# Experience of developing a specific fusion safety related standard

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# Outline

- Development of ISO 18518
- Lessons learned
- C&S need question through examples of nuclear analyses
- Summary

# ISO 18518 – a specific fusion safety related standard

- **Magnetic fusion facilities — Requirements for the safety systems raised by the application of the superconducting technology**

International Standard

**ISO 18518**

**Magnetic fusion facilities — Requirements for the safety systems raised by the application of the superconducting technology**

*Installations de fusion par confinement magnétique - Exigences applicables aux systèmes de sûreté soulevées par l'application de la technologie supraconductrice*

First edition
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ISO 18518:2025(en)

## Foreword

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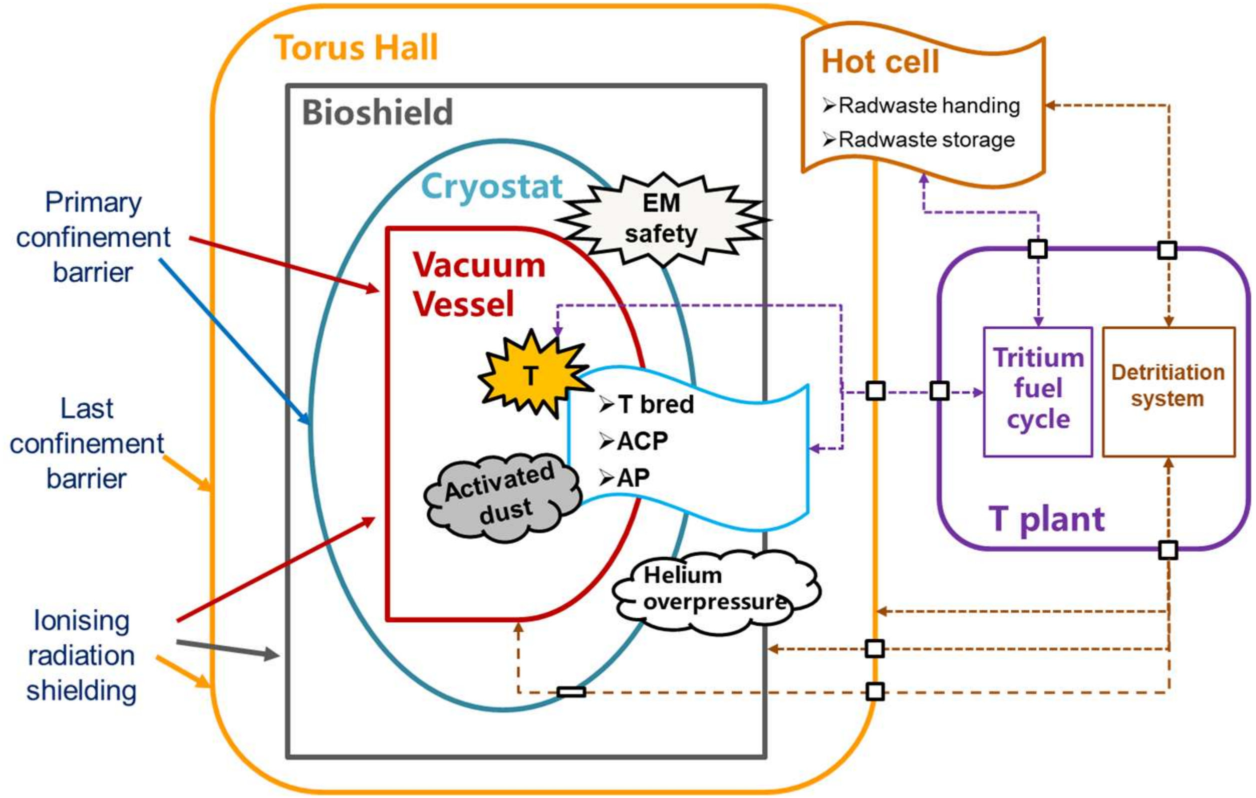
This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

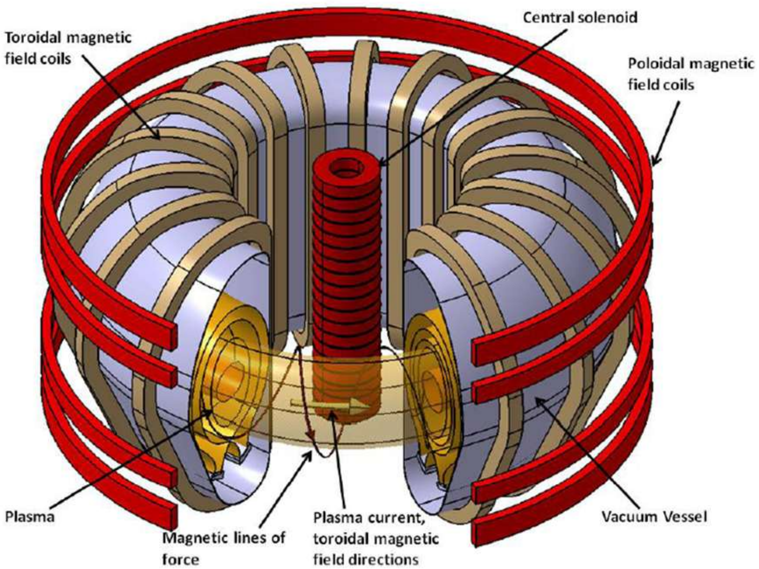
# Motivation (1/2)

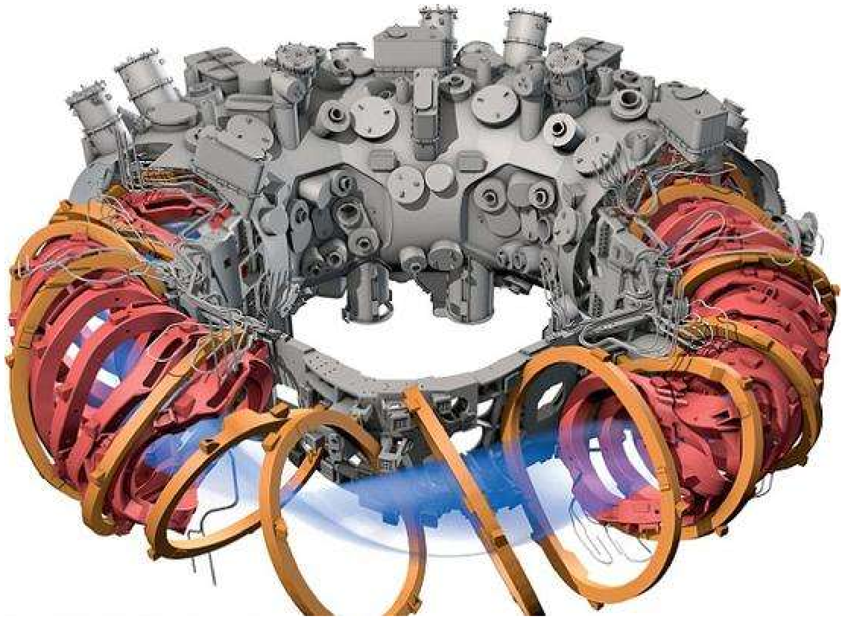
- **Safety functions of a D-T fusion device**
  - Confinement of radioactive and explosive materials
  - Limitation of ionizing radiation



# Motivation (2/2)

- **Magnets (esp. SC) are essential components in magnetic confinement fusion devices, inc. tokamak and stellarator**
  - to confine and shape the fusion plasma core
  - to drive the plasma current
- Superconducting magnets systems are located outside the vacuum vessel (1st confinement barrier in fusion reactor) and inside the cryostat (may serve as 2nd safety or cryogenic confinement barrier)



# Safety requirements

- **Tritium inventory control**
  - Normal operation
  - Incidents & accidents
  - Internal & external hazard
- **ALARA principle**
  - for radioactive and hazardous inventories for the site, plants, zones, systems and components
  - Shielding adequacy for hands-on operation and personnel access
- **Radiological zoning** – internal&external dose limits and constraints
- **Materials activation** to alleviate the radwaste management
- **Operation** programme and performance

# Safety justification

- **Safety provisions** for both normal operation and accident scenarios
  - To protect workers, the public and the environment
  - To prevent accidents
  - To mitigate the consequences
  - To minimise radioactive waste hazards
- **Safety justification needed** to demonstrate the design of components and integration will deliver a safe operation
  - Defense in depth to be implemented for fusion facility
  - To determine the limits and to apply ALARA principle
- **To guide the design, inc. safety implementation**
  - How to justify the design ➔ Functional qualification
  - How to meet safety requirements ➔ Safety qualification

