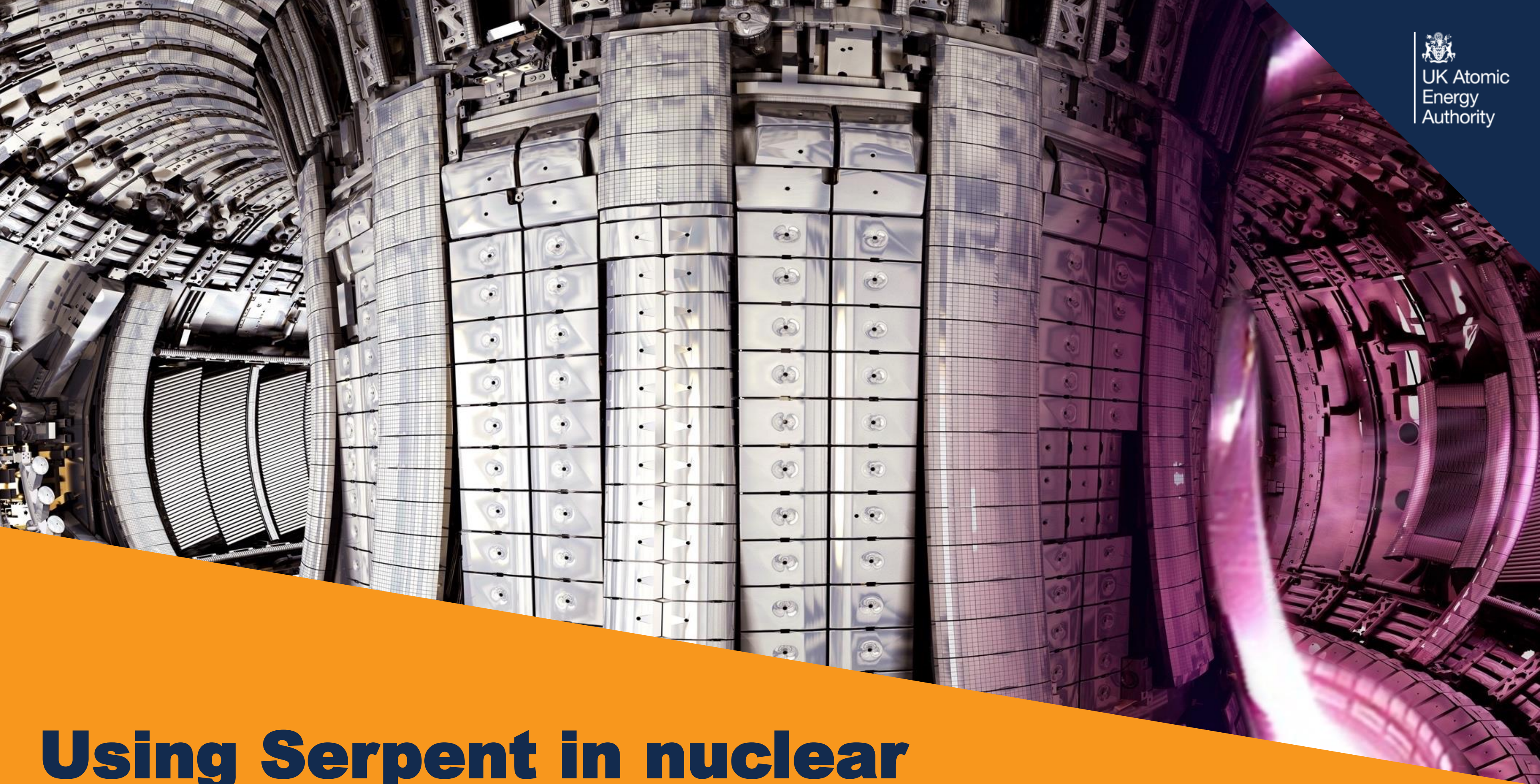


Using Serpent in nuclear fusion analysis

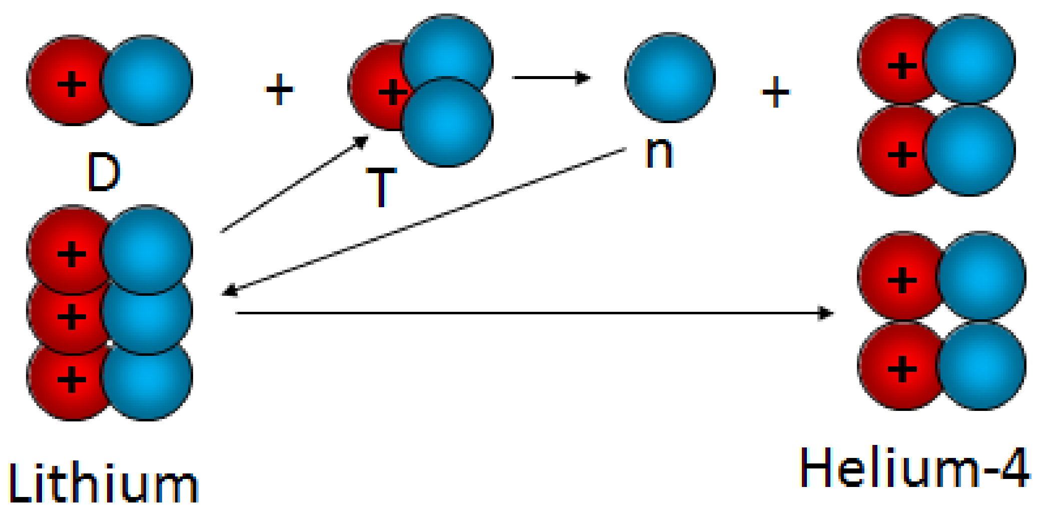
Bethany Colling, A. Burns, A. Davis, A. Turner

Contract for the Operation of the JET Facilities Co-Funded by Euratom
This work was funded by the RCUK Energy Programme [Grant number EP/P012450/1]

Nuclear fusion

UK Atomic Energy Authority

- Potential source for future baseload energy.
- Deuterium (D) – Tritium (T) fusion reaction.
- 14 MeV neutrons produced.
- Tritium fuel production through lithium – neutron interactions.



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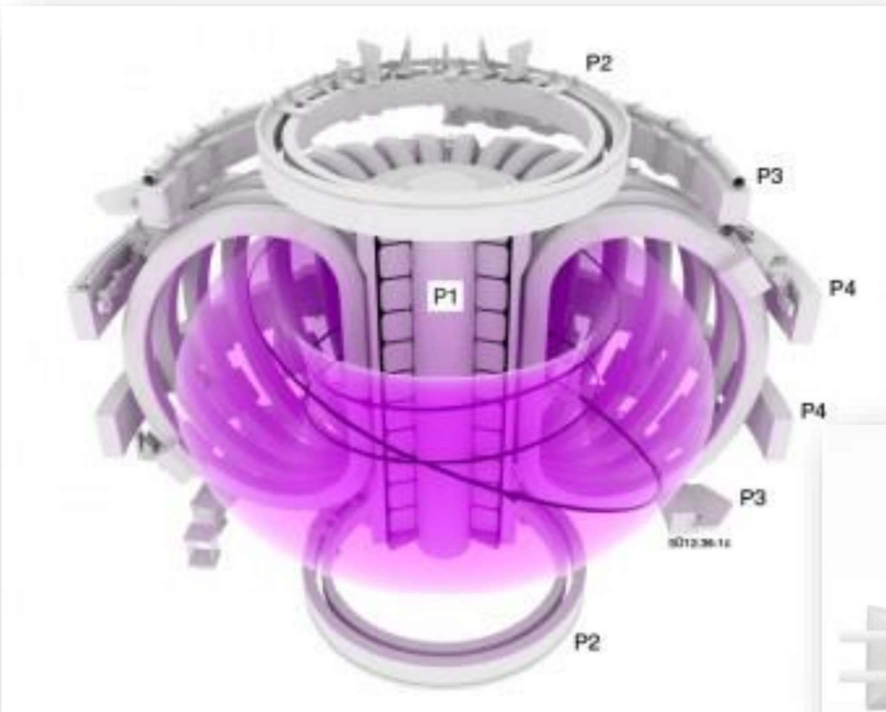
Magnetic confinement fusion

