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Integrated design of tokamak building concepts including ex-vessel maintenance

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ABSTRACT

The EU-DEMO (referred to as DEMO) tokamak complex currently consists of three buildings, like in ITER: the tokamak building, the tritium building and the diagnostics building. The tokamak building houses the tokamak itself and the numerous plant systems that interface with the necessary systems to produce and control the plasma. It is designed to permit assembly, operation and maintenance of the DEMO tokamak. The vacuum vessel is organized in 8 sectors, with radial ports at the lower and equatorial levels and one vertical upper port. The general architectural structure is arranged around the tokamak with a cylindrical bioshield of 2m thickness around the cryostat and floor levels corresponding to the cryostat penetrations. Additional levels are used for the integration of auxiliary equipment for the various plant systems and for accident mitigation systems. Currently, the tokamak building also represents the final nuclear confinement barrier for the radioactive material towards the environment and the public. This safety function requires the plant and safety systems to limit the release of radioactive substances during normal operation and in accidental conditions well below the safety limits. The complexity of a fusion power plant, like DEMO, with regards to integration of plant systems is much higher than that in a fission power plant due to the larger number of plant systems. Three main criteria drive the integration work of the plant systems inside the tokamak building: (i) safety requirements, (ii) functional requirements of the plant systems themselves and (iii) the maintenance approach. Cost considerations are also taken into account together with the normal and accidental environmental conditions in the various areas of the tokamak building that might challenge the qualifications of structures, systems and components (SSC). The layout of the tokamak building has to be further developed in the Concept Design Phase to follow the plant design evolution providing feedback to the various designers in order to assure that DEMO meets the cited design criteria with an optimized and licensable layout of the most complex nuclear building.

1. Introduction

The study of an integrated design of tokamak building concepts including ex-vessel maintenance was conducted during the Pre-Concept Design (PCD) Phase within the Key Design Integration Issue (KDII) [1] activities.

Two variants of the layout of the tokamak building were developed which are described in section 2:

- Ex-vessel remote maintenance oriented

Where Tokamak accessibility by remote maintenance (RM) tools is prioritized

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- Compartmentation oriented

Where Safety and licencing requirements are prioritized

For the compartmentation oriented tokamak building variant, suitable configurations of the major plant systems inside the tokamak building were developed for the two breeding blanket concepts currently considered:

- Helium-cooled Pebble Bed (HCBP) breeding blanket
- Water-cooled Lithium Lead (WCLL) breeding blanket

For the time being, the design layout of the two other nuclear buildings are not included in this KDII6 work, namely:

- Tritium Handling Facility
- Active Maintenance Facility (AMF)

The ex-vessel RM oriented building proposal was performed by RACE (*UK Atomic Energy Authority Culham Science Centre)*, focussing on the building requirements from an RM prospective. The plant systems integration and the safety requirements of the DEMO plant were not addressed in favour of optimising the RM performance.

In the compartment oriented building developed by the central team in Garching, described after chapter 2, priority was given to the safety and licencing requirements. This option includes the integration of plant systems to identify the source terms of hazards, essential for safety and licencing described in chapter 3 to 5. Status input was also provided for the down selection process of the two current BB variants HCBP and WCLL.

2. Building variants

2.1. Ex-vessel remote maintenance oriented

This section describes the principal features of the Tokamak Building concept developed during the PCD Phase, to address primarily ex-vessel RM constraints. In this case, the design driver of this building variant is the facilitation of the maintenance operations proposed. Only a preliminary layout of the building is available and additional work is required to integrate a number of plant systems currently unaccounted for. The principal features are:

- Use of Containment Cells to facilitate access to In- Bioshield and In-Vessel components. Most notably:
- The Upper Maintenance Hall is configured as a single Containment Cell through which the following areas are accessed:
- Central Solenoid Magnet
- Upper Port (temporary confinement will be installed prior opening the Vacuum Vessel)
- Various In-Bioshield areas
- Upper Pipe Chase
- Eight Containment Cells located around the machine at the Lower Port level, with each Cell servicing two Lower Ports.
- A single huge Containment Cell around the Neutral Beam Injectors.
- Relocation of the Vertical Pipe Chutes from the Containment Cells to the Transportation Corridors. Illustrated in Fig. 1. The upper image shows the current (left) and proposed (right) locations of the Chutes (circled green). The lower image is a CAD model of the lower port containment cell with the chutes removed. Pipe chutes within cells can be seen in Fig. 1 (also circled green).
- Shielded Transportation Corridors circling all levels of the building. These areas facilitate the transfer of radioactive components between the Containment Cells, in the Tokamak Building, and the AMF.

This approach results in a building with the following characteristics:

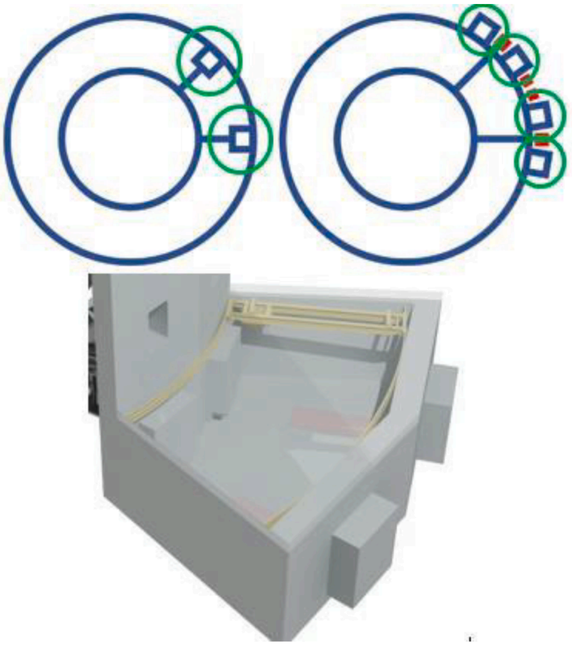


Fig. 1. Proposed location of the Vertical Pipe Chutes.

- Sufficient space around vessel ports to facilitate access for maintenance, e.g. items of power plant hardware can be removed and installed as single units.
- Space local to the point of work is available for storage of RM equipment.
- Easier access for rescue and recovery operations.
- Minimisation of maintenance durations.
- Minimisation of RM equipment inventory.
- Greater potential for large tritiated volumes.
- The potential for the spread of contamination outside the Bioshield. It is anticipated that decontamination of Containment Cells would be necessary to permit operator access.