# Gaps to be filled

- **Specific requirements raised by applying the superconducting magnets in nuclear fusion facilities**
  - Penetrations through vacuum vessel, cryostat and building walls
  - Shielding capability
  - E-M load on the vacuum vessel
  - Magnetic field environment for electronics that are necessary for nuclear instruments and measurement, e.g. to monitor N/P production and fusion power
  - Magnetic measurement to be placed inside the vacuum vessel
  - Hazard associated with superconducting magnets, e.g. loss of superconductivity (quench), Parschen breakdown following helium and voltage leakage

# Development consideration

- **Confinement related**
  - To mitigate the risk and consequence of hazard associated with superconducting magnet systems, e.g.
    - ➢ Accidental discharge of the magnetic energy – impact on $1^{st}$ confinement barrier;
    - ➢ Accidental outbreak of the cryogenic helium – impact on cryostat and penetrations through building walls
- **Radiation protection related**
  - To reduce/minimise the radiological dose exposure
    - ➢ To enhance the performance and reliability of superconducting magnet in a nuclear environment
    - ➢ To facilitate the maintenance and repairability of large scale superconducting magnet

# Limitation and difficulties

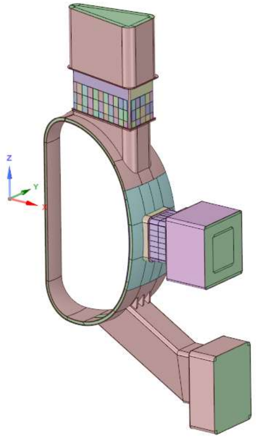
- The immaturity of the fusion safety system and framework
- The overlap of the radiation safety between fusion and fission applications
- The narrowness of the specific technology application in fusion
- The prevention of the content repetition from other existing and under-development standards

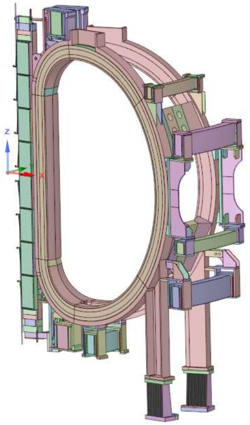
**C&S need question/discussion**

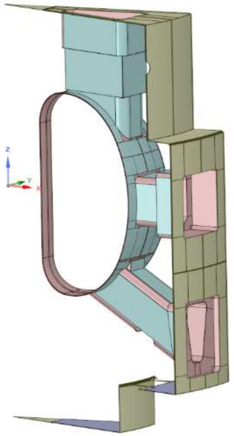
**through examples of nuclear analyses**

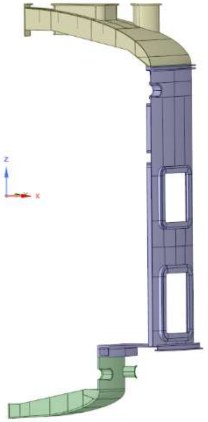
# Neutronics modelling & verification

- **CAD models**

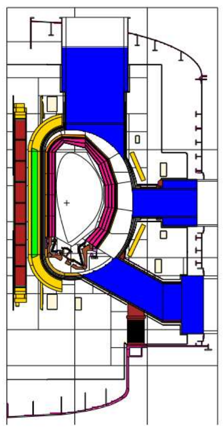

Vacuum Vessel

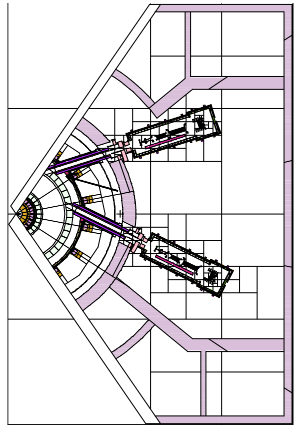

Coils

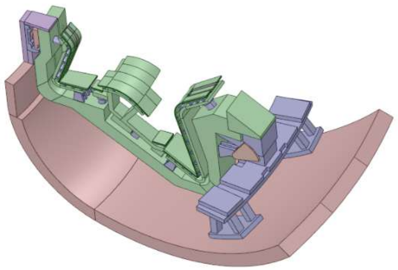

Thermal shield

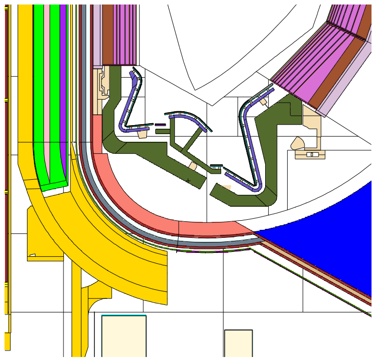

Cryostat

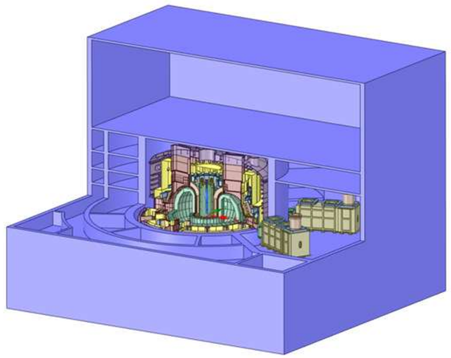
- **Neutronics models**

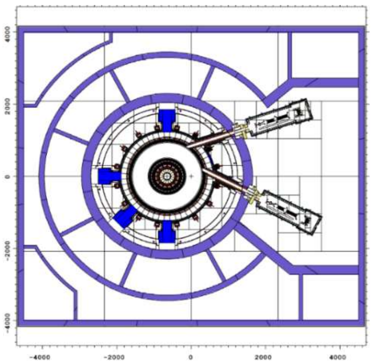

22.5° sector


112.5° NBI


Divertor




Tokamak + building

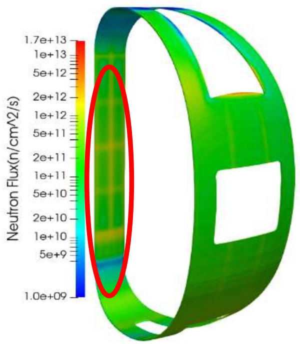

360° model

# Shielding analysis

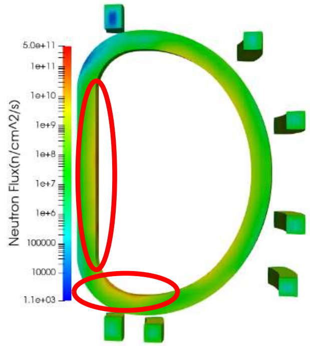
- **Shielding Requirements for Irradiation-Sensitive Components**

  - ☐ **VV design limit**
    - Ensure the reduction in fracture toughness not exceed 30%: DPA < 2.75
    - Ensure rewelding performance: He production < 1 appm
  - ☐ **TFC design limit,** ensure superconductivity, consider cooling capacity:
    - NHD: steel case < 2E-3 $W/cm^3$, conductor < 1E-3 $W/cm^3$
    - Fast neutron fluence: insulator < 1E18 $n/cm^2$, conductor < 1E19 $n/cm^2$