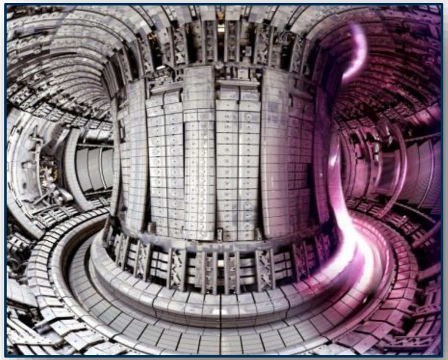


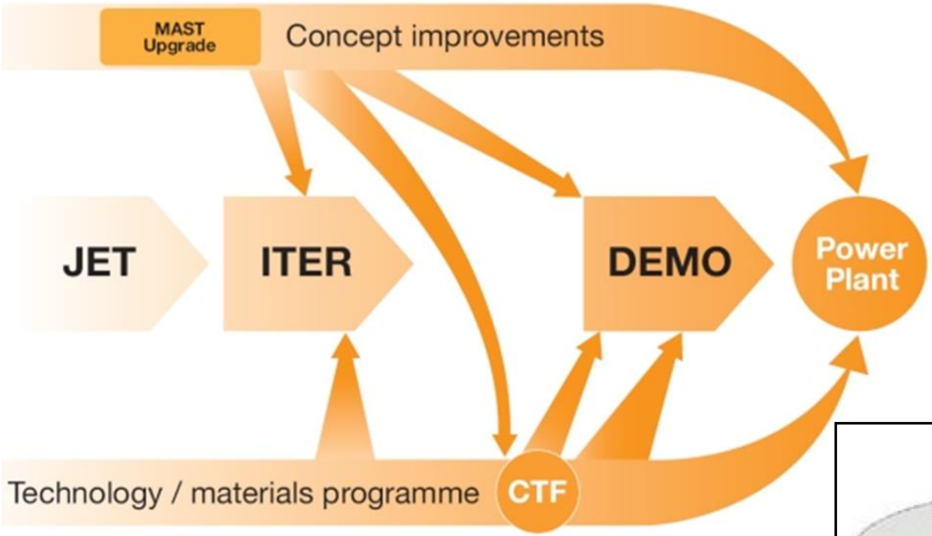
Reproduced with permission, EUROfusion

- DT plasma contained in vacuum chamber using magnetic fields.

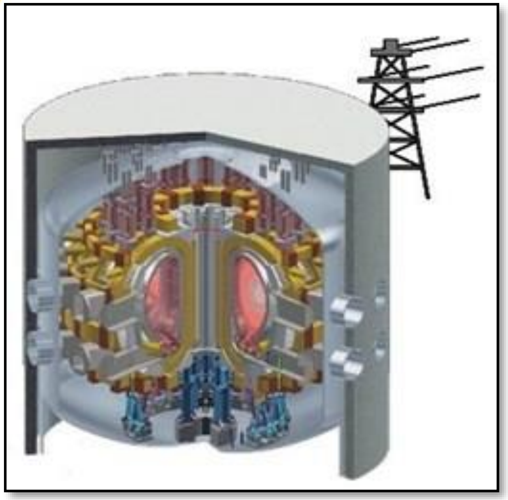
Pathway to commercial fusion energy

JET





DEMOnstration plant concepts



ITER construction

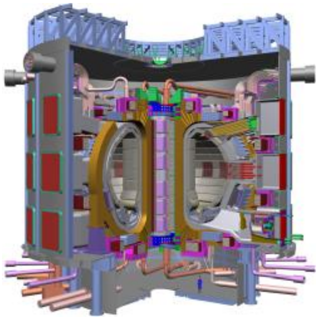
CCFE neutronics activities

UK Atomic Energy Authority

EFDA JET

iter
china eu india japan korea russia usa

FUSION FOR ENERGY



EUROfusion

NNUF
National Nuclear User Facility

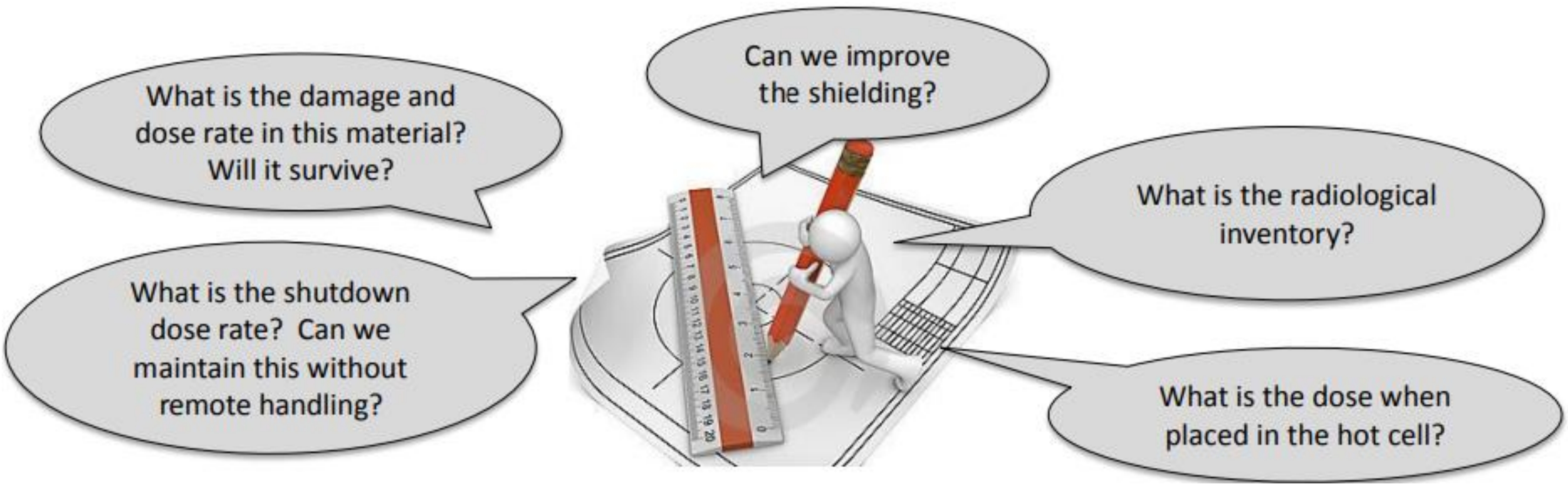
CCFE
CULHAM CENTRE FOR FUSION ENERGY

ITER neutronics activities

Fusion is entering a ‘nuclear phase’, with significant emphasis on nuclear safety, shielding and activation.

