Max-Planck-Institut für Plasmaphysik

En route to high-performance discharges: Insights & guidance from high-realism gyrokinetics

T. Görler[1*], A. Di Siena[1], H. Doerk[1], T. Happel[1], S.J. Freethy[1,2], I.-G. Farcas[3] , A. Bañón Navarro[1], R. Bilato[1], A. Bock[1], J. Citrin[4], G.D. Conway[1], A. Creely[2], P. Hennequin[5], F. Jenko[1], T. Johnson[6], C. Lechte[7], T. Neckel[3], E. Poli[1], M. Schneider[8], E. Sonnendruecker[1], J. Stober[1], A.E. White[2], ASDEX Upgrade Team[1], and JET Contributors[9]

[1]Max-Planck-Institut für Plasmaphysik, Garching, Germany • [2]MIT, Plasma Science and Fusion Center, USA • [3]Technical University of Munich, Chair of Scientific Computing, Germany • [4]DIFFER, Eindhoven, The Netherlands • [5]Laboratoire de Physique des Plasmas, Ecole Polytechnique, France • [6]VR Association, EES, KTH, Stockholm, Sweden • [7]IGVP, University of Stuttgart, Germany • [8]ITER Organization, St. Paul-lez-Durance, France • [9]See the author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001

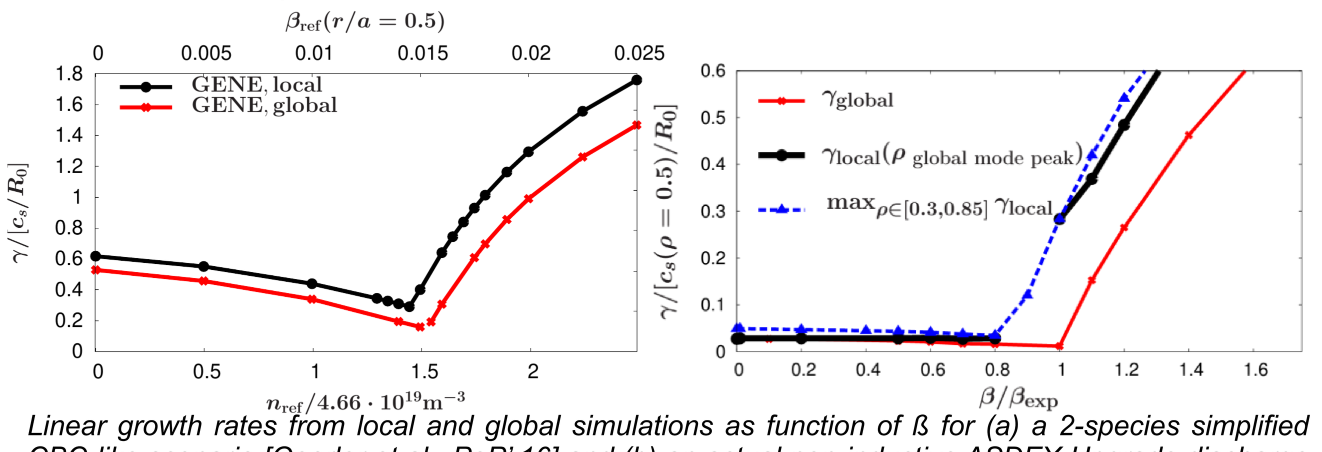
I. Motivation

- High-performance discharges ↔ relevance of electromagnetic fluctuations and fast ions
- Ab initio gyrokinetic simulations in this regime still rare – need to address, e.g., the following questions to inform quasilinear models:
  - Are finite-gyroradius effects relevant?
  - Are highly electromagnetic microinstabilities, e.g., kinetic ballooning modes (KBMs) able to constrain core turbulence?
  - Why are fast-ion effects found to be qualitatively different, for instance, between NBI/ICRH heated JET L-modes and DIII-D QH-modes/non-inductive AUG plasmas? Relevant only in electromagnetic framework?
- How reliable are state-of-the-art gyrokinetic simulations?