- **Neutron Leakage**

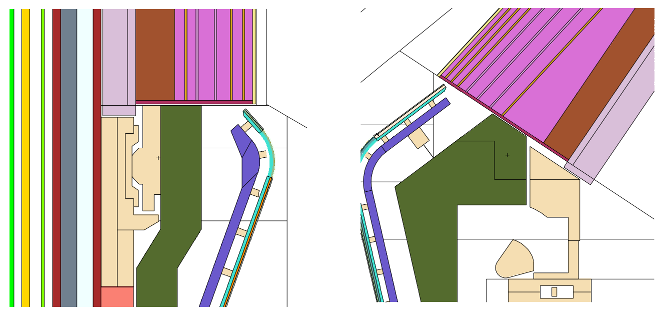



(a) VV

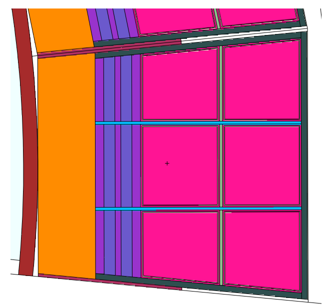



(b) TFC & PFC

- **Shielding Design**



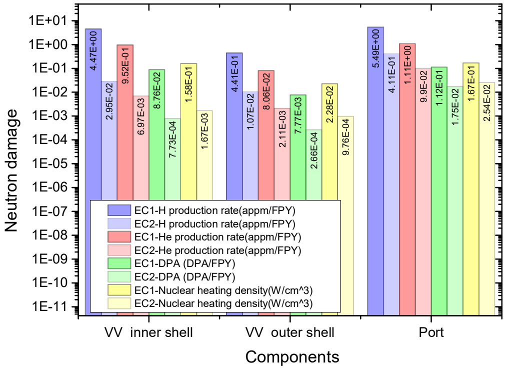
(a) Gap between BLK & DIV



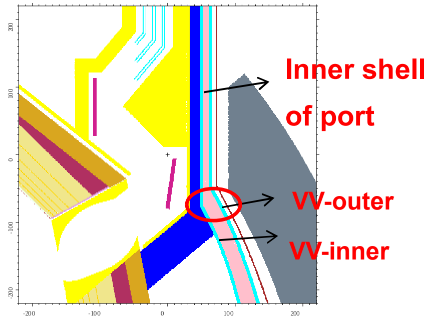
(b) Gap between BLK modules

# Neutronics analysis for ECRH

- **VV-inner**

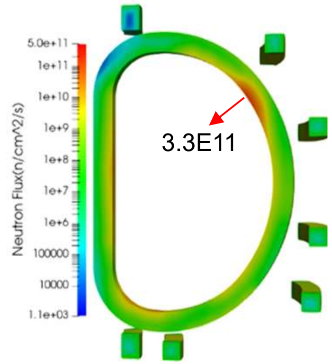



(a) maximum of irradiation damage

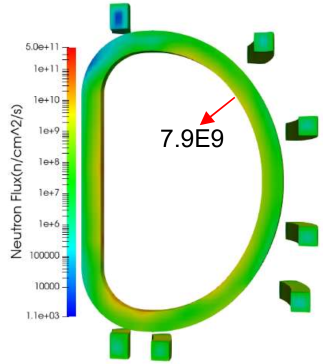



(b) tally region

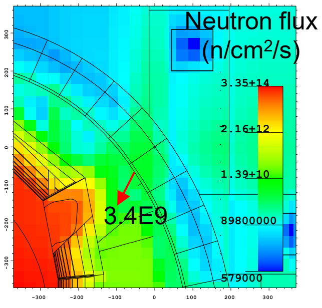
- **Superconductor coils**



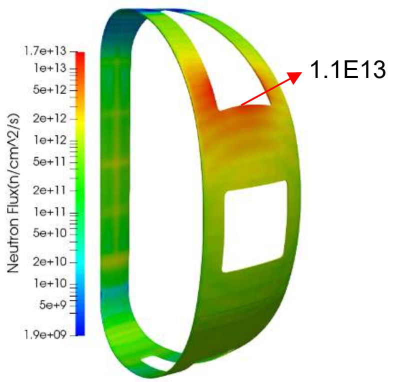

(a) EC1



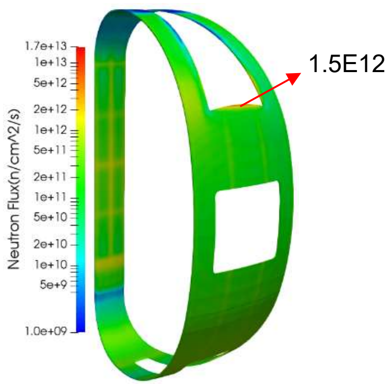

(b) EC2




(c) fast neutron flux of EC2




(a) EC1

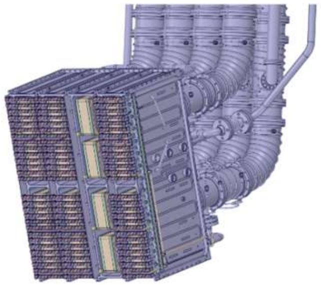


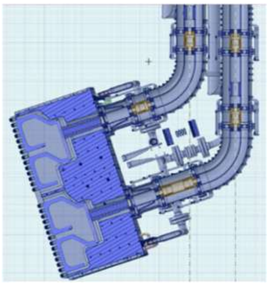

(b) EC2

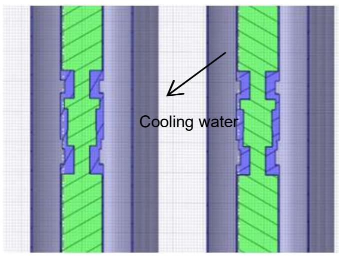
- ✓ The peak damage of VV is at the junction between VV and port.
- ✓ The VV damage of EC2 are approximately 1-2 orders of magnitude lower than those of EC1.
- ✓ In EC2, the maximum VV damage is $9.9 \times 10^{-2}$ He-appm/FPY and $1.75 \times 10^{-2}$ DPA/FPY, which meets the limits after 10 FPY of operation.
- ✓ After shielding optimization, all TFC parameters are reduced by approximately 2 orders of magnitude and are below the limits

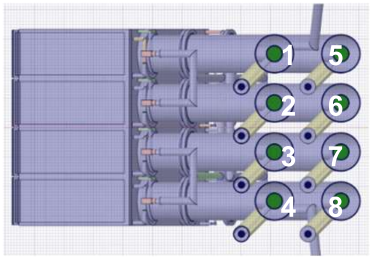
# Neutronics analysis for ICRF

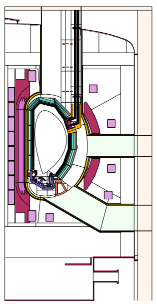
- **Models**

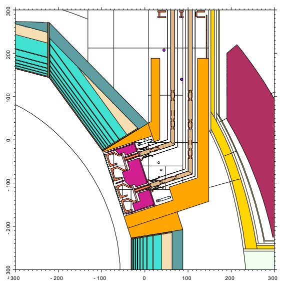


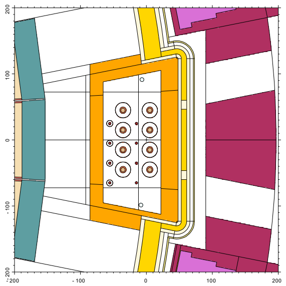




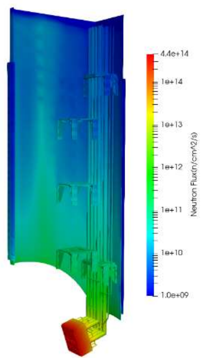



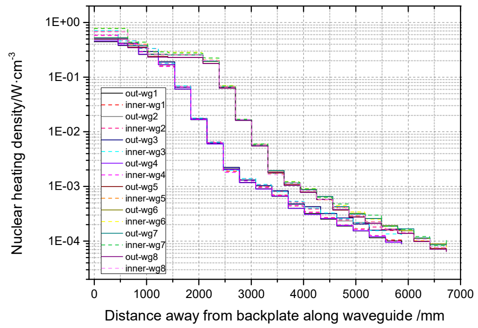



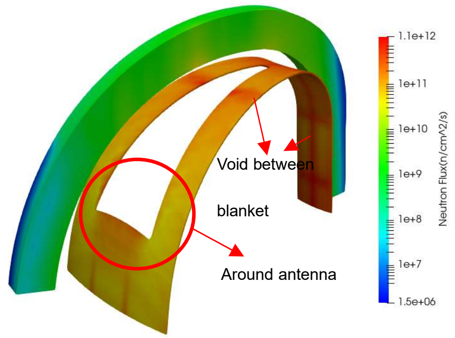




- **Nuclear analysis**





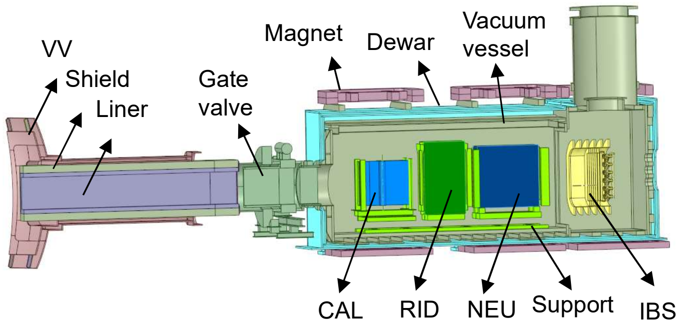



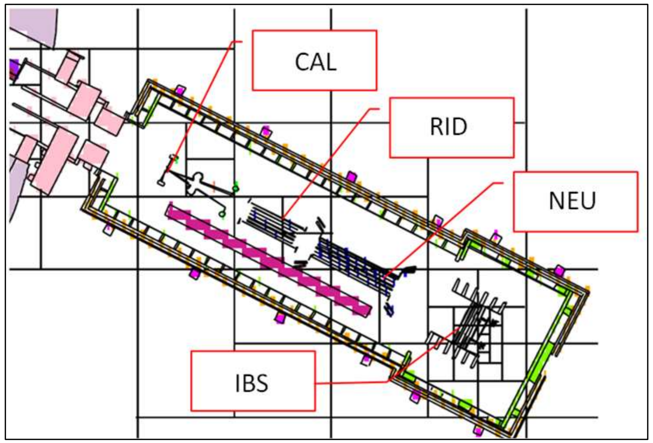

- ✓ Maximum DPA, gas production and NHD are 12 DPA/FPY, 121 He appm/FPY, 740 H appm/FPY and 29.8 W/cm$^3$
- ✓ NHD attenuation of the inner and outer waveguides with the same number is basically consistent, with maximum values of 0.783 and 0.525 W/cm$^3$