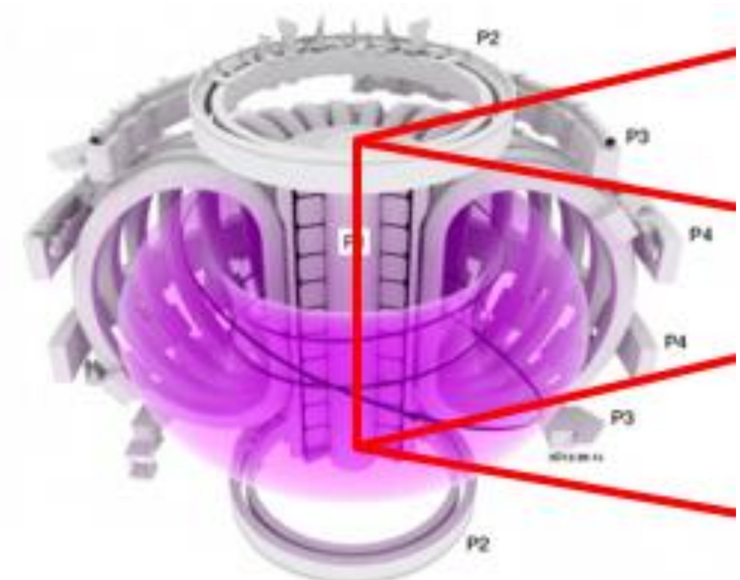
ITER analysis is often a shielding and activation study.

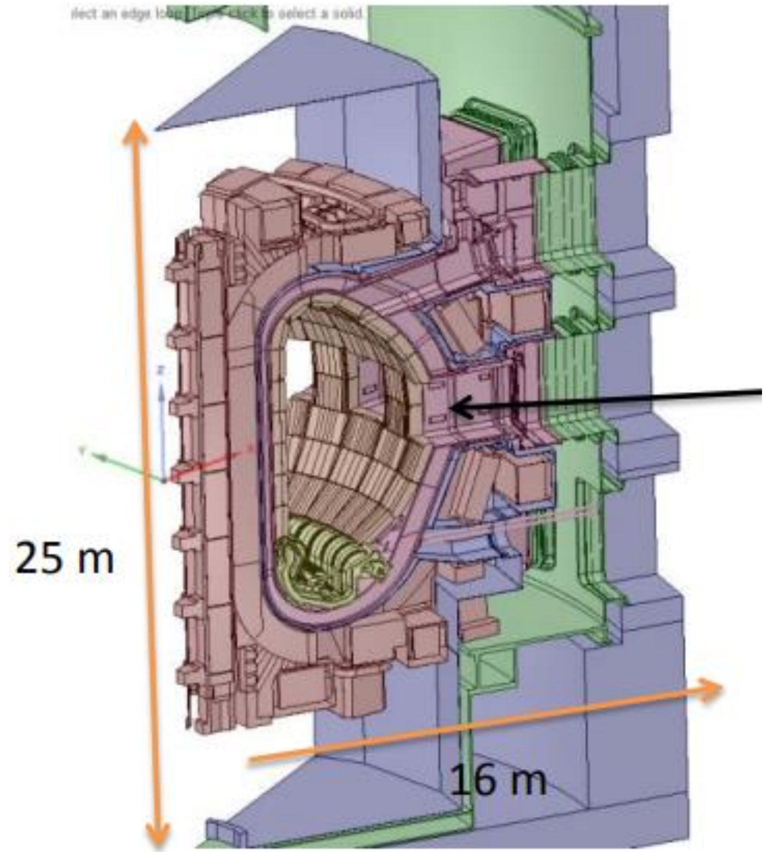
- Questions we are trying to answer for design engineers:



- Quantities needed: neutron flux, nuclear heating, absorbed dose rate, gas production, radiological inventory, shutdown dose rate.
- 3-D mesh results and component (cell) results.

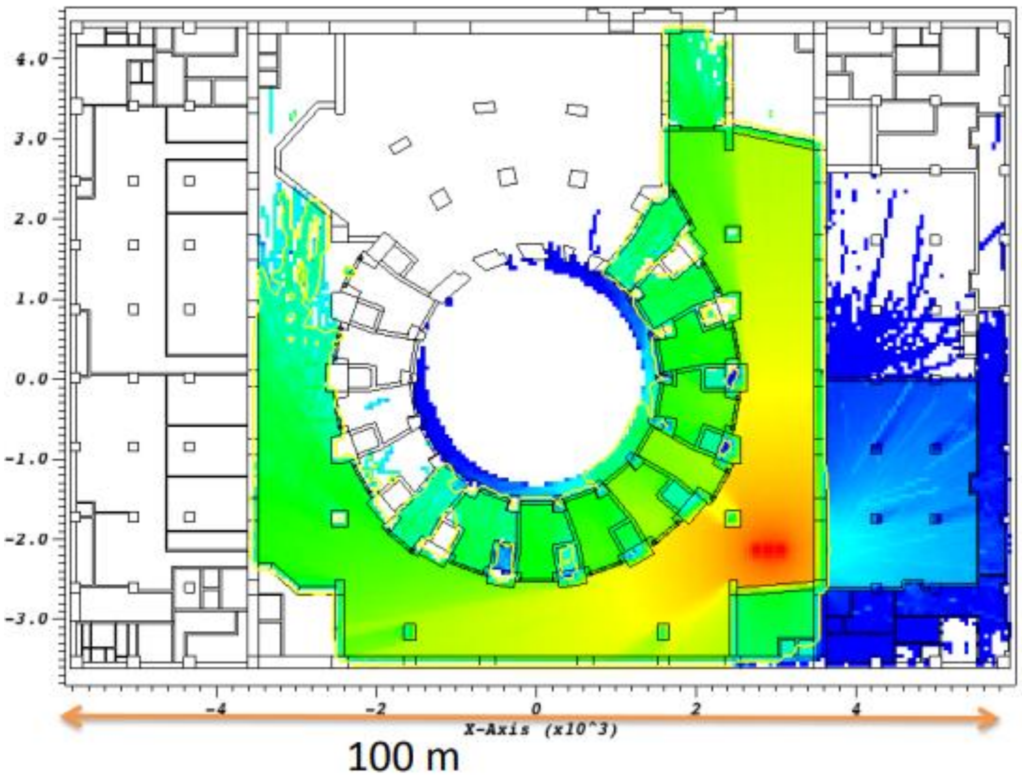
The sector model – taking a segment of the full 360 degree tokamak





Not always a sector model

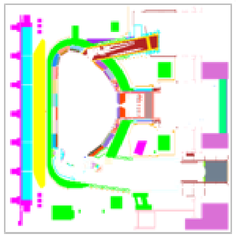
Top down view through tokamak building



Typical neutronics workflow

UK Atomic Energy Authority

Neutronics model

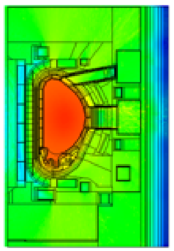


CAD conversion

ANSYS SpaceClaim

FDS SuperMC

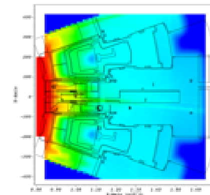
Global variance reduction (GVR)

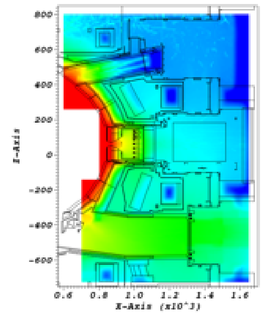


WWITER

ADVANTG

Oak Ridge National Laboratory





MCNP6

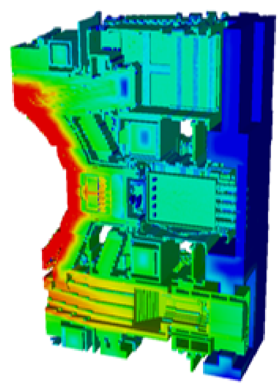
Coupled neutron-photon transport with GVR

