolometers are installed in five different toroidal locations with four poloidally distinct channels, the poloidal and toroidal asymmetries can be assessed. I observed the highest poloidal and toroidal asymmetries at the MFA for the pellets with 100% D₂ and low neon doping. As deuterium will mostly contribute to the radiation pre-ionization, neon can radiate strongly as it spreads (partially ionised) along the field lines. With increasing neon content, the poloidal asymmetry as well as the toroidal peaking factor is decreasing. This observation – together with the decision of the ITER organization to change the FW material to tungsten – reduces the fear of “flash-melting” for pellets with high neon content. Also, a similar TPF-value is observed for single and synchronised/staggered injections. Note, that the TPF does only indicate the toroidal peaking, not necessarily the toroidal asymmetries. While the TPF decreases with increasing neon content, the toroidal asymmetries (i.e. the S5-S9-asymmetry) increases.

For the two neighboring sectors of the injection location (S1 and S15), the radiation is not equally distributed. When comparing the neon doped injections, lower values of $v_{\perp}$ tend to show higher radiation in the co-current (and co-plasma rotation direction in the edge), whereas lower $v_{\perp}$ -values seem to show higher radiation in the counter-current direction. This may be connected to the sheared plasma rotation profile at the separatrix as smaller (but faster) and larger (but slower) fragments may have different penetration characteristics. For the low neon doped pellet in the transition from convex to linear CQ-shapes, I also observed a connection to the early CQ duration, which may be in line with observations from modelling of MGI for EAST [295].

Outlook

In total, the first SPI experiments at AUG in the 2022 experimental campaign had a significant impact on the design decisions for the ITER DMS. Given the benefit of larger & faster fragments produced by the 12.5°, rectangular shatter head geometry on the material assimilation and radiated energy fraction, the present design choice for the ITER midplane injectors foresees a rectangular shattering unit with the shallowest possible angle of 15.5° for the given design space [109, 220].

Another aspect is the reduced fear of so-called “flash-melting” given my results (and those from other experiments) regarding the toroidal peaking during the MFA, playing alongside with the decision to change the FW material to tungsten [11, 12].

All of this is a combination of physics understanding – which can be obtained from well diagnosed experiments like ASDEX Upgrade – but also the modelling efforts that go alongside these experiments. This is highlighted by the AUG SPI project, in which experiment and modelling are strongly coupled: valuable insight for the data interpretation are obtained from modelling and on the other hand, these codes are validated and enhanced by the experimental output. Ultimately what scales to ITER are not the measurement values from AUG directly but the physics understanding embedded into scalings and codes capable of extrapolating to ITER.

But the SPI project at ASDEX Upgrade is far from being finished: after the two year operational break of ASDEX Upgrade between 2022–2024 to install the new upper divertor,

the SPI system was successfully re-commissioned and first injections into plasmas were performed on December 12th, 2024.