2.2. Compartmentation oriented

In the compartmentation oriented approach, the integration of the plant systems in the building aims at sub-dividing the tokamak building into sealed areas in order to reduce the possibility of spreading contamination. This significantly facilitates the respect of safety principles, e.g. minimization of radioactive inventories in a fire zone to limit the inventory of radioactive source terms that can be released in normal conditions and in case of an accident, ventilation zoning that depends on the risk of contamination, increase accessible radiation zoning, segregation between two redundant safety systems. In parallel, the lessons learned from ITER are considered, in particular:

- Control the spread of contamination into the building: the ITER approach for in-vessel maintenance is adopted where a cask docked to the vacuum vessel
- (VV) is operated within a sealed port cell [2]. Since the DEMO port cells with internal volume of ~800m^3 are significantly larger than those in ITER (200 m^3 [3]) the control of contamination in DEMO is even more challenging.
- The volumes of rooms requiring detritiation (permanently or after an accident) are limited as far as possible since the detritiation system is a Safety Important Classified (SIC) system (e.g. size of emergency diesel generator and other SIC auxiliaries), and produces tritiated water.
- The limited increase of particularly crowded areas for better access for Remote Handling (RH) tools.

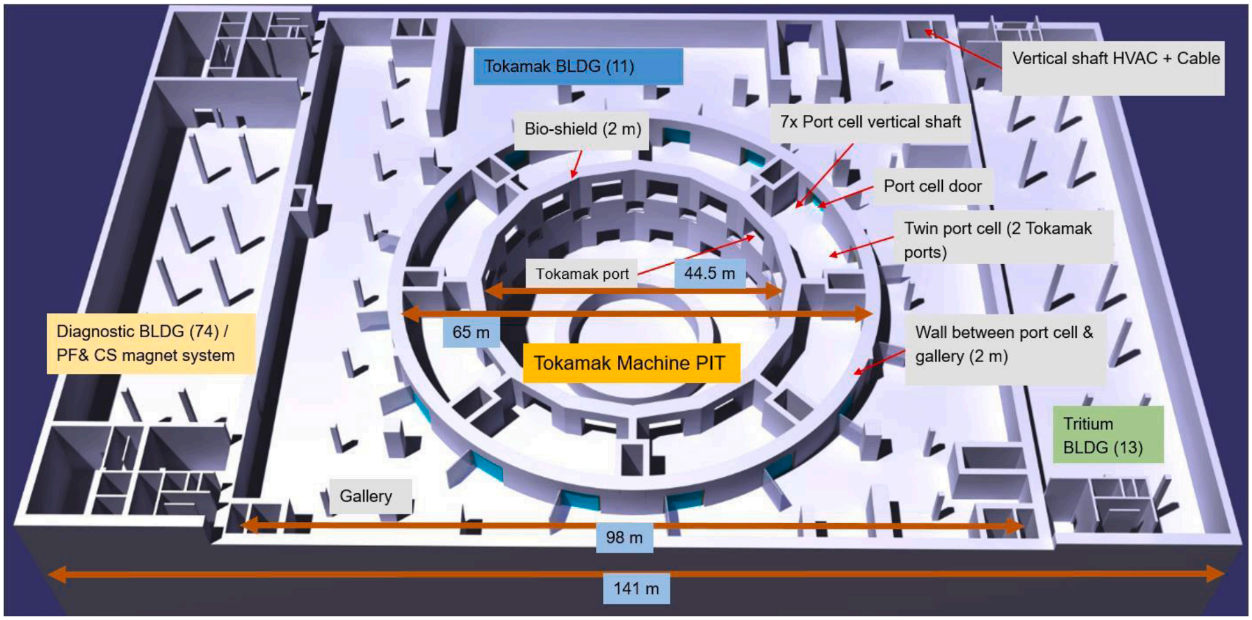


Fig. 2. DEMO Tokamak building level associated to VV lower ports (B2 level).

- The increase of radiation shielding and the routing of piping carrying radioactive hazardous fluids in separate corridors to protect other plant equipment, in particular SIC electronics and electrical equipment.

The building layout must also meet the following safety requirements:

- Limitations of the radioactive inventories that can be mobilised by a Design Basis Event (DBE), such as,
- e.g. ex-VV loss of coolant accident (LOCA), fire, local explosion, flooding, pipe whipping,
- Avoidance of Common Mode Failure (CMF) of SIC systems (e.g. redundant divisions)
- Minimization of radioactive contamination and chronic releases.

The above requirements are fundamental to meet the licensing requirements considering the relevant safety guides and standards (e.g. EUR, RCCs, RG, IAEA) and the licensing experience of ITER. The three main licensing targets are:

- No evacuation of the population for any DBE and beyond DBE, including extended design conditions (post Fukushima design criteria)
- Occupational radiation exposure to the DEMO staff
- $\leq$ 700 mSv*p/y
- Annual tritium release limit in normal operation (order of 1-few g/year).

The list of plant systems already integrated includes the Breeding Blanket (BB), Primary Heat Transfer System (PHTS), the Tritium Extraction and Removal System (TER), the cryo-distribution, the magnet feeders, the toroidal field (TF) coil Fast Discharged Units (FDU), and the PHTS drain tanks and the vacuum vessel pressure suppression system (VVPSS).

Since the design of the building and the plant systems is so far not sufficiently mature, the Failure Mode and Effects Analysis (FMEA) of the RH system has not yet been done. The preliminary Reliability, Availability, Maintainability, and Inspectability (RAMI) analysis of the PHTS and the Balance of Plant (BoP) met the set targets [7-9].

3. Tokamak complex description

The DEMO tokamak complex currently consists of three buildings: tokamak building, tritium building and diagnostic building, see Fig. 2. It is a large reinforced concrete structure with dimensions of approx. L=141m x W=98m, H=90m. The complex shares a common rectangular basement with seismic isolators between the ground and the building to soften the seismic response spectra and minimize relative vertical displacements. The seismic isolators significantly reduce the seismic loads to be considered in the design of the systems and components inside the tokamak complex. The ground level of the tokamak complex is currently defined by the floor level of the Heating Neutral Beam (HNB) cell for an easy installation of the heavy HNB vessel and components without lifting operation.

