PPPL PRINCETON PLASMA PHYSICS LABORATORY

ITER INTERNATIONAL SCHOOL

IIS2025 14th ITER International School
Integrated Modeling in Magnetic fusion Plasmas
June 30 – July 4, 2025, Aix-en-Provence (France)

Use of Integrated Models for Neutronic Analysis

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July 4, 2025

Outline

- Neutrons in Fusion
  - Fusion Reactions
  - Tritium Breeding
  - Material Damage
  - Spin Polarized Fusion
- Modeling
- Integration with Plasma Codes
- Integration with Engineering Codes:
  - Fluid, Heat and Mass Transfer analysis
  - Structural Analysis
- Integrated Analysis for ITER at Jet
- Conclusions

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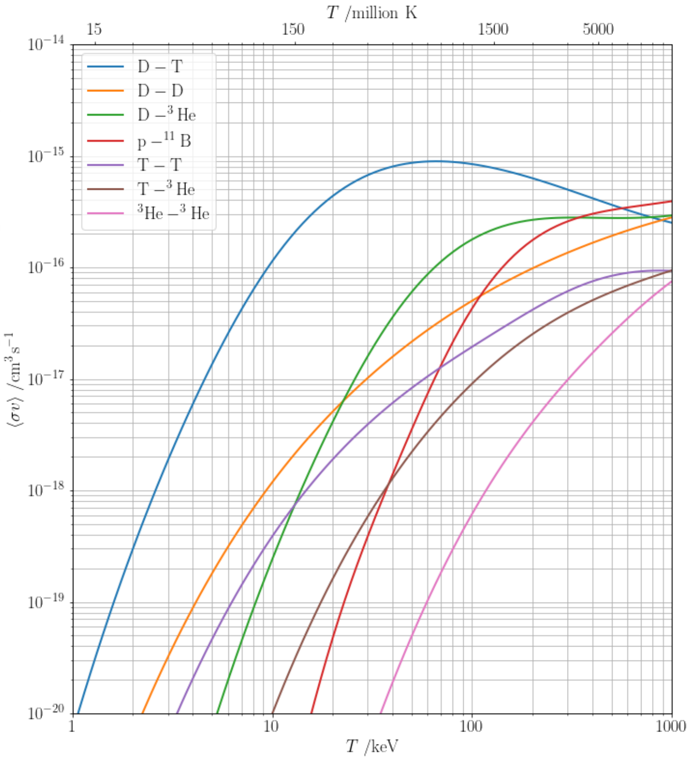
The D-T fusion reaction is the most achievable

fuel	⟨σv⟩/T²	penalty/ bonus	inverse reactivity	Lawson criterion	power density [W/m³/kPa²]
$^2_1D–^3_1T$	**1.24×10^{-24}**	**1**	**1**	**1**	**34**
$^2_1D–^2_1D$	1.28×10^{-26}	2	48	30	0.5
$^2_1D–^3_2He$	2.24×10^{-26}	2/3	83	16	0.43
$p^+–^{11}_5B$	3.01×10^{-27}	1/3	1240	500	0.014

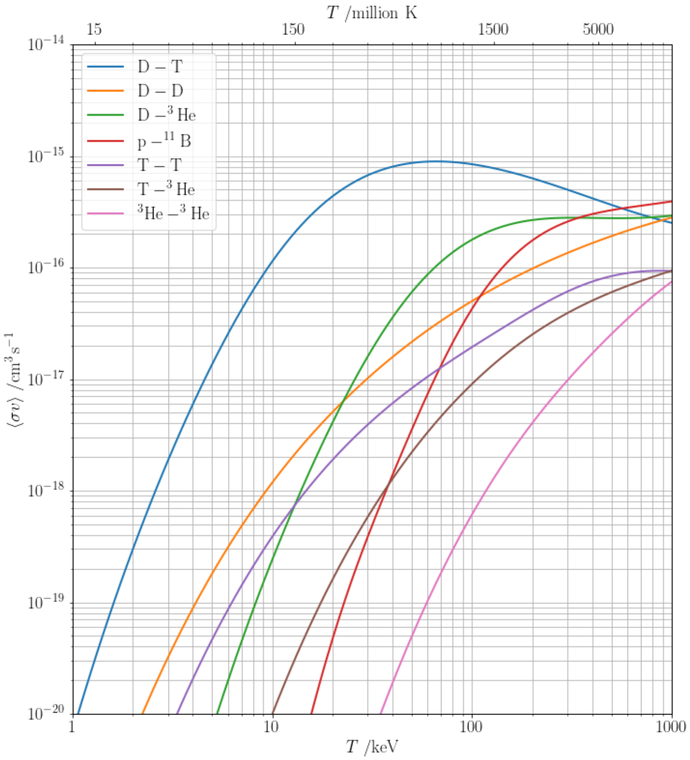
$$D + T \rightarrow {}^4He + n$$



The D-T fusion **reaction** provides the most power

Neutrons in Fusion Reactions

fuel	Z	E_{fus} [MeV]	E_{ch} [MeV]	Portion of Fusion Energy released as neutrons
$^{2}_{1}D$–$^{3}_{1}T$	**1**	**17.6**	**3.5**	**0.80**
$^{2}_{1}D$–$^{2}_{1}D$	1	12.5	4.2	0.66
$^{2}_{1}D$–$^{3}_{2}He$	2	18.3	18.3	≈0.05
p^{+}–$^{11}_{5}B$	5	8.7	8.7	≈0.001



$$D + T \rightarrow {}^{4}He(3.5MeV) + n(14.1MeV)$$

The D-T fusion reaction releases 80% of energy as neutrons

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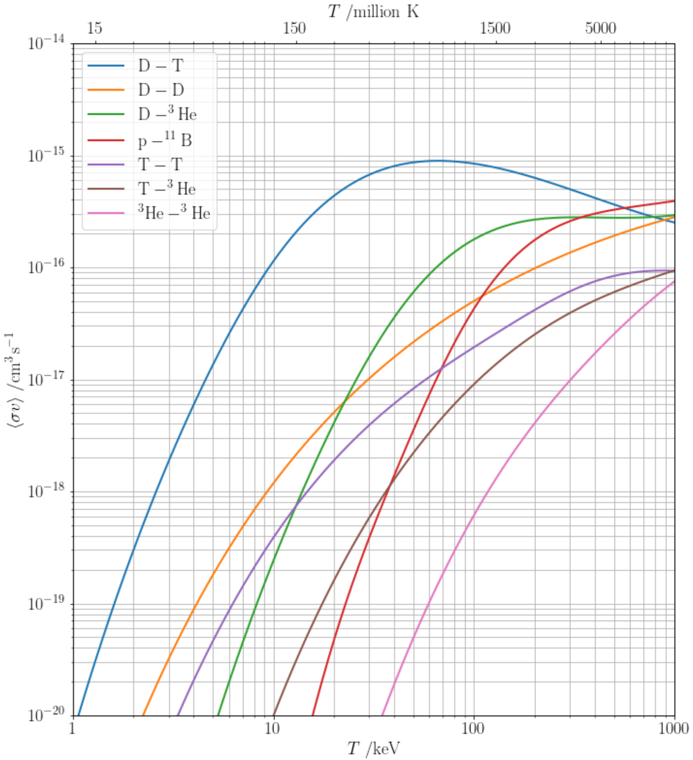
The need for tritium breeding

$$D + T \rightarrow {}^{4}He + n$$

- The D-T fusion reaction is the most achievable
- Tritium decays with a 12.3 year half-life, and therefore has no natural supply
- Small amounts produced by fission reactors can supply short-pulse research devices
- But 55.6 kg T/GW_f-yr is required for sustained operation
- This will require that it use the fusion neutrons to breed its own tritium supply, with a tritium breeding ratio (TBR) > 1



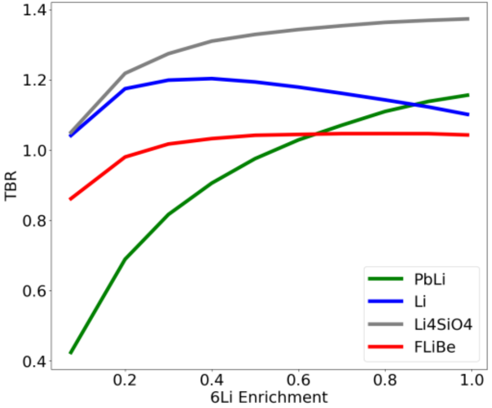
T breeding from Li

$$T + D \rightarrow {}^4He + n$$

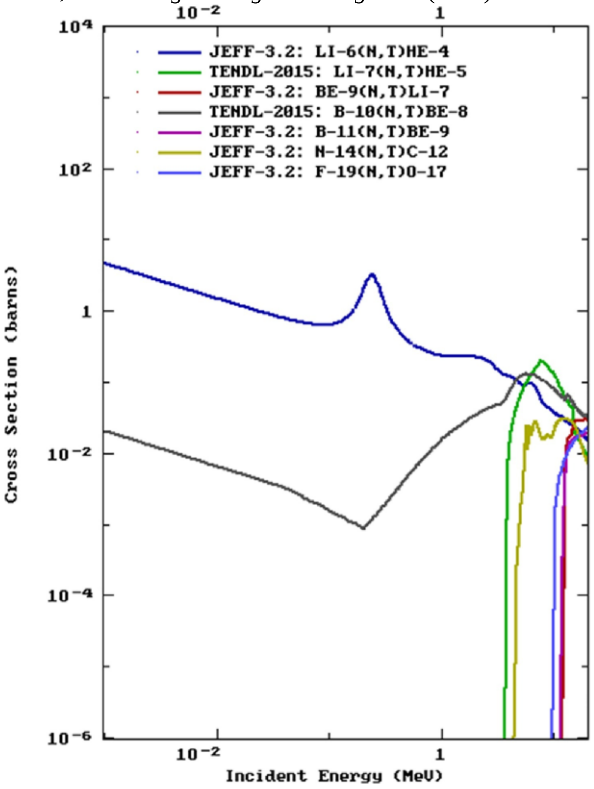
$$T + {}^4He \leftarrow Li + n$$

- Fusion neutrons can produce lithium from both naturally occurring isotopes:
  - n + ^{6}Li → ^{4}He + T + 4.785 MeV
    - Large cross section at thermal energies
    - Exothermic: produces additional energy!
  - n + ^{7}Li → ^{4}He + T + n' - 2.5 MeV
    - Produces tritium *and* a neutron

- It is advantageous to enrich in ^{6}Li to an extent (typically 40-90%) that depends on the blanket concept and other materials present

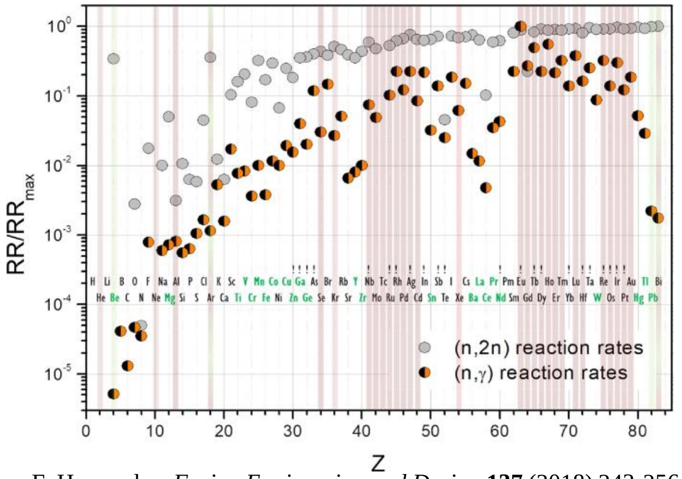


F. Hernandez, *Fusion Engineering and Design* **137** (2018) 243-256.

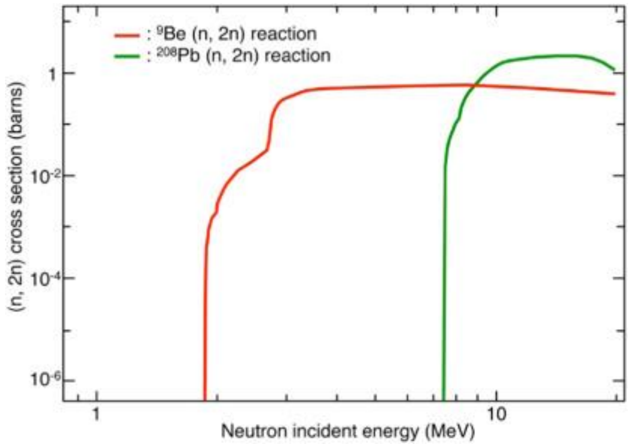


Neutron multipliers

- TBR = 1 is achieved when *every* fusion neutron produces a triton from lithium
- The multitude of other structures and components necessarily present in a fusion reactor will also absorb neutrons
- This can be compensated for by incorporating neutron multipliers, elements that undergo (n,2n) reactions
- Good multipliers have a high (n,2n) cross section and low total absorption cross section- Be and Pb are primary candidates
- Beryllium is a superior multiplier but has drawbacks (toxicity, supply chain, U impurities)



F. Hernandez, *Fusion Engineering and Design* **137** (2018) 243-256.

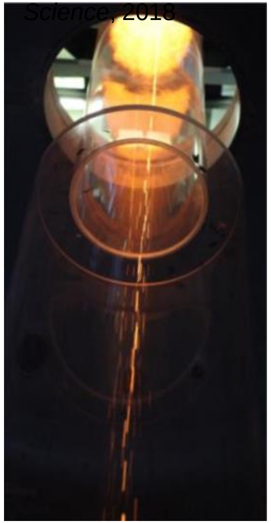


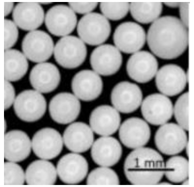
M. Nakamichi, in *Comprehensive Nuclear Materials* 2nd ed (2020).

Candidate breeder/multiplier materials

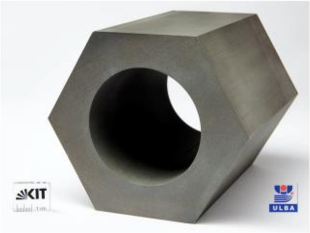
- Breeders
  - Liquid Metals:
    - Lithium (T_{melt} = 180 ºC)
    - $Pb_{84.3}Li_{15.7}$ (T_{melt} = 235 ºC)
  - Solids: separate breeder and multiplier
    - Ceramic breeders: Li_2TiO_3, Li_4SiO_4
      - Others with less favorable absorption/neutron activation possible
    - Multipliers:
      - Be (metal)
      - Beryllide intermetallics: $Be_{12}Ti$, $Be_{12}V$, $Be_{12}Cr$
        - Others with less favorable absorption/neutron activation possible
  - Molten Salts:
    - FLiBe [2LiF + BeF_2] (T_{melt} = 459 ºC)
    - FLiNaBe [LiF + NaF + BeF_2], (T_{melt} = 305 ºC)

Solid ceramic breeders
F. Hernandez, *IEEE Transactions on Plasma Science*, 2018





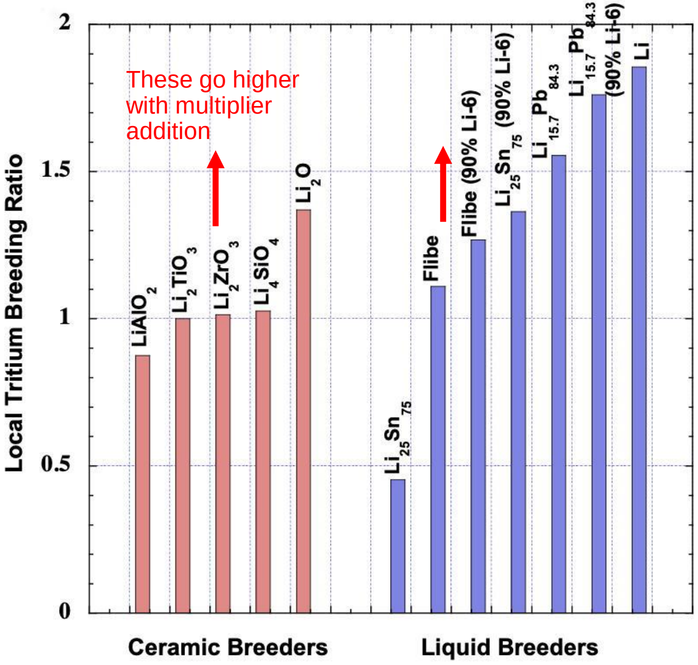
Beryllide intermetallic multipliers



R. Gaisin, *Fusion Engineering and Design* **161** (2020) 111862.

Can we achieve TBR > 1(+ε)?

- Clearly yes in idealized configurations
- Whether achievable in a fusion reactor is a que
- Multipliers need to offset neutrons lost throug
  in all other components and materials,
  - e.g. FW, blanket structure, divertor, pellet inject
    components, diagnostics, etc.

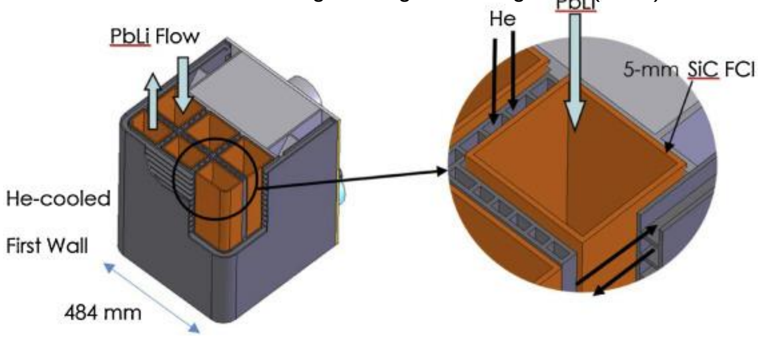


L. El-Guebaly, in “Fusion Energy and Power: Applications, Technologies and Challenges” (2015)

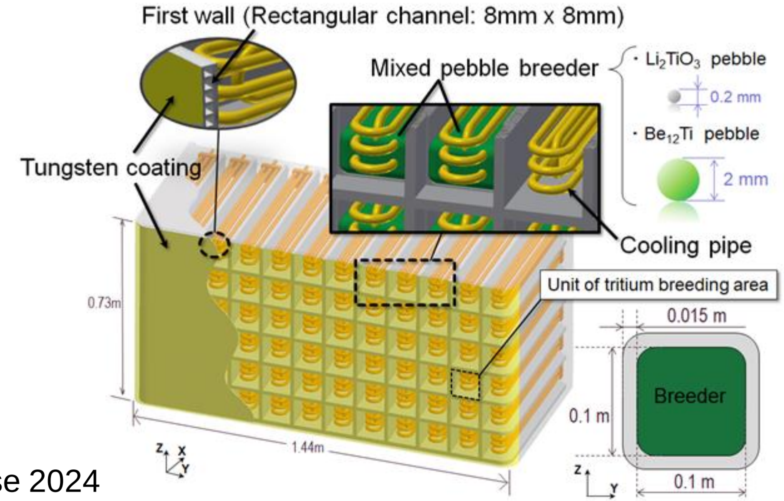
Blanket Concepts

- Blanket concepts pair breeder/multiplier with structural and other materials and coolants based on their compatibility
  - PbLi, solid breeders typically paired with RAFM steel structure and helium or water coolant
    - These are the most studied designs
  - Lithium traditionally paired with vanadium
    - It may help getter impurities (O, H, T) that would otherwise significantly impact vanadium
    - Poor or questionable compatibility with other candidate structural materials
  - Material solution for FLiBe unclear
    - High melt temperature (459 ºC) leaves little/no temperature window for operation with RAFM steel (< 550 ºC)
    - Corrosion compatibility with all materials a concern

US Design – Dual Cooled Lead Lithium (DCLL)
M. Abdou et al. / Fusion Engineering and Design 100 (2015) 2–43

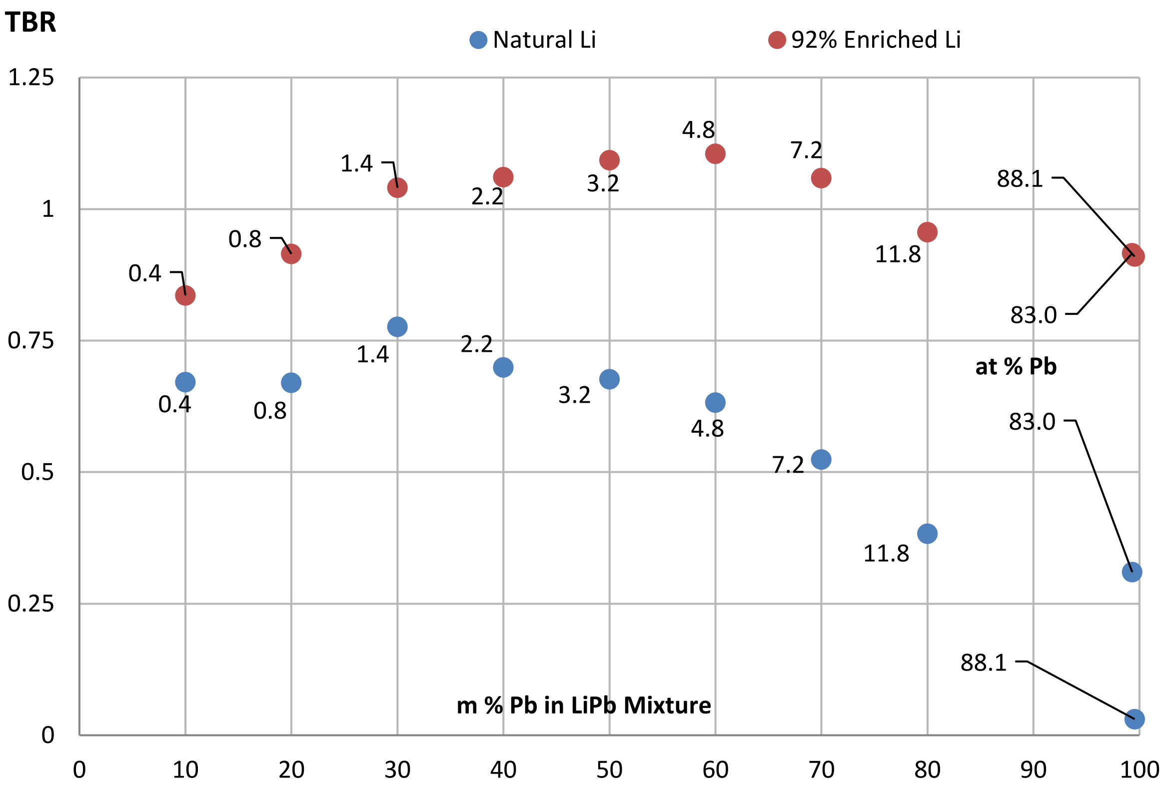


JA DEMO Design – Water Cooled Ceramic Breeder (WCCB)
Y. Someya, 2018 US-JA Workshop