- ✓ Maximum damage of TFC and VV is located at the area around the antenna
- ✓ The current shielding design can meet the shielding requirements

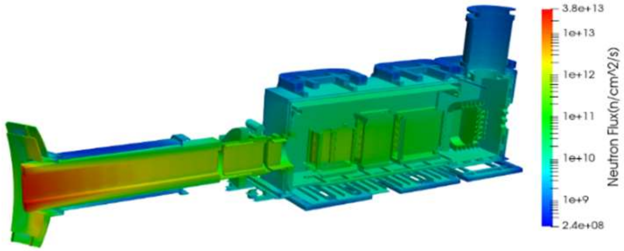
# Neutronics analysis for NBI

- **Models**

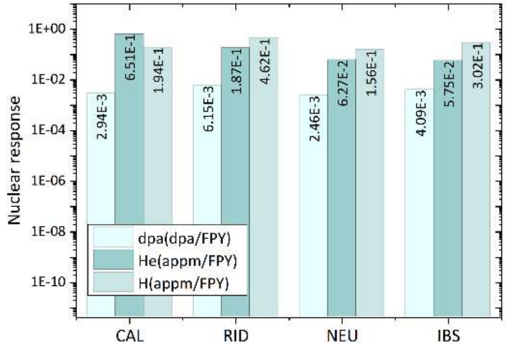



- **Nuclear analysis**




(a) Neutron flux for NBI



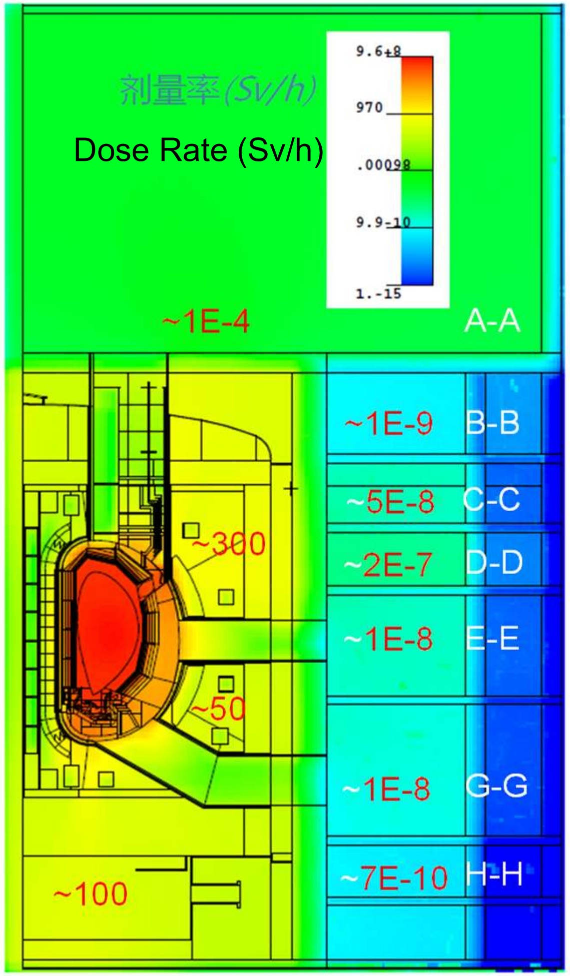

(b) irradiation damage

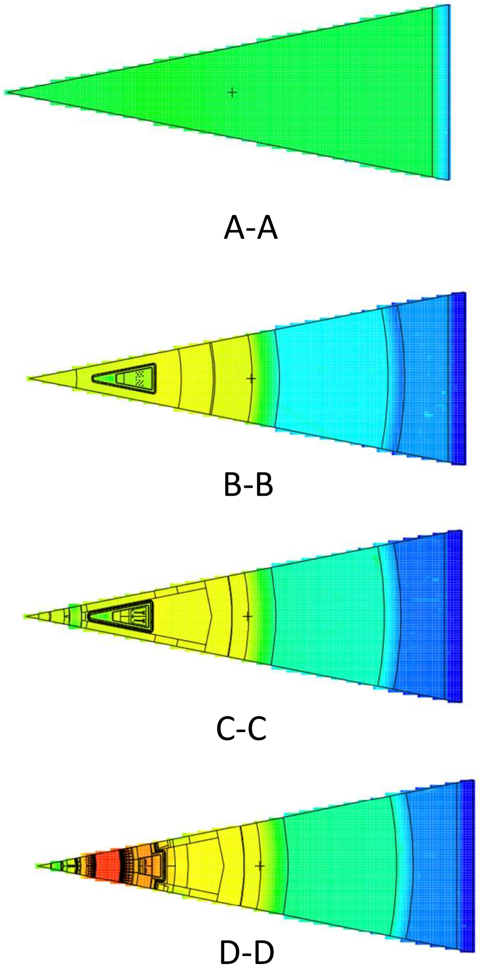
- ✓ There is no shielding design in the vacuum box of NBI. The flux and irradiation damage of sensitive components remain consistent, DPA values all below the design limit of 1 DPA/FPY
- ✓ Maximum of NH values for CAL, RID, NEU and IBS are 2.36E-04, 4.58E-03, 2.05E-03 and 4.11E-03 W/cm$^3$

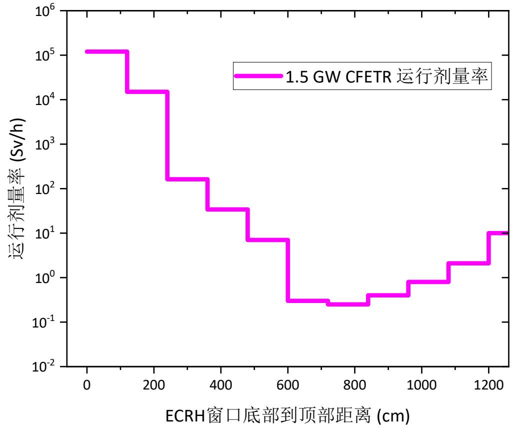
- ✓ The inclined port provides a certain shielding, and the neutron flux decreases by 1-2 orders of magnitude from the liner to the gate valve. The parameters of VV and TFC can meet the design limits.

# Dose Rate during operation

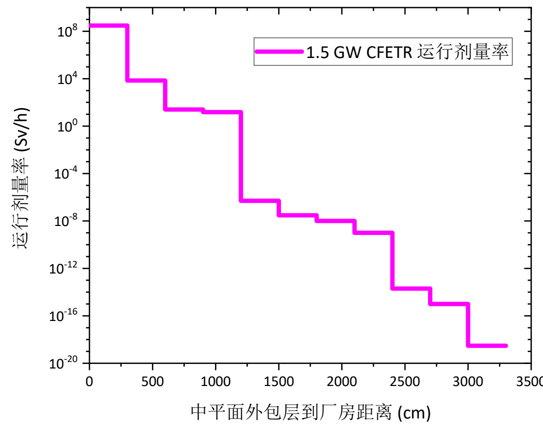
## Operation dose rate (under 1.5 GW fusion power)




Operation dose of ECRH port (Sv/h) (bottom to top)

