Codici nucleari per la tecnologia e la fisica della fusione

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ENEA UTFUS-TECN

Supercomputing, applicazioni e innovazioni:
le attività scientifiche in ENEA supportate da CRESCO

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Outline

Introduction to UTFUS-TECN Nuclear Analysis Activities

MCNP High Performance Computing aspects

Monte Carlo calculations for fusion neutronics

Applications

- Nuclear analysis for the design of ITER components

Code development

Advanced D1S method for 3D shutdown dose rate calculations and validation

CRESCO Resources

Introduction

- Extensive use and development of MCNP Monte Carlo code for fusion neutronics
- Nuclear Analysis with last versions of the **MCNP/MCNPX** Monte Carlo codes
- Activation Analysis with **FISPACT** inventory code
- Applications to ITER, DEMO, JET, JT-60SA and FAST tokamaks
- FNG benchmark experiments for validation of Nuclear data
- Neutron Diagnostics design
- Development of Advanced Direct 1 Step method for shutdown dose rate calculations

MCNP High Performance Computing

- **MCNP/mcnpx,** in their parallel implementation, represent an **embarassingly parallel** case:
  - no communication between processes during the relevant computation stage
- could be a good candidate for a development on GPGPU architectures?
- the configuration and *making* script, in the various versions, are not up-to-date compared with the current state of the processor and compilers, requiring a correction work
- The codes have been compiled on the different section of CRESCO, for all compilers type, for the OpenMPI MPI implementation, passing (within some limits) the regression tests
- the Intel compiler proves superior, at least on the CRESCO section 2. The work treated adopts this compiler
- the multithreading is switched-off

Monte Carlo calculations for Fusion neutronics

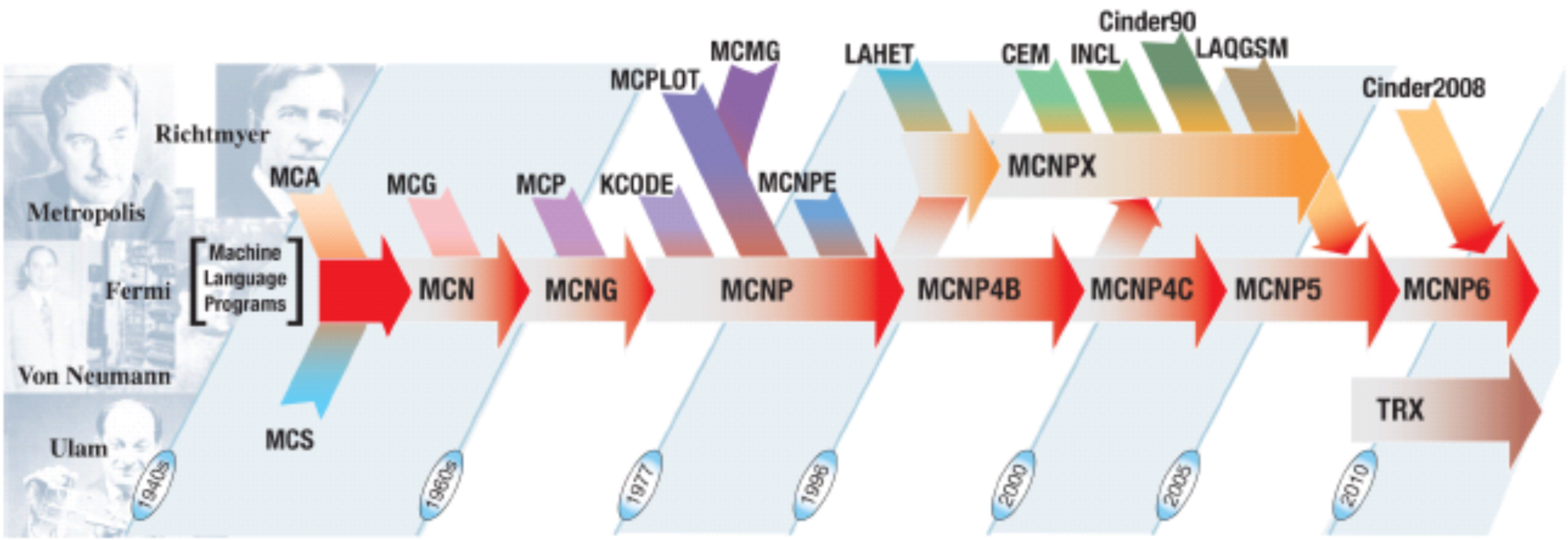
MCNP radiation trasport code

MCNP is a radiation transport code

- Monte Carlo N-Particle
- Particle transport (neutron, photon, electron, proton, muon, heavy ions, etc.)
- User defined source, geometry, tally information, variance reduction
- Relies on nuclear and atomic data, or models when not available
- Original algorithms created in 40s & 50s

Last versions MCNP5 v 1.60 - MCNPX v 2.7.0.

MCNP6 = MCNP5 + MCNPX + new features (unstrucured mesh tally, trasport of photons and electrons at lower energies, …) – last Beta 3 version on Dec 2012



MCNP in fusion neutronics

The stocastic approach is applied to neutron/photon transport through the simulation of real physical processes on microscopic level with interaction probabilities given by nuclear cross-sections.

Calculation of the spatial, angular and energy distribution of the neutrons

- Tritium breeding, nuclear heating, activation, transmutation, gas production, displacement damage etc.

All nuclear reaction rates can be calculated if the associated nuclear cross sections or physics models are available

Compared with deterministic (macroscopic) approach:

Advantages:
- Exact treatment of the transport process
- Exact source modeling capability
- Continuous energy treatment of the cross section

Disadvantages:
- Requires variance reduction techniques to improve accuracy
- Cannot generate accurate results in all locations
- Many particles histories and large CPU time needed to obtain accurate results

*The **MCNP5 Monte Carlo Code** is the **main tool** for 3-D neutronic analyses in fusion neutronics*

Relevant quantities/entities in MCNP

MCNP general run

- **Geometry** modelisation (manual/CAD-MCNP interfaces/direct CAD)
- **Materials** description (chemical compositions/density)
- Selection of **nuclear data libraries**
- **Source** specification
- **Particle transport** setting (transported particles, cut-off, physics …)
- **Variance reduction** (if needed)
- **Tally specifications**

MCNP parallel run

- Check for statistical output results
- Optimisation of variance reduction (if needed)
- Analysis of output results

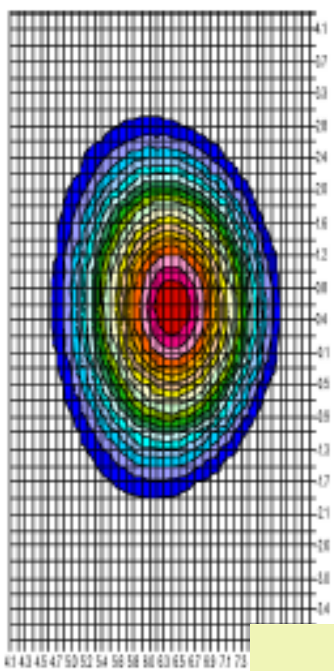
Neutronic analyses for a tokamak device with MCNP

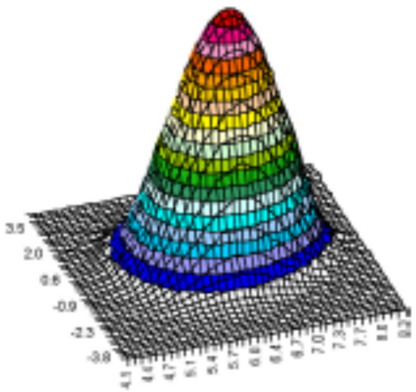
- **Neutron and gamma fluxes and spectra**
- **Energy deposition**
  - Distribution of nuclear heating (neutrons +secondary gammas)
  - Dose in critical components (e.g. insulators)
- **Shielding analysis**
  - Protection of critical components (e.g. superconductive coils)
- **Tritium Breeding (ITER TBM and reactors blankets)**
  - Materials selection & optimisation of the Configuration
- **Neutron induced damage and transmutation**
  - Degradation of the physical and mechanical properties of the components → life of the components
- **Activation & dose rate analyses**
  - Safety & management of radioactive waste
  - Maintenance
  - Occupational exposure to radiation worker
- **Neutron diagnostics design and performances**

MCNP Calculations for ITER

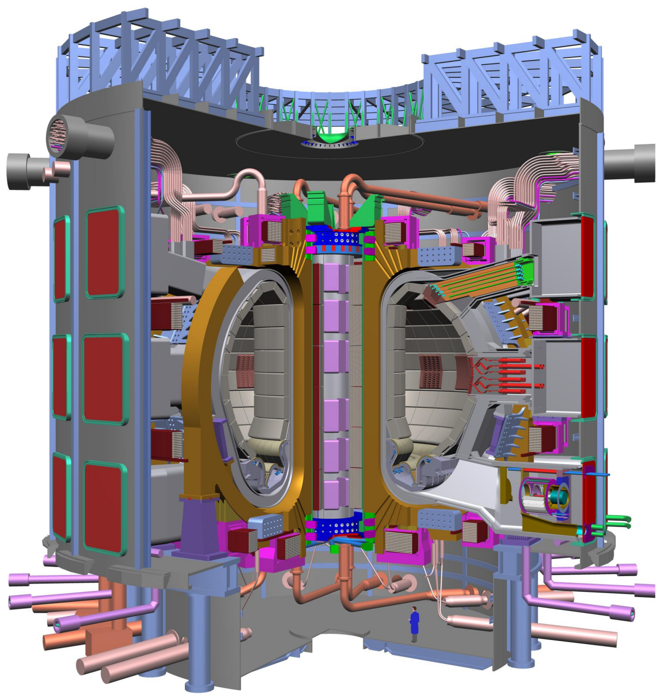
ITER

The experimental reactor ITER (*International Thermonuclear Experimental Reactor*) is under construction in Cadarache with the aim of demonstrating the scientific and technical feasibility of fusion as energy source.