*Paul Humrickhouse 2024

TBR for PPPL Spherical Tokamak Advanced Reactor STAR 2D model



TBR for PPPL Spherical Tokamak Advanced Reactor STAR 2D model

Breeder Midplane Thickness cm		Multiplier Midplane Thickness cm			PbLi mixture	TBR	
IB	OB	IB Be	OB Be	OB Pb	at % Li	Natural Li	92% Li_6
21.9	47.042	0	23.65	0	17	0.269	0.76
21.9	43.81	0	0	0	17	0.31	0.916
21.9	43.81	2.2	0	0	17	0.369	0.502
21.9	43.81	0	2.5	0	17	0.404	0.971
21.9	43.81	2.2	0	0	40	0.502	1.21
21.9	47.042	0	23.65	0	40	0.508	
21.9	81.87	0	0	0	17	0.544	1.08
21.9	87.37	0	0	0	17	0.615	1.239
21.9	43.81	0	0	0	40	0.632	1.105
0	43.81	55.9	0	0	40	0.663	1.1066
21.9	43.81	0	2.5	0	40	0.7	1.203
21.9	**81.87**	0	3	0	17	0.832	**1.326**
21.9	**81.87**	0	3	0.5	17	0.875	**1.355**
21.9	**81.87**	0	0	0	100	1.101	
21.9	**81.87**	0	3	0	40	1.137	**1.46**
21.9	**81.87**	0	3	0.5	40	1.177	**1.493**
21.9	**84.87**	0	0	0	100	1.257	
21.9	**81.87**	0	3	0	100	**1.312**	
21.9	**81.87**	0	3	0.5	100	**1.336**	1.186

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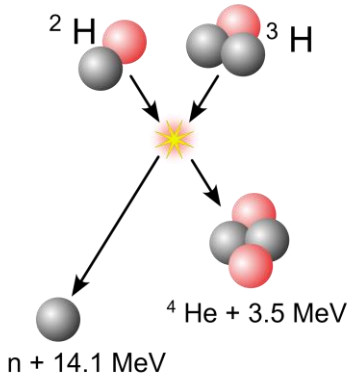
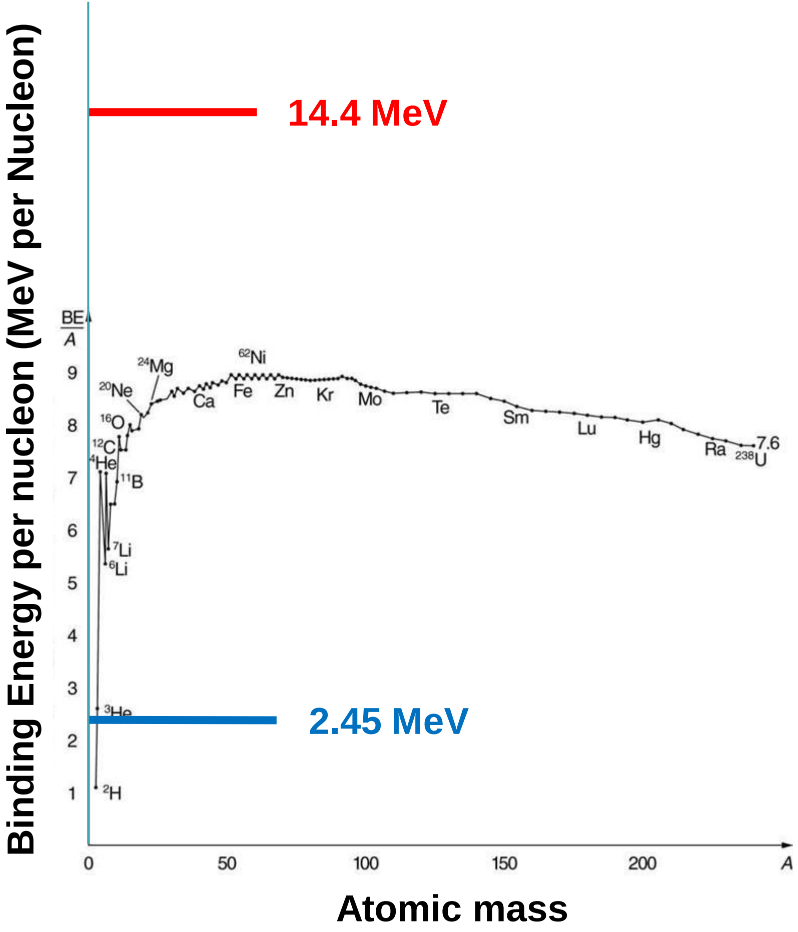
High Energy Neutrons

D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)

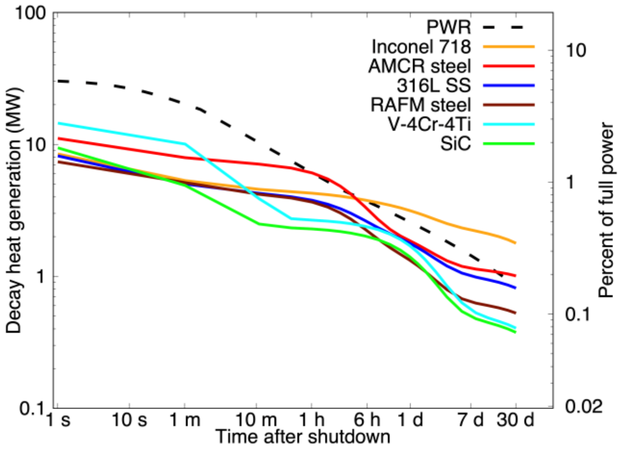


D + D → ^{3}He (0.82 MeV) + n (2.45 MeV)

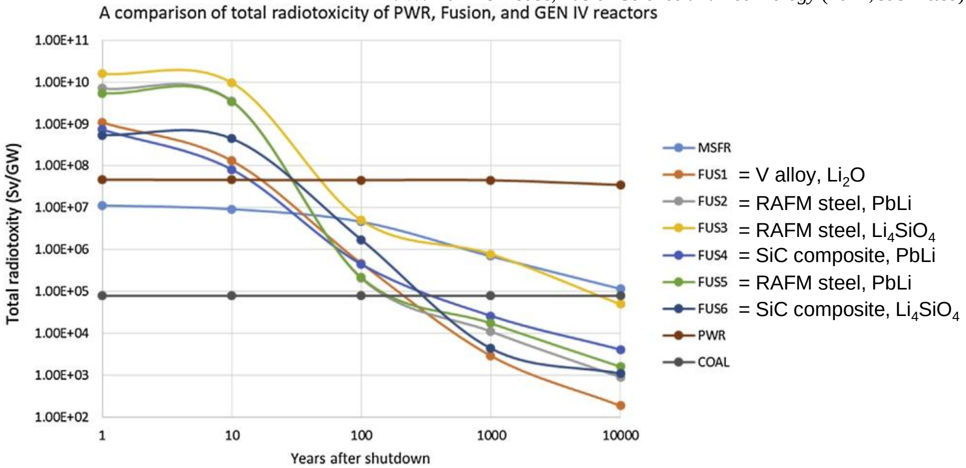


Neutron activation considerations

- When considering other elements in breeder, multiplier, or structural materials, neutron activation is a primary consideration
- All D-T fusion reactors will create significant quantities of radioactive material
- Avoidance of long-lived waste and high decay heat (active cooling) requires *low-activation materials*
    - Many common alloying elements (Ni, Co, Mo, Nb, etc.) need to be avoided



P. W. Humrickhouse, *Fusion Science and Technology* (2024, submitted)



M. Zucchetti, *Fusion Engineering and Design* **136** (2018) 1529-1533.

Structural Materials

- The need to reduce short (decay heat) and long (waste) term activation has driven the development of structural materials for fusion
- Three primary candidates:
  - Reduced-Activation Ferritic/Martensitic (RAFM) Steel
    - Most mature option, likeliest for near-term deployment; examples:
    - F82H (Fe-8Cr-2W-0.2V-0.04Ta)
    - EUROFER-97 (Fe-9Cr-1W-0.2V-0.12Ta)
  - Vanadium Alloys
    - V-4Cr-4Ti
  - Silicon Carbide (SiC) composites

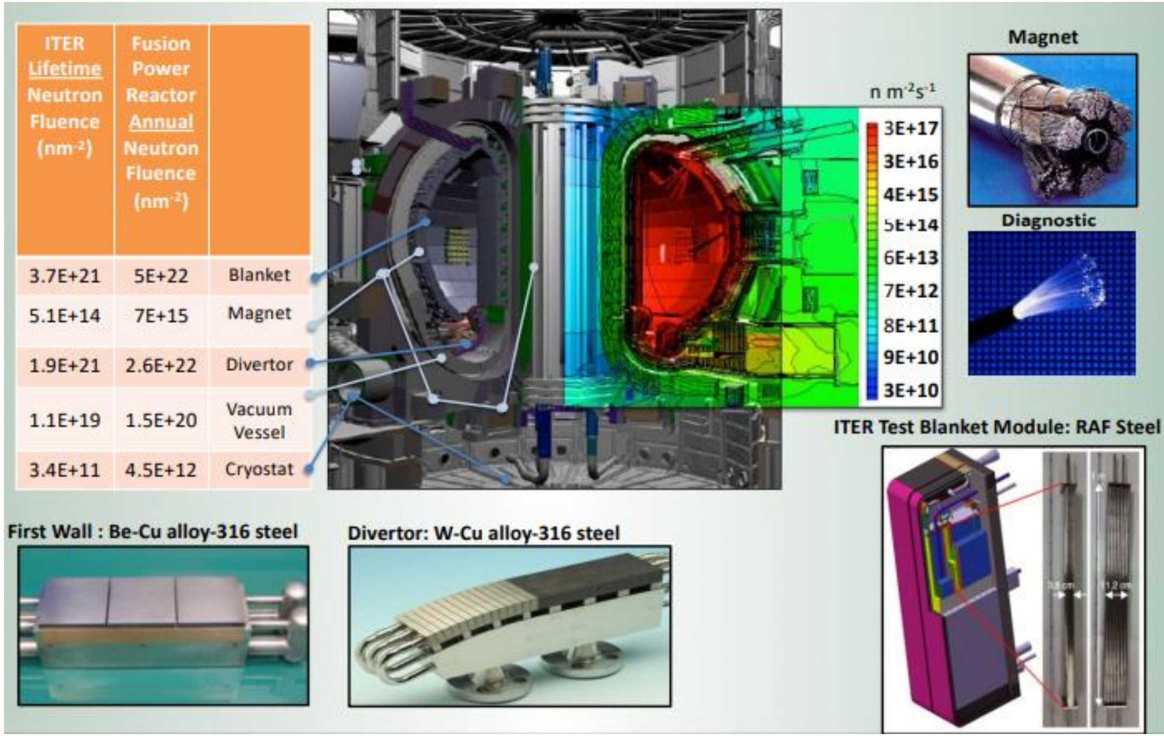
Other materials

- Coolants
  - Solid breeders require a coolant
  - Liquid breeders can in principle also act as a coolant, but have some drawbacks for this purpose
    - High pressure drops due to magnetohydrodynamic forces (liquid metals) or high viscosity (molten salts) at high flow rates
    - Other undesirable properties such as low thermal conductivity in molten salts
  - In both cases, primary coolant candidates are:
    - Helium
    - Water
- Tungsten
  - Tungsten appears in many components in and around the breeding blanket:
    - Plasma facing materials in the divertor
    - Armor on the FW/blanket
    - Conducting shells used to stabilize the plasma
    - Shielding
  - Its effect on breeding may be mixed; it's a strong thermal absorber but can also multiply at high energy*

*B. Sorbom et al., *Fusion Engineering and Design* **100** (2015) 378-405.

Scientific & Technical Challenges for Fusion Materials are Significant

- Future D-T fusion reactors represent a uniquely hostile operating environment:
    - High temperatures
    - Reactive coolants
    - Large time-dependent thermal-mechanical stresses
    - Intense radiation (both plasma and neutrons)
- Materials selection will strongly impact the Technical Viability, Safety, and Economics of future fusion reactors
- Neutron irradiation leads to atomic displacements:
    - Is expressed in terms of displacements per atom – dpa
    - Lifetime exposures are expected to be greater 100 dpa (10 MW-y/m2)
    - Atomic displacements lead to significant microstructural evolution and bulk property degradation
- Higher neutron energy (14.1 Me) results in:
    - Much higher gaseous transmutation (He and H)
    - Different solid transmutations (material system dependent)

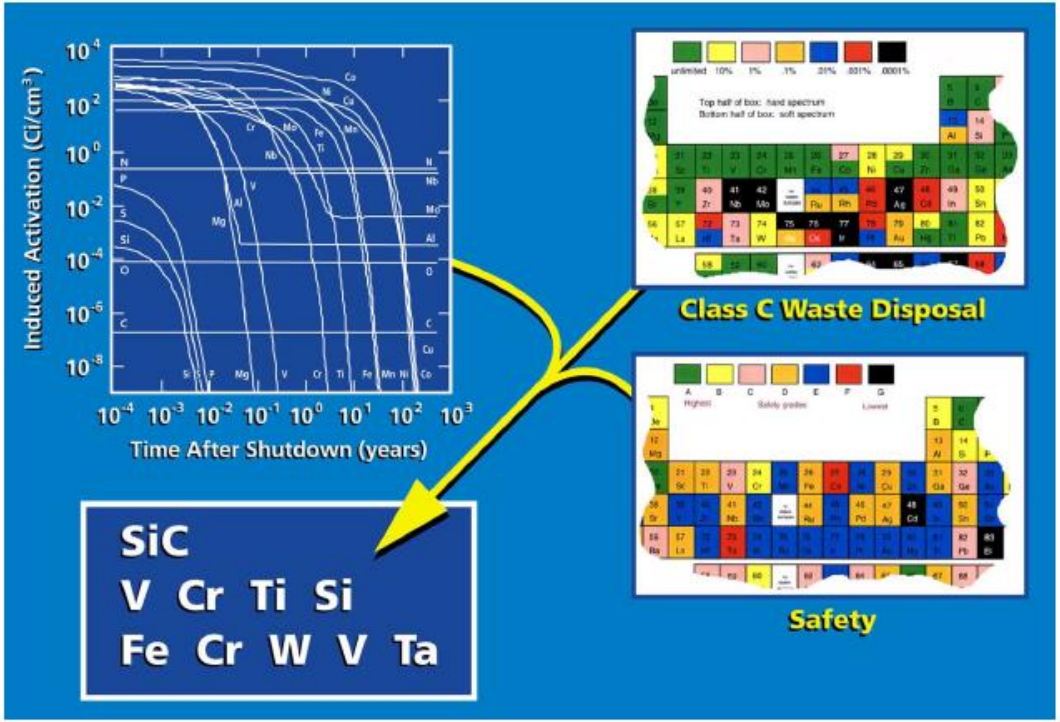


ITER Lifetime Neutron Fluence (nm^{-2})	Fusion Power Reactor Annual Neutron Fluence (nm^{-2})	
3.7E+21	5E+22	Blanket
5.1E+14	7E+15	Magnet
1.9E+21	2.6E+22	Divertor
1.1E+19	1.5E+20	Vacuum Vessel
3.4E+11	4.5E+12	Cryostat

* Fusion Material Damage FES perspective G. Shaw 2024

Fusion Materials: Low-induced radioactivity

- Materials strongly impact environmental and safety aspects of fusion
- Many materials are not suitable for various technical:
  - Performance
  - Safety
  - Waste
- Leading candidate materials:
  - RAFM and Advanced Steels
  - SiC composites
  - Tungsten alloys



* Fusion Material Damage FES perspective G. Shaw 2024

Irradiation effects on structural materials

- Exposure to neutrons degrades the mechanical performance of structural materials and impacts the economics and safety of current & future fission power plants:
  - Irradiation hardening and embrittlement/decreased uniform elongation (< 0.4 Tm)
  - Irradiation (<0.45 Tm) and thermal (>~0.45 Tm) creep
  - Volumetric swelling, dimensional instability & growth (0.3 - 0.6 Tm)
  - High temperature He embrittlement (> 0.5 Tm); Specific to fusion & spallation accelerators
- Additional environmental degradation due to corrosive environments (SCC, uniform/shadow corrosion, CRUD)

304 Stainless steel irradiated in EBR-II, 380°C, ~22 dpa, 1% swelling

Variables

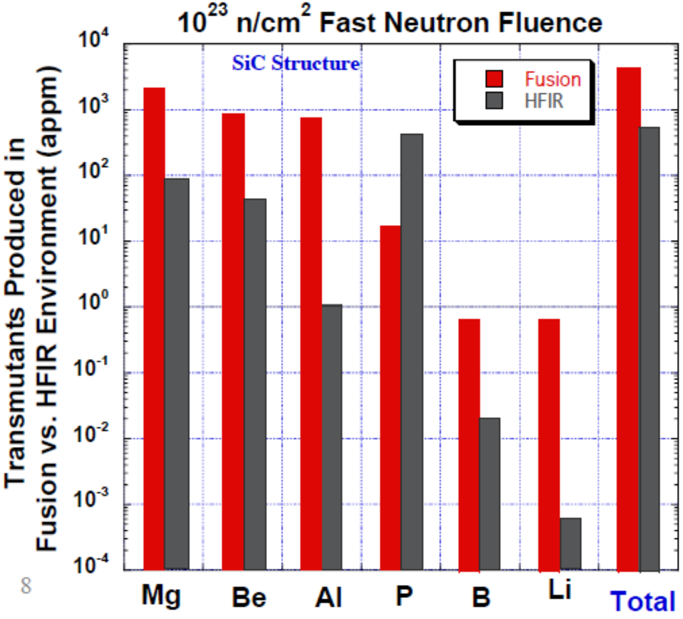
- Structural Materials (Fe-based steels, Vanadium and Ni-based alloys, Refractory metals & alloys, SiC) and composition
- Zr alloy cladding
- Initial microstructure (cold-worked, annealed)
- Irradiation temperature
- Chemical environment & thermal mechanical loading
- Neutron flux, fluence and energy spectrum
  - materials test reactor irradiations typically at accelerations of 10^2 – 10^4

Synergistic Interactions

* Fusion Material Damage FES perspective G. Shaw WANDA 2024

Solid Transmutations

- In addition to the significant gaseous transmutations, some materials such as SiC experience significant solid transmutations in a fusion spectrum
  - Burn-in: Variety of nuclear reactions with different threshold energies (En > 3 MeV) produce 6 transmutants: Mg (58%), Be (22%), Al (20%), P, B, Li.
  - Also results in non-stoichiometric burn-out
- Consequences are largely unknown, but will likely impose significant effects, especially in combination with gaseous transmutation production
- These are fusion-specific issues which cannot be readily simulated using existing techniques
- **Uncertainties in ND/cross sections at/above 10 MeV**



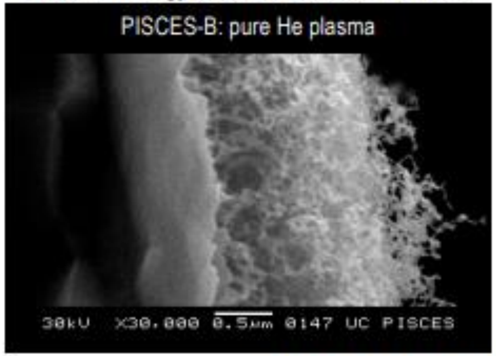
Comparison of solid transmutations in SiC in a Fusion vs thermal fission reactor environment

M. Sawan, Y. Katoh, and L. L. Snead, "Transmutation of Silicon Carbide in Fusion Nuclear Environment," J. Nucl. Mater., 442, 1–3, S370 (2013).

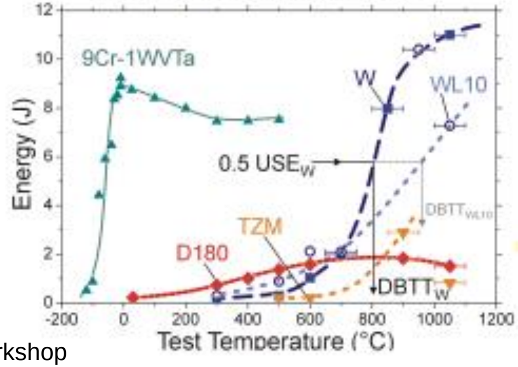
Plasma Facing Components*

- Typical materials considered for PFM include grap although this list has been modified by considerati
- Tungsten alloys leading candidates as divertor stru excellent thermo-physical properties.
- However, critical issues need to be addressed:
  - Creep strength
  - Fracture toughness (DBTT)
  - Microstructural stability (Recrystallization)
  - Low & high cycle fatigue • Oxidation resistance
  - **Effects of neutron irradiation (hardening & embrittl H)**
- Several computational and experimental efforts to improve the performance of tungsten PFCs are no

Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, *La Jolla, CA*



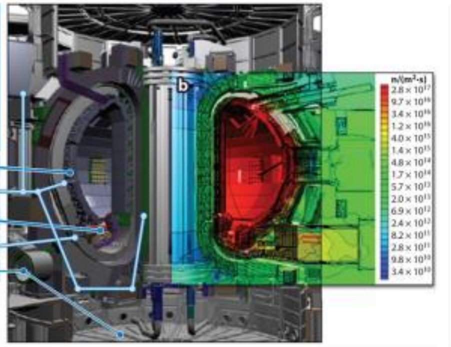
M. Rieth, A. Hoffmann, HHFC, 2008



* Road mapping Plasma Facing Materials For FPP – B. D. Wirth et al. – Presented 2023 Materials Road-mapping workshop

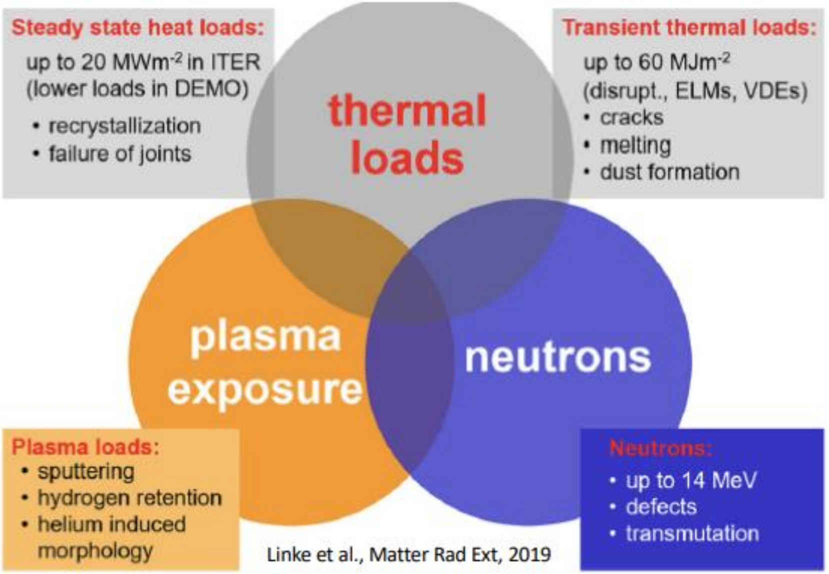
Plasma facing materials and the fusion environment

ITER: lifetime fast neutron fluence (n/m²; E > 0.1 MeV)	DEMO fusion power reactor: annual fast neutron fluence (n/m²; E > 0.1 MeV)	Component
3.7×10^{21}	5×10^{22}	Blanket
5.1×10^{14}	7×10^{15}	Magnet
1.9×10^{21}	2.6×10^{22}	Divertor
1.1×10^{19}	1.5×10^{20}	Vacuum vessel
3.4×10^{11}	4.5×10^{12}	Cryostat



Zinkle and Snead, Annual Reviews 2014

PFM requirements ultimately require engineered forms of W with mechanistically driven stability.



