Strategical Approach for the Neutronics in the European Fusion Programme

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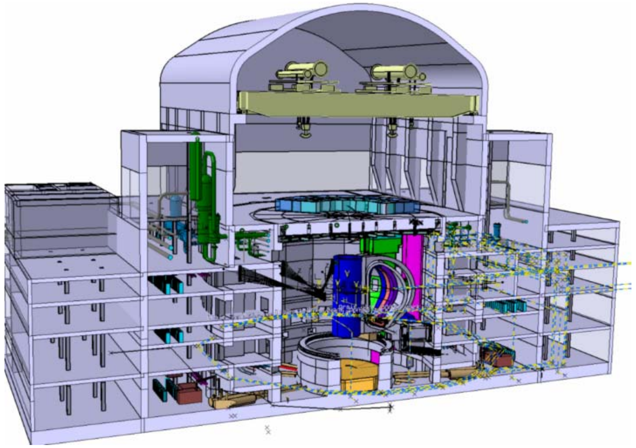
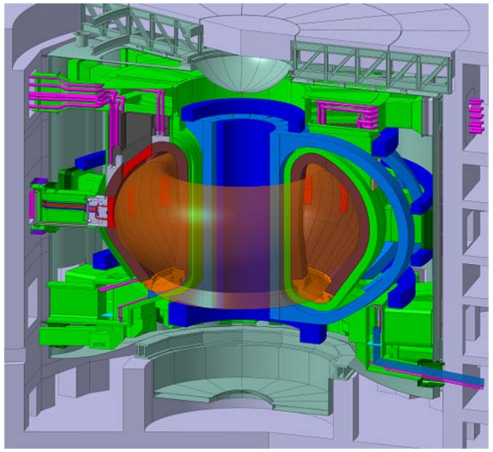
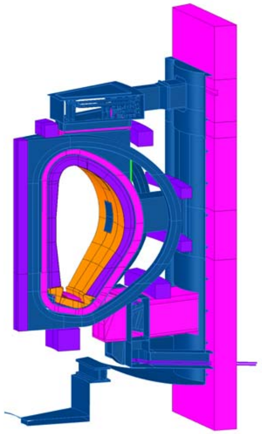
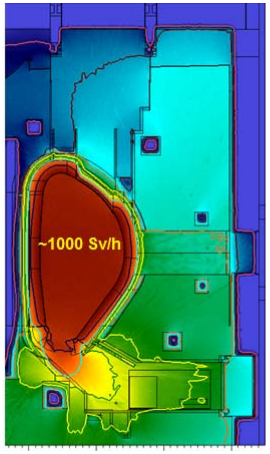






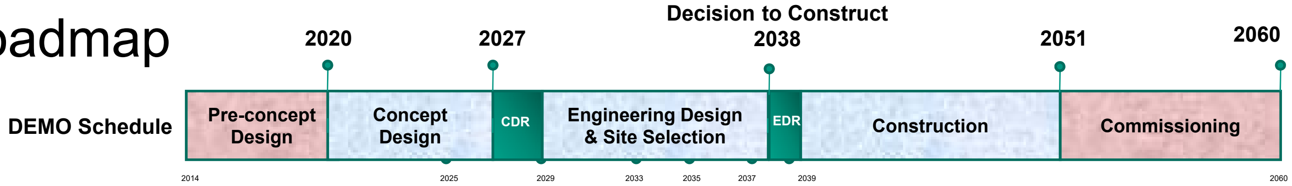


Content

- Introduction
- Nuclear Design Integration
- Neutronics strategical approach for DEMO
- System-engineering integration
- Recent applications
- Future Plans
- Conclusions

