CAD-Based Shielding Analysis for ITER Port Diagnostics

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Objectives – CAD-based MCNP Monte Carlo radiation transport and activation analyses for the Diagnostic Upper and Equatorial Port Plugs (UPP #3 and EPP #8, #17 – results presented)
3 modeling approaches of CAD-based Monte Carlo transport simulations:

1. **Constructive Solid Geometry (CSG)** – traditional approach with **CAD to Monte Carlo models conversion codes**:
   - MCAM (FDS team, China)
   - McCAD (KIT fusion neutronics group, Germany)

2. Unstructured Mesh (UM) geometry in MCNP6 (LANL, USA);

3. Direct particle tracking technique with Direct Accelerated Geometry Monte Carlo (DAGMC) library – developed by University of Wisconsin–Madison, USA.

**Stages of CAD-to-MC models geometry conversion to CSG model of MCNP:**

1) Geometry simplification – remove the unnecessary details
2) Approximation of free-form and spline surfaces to 1\textsuperscript{st} and 2\textsuperscript{nd} order surfaces of MCNP
3) Material definition with homogenization setting up the material mixtures for the simplified cells, such as steel-water shield 60 vol.% steel – 40 vol.% water.
Tallying procedure in MCNP models with lost particles

- CAD-to-MC geometry conversion of tokamaks (ITER, DEMO) with all their complex engineering and diagnostic systems is performed with some level of approximation. Approximations could cause geometry errors and as the consequence – lost particles.

- **Big problem with lost particles**: If one of particles in a history is lost, MCNP cancels all tallies calculated during the history and all banked particles are erased.

![Diagram of single source particle loss](image)

- **(a)** Schematic explanation of MCNP lost particles handling procedure, from Ref. (*) JAEA report

- **(b)** all tallies calculated in this history are cleared

Ref. (*)
Example of lost paricles in ITER Upper Port with strong particle splitting

**V1: Diagnostic Upper Port (DUP)**

ITER plasma side  | DUP back-side
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Neutron source in plasma

**V2: Diagnostic Upper Port (DUP) with lost particles at the back-side**

ITER plasma side  | DUP back-side
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Neutron source in plasma

Neutron fluxes in DUP **Closure Plate** of 2 MCNP models (the same neutron source, the same DUP model, just 10e-3 lost paricle rate at the DUP back-side)

| Energy       | V1: Diagnostic Upper Port (DUP), n/cm2/s | V2: Diagnostic Upper Port with lost particles at the back-side, n/cm2/s |
|--------------|-----------------------------------------|---------------------------------------------------------------------|
| 0&lt;E&lt;0.1 MeV | 1.76E+08                                | 1.37E+06                                                            |
| 0.1&lt;E&lt;1 MeV | 1.04E+08                                | 1.45E+05                                                            |
| 1&lt;E&lt;20 MeV | 8.06E+06                                | 1.29E+03                                                            |
| Total        | 2.88E+08                                | 1.52E+06                                                            |

**Conclusion:** we must keep lost paricle rate at very low level of 10e-7 - 10e-9
Example 1:
Tritium and Deposit Monitor (T-monitor) & Core-Imaging X-ray Spectrometer (CIXS) neutronics analysis with Local MCNP model of ITER Equatorial Port Plug (EPP) #17
Initial MCNP local model of the CIXS Diagnostics apertures only

Resulting MCNP local model with Diagnostics apertures of two systems: Tritium (T) monitor & CIXS

7 mirrors M1-M7 have been modelled - along the optical pathway, started from the front mirror M1, ended by M7 inside the optical box attached to the Closure Plate.

DFW “V” shape is the old version but we supposed this has no impact on the presented results.
Total neutron flux for EPP17 with CIXS only

Map of total n-flux for the CIXS model having no-collimated LOS beams

Map of total n-flux for the CIXS model with collimated LOS beams

CAD model of the original CIXS shielding

Collimators:
- 4 x plates per beam
- 1-m long
- Tungsten (W)

Inside 3 slots with LOS beams

Ex-port Crystals

In-port Crystal

Rectangular opening reserved for NAS

Port Interspace (Pl)

Vacuum extension flange

3 Line-of-Site (LOS) apertures

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Total neutron flux for EPP17 with CIXS and TD-monitor