Linke et al., Matter Rad Ext, 2019

An eye toward a fusion pilot plant

- 14.1 MeV neutron flux $>10^{14}$ n/(cm²·s)
- First wall power load: 2 MW/m²
- Divertor: 10-20 MW/m²

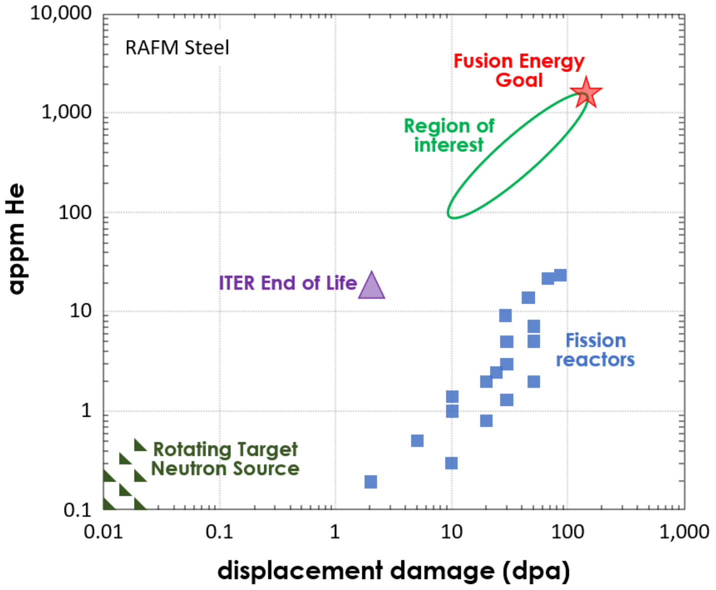
C. Bachmann et al., FED, 2015; G. Federici et al., FED 2014

For essentially all ITER components, current materials systems **<u>will not survive</u>** the anticipated DEMO (or a compact FPP) lifetime.

* Road mapping Plasma Facing Materials For FPP – B. D. Wirth et al. – Presented 2023 Materials Road-mapping workshop

Fusion Materials knowledge base

- **Key Point:** Fusion materials development requires both displacement damage and transmutation generation in BULK samples
  - Iron based materials (RAFM steels) are used as a reference material (10 appm He/dpa)
  - Generally, need to reach damage levels greater than 10 dpa/100 appm He to see effects



	1st DEMO Blanket						2nd DEMO Blanket						Adv. DEMO						
Data base need	<20 dpa/200appm He						~50 dpa/500appm He						>100 dpa/1000appm He						
Materials	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM
Irradiation effects																			
Hardening/Embrittlement	Green	Yellow	Red	Yellow	Yellow	Red	Yellow	Red	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red
Phase stabilities	Green	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Red	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red
creep & fatigue	Green	Yellow	Red	Yellow	Red	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Volumetric swelling	Green	Yellow	Red	Yellow	Green	Yellow	Yellow	Red	Red	Yellow	Yellow	Red	Yellow	Red	Red	Red	Red	Red	Red
High Temp He&H effects	Yellow	Red	Red	Red	Yellow	Yellow	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Green: Adequate knowledge base exists
Yellow: Partial knowledge base exists
Red: No knowledge base

Note: He levels are only for FM steels

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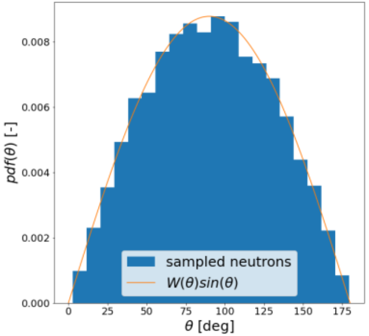
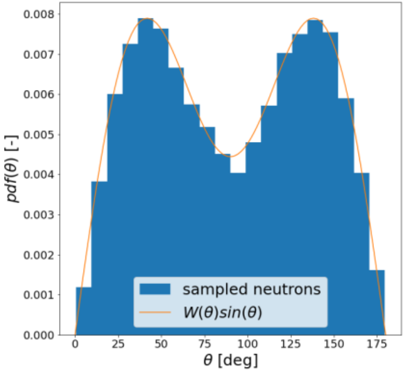
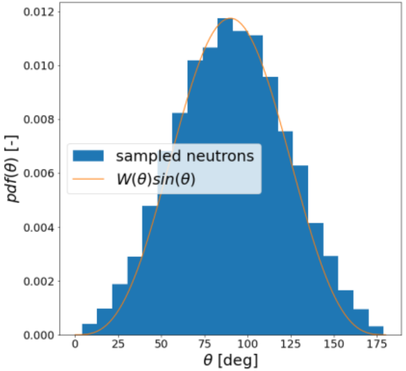
Spin Polarised Fusion



Unpolarized

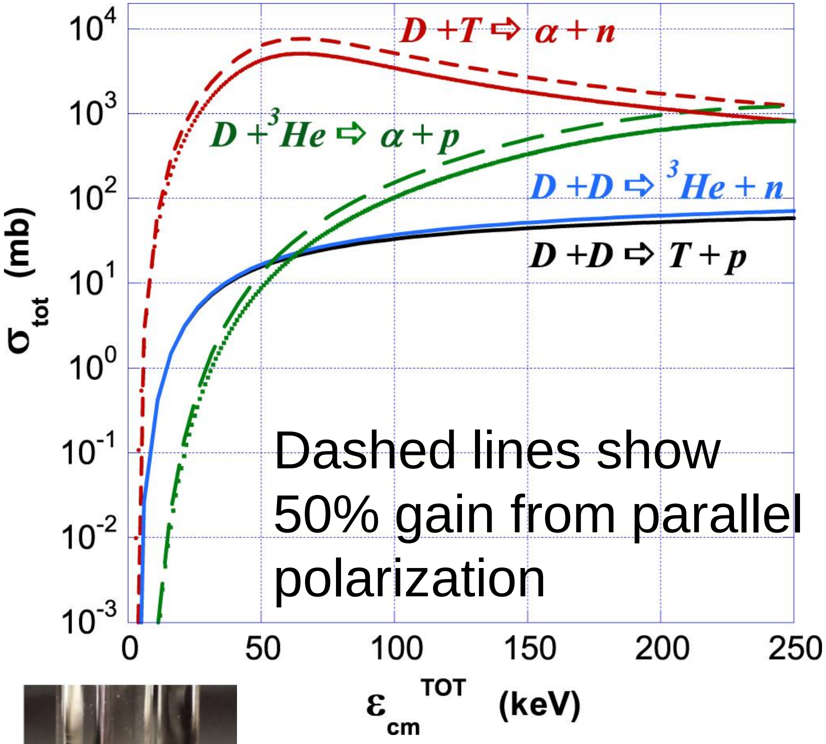


Parallel



Perpendicular

Distributions of nuclear source relative to magfnetic field.
J. Bae et al submitted to NF (2025)
Data from:
M. B. Chadwick, et al. ENDF/B-VII.1 Nuclear Data for Science and Technology. Nuclear Data Sheets,112(12):2887–2996, December 2011.



The typical placement of a 2 mm diameter GDP pellet (which appears amber in this photograph) above a Pyrex bead within a 3 mm Inside-Diameter (ID) tube for permeation imaging.

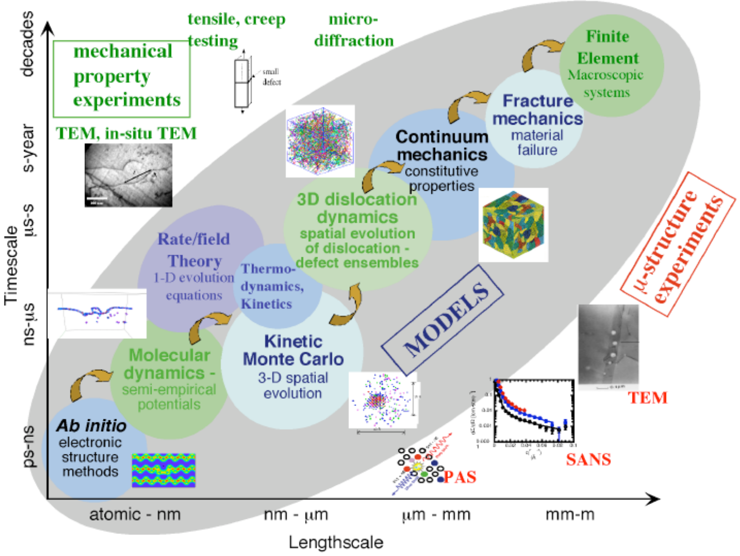
Baylor et al. 2023 Nucl. Fusion 63 076009

Outline

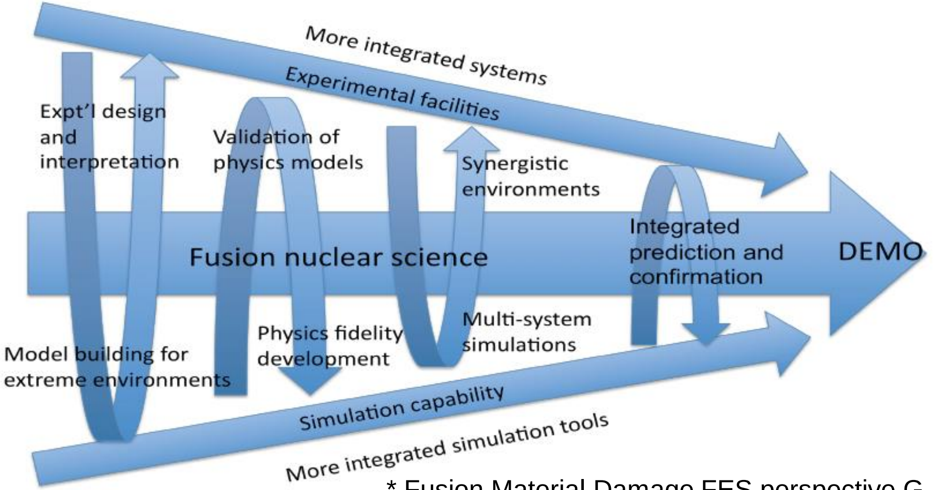
- Neutrons in Fusion
  - Fusion Reactions
  - Tritium Breeding
  - Material Damage
  - Spin Polarized Fusion
- **Modeling**
- Integration with Plasma Codes
- Integration with Engineering Codes:
  - Fluid, Heat and Mass Transfer analysis
  - Structural Analysis
  - Integrated Analysis for ITER at Jet
- Conclusions

Fusion Materials theory and modeling

- General premise is to apply complementary modeling, experimental and theoretical techniques at appropriate scales to determine underlying mechanisms
- Given the lack of experimental facilities that fully represented loading environments – data gaps and uncertainties still exists.



- Uncertainties and errors are found – and ideally must be quantified – at every level
- Significant opportunities for examples of computational thermodynamics to tailor improved material properties (advanced ferritic/martensitic alloys, Cu-based alloys, etc.)

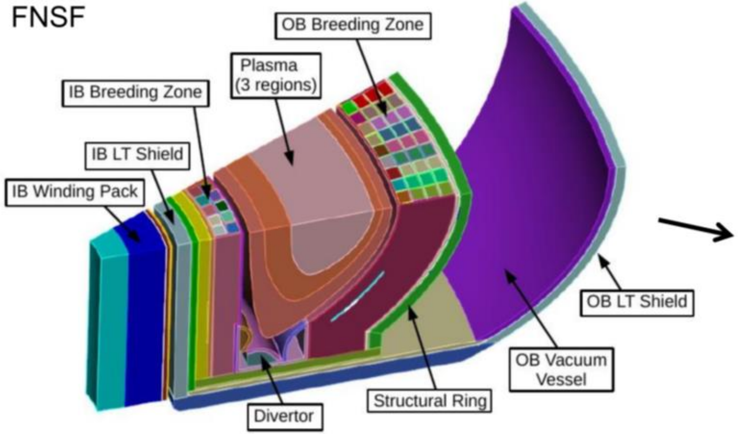


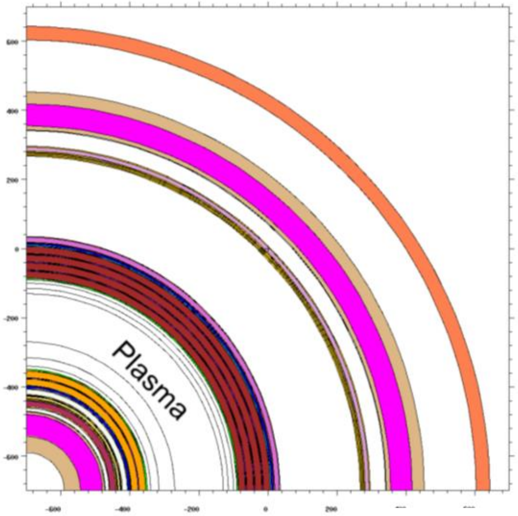
* Fusion Material Damage FES perspective G. Shaw 2024

Verification of Crossection Libraries

1-D Cylindrical Computational Benchmark Models

1. FNSF- *Fusion Energy Systems Studies Fusion Nuclear Science Facility*
   - **Coolant:** He gas, **structure:** RAFM steel, **blanket:** PbLi, **shielding filler:** WC, borated steel
2. FNSF FLIBE- *FNSF with a 2(LiF)-1(BeF_2) blanket*
   - **Coolant:** He gas, **structure:** RAFM steel, **blanket:** flibe, **shielding filler:** WC, borated steel
3. ITER- *Early ITER design*
   - **Coolant:** water, **structure: SS-316**, **blanket:** none, **shielding filler:** borated steel

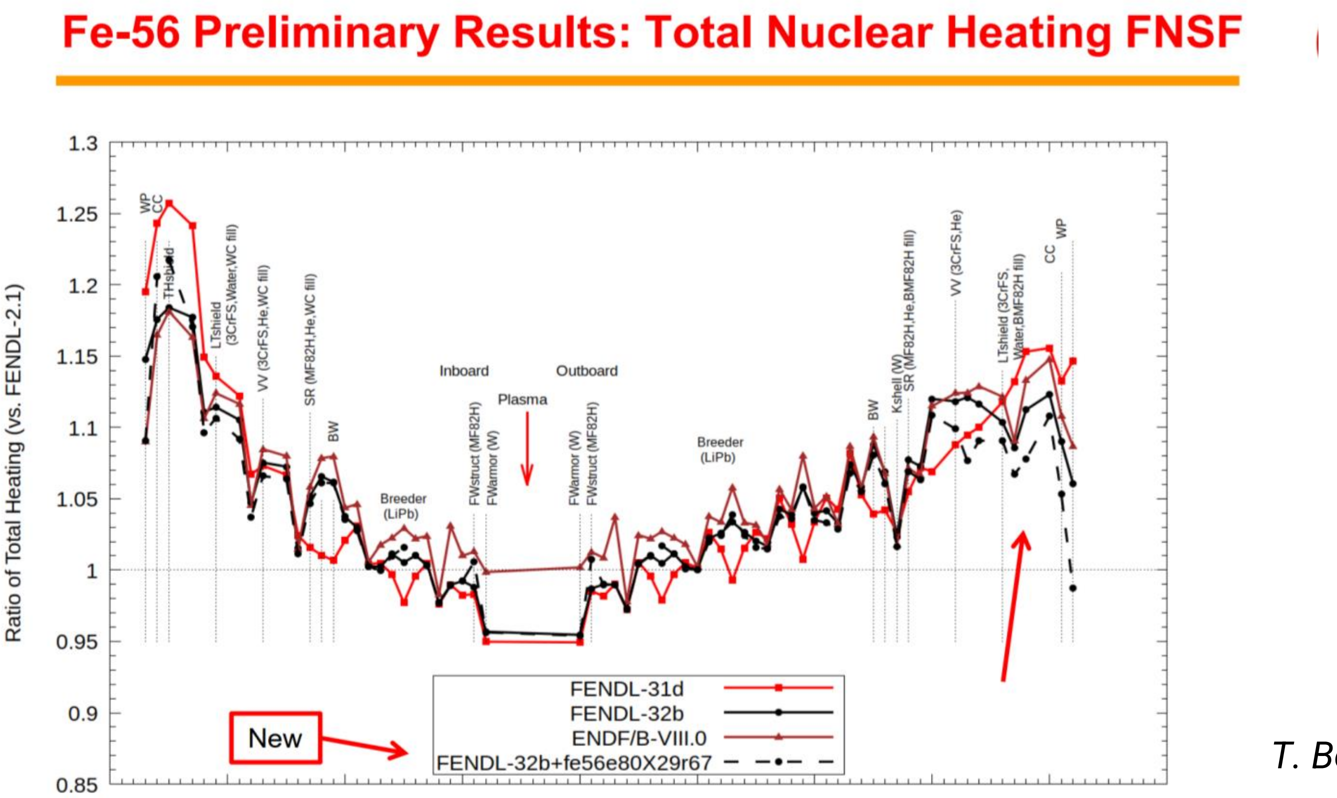




T. Bohm 2024

T. Bohm et al. "Initial Neutronics Investigation of a Liquid Metal Plasma Facing Fusion Nuclear Science Facility, *Fusion Science and Technology*, 2019.

Verification of Crossection Libraries



T. Bohm 2024

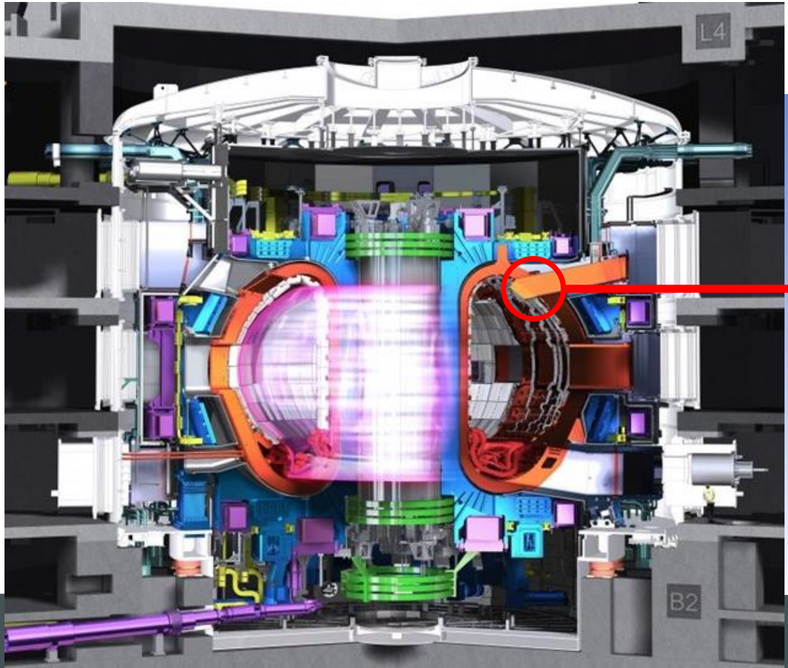
Integrated simulation for Fusion Technology

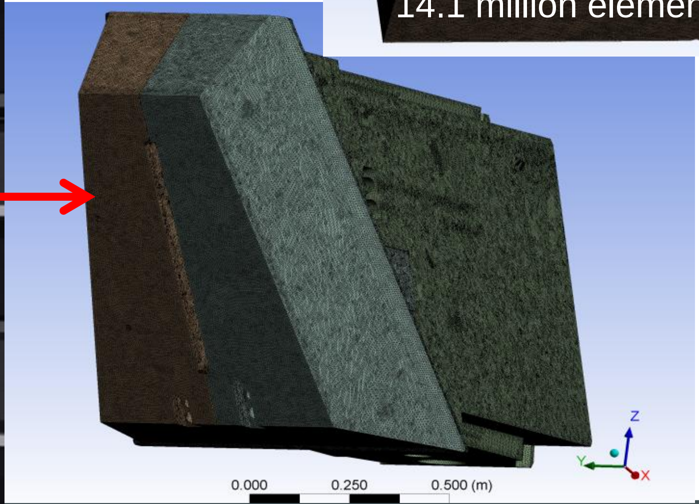
Engineering and physics systems integration modeling and simulations are required to support the engineering design of an FPP.