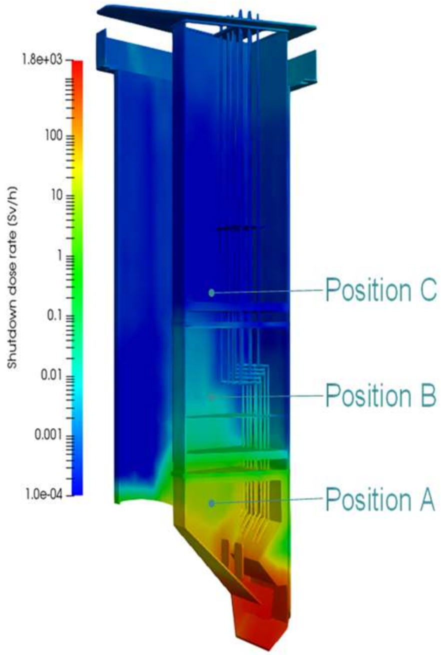


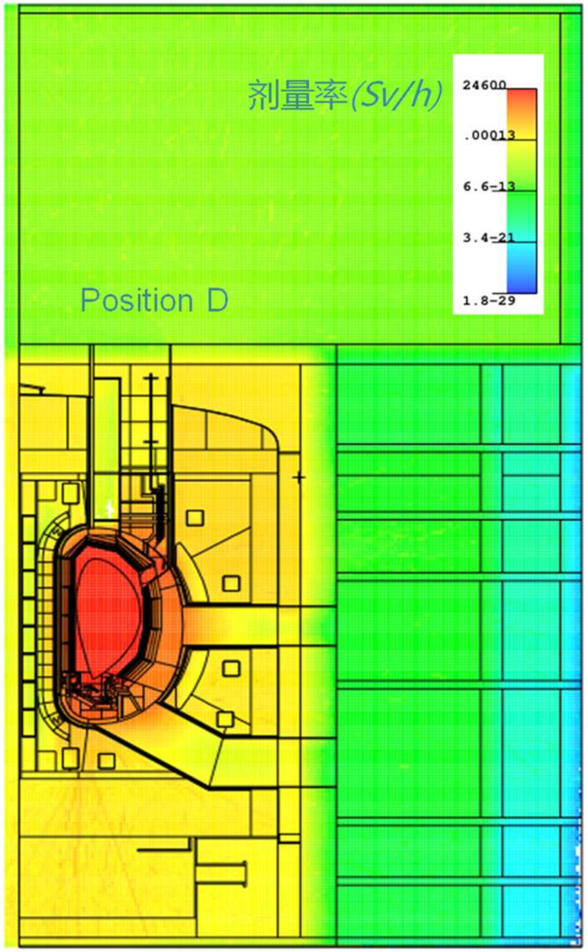

Operation dose of mid-port (Sv/h)

- **Operation dose rate of CFETR@1.5GW:**
  - Port-cell < 2.5 uSv/h
  - Ceil (area A)~100 μSv/h
- **ECRH penetration increases the dose rate**

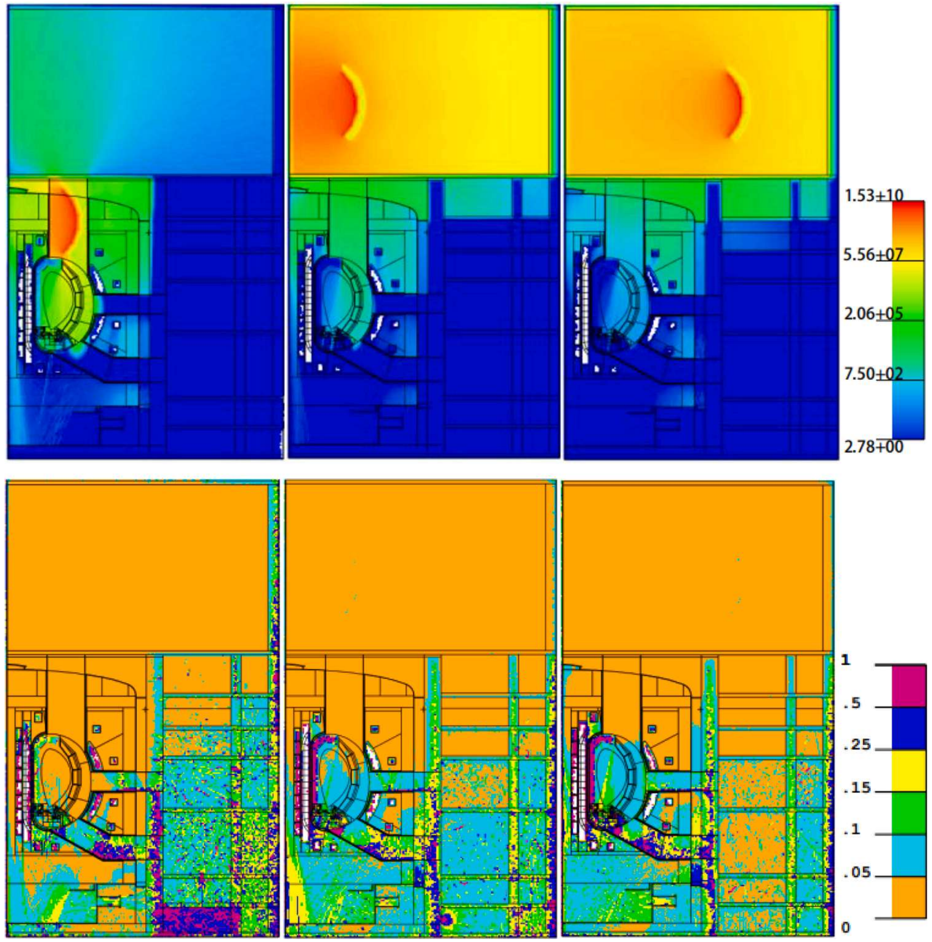
# Dose rate after shutdown

| Irradiation scenario | |
| --- | --- |
| Fusion Power | Irrad. time (FPY) |
| 200 MW | 1 |
| 500 MW | 2 |
| 1 GW | 5 |
| 1.5 GW | 2 |




Shutdown dose rate @12 day



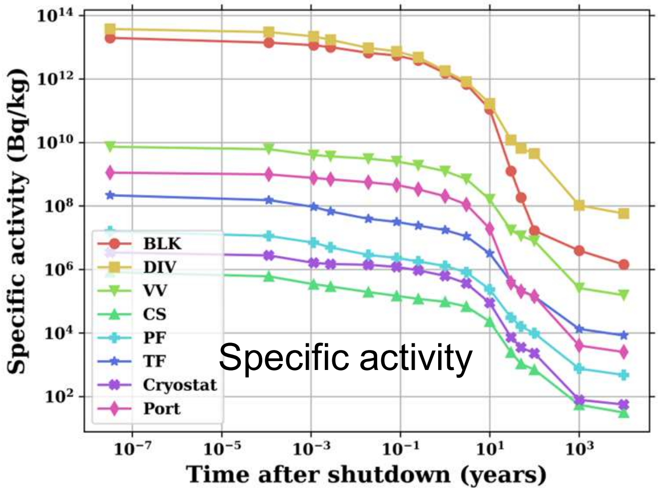

SDDR of **moving blanket** by NASCA-OTF (uSv/h)

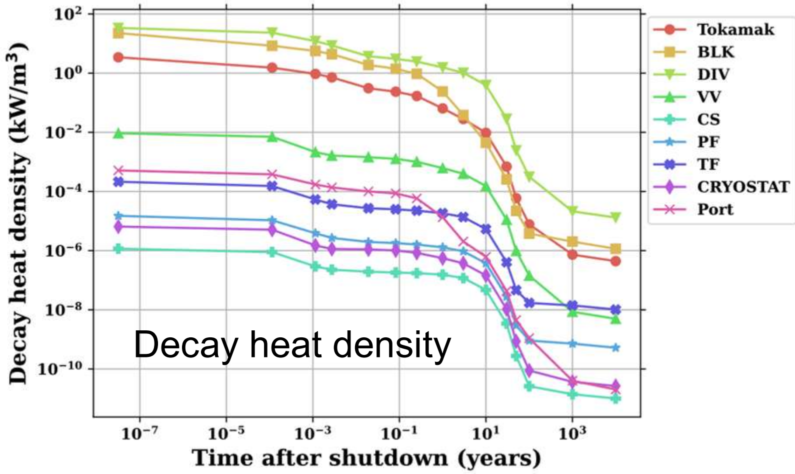
# Activation evaluation for CFETR

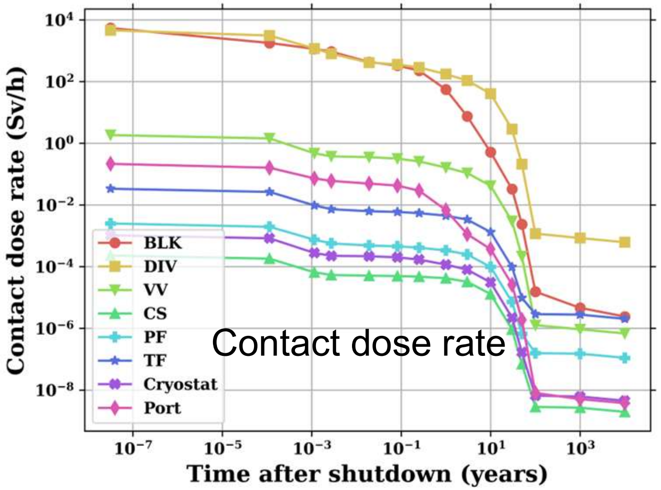
Calculated information

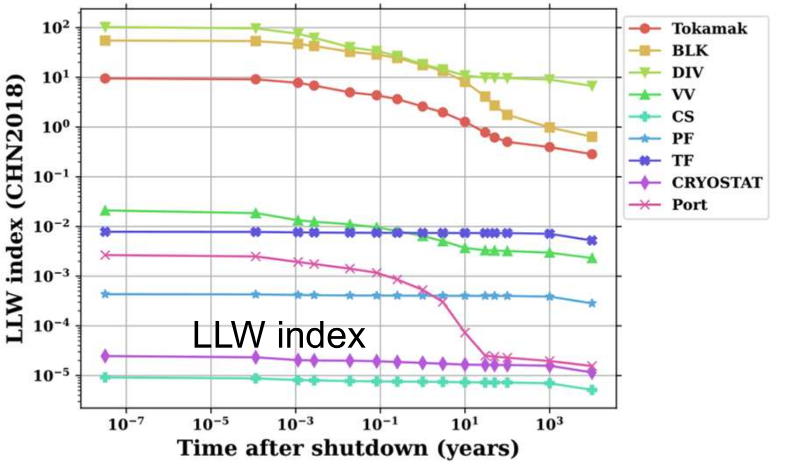
- Volume/mass
- Activation responses
- Radwaste classification indexes (CI/VLLW/LLW/ILW)
- Cooling time requirement for different level