Secondary responses:

- Nuclide inventory
- Radioactive waste
- Shutdown dose rates

Decay gamma source from MCR2S

MCR2S

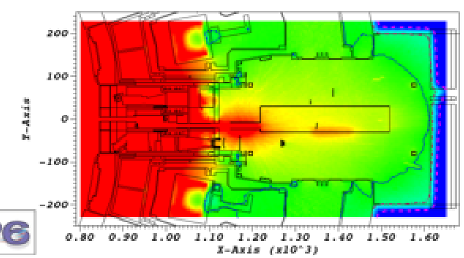


Primary responses:

- High resolution neutron/ photon flux maps
- Gas production
- Heating
- Material dose/dpa rates

Photon Transport (SDDR)

MCNP6



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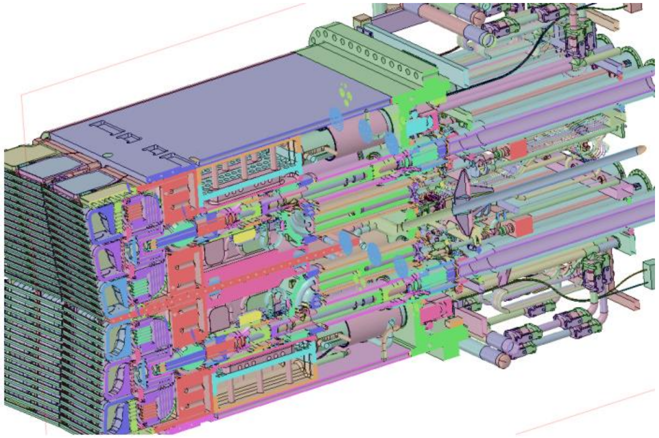
Neutronics modelling



Engineering CAD

Simplification

Conversion to MCNP

Conversion fails

Conversion successful

Integrate into main model (e.g. with universe structure)

Integration fails (lost particles)

Integration successful (lost particles?)

Considerations for alternative workflows

Key issues:

- Does it get the ‘right’ answer?
- Ease of use, assigning materials, tallies etc.
- Practical on current machines for appropriate geometry resolutions (run time, memory).
- Ease of geometry production (incl. availability and accessibility of meshing tools if required).

Alternative Monte Carlo-based workflows

MCNP6v1.0, v1.1-b	DAGMC-MCNP5	Serpent-2
CSG	US	CSG
UM		US
		~~UM~~

constructive solid geometry (CSG)
unstructured volume mesh (UM)
unstructured surface mesh (US)

Could not find a suitable workflow to create model.

Applications of Serpent 2 Monte Carlo Code to ITER neutronics analysis

A. Turner[1], A. Burns[1], B. Colling[1*], J. Leppänen[2]

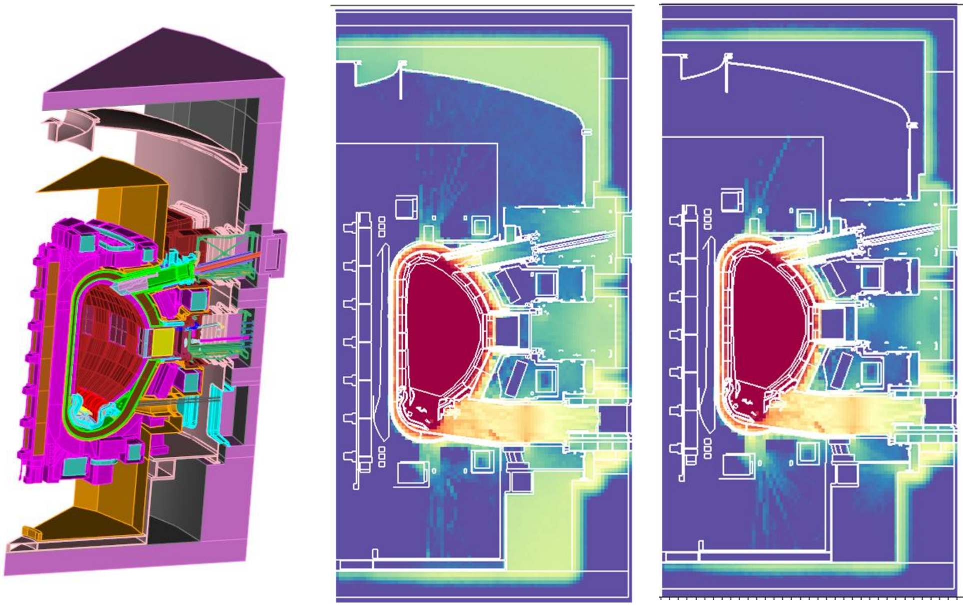
1: UK Atomic Energy Authority (CCFE), Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

2: VTT Technical Research Centre of Finland, Kivimiehetie 3, FI-02150 Espoo, Finland

**Corresponding author: bethany.colling@ukaea.uk*

DAGMC – CAD based workflow

- DAGMC (http://svalinn.github.io/DAGMC) is an open source toolkit that allows a user to transport particles on CAD based geometries.
- Developed by the Computational Nuclear Energy Research Group (CNERG - http://cnerg.github.io/) at the University of Wisconsin-Madison and UKAEA.
- Its purpose is to enable particle transport on very detailed and complex geometries, by having a core geometry library which can be plugged into any Monte Carlo code.



DAGMC - Integration

UK Atomic Energy Authority

Collaboration between UW-Madison and UKAEA on code independent, robust, and efficient methods for CAD based radiation transport

Complete and available

- FLUKA
- MCNP6
- MCNP5
- GEANT4
- Tripoli4
- Shift

In progress

- OpenMC

Proposed

- EGSnrc
- PHITS (Particle and Heavy Ion Transport code System)
- Serpent2

Not currently planned

- Penelope
- Mercury
- MARS

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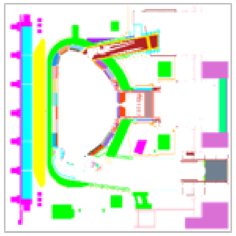
Where could we use Serpent?

Neutronics model



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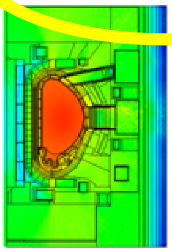

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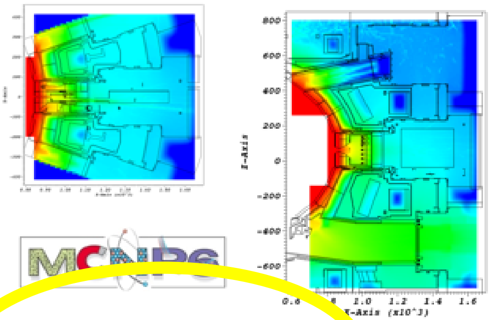
Oak Ridge National Laboratory



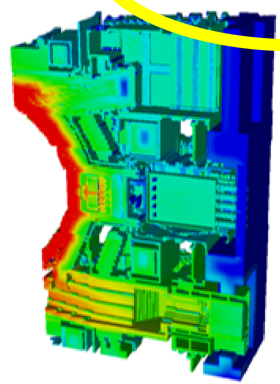
MCNP6

Coupled neutron-photon transport with GVR

Primary responses:

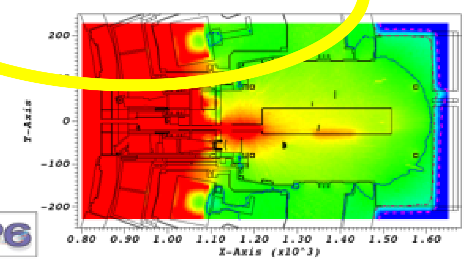
- High resolution neutron/ photon flux maps
- Gas production
- Heating
- Material dose/dpa rates

MCR2S



Decay gamma source from MCR2S

Photon Transport (SDDR)



MCNP6

Secondary responses:

- Nuclide inventory
- Radioactive waste
- Shutdown dose rates

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CCFE Culham Centre for Fusion Energy

Serpent 2 for coupled neutron, photon fusion neutronics calculations

CCFE has performed some assessment of various aspects of Serpent 2 and the suitability for fusion neutronics:

- Comparison with computational results (MCNP) for ITER in-vessel values.
- Application of mesh-based geometry incl. practical considerations and ease of use.
- Computational speed and memory requirements.
- Effectiveness of MPI and threading for large models.

Testing and benchmarking is essential prior to use in ITER analysis.

What benchmarks?

UK Atomic Energy Authority

iter
china eu india japan korea russia usa

IDM UID
VP6DJL

VERSION CREATED ON / VERSION / STATUS
07 Feb 2018 / 1.4 / Signed

EXTERNAL REFERENCE / VERSION

Report

Instructions on qualification of radiation transport codes

This document describes the verification and validation (V&V) procedure of the radiation transport code to be applied in ITER radiation analysis.

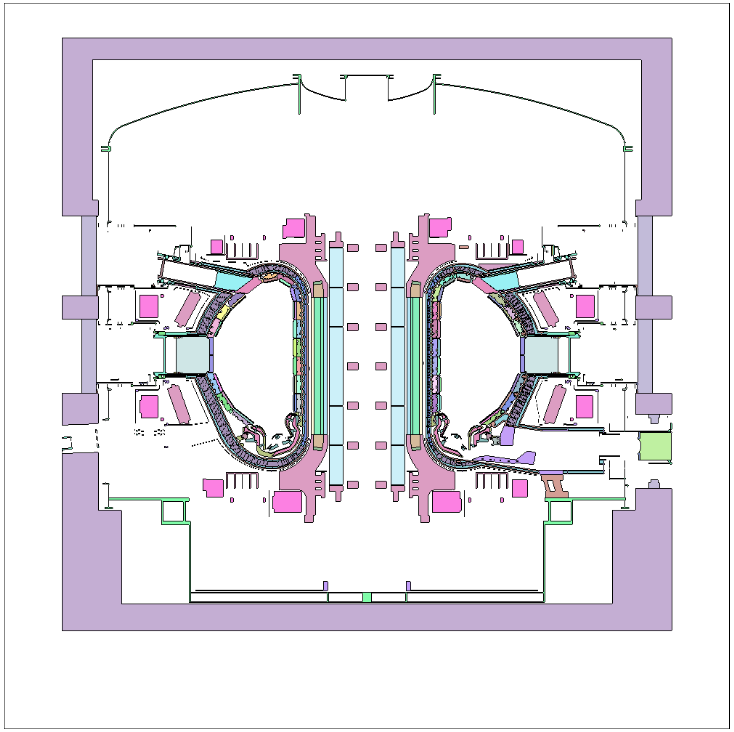
- Developing a set of fusion-relevant benchmarks and an automated method for conducting each test.
- Include the ITER requirement tests.
- Computational and experimental comparisons.

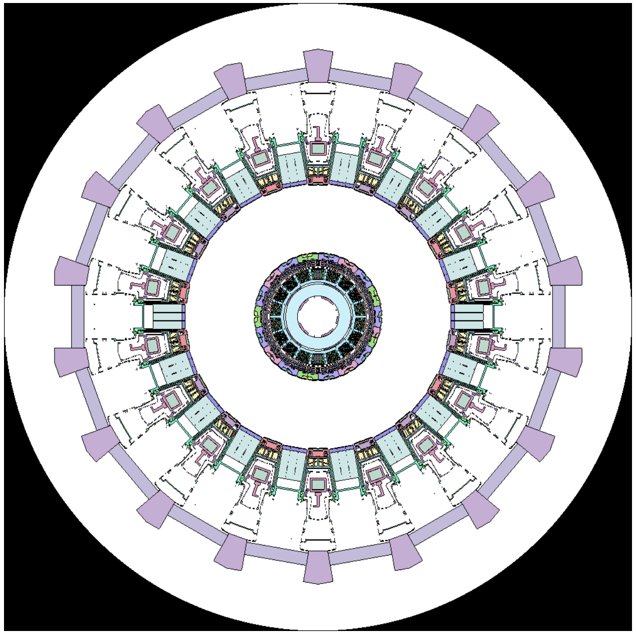
ITER reference model 'C-Model'

UK Atomic Energy Authority

- 40 degree sector modelled in MCNP with reflecting boundary conditions
- Model comprises: surfaces 108450, cells 70374

- Full 360 model created in Serpent 2 using universe symmetry by reflection with the 40 degree geometry definition.





Serpent2

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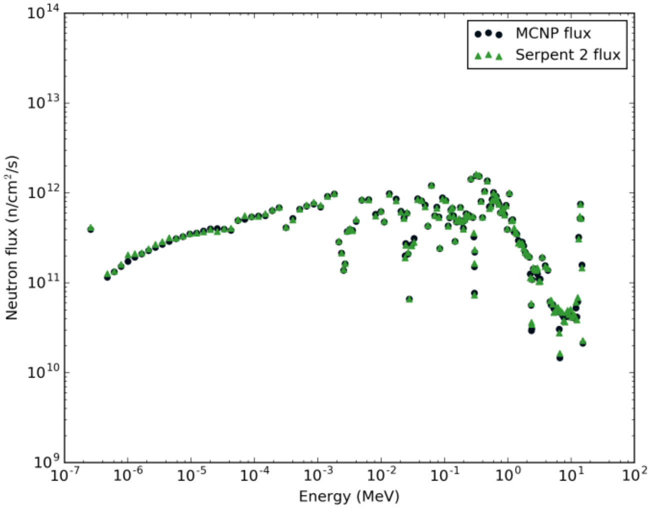
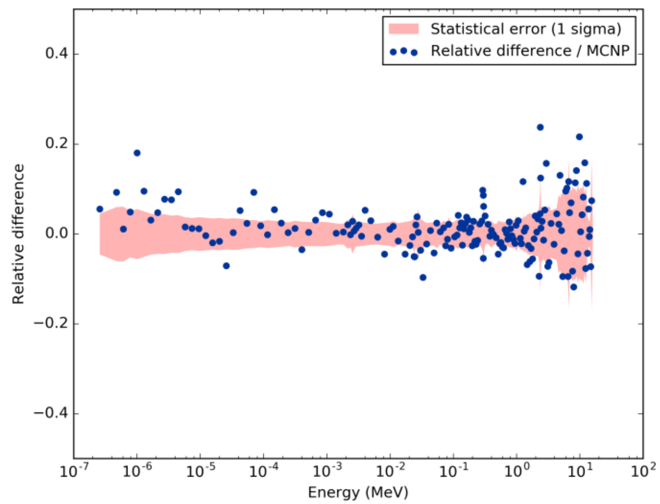
Comparison results – flux spectra