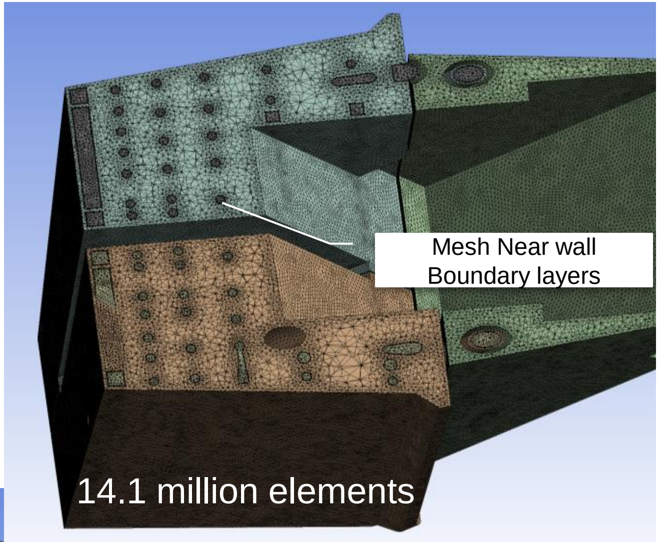
- Physics, system and process models can be combined into comprehensive full device models which will likely contribute to evaluating the operations and maintenance of the pilot plant
- Modeling and simulations incorporating multiple physics and multiscale phenomena with increasing fidelity into simulations to evaluate the refine design options
  - High fidelity simulations will benefit from exascale computing and enable reduced models including via artificial intelligence
- Engineering computer aided design, structural analysis and process and control modeling will provide an important opportunity to optimize the design and integration of the FPP
- Given the lack of prototypic experimental facilities

Multiphysics analysis

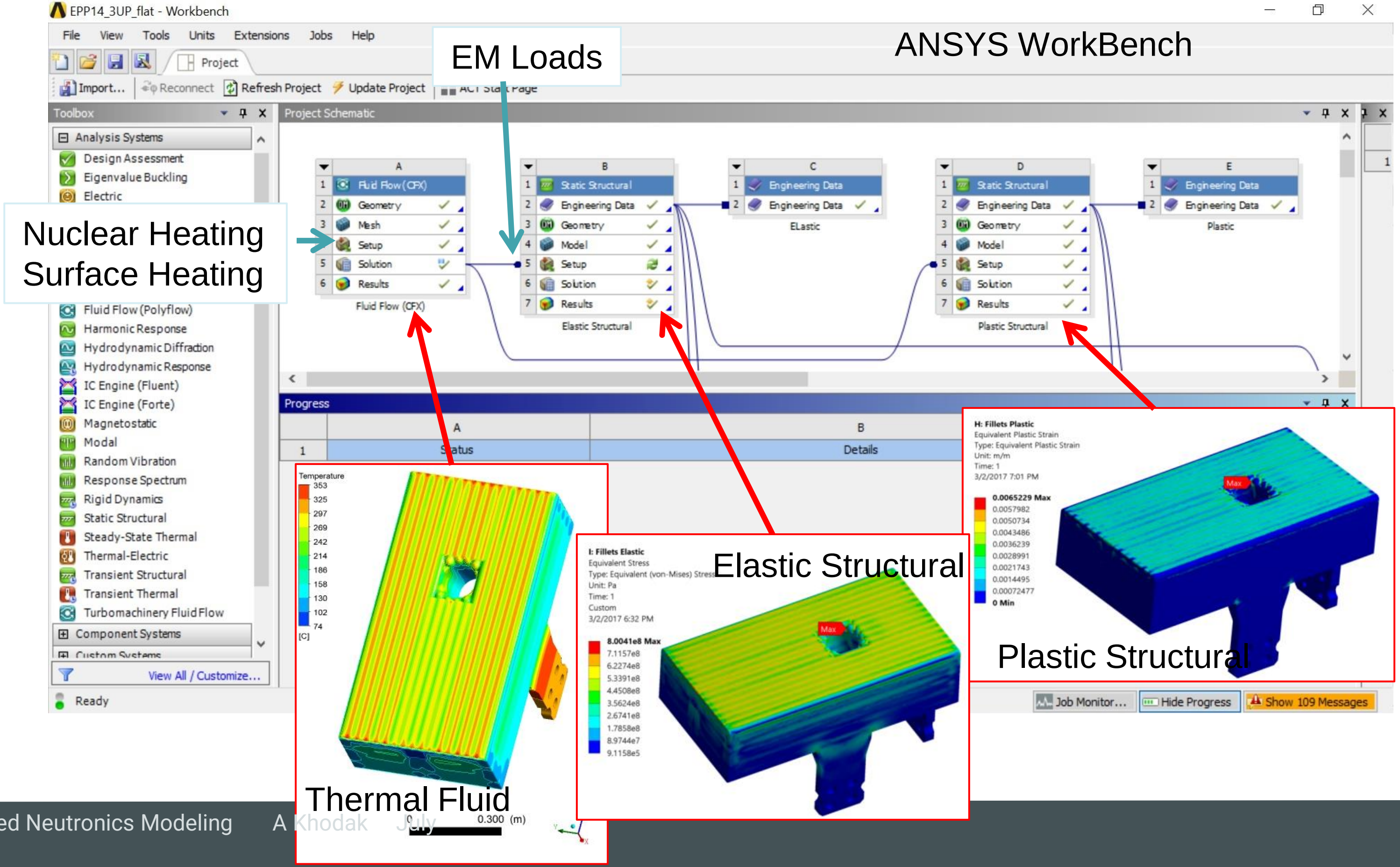
The analysis of many fusion applications such as diagnostic first wall requires integrated Multiphysics analysis



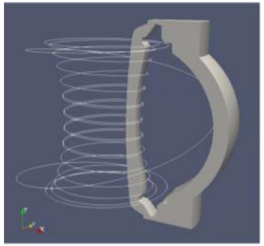


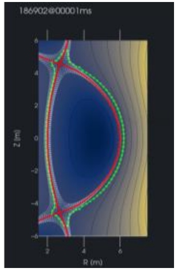


ANSYS allows coupling neutronics results with thermo-fluid and structural analysis

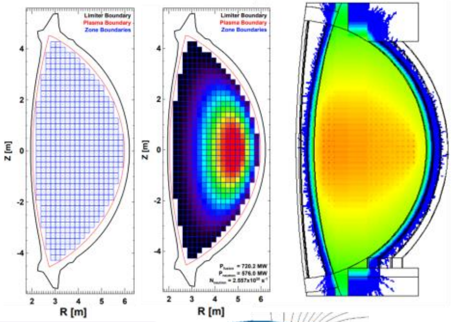


Multi-Physics-Engineering Virtual Prototyping System

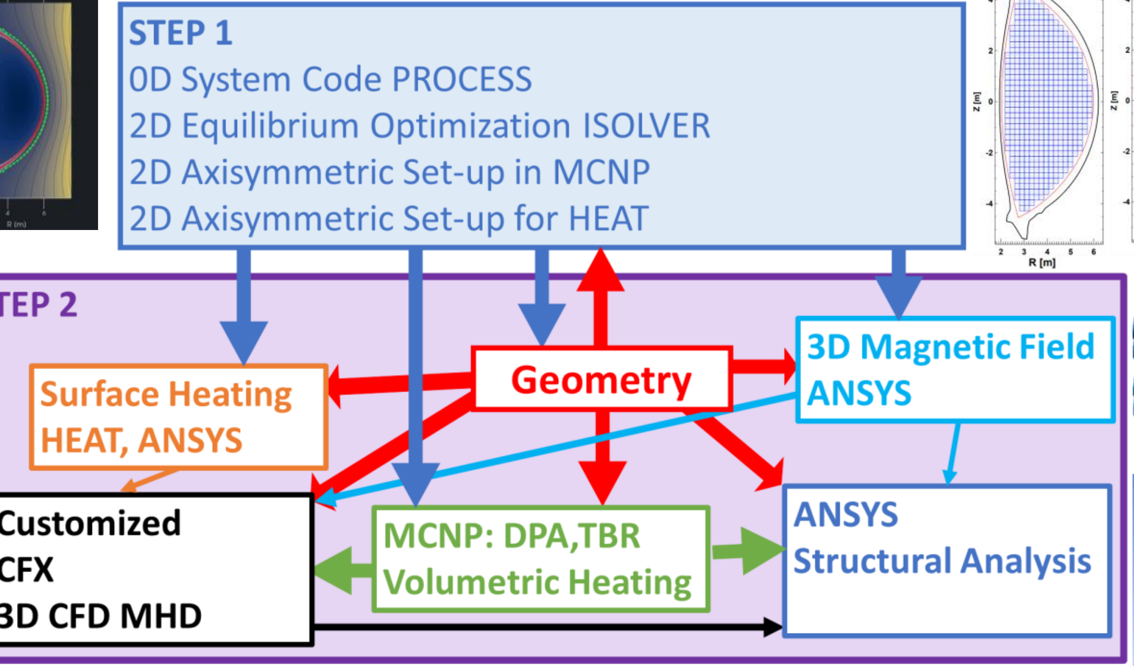


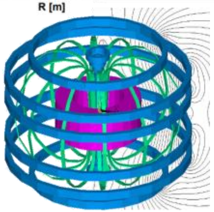


Magnetic field line trace from the blanket surface starting at midplane with the equilibrium used in HEAT

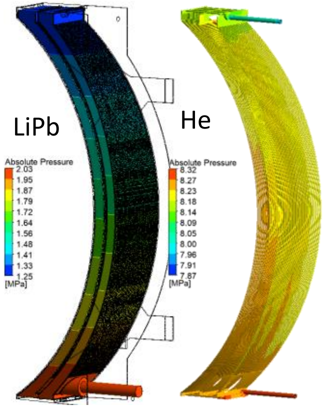


Neutron Source from ISOLVER Interpolated into MCNP

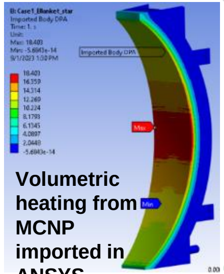




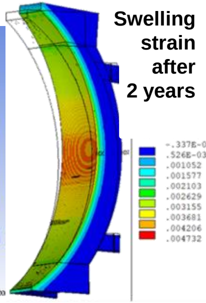
Axisymmetric magnetic field obtained using ISOLVER and PF and TF coils geometry used for 3D interpretation in ANSYS



Absolute pressure in He coolant (left) and Li-Pb (right) fluid zones of the Out-Board blanket



Volumetric heating from MCNP imported in ANSYS



Swelling strain after 2 years

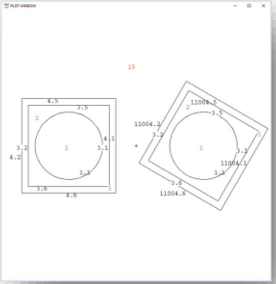
3D structural analysis model includes FEM model of irradiation induced swelling, hardening and creep effect

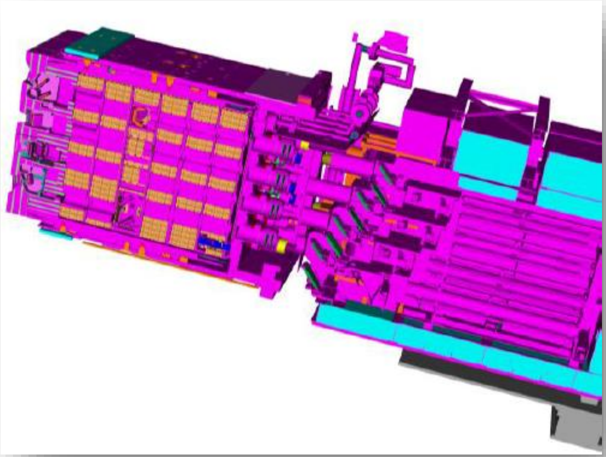
29th IAEA Fusion Energy Conference – October 16-21, 2023 – London, UK:
P8 - 2200 *Khodak et al. "Virtual Prototyping System for Design and Optimization of the Tritium Breeding Blankets for Fusion Power Plant"*
Khodak et al. FED 2023 https://doi.org/10.1016/j.fusengdes.2023.113692

Radiation Transport Model

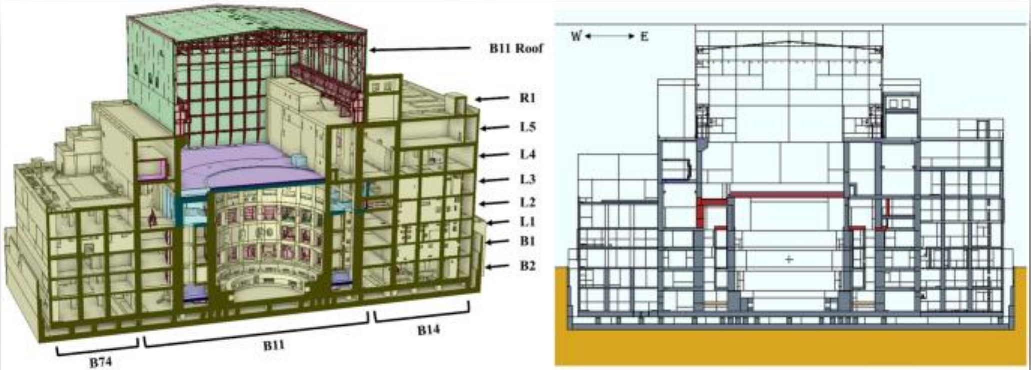
Input for radiation transport

- Geometry
- Materials





- Sources
- Irradiation scenario
- Cooling time



*Godsey, Harb, Loughlin Neutronics for Iter Presentation 2025

Tallies

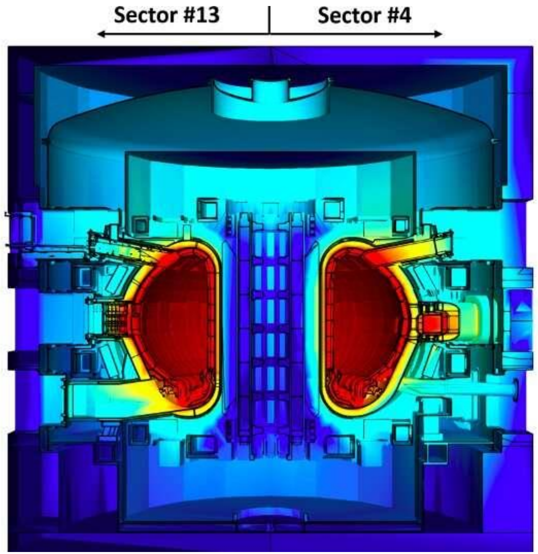
A tally is the accumulation of the nuclear responses from each history at the tally location. Cell based or on a mesh.

Tallies can include:

- Neutron flux
- Gamma flux

And depending on the material

- Nuclear heating (n or γ)
- Reaction rates (activation, transmutation))
- Damage
- Biological dose (and other responses)



These can be computed as a function of particle energy and as a function of space.

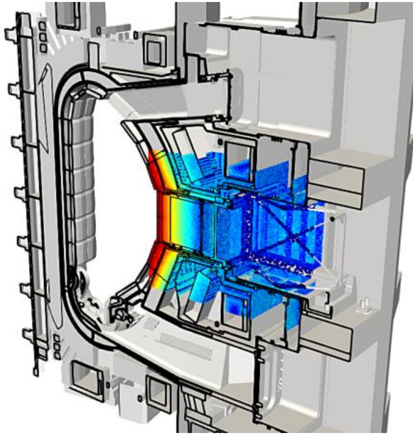
The errors on the tally are also very important

**Godsey, Harb, Loughlin Neutronics for Iter Presentation 2025*

Activation and Shut-down dose rates

Nuclear reactions in a material can render it radio-active. The decay of this radioactive material, with a characteristic half-life and energy, leads to a radiation field that can give rise to decay heat, and dose to equipment or personnel.

When the radio-isotope inventory is determined, a secondary source is created. The transmission of radiation from this source is computed in another phase of the calculation.

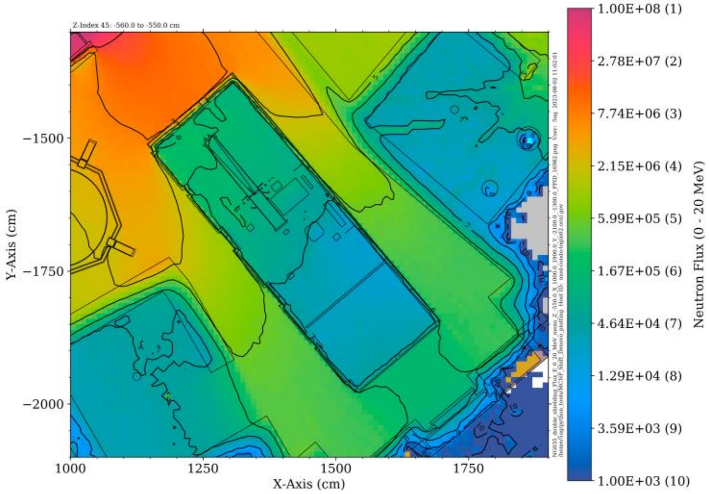


Decay photon source in an ITER generic equatorial port interspace (UNED)

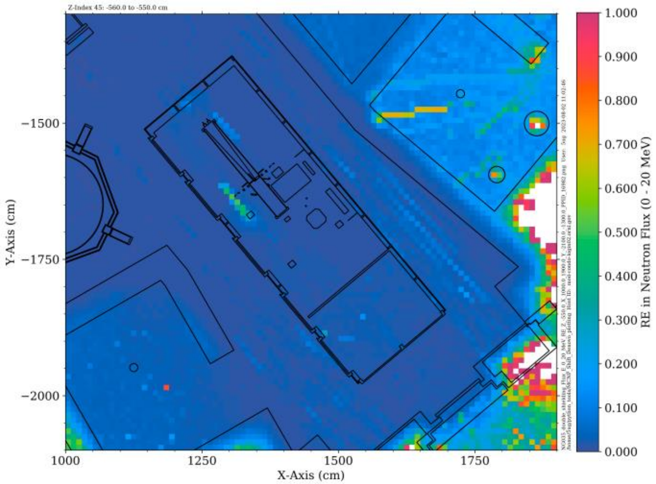
*Godsey, Harb, Loughlin Neutronics for Iter Presentation 2025

Uncertainties

Neutron Flux



RE in Flux (1-sigma)



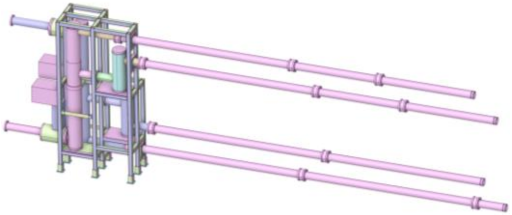
Monte Carlo is a stochastic process.

As you get further from the source the response is lower and the errors are higher (warning: over-simplification)

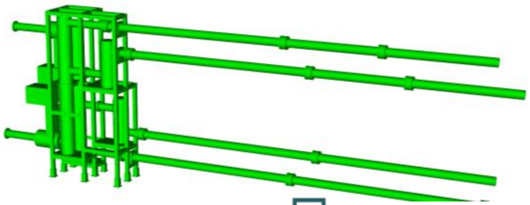
*Godsey, Harb, Loughlin Neutronics for Iter Presentation 2025

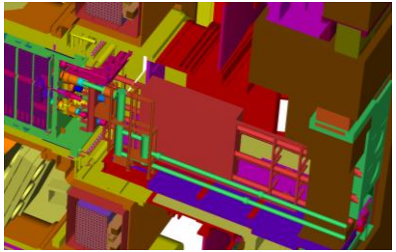
ITER Analysis: Model Preparation

Original CAD in STEP is defeatured

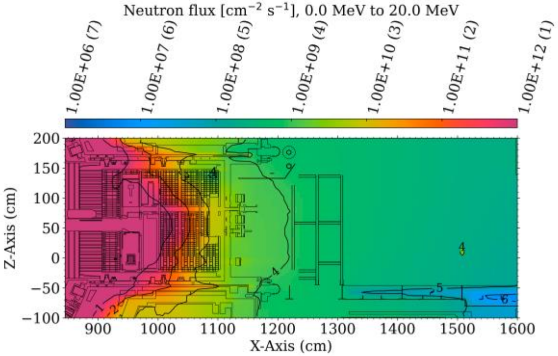


Defeatured CAD converted to MCNP





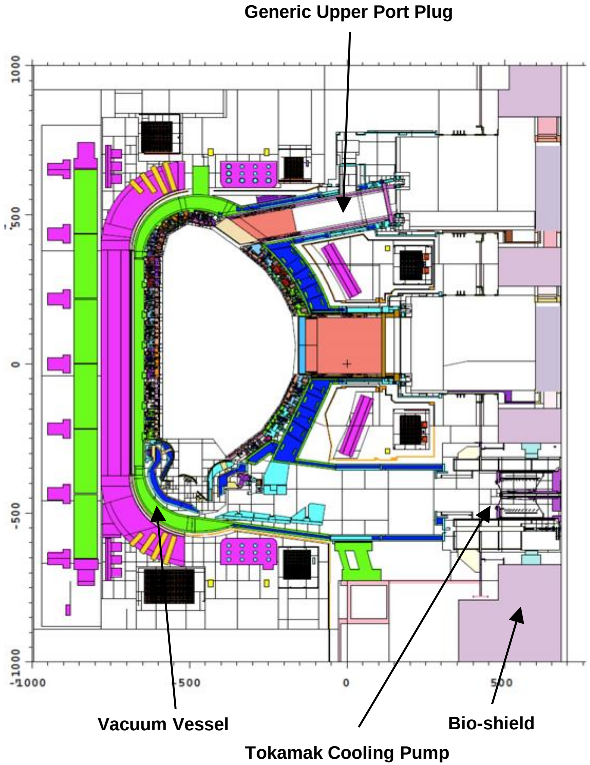
Converted CAD integrated into ITER reference model



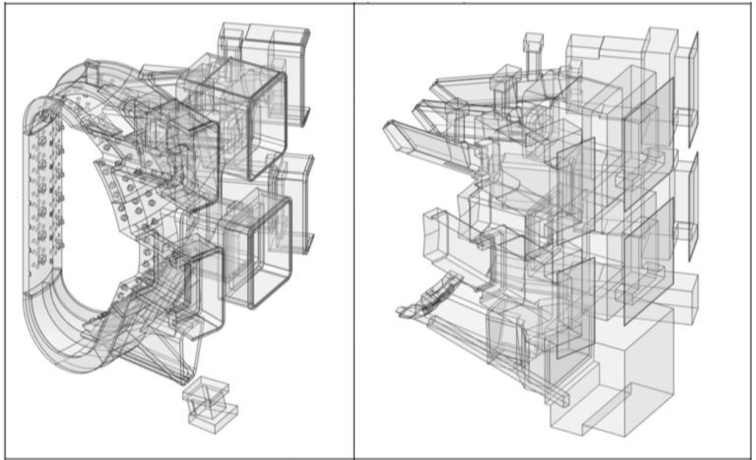
Results from integrated model

ITER Sector Model

- C-model [1] is a reference MCNP model representing a single ITER sector, spanning 40º toroidally.
- The model is comprised of space reservations, envelopes, that are filled with representative models of the coils, vacuum vessel, blanket, etc.
- Generic envelope fillers can be replaced by a detailed model of the concerned port, ex. UPP#11.
- Useful to assess localized nuclear responses in most ITER ports, excluding NBIs and their neighbors.
- Care must be taken in defining boundary conditions.



ITER C-Model
[C-model_R181031 model document v1.5, ITER IDM ref. XETSWC, 2019.]

