Business from technology

Generating of fusion plasma neutron source with AFSI for Serpent MC neutronics computing

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Outline

Introduction to magnetically confined fusion

Neutron production in a plasma

- Reactions
- General features in the modelling of neutron source in toroidal geometry

Tools

- Codes & code systems

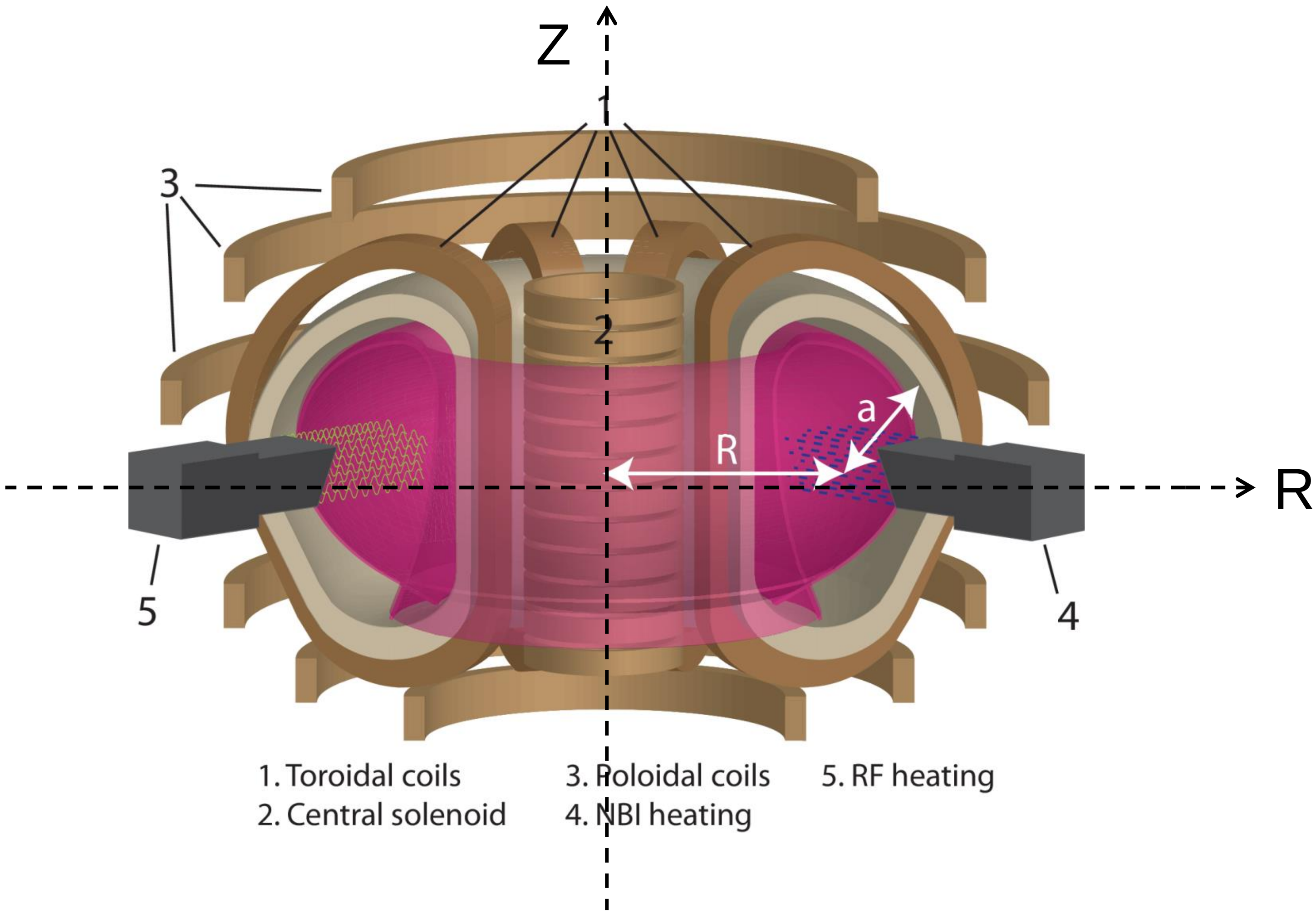
Serpent neutron source

- Data structure
- Example cases

Conclusions, further studies & open questions

- Remarks
- Questions?