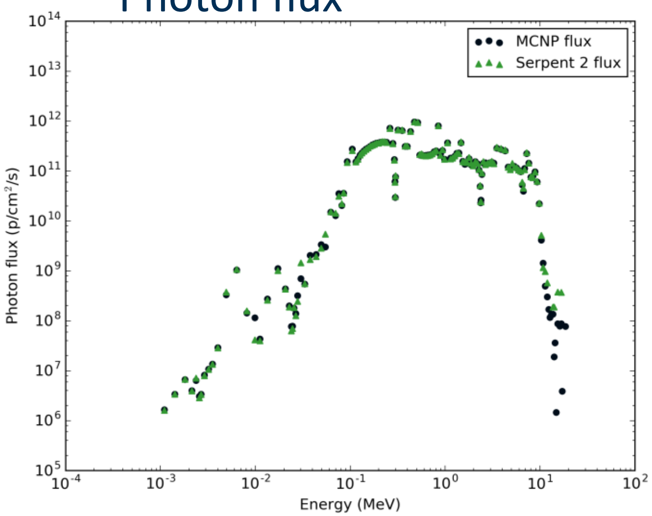
UK Atomic Energy Authority

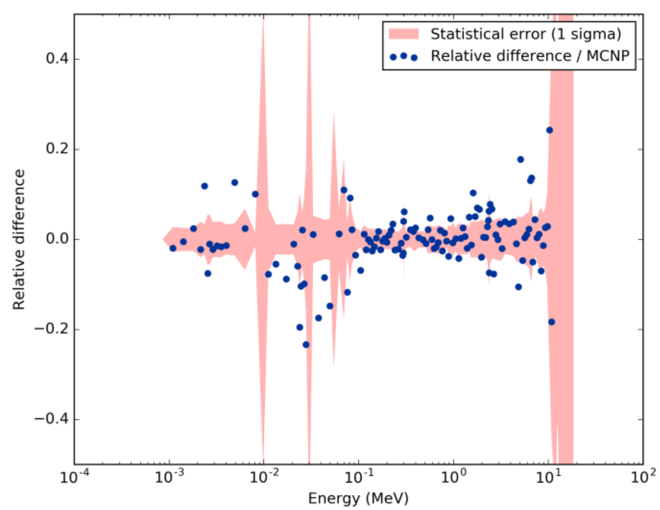
Neutron flux

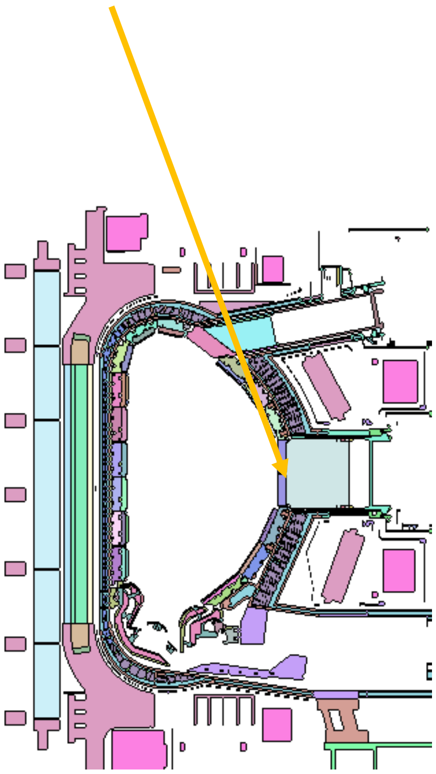




Photon flux







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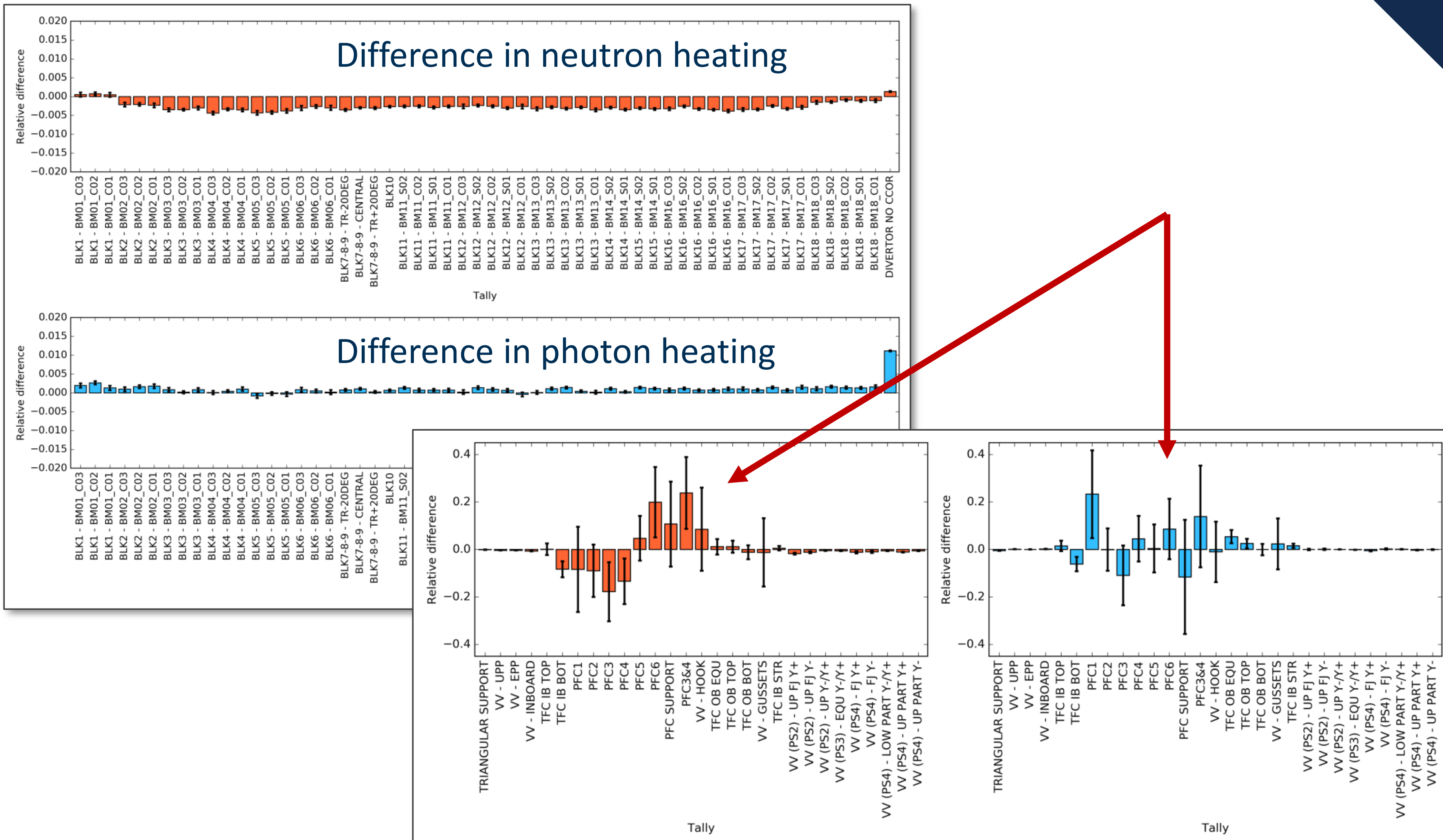
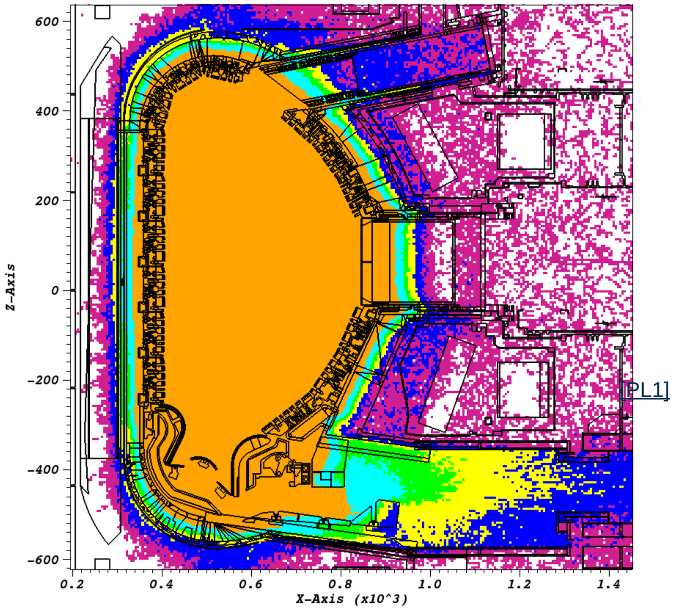
ITER – C-Model