Introduction

- European Fusion Roadmap
  - DEMO
  - IFMIF/DONES

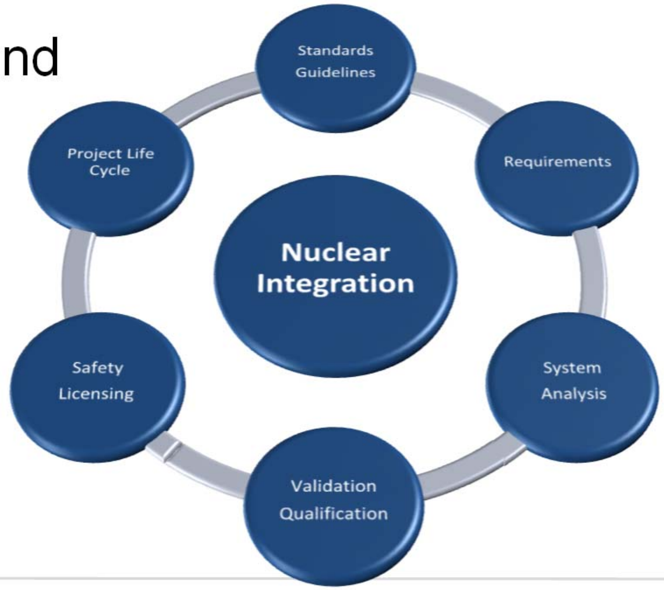


- Experience in nuclear fusion technology R&D
  - Strengthening nuclear design integration
  - Improving nuclear safety culture
  - Identification of transversal, plant-level functions
- Neutronics plays a fundamental role for the design, operation and safety of these facilities including the evaluation and verification of their nuclear performances.

Nuclear Design Integration

Identification, analysis and resolution of all radiation induced issues along the full life cycle of the nuclear installation.

- „Nuclear Design Integration“: attention to the design phase adopting appropriate technical and administrative measures.
- EU DEMO Conceptual Design Phase
  - DEMO Design Authority supported by DEMO Central Team
  - Nuclear Design Integration with dedicated responsibility.



Neutronics Strategical Approach

Progressing Nuclear Design Integration by integration of neutronics workflows in system-engineering design processes.

Design iterations with full accountance of nuclear design and radiological protection objectives.

- Based on: Qualified computational methodology | Configuration & requirement management
- Aiming at: **Established procedures**

⇨ Validated nuclear performance parameters

⇨ Requirement verification and design validation

Methodological Approach for DEMO*

Neutronics workflows stipulated by Neutronics Guidelines.

Recommendation on use of tools, data and requested nuclear responses.

Tools

- Radiation transport: MCNP, TRIPOLI
  - SERPENT, GEANT4, OpenMC …
- Activation: FISPACT-II, ACAB
- Shutdown coupled codes: MCR2S, R2S-UNED, R2Smesh, AdD1S
  - cR2S (to be released)

Data

- Neutron transport: JEFF, FENDL
- Activation: TENDL
- Response files: for damage and gas production

* IFMIF/DONES neutronics is based on similar approach with specific pecularities:

- Neutron source from d-Li
- Deuteron/proton nuclear data
- …

System-Engineering Integration

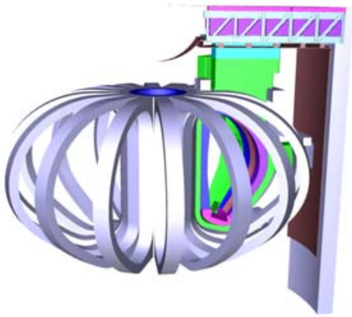
Current focus on prime ingredients

➡ Requirement Management

- Common understanding of requirements (specifications)
- Complete and good requirements
- Product and process requirements
- Transversal functions and requirements

➡ Configuration Management

- Configuration definition and change control
- Up-to-date, referenced and applicable data
- Consistency of engineering/configuration and neutronics models
- Data management



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Requirement Management

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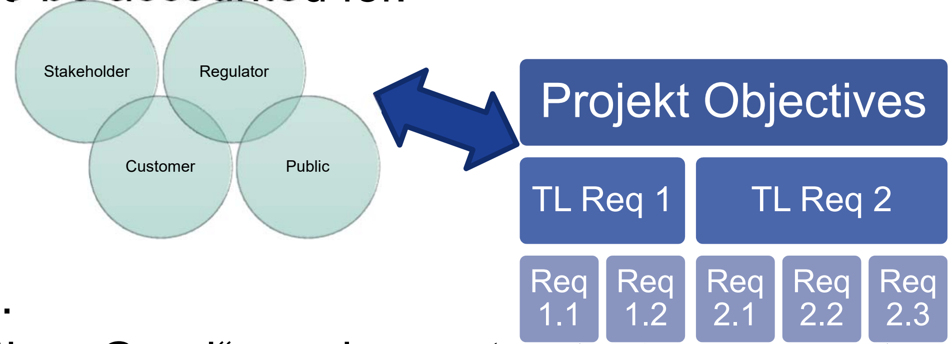
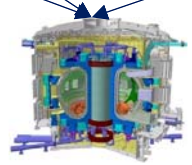
- Requirements derived from project objectives (goals) to describe a condition or capability to be met or possessed by an item in the scope of the project. External constraints/regulations need to be accounted for.



