Fusion Neutronics

UW Madison

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Outline

- Introduction
- Neutron Transport
- Neutronics Modelling
- Direct Accelerated Geometry
- Many MC Codes
- Use of Deterministic Codes

The University of Wisconsin-Madison

- $\sim$ 42,000 students
- Celebrated its 150th Anniversary in 2011
- Nuclear Engineering Department is ranked #3 among US universities (US News 2013)
- 400 fusion related PhD students graduated during the past 50 years
- UW Energy Research:
  - more than 130 different projects campus wide
  - $50 million anually in energy research ($15M in fusion)
  - 5 major fusion programs supporting 4 fusion experiments

UW Fusion Program

Engineering Physics Department

- Fusion Technology institute (`http://fti.neep.wisc.edu`)
- IEC Experiment (`http://iec.neep.wisc.edu`)
- Pegasus Laboratory (Spherical Torus - `http://pegasus.ep.wisc.edu`)
- Plasma Theory and Computation (`http://www.cptc.wisc.edu`)

Physics Department

- Madison Symmetric Torus Lab (RFP - `http://plasma.physics.wisc.edu`)

Electrical Engineering Department

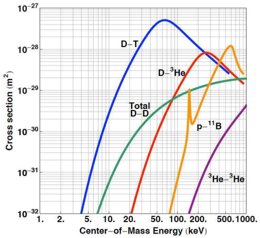
- Helical Symmetric Experiment Laboratory (Modular Stellarator `http://www.hsx.wisc.edu`)

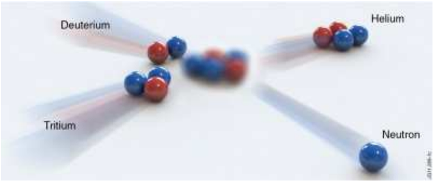
What is neutronics?

The Oxford English Dictionary defines “neutronic” as
Physics. Of or relating to a neutron or neutrons; consisting of neutrons.

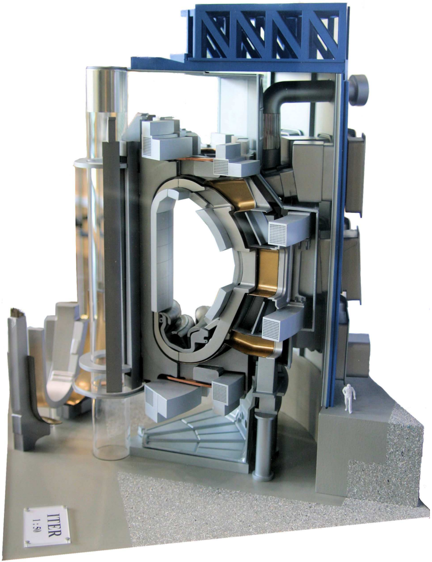
In the sense of this talk, we are most concerned with neutrons produced via the DT fusion reaction

$$D + T \rightarrow^{4} He + n + 17.6MeV$$





- Primarily concerned with the simulation of of neutrons born in the plasma and determination of their flow outwards towards the blankets and vacuum vessel



Fusion Neutronics

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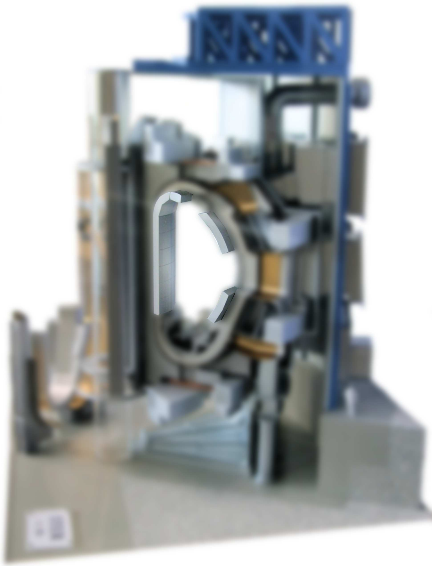
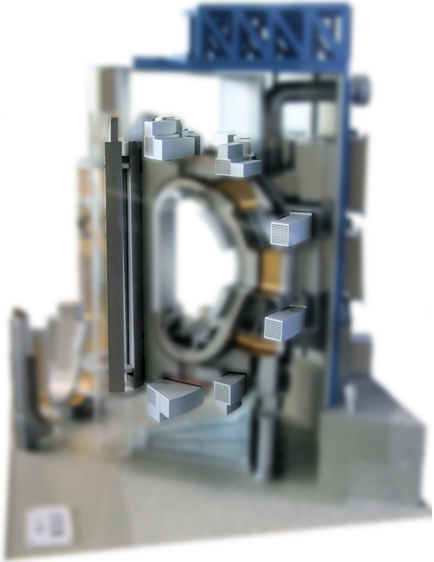
- We must ensure that the system is tritium self sufficient