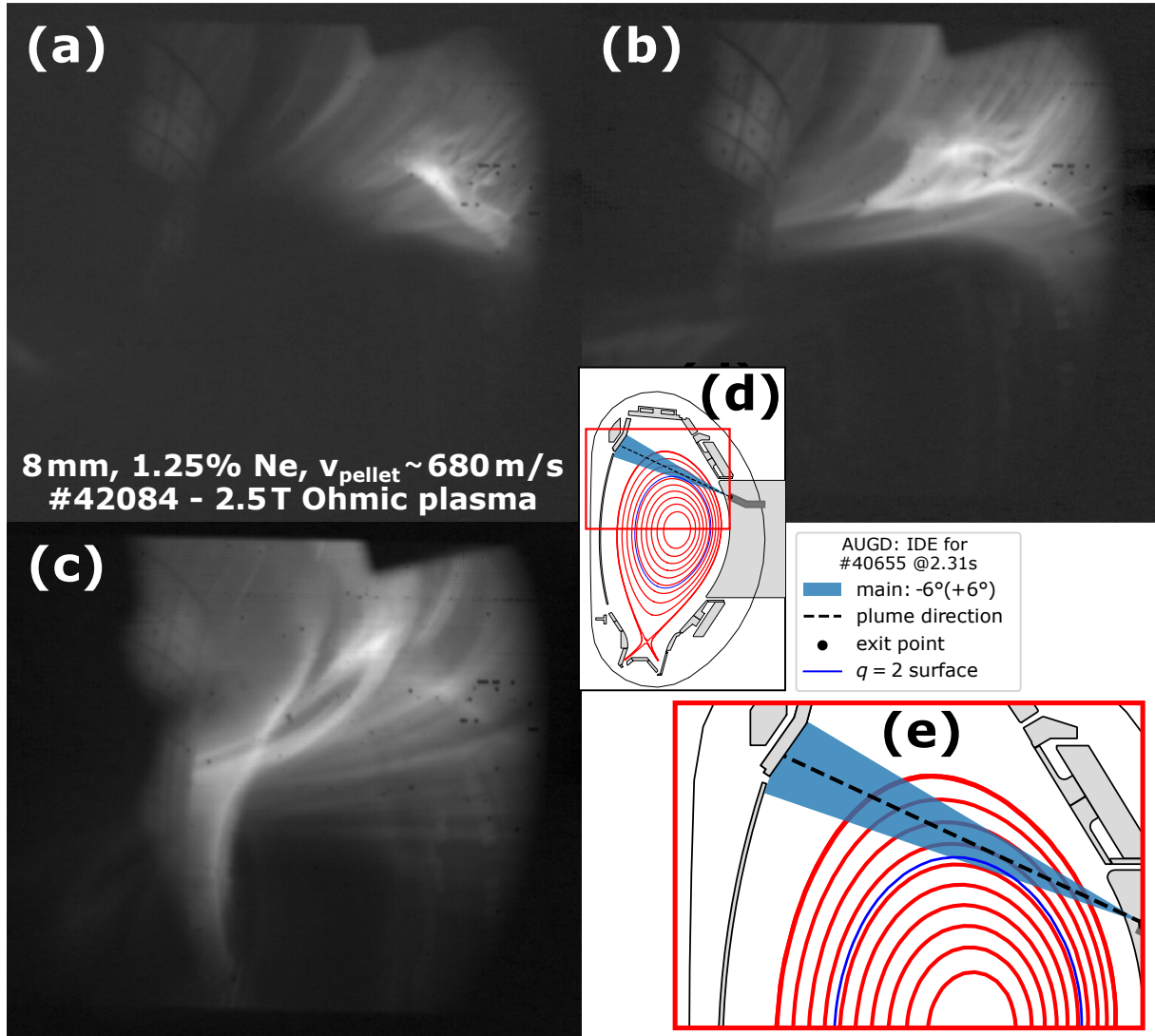


FIGURE 7.01: The first injection of a $f_{\text{neon}} = 1.25\%$ Ne pellet via the upwards-directed shutter head on December 12th, 2024. (a)–(c) show the injection recorded by a UHS camera (different view compared to 2022 experiments as indicated in (d) & (e)). While intentionally missing the $q = 2$ rational surface, it still caused a disruption. The plots in (d) and (e) are created by P. Haldestam.

For the first time at ASDEX Upgrade, a 100% D₂ pellet had been injected into a RE-beam during the benign termination studies. Additionally, a 1.25% Ne pellet was injected via the upwards-directed 25°, rectangular shutter head (see figure 7.01). Even though the main fragment plume seemed to miss the $q = 2$ rational surface as intended, the plasma disrupted. Hereby, the radiating region seemed to bend downwards around the upper edge of the plasma following the poloidal flow direction in the SOL. While these discharges will soon be studied in more detail, this already gives hope that missing the $q = 2$ in case of late upper-port injections in ITER may still contribute to the disruption mitigation. The new dispersion interferometer [267] will provide new insights into the fragment ablation processes, that are otherwise difficult to assess quantitatively.

Finally, another big puzzle piece is to test the sensitivity of the synchronised and staggered injection schemes – i.e. delayed fragment arrival in the plasma. For this, the independent guide lines and two identical 12.5° , rectangular shatter heads pointing downwards will play a key role.

At this point I want to gratefully pause for a second to recognise & value what we as a team had achieved in the past years and I am looking forward to contribute to the upcoming experiments and the ITER disruption mitigation system.

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Appendix A

Appendix

A.1 Cut-off frequency for ECE-measurements

The cut-off density is given as [116]

$$n_{\text{crit}}^{X,l} = l(l-1) \cdot \frac{\epsilon_0}{m_e} \cdot \mathbf{B}^2 \Rightarrow n_{\text{crit}}^{X2} = 1.94 \times 10^{19} [\text{m}^3\text{T}^{-2}] \cdot \mathbf{B}^2, \quad (\text{A.01})$$

with vacuum permittivity (ϵ_0), electron mass (m_e) for the X-mode of order l . For our typical magnetic fields strengths of 1.8 T (on axis), the cut-off frequencies of the X2 mode (typically observed [116]) are in the order of $\approx 6.3 \times 10^{19} [\text{m}^3]$, which is often reached in the pre-disruption phase of the plasma (compare figures 4.07b – II and 4.08b – II).

A.2 Mapping of the Barrels

(...) in flight dir.	(left) GT1	GT3 (top)	(right) GT2
8 mm inner diameter			
FV1 (left)	B1	–	–
FV2 (mid)	–	B2	–
FV3 (right)	–	–	B3

TABLE A.01: Mapping of the FVs to the different GTs via the 8 mm barrels. While the barrels for the 1, 2, and 4 mm pellets are flexible, the 8 mm barrels only allow the dedicated mapping shown in this table. In total, the following number of barrels is available: 1×1 mm, 1×2 mm, 3×4 mm, 3×8 mm. More details about the mapping and numbering conventions are available in the report by G. Papp [221]

A.3 Accidental pellet creation

In one case (denoted as “174 + 1” in table 3.03), it was planned to test an injection without a pellet as a reference. The expectation was to see no effect since $\sim 99.96\%$ of the propellant gas are removed [29]. However, the discharge (#40929 – pellet ID #1880) disrupted and we observed a pellet in the OPD recording. We used the central GT for this test, that was not planned to be used on that shot day. Therefore we did not explicitly close the gate valve between the unused barrel and the expansion tank after pumping.

When the pellet gas is pumped away after a pellet creation, the gate valve towards the expansion volumes is opened to remove the residual gas in the systems. The creep-flows of the gas from the two side barrels into the first expansion volume and back into the central barrel was apparently enough material to build up a pellet over the time of the entire shot day. Afterwards, the test was repeated, this time without a pellet as expected.

A.4 VPEStates of the DCS

The different VPEState-values as taken from the DCS [305].

```
<MODULE name="trajectories">
<DECLARATIONS>
<SWITCH name="sw:Con/VPE/State" type="uint32_t">
<SETTING name="idle" value="0"/>
<SETTING name="hold" value="1"/>
<SETTING name="plasma_to_circ" value="2"/>
<SETTING name="plasma_to_zero" value="3"/>
<SETTING name="ff_to_zero" value="4"/>
<SETTING name="decay" value="5"/>
<SETTING name="done" value="15"/>
</SWITCH>
```