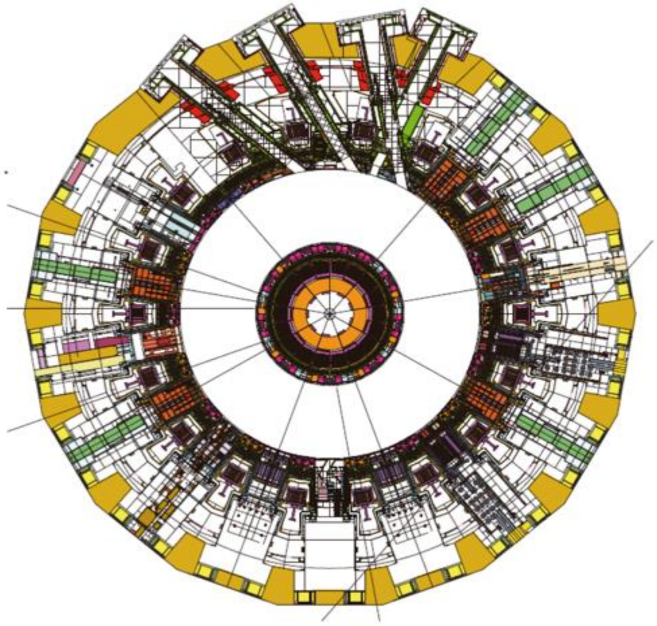


Envelopes for Vacuum vessel (PBS-15)	Envelopes for Upper, equatorial, and lower port plugs (Multiple PBS – 15, 26, 31, 51, 52, 54-57)

C-Model Envelopes

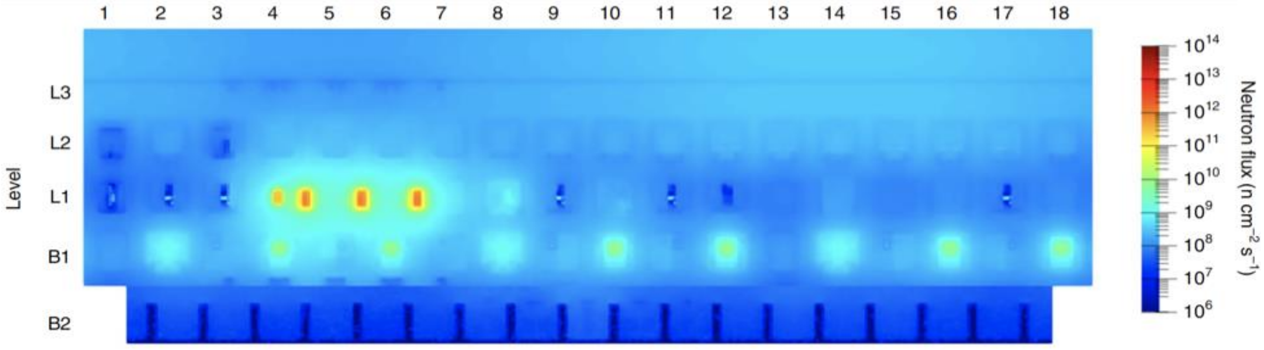
ITER 360º Model

- E-lite is a full 360° MCNP model of ITER tokamak [].
- A faithful representation of the fusion environment is essential to ensure a high accuracy of the concerned nuclear responses.
- It is important to capture cross-talk between ports.
- The image below shows the neutron flux in the ITER tokamak due to plasma neutrons,
  - C-Model can be used for most ports, except NBIs and their neighbors.
  - Proper port fillers should replace generic ones to capture cross-talk.



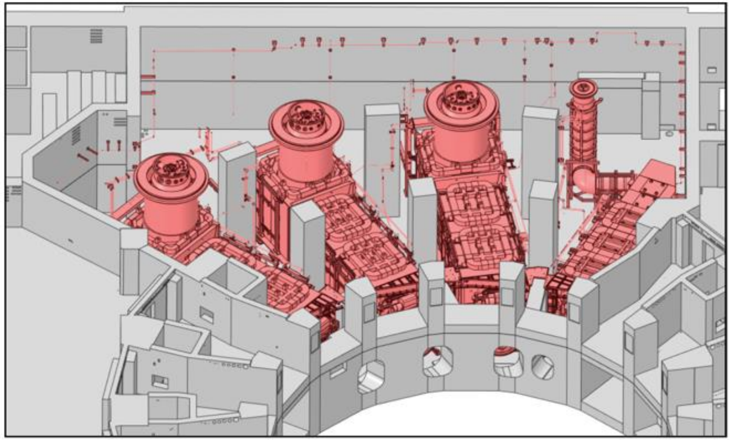
Plot of E-Lite Model at L1

[E-lite 360º MCNP model - Model Report, v1.1, ITER IDM ref. 2RLM3G, 2020]

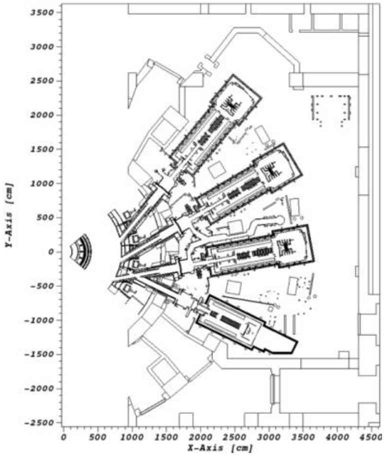


Neutron Flux at the Bio-Shield [5]

ITER NBI Cell



CAD Model of the NBI Cell
[NB Cell & HV Deck - MCNP model v1.0, ITER IDM ref. 2SGT5W, 2020]



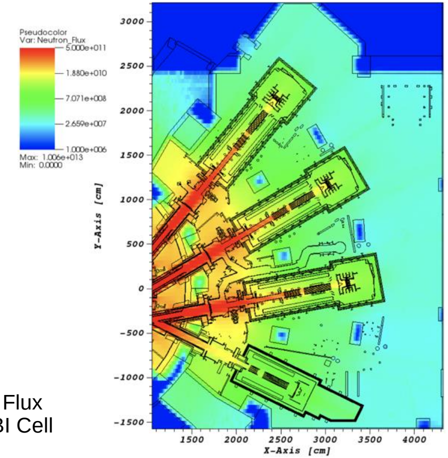
MCNP Model of NBI Cell
[Deliverable 5 - Final report v1.0, ITER IDM ref. Q73NR8, 2015]

The plasma in ITER will be heated through injecting accelerated deuterium atoms.

ITER will have three heating and one diagnostic Neutral Beam Injectors (NBI), residing in the NB cell.

The MCNP model spans 80° toroidally.

Due to the streaming ducts, and penetration of NBI through the bio-shield, neutron flux is high in the NBI cell.

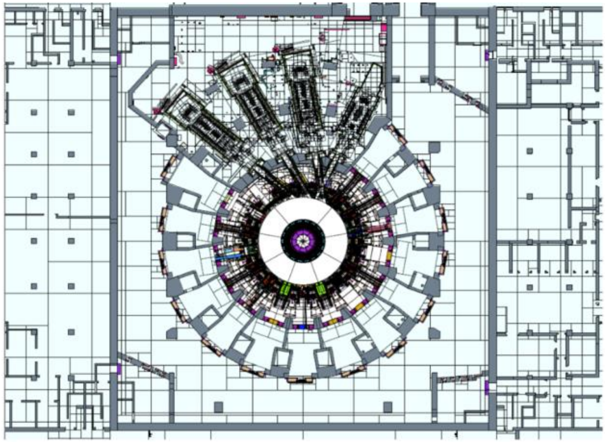


Neutron Flux
in the NBI Cell

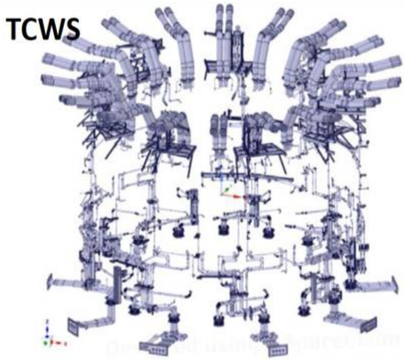
ITER Full Model

Combines the E-Lite model with the MCNP model of the Tokamak building, the neutral beam cell and the plasma neutron source and the activated water γ-ray source.

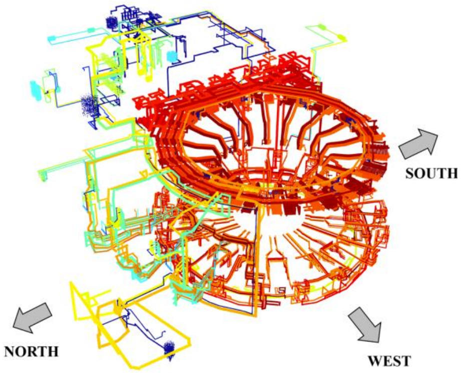
It is useful in assessing nuclear responses and for capturing all cross-talk (e.g., NB cell to port cell).



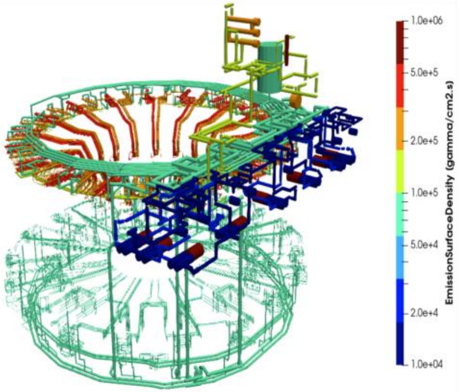
ITER Full Model at L1 [R. Juarez, et al., Nature Energy, 2021]



CAD Representation of TCWS
[E-lite 360º MCNP model - Model Report, v1.1, ITER IDM ref. 2RLM3G, 2020]



Activated water source



Emission Density from Activated Corrosion Products at EOL
[DDR Maps report per area status N+1, ITER IDM ref. 68VR7F, 2022]

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  - Structural Analysis
- Integrated Analysis for ITER at Jet
- Conclusions

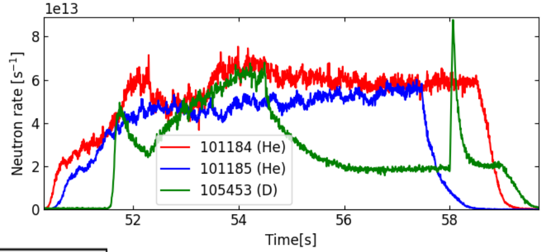
Modelling realistic neutron sources and synthetic diagnostics

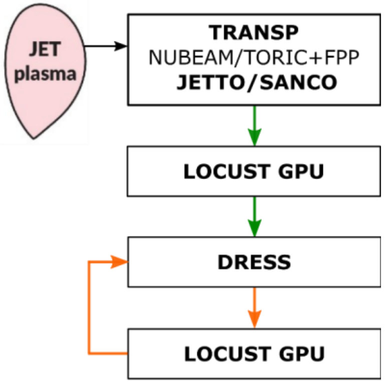
UK Atomic Energy Authority | UPPSALA UNIVERSITET | Institut "Jožef Stefan" Ljubljana, Slovenija

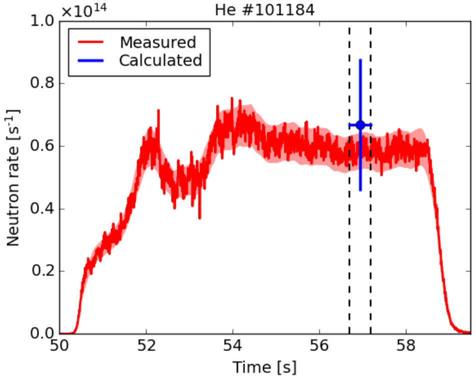
JET

JET p+Be fusion experiments analysed with novel integrated modelling workflow (ITER PFPO motivation)

Experiment







[Ž. Štancar *et al* 2021 *Nucl. Fusion* **61** 126030]

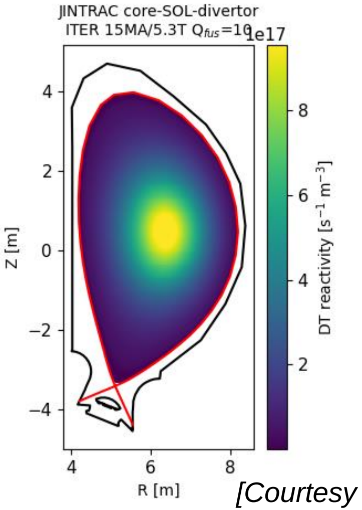
Exp. vs calc.

ITER

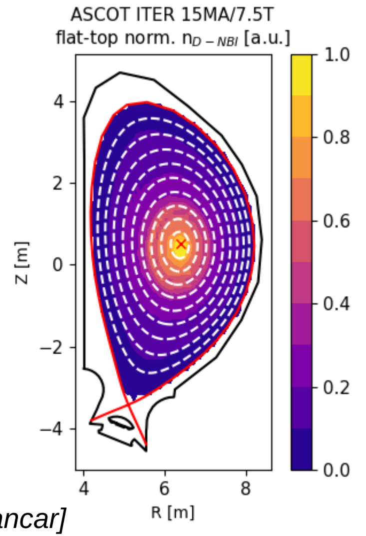
ITER 15MA/7.5T baseline Q_{fus}=10 scenario modelled with JINTRAC core-SOL-divertor coupling & IMAS output → being coupled to DRESS (IMASified) and ITER MCNP, standardized and routine

JINTRAC-DRESS-MCNP

Total emissivity



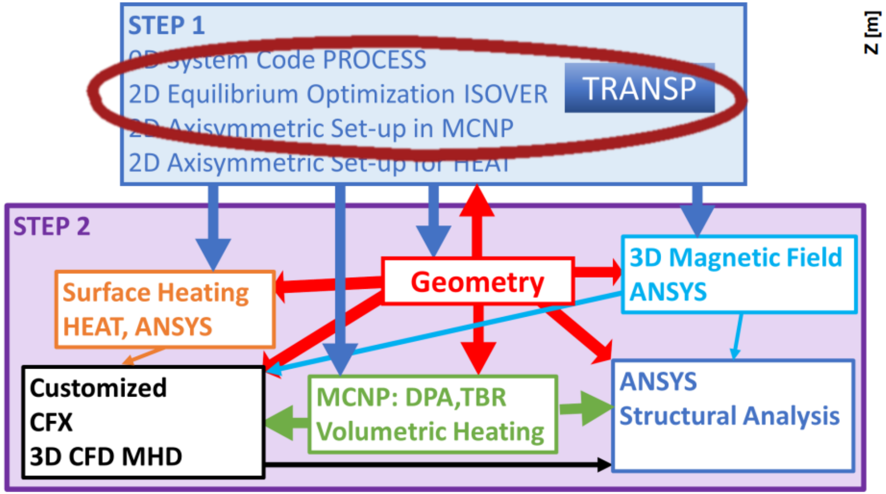
Fast ion density

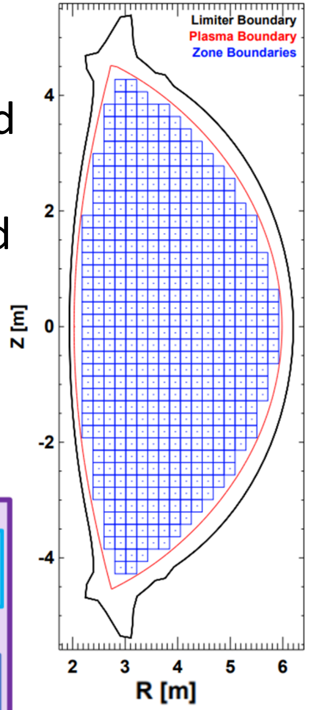


[Courtesy of Z. Stancar]

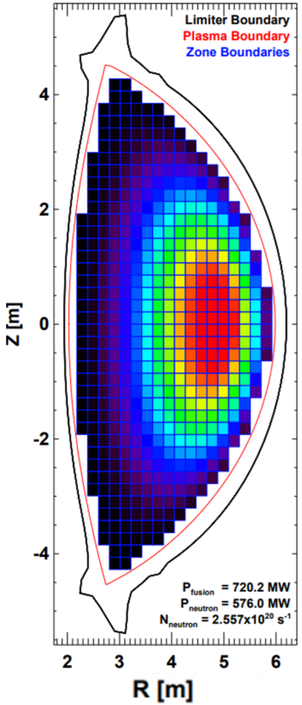
Neutron Source Interpolation for Neutronics Code MCNP

- Automatic spatial NS distribution transfer from ISOLVER to MCNP
- Connection to TRANSP can be achieved in a similar manner
- IMAS interface connection can be used

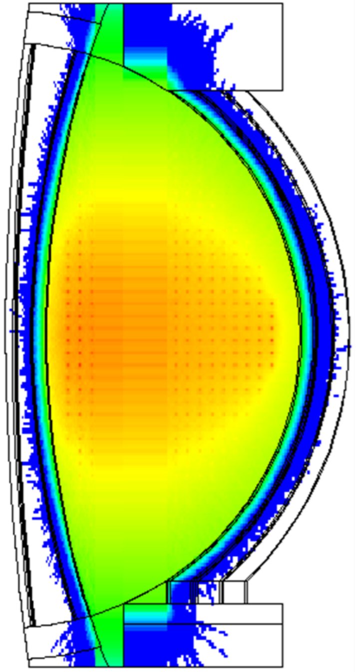




R,Z grid and plasma zone boundaries defined in iSOLVER



Neutron power density profile mapped onto the R,Z grid for import into MCNP



Relative intensity of neutrons born in MCNP model visualized by plotting neutron flux (E>13.99 MeV)

Linn et al. SOFE 2023

3D Neutronics Source

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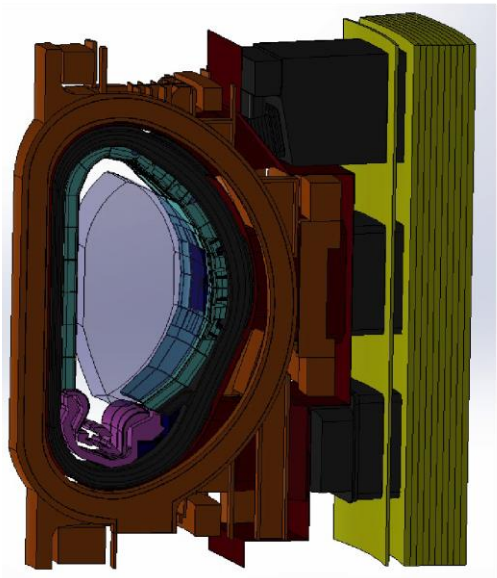
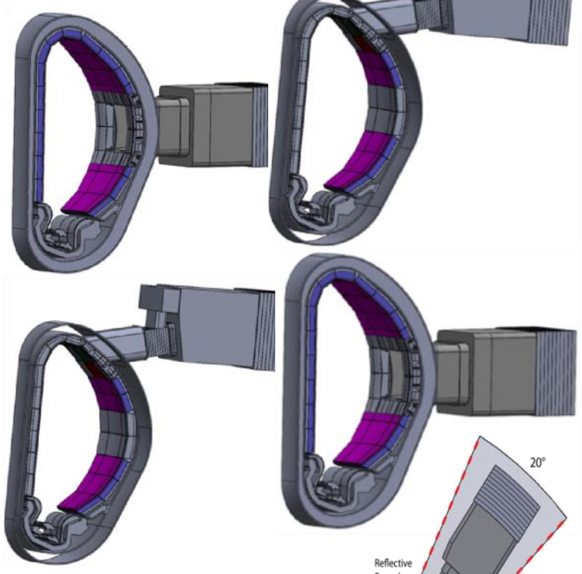
  - Spin Polarized Fusion
- Modeling
- Integration with Plasma Codes
- Integration with Engineering Codes:
  - **Fluid, Heat and Mass Transfer analysis**
  - Structural Analysis
- Integrated Analysis for ITER at Jet
- Conclusions