| Components | Volume ($m^3$) | Mass (t) |
|---|---|---|
| BLK | 1.15E3 | 5.03E3 |
| DIV | 2.25E2 | 1.37E3 |
| VV | 6.33E2 | 3.96E3 |
| CS | 2.25E2 | 1.42E3 |
| PF | 5.14E2 | 3.37E3 |
| TF | 1.45E3 | 1.01E4 |
| Cryostat | 6.89E2 | 5.54E3 |
| Port | 4.88E3 | 1.32E4 |

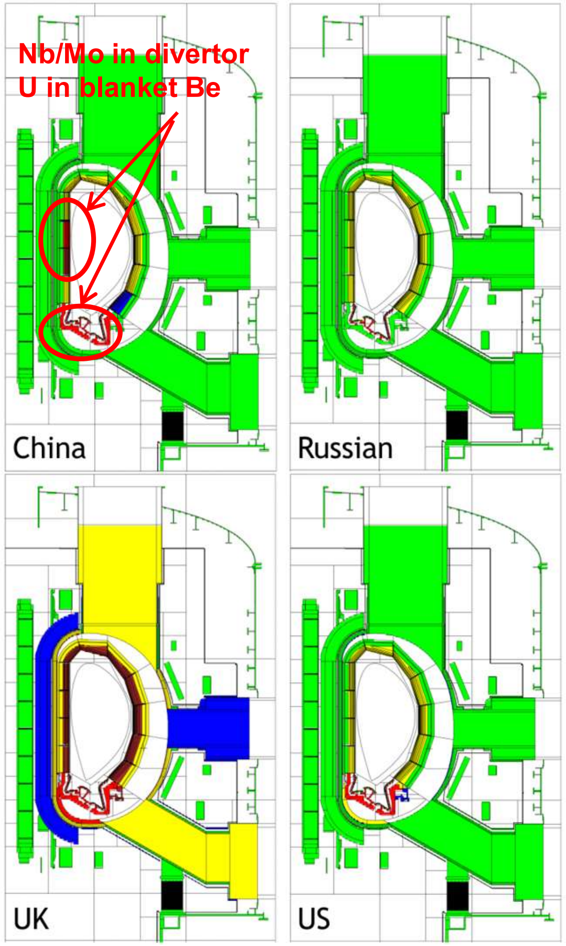


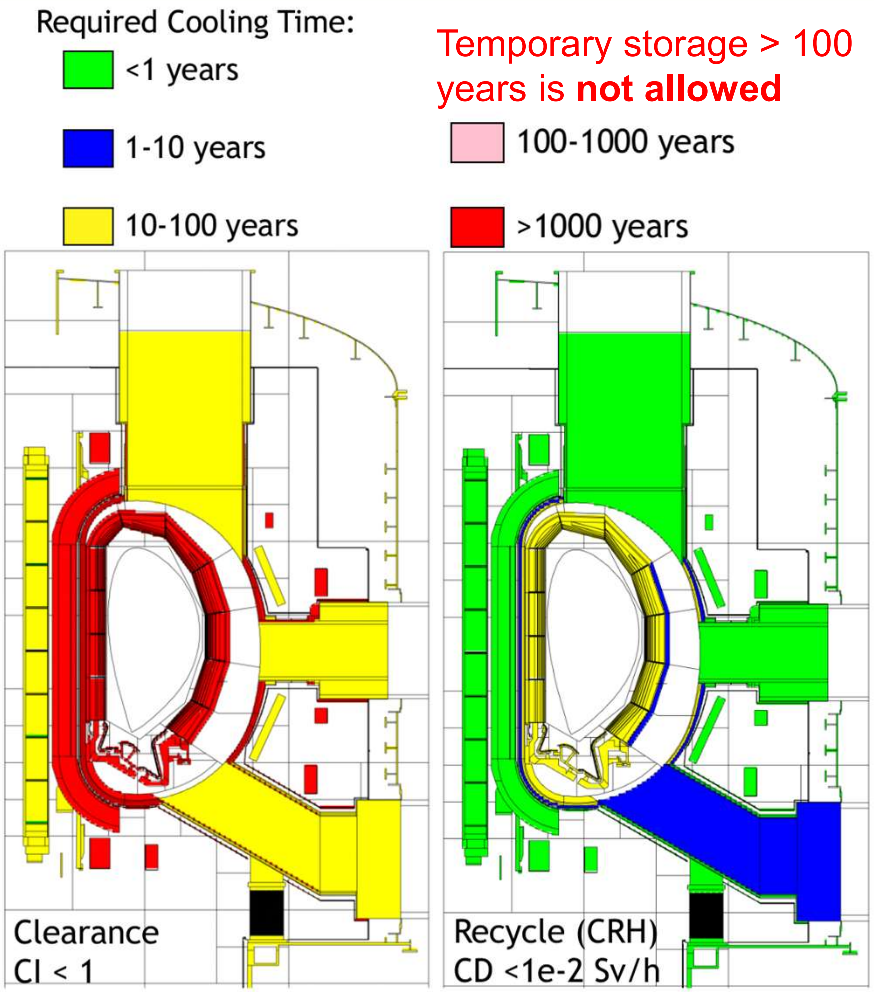



# Radwaste assessment




Required cooling time to LLW

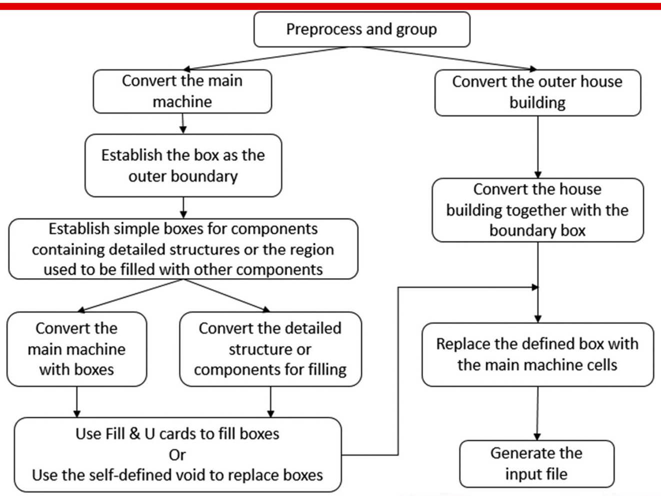


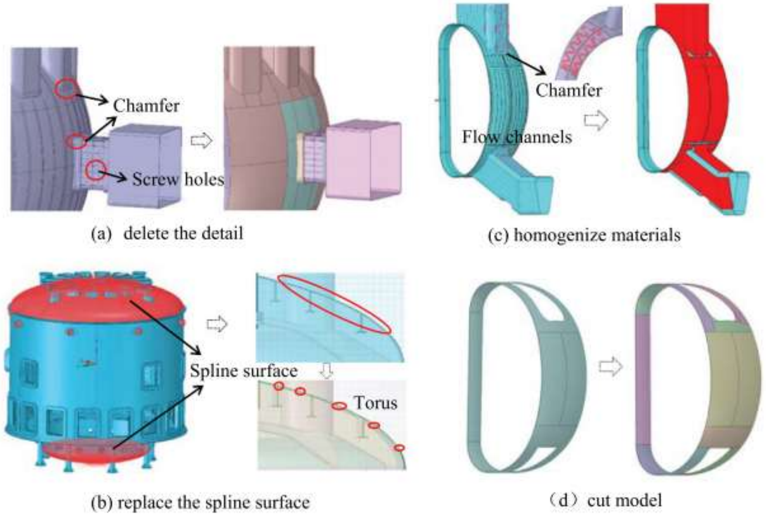

To clearance level

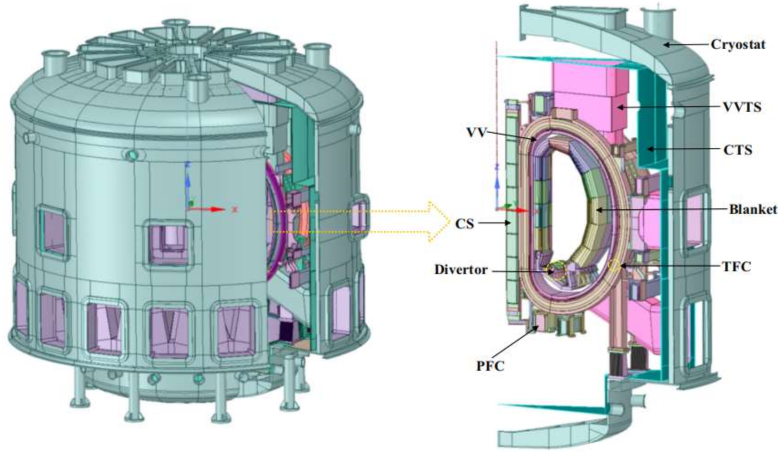
To recyclable level

Zhang, X. et al. Activation analysis and radwaste assessment of CFETR. Fusion Engineering and Design 176, 113036 (2022).

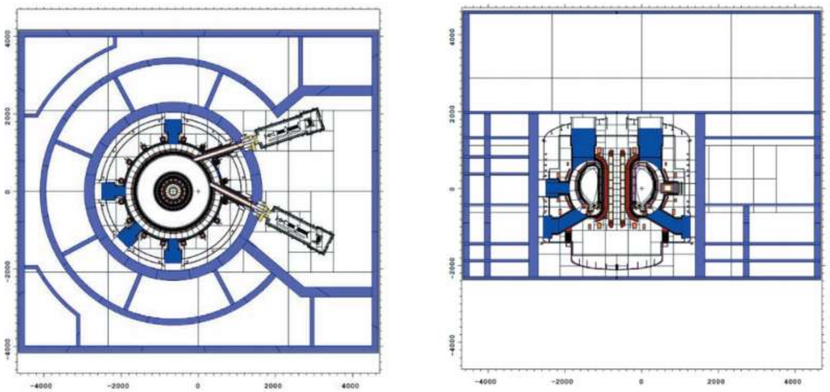
# cosVMPT: CAD to neutronics model conversion




CFETR (2020) CAD engineering model in 360-degree



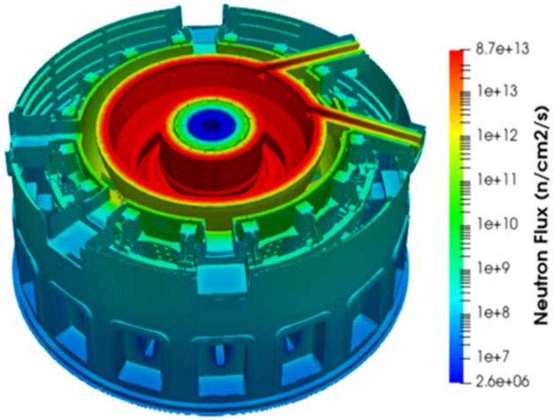
Neutronics model of CFETR in 360-degree