A.5 Bug in foil bolometer channels

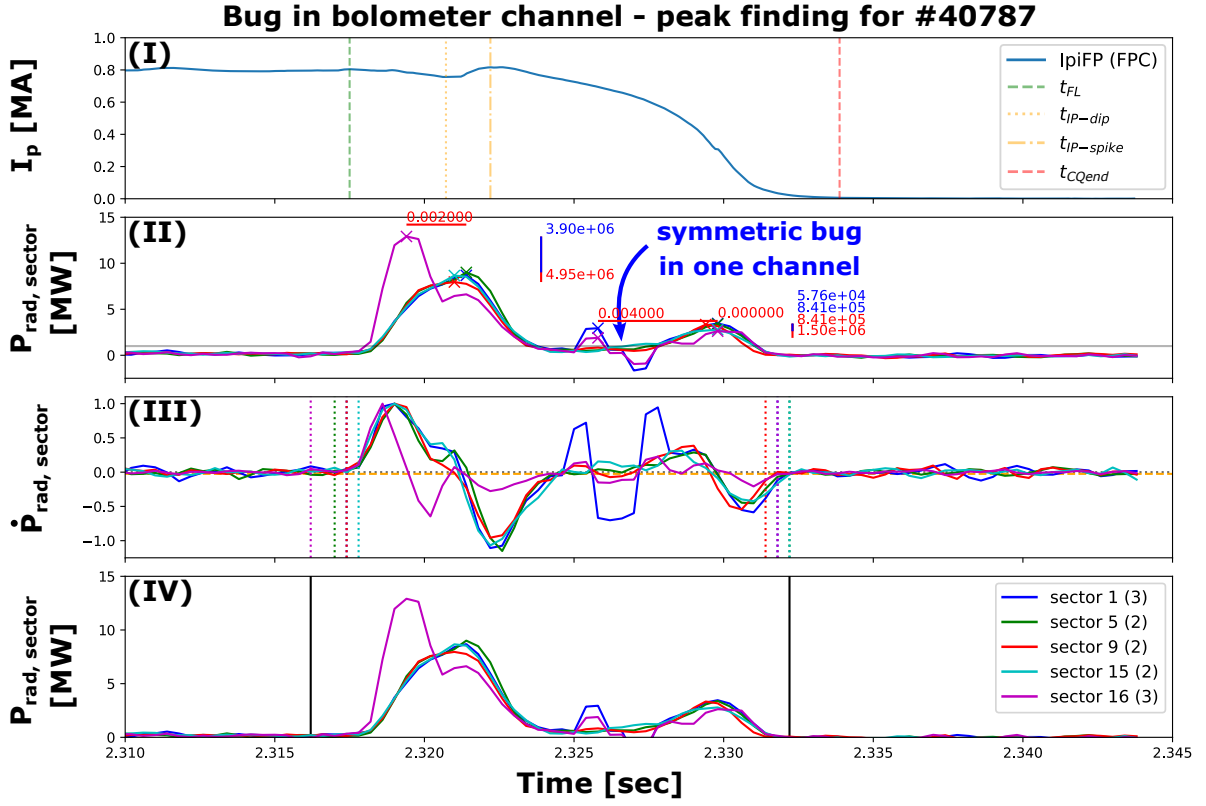


FIGURE A.01: Bug in the foil bolometer $P_{rad, sector}$ -signals. The up/down-symmetric bug in the measurements does complicate the peak finding process and consequently often excluded from the analysis. However, the values of W_{rad} are not affected, as integrating over time this bug disappears due to it's symmetry.

A.6 Subsets of the 2022 SPI discharges

Possible injection schemes: *single*, *early pellet*, *dual (sync./staggered)*, *dual with early pellet*

Target plasmas in 2022: *SPI H-mode*, *Ohmic*, *2.5T H-mode*, *low T_e* , *High W_{plasma}*

Disruptions with a pre-IP-spike VPE and the two MGI triggered disruptions are often filtered out – SPI caused disruption is **True** if no pre-IP-spike VPE is observed in case of a disruption.

Signals are tagged as *corrupted foil bolometer signals* if they either show invalid signals or have large bugs as shown in appendix A.5.

Subset name	D [mm]	SPI scheme	detachm. state (figure 3.14)	target plasma	VPEState- change or MGI	SPI caused disruption	corrupted foil bolo. signals	#pellets / #discharges
full dataset	4/8	all	all	all	✓/✗	✓/✗	✓/✗	270/227
4+8/single	4/8	single	1, 3, 4	all	✗	✓/✗	✗	112/112
4+8/single/VPE	4/8	single	1, 3, 4	all	✓/✗	✓/✗	✗	121/121
4+8/single/1.8H/VPE	4/8	single	1, 3, 4	SPI H-mode	✓/✗	✓/✗	✗	98/98
8/single/1.8H	8	single	1, 3, 4	SPI H-mode	✗	✓/✗	✗	69/69
8/single/1.8H/VPE	8	single	1, 3, 4	SPI H-mode	✓/✗	✓/✗	✗	75/75
8/single+dual/1.8H/VPE	8	single+dual	1, 3, 4	SPI H-mode	✓/✗	✓/✗	✗	99/87
4+8/single/1.8H	4/8	single	1, 3, 4	SPI H-mode	✗	✓/✗	✗	90/90
8/single/1.8H/distr	8	single	1, 3, 4	SPI H-mode	✗	✓	✗	60/60
8/single/1.8H/distr/VPE	8	single	1, 3, 4	SPI H-mode	✓/✗	✓	✗	66/66
8/single/1.8H/distr/corr	8	single	1, 3, 5	SPI H-mode	✗	✓	✓/✗	84/84

TABLE A.02: Subsets used throughout this thesis for analysis and displayed plots.

A.7 Success rate of pellet launches

detachment state	#pellets
successful	222
single early pellet	8
sync./staggered with early pellet	$1 \times \text{both early} + 1 \times \text{one early} = 3$
early pellet into the torus gate	4
stuck pellets (none arrived in plasma)	12
one of two pellets stuck	8
broken pellets	5
accidental pellet (see A.3)	1
success rate	$227/263 = 84.4\%$

TABLE A.03: Number of successful pellet launches compared to issues in pellet launching (issues in discharges not listed). Overall a high success-rate of 84.4% is achieved due to the high system reliability, experience and recipe development for each planned pellet realisation. Note, pellets counted as “not successful” like e.g. broken or early pellets may still be useful for the analysis as shown by P. Lang *et al.* [198]