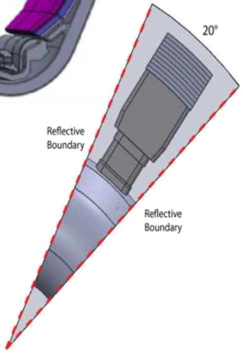
Loads – Volumetric Heating

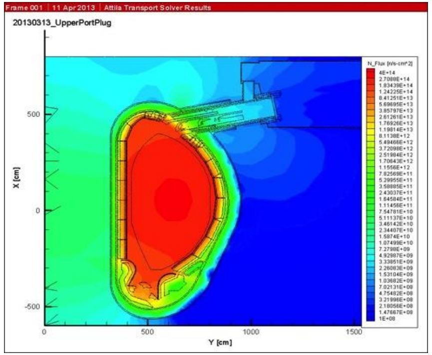
Full ITER Solidworks Model

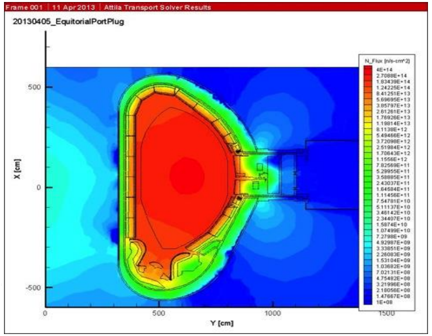


Simplified ITER DFW Heatin
Solidworks Models





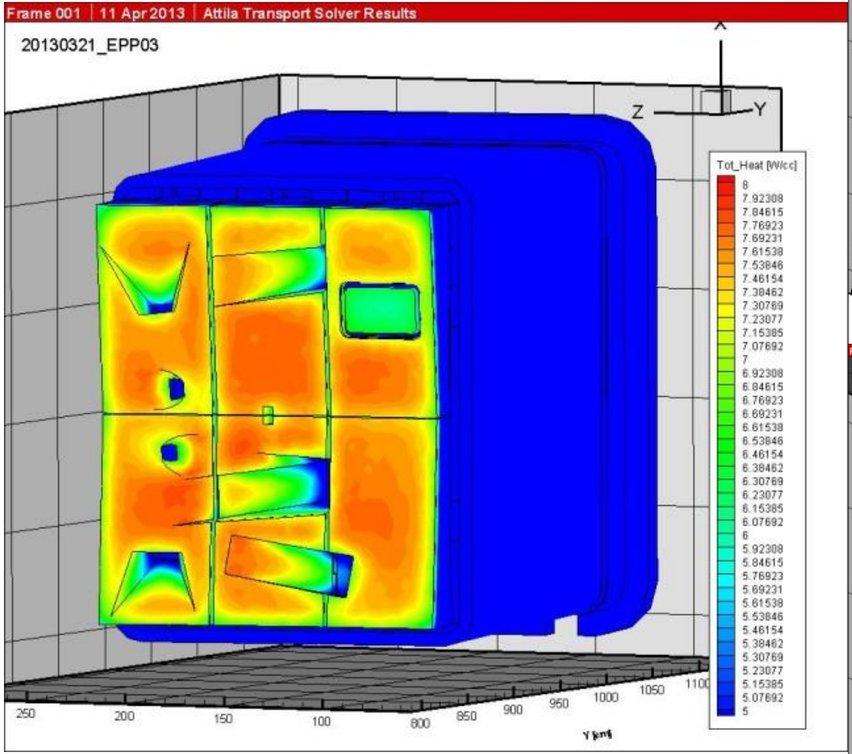


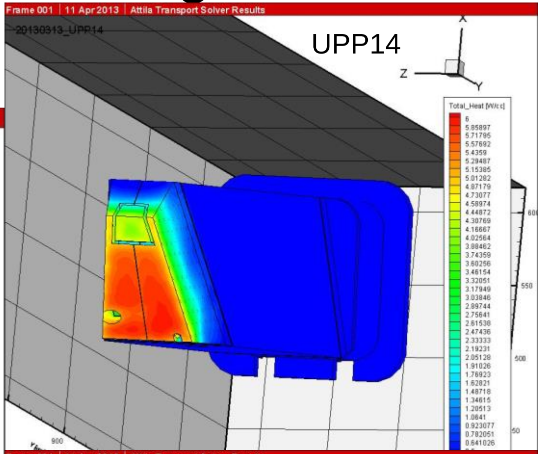


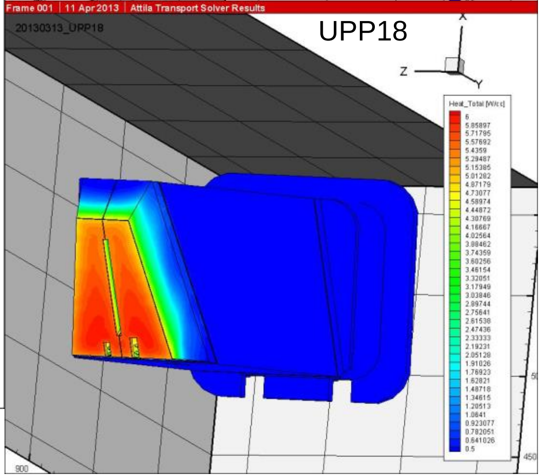
Nuclear Analyses Sector Model

Loads – Volumetric Heating

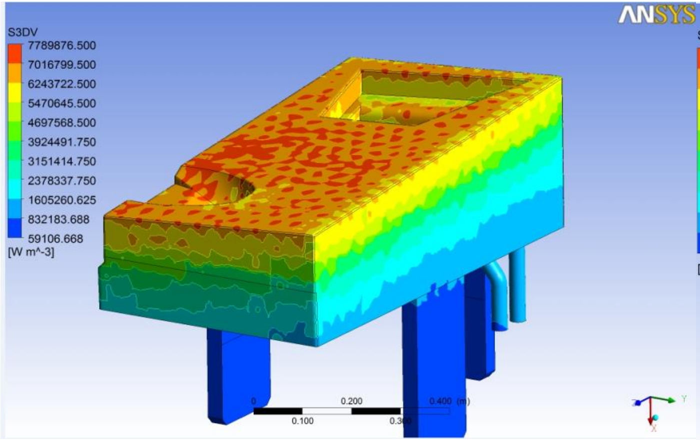
Nuclear Analysis EPP03

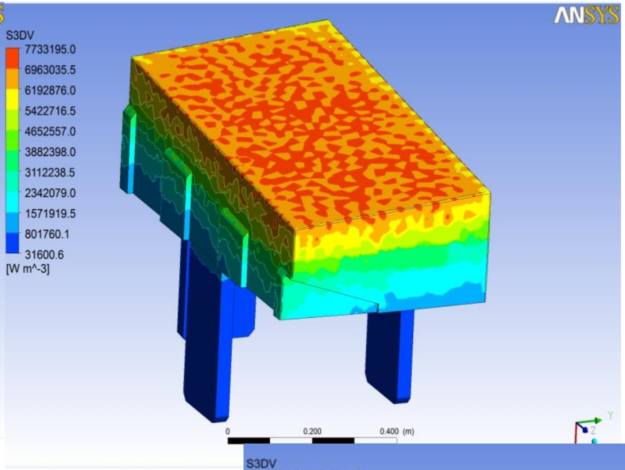


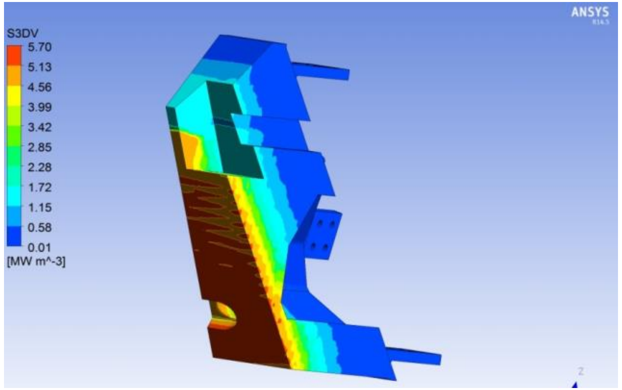


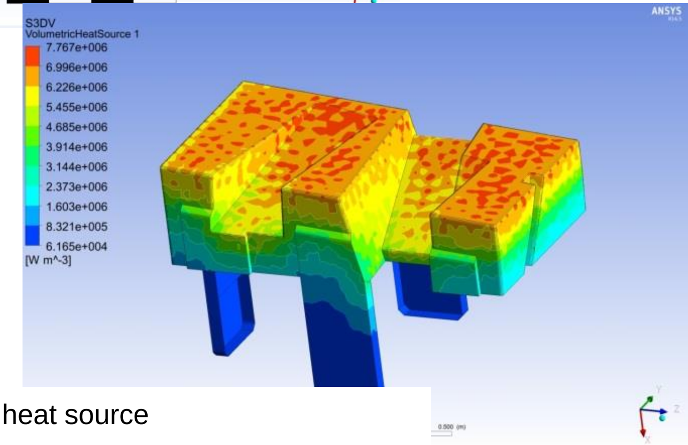


Loads – Volumetric Heating









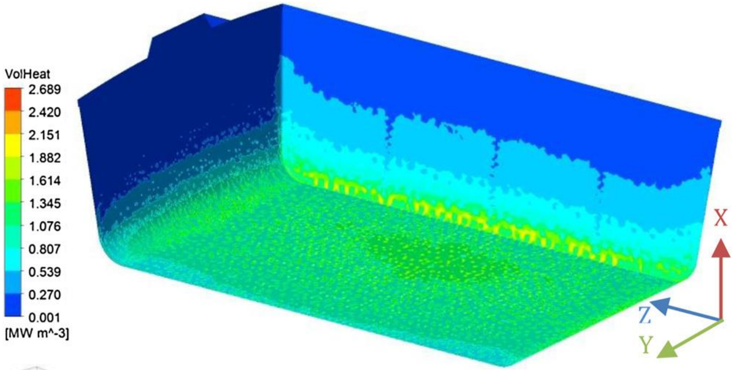
Volumetric heating distribution transferred to CFX as a heat source

PPPL MVP MHD MODEL

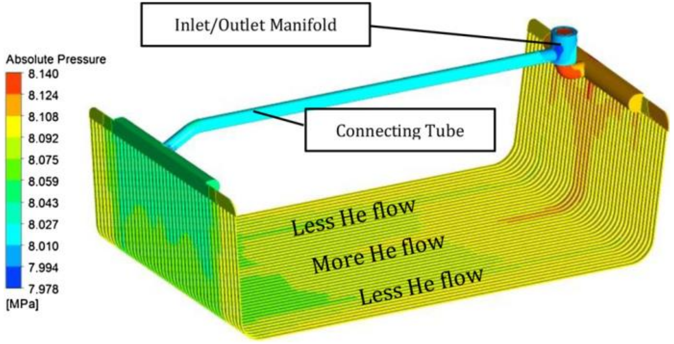
- Customized ANSYS CFX
- Magnetic Vector Potential (MVP) MHD model
- Validated for high Hartmann Numbers

Two Fluid CFD analysis Conjugate Heat Transfer

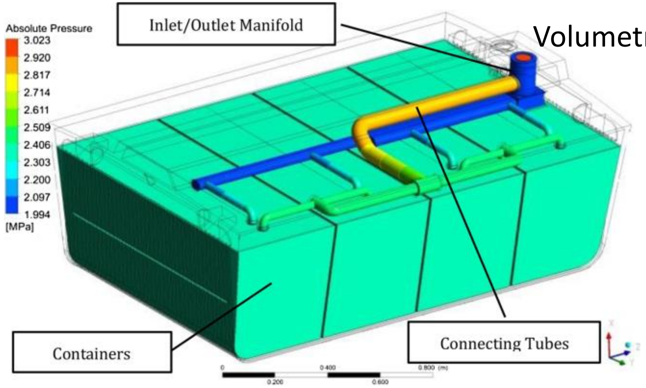
Volumetric Loading from Neutronics code



Volumetric heat source imported from Attila.



He coolant pressure distribution

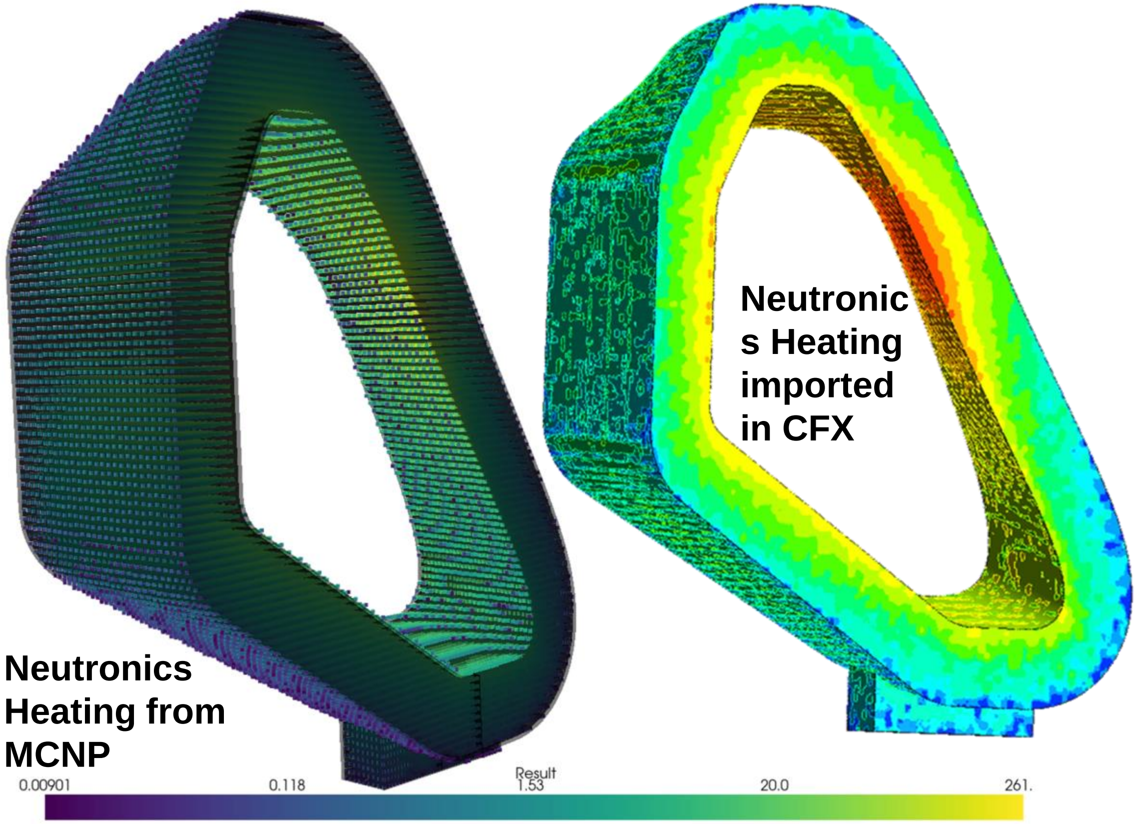


Pressure distribution in Li17PB

Khodak et al. FED 2018

Python scripts used to convert MCNP output to importable mesh tallies

- MCNP Cylindrical Mesh tally was used to acquire the nuclear heating
- Multiplication factor for heating was calculated per unit volume for a 2800MW plasma



Outline

- Neutrons in Fusion
  - Fusion Reactions
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  - **Structural Analysis**
- Integrated Analysis for ITER at Jet
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Incorporating irradiation-induced material degradation into ANSYS structural simulations using User Programmable Features (UPF)

* **A liquid metal blanket is a dominant design option for the next step of fusion devices**. Compared to ITER, the plasma facing and breeding-blanket components of the fusion power plant will suffer intense irradiation by a fluence of 14 MeV neutrons, which leads to the formation of transmutation products and irradiation defects. Structural simulation should incorporate neutron irradiation effect on the physical and mechanical properties for accurate evaluation.

* **Both mechanical strength and thermal behaviors will be changed**, include:

- small voids and density change;
- lattice defects and internal deformation;
- embrittlement and strength reduction;
- microcracks and fracture toughness reduction etc.;

* However, **most present machine design and analysis didn't include nuclear irradiation effect** due to general lack of predictive modeling method.

***** Recently, more and **more studies have been done to measure the material property change and characterize irradiation damage**, like voids density and hardness change of F82H.

* We developed the technique of **FEM implementation using ANSYS UPF to include irradiation induced material degradation effect in our models**, to simulate and predict structure behavior, strains and stresses.

JPhys Energy

PAPER • OPEN ACCESS

Irradiation damage concurrent challenges with RAFM and ODS steels for fusion reactor first-wall/blanket: a review

To cite this article: Arunodaya Bhattacharya *et al* 2022 *J. Phys. Energy* **4** 034003

Radiation effects on stress evolution and dimensional stability of large fusion energy structures

Arian Ghazari[a,*], Ruggero Forte[b], Takuya Yamamoto[c], Robert Odette[c,1], Nasr Ghoniem[a]

[a] Department of Mechanical and Aerospace Engineering, University of California Los Angeles, Los Angeles, CA 90095, USA
[b] Dipartimento di Ingegneria, Universitá di Palermo, Viale delle Scienze, 90128 Palermo, Italy
[c] Department of Mechanical Engineering, University of California Santa Barbara, Santa Barbara, CA 93106, USA

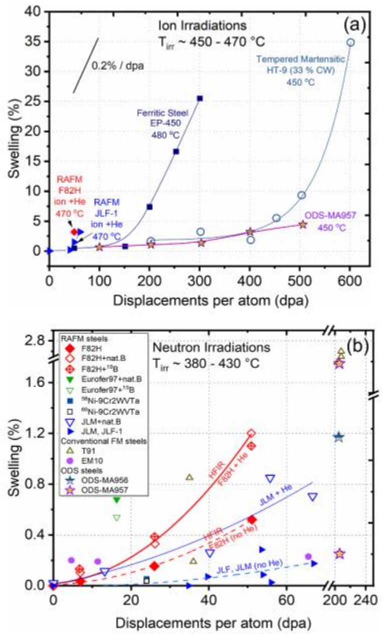


Figure 19. (a) Cavity swelling in ion irradiated and (b) neutron irradiated RAFM, conventional FM and ODS steels. For neutron irradiations, the effect of He on swelling is simulated by B doping and ^{58}Ni/^{60}Ni isotopic tailoring technique. Data used from [87, 99, 119, 199, 208, 308, 309, 311–317]. Figure (a) reprinted from [309], copyright (2014), with permission from Elsevier.

Hardening effect due to irradiation

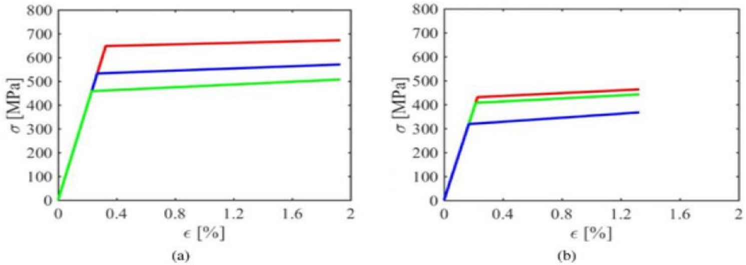


Fig. 10. Stress-strain relationships according to the linear hardening model at BOL (0 dpa, green curve), 45 dpa (blue curve) and 90 dpa (red curve) for (a) 375 ∘C and (b) 500 ∘C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Swelling strain Vs. DPA

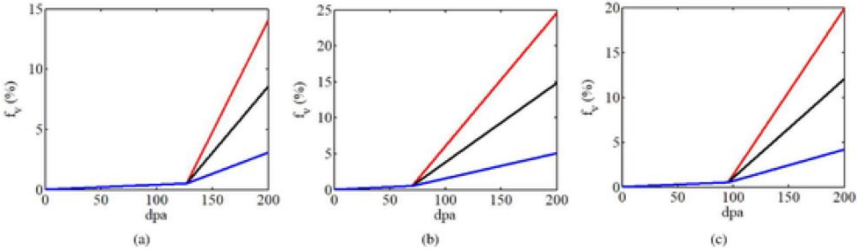


Fig. 11. Void swelling (f_v) as a function of neutron displacement damage dose (ϕ) in dpa at (a) 350°C, (b) 500°C, and (c) 600°C considering worst case (red curve), reference case (black curve which is used in our simulations) and best case (blue curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Brief introduction about ANSYS UPF (User Programmable Features)

* ANSYS is a commercial finite element analysis software with integrated modules like EM, thermal, structural, fluid etc. Currently it doesn't support nuclear swelling simulation.
* But ANSYS has an open architecture, allowing users to write their own subroutines in Fortran or C and link them to ANSYS, so that users can add new functions to their own ANSYS. For instance, users can define a new element, a new material behavior, nuclear swelling effect, or a modified failure criterion etc. This is called User Programmable Features (UPF).
* UPFs provide the capabilities like:

------ read data from ANSYS database, either process them or use them for further computation.

------ existing routines for users to specify various types of loads. In our case, we specify "fluence" load to represent neutron flux DPA.

------ modify and monitor existing elements. In our case, we add swelling strain to a structural element.

------ define new material properties: plasticity, creep, swelling law, hyper-elasticity etc. We define our swelling law.

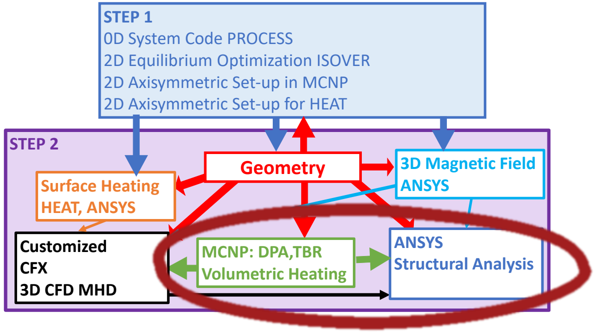
------ define new elements and may adjust nodal orientation matrix.

------ create a custom design optimization routine etc.

```
      subroutine usersw
     (option,elem,intpt,mat,proptb,ncomp,epswel,
     x  epel,e,nuxy,fluen,dfluen,tem,dtem,toffst,timvll,timvnc,usvr)
      integer option,elem,intpt,mat,ncomp
      double precision  proptb(*),epswel,epel(ncomp),e,nuxy,
     x  fluen,dfluen,tem,dtem,toffst,timvll,timvnc,usvr(*),
     x  delswl,eptot(3)
```

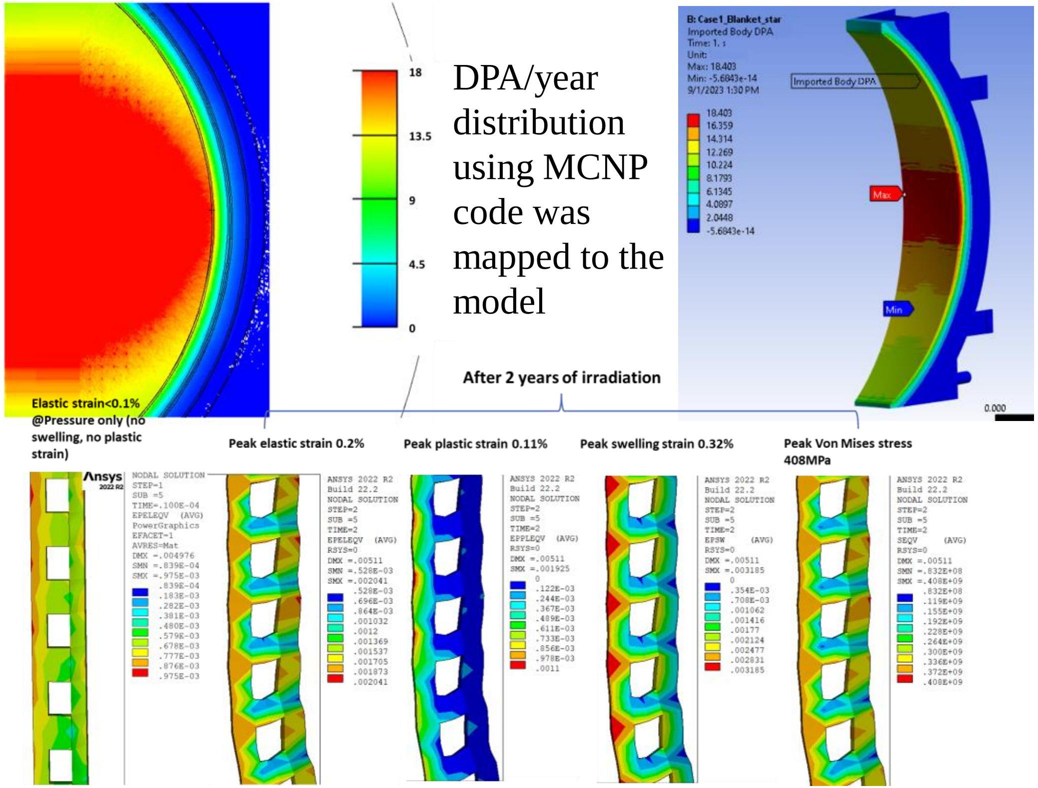
```
      if (fluen .le. proptb(68)) then
         delswl = proptb(67)*dfluen
         epswel = epswel + delswl
       else
         delswl = proptb(69)*dfluen
         epswel = epswel + delswl
       endif
```

Structural Analysis 3D Neutronic Swelling Model



- Neutronics Swelling and Hardening are introduced in ANSYS ADPL using User Defined Functions for Properties
- DPA values are imported from MCNP

H.Zhang et al. IEEE TPS 2024



After 2 years, close look (500x) at the strains of first wall shows a complex strain-stress state which may initiate microcrack

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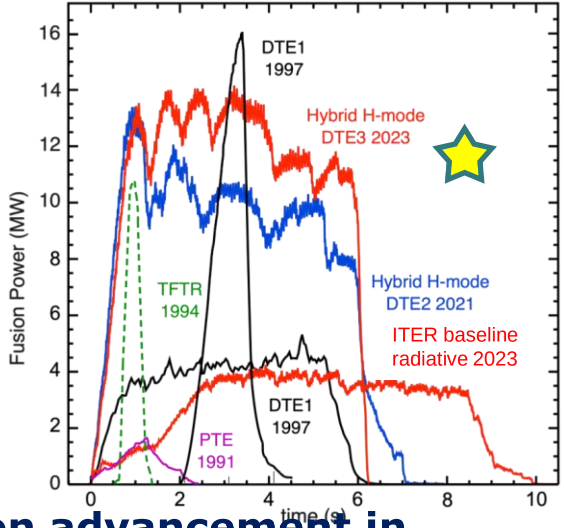
Deuterium-Tritium operations at JET

DT operations in tokamak only at JET & TFTR

- **1991 JET Preliminary Tritium Experiments (PTE)**
- **1994-96 TFTR**
- **1997 JET DTE1 in CFC wall- P_{fus} 16.1 MW record!**
- **2003 Trace Tritium Experiment (TTE)**
- **2021 JET DTE2 in Be/W wall**
- **2023 JET DTE3 in Be/W wall –E_{fus} 69 MJ**

new record!