1. Wu, Q. et al. Neutronics Modeling and Nuclear Analysis Based on the Full CAD Geometry of CFETR. Fusion Science and Technology 79, 274–283 (2023).
2. Lu, P. et al. Progress on neutronic analysis for CFETR. Nucl. Fusion 62, 056011 (2022).
3. Du, H. et al. Development of an assistant program for CAD-to-cosRMC modelling. Fusion Engineering and Design 157, 111662 (2020).
4. Du, H. et al. Development of cosVMPT and Application of Creating 3D Neutronics Model for 360-Degree CFETR. J Fusion Energ 40, 2 (2021).

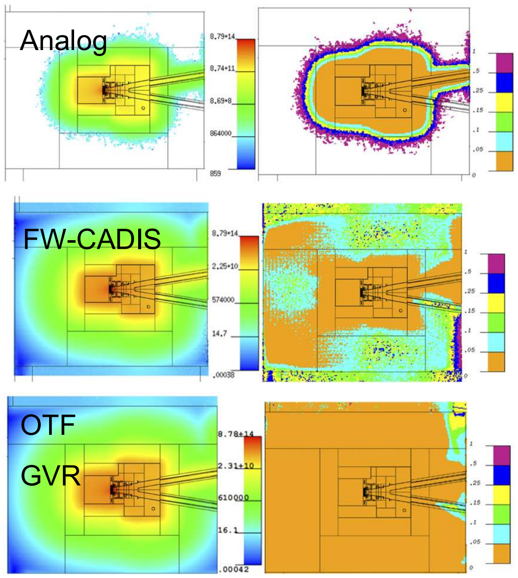
# OTF GVR: global variance reduction for MC

On-the-fly (OTF) global variance reduction (GVR)

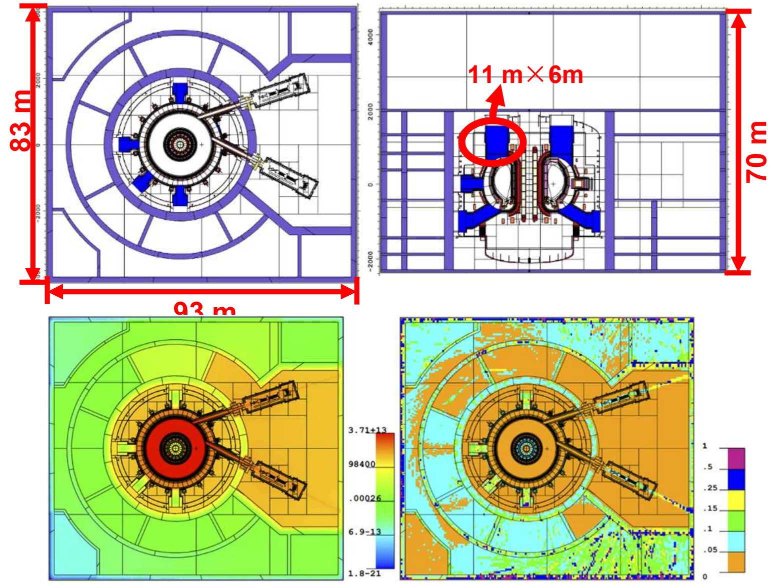
- on-the-fly automatical update of weight window (WW)
- unbaised, high-effiencient outflow control with dynamic upper bounds of WW to mitigate over-splitting
- supports n\np\p modes and multi-group
- prooved to be effiencient for complex model of fission/fusion/accerlerator