A.8 Neutral pressure increase during SPI-induced disruption

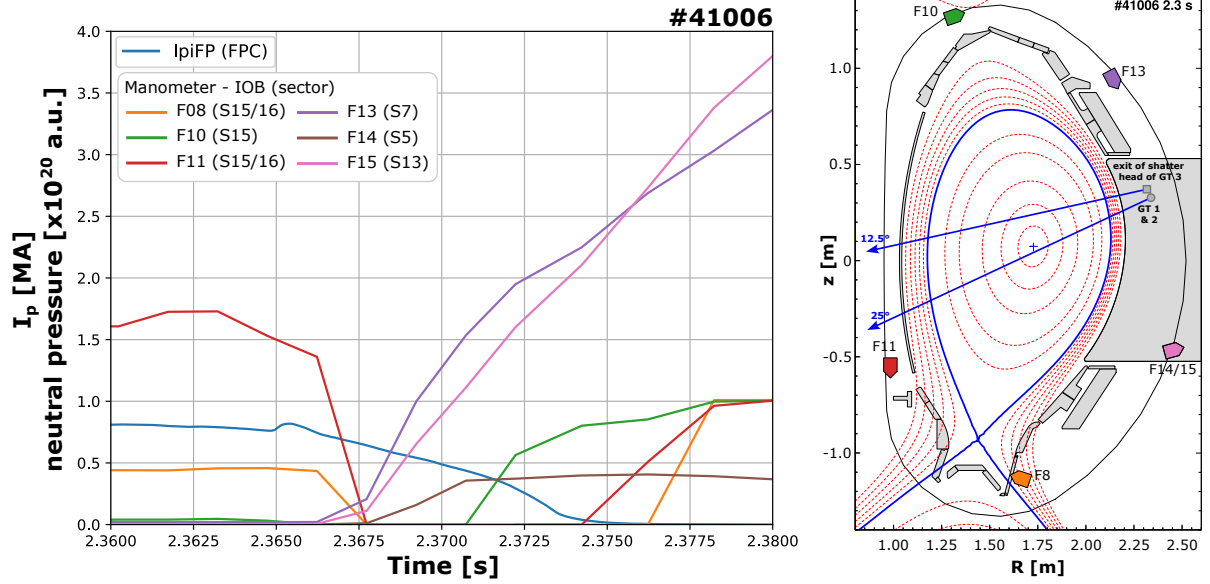


FIGURE A.02: Plasma current and manometers measurements (indicating the neutral pressure).

A.9 D_α filters for UHS cameras at AUG

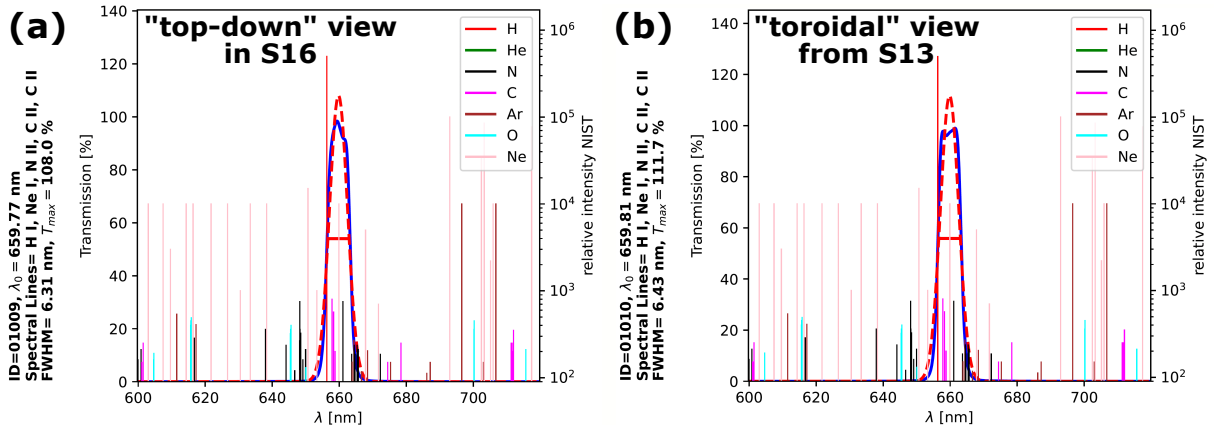


FIGURE A.03: Spectral specifications of the D_α -filters applied to the UHS camera views from figure 4.04(a, b) to prevent saturation. Image also included in an ITER report by G. Papp [306].