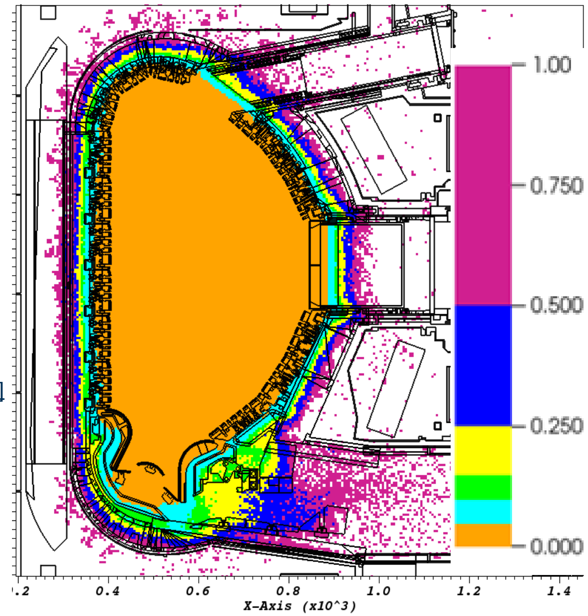

Difference in neutron heating
Difference in photon heating
Relative difference
Tally
TRIANGULAR SUPPORT
VV - UPP
VV - EPP
VV - INBOARD
TFC IB TOP
TFC IB BOT
PFC1
PFC2
PFC3
PFC4
PFC5
PFC6
PFC SUPPORT
PFC3&4
VV - HOOK
TFC OB EQU
TFC OB TOP
TFC OB BOT
VV - GUSSETS
TFC IB STR
VV (PS2) - UP FJ Y+
VV (PS2) - UP FJ Y-
VV (PS2) - UP Y-/Y+
VV (PS3) - EQU Y-/Y+
VV (PS4) - FJ Y+
VV (PS4) - FJ Y-
VV (PS4) - LOW PART Y-/Y+
VV (PS4) - UP PART Y+
VV (PS4) - UP PART Y-

Statistical uncertainty

MCNP statistical error map



Serpent statistical error map



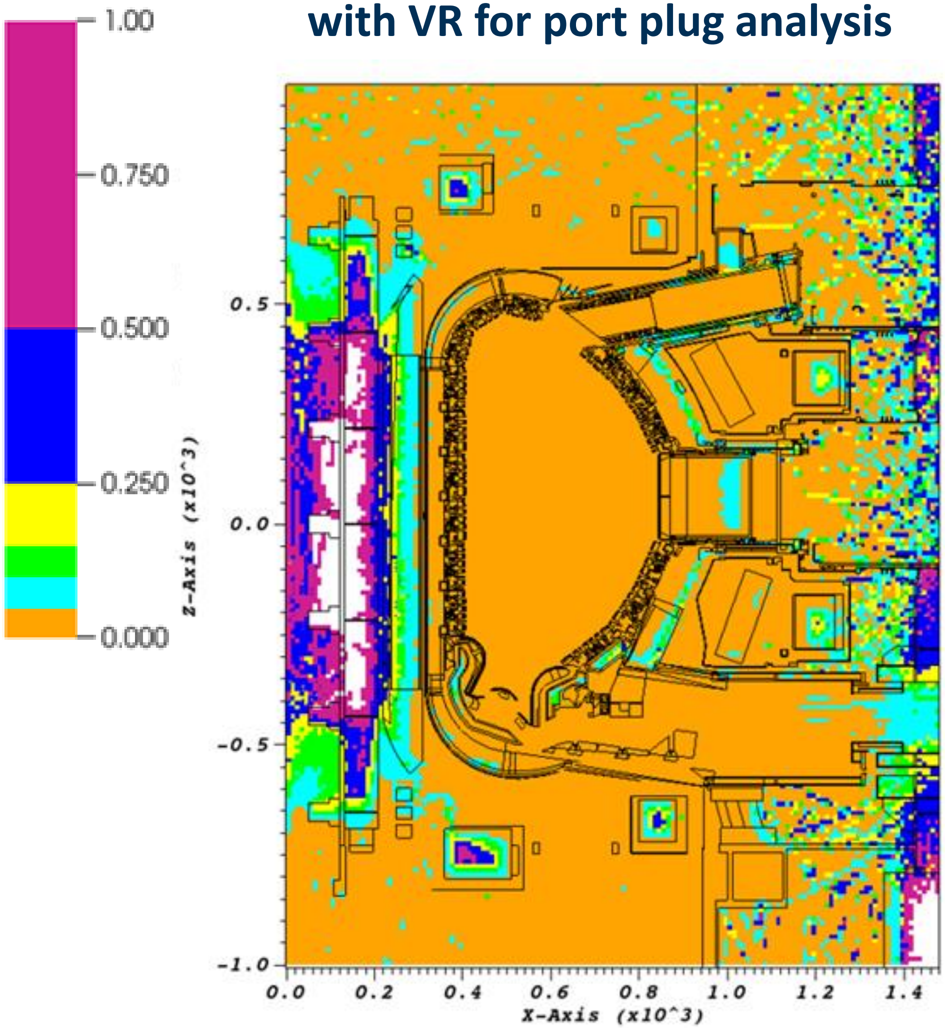
	MCNP6	Serpent 2
Histories run	10^9	10^9
Cores	128	256 (32 MPI x 8 OMP)
Wall time (h)	19.7	31.9
Memory (GB) per MPI task	2.9	37.6 (2.5 'opti1')

FoM = $1/R^2T$ Resulting statistical error achieved (R) Compute time (T)

- The figure of merit (FoM) for the blanket cell tallies in Serpent was found to be typically 3 to 5 times lower than MCNP, thus requiring 3-5 times the computing time to achieve the same level of tally statistical accuracy.