ITER Neutron source



ITER aims to produce a significant amount of fusion power

P_{fus}=500 MW x 400 s

$$N_{fus}(500MW)/s = \frac{500MW}{17.58MeV} = \frac{500MW}{17.58MeV\times 1.6\times 10^{-19}Ws} = 1.77\times 10^{20}s^{-1}$$

How many neutrons will be produced in ITER?

P_{fus} = 500 MW= $N_{fus} \cdot E_{fus}$
N_{fus} = number of fusion reactions per second

E_{fus} = 17.58 MeV
E_n= 14.06 MeV

$$N_{fus}(500MW)/s = \frac{500MW}{17.58MeV} = \frac{500MW}{17.58MeV \times 1.6 \times 10^{-19} Ws} = 1.77 \times 10^{20} s^{-1}$$

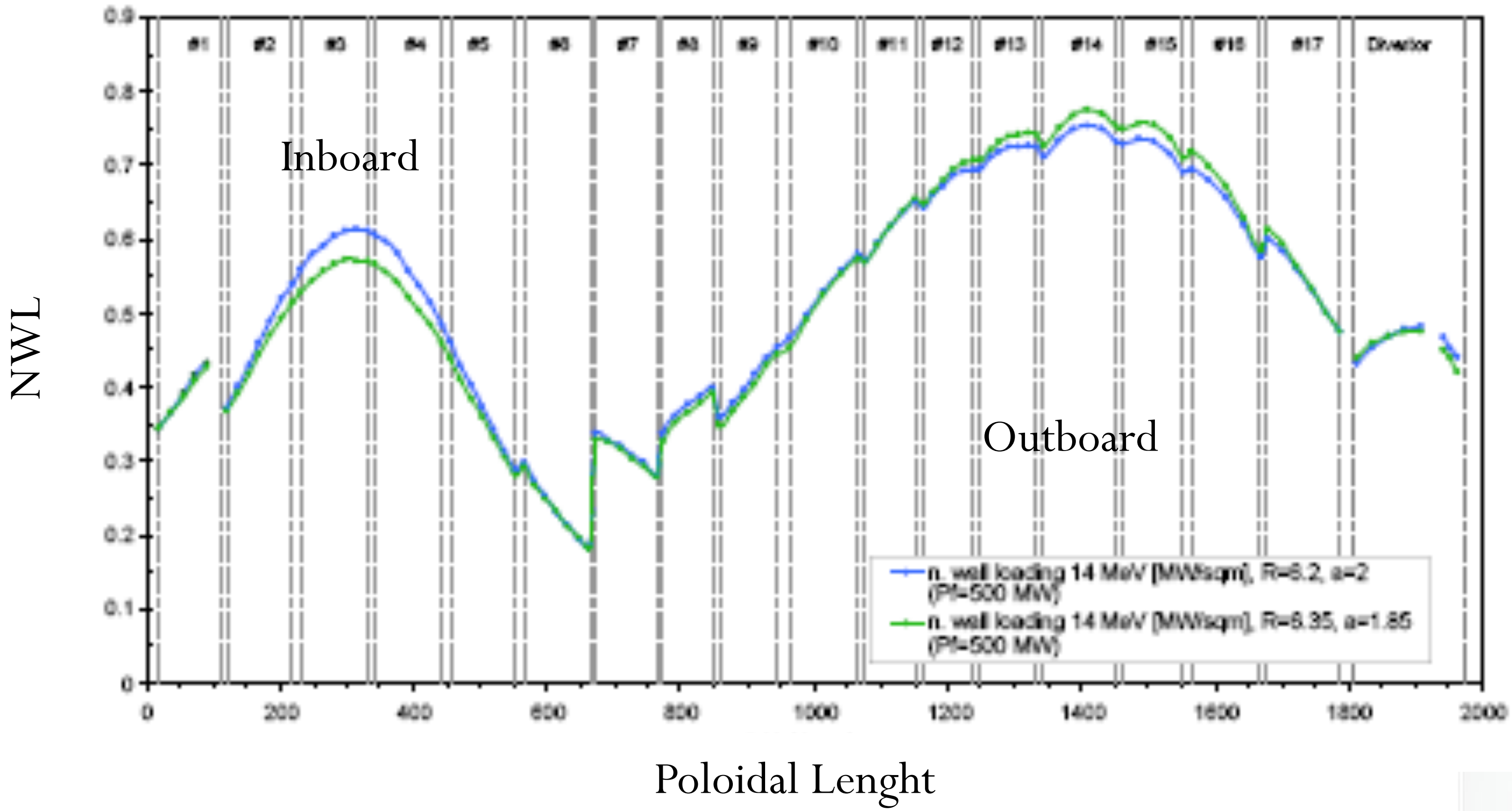
DT Neutrons:
- Short high power pulses

P_{fus} = 500 MW →N/s =1.77×10^{20} s^{-1} (400 s)

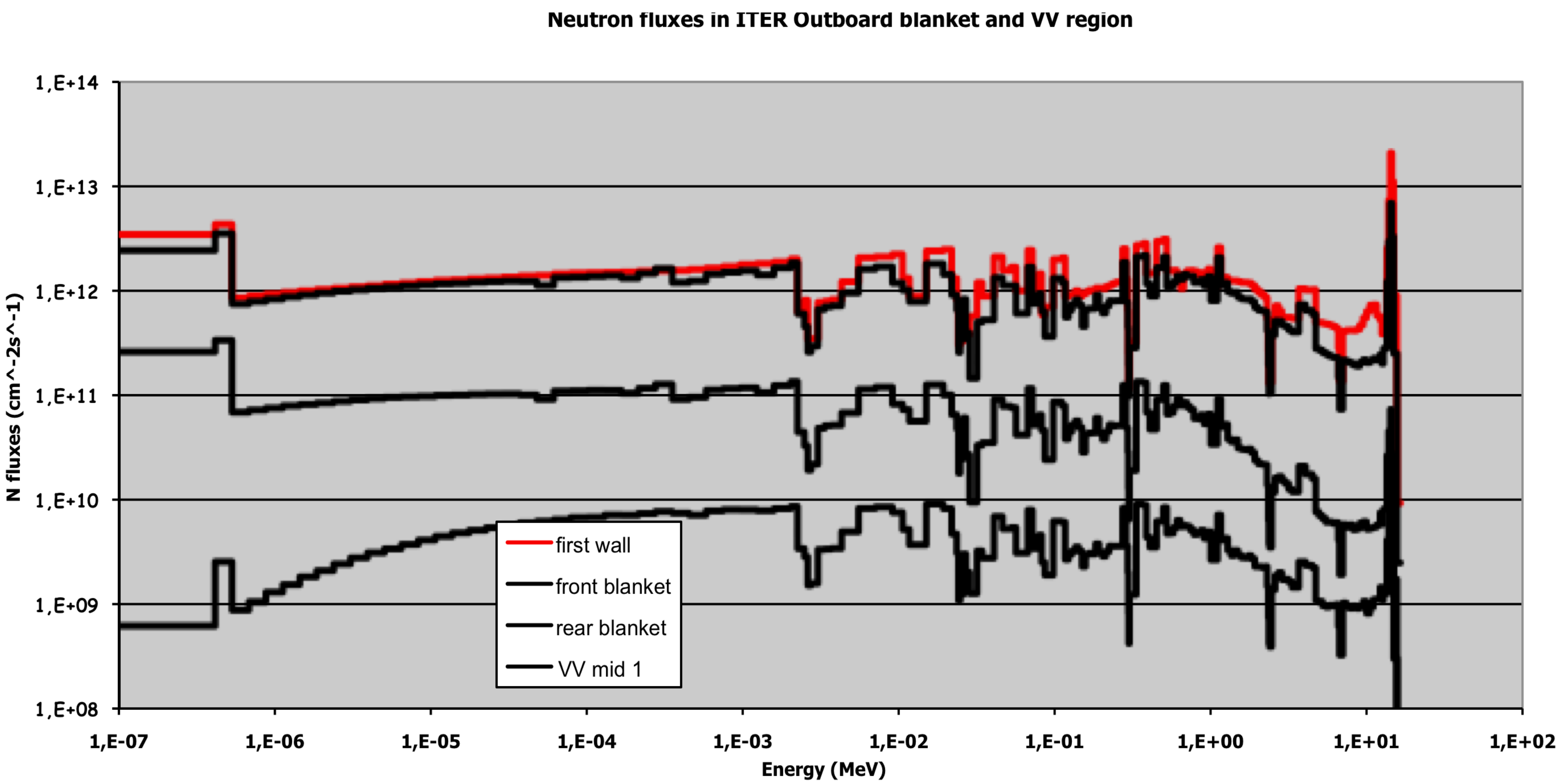
- Long steady state pulses

P_{fus} = 356 MW (3000 s) →N/s =1.26×10^{20} s^{-1} (3000 s)