→ *dedicated studies with the gyrokinetic code GENE (genecode.org)*

II. Nonlocal global EM effects

- Electromagnetic (EM) finite-size studies still rare (expensive) → here: 2 examples



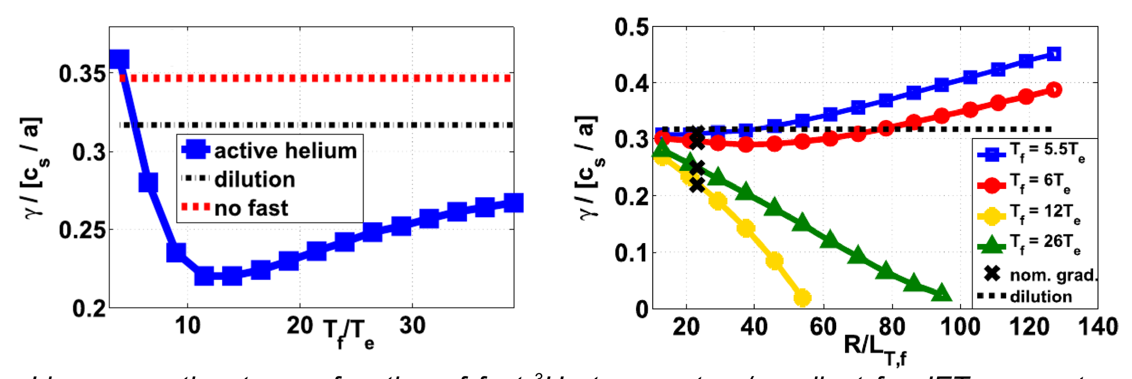
Linear growth rates from local and global simulations as function of ß for (a) a 2-species simplified CBC-like scenario [Goerler et al., PoP' 16] and (b) an actual non-inductive ASDEX Upgrade discharge [Doerk et al., Nucl. Fusion '18] with kinetic electrons, deuterium and fast ion species.

- Both cases demonstrate:
  - Relative growth rate reduction whose amplitude seems to depend on the particular microinstability (here: ITG vs. KBM/Alfvénic ITG)
  - Consequence: KBM threshold upshift which is usually not yet considered in reduced models (often fluxtube-based)
- Non-inductive AUG case exhibits profiles close to KBM threshold ↔ revision of reduced models required for this parameter regime
- Global EM simulations remain challenging and require on-going algorithmic optimizations ↔ block-structured velocity space grids recently implemented in GENE [Jarema et al., CPC '17]

III. A new fast-ion resonance effect

- Quiescent H-modes at DIII-D, strongly heated JET discharges, non-inductive AUG plasmas etc.: fast ions necessary in GK simulations to reach realistic heat flux levels → impact, however, qualitatively different
- A key effect explaining different levels of stabilization (even electrostatically):

fast ion – wave resonance [III.1]

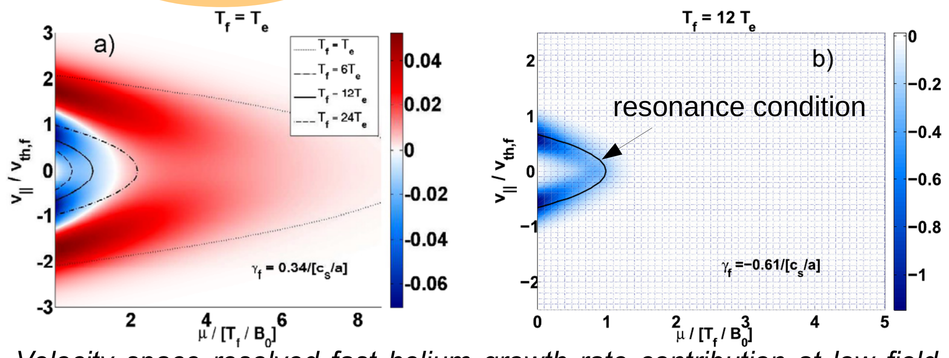


Linear growth rates as function of fast ^{3}He temperature/-gradient for JET parameters [Citrin et al., PRL '13]. Taken from [III.1].

- Fast ion growth rate contribution: $\gamma_f = -\frac{1}{E_{\mathrm{pot}}}\frac{\partial E_{\mathrm{kin}}}{\partial t}$

$$\propto \omega \int \mathcal{J}\left(v_\parallel^2+\mu B_0\right)\frac{\left[\frac{R}{L_n}+\frac{R}{L_T}\left(v_\parallel^2+\mu B_0-\frac{3}{2}\right)\right]F_0}{\omega+\frac{T}{q}\left(\frac{2v_\parallel^2+\mu B_0}{B_0}\right)k_y\mathcal{K}_y}\mathrm{d}x^3$$