Using variance reduction

MCNP statistical error map with VR for port plug analysis



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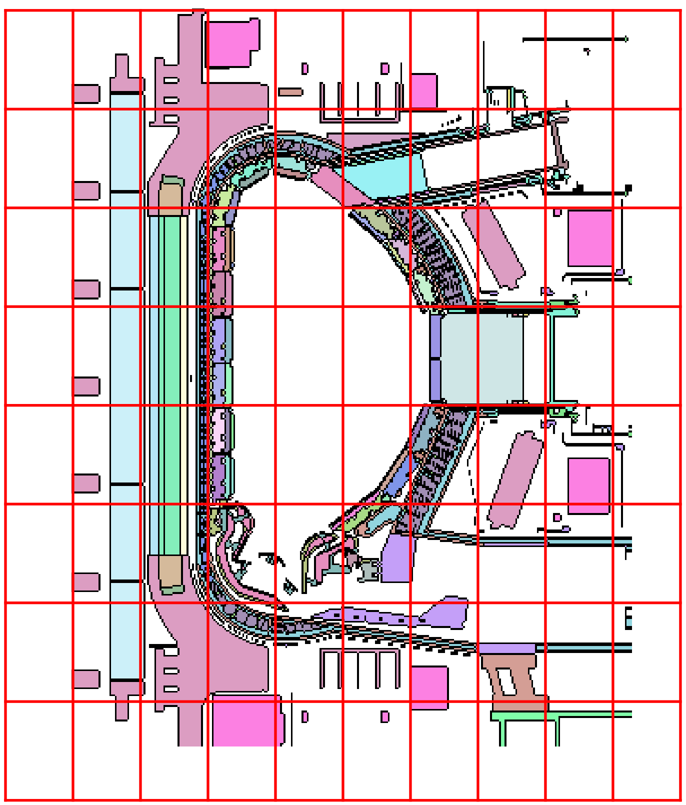
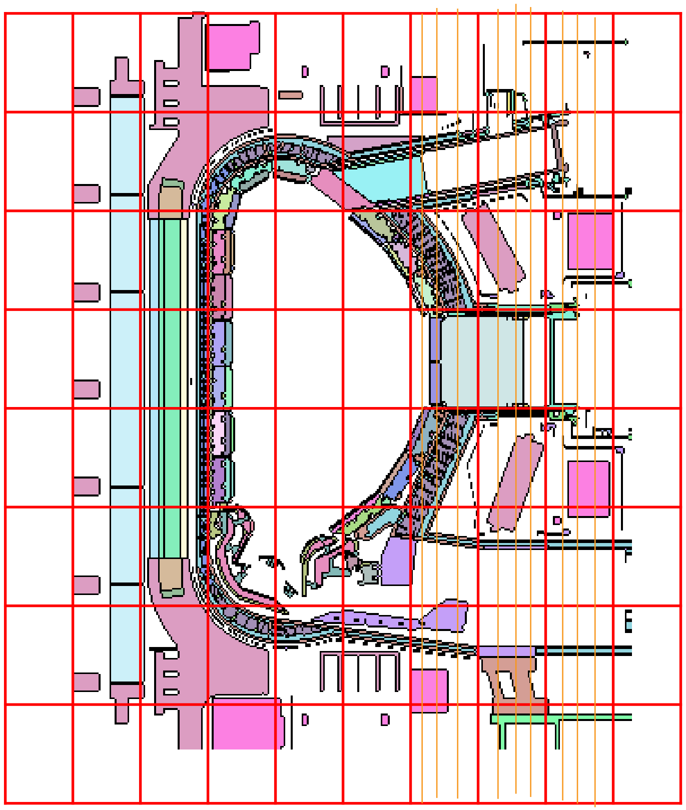
Weight windows – mesh size

In Serpent need to have uniform mesh size.





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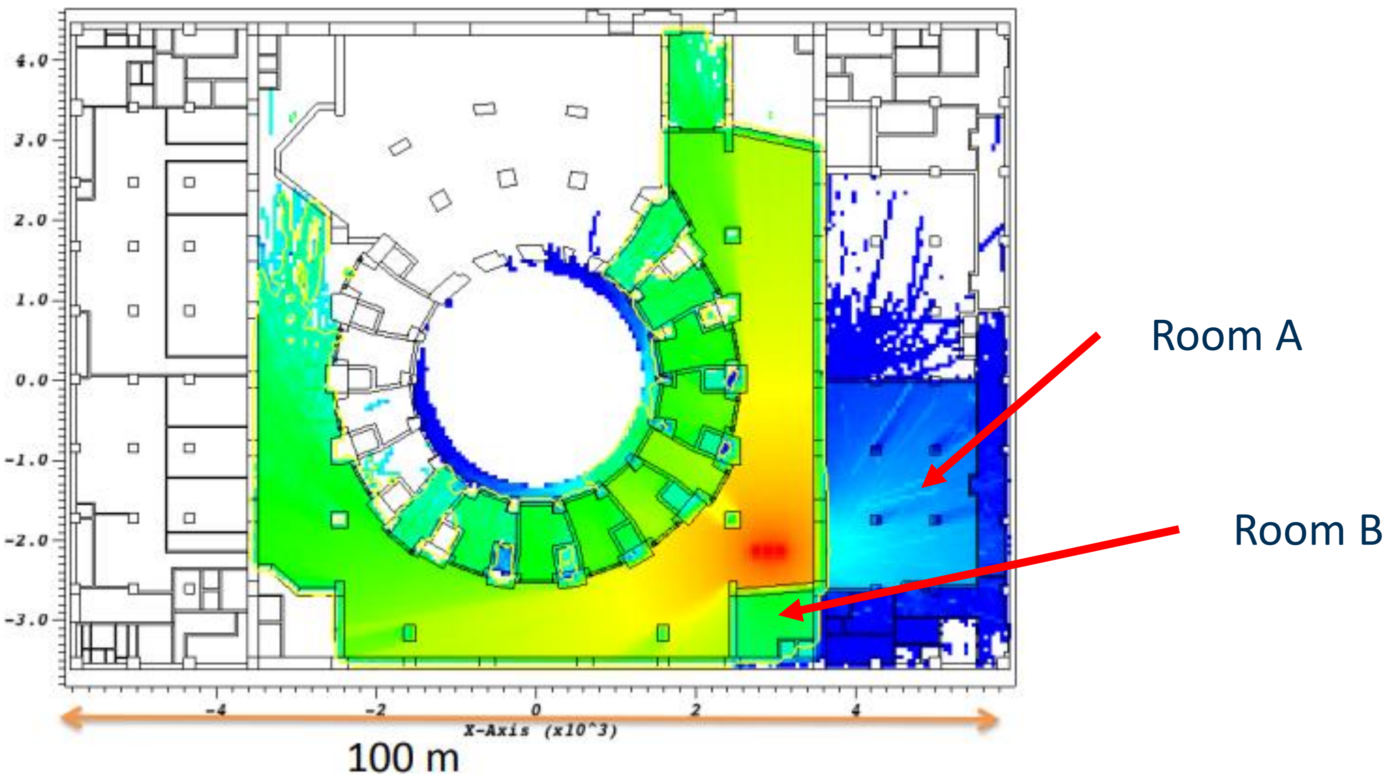
Zero importance regions

In Serpent no importances, one ‘outside’ kill region.



Summary / ongoing / future work

- Initial Serpent (neutron, photon) transport results seem reliable and agree well with MCNP for in-vessel ITER calculations.
- Need to perform more rigorous benchmarking.

- Serpent could offer some advantages over current MCNP workflow.

- Variance reduction (with weight windows).
- Memory usage – noted significant reduction if using opti1.
- Computationally slower – again perhaps some optimisation and trade off with memory usage.
- Tallying: tally segmentation, multicell tallying, cell flagging/ zero importance.

- Developments in Serpent 2 very encouraging for fusion applications, need to consider future licensing conditions for ITER related tasks/ fusion research.

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