ITER Neutron wall loading poloidal profile

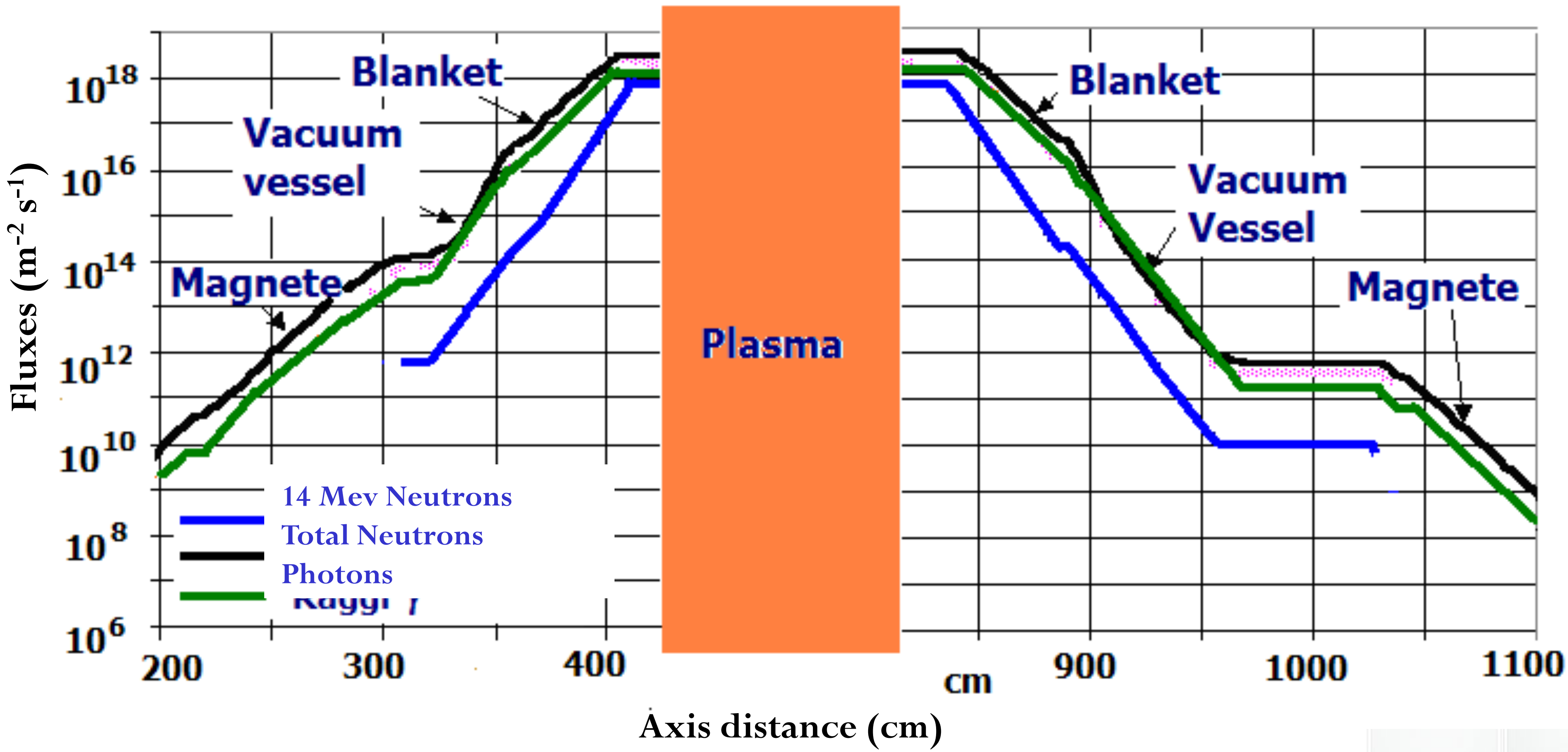


ITER Neutron flux spectra

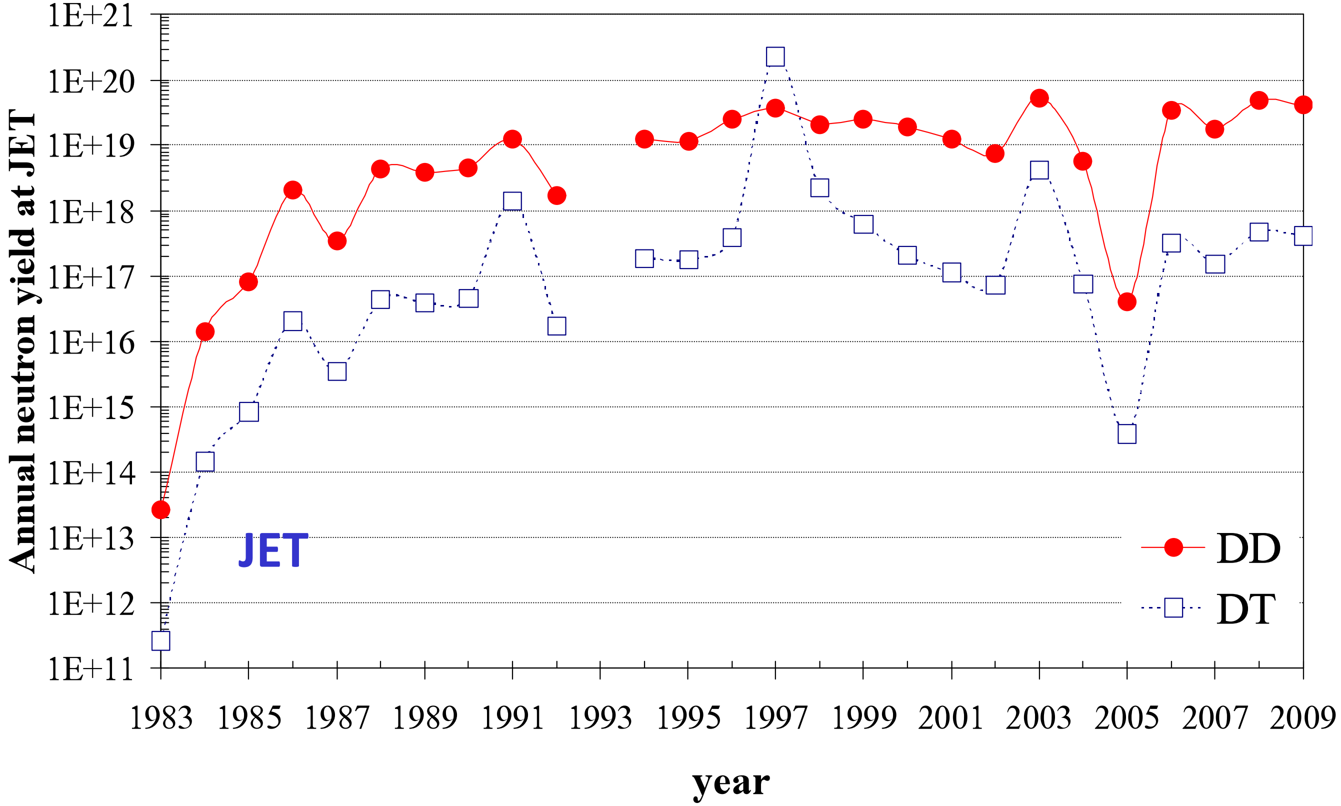


Neutrons attenuation along radial middle axis (1D)

ITER Radial distribution of fluxes at midplane



Comparison with JET neutron yields



Total DD N yield at JET from 1983 to 2009 4.2×10^{20}

Total DT N yield at JET from 1983 to 2009 2.4×10^{20}

Same order of magnitude of the neutrons produced by ITER in 1s!!