- Stabilizing effect: resonance amplifies dominantly negative region of dF_0/dr

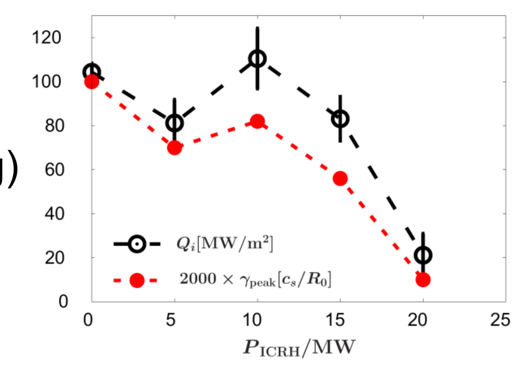


Velocity space resolved fast helium growth rate contribution at low field side for (a) thermal and (b) T_f/T_e = 12. Taken from [III.1].

- Necessary condition: $\eta_f = \frac{L_{n,f}}{L_{T,f}} > \frac{2}{3}$

(more often found for ICRH heating)

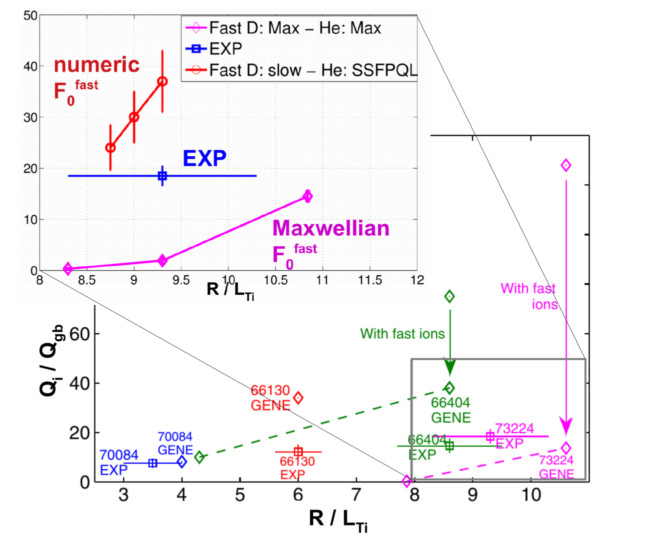
- Effect prevails in electromagnetic and nonlinear simulations
- Impact on ITER/DEMO performance?
  - hot α-particles in dilution limit (see above)
  - possible relevance for ramp-up phase



Linear and nonlinear flux-tube results as function of the fast ion power deposition in the ramp-up phase of the ITER standard scenario. See [III.1] for details.

[III.1] A. Di Siena et al., Nucl. Fusion 58 (2018), 054002

IV. Realistic fast ion models in GK turbulence

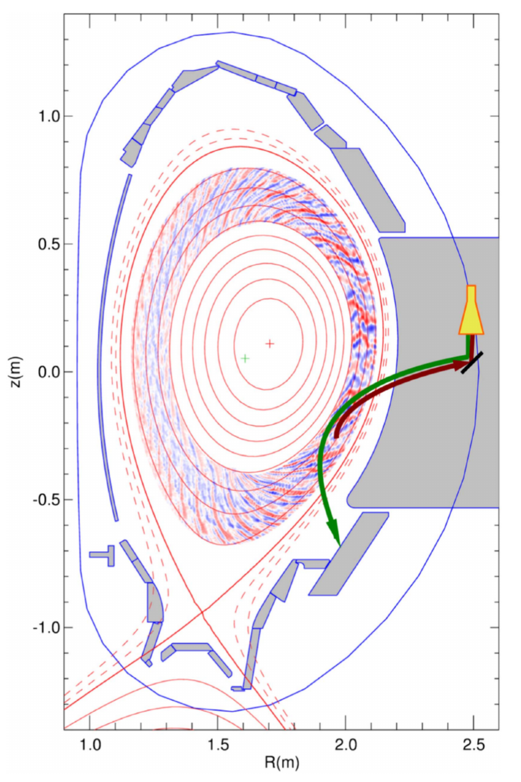


Nonlinear GENE results with slowing-down distributed fast D and fast ^{3}He from TORIC-SSFPQL compared to previous results [Citrin et al., PRL '13] using equivalent Maxwellian fast ion distributions.