The tokamak and tritium buildings represent the final boundary to the environment for radiation hazards. Part of the diagnostics building is also defined as confinement barrier to avoid the classification of the numerous penetrations between the tokamak and diagnostics buildings as confinement penetrations.

3.1. Tokamak building

The tokamak building houses the tokamak and numerous plant systems. It is designed to permit assembly and operation of the DEMO torus with a BB of 16 sectors, each with radial ports at three building floor levels and one vertical upper port. The general architectural structure is arranged around the tokamak, providing a cylindrical bioshield of 2m thickness around the cryostat and floor levels corresponding to the cryostat penetrations. Additional levels above and below the machine are used for the integration of auxiliary equipment.

The confinement safety function of the tokamak building requires to limit the release of radioactive substances during normal operation and in accidental situations to within the safety targets. The building is designed to withstand seismic events with an expected reoccurrence of 10,000 years, an airplane crash (Boing 747, Military Jet) and an internal over- pressurization due to ex-vessel loss of coolant accident (LOCA).

The internal structure of the tokamak complex is characterized by compartmentation and segregation of volumes to avoid common cause failures from redundant divisions and to limit volumes affected by various hazards, in particular:

- Release of tritium or activated corrosion products from Plasma Facing Component (PFC) cooling loops.
- Contamination with radioactive substances, in particular dust and tritium, during in-vessel maintenance.
- Neutron and/or gamma radiation emitted from PFC cooling water systems and Lithium Lead (LiPb) pipes.
- Fire, explosion or flooding

Based on the Return of Experience (RoX) of ITER, the tokamak building is arranged in six major volumes, consisiting of:

- Machine pit (inside the bioshield and accessible with the tokamak building cranes)
- Twin port cells (a compartment to envelop the area outside the bioshield in front of two VV ports, only on floor levels associated with lower and equatorial ports)
- Galleries (extending to the external building walls)
- Maintenance hall above the bioshield roof
- Heat transfer system vault
- Neutral beam cell

The tokamak building accommodates the transportation routes for the internal components removed from the VV on the floor levels associated with the lower and equatorial VV ports. On these levels the tokamak building connects with the AMF, where vertical transportation of radioactive components is carried out. Radiation shielding of the hot components is provided by the internal and external building walls. During in-vessel maintenance the port cell is the second confinement barrier, the external tokamak building walls are the third and final confinement barrier, see Fig. 3.

The height of the assembly hall (see Fig. 4) allows for the blanket removal through the vertical upper ports.

The maintenance breeding blanket hall belongs to the final confinement barrier for the Deuterium Deuterium (DD) and Deuterium Tritium (DT) phase of DEMO.

The general arrangement of the building follows the levels of the machine ports. The upper (pipe chase), equatorial, lower level and lower pipe chase have access to the machine via ports. The vertical upper port connects the machine to the maintenance hall to allow the blanket replacement. The tokamak building also has two intermediate levels, upper feeder and Q-level which have no access to the tokamak machine by a VV port and therefore there are not associated port cells outside the bioshield. These levels are dedicated to magnet feeders. In addition these levels allow the installation of cubicles or other radiation sensible equipment.

Three types of vertical shafts are implemented inside the tokamak building with dedicated purposes, see Figs. 5 and 6, consisting of:

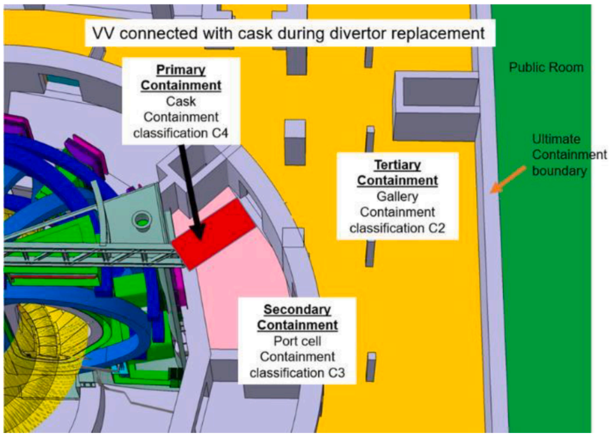


Fig. 3. Confinement barriers and containment areas during in-vessel maintenance with cask docked to the VV.

- Bioshield vertical shafts for pipe work hosting divertor & limiter PHTS to provide shielding by the 2m thick bioshield.
- Port cell vertical shafts containing pipework running from lower pipe chase to upper pipe chase and pipe work of auxiliary systems serving port cells. This vertical shaft is inside the port cell to have three out of four walls to enter into a port cell.
- Gallery vertical shafts used to route cable trays, building services and dedicated Heating Ventilation Air Conditioning (HVAC) shafts.
- Vertical shafts for the cryo-distribution system (cryolines)

4. Plant systems integration

4.1. Integration requirements

The complexity of a fusion power plant like DEMO with regards to integration of plant systems is much higher than in a conventional nuclear power plant (fission) due to the larger number of plant auxiliary systems.

Three main points drive the integration work of the plant systems inside the tokamak building: (i) safety requirements, (ii) functional requirements of the plant systems themselves and (iii) the maintenance approach. Cost considerations will be further preciously taken into account in the final design.

4.2. Safety requirements

The safety requirements of plant system layout are devoted to:

- Avoid common-mode failure of redundant safety functions;
- Limit the inventory of radioactive source terms and enthalpies that can be released by a single failure;
- Minimise the occupational radiation exposure during operation and maintenance;
- Avoid that non-SIC components might challenge a safety function.

Therefore, physical segregation between certain systems is applied at the maximum extent to avoid knock on effects. For example, a guillotine break of a high energy pipe must not challenge a fuelling pipe containing deuterium or tritium.

Components and systems need to be located in areas with environmental conditions that allow their qualification and then reliable operation. The DEMO room book [13] defines, for all areas of the tokamak building, the environmental conditions such as magnetic field, γ radiation, neutron flux, seismic floor response spectra, fire loads, pressure, temperature and humidity in normal and accidental conditions.

4.3. Functional requirements

Studying the layout aids in identifying system integration issues, and to develop a technically feasible, operable, maintainable and safe plant design. It enables the identification of areas in which there are significant technical uncertainties, and to provide a clear basis for safety and cost analysis and further improvements. Other buildings such as the control building and the turbine building are similar to those in fission nuclear plants, and their arrangements can be adapted to DEMO. However, investigations into the impact of plant maintenance and the potential limitations coming from the licensing regulation, which were only given preliminary consideration in this study, must be continued in the future.