ITER design radiation requirements

- **Toroidal Field Coil heating**
  - ✓ **14 kW Integral**
  - ✓ **1 mW/cm^3 on SS**
  - ✓ **2 mW/cm^3 on Cu winding pack**
  - ✓ **Fast neutron fluence (E> 0.1 MeV) < 10^{23} n/m^2**
  - ➢ Blk thickness constant 45 cm
  - ➢ VV+blk thickness (~80 cm inb.120 cm outb.)
- **Dose to the insulator: 10 MGy**
- **Reweldability of the SS**
  - ✓ **1 He appm thick**
  - ✓ **3 He appm thin**
  - ➢ He comes out from (n,^{10}B) reaction,
  - ➢ B content in SS is 0.001- 0.002 % wt
- **Occupational dose after shutdown**
  - **100μSv/h inside the bioshield 10^6 s after shutdown**

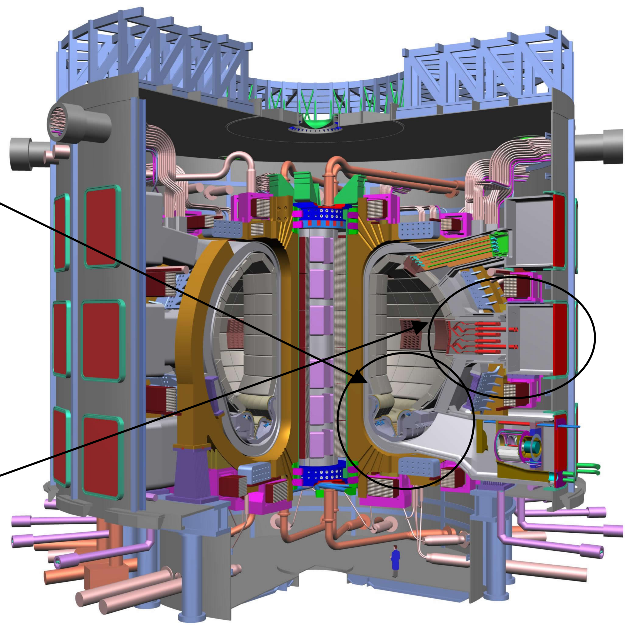
ITER Nuclear Analysis Report (NAR) 2004

Neutronic analyses are required for ITER design

Applications to ITER neutronics (CRESCO)

- Full-W Divertor

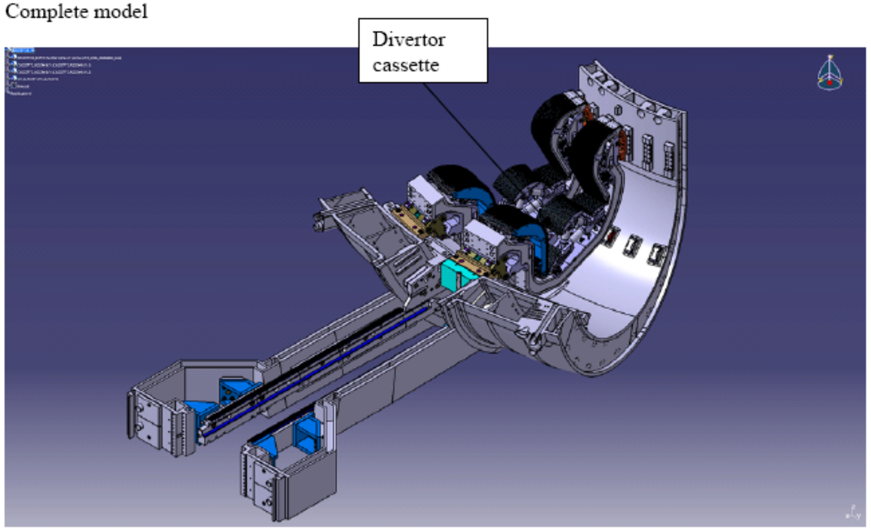
- TBM Port plug studies



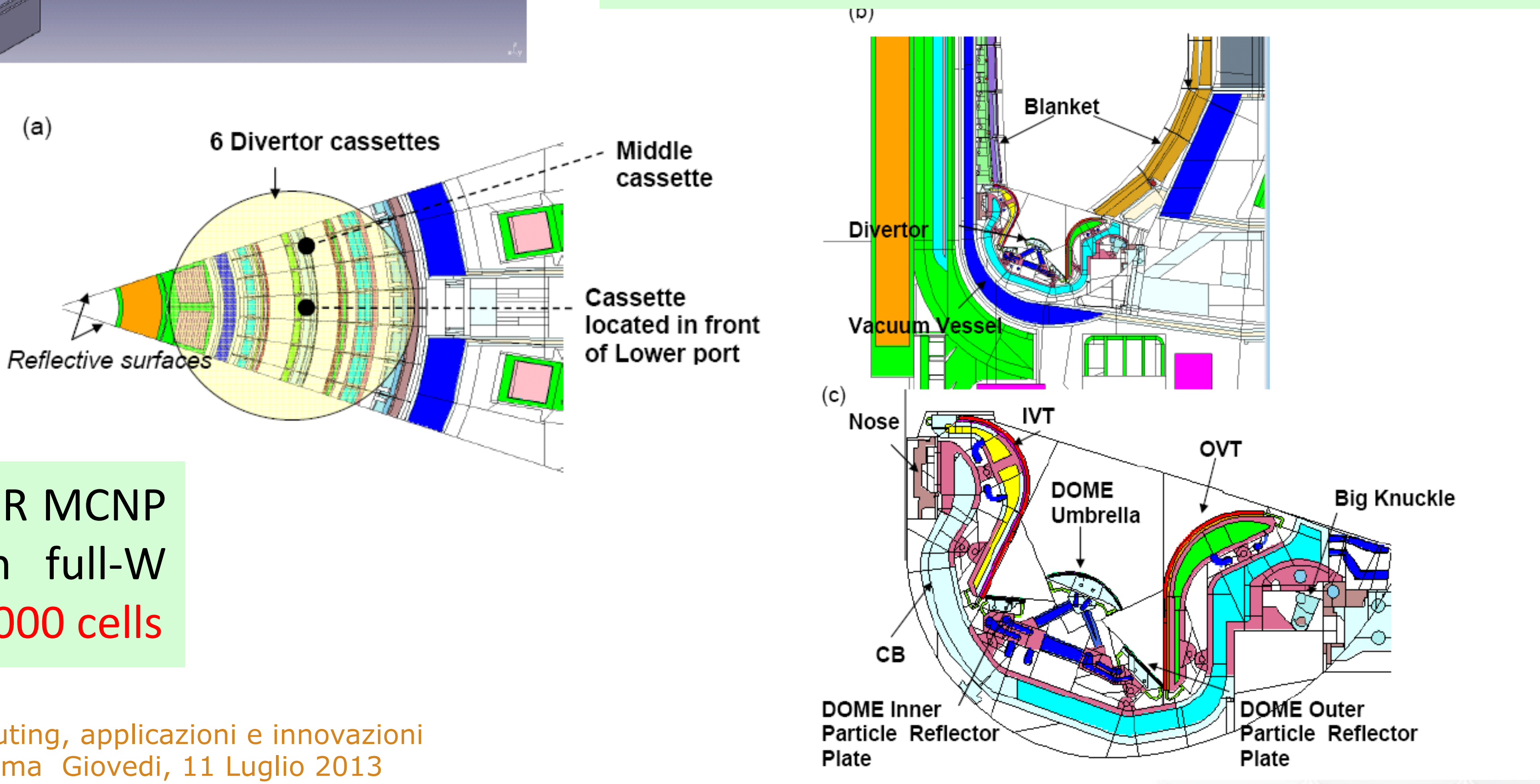
ITER, P_{fus} 500 MW
DT rate 1.77 10^{20} n/s

ITER Full-W Divertor

Complete model

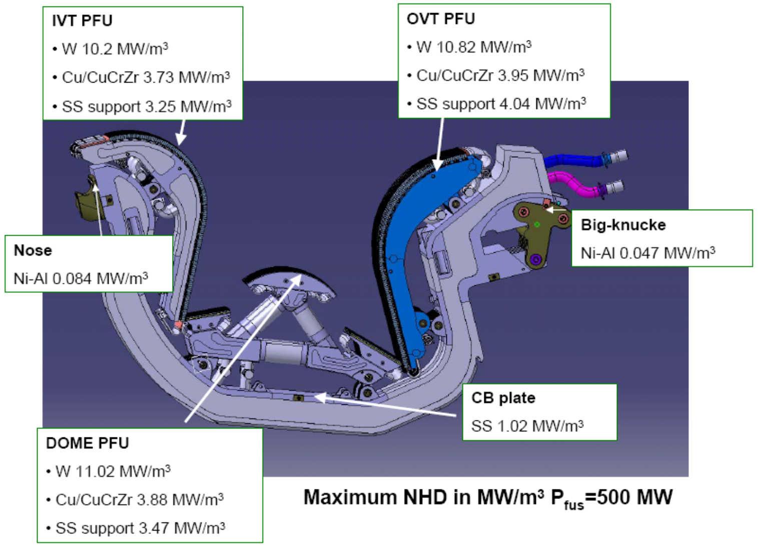


- 3D nuclear analysis of the last design of ITER full-W divertor with MCNP5 & FENDL2.1
- Calculate nuclear heating, damage and He production in divertor components
- Evaluate impact on design and maintenance of the system