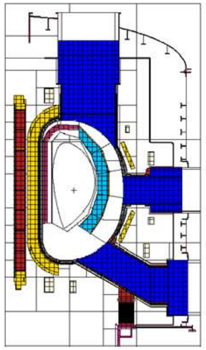

Application to the CFETR 360-degree model

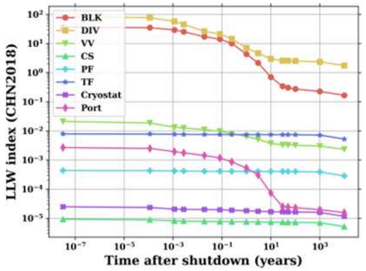



IFMIF-DONES test cell (TC) benchmark

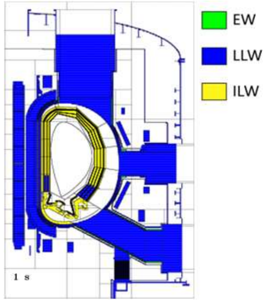


# NATF: activation & radwaste analysis

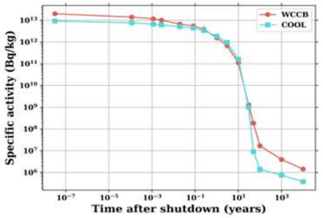

cutting optimization



radwaste index



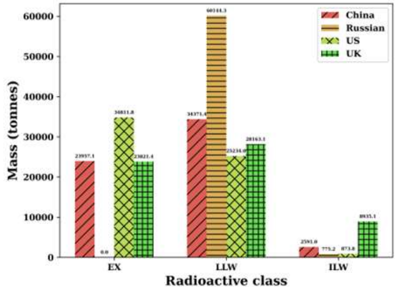
radwaste classification



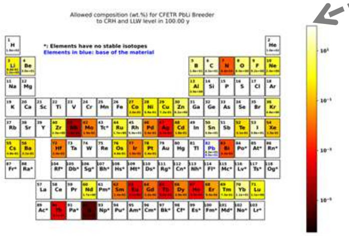
Activation responses

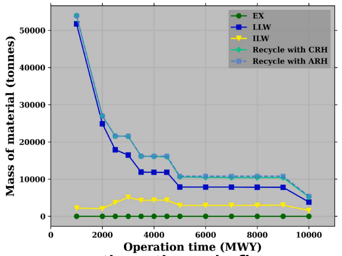
**NATF**

**Couping MC & FISPACT-II**

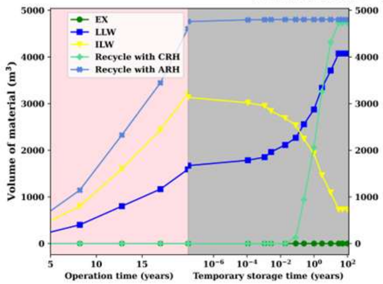


radwaste inventory


impurity control



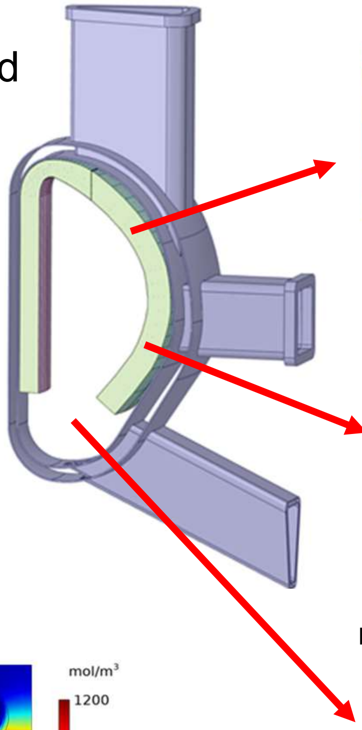
operation time influence

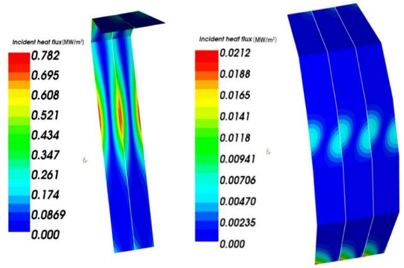


radwaste evolution

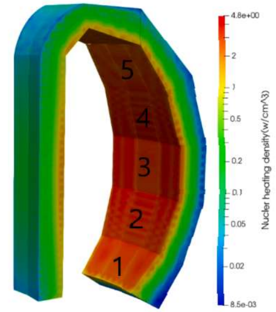
# Estimate of in-vessel retention

- **Preliminary estimate of T retention and permeation**
  - In-vessel components (first wall, blanket and divertor) to be designed
  - T injection flux assumed: 1E22~5E23 /$m^2$/s
  - Operation duration: 1600s*50 (pulse) & 20000s (steady-state)
  - Temperature referred to ITER and/or CFETR to estimate its impact
- **Variables and uncertainties**
  - Plasma particle flux and energy
  - Temperature distribution in PFCs
  - Fraction of T variable in the exhaust
  - Processing scenario

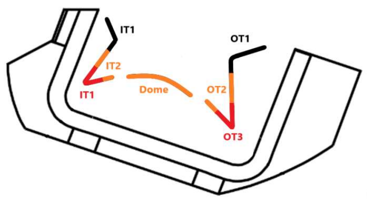




Heat flux for CFETR (F. Nian, 2023)

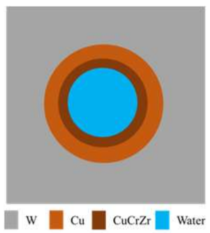



Nuclear heat for CFETR (Y. Wu, 2023)



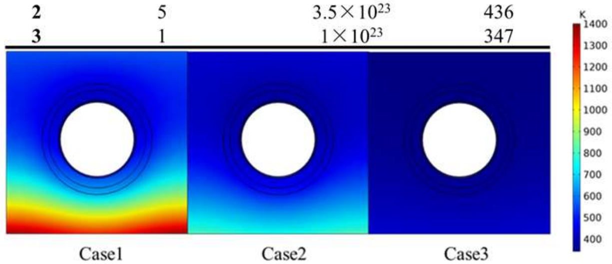

CFETR DIV Temp. distribution (Y. Wu, 2023)

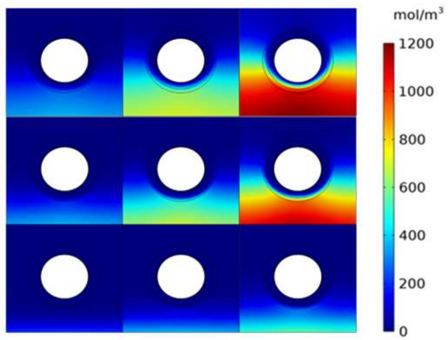
| Temperature (K) | OT1 | OT2 | OT3 | Dome | IT1 | IT2 | IT3 |
|---|---|---|---|---|---|---|---|
| W | 1065 | 833 | 1182 | 1070 | 1065 | 833 | 1182 |
| Cu | 749 | 641 | 802 | 718 | 749 | 641 | 802 |
| CuCrZr | 691 | 579 | 746 | 634 | 691 | 579 | 746 |




Divertor monoblock

| Case | Heat flow($MW \cdot m^{-2}$) | Particle flow ($m^{-2} \cdot s^{-1}$) | $T_{rear}$(K) |
|---|---|---|---|
| 1 | 10 | $5\times10^{23}$ | 552 |
| 2 | 5 | $3.5\times10^{23}$ | 436 |
| 3 | 1 | $1\times10^{23}$ | 347 |

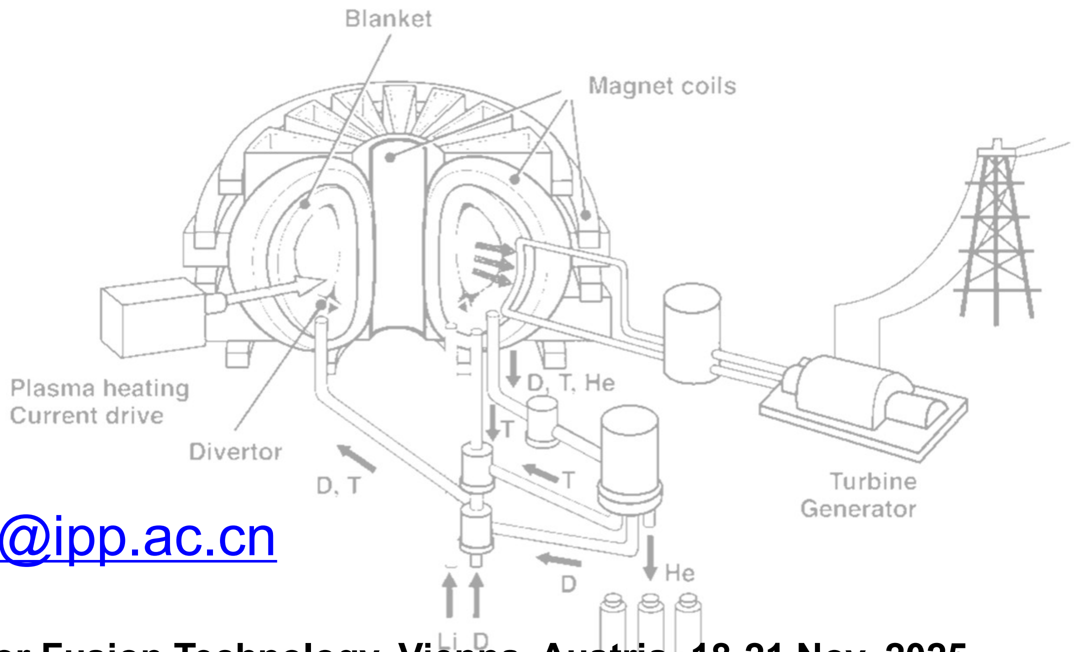


# Summary

- **For fusion facilities with "limited" (lower) risks**, it is practical to adopt existing code and standard for the design and fabrication, however, attentions to be paid to ensure the consistency of main systems for the entire facility
- C&S development more essential **for DEMO and FPP** to meet the need of high availability, reliability and stability, especially large uncertainties related to innovative technologies, the 14MeV neutron induced radiation damage and the long-term performance in an environment with the combination of multiple loads
- Data and experiences to be obtained, in parallel, from the operation of those fusion facilities and dedicated test facilities **to establish database for C&S**
- **Nuclear and radiation safety** may be subject to **national regulations**, e.g. T inventory control and management ➔ high level C&S and specific application

# Thanks for your attention!

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