- Collection, priorisation and elaboration.
- Hierarchical order, allocation, propagation.„Good“ requirements, e.g.:
  - Traceable to the origin
  - Consistent
  - Verifiable



„Neutronics Requirements“

- Task oriented
  - To provide nuclear responses of interest

Impact of radiation sources/fields	Provision of nuclear parameters
•System design	•Tritium production
•Plant operation	•Heating/power generation
•Plant maintenance	•Shielding performance
•Licensing	•Activation, decay heat, shutdown dose
•Safety case	•Radiation damage, transmutation, gas production
•Decommissioning	

➡ Design of breeding blanket for DEMO: HCPB and WCLL design concepts

„Neutronics Requirements“

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- Task oriented
  - To provide nuclear responses of interest
  - To provide protection (shielding) requirements
  - To verify compliance with load specifications and protection requirements

Nuclear loads

“Design against loads”

Radiation sources

Primary loads: e.g. heating, damage

Secondary loads: e.g. decay heat, shutdown dose

<u>Limits on loads</u>

Nuclear shielding

“Design for shielding”

Radiation transport

Plasma neutron responses

Activation and decay responses

<u>Limits on exposure</u>

<u>Shielding requirements</u>

„Neutronics Requirements“

- Load specifications related:
  - To define nuclear loads on systems, structures and components
- Protection requirements related:
  - To limit radiation loads relative to design or damage limits of sensitive and critical systems
  - To constrain and limit exposure to ionizing radiation (ALARA)
- Quality requirements related:
  - To follow Established Procedures

Nuclear shielding requirements

- Investment protection
  - Ageing and damage limits
- Radiological protection
  - Exposure rate constraints/targets

Component/ location	Requirement	Limit (target)
Port interspace	Shutdown dose rate 12 days after shutdown	~500 µSv/h (target)
Port cells (occasional access)		100 µSv/h (target)
Maintenance hall above tokamak		Tbd.
In-cryostat area, [7]		100 µSv/h (target)
Tokamak building areas beyond port cells requiring frequent access, [7]	Shutdown dose rate 1 day after shutdown	10 µSv/h (target)
Critical electronic equipment	Neutron fluence during operation	0.01 n/(cm²s)
Non-critical electronic equipment		100 n/(cm²s)

Component/ location	Requirement	Limit (target)
Starter blanket FW	Displacement damage to Eurofer	20 dpa
2nd blanket FW		50 dpa
Divertor cassette body (@ 180°C), [8]		6 dpa
Divertor PFCs, [9]	Displacement damage to CuCrZr	10 dpa, possibly up to 20 dpa
VV	Displacement damage	2.75 dpa
	Nuclear heating, [10]	0.5-1 W/cm³ (target)
	Activation, [2]	Minimize (target)
Cutting/re-welding location in IVC cooling pipes	Helium production	1 appm
Superconductors, [11], [12]	Total neutron fluence to epoxy insulator	10^{22}/m²
	Fast neutron fluence to the Nb3Sn	10^{22}/m²
	Neutron fluence to Cu stabilizer between TFC warm ups	1-2·10^{21}/m²
	Nuclear heating in winding pack	50 W/m³

From baseline documentation

Plant Safety Requirement Document

Plant Load Specification → Nuclear Analysis Handbook

Plant Description Document

„Established Procedures“

„Set of processes, instructions and guidelines which is qualified for the requested purpose usually on the basis of state-of-the art technology, proven methods and tools and good practices.”