The layout of the building has been preliminarily defined to allow the assessment of the initial configuration of the plant system and the related interconnections:

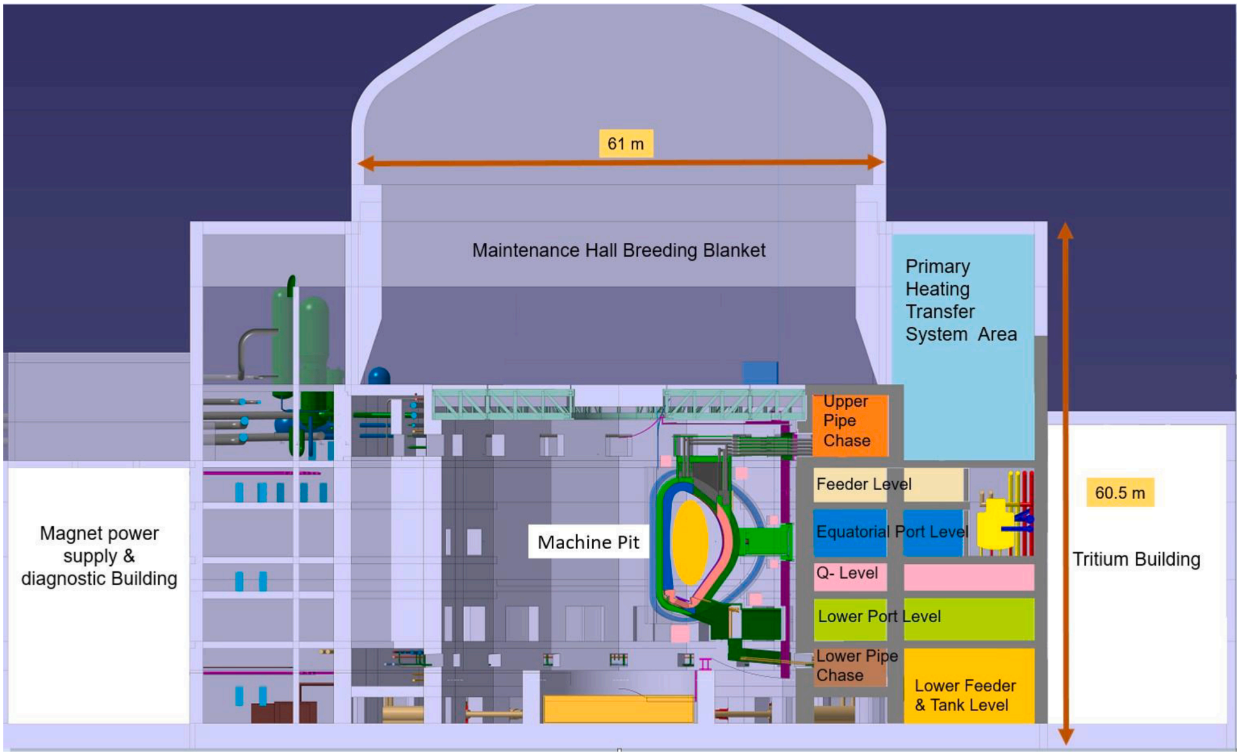
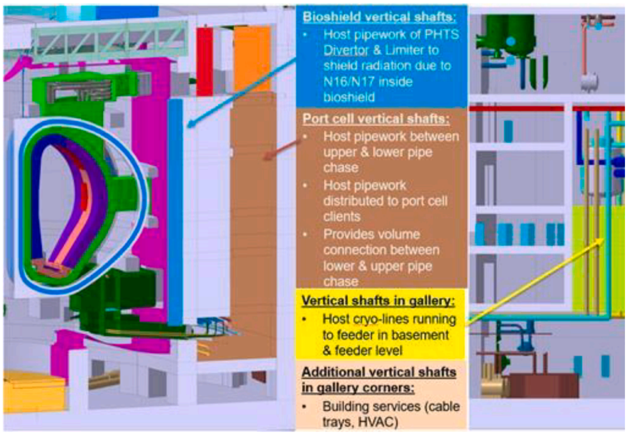


Fig. 4. Tokamak complex level arrangement.


Bioshield vertical shafts:
- Host pipework of PHTS Divertor & Limiter to shield radiation due to N16/N17 inside bioshield

Port cell vertical shafts:
- Host pipework between upper & lower pipe chase
- Host pipework distributed to port cell clients
- Provides volume connection between lower & upper pipe chase

Vertical shafts in gallery:
- Host cryo-lines running to feeder in basement & feeder level

Additional vertical shafts in gallery corners:
- Building services (cable trays, HVAC)

Fig. 5. Vertical shafts in tokamak building.

- The neutral beam should enter the plasma chamber at the equatorial plane. It should be noted that in the future a DEMO reactor operating solely with Electron-Cyclotron will be investigated as a matter of priority.
- The torus vacuum pumping system is located at the divertor level.
- Any drain tanks should be placed at the lowest level.
- The pellet injection system is to be located in proximity of the machine to reduce losses of fuel gas inside the flight tube.

Auxiliary systems have to be nearby their clients that are spread throughout the entire machine and have to be routed nearly everywhere as, e.g.:

- Service vacuum system
- Electrical power supply system
- Compressed air system
- Control and data acquisition system

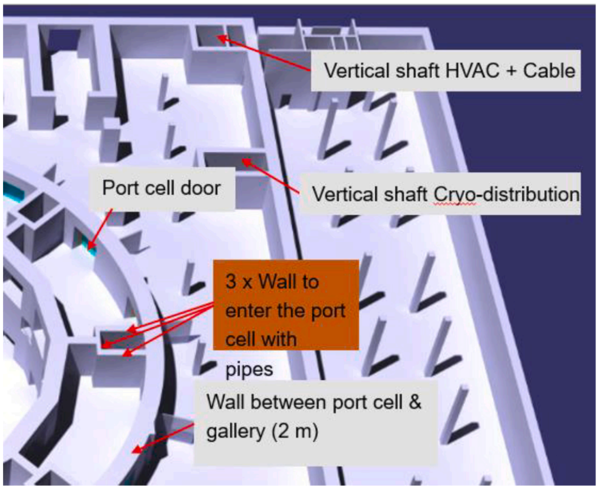


Fig. 6. Walls between port cell and vertical shaft to enter pipes & services.