Total neutron flux $(n/cm^2/s)$:
- DFW ~ $1e14$
- First mirrors ~ $3e12$
- Port Interspace (PI) ~ $1e7$

Averaged in PI ~ $1e7$

At CIXS ex-port crystal ~ $1e10$
Distribution of decay gamma sources for SDDR
Comparison of the SDDR distributions in MCNP fine mesh

SDDR in CIXS-only model vs. SDDR in TD-monitor & CIXS model

Decay gamma streaming pathways:
1) 0.5 cm gaps between DSM #2 and #3
2) CIXS

Decay gamma streaming pathways:
1) 0.5 cm gaps between DSM #2 and #3
2) CIXS
3) TD-monitor
SDDR horizontal distributions and effect of TD-monitor on SDDR

Horizontal SDDR (microSv/h) distributions in spherical detectors of TD-monitor & CIXS model

| Layer # | Detectors location in horizontal distribution | Left | Right |
|---------|---------------------------------------------|------|-------|
| L1      | Below the TD-monitor, at 30cm from CP       | 134  | 210   |
|         |                                             | 209  | 120   |
| L2      | Behind the TD-monitor, at 66cm from CP      | 27   | 59    |
|         |                                             | 78   | 69    |
| L3      | Far from TD-monitor, 100cm from CP          | 12   | 56    |
|         |                                             | 72   | 58    |

Horizontal SDDR (microSv/h) distributions in detectors of CIXS-only model

| Layer # | Detectors location in horizontal distribution | Left | Right |
|---------|---------------------------------------------|------|-------|
| L1      | Below the TD-monitor, at 30cm from CP       | 121  | 193   |
|         |                                             | 194  | 117   |
| L2      | Behind the TD-monitor, at 66cm from CP      | 32   | 66    |
|         |                                             | 74   | 63    |
| L3      | Far from TD-monitor, 100cm from CP          | 11   | 56    |
|         |                                             | 67   | 55    |

Effect of TD-monitor on SDDR in spherical detectors. Difference of SDDR (microSv/h) in two models: (TD-mon & CIXS model) – CIXS-only model

| Layer # | Detectors location in horizontal distribution | Left | Right |
|---------|---------------------------------------------|------|-------|
| L1      | Below the TD-monitor, at 30cm from CP       | 13   | 17    |
|         |                                             | 15   | 3     |
| L2      | Behind the TD-monitor, at 66cm from CP      | -5   | -7    |
|         |                                             | 4    | 6     |
| L3      | Far from TD-monitor, 100cm from CP          | 1    | 0     |
|         |                                             | 5    | 3     |

Gamma shadow effect for 2 detectors at L2 due to the shield of TD-mon box
Summary and Recommendations

- Neutronics analysis was performed in the MCNP Local model of **EPP17** included only the apertures of two Diagnostics: TD-monitor and CIXS.
- The results include neutron and gamma fluxes and nuclear heating on **7 mirrors** of the TD-monitor, neutron fluxes and SDDR estimated in spherical detectors and with 3D distributions in EPP17:
  - Nuclear heating on mirrors is up to **0.77 W/cm³** (cooling might be required).
  - SDDR in spherical detectors at the bottom of TD-monitor shield box (at 30 cm from Closure Plate) reaches **210 microSv/h**, with a contribution of **17 microSv/h from TD-monitor**.
  - Shield block behind the TD-monitor contribute to a decrease on **7 microSv/h** – gamma shadow effect.
  - These are relative SDDR values of Local MCNP model. Final values request inclusion of all the tenants of EPP17 (TD-monitor, CIXS, Vis/IR system, and Divertor Thermography) – future task of EPP17 port plug integration, with inclusion of all the sorts of the gaps, radiation cross-talks between the ports, and environmental effects in global MCNP C-lite model.

Recommendations for TD-monitor design improvement:

- Increase vertical shift (M4-M5) of the dog leg inside the port plug - to prevent possible direct neutron streaming.
- Shield block behind the TD-monitor optical box appears as a “neutronic relevant option”.

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Example 2:
Tangential Neutron Spectrometer (TNS) inside the EPP #8 with 7 Diagnostics in C-lite v.2
Tangential Neutron Spectrometer (TNS) integrated inside the Diagnostic Equatorial Port Plug (EPP) #8

Diamond detectors and fission chambers are installed in TNS as neutron detectors. High fluxes ($10^9$ n/cm$^2$s – $10^{10}$ n/cm$^2$s) will allow at least 100 ms spectroscopy time resolution.