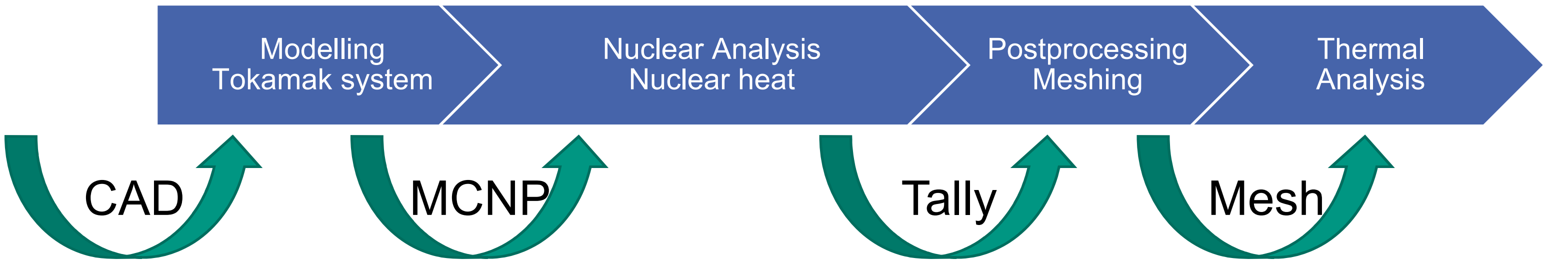
- Due to lack of fusion neutronics Codes&Standards there is need to define references and quasi-standards.
- Including generic requirements on roles&responsibilities and suitable qualification/experience of involved actors.
- Including specific technical requirements on the activities and artefacts of the processes.
- Accounts for impact on performance, safety, cost and schedule by graded approach (level of rigorousness).

Configuration management

- Identification of data to be put under configuration control and to be assigned to (technical) baseline documentation.
  - Input, intermediate, output data
  - Established procedures
- Databases and configuration control documents are progressively issued:
  - Geometry models for radiation transport (MCNP input)
  - Material specifications
  - Radiation source terms
  - In future: Protection Important Components and Activities (safety classification)
- Nuclear Analysis Handbook (→ Plant Load Specification)
  - Living document to follow configuration/design changes and to provide reference data.
- Applicability assessment

Data management

- Up-to-date, referenced and applicable data items
  - Change control, traceability, and applicability range
- Series of subsequent analysis activities
  - Upstream analysis result (or model) used in downstream calculation (or modelling)



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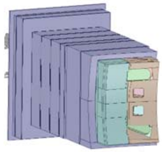
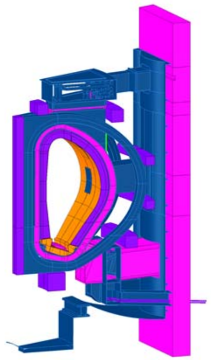
Data classification

- Problem-specific data
  - Material definitions, geometry models, assembly, operational conditions, environmental conditions, etc.
- Reference project data
  - Same as above, but for general applications
- Generic project-independent data
  - Nuclear cross sections, response functions, etc.
- Deficient/missing data
  - Use of assumptions





Verification & Validation

Databases, repositories

Change and version control

Continuous improvement

Sensitivity studies

Recent applications

- Breeder Blanket neutronics design support
- DEMO tokamak global shielding improvements
- DEMO sky-shine calculations

Breeder Blanket neutronics design support

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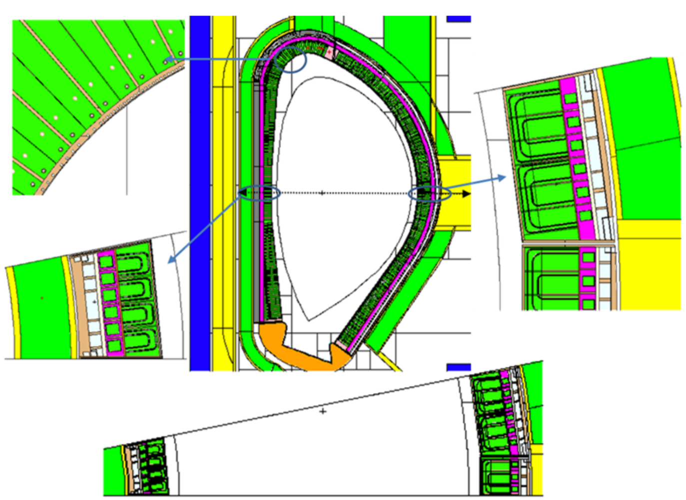
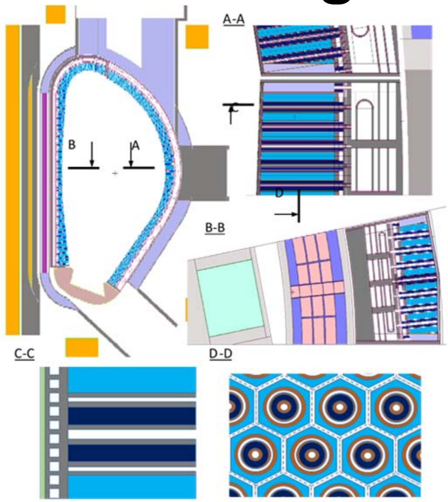