A.10 IP-spike-values during SPI-induced disruptions

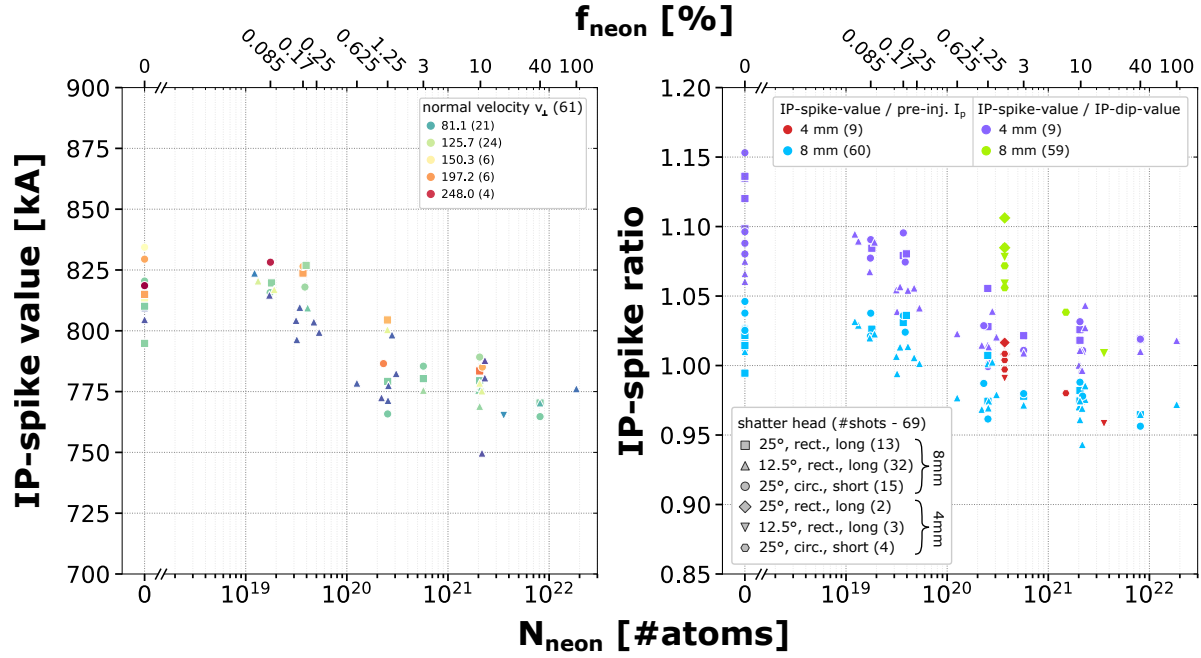


FIGURE A.04: IP-spike-values of the disruptions. In (a) the absolute values are shown as a function of N_{neon} and with colour coding $v_{\perp}$. The relative IP-spike-fractions w.r.t. the average pre-disruption plasma currents and the IP-dip-values are shown in (b). With increasing neon content in the pellet the IP-spike-value decreases, alongside with a decreasing pre-TQ and CQ duration as shown in figure 5.07(f, g). IP-spike-values of up to 105% of the pre-injection average or 115% of the IP-dip-value are visible for 100% D_2 , whereas the IP-spike is below the initial I_p value for injections with $\approx 4 \times 10^{20}$ Ne atoms.

A.11 Current quenches of 4 mm pellet injections

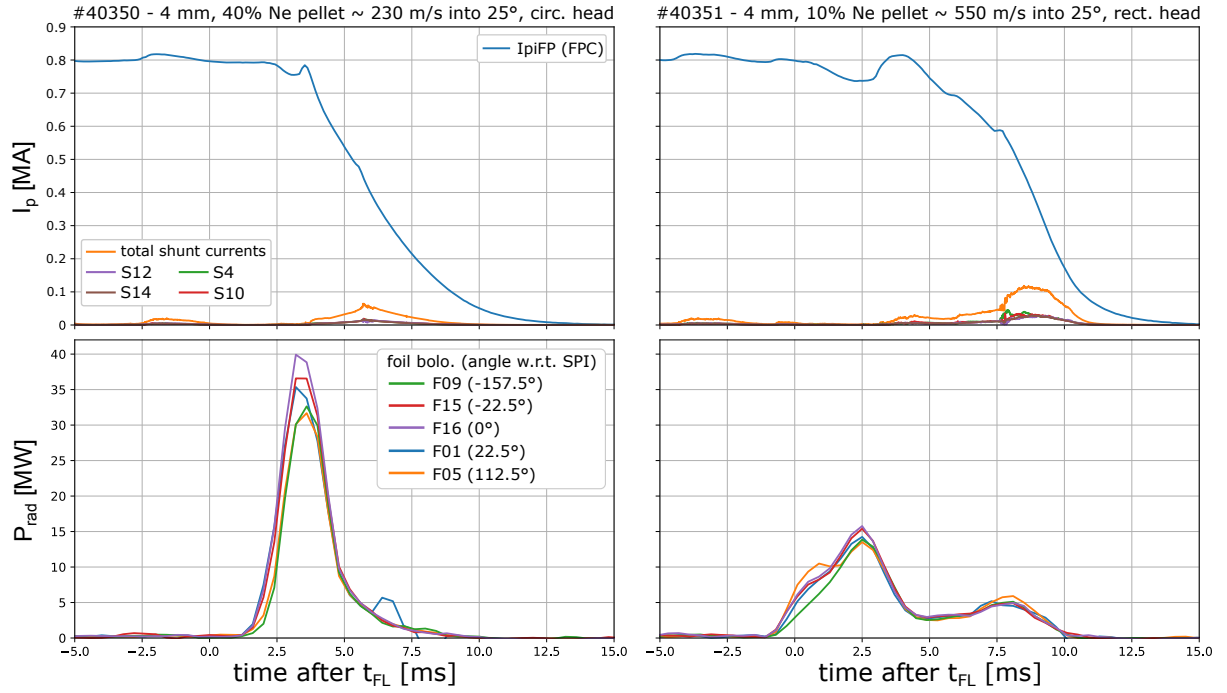


FIGURE A.05: Injection of 4 mm pellets with (a) 40% and (b) 10% Ne. The 40% Ne injection showed a similar behaviour compared to the 8 mm pellets with 10% Ne, which share a similar total amount of N_{neon} . While the 4 mm, 10% Ne pellet has a comparable N_{neon} to a 8 mm, 2% Ne pellet (see figure A.04(b)), the disruption seems to have a more violent CQ phase which may be connected to the VDE behaviour.

A.12 Fitting parameters for f_{rad}

TABLE A.04: The fit parameters **a** and **b** from figure 6.05 with their errors (least squares residual). In figure 6.05(a), **b** was fixed to 6.57×10^{19} , hence lower values of **a** are optimal. A direct comparison of fit parameters for figure 6.05(b) is **not** recommended as **a** and **b** are not orthogonal to each other. Fitting was done with the `scipy.optimize.curve_fit` package and the errors calculated as `np.sqrt(np.diag(pcov))` [290]. Table published in paper A [52].

fit number	a param.	a error (in %)	b param.	b error (in %)
figure 6.05(a) – shatter geometry effect – $\ddagger$ fixed parameters				
(t) (total; black)	1.81×10^{19}	1.23×10^{18} (6.8%)	6.57×10^{19}	6.70×10^{18} (10.2%)
① (25° rect.)	2.17×10^{19}	1.54×10^{18} (7.1%)	$6.57 \times 10^{19\ddagger}$	–
② (25° circ.)	1.91×10^{19}	1.50×10^{18} (7.9%)	$6.57 \times 10^{19\ddagger}$	–
③ (12.5° rect.)	1.67×10^{19}	4.79×10^{17} (2.9%)	$6.57 \times 10^{19\ddagger}$	–
figure 6.05(b) – shatter geometry effect – open parameters				
① (25° rect.)	2.73×10^{19}	3.77×10^{18} (13.8%)	9.52×10^{19}	2.00×10^{19} (21.0%)
② (25° circ.)	2.15×10^{19}	3.37×10^{18} (15.7%)	8.14×10^{19}	2.08×10^{19} (25.6%)
③ (12.5° rect.)	1.50×10^{19}	9.32×10^{17} (6.2%)	5.48×10^{19}	4.97×10^{18} (9.1%)
figure 6.06(a) – normal velocity $v_{\perp}$ effect – open parameters				
① (low $v_{\perp}$)	1.42×10^{19}	1.39×10^{18} (9.8%)	5.00×10^{19}	7.37×10^{18} (14.7%)
② (medium $v_{\perp}$)	1.85×10^{19}	1.60×10^{18} (8.6%)	6.74×10^{19}	8.19×10^{18} (12.2%)
③ (high $v_{\perp}$)	2.82×10^{19}	5.08×10^{18} (18.0%)	1.13×10^{20}	3.71×10^{19} (32.8%)