Fusion Neutronics

- Primarily concerned with the simulation of of neutrons born in the plasma and determination of their flow outwards towards the blankets and vacuum vessel
- We must ensure that the system is tritium self sufficient
- We must ensure that the nuclear heating of the superconducting magnets is sufficiently low



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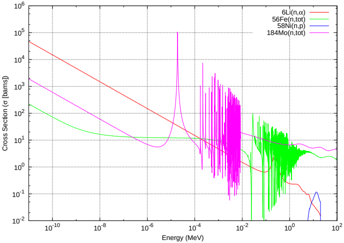

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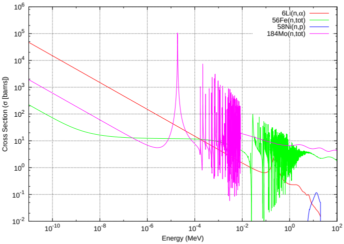
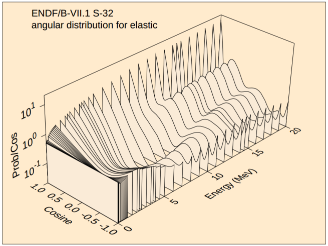
- Neutron physics well understood thanks to the nuclear power industry
- Well defined nuclear data





Neutron Transport

Boltzmann Transport Equation (for neutral particles)

$$\frac{1}{v}\frac{\partial}{\partial t}\phi(\vec{r},E,\vec{\Omega},t)+\vec{\Omega}.\nabla\phi(\vec{r},E,\vec{\Omega},t)+\Sigma_t(\vec{r},E,\vec{\Omega},t)\phi(\vec{r},E,\vec{\Omega},t)$$

$$=\int_{E'}\int_{4\pi}\Sigma_a(\vec{r},E'\rightarrow E,\vec{\Omega}'\rightarrow\vec{\Omega},t)\phi(\vec{r},E',\vec{\Omega}',t)d\Omega'dE'+S(\vec{r},E,\vec{\Omega},t)$$

Need to solve transport equation to determine the results we're interested in

Monte Carlo

- Slow
- Good representation of physics
- High fidelity geometry representation

Deterministic

- Fast
- Limited representation of physics
- Lower fidelity geometry

The Monte Carlo method

The Monte Carlo methods simulates individual particles histories, attempting to exactly replicate the physics of neutron slowing down and capture within the geometry of interest.

- High geometry resolution
- Computationally slow
- Good representation of physics

Due to the high geometry resolution that MC allows it is the preffered method for performing calculations, well validated by the fission industry.

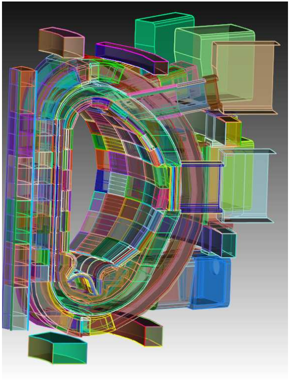


Figure : Simple CAD model of the ITER "Benchmark" geometry

The Monte Carlo method

Follow individual particle histories within problem through their "life" until they are absorbed or leave the system. Several codes available to perform this task the best known is MCNP from Los Alamos National Laboratories (LANL). Probability of absorbtion is determined by nuclear data, i.e. cross sections.

1. Particle born (with Energy and direction) according to defined distribution
2. Particle tracked to nearest boundary or event location
3. If interaction occurs change direction or get absorbed, if it doesn't get absorbed then...
4. Repeat until particle leaks or gets absorbed

- Computationally fast
- Problems with solution artefacts at low expansion orders

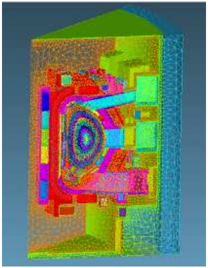


Figure : Atilla^{TM}mesh of simplified ITER model

- Poor Geometry resolution (historically)
- Low energy resolution

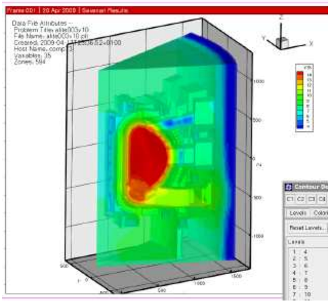


Figure : Atilla^{TM}results of simplified ITER model

So what are the problems in neutronics modelling?