Top view on ITER vacuum vessel

2 neutron detectors of Tangential Neutron Spectrometer (TNS)
Task: eliminate radiation cross-talk from the Fast Ion Loss Detector (FILD or Lost Alpha - LAM) to Tangential Neutron Spectrometer (TNS) in EPP #8

The purpose of TNS spectrometer is to measure spectra of neutrons flying in tangential direction as a collective D-T plasma rotation. In result to estimate the Doppler energy shift of the neutron spectrum emission. **Problem** was noise of neutrons coming from other Diagnostics.
Photon heating (W/cm$^3$) for EPP8 (7 diagnostics included in EPP#8) – impact of Lost Alpha Monitor (LAM) on neutron energy spectrum in two Detectors of TNS.
Modification of the FILD pathway

Original FILD

1st leg

2nd leg

Impact of FILD on TNS

Original pathway in FILD

TNS detector

Turned FILD

1st leg

2nd leg

Original FILD

Impact of FILD on TNS

Turned FILD

Modification of the FILD pathway

TNS detector

Plasma
Investigation was carrying on for the Central TNS detector. In the original EPP #8 model the distance between TNS and 1st leg of FILD was 10 cm, in the turned model it is 60 cm.

Turning upside-down of the FILD pathway helps to increase the 14-MeV peaking factor in energy resolution of the central TNS detector.

Turned FILD configuration stops neutron streaming from the FILD pathway to the Central TNS detector.

For measuring of n-spectrum in Central Det. #2 the turned FILD option is an equivalent to one of its absence – option of totally filled FILD (LAM – as FILD called before): “TNS-no-LAM” case on the spectra plots next slide.
In Central TNS Detector #2 the neutron spectra are coincided for two cases:
1) Totally removed LAM (FILD)
2) Turned upside-down LAM (FILD)
Example 3:
Shutter and the main Diagnostic path of the Charge eXchange Recombination Spectroscopy (CXRS) in UPP #3
Upper Port Plug #3 with Charge eXchange Recombination Spectroscopy (CXRS)

- Collects visible light emitted by Diag. Neutral Beam (DNB)
- Analyses the light ➔ Ion Temp., Plasma Rotation, Impurities

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Impact of CXRS shutter – on neutron flux streaming
Case #1:
UPP-CXRS with GDC
4 pathways of neutron streaming:
1 – Gaps all-round the UPP
2 – CXRS shutter
3 – CXRS main optical path
4 – GDC electrode

Case #2:
UPP-CXRS except GDC
3 pathways of neutron streaming:
1 – Gaps all-round the UPP
2 – CXRS shutter
3 – CXRS main optical path

Neutron pathway analysis:
Case #1 vs. Case #2:
Case 1:
UPP-CXRS with GDC
4 pathways of neutron streaming:
1 – Gaps all-round the UPP
2 – CXRS shutter
3 – CXRS main optical path
4 – GDC electrode

Neutron pathway analysis:
Case #1 vs. Case #3:

Case 3:
Generic UPP
1 pathway of neutron streaming:
1 – Gaps all-round the GUPP
Conclusions

• The phenomenon of in-port cross-talk was investigated for the diagnostic systems deployed in two Equatorial Port Plugs (EPP) #17 and #8, and for the components of Upper Port Plug (UPP) #3.

• The T-monitor & Core-Imaging X-ray Spectrometer (CIXS) inside the Diagnostic Generic EPP are analysed in EPP#17 local MCNP model of ITER. While EPP#8 and UPP#3 are modelled globally with C-lite v2 and B-lite v3 models, respectively.

• Multiple sets of diagnostic equipment inserted inside the same Port Plug create additional pathways for radiation streaming along the diagnostic channels and labyrinths (e.g. optical pathways) – the reason of in-port radiation cross-talk between different diagnostic systems.

• Demonstrated that in order to take advantage of particular shielding improvements in full extent, we should also assess the mutual influence of every Diagnostic system installed inside the same port.

• This subject is important for Diagnostics designing at the stage of port integration to ensure engineering and maintenance solutions for the Diagnostic tenant systems.