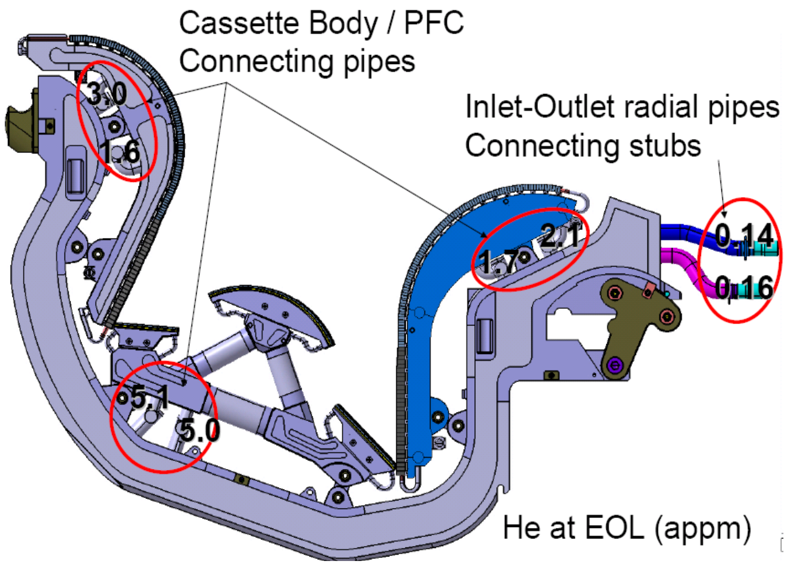
B-lite v2 ITER MCNP model with full-W divertor. 25000 cells

ITER Full-W Divertor

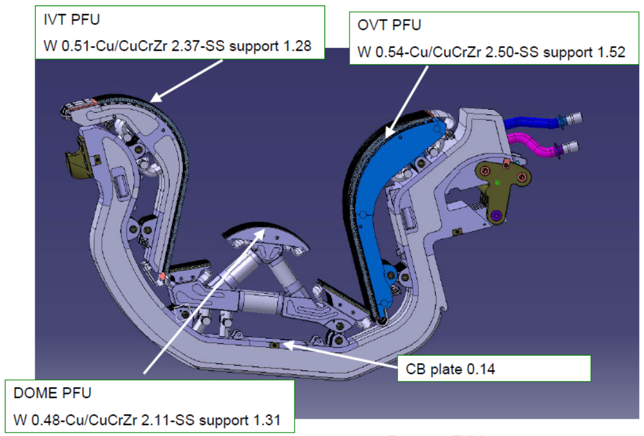


Maximum NHD in MW/m³ P_{fus}=500 MW

Nuclear heating density → Thermal analysis



He-production → Reweldability



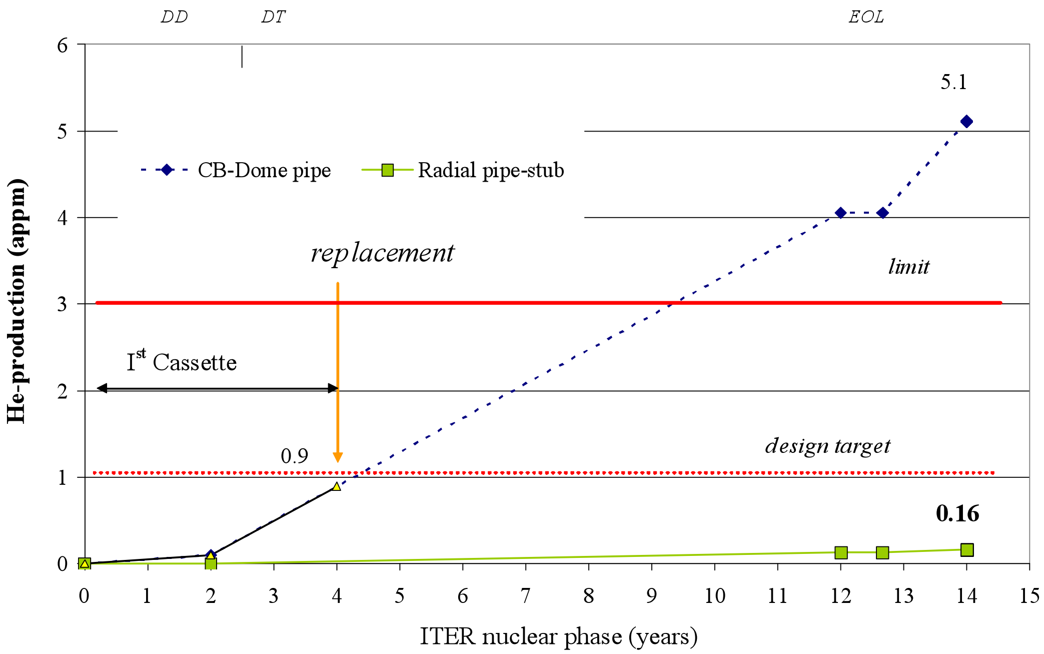
Dpa at EOL

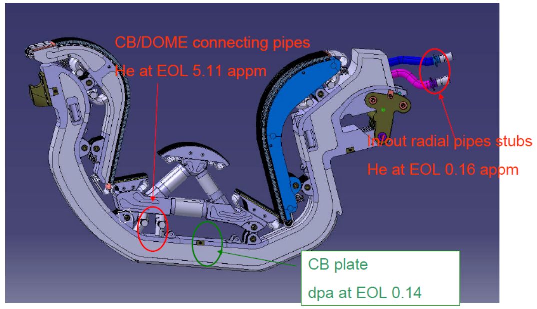
Damage

1200 cores x 24 hours for nuclear heating density calculation (5x10⁸ n)

ITER Full-W Divertor

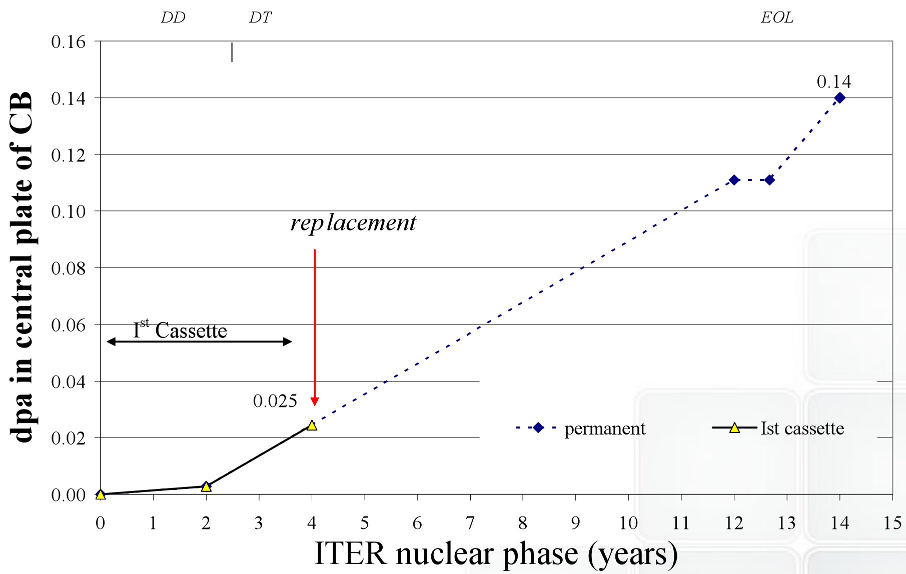
He-production & DPA vs years of ITER operations (nuclear phase)