- Cry-distribution system

4.4. Maintenance approach

Maintenance of plant components requires the provision of access and hence large volumes that are either free or can be cleared. Maintenance concepts must comply with fundamental safety requirements as cited above, physical segregation and avoidance of radioactive contamination spread. Two principle methods of maintenance are foreseen, manually by personnel and remote by dedicated tools. The choice depends on factors like environmental conditions (particularly radiation dose to the workers), complexity, capability, frequency and time requested which might affect the plant availability. The first assessment of maintenance operation, frequency, man power and required time has constituted the basic elements to assess the occupational radiation exposure. In addition locations where radiological permanent shielding design needs to be improved to meet the ALARA criterion have been highlighted:

Critical areas from a radiation dose point of view are:

- Upper pipe chase
- Lower pipe chase
- Vertical shaft
- Lithium Lead components rooms
- PHTS vault

The option for temporary shielding needs to be considered during maintenance. This is necessary to protect staff against radiation exposure from components around the working location or sensitive electronic equipment endangered by transported hot in-vessel components.

During in-vessel maintenance, of course, ex-vessel maintenance actions might take place if the radiation field permits. Short period of ex-vessel maintenance may not require a shutdown or warm up of big systems, like magnets.

Components requiring replacement need to be located in areas with sufficient access corridors to transport the component, e.g. the heat exchanger of the PHTS might need replacement once per plant life time. For foreseen replacement through the roof, access corridors are located in the top level of the tokamak despite, from a seismic point of view, heavy parts should be located at the bottom.

5. Overview over hazards caused by plant systems

Different machine and plant system status like normal operation, dwell, shutdown and accidental, cause related hazards either in normal or accidental conditions. The following strategies are implemented in DEMO to mitigate hazards inside the tokamak complex building:

- Improve neutron and gamma shielding and reduce radiation streaming through penetrations
- System segregation, i.e., High energy pipes from tritium pipes, cryo lines from cooling system pipes or cable.
- Adequate thicknesses of the separating walls between segregated plant systems
- Minimization of affected building areas by subdivision of rooms
- Cleaning process and cleaning systems, e.g. detritiation system
- Surfaces of components and walls with characteristic limiting adsorption of Tritium

Analysis is ongoing for when a component might be located in the tokamak adjacent buildings. That will have the advantage of reducing the dose to the staff, the qualification challenge and a possible access also during operation increasing, therefore, the RAMI.

5.1. Hazards assessment criteria

5.1.1. Tritium release into the building

Chronic and accident release of tritium into the building is a hazard caused by tritium containing systems. The limit for serving a room by the detritiation system (DS) depends on the concentration of tritium per volume inside the room. In ITER the threshold to switch from HVAC to DS is 10^8 Bq/m3. In DEMO the threshold for DS intervention is assumed the same, Table 1. The alarm for evacuation will be the dose corresponding to 1 Derived Air Concentration DAC in agreement with ALARA criterion.

Table 1
Threshold of tritium concentration inside a room to switch from HVAC to DS.

HVAC Range	DS Range
$<10^8$ [Bq/m3]	$\geq 10^8$ [Bq/m3]

During HVAC operation, air with very small tritium concentration is released to the environment through the stack (under continuous monitoring). This amount is accounted in the global release of the plant, which is limited to 1-few g / year Table 2. details the plant hazards in different machine states.

5.1.2. Neutron and gamma radiation

Table 3 reports the limits for radiation exposure of the staff and the integrated radiation dose for the electronic equipment.

5.1.3. Building over-pressurization

Depending on the enthalpy of the systems, which might be released into rooms during an accidental event, the rooms have to withstand a certain overpressure and guarantee a defined leak tightness (values adopted in the accident deterministic accidents), see Table 4.

5.1.4. Radiation shielding

5.1.4.1. Divertor & Limiter PHTS. To mitigate radiation issues coming from PFC cooling water due to N16 and N17, different solutions have been proposed [5,10].

The divertor and limiter coolant water pipes run vertically between Cryostat and bioshield, in order to increase the delay time where the bioshield function as the radiation protection towards ports and galleries see Fig. 7. Due to this increase in delay time inside the bioshield for the upper limiter coolant ~6.0s and the equatorial limiter coolant ~4s, the radiation dose outside the bioshield is reduced. As a lesson learned from ITER where the divertor PHTS causes a high radiation dose in the lower port cells, in DEMO the divertor pipe work is routed from the lower port through the outer wall annexes towards the lower pipe chase where the ring manifolds are located, see Fig. 8. This routing scheme avoids excessive radiation fields in the lower port cell.

Calculations with a simplified neutronic model have been performed to evaluate the dose rate and neutron flux due to pipes with activated water. The pipe work inside the pipe chases and inside the bioshield are

Table 2
Plant system hazards in different machine states.

Plant systems	Machine state Plasma operation	Dwell	Shutdown	Hazards
Divertor / limiter PHTS	Neutron and gamma radiation (N^{16}, N^{17}, ACPs)	Gamma radiation (ACPs)		Gamma radiation Pipe whipping Tritium/ACP release Rise of room temperature
BB (WCLL) PHTS BB (HCPB) PHTS	Chronical tritium release			Pipe whipping Tritium/ACP release Rise of room temperature
WCLL LiPb loop	Gamma radiation (from radioactive isotopes of activated LiPb and ACPs) Chronical tritium release			Gamma radiation Tritium/ACP release Rise of room temperature
HCPB He purge loop	Chronical tritium release			Tritium release
Tritium system – DT pipework	Chronical tritium release			Tritium release
Cryodistribution – 4K / 80K lines	n/a			Rise of room temperature Freezing of adjacent services

Table 3
Limits for radiation exposure of staff and of equipment [2, 4, 6].

Occupational exposure	Non-critical electronic equipment (lifetime)	Critical electronic equipment (lifetime)
≤100 μSv/h for controlled access 20 mSv/y individual dose limit 700 mSv/y collective DEMO dose target	10 Gy 100 n/(cm^2 s)	1Gy 0.01 n/(cm^2 s)

Table 4
Room leakage rate limits.