A.13 Radiated energy fractions for the 10% Ne injections

pellet ID – discharge	shatter head	v_{pellet} [m/s]	$v_{\perp}$ [m/s]	v_{fragment} [m/s]	f_{rad}
#1923 – #40990	12.5°, rect.	212.8	46.1	210.3	0.85
#1915 – #40952	12.5°, rect.	591.0	127.9	584.0	0.82
#1914 – #40951	25°, circ.	457.3	193.3	435.9	0.82
#1913 – #40950	25°, rect.	505.1	213.5	481.5	0.81
#1972 – #41197	12.5°, rect.	631.4	136.7	623.9	0.8
#1895 – #40938	12.5°, rect.	436.3	94.4	431.1	0.8
#1893 – #40937	12.5°, rect.	436.4	94.5	431.2	0.78
#1695 – #40671	12.5°, rect.	471.1	102.0	465.5	0.78
#1928 – #40997	12.5°, rect.	197.6	42.77	195.3	0.78
#1698 – #40674	25°, circ.	252.9	106.9	241.1	0.77
#1912 – #40949	12.5°, rect.	214.6	46.5	212.1	0.77
#1697 – #40673	25°, rect.	221.3	93.5	210.9	0.76

TABLE A.05: 10% Ne pellets from figure 6.06(c) ordered by descending f_{rad} -values. A larger fraction of pellets with higher values of $v_{\perp}$ (and also higher values of v_{fragment}) are in the top half of the table, indicating a potential minor effect, that would be opposite to the trend for neon doped pellets ($f_{\text{neon}} < 1\%$ Ne).

A.14 Poloidal radiation tracking with the AXUV diodes

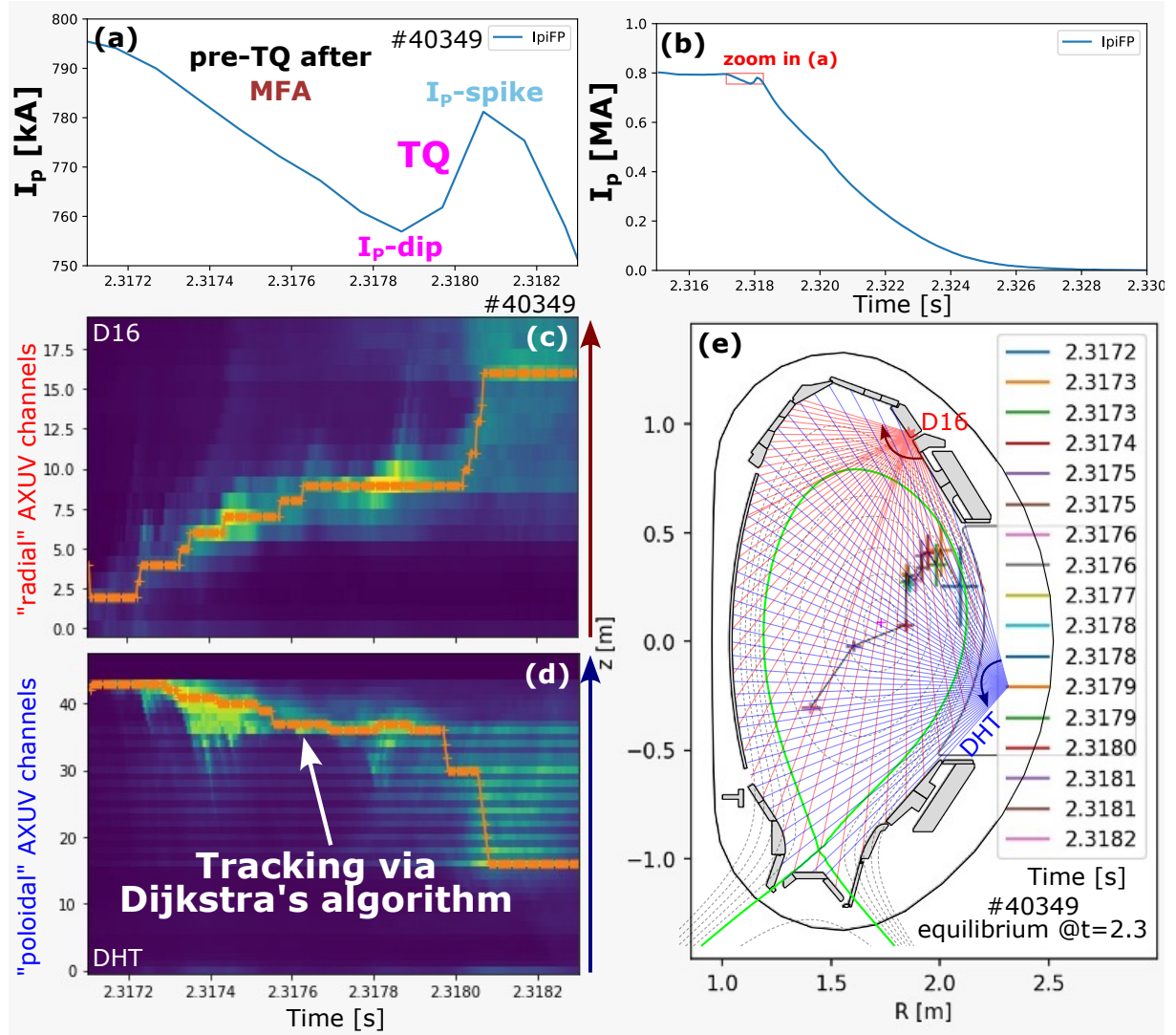


FIGURE A.06: Tracking of the pellet cloud in the poloidal plane via the AXUV diode arrays – D16, DHT in S16 in this example. In (a, b) the plasma current, (c, d) 2D-plot of the AXUV channels, (e) tracking in the poloidal plane. The tracking in the 2D plots of the AXUV channels is done via my implementation of Dijkstra's algorithm to track modes in spectrograms [129,130]. The tracking from the AXUV channels is then combined into a poloidal tracking. Tracking code developed by J. Svoboda and myself [307]. 2D and tracking plots (c, d, e) generated by J. Svoboda.