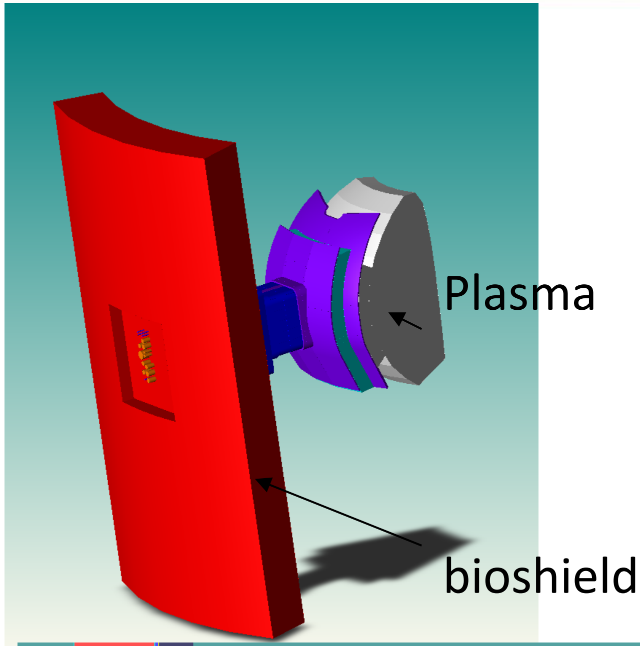


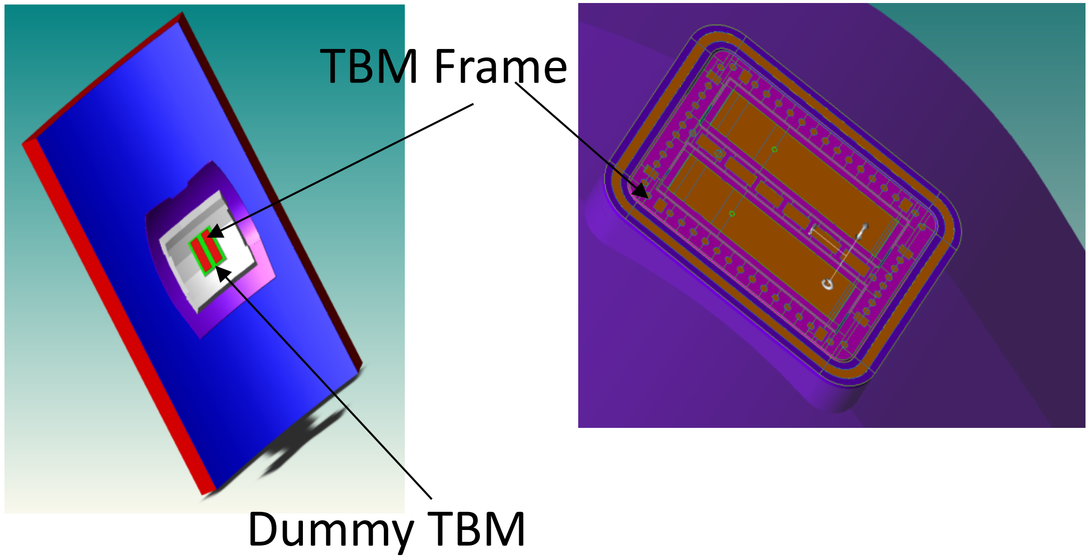
← He production in the pipes

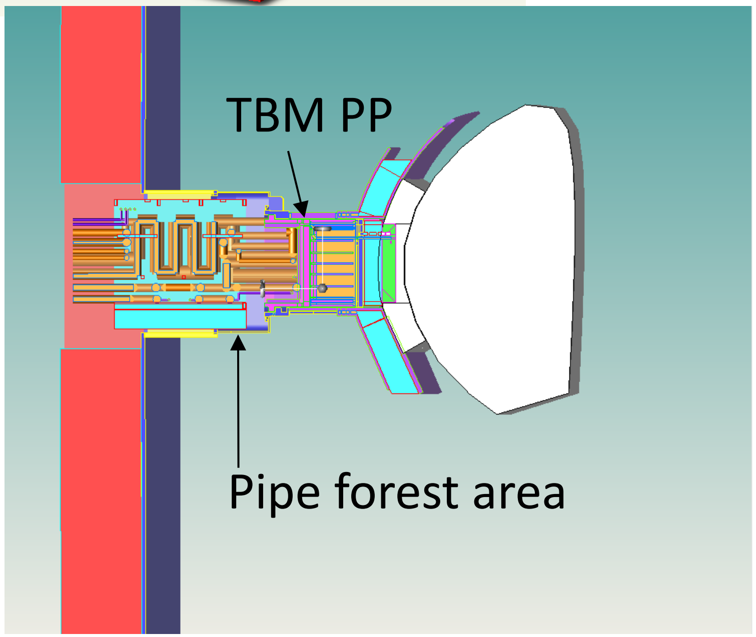
dpa in Cassette Body →

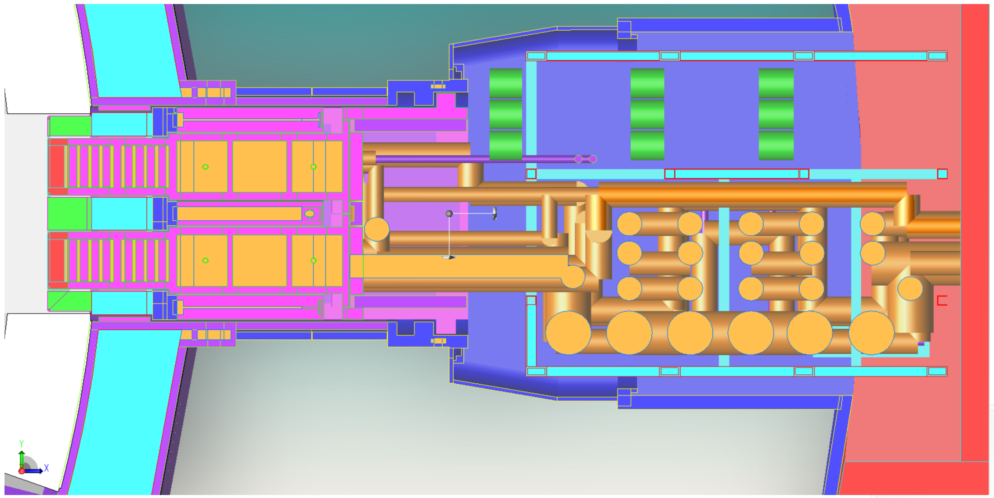


TBM Port Plug Neutronic Studies

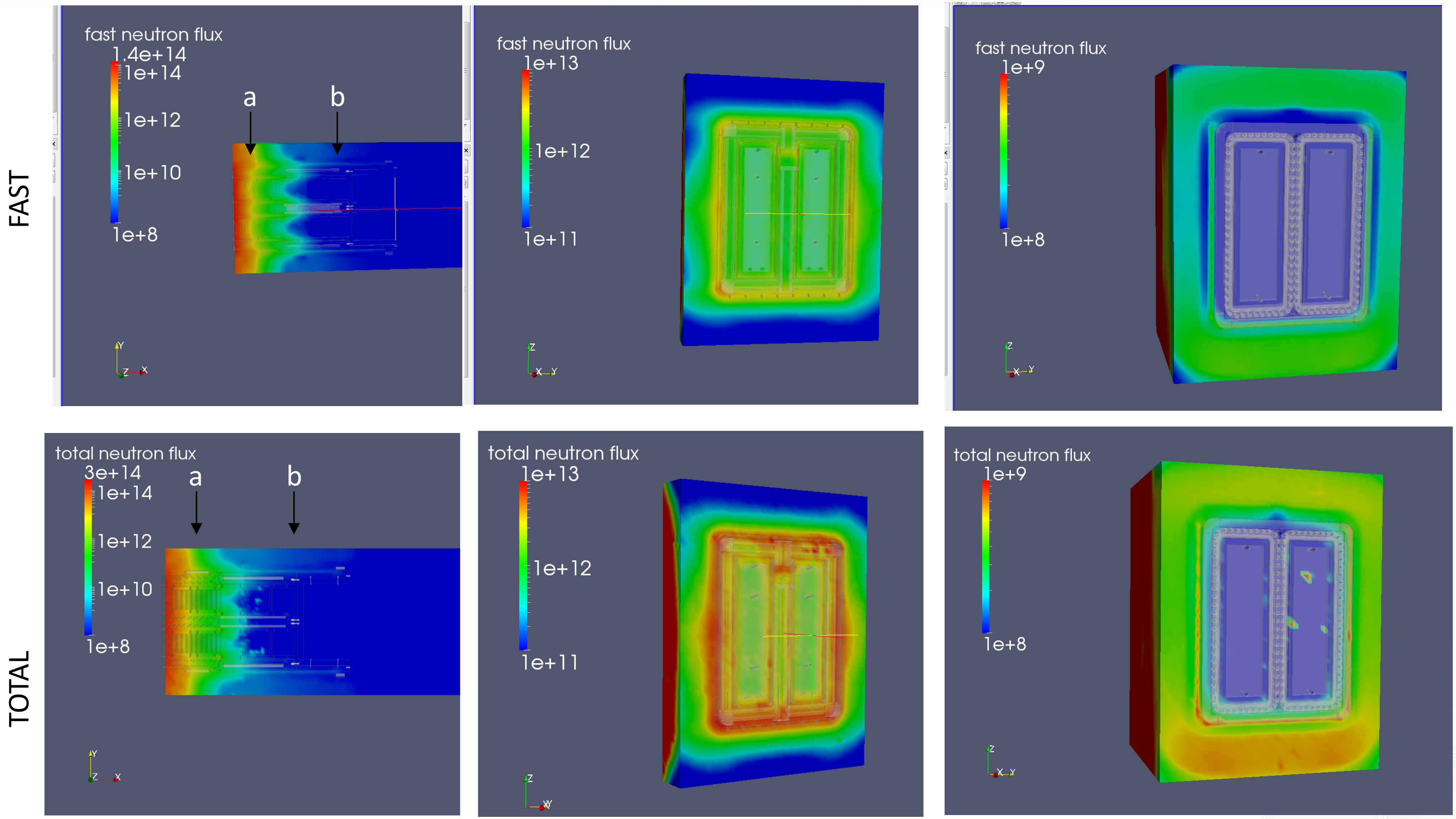








TBM PP Neutron fluxes (n/cm²/s)