Water**C**ooled**L**ithium**L**ead

New cooling layout IB

PbLi (90% ^{6}Li)

Water (15.5 MPa)



Helium**C**ooled**P**ebble**B**ed

Radial fuel breeder pins

Li_4SiO_4 (35 mol% Li_2TiO_3)

$Be_{12}Ti$

He (8 MPa)

Component	HCPB [MW]	WCLL [MW]
Total BB	1941	1739
Divertor	169	133.4
VV	45	8
Total reactor	2155	1880.4
Global energy multiplication	1.35	1.18

TBR	HCPB	WCLL
Inboard	30 %	30.3 %
Outboard	70 %	69.7 %
Total	1.18	1.15

➡ Continous effort on optimizing nuclear performance (incl. shielding) under design constraints

DEMO tokamak global shielding improvements

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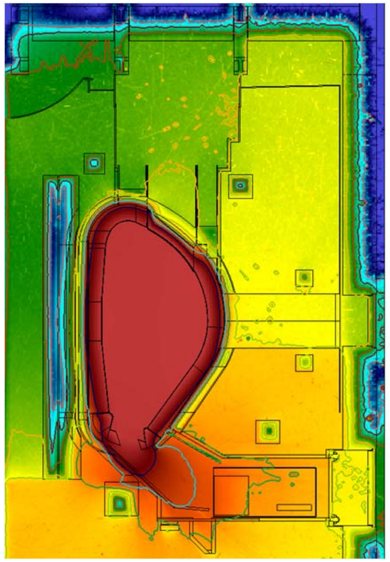
Strategical approach

- Status of protection requirements and priorities
- Assessment of radiation mapping from plasma neutron source
- Identification of key configuration and design options
- Study of advanced „baseline“ configuration: VV and intercoil shields
- Study of various options at port level



DEMO tokamak global shielding improvements

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Status of protection requirements and priorities

- Protection objectives
  - Radiation sensitive equipment: „to the limit“
  - Worker protection: „ALARA“
  - (concurrent or competitive objectives!)
- Radiation source inventories
  - Identification, quantification (source strength)
  - Localization (movable/transported sources)

➡ Radiation transport and shielding analysis

DEMO tokamak global shielding improvements

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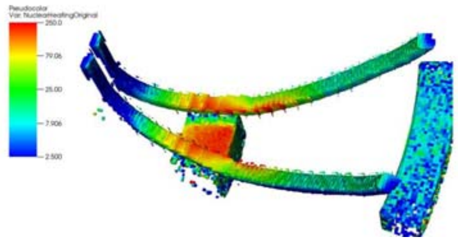
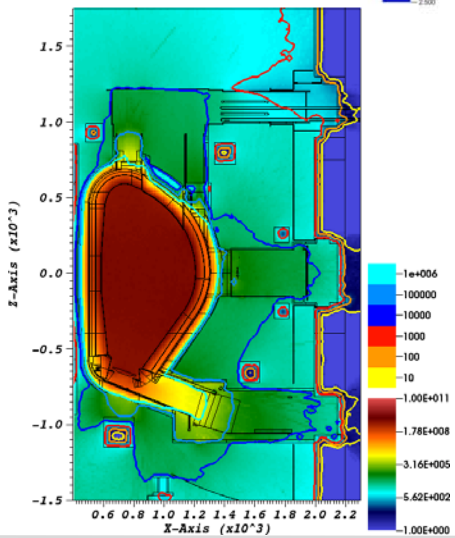
Assessment of radiation mapping from plasma neutron source

- Excessive radiation loads
  - Hot spots of nuclear heating density in TFC
  - Leakage through ports and penetrations (pipework)
  - Attenuation through in-vessel and vessel barrier