Room	Leak rate and pressure
Tokamak Complex: PHTS equipment room, lower and upper pipe chases and all pipe shafts and guard pipes.	≤ 100 volume %/day at 100 kPa pressure differential ≤ 5.5 volume %/day at 0.3 kPa pressure differential
Tokamak Complex: Gallery rooms (rooms containing vacuum vessel pressure suppression system, volumes containing piping for fuelling and vacuum pumping between port cells and tritium plant building, all galleries at all levels, and Cryostat space room)	≤ 100 volume %/day at 0.3 kPa pressure differential ≤ 820 volume%/day at 20 kPa pressure differential
Tokamak Complex: Drain Tanks Room	≤ 100 volume %/day at 100 kPa pressure differential ≤ 5.5 volume %/day at 0.3 kPa pressure differential
Tokamak Complex: Port cells	≤ 100 volume %/day at 0.3 kPa pressure differential ≤ 1420 volume%/day at 60 kPa pressure differential

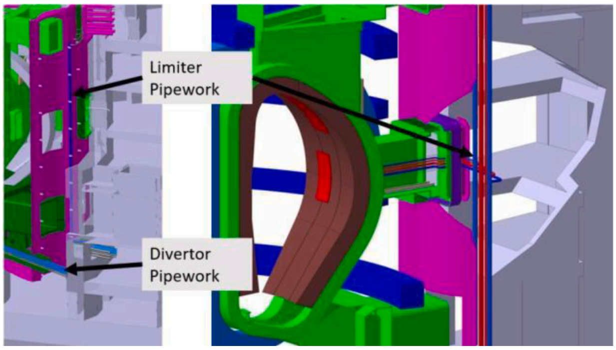


Fig. 7. Divertor and limiter pipes carrying activated cooling water routed inside the bioshield to protect radiation-sensitive electronics and electrical equipment inside the tokamak complex.

represented by one big pipe in dedicated locations with the same amount of water.

5.1.4.2. WCLL PHTS. Studies have been performed to better understand the issue of activation of water (inside plasma facing components) and the production and decay of short-lived N16 and N17 which causes neutron and gamma radiation [5,10,11]. The radiation caused by N16 requires dedicated shielding to protect equipment Table 5. This issue is a driving factor for the upper pipe chase layout and the routing of this highly-activated water. N17 is also a neutron emitter, which can activate components but its weight in percentage is much smaller Table 6.

Analysis is currently ongoing to evaluate the radiation dose level, which challenges the qualification of valve actuators and electronic equipment.

Radiation emitted from activated corrosion products (ACPs) in PFC coolant is also an issue for access of maintenance personnel. The relevant shutdown dose rate (SDDR) depends on the machine operating time. The chemical and volume control system (CVCS) can reduce substantially the concentration of ACPs, which are an important source of the gamma radiation. In addition a chemical oxidation decontamination, during plant life time and before maintenance, can reduce substantially the active inventory inside the plant systems. A LOCA would release the ACPs into the building. Therefore, the access of personnel to the affected area will be limited or forbidden.

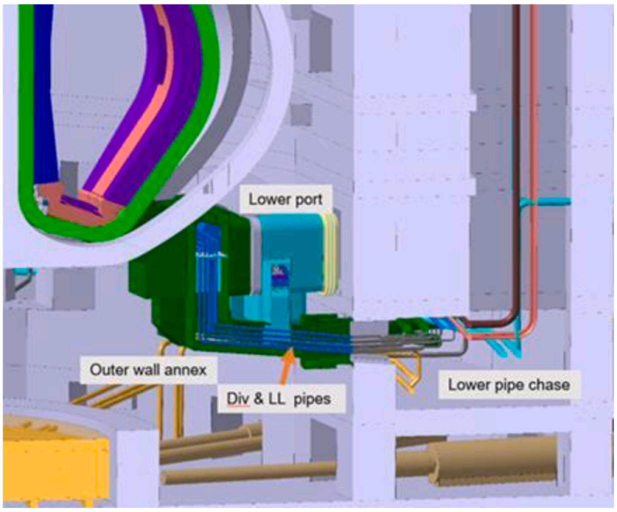


Fig. 8. Pipe routing through outer wall annex to lower pipe chase.

Table 5
Lifetime dose on equipment [Gy/ 6 fpy] due to radiation emitted by activated cooling water in the upper pipe chase.

Room	Gy/6 fpy	Local shielding around pipes
Upper pipe chase	2000	none
	100-1000	5cm lead
Adjacent room with separating wall:		
- 1.0m standard concrete	2	none
- 1.5m standard concrete	0.1	none
- 1.0m heavy concrete	0.1	5cm B4C, 2cm steel
- 1.25m heavy concrete	0.05	5cm B4C, 2cm steel
	0.0001	5cm lead

Table 6
Dose on personnel during shutdown for maintenance due to radiation emitted from activated pipework based on [5].

Room	Dose
Upper pipe chase	10,000 μSv/h
Adjacent room with separating wall:	
- 1.25m standard concrete	0.01 μSv/h

5.1.4.3. HCPB PHTS. Chronic coolant leakage from pipe work and components (e.g. HX, compressors) into the environment is estimated to be ~ 10% of the inventory from a helium loop per year [6]. The key difference from an occupational dose perspective between WCLL and HCPB models is that the tritium in the helium system exists as tritium gas and in the water system as tritiated water.

Until now only the global release of the PHTS pipes along the whole system layout is assessed with 0.6 mg/d. To define the tritium concentration in dedicated rooms like the upper pipe chase, the assessment has to be further differentiated. The release in one room depends on the length of pipe work and the number of leaking components like valves and compressors. These calculations were performed in the KDII2 [11] activities.

5.1.4.4. Lithium lead (LiPb) system. The LiPb activates under neutron exposure and emits gamma radiation [5]. To achieve the defined limits for equipment during operation and staff during maintenance, the system has been routed in dedicated rooms and shafts with the necessary shielding walls. The required wall thicknesses are described in the following Table 7 & Table 8. The results indicate that no personnel access is possible in rooms containing significant amounts of activated LiPb, even after draining the loops. Access in neighbouring rooms is possible due to the appropriate sizing of shield walls.

The dose values in Table 8 are calculated for a transfer time of 27 s between the locations of activation and exposure. The large differences between pipe and tank cases for no shielding configuration are explained by:

- the different cooling times considered, and
- the different thickness of the pipe and tank walls

The LiPb pipes are single pipe 22 m length, 370/307 mm outer/inner radius internal radius made of P22 alloy.