[F. Rimini, EPS 2024]

Unique high-performance DT campaigns for nuclear fusion advancement in physics, technology and operations

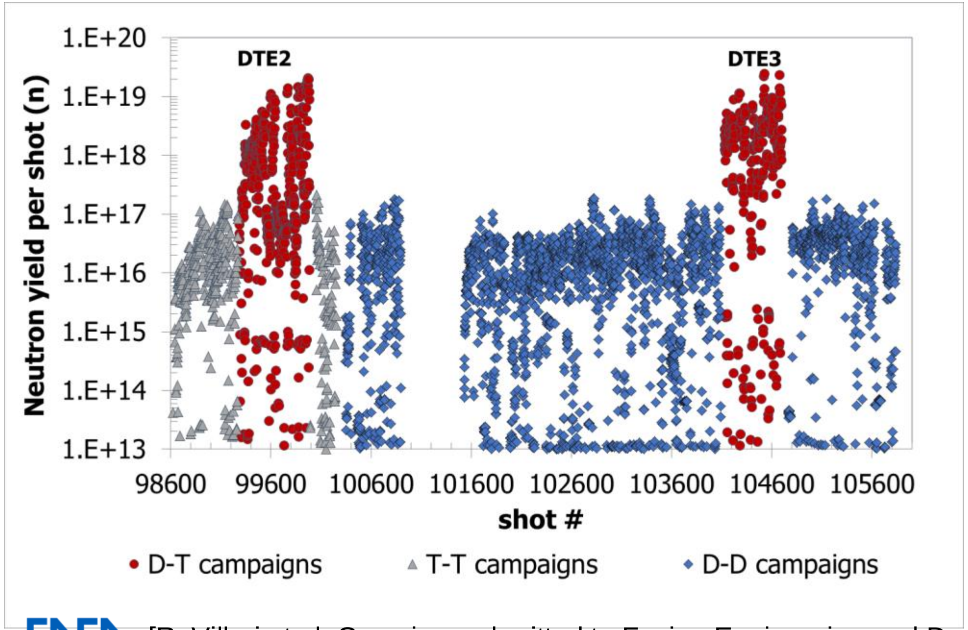
[X. Litaudon et al 2024 Nucl. Fusion 64 112006] [C.F. Maggi et al 2024 Nucl. Fusion 64 112012] [R. Villari et al, Overview submitted to Fus. Eng. and Des.]

* R. Villari 2024

Neutron production at JET 2021-2023

DTE2

DTE3



DTE2 campaign@8.48x10^{20} n

DTE3 campaign@7.31x10^{20} n

1.57x10^{21} n!

1.83x10^{21} DT Neutrons over 40 years of operations

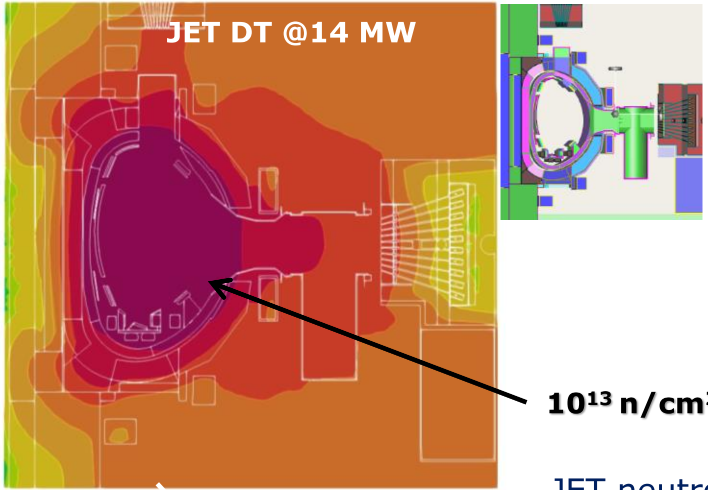
… more than 80% in the last DT campaigns!

[R. Villari, SOFT-2024 , "Overview of Deuterium-Tritium nuclear operations at JET" Plenary-4.1]

ENEA [R. Villari et al, Overview submitted to Fusion Engineering and Design

* R. Villari 2024

Representativeness of JET DT for ITER- Neutron flux



10^{13} n/cm²/s

JET neutron flux inboard FW **~10^{13} n/cm²**

N flux

- **10^{13} n/cm²/s @ rear ITER blanket**
- **Max 2x10^{13} n/cm²/s @ One order of magnitude less than ITER First Wall**

Cumulated JET total neutron fluence max inboard FW **~10^{16} n/cm²**

N fluence

N fluence 10^{16} n/cm² in ITER

- **@rear port plugs at the end of ITER DT-2**
- **@middle ITER port plugs-rear blanket at the end of ITER DT-1 (~1/100)**

JET DT relevant for ITER technologies!

* R. Villari 2024

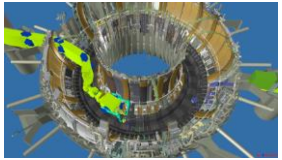
Verification of 14 MeV neutron calibration

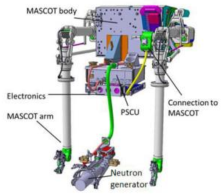
- **Neutron calibration: critical scientific and regulatory importance → <u>< ±10% target accuracy of ITER</u>**

- **JET Neutron calibration @14 MeV with Neutron Generator (2017) →Total uncertainty <u>±6%</u>**

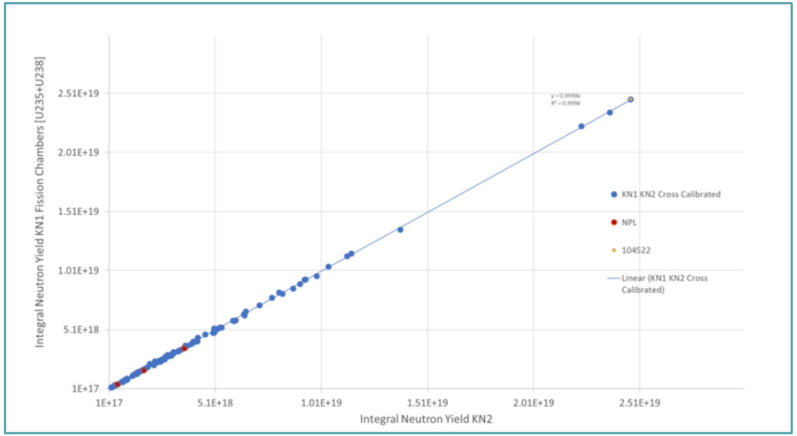
- **JET Neutron DT Plasma calibration (2021-2023)**
  - Several high yield shots measured during DTE2-DTE3 → rigorous cross calibration of U235&U238 Fission chambers
  - Multiple dosimetry foil measurements → Activation foil system shots show excellent agreement
  - Continuous monitoring and cross calibration checks

  → **Total uncertainty <u>±10%!</u>**





[P. Batistoni NF. 58 (2018) 106016]



[Z. Ghani]

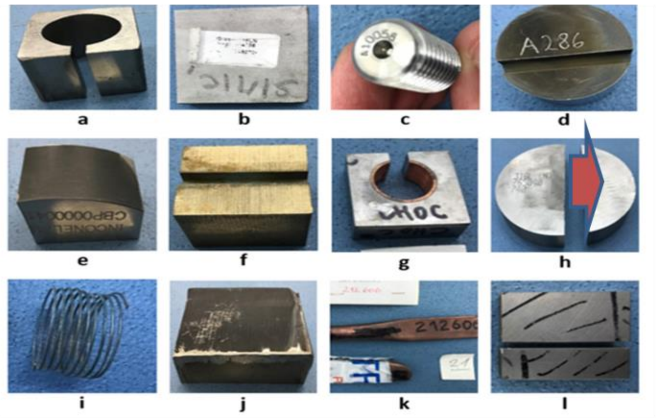
- **Successful operation in vessel of NG+ PS + detectors + electronics with RH**
- **Demonstration & verification of the methodology**

* R. Villari 2024

Activation of real ITER materials

Unique irradiation under 14 MeV neutrons of REAL ITER materials used in the manufacturing of the main tokamak components

- Activation measurements of irradiated ITER material samples and dosimetry foils in DT
- Characterization and data validation for the predictions of ITER materials activation

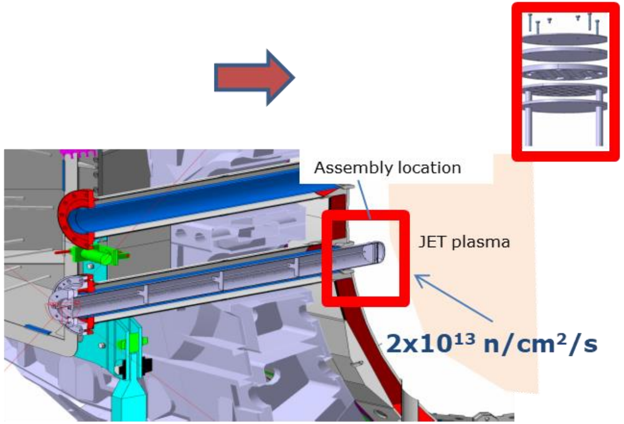


Nb3Sn, SS316L steels from various manufacturers, SS304B, Alloy 660, Be, W, CuCrZr, OF-Cu, XM-19, Al bronze, Nb3Sn, NbTi and EUROFER

* R. Villari 2024

27 ITER materials

Long-term irradiation station assembly (LTIS)



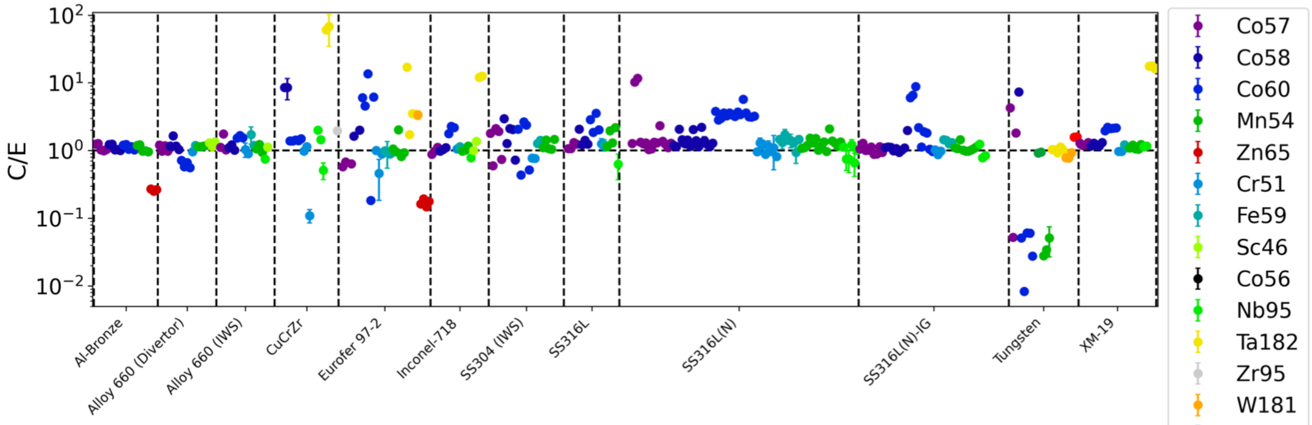
[Packer ,NF (2021) 61 116057]

MCNP + FISPACT-II calculations to predict activity in each ITER sample

Gamma spectrometry techniques to identify and quantify nuclide activities

UK Atomic Energy Authority · IJS · IFPiLM · ENEA

Validation of ITER materials neutron induced activation



Comparison between predictions MCNP6 + FISPACT II & measurements

@DTE2 715 days of irradiation $5x10^{15}$ n/cm^2

[L. Packer, Nuc. Fus., 64, 2024, 10]

- **Demonstrated codes reliability**
- **Improved gamma measurements techniques**
- **Evidenced contamination (brass) due to manufacturing & cutting techniques**
- **Lack of accuracy in elemental composition in material certificates ? → Independent analysis**
- **Adviced more sensitive measurement techniques (radiometric and mass-based) for long-lived nuclides relevant for waste and decommissioning**

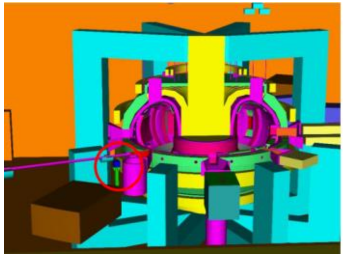
DTE3 samples analysis ongoing

* R. Villari 2024

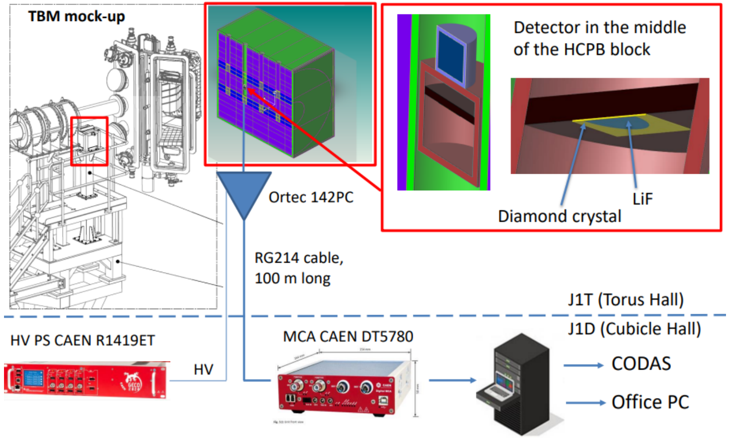
Tritium production in TBM mock-up under DT

Diamond detector for online measurement of tritium production rate in HCPB TBM mock-up

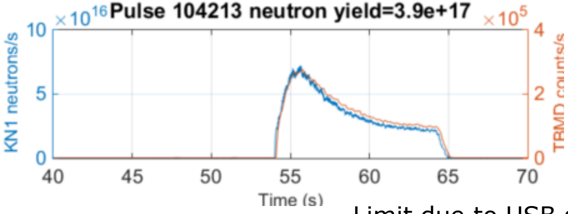
- **Test of detectors**
- **Validation of TBR prediction in tokamak**

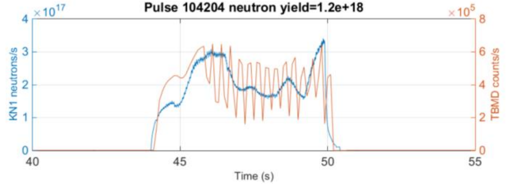


Same mock-up used at FNG for HCPB TBM experiment



- **@DTE2 Pile-up/saturation > 10^{15} n/s**
- **@DTE3 Upgrade of measurements chain → T production measured up to 4×10^{17} n/s**
- **Measurements issues in high performance & harsh environment → lesson learnt on detectors design and operations**
- **Tritium production $C_{MCNP}/E = 0.77$**





Limit due to USB slow data transfer rate

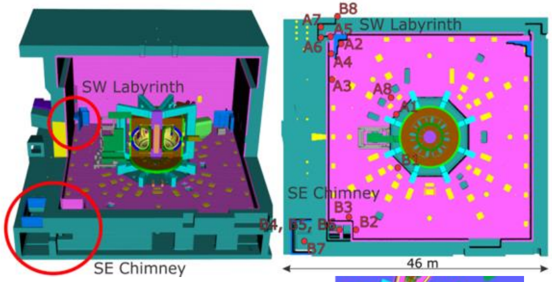
* R. Villari 2024

[N. Fonnesu, EPJPlus, 139 (2024) 893]

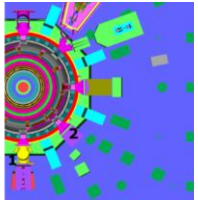
Neutronics benchmark experiments

Neutronics experiments for validating in a real fusion environment the neutronics codes and nuclear data used in ITER nuclear analyses

- On operation: Neutron fluence streaming in penetrations in large /complex volumes
- Off-operation: Shutdown dose rate (SDDR) in maintenance area



- **DD, TT & DTE2-3 benchmarks**
- **23 positions**
- **>40 m from the plasma**
- **8 orders of magnitude variation**

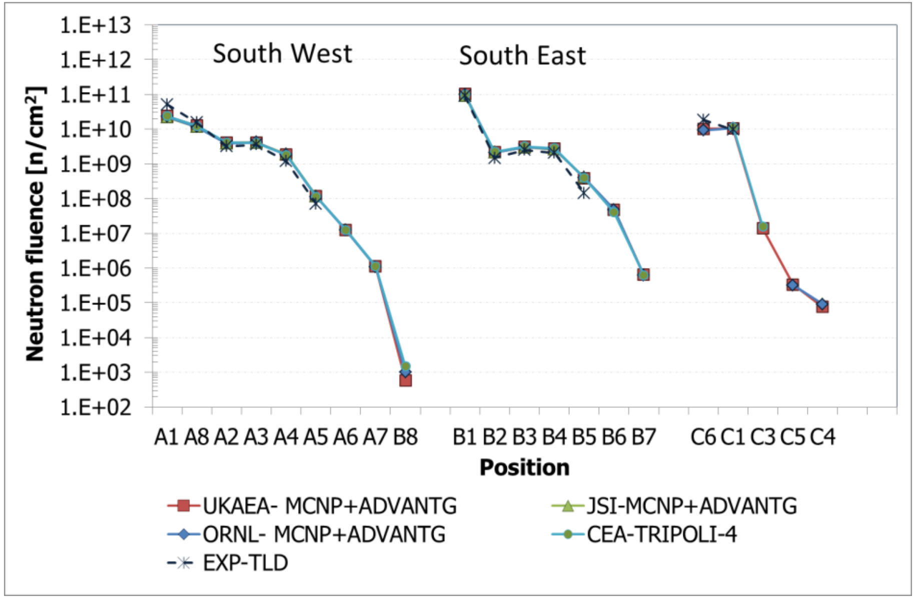


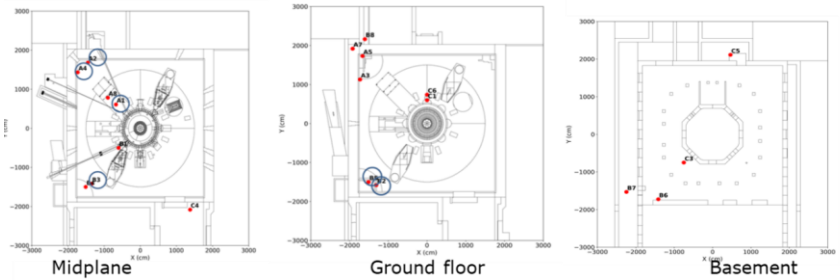
Accurate measurements for quantitative comparison to simulations → Validation

- **Neutron streaming – radiation transport MCNP, ADVANTG, TRIPOLI-4©+ OPEN MC**
- **SDDR - Rad transport+ Activation: Direct 1-Step) ADVANCED D1S, D1SUNED, N1S**
  Rigorous-2 steps) R2SUNED, R2Smesh, MCR2S, ORNL R2S

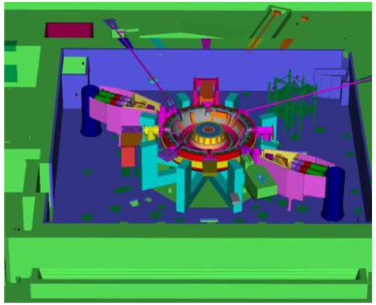
* R. Villari 2024

Neutron Streaming benchmark





TT experiment
8.50×10^{18} n on 240 days
- 59.3% by T-T reactions
- 40.2% by D-T reactions



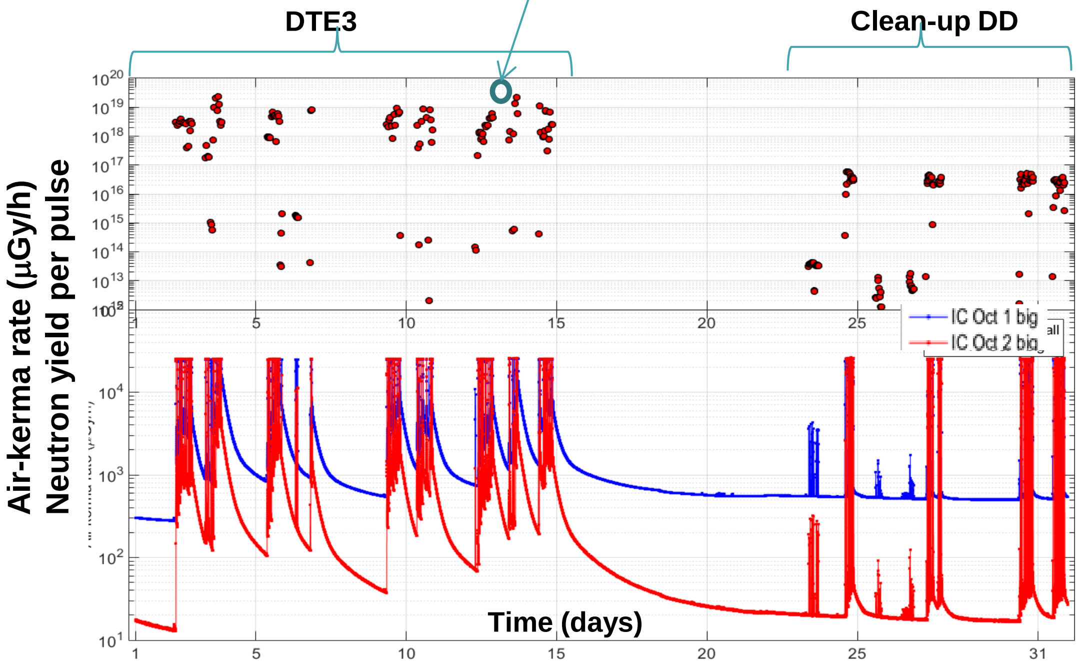
- ✓ **C/E 0.4 (A1)- 2.9 (B5)**
- ✓ Increase of the overestimation with the distance from the machine
- ✓ TRIPOLI-MCNP agreement within 7 %

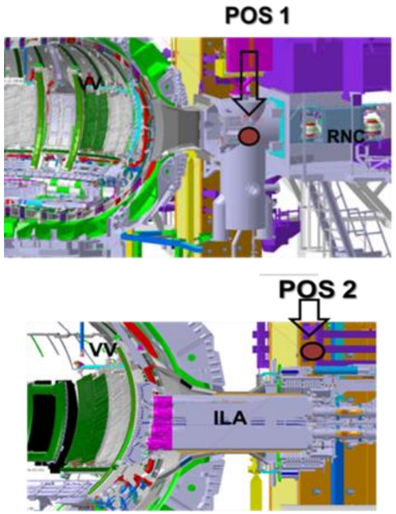
- **Implemented robust techniques for neutron fluence measurements**
- **Demonstrated reliability of the codes for nuclear analysis - general conservative predictions**
- **Key role of accurate modeling & materials description following machine evolution**

* R. Villari 2024

Shutdown Dose Rate Measurements during DT

- Continuous online measurements since 2016- still ongoing
- Full correlation with JET N diagnostics