- **The direct (or near direct) use of CAD in modelling**
- The use of as many MC codes as possible
- **The use of overlapping BTE solution techniques**
- Coupling of Radiation Transport codes to FE codes for Heat Transfer/Structural analysis
- Calculation of shutdown gamma ray dose rate

Direct use of CAD Geometry

There are two methods for direct (or near direct) use of CAD

- Translation
- Direct

Translation involves taking the CAD definition and translating that defnition into a number of Constructive Solid Geometry (CSG) primatives, e.g. spheres, cones, torii. This is the approach taken by McCAD and MCAM.

Direct use involes taking the actual CAD geometry and either taking the representation as is and tracking upon that (OiNK and DAG), or taking the surfaces defined in the geometry and faceting them DAG.

DAG - Direct Accelerated Geometry

The approach favored at UW is the Direct Accelerated Geometry (DAG) approach, the complex CAD model goes effectively unmodified and instead we use a faceted representation of the surfaces.

Direct Accelerated Geometry

DAGMC software library based on open source geometry & mesh libraries

- CGM: Common Geometry Module Core of CUBIT application (SNL) Based on various solid modeling engines
- ACIS, CATIA/CAA, Solidworks, (OpenCascade)
- MOAB: Part of ITAPS SciDAC effort Extensible & efficient mesh/facet representation

DAG Enabled Codes

- MCNP5
- FLUKA
- Tripoli4
- Geant4
- Shift

Codes awaiting DAG

- Serpent/Serpent2
- OpenMC
- Mercury
- MCNP6

- Only need to represent the bounding surfaces of the volume
- loop over the surfaces that belong to the volume and generate facets