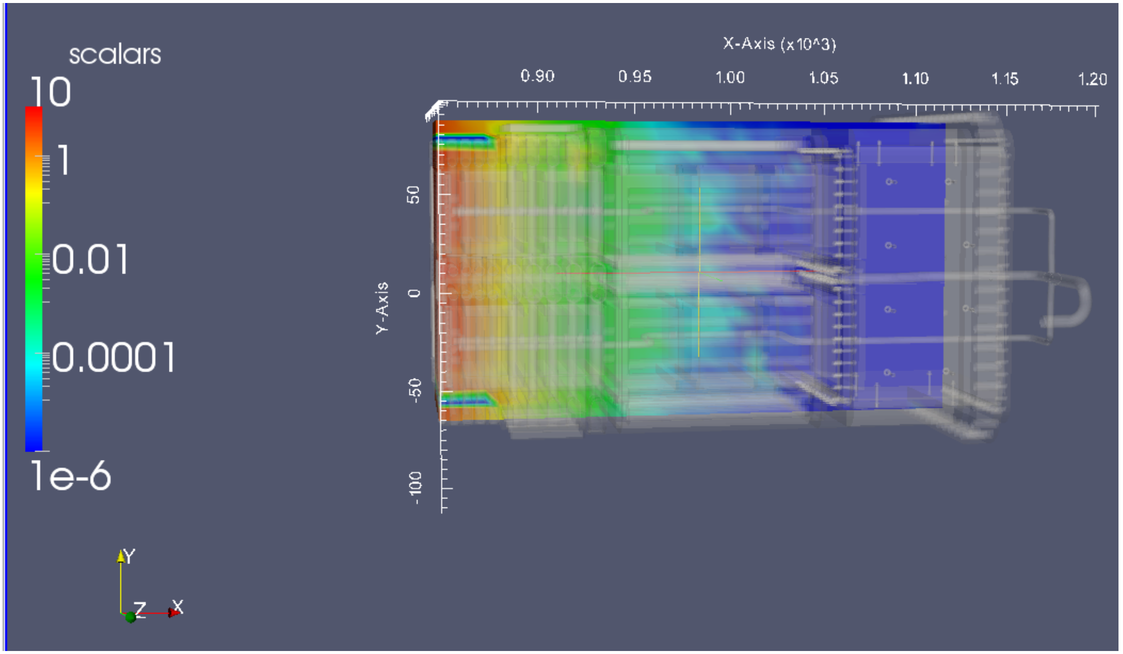
Paraview

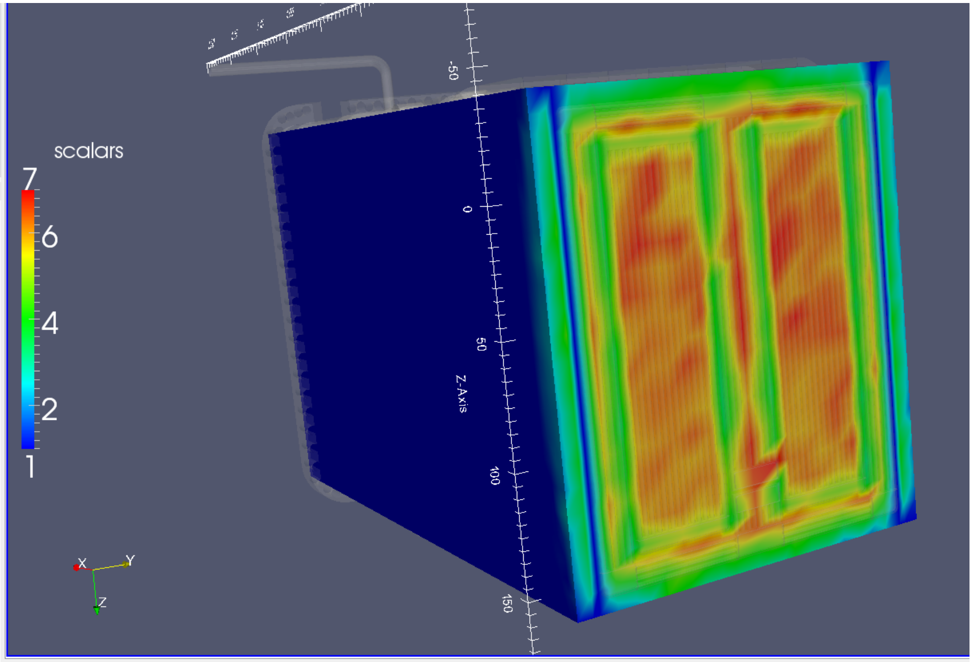
MCNP meshtally results mt2vtk tool (KIT) → vtk

Design model → stl

TBM PP Nuclear heating

Nuclear Heating (W/cm^3) global map in SS components





- Tailored MCNP5 meshtally maps for providing input data for thermal analysis
- Tools for interfacing with finite element codes (e.g. ANSYS)
- MCNP6 unstructured mesh tally capability → symplify interface

CODE DEVELOMENT

- Advanced **D1S** method for **3D shutdown dose rate calculations**

- Shutdown dose rate benchmark experiments at JET (Culham, UK) tokamak

Principles of Direct 1-step method

MCNP:
3-D transport: n + decay γ
Hp : $T_{irr} \rightarrow 0$, $\tau_k \rightarrow 0$

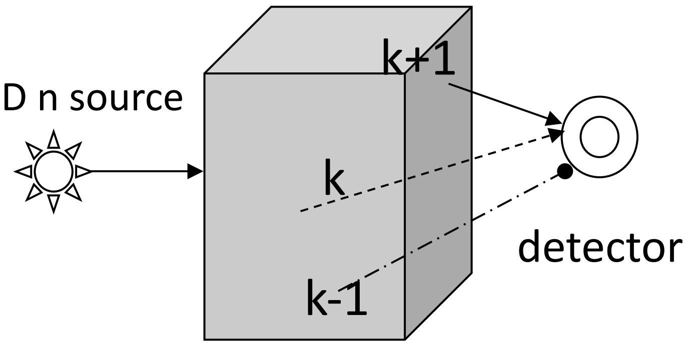
I) Representative material (all parent nuclides)

I) Irradiation histories

FISPACT Inventory code

I) Representative neutron flux

I) DT & DD n source



O) time correction factor for each k-radionuclide (indipendent on Φ, σ, ρ)

O) Dose contribution due to k-radionuclide (indipendent on t)

Gamma dose rate

MCNP modified version.
γ generated only by activated radionuclides:
decay γ emitted as prompt

Advanced D1S for shutdown dose rate

Advanced D1S is an improved version of D1S developed by ENEA in 2011.
In a Standard D1S coupled n/g transport:

- Time evolution: discrete/postprocessing
- No mesh tally capabilities

→ **Advanced D1S (2011)**

New features for Dose rate/decay gammas- Modified MCNP subroutines for:

- **Time evolution: continous/semi-automatic standard cells and surface based tallies**
- **MESHtally maps neutron and decay gammas in single run.**
  At the moment 1 single cooling time per run (discrete)
- **MESHtally: discrete time evolution of dose rate per run per nuclide**

→ **Advanced D1S live (under development)**

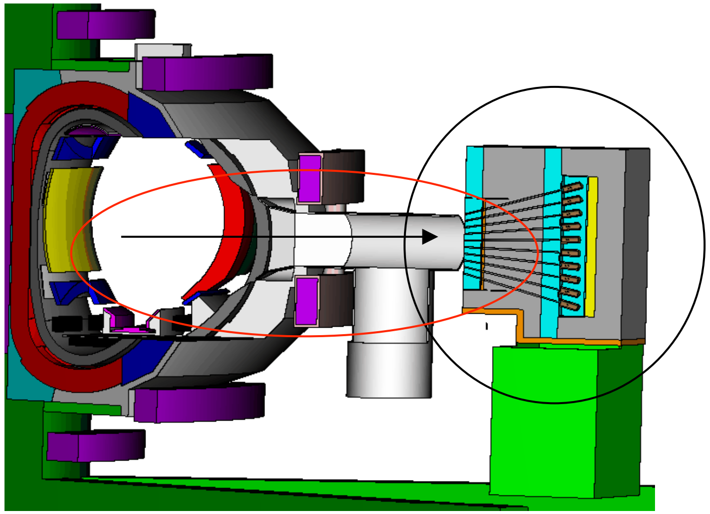
Continuous time evolution of dose rate in single run:

- cells and surface based tallies (in progress)
- MESHtally & user-friendly version

2009-2010 Shutdown Dose rate Benchmark experiment at JET

The benchmark performed as a preliminary experiment on JET during the 2009 shutdown for installation of ILW

Geiger Müller type detectors for dose rate along the axis of the main horizontal port of Octant 1.
Additional measurements inside the plasma chamber with a ionization chamber mounted on a mascot system



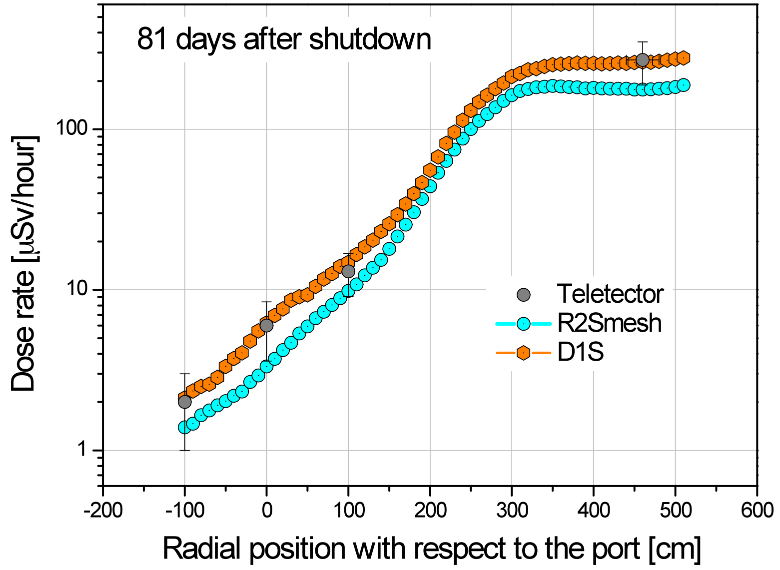
Dosimeters commonly used for radiological protection survey at JET