Range ~ 4μSv/h -20 mSv/h

SDDR ITER requirements

< 100 μSv/h at 10^6 s after shutdown in Port Interspace

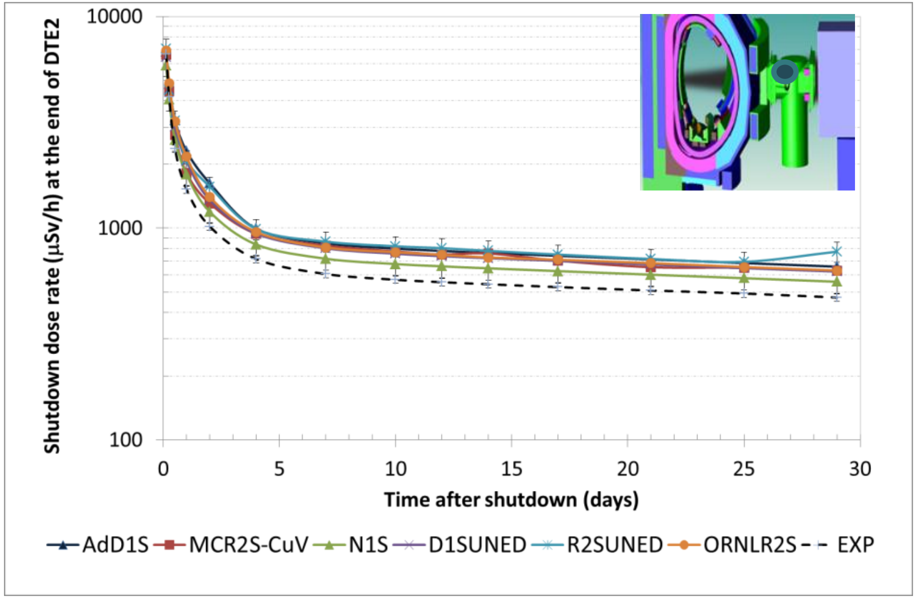
< 10 μSv/h at 1 day after shutdown in Port Cell

- **Unique database of shutdown dose rate measurements in tokamak within relevant ITER range correlated with plasma operations**
- **Characterization of shutdown dose rate field during operations & decommissioning**

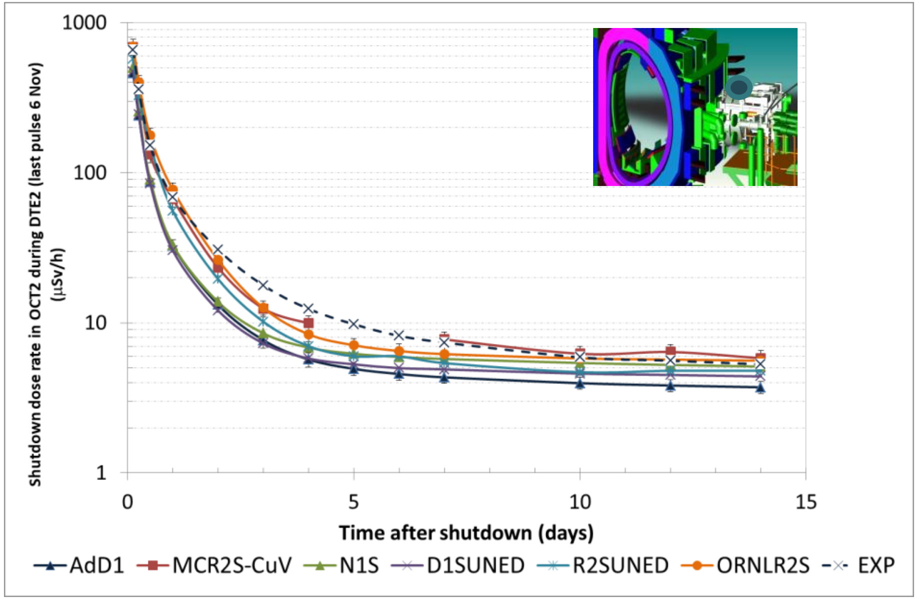
* R. Villari 2024

Validation of Shutdown Dose Rate predictions

POS 1) Side port in OCT 1



POS 2) Top of ITER-like Antenna in OCT 2



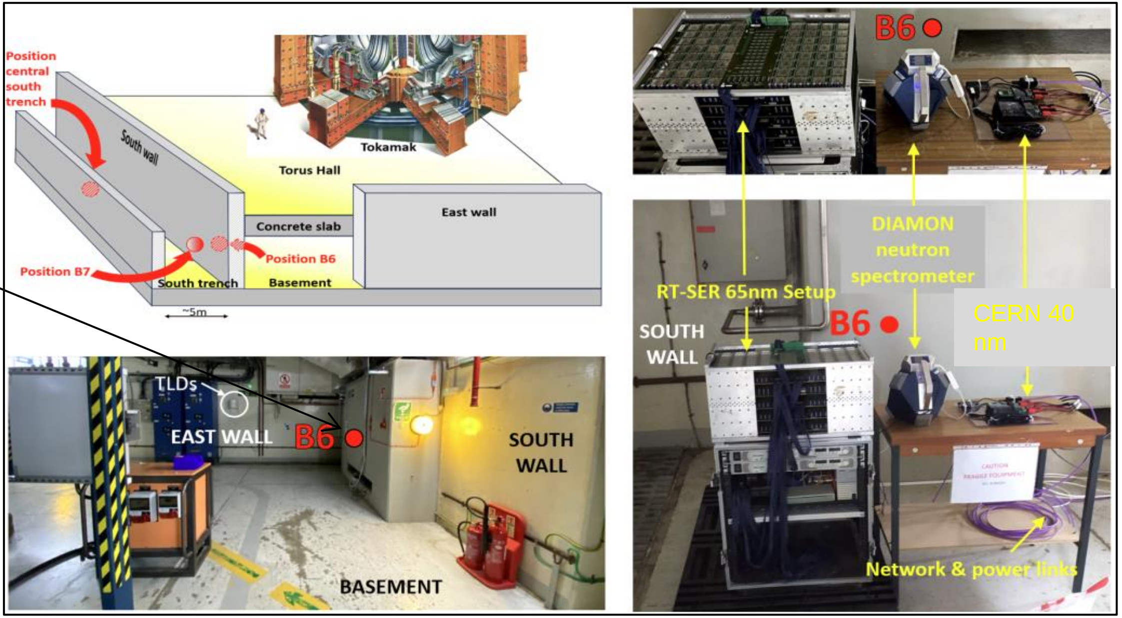
- **Validation of SDDR tools**
- **Artifacts in computational tools → code developments and new features**
- **Key roles of material impurities and machine configuration changes**

* R. Villari 2024

Neutron induced Single Event Effect (SEE) experiment on electronics

Unique systematic study of SEE effects on electronics in tokamak under DT

~2x10^5 n/cm^2/s
during DTE3



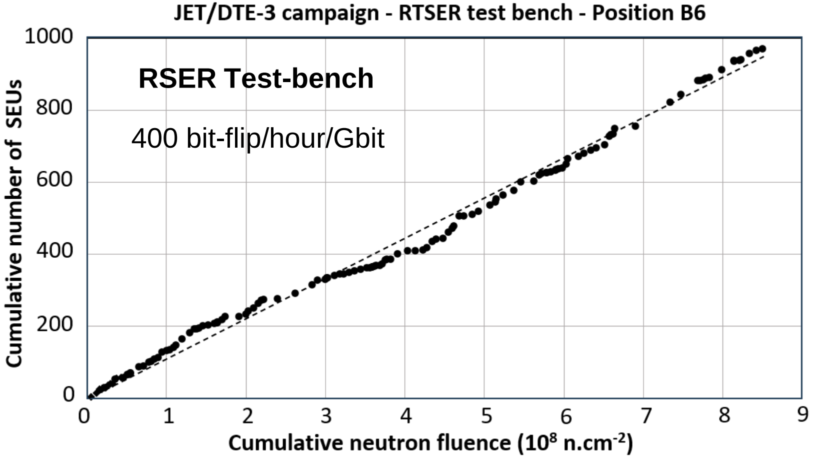
- **RTSER test bench = 384 chips of 8.5 Mbits STM 65 nm SRAM (total 3.2 Gbits)**
- **CERN test bench = 2 chips of 32 Mbits ISSI 40 nm SRAM (1 with B_4C shield, 1 w/o)**

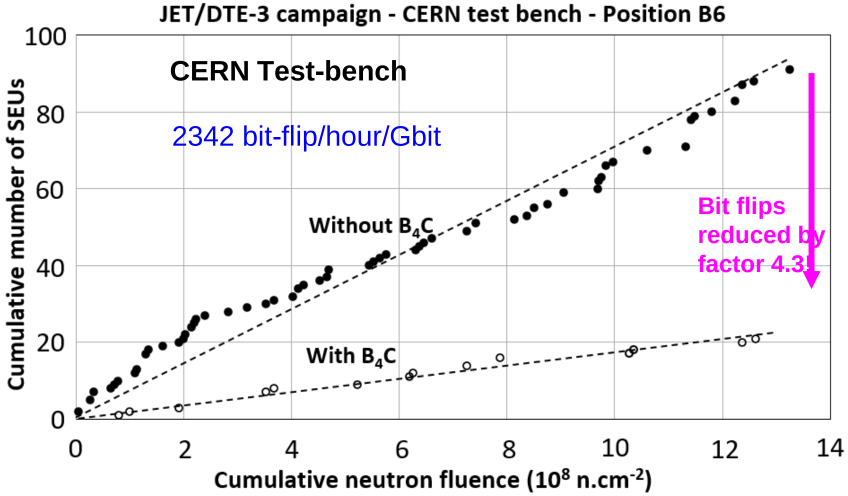
Validation of Single Event Rate Predictions

[M. Dentan, IEEE TNS, NSREC 2024 proc.] * R. Villari 2024

cea
Aix Marseille université Socialement engagée
IPR Institut de Physique de Rennes
UK Atomic Energy Authority
CERN

Validation of Single Event Rate predictions in DT & preliminary study of B_4C shield!





Reliability degradation factor ~10^7

Bit-flips Predictions/Measurements: 0.87 (RTSER) & 1.07 (CERN)

- **Validation of methods & models for neutron-induced bit-flips prediction!**
- **High bit-flip rates and strong reliability degradations in fusion reactors conditions**
- **Evident reduction of bit-flips with B_4C shield → can be further improved**

* R. Villari 2024

[M. Dentan, IEEE TNS, NSREC 2024 proc.]

JET water activation experiment during DTE3

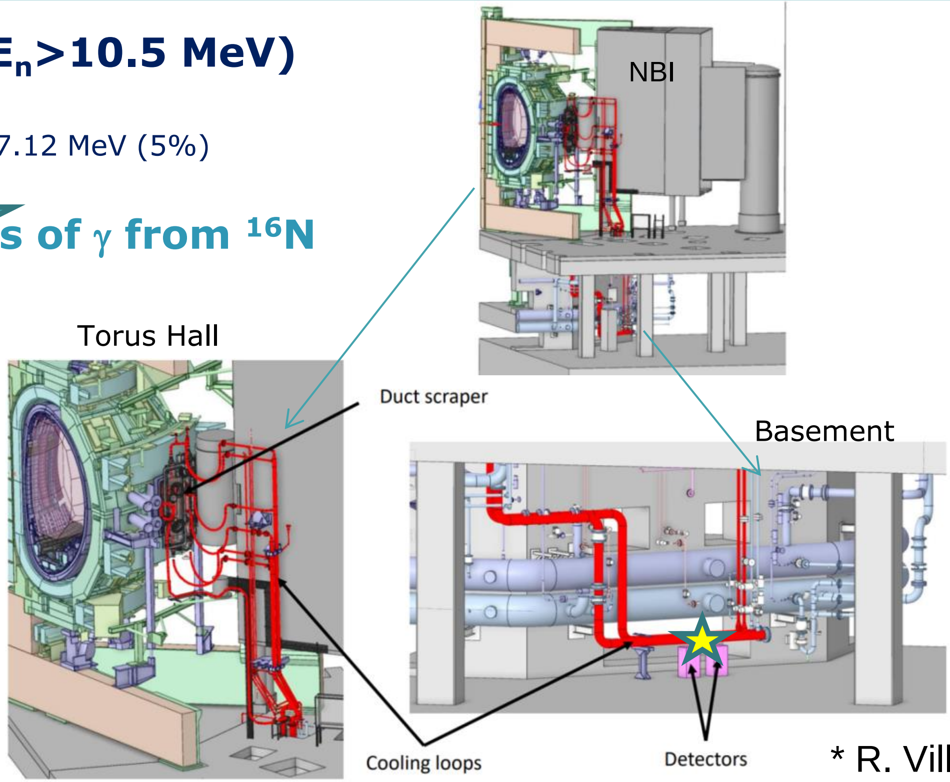
Unique experiment in real tokamak water cooling loop under DT for the validation of water activation predictions in ITER

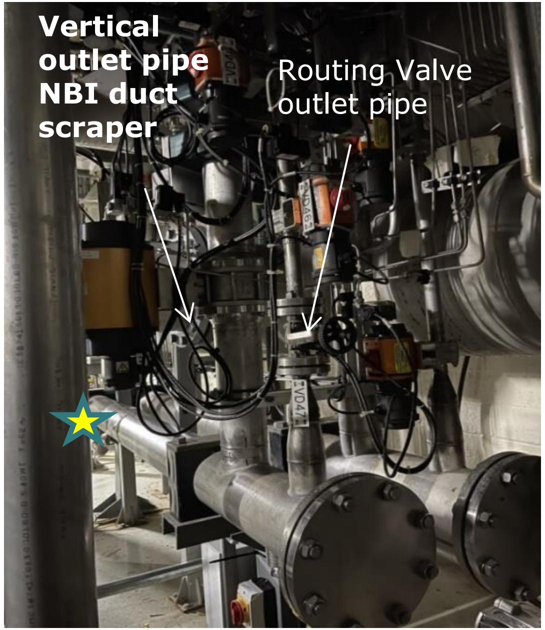
$^{16}O(n,p)^{16}N$ (E_n>10.5 MeV)

$T_{1/2}$ 7.13 s β decay:
γ 6.13 MeV (69%)& 7.12 MeV (5%)

Measurements of γ from ^{16}N decay

NBI duct scraper cooling loop





Oct 4 Basement Pipe forest

* R. Villari 2024

ENEA UK Atomic Energy Authority IJS

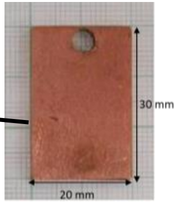
Activated Corrosion Products tests & studies on CuCrZr

- **APCs represent a critical source of radioactive contamination** → their diffusion inside the cooling systems depends on several mechanisms (advection, erosion, abrasion, convection, deposition, corrosion, dissolution-precipitation, radiation field)
- In the framework of the ACP PrIO task & EEG 'Impact of Activated Corrosion Products on ITER ORE, **analyses and experimental activities are in progress to increase the accuracy of evaluation and modelling of the ACPs in fusion**
- **RINA CuCrZr corrosion experiment (corrosion of CuCrZr -> contribute to ^{60}Co and radioactive isotopes generation and spreading)**

- ITER Baking:
- 240°C
- 44 bar
- $pH_T \sim 7.6$
- $O_2 \sim 10$ ppb
- Static water

CuCrZr sample- provided by F4E

Autoclave

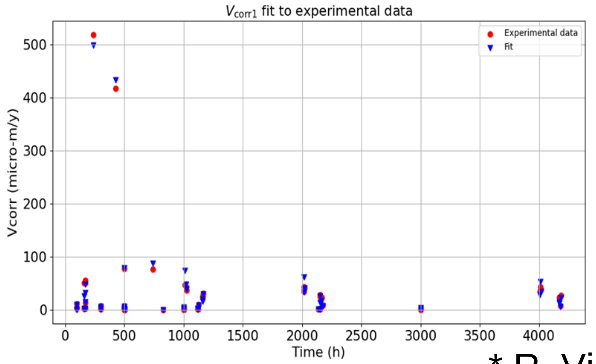


Exposure time (h)	Average corrosion rate (μm/y)
500	0.7
1000	1.1

[S. Noce, submitted to FED]

RINA results, jointly with ~70 CuCrZr corrosion rate experimental data available in literature have been used to define **a new CuCrZr uniform corrosion semi-empirical law**

Corrosion rates - new corrosion law fitting vs experiments



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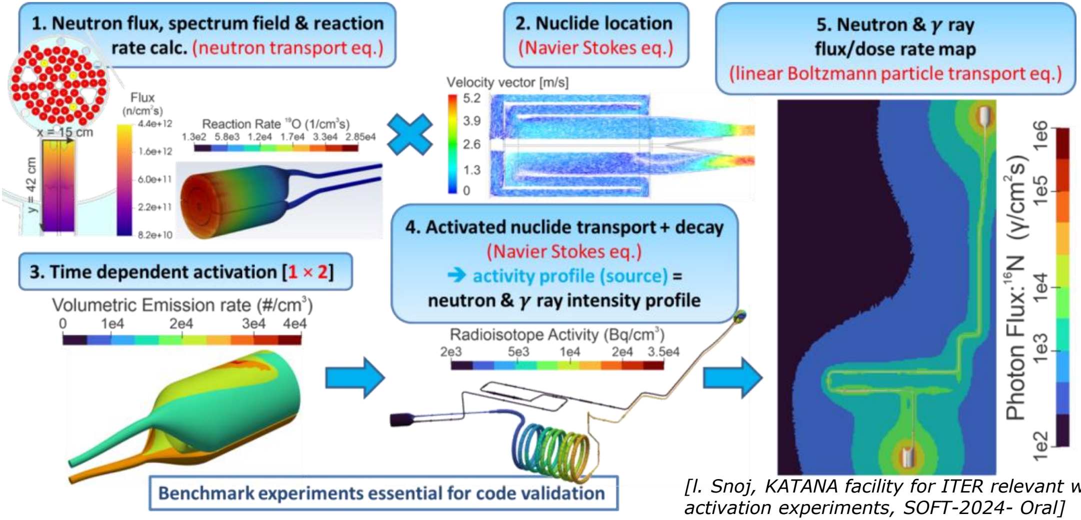
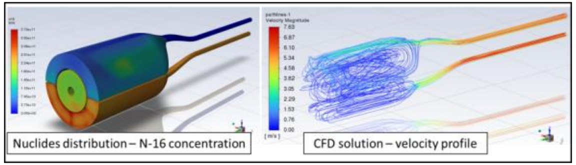
Fluid activation tools development and experiment for extrapolation to ITER relevant conditions

Different fluid activation codes: FLUNED (UNED), RSTM (F4E) , GammaFlow-ActiFlow (UKAEA)) utilise different approaches and underlying CFD codes



[I. Snoj, KATANA facility for ITER relevant water activation experiments, SOFT-2024- Oral]

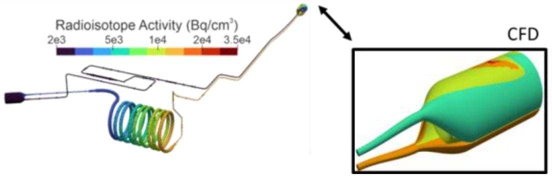
Radio Species Transport Model (RSTM)– Ansys FLUENT® UDS based tool



[R. Pampin, et al. FED, vol 203, 2024, 114466]
[E. Masia, et al. submission to FED]

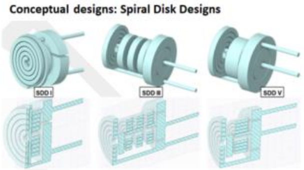
FLUNED- OpenFoam

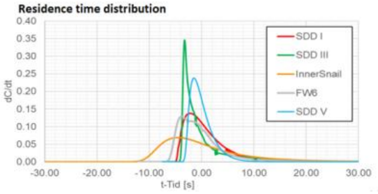
-> Complex components: FLUNED (CFD methodology)
-> Piping: FLUNED-SL (system level approach, i.e., less detailed)



2025: KATANA loop design & manufacturing with new ITER relevant head

Conceptual design to preserve hydraulic features, residence time, Re & orientation of neutron flux gradients from an ITER First Wall





SDD_I showed a strong resemblance with an ITER FW- Too complex shape
A manufactured based design has been proposed & analysis will be conducted to verify ITER relevancy + compatibility with Radial Piercing port

* R. Villari 2024

Neutron induced Single Event Effect tests on electronics under the same neutron spectra as in ITER - GENeuSIS

GENeuSIS

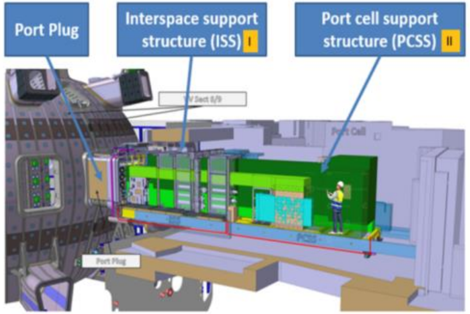
General
Experimental
Neutron
Systems
Irradiation
Station

Novel neutron test bed facility for testing diagnostics, electronics and critical ITER components

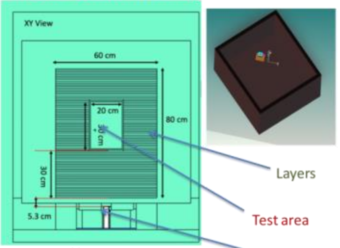
Materials assembly as moderator in front of 14MeV Neutron Generator (FNG) to replicate the required neutron energy spectra distribution.

Neutron energy spectra as in ITER Port Cell: unique facility for testing Single Event Effects (SEE) on electronics with ITER-like neutron spectrum

Radiation qualification of safety electronics



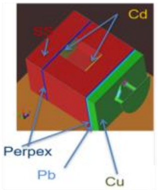
MCNP radiation transport simulations



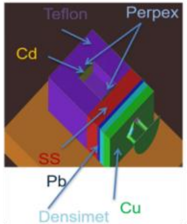
- Assembly 60x80x60 cm
- Test cavity 20x30x20 cm

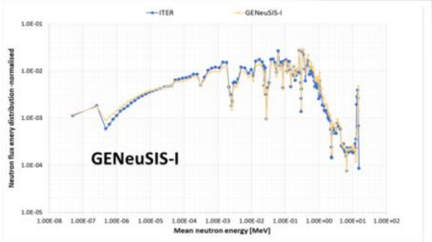
FNG MCNP DT neutron source + geometrical model of target/ building + assembly

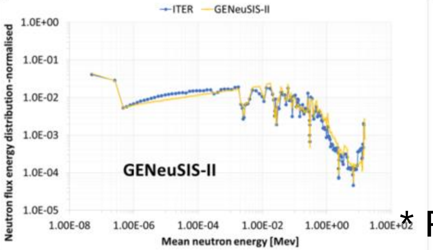
Port Interspace (GENeuSIS-I)



Port Cell (GENeuSIS-II)







SEE tests on electronics in PC-like environment

* R. Villari 2024

Outline

- Neutrons in Fusion
  - Fusion Reactions
  - Tritium Breeding
  - Material Damage
  - Spin Polarized Fusion
- Modeling
- Integration with Plasma Codes
- Integration with Engineering Codes:
  - Fluid, Heat and Mass Transfer analysis
  - Structural Analysis
- Integrated Analysis for ITER at Jet
- **Conclusions**

Conclusions

- Integrated Neutronics modeling is a vital part of fusion device designs
- Neutronics Analysis is in the center of Multiphisics Analysis Workflow
- Jet Experiments Provided Important Benchmarks for Integrated Model Validation