➡ Shielding from the source

➡ Streaming and leakage mitigation

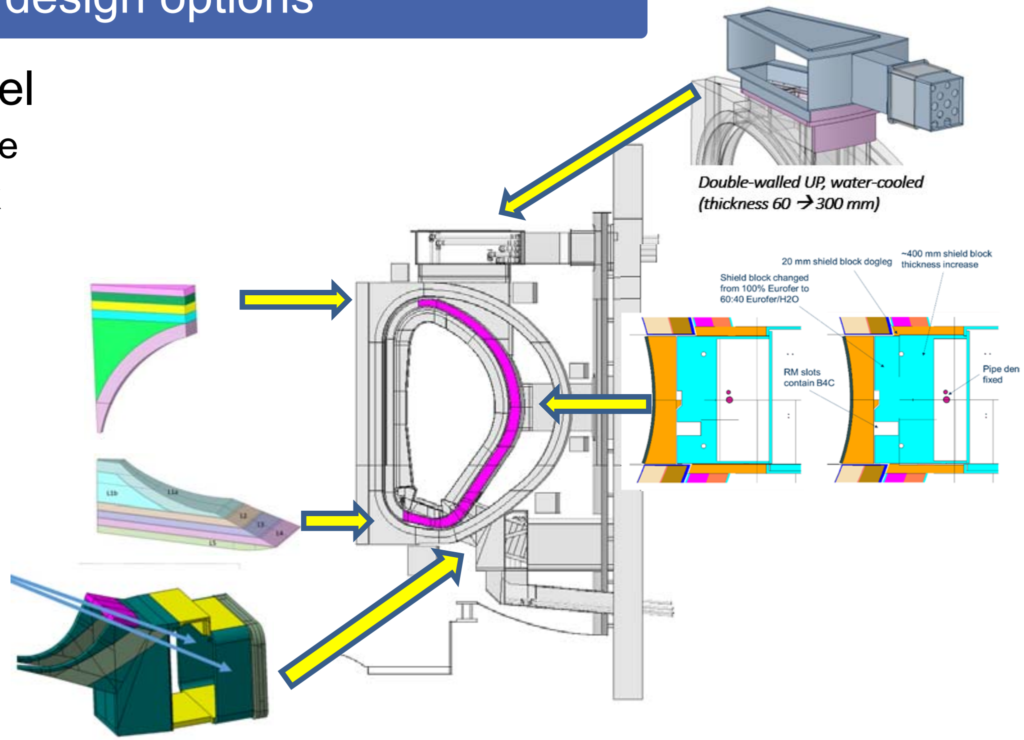




DEMO tokamak global shielding improvements

Identification of key configuration and design options

- Primary shield barrier: Vacuum Vessel
  - Thickening of In-Wall Shield at outboard side
  - Filling in of top/bottom inter-coil shield block
- Bulk shield extensions: Equatorial port plugs
  - Radial extent of shield blocks
- Streaming mitigation: Upper port penetrations
- Leakage mitigation: Port duct walls



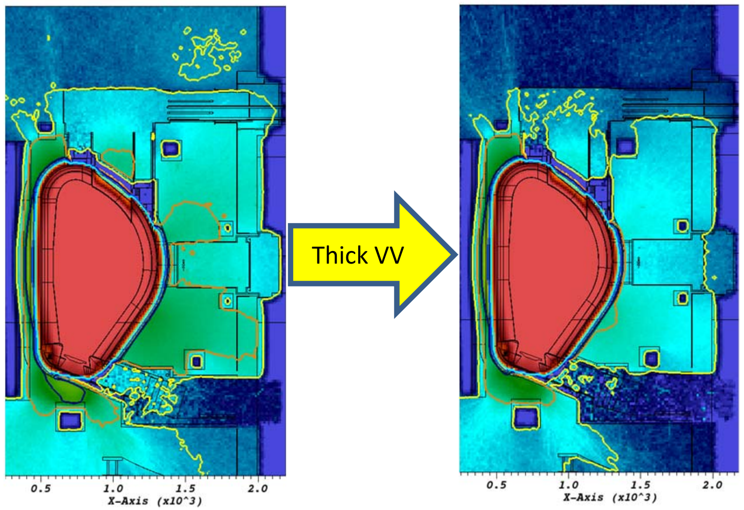
DEMO tokamak global shielding improvements

Study of advanced „baseline“ configuration: VV and intercoil shields

- Generic layout of system architecture

  → Design approach towards global performance

- Neutron transport with blocked port openings
  - Performance of bulk shield barrier
  - Overall reduction of in-cryostat neutron flux by 1-2 orders
  - Promising reduction at top/bottom of tokamak
- Shutdown dose rate global maps (in progress)