5.1.5. Ex-vessel loss of coolant

In the case of an ex-vessel LOCA PHTS event, the affected rooms have to withstand an overpressure of 1 bar and guarantee a leak tightness to the adjacent volumes. RoX from ITER is that this requirement is difficult to achieve. Due to the different layouts of the systems for helium and water in terms of loops, the lost inventory is different and the expansion volume needed is related to these amounts. In the current design the provided volume inside the PHTS area (120000m3) is not sufficient for an ex-vessel LOCA for the water cooled PHTS Breeding Zone (BZ) system as the peak pressure can reach values far beyond 2 bar absolute, as the BZ PHTS only consists of one circuit (subdivided into 2 connected loops). Therefore a partition of the single circuit seems unavoidable if the current pressure design limit for the building cannot be increased. For helium the current volume of the PHTS area (136000m3) is enough to keep the peak pressure below 1.7 bar (absolute) as the HCPB BB PHTS layout foresees 8 separate cooling circuits [12].

The evaluation of the free volume as expansion volume inside the building in case of an ex-vessel LOCA is done with a CAD model, see Fig. 9. The occupied volume of installed components must be subtracted from this CAD model result.

An additional issue of the ex-vessel LOCA is the amount of tritium which is released due to this event. As the inventory of tritium inside the water of the PHTS is much higher than in helium it has to be taken into account safety wise [14]. Tritiated water and water vapour is about 10, 000 times more hazardous than tritium gas. Once released into the adjacent rooms, however, tritium gas will slowly convert to vapour by surface interactions and humidity of the air, thus creating a significant airborne concentration of tritiated vapour. Detritiation equipment would be required to keep airborne tritium concentrations and environmental releases within safe limits for both helium and water cooling systems. The overall tritium inventory inside the helium coolant is much lower (best case ~ 0.003 g with Coolant Purification System (CPS)) than in the water coolant (best case ~30 g with CPS). The detritiation system must be capable to handle this high amount of tritium to achieve the accepted leakage rate through the last containment boundary.

Table 7
Dose rate on ex-vessel equipment [Gy/time] due to radiation emitted by activated LiPb based on [5].

Room	Dose
Room with LiPb piping	20 Gy/h ≙1.0 MGy/6 fpy
Adjacent room with separating wall:	
- 0.5m standard concrete	0.01 Gy/h ≙ 525 Gy/6 fpy
- 1.0m standard concrete	10^{-5} Gy/h ≙ 0.525 Gy/6 fpy
LiPb drain tank room	n/a
Adjacent room with separating wall:	
- 0.5m standard concrete	$4\bullet10^{-4}$ Gy/h ≙ 21 Gy/6 fpy
- 1.0m standard concrete	$6\bullet10^{-6}$ Gy/h ≙ 0.3 Gy/6 fpy

Table 8
Occupational Radiation Exposure (ORE) [5].

Room	Dose, days after plasma shutdown
Room with LiPb piping	8 Sv/h (1 day)
Adjacent room with separating wall of 1.25m standard concrete	2 μSv/h (1 day)
LiPb drain tank room	
- full tank	30-40 mSv/h (1 day)
- tank containing 0.3 m^3	6-7 mSv/h (1 day) 0.8-1 mSv/h (12 days)
Adjacent room with separating wall of 1.25m standard concrete	0.08 μSv/h (1 day)
- full tank	negligible (1 day)
- tank containing 0.3 m^3	

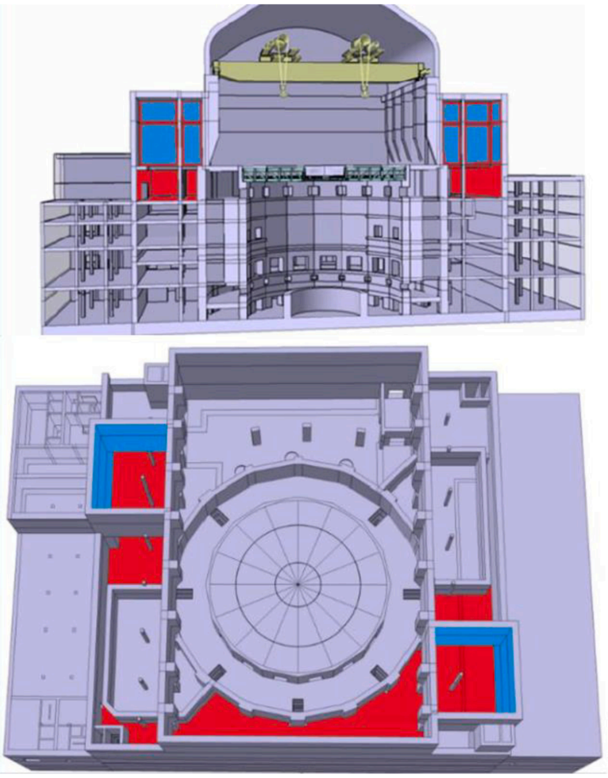


Fig. 9. Volume PHTS WCLL equipment room.

5.1.6. Specific mitigation strategies

The layout of tokamak building presents several criticalities as shown in the previous paragraphs. Further specific challenges are presented here together with the relevant mitigations.

5.1.6.5. Protection of cubicles from radiation dose. To protect electrical equipment to be deployed in so- called cubicles from intense radiation exposure, it is suggested to place them, when possible, on intermediate plant levels not exposed to radiation e.g., Q-level & upper feeder level sufficiently far away from any radiation hazard pipework and with any presence of VV ports, see Fig. 10.