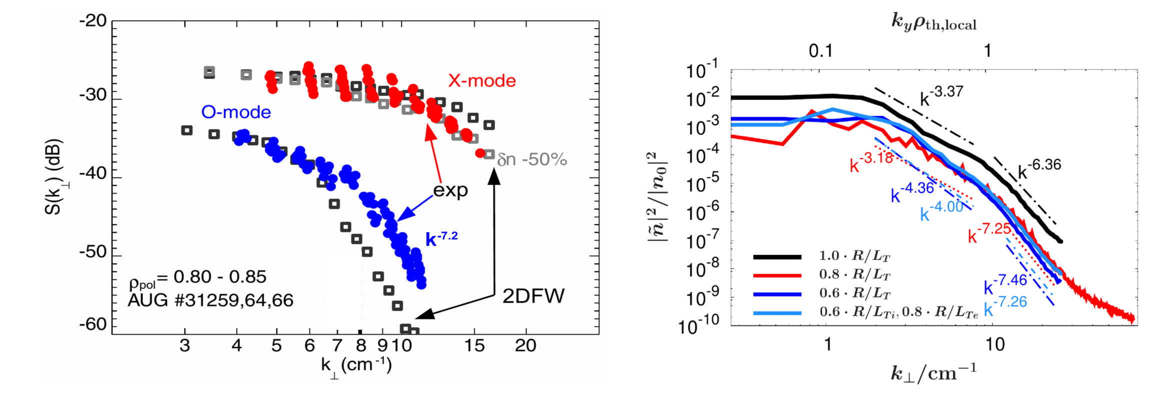
- Recent GENE extension [Di Siena et al., PoP '18]: Arbitrary background distribution functions instead of hard-wired (equivalent) Maxwellians
- Example: Revision of equivalent Maxwellian based results in [Citrin et al., PRL '13] with slowing-down distribution approximating SPOT/NEMO results for fast NBI Deuterium and numeric distribution from TORIC-SSFPQL (or SELFO) for the ICRH generated fast ^{3}He
- Heat and particle (not shown) agreement greatly improved

→ realistic fast ion models / integrated modeling crucial for reliable prediction of strongly heated plasmas

V. State-of-the-art validation

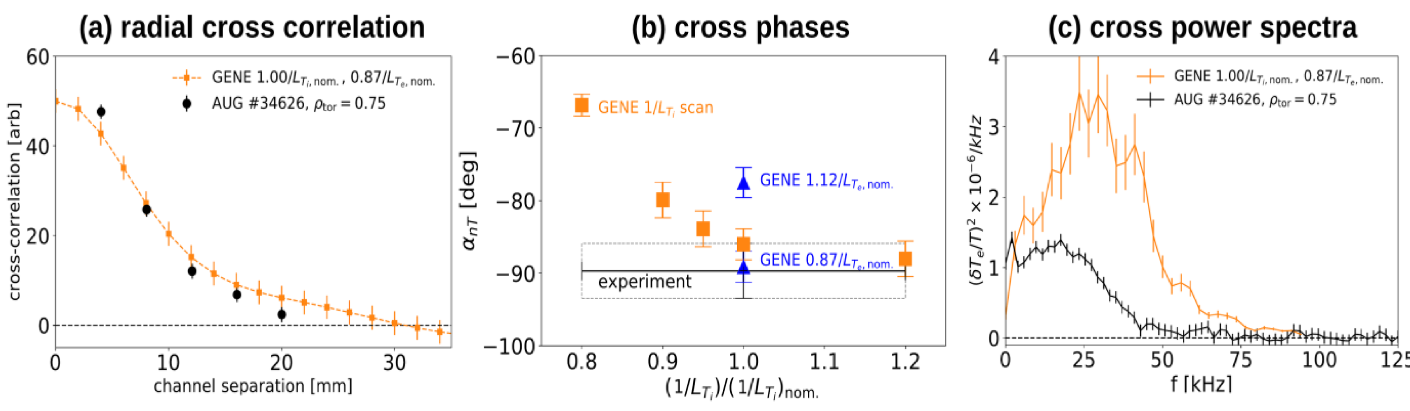


Synthetic Doppler Reflectometry: 2DFW simulations with IPF-FD3D on top of the density fluctuations obtained from GENE. Taken from [Lechte et al., PPCF '17].



Density fluctuation spectra obtained (a) from Doppler reflectometry and flux-matched GENE+2DFW simulations (see [Happel et al., PPCF '17] for details) and (b) from raw GENE data for various temperature gradient settings.