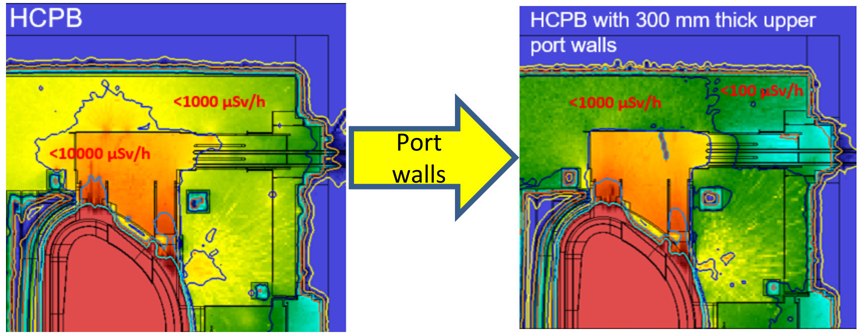
DEMO tokamak global shielding improvements

Study of various options at port level

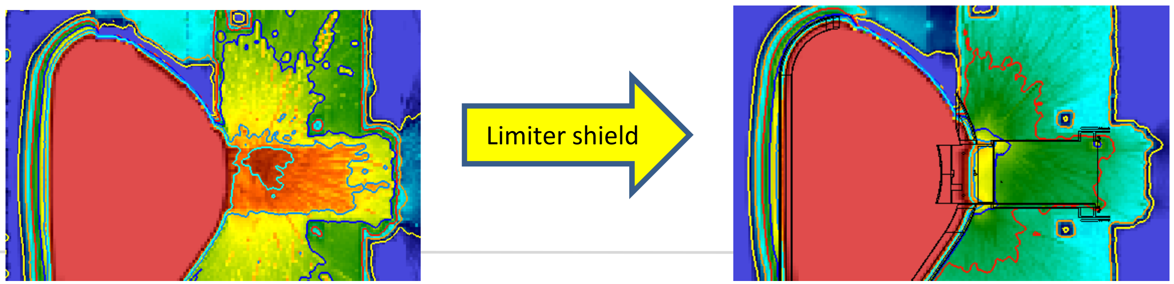
- Streaming and leakage mitigations

➡ Standardized local shield options

➡ Reduction of radiation cross talk effects

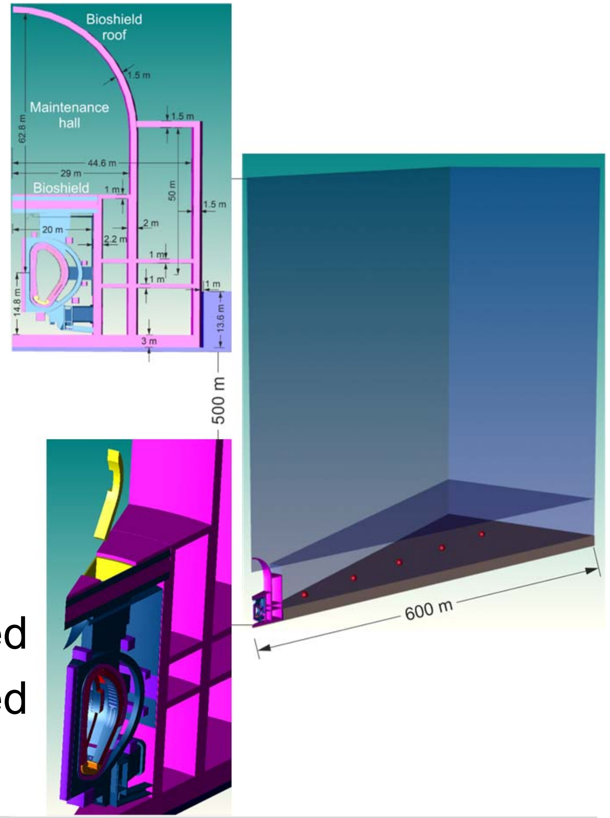


- Promising improvements on SDDR in port interspaces and in-cryostat volumes



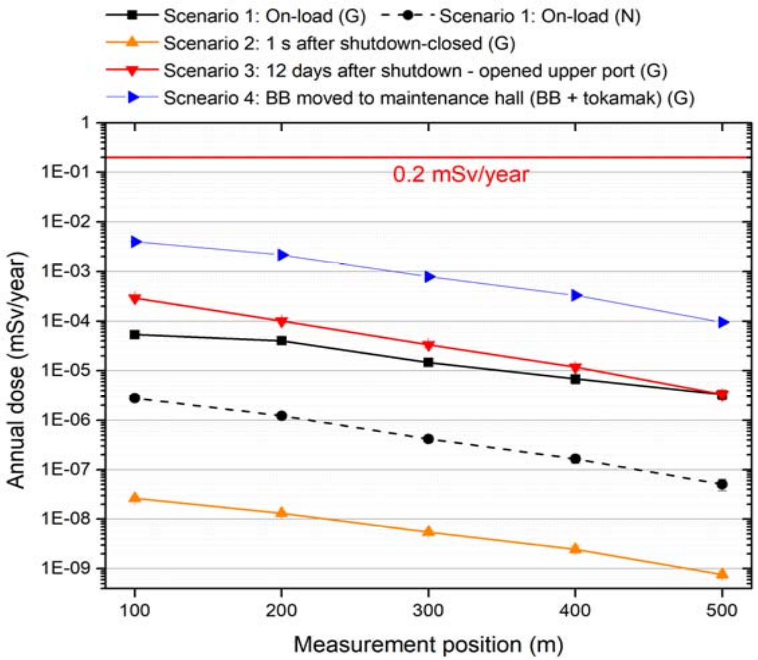
DEMO sky-shine calculations

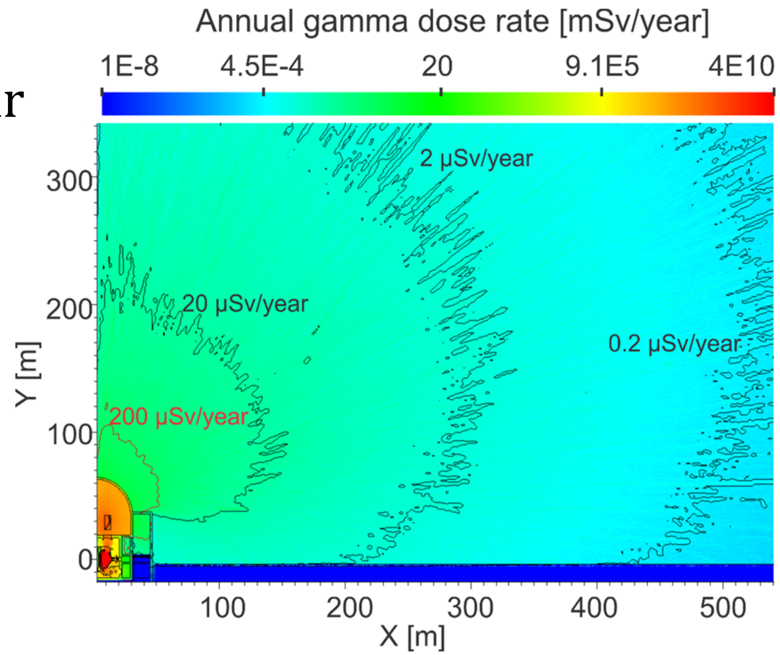
- Computational method and tools
  - ADVANTG 3.0.3. for variance reduction (Denovo)
  - MCNP5 v1.6 and MCNP 6.2
  - MCNP source subroutine for reading Common decay gamma source files
  - Ambient dose equiv. $H^{*}(10)$ with flux-to-dose conversion coeff. (NCRP-38, ICRP-74)
- Scenarios
  - 1: On-load operation (plasma source)
  - 2: 1 second after shutdown
  - 3: In-vessel maintenance where the upper port is opened
  - 4: In-vessel maintenance where the upper port is opened and the BB is moved into the upper maintenance hall



DEMO sky-shine calculations

- Dose rate limit at site boundary $200\ \mu Sv/year$





Annual dose rate at site boundary with large margin below limit

(plasma neutron source and associated tokamak activation)

Future plans

- Enhancing neutronics framework
  - Processes for nuclear design integration
  - Quality assurance system
  - Focused R&D on coupled tools and interfaces
  - Qualification of workflows, including alternative MC transport codes
  - R&D on nuclear data development and experimental validation
- Exploitation of collaborative efforts
  - Nuclear Data: JEFF, FENDL, …
  - Radiological protection: ITER Organization
  - Neutronics worksflows in nuclear design integration: US-DOE (U Wisconsin; ORNL)

Conclusions

- Strategical approach for neutronics aims at integration of neutronics workflows into system-engineering context of Nuclear Design Integration.
- The workflows (established procedures) build on qualified methodology and suitably adopted configuration/requirement principles.
- Comprehension of radiological protection objectives and their project implementation is a key prerequisite.
- Neutronics plays a fundamental role in defining global shielding strategies and verification of solutions.
- Future work includes streamlined R&D on qualified and efficient tools, data and workflows in collaboration with the international fusion neutronics community.

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Thank you for your attention!

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