5.1.6.6. Pipe whipping. In order to mitigate the consequences of pipe whipping event due to a guillotine break of a high-energy pipe, specific

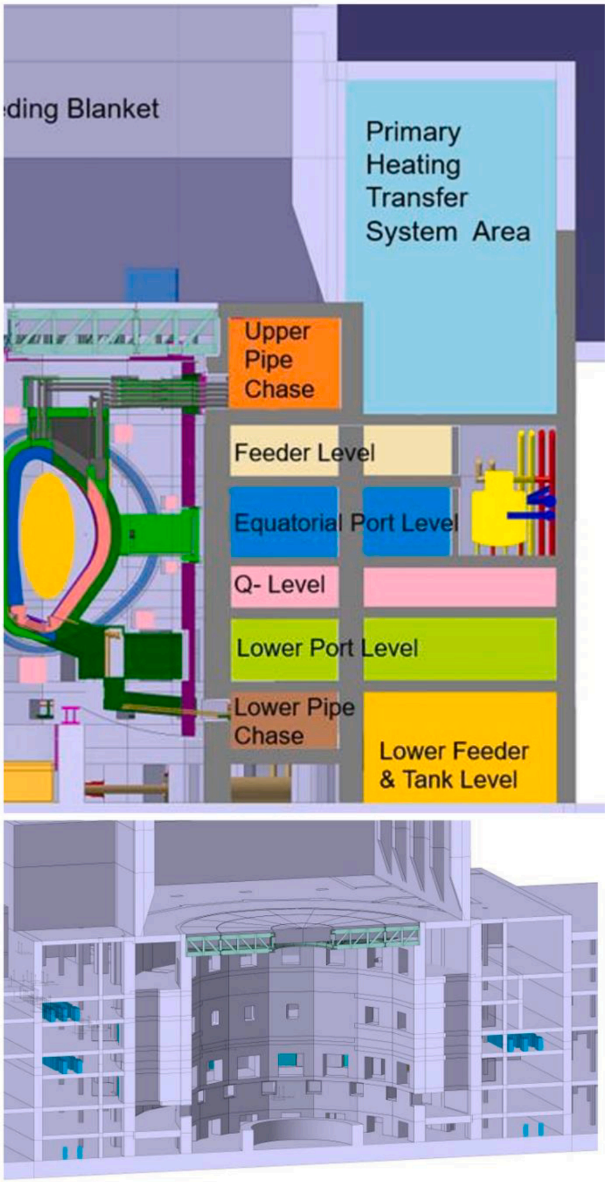


Fig. 10. Intermediate low radioactivity levels; Q- level & feeder level for integration of cubicles.

requirements and precautions for the layout of safety systems within the rooms containing PHTS pipes, such as:

- Pipe routed in dedicated vertical shafts
- Separation up to Segregation (e.g. for SIC-1 component)
- Same Diameter & Same Thickness Rule
- Adoption of restrains of the pipes according to a dynamic analysis

5.1.6.7. Release of cryogenic fluid. DEMO magnets, and relevant thermal shields, need a huge quantity of He at 4k and 80k to maintain their status of superconductivity with an adequate margin to face the electromagnetic and thermal transients. From a preliminary evaluation, the quantity of He at 4k overcomes 20 ton. Therefore the 4K and 80K helium pipes of the cryo-distribution will be arranged inside dedicated shafts and areas in order to mitigate the relevant hazard in particular the overpressurization of the volumes and also to avoid damage due to the chilliness on other systems, equipment and pipework. Involvement of industry in this areas at the early design stage has proven to be very valuable.

6. Lesson learned from ITER

As detailed in previous chapters, maximum consideration to ITER experience is given for the DEMO layout, with particular reference to the Tokamak building. The main lessons learned are:

- The homogeneous development of the design of the main systems is essential in order to optimise the overall layout.
- The accurate shielding from γ and neutron radiation coming from the VV through the several tens of penetrations and from activation of the water (Nitrogen and ACP) of the PFC PHTS.
- The early definition of layout criteria in a nuclear building: specially the maintenance and safety criteria.
- The early definition of SIC SSC and the relevant implications in terms of design criteria and standards.
- The importance of the zoning definition early in the design phase, including fire, ventilation (pressure cascade versus contamination risk), radiation, etc.
- The control of radioactive contamination as close as possible to avoid spreading of contamination on large volume and the consequent need of complex decontamination system (as, e.g. DS).
- The leak tightness of the tokamak building under accident conditions has to be warranted with a good margin as it is the fundamental parameter adopted in safety analysis to demonstrate that DEMO meets the safety goal of limited releases and no-evacuation. This operation limit has to be checked each few years and this test is complex considering the huge volumes of the few zones to be tested.
- The layout should meet the ALARA principle for ORE of DEMO. In that respect, when possible, locate
- the components out of the tokamak building for an easier maintenance (higher RAMI) and a smaller ORE.
- The spreading of the nuclear safety culture among all SSC designers in nuclear buildings and particularly in the tokamak building is important to build up the DEMO design in view of the nuclear license process.

7. Conclusions

This paper describes two concepts of the tokamak building layout with particular regard to the maintenance approach of PFC components:

- Compartment-oriented building layout:

It implies divisions of the volumes inside the nuclear tokamak building to minimize the volumes affected by contamination and hazards due to the considered accidents.

During in-vessel maintenance, transfer casks are docked to the VV providing primary confinement. They operate in sealed port cells providing secondary confinement. The spread of contamination into other building areas is therefore minimized in accordance with the ALARA principle prescribed by the nuclear licensing authority. The port cells also segregate the building.

- Maintenance-oriented building layout:

Instead of port cells, larger containment cells are implemented into the building layout. These provide primary confinement as no casks are used for in- vessel maintenance. This approach facilitates the access into the VV and the sequential use of different RH tools and is expected to accelerate the in-vessel maintenance operations.

Based on the information available to date, the compartment-oriented building layout is preferred chosen in spite of its disadvantages regarding the accessibility of in-vessel components by RH tools. The maintenance- oriented building layout presents concerns regarding insufficient contamination control and non-compliance with the ALARA principle. The licensing process may be compromised in cases where contamination spreads into:

- areas which need human access,
- multiple building areas,
- leak of contamination into the environment in normal or accident conditions

Further work is required to quantify the issues associated with each of the building layouts such that a building architecture can be chosen for DEMO which meets the needs of both safety and maintenance.

CRediT authorship contribution statement

C. Gliss: Conceptualization, Methodology, Validation, Visualization, Supervision, Writing – original draft. **C. Bachmann:** Conceptualization, Writing – review & editing. **S. Ciattaglia:** Conceptualization, Writing – review & editing. **B. Drumm:** Conceptualization, Methodology, Validation, Visualization, Supervision, Writing – original draft. **M. Gracia Camacho:** Methodology, Formal analysis. **I. Moscato:** Conceptualization, Writing – review & editing. **T. Mull:** Writing – review & editing. **I. Palermo:** Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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