- **Crucial for reliable prediction: Continuous validation vs. experimental measurements (beyond transport comparisons)**
- *Comparison with ASDEX Upgrade Doppler reflectometry:*
  - very good qualitative agreement – sophisticated synthetic diagnostic involving IPF-FD3D [Lechte, IEEE Trans. Plasma Sci. '09] crucial → helped to resolve long-standing issue on spectral roll-over mismatch (non-linear scattering relevant!)
  - gyrokinetic simulations furthermore provide insights on sensitivity of spectral properties on turbulence drive and fine-scale behavior

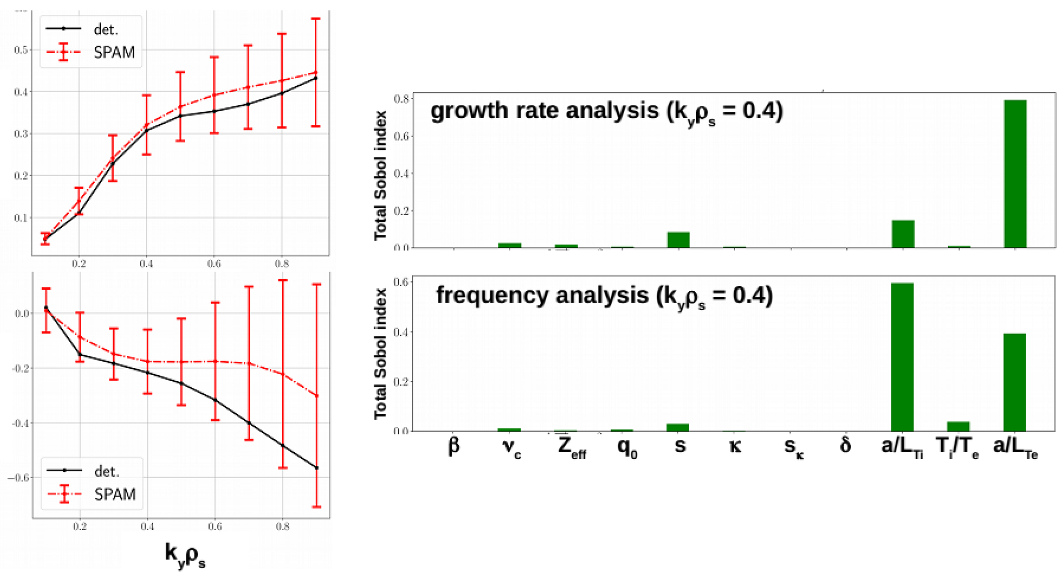


Comparison of CECE measurements (black) and post-processed flux-matched GENE simulations (orange, blue) for (a) the radial cross correlation, (b) electron density-temperature cross phases and (c) electron temperature fluctuation cross power spectra. See [Freethy et al., PoP '18] for further details.

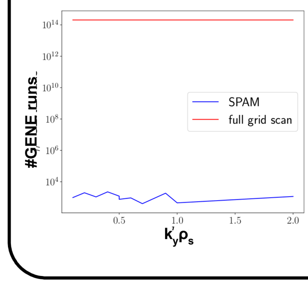
- *Remarkable agreement with new correlation electron cyclotron emission (CECE) diagnostic at ASDEX Upgrade*
- deviations found in cross-power spectra → details of synthetic diagnostics / physics input uncertainties?

VI. First steps towards forward Uncertainty Quantification (UQ)

- Challenge for turbulence simulations: high-dimensional sensitivity assessment ↔ computationally extremely demanding
- Idea:
  - Construct dimension-adaptive sparse grid surrogates
  - Exploit sensitivity information to further tune the adaption
- Method [Farcas et al., to be subm. '18]
  - Sparse approximation based on pseudo-spectral projection operators constructed on nested Leja sequences



Example of a GENE forward-UQ analysis [Farcas et al., to be submitted '18] for linear simulations for AUG #33585. Linear growth rates and real frequencies with error bars considering uncertainties in 11 input values are displayed on the left. Their individual impact at fixed wave number can be assessed by the total Sobol indices which are shown on the right.



Computational expense reduced by orders of magnitude!

Conclusions

Gyrokinetics closing in on important aspects of high-performance plasmas

- Global electromagnetic studies: Finite-gyroradius effects may shift KBM onset → important for modeling
- Identification of a new wave – fast ion resonance effect which could possibly be exploited by heating scheme optimization ↔ nonlinear interplay with EM stabilization important topic
- Realistic fast ion distribution functions have been implemented and significantly improve agreement with experiment
- Comprehensive validation studies increase confidence in gyrokinetic predictions and provide guidance for diagnostics design/interpretation
- Uncertainty quantification – promising steps properly addressing high-dimensional character shown

*Corresponding author:
tobias.goerler@ipp.mpg.de

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