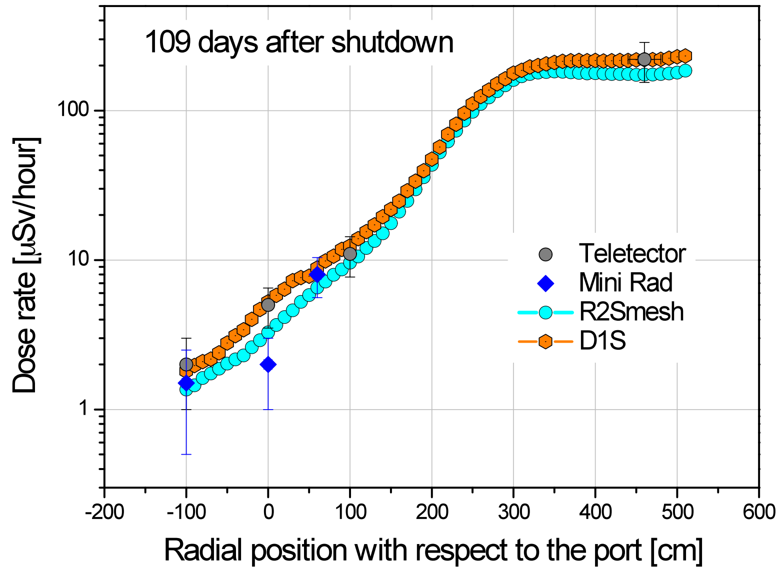
Cooling time range of the data: from **81 days** to **263 days** after the shutdown

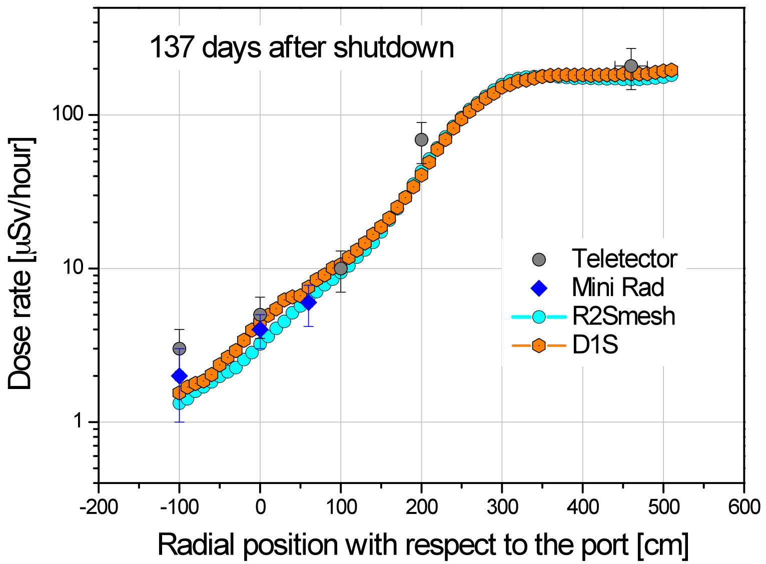
Detectors calibrated in terms of H(10)*

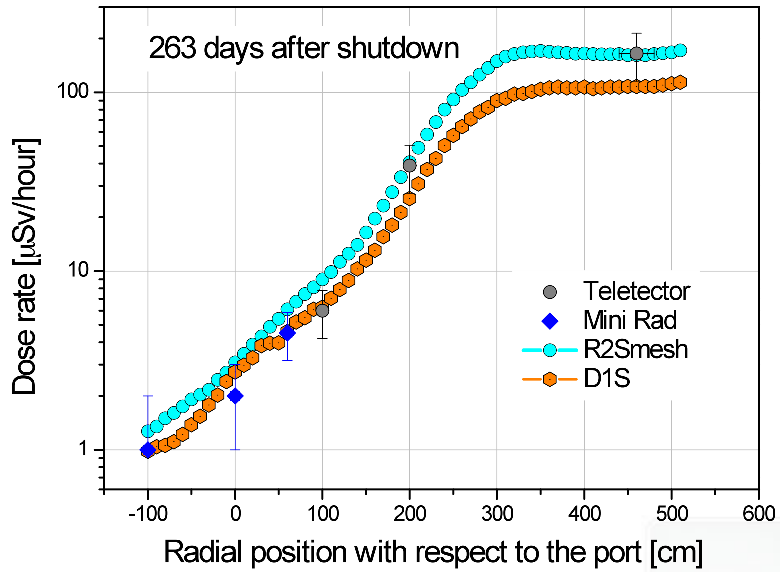
Villari et. al, Fus. Eng. Des., vol 87 pp 1095 (2012)

JET benchmark experiment:
R2S & D1S results of shutdown dose rates vs. measurements



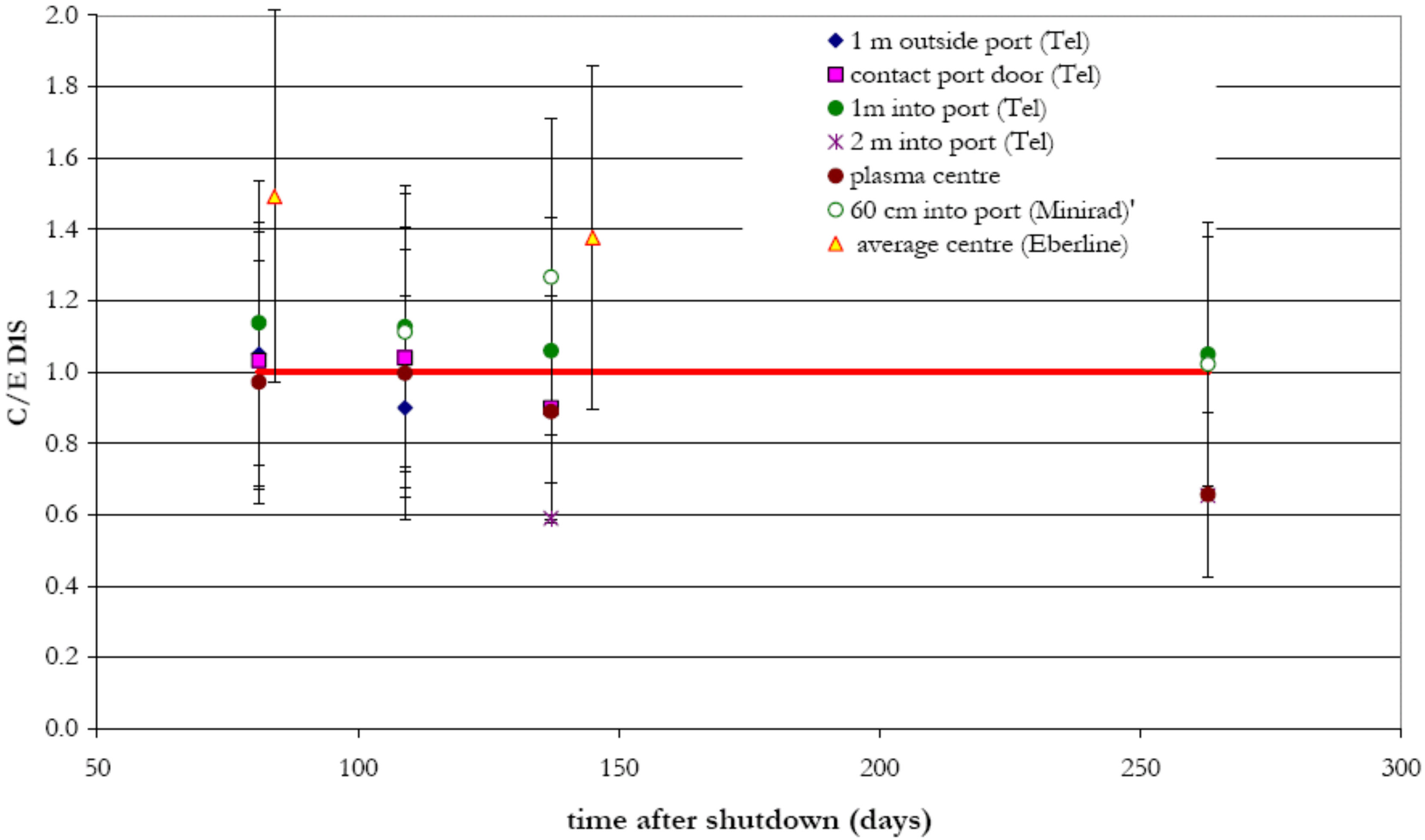






2009-2010 Shutdown Dose rate Benchmark experiment at JET

Advanced D1S C/E vs time after shutdown



Expected CRESCO resource requirements

- $1x10^6$ hours (2013)
- $5x10^6$ hours (2014)

For nuclear analyses on ITER, DEMO, JET and FNG studies