A.15 Used lines of sight of the soft X-ray

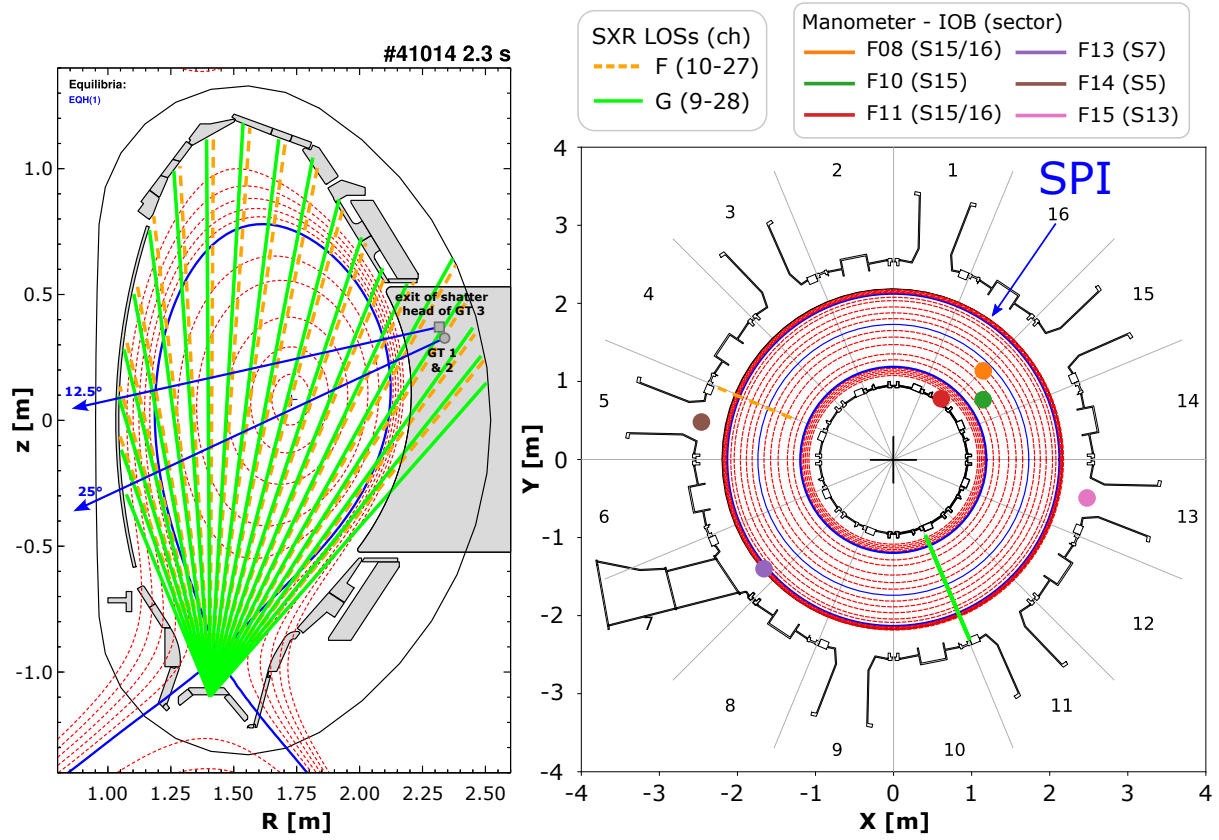


FIGURE A.07: Lines of sight of the SXR measurements displayed in figure 6.13(e, f, k) and the toroidal manometer positions from figure A.02.

List of Acronyms

4 mm	pellet with 4 mm diameter
8 mm	pellet with 8 mm diameter
a	plasma minor radius
a	radiation fit parameter
ASDEX	Axially Symmetric Divertor Experiment
AUG	ASDEX Upgrade
AXUV	Absolute eXtended UltraViolet
B	barrel
B	magnetic field
b	assimilation fit parameter
B_{pol}	poloidal magnetic field
B_{tor}	toroidal magnetic field
β	ratio of plasma pressure to magnetic pressure
BH	barrel heater
c_0	speed of sound of the propellant gas
CAD	computer-aided design
CER	Center for Energy Research
ch	channel
CO₂	carbon dioxide
CQ	current quench
CV	computer vision
D	pellet diameter
D_α	emission from Balmer- α transition for deuterium
$\bar{d}_{\text{frag}}$	mean fragment size
D₂/D	deuterium
DCN	deuterium cyanide
DCS	discharge control system
DIII-D	Doublet III with D-shaped plasma
DMS	disruption mitigation system
DREAM	Disruption and Runaway Electron Analysis Model
Δt_{CQ}	duration of the CQ

$\Delta t_{\text{CQ}}^{100 \rightarrow 80}$ unscaled duration of the CQ (100% $\rightarrow$ 80%)