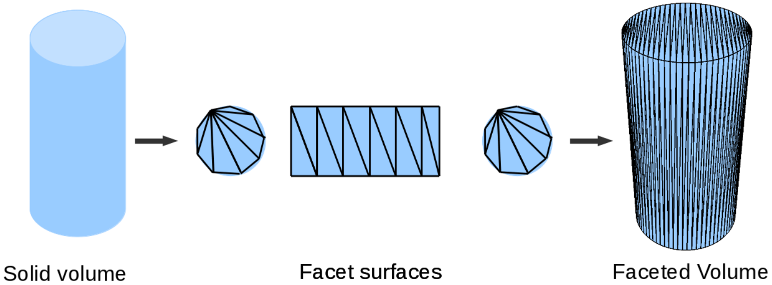


Figure : Example of faceting

DAG Example

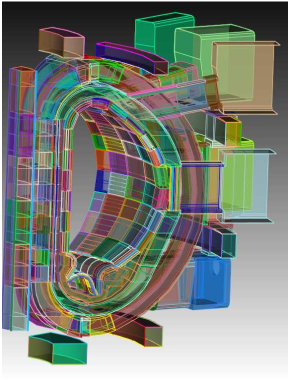


Figure : Simple CAD model of the ITER “Benchmark” geometry

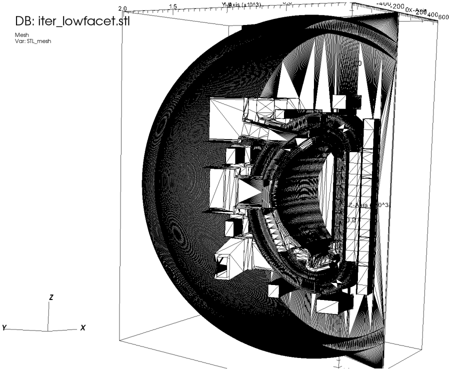


Figure : Faceted (1×10^{-2}) representation of the ITER “Benchmark” geometry

DAG Calculation Examples

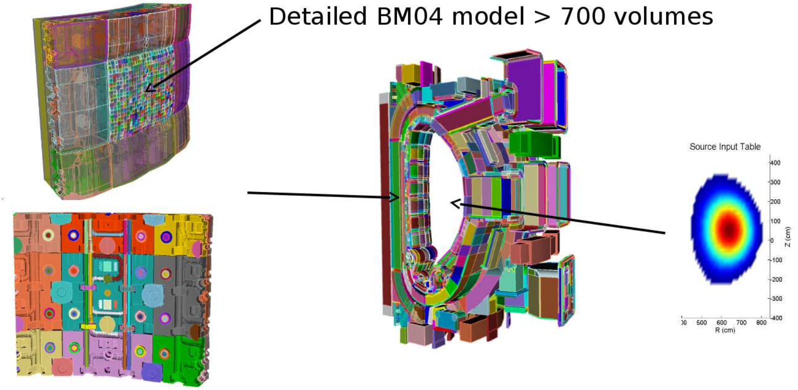


Figure : ITER geometry including detailed blanket module description

DAG Calculation Examples

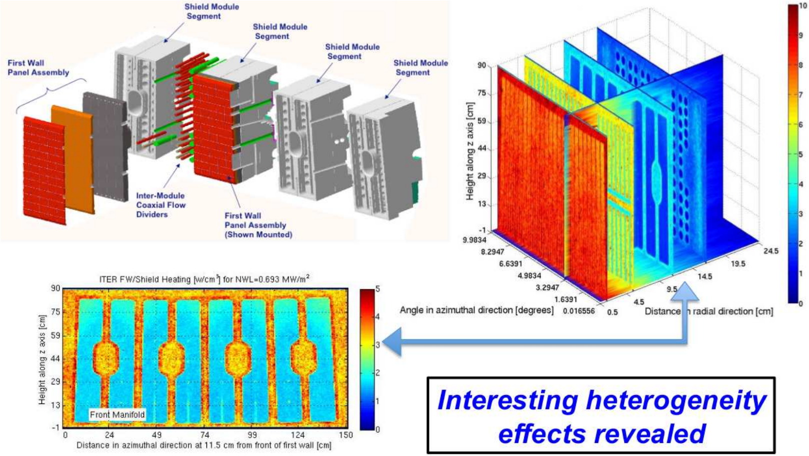


Figure : ITER Blanket module study

Neutronics Modelling

- The direct (or near direct) use of CAD in modelling
- The use of as many MC codes as possible
- **The use of overlapping BTE solution techniques**
- Coupling of Radiation Transport codes to FE codes for Heat Transfer/Structural analysis
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Deterministic and Hybrid Methods

Determinisitic codes have shortfalls when is comes to use in fusion devices

- Limited geometry resolution (typically modelled as 3d cartesian mesh with the exception of Atilla)
- Replication of energy domain at each mesh point
- Limited angular resolution
- Computational artifacts

However Deterministic Codes like Denovo (ORNL), PartisN (LANL) can be used to generate importance or weight window maps used to help the monte carlo code calculation.

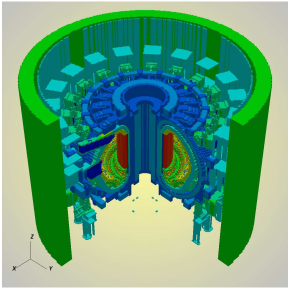


Figure : Denovo model of the ITER geometry (ORNL)

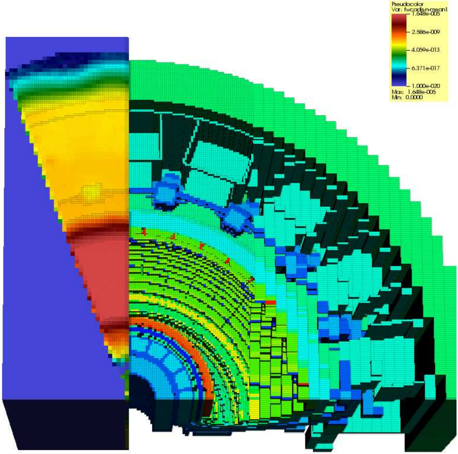
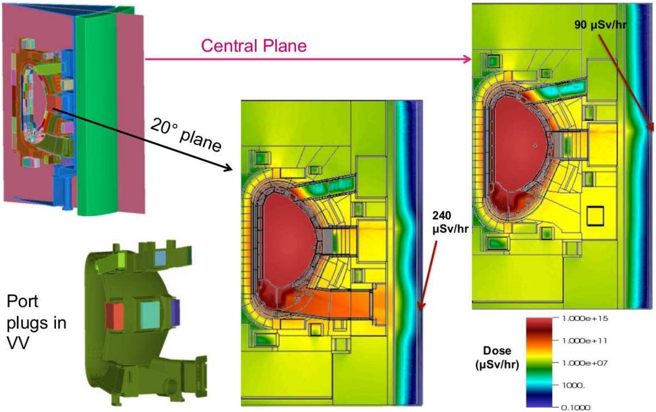


Figure : Flux from the ITER geometry (ORNL)

Use of S_N/P_N codes as input to MC codes

Using the solution shown previously we can generate importance/weight maps to speed up the MC calculation.



Conclusions

- Engineers only ever want more detail in their geometry, highlighting the importance of DAG
- Coupling of deterministic codes with MC codes will be more important in the future
  - As problems become more challenging need to leverage the benefits of both methods
  - Advances in computing mean that both methods speed up over time
- DAG facilitates the testing of MC codes since they can use the same underlying geometry
  - Will allow standardised scoring schemes
  - DAG behaves like a standard interface to MC codes