$\Delta t_{\text{pre-TQ}}$ pre-TQ duration

E_{crit} critical electric field

E_{heating} heating estimate

EAST Experimental Advanced Superconducting Tokamak

ECE electron cyclotron emission

ECRH electron cyclotron resonance heating

EM electro-magnetic

EPC electronic pressure controller

ϵ_0 vacuum permittivity

η plasma resistivity

$f_{\text{assimilated}}$ fraction of the assimilated to injected pellet material

f_{c} coupled energy fraction

f_{neon} percentage of neon in the pellet

f_{rad} radiated energy fraction

f_{th} thermal energy fraction

FC fragment camera

FL first light

front volume volume between the front of the pellet and first gate valve

FV fast valve

FW first wall

$G_{\text{rad}}(T_e)$ electron temperature dependent pre-factor

γ adiabatic index

GH generator heater

GHr power setting of the GHs for pellet detachment

GMV pellet gas mixing volume

GRE global reconnection event

GT guide tube

GUI graphical user interface

H-mode high confinement mode

H_2/H protium

HFS high field side

HL-2A Huan-Liuqi-2A

I_{halo} halo current

ICRH ion cyclotron resonance heating

INDEX disruption simulator

IO ITER organization

I_{p} plasma current

IP-dip minimum in the plasma current before the IP-spike

IP-spike plasma current spike

IPP Max Planck Institute for Plasma Physics

ITER Presently, the largest tokamak under construction in Cadarache, France

$\mathbf{j}$ current density

J-TEXT Joint Texas Experimental Tokamak

JET Joint European Torus

JOREK non-linear, extended MHD code

KSTAR Korea Superconducting Tokamak Advanced Research

$\mathbf{L}$ pellet length

L_{p} plasma inductance

L_{ch} chord length

L-H-transition transition from L-mode to H-mode

$\mathbf{L}_{\text{head}}$ shatter head length after the miter bend

L-mode low confinement mode

$\mathbf{L}_{\text{nom}}$ nominal pellet length

$\mathbf{L}_{\text{rad}}(T_{\text{e}})$ electron temperature dependent radiation factor

LCFS last closed flux surface

LED light emitting diode

LFS low field side

li plasma internal inductance

LOS line of sight

LSN lower single null

$\mathbf{M}_{\text{neon}}$ molar mass of neon

MARFE multifaceted asymmetric radiation from the edge

$\mathbf{m}_{\text{e}}$ electron mass

MFA main fragment arrival

MGI massive gas injection

MH main heater

MHD magneto-hydrodynamic

ML machine learning

MMI massive material injection

μ_0 vacuum permeability

$N_{\text{assimilated neon}}$ number of assimilated neon atoms in the plasma

N_A Avogadro number

n_{imp} impurity density

N_{neon} estimated number of neon atoms

NBI neutral beam injection

n_e electron density

Ne neon

$\overline{n_e}$ line averaged electron density

$\tilde{n_e}$ line integrated electron density

NIF National Ignition Facility

OPD optical pellet diagnostic

ORNL Oak Ridge National Laboratory

OV observation volume

p plasma pressure

P_{ch} radiated power of a certain channel

p_{crit} critical momentum

p_e electron momentum

P_{ECRH} ECRH power

$P_{\text{ex. Ohmic}}$ externally driven Ohmic power

P_{FV} propellant gas pressure

$P_{\text{FV}}/\rho L$ mass density normalized propellant pressure

$P_{\text{in. Ohmic}}$ internally converted Ohmic power

p_{inlet} inlet pressure

P_{NBI} NBI power

P_{rad} total radiated power

$P_{\text{rad, sector}}$ radiated power in an individual sector

$P_{\text{rad, max}}^{\text{total}}$ global maximum of P_{rad} for all measurement sectors

$P_{\text{rad, X, peak}}^{\text{SY}}$ local maximum of P_{rad} for the Xth radiation peak in sector SY

$P_{\text{rad, max}}^{\text{SY}}$ global maximum of P_{rad} in sector SY

P_{thFW} thermal energy flux to the wall

pellet ID pellet identification number

PFC plasma facing component

Φ toroidal angle

PME plasma movement event

pre-IP-spike VPE Disruptions in which a change of the **VPEState** is triggered prior to the IP-spike

pre-TQ pre-thermal quench

Ψ_{p} poloidal magnetic flux

Ψ_{t} toroidal magnetic flux

PSL passive stabilising loop

q plasma safety factor

q_{95} plasma safety factor at $\rho_{\text{pol}} = 0.95$

q_{edge} plasma safety factor at the edge

R plasma major radius

RE runaway electron

ρ pellet mass density

ρ_{neon} neon mass density

ρ_{pol} plasma normalized radius

S sector

S5/S9-asymmetry absolute asymmetry between S5 and S9

SOL scrape-off layer

SPI shattered pellet injection

SPI H-mode 1.8 T H-mode used for the SPI experiments

STARWALL code package to study linear 3D MHD stability in presence of ideal/resistive conductive structures

SXR soft X-ray

T plasma temperature

t_{blockage} blockage time

t_{CQend} end time of the CQ

T_{div} temperature difference between the inner and outer divertor halves

t_{end} integration interval end-marker

t_{FL}	time of the FL
t_{freezing}	“freezing” time
$t_{\text{IP-dip}}$	time of the IP-dip
t_{LCFS}	loss-time of the last closed flux surface
t_{MFA}	time of the MFA
$T_{\text{min}, \chi_{\parallel}}$	threshold temperature for the heat flux estimate
t_{start}	integration interval start-marker
t_{TQ}	TQ onset time
T_2/T	tritium
T_e	electron temperature
tokamak	<i>toroidal chamber with magnetic coils</i>
TPF	toroidal peaking factor
TQ	thermal quench
U_{loop}	loop voltage
UHS	ultra-highspeed
v_{fragment}	mean fragment velocity
V_{max}	maximum gas expansion rate into vacuum
$v_{\parallel}$	parallel velocity component
v_{pellet}	pre-shattering pellet velocity
V_{pellet}	estimated pellet volume
$v_{\perp}$	perpendicular velocity component
VDE	vertical displacement event
$V_{\text{full-shadow}}^{360^\circ}$	full-shadow-360°-expanded Volume
$V_{\text{half-shadow}}^{360^\circ}$	half-shadow-360°-expanded Volume
VPEState	system state of the VPE in the DCS
W_c	coupled energy
$w_{\text{ch},360^\circ}$	channel specific weighting factors
$w_{\text{ch},S}$	sector weighting factors for each channel
W_{con}	conducted/convected thermal energy
W_{heat}	excess heating
$W_{\text{in. Ohmic}}$	energy transfer via the internally converted Ohmic power
W_{mag}	magnetic energy

W_{plasma} energy dissipated in the plasma

W_{rad} radiated energy

W_{RE} RE energy

W_{th} thermal energy

w.r.t. with respect to

XPR X-point radiator

Z nuclear charge number

Z_{curr} vertical position of the current centroid