Tokamak concept & geometry



Computational fusion neutron source - generally

Neutron production rate per reaction

$D + D \rightarrow {}^{3}He + n + 3.27 MeV$

$D + T \rightarrow {}^{4}He + n + 17.60 MeV$

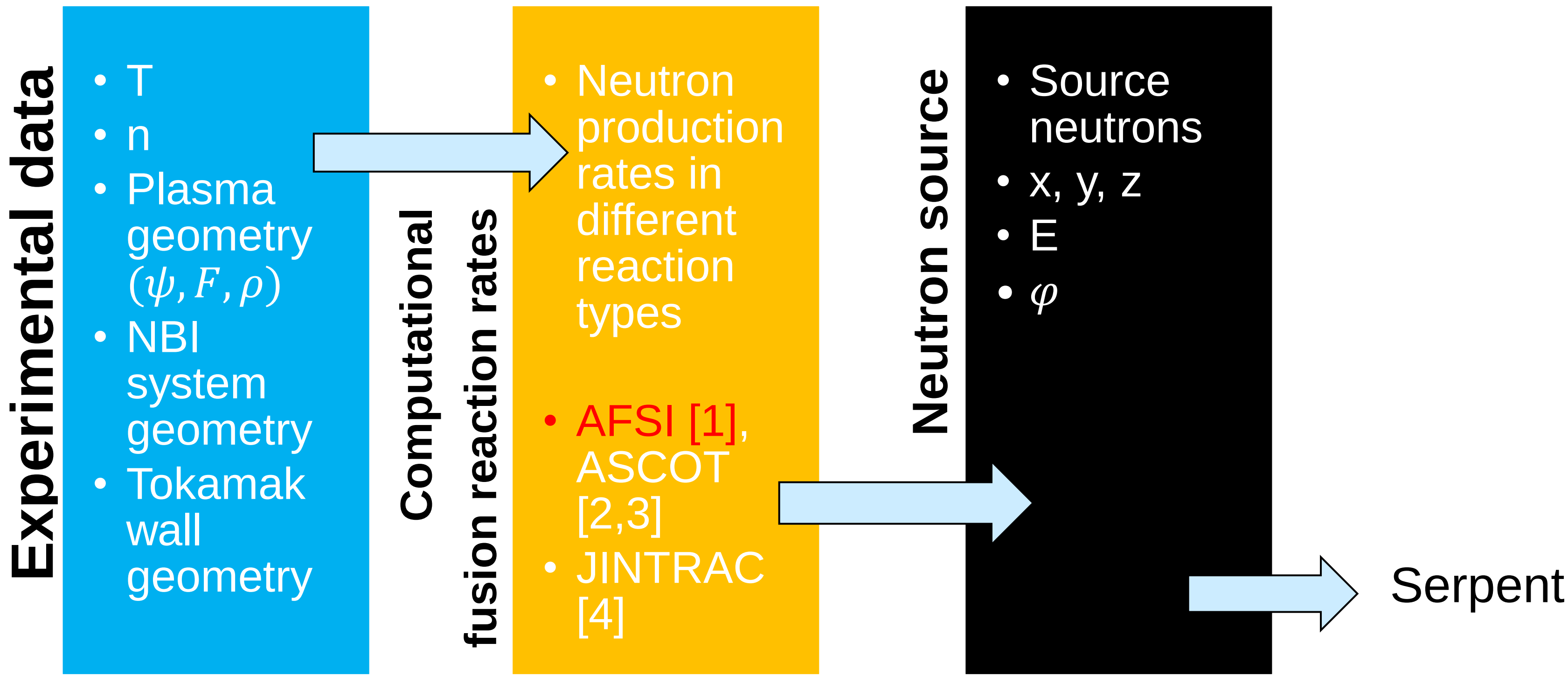
Different reaction types

- Thermal DD
- Thermal DT (main plasma, ~1-10 keV)
- Fast DD (RF heated and NBI particles ~100 keV-1 MeV)
- Fast DT
- Thermal-Fast DD
- Thermal-Fast DT
- Fast-Thermal DT

Neutron is defined:

- Location
- Energy
- Direction

Connection between plasma physics and neutronics



[1] S. Äkäslompolo, O. Asunta, P. Sirén: AFSI Fusion Source Integrator for tokamak fusion reactivity calculations. Under preparation.
[2] J. A. Heikkinen et al. 2001 J. Comput. Phys. 173 527-548.
[3] E.Hirvijoki et al. 2014 Computer Physics Communications 185 1310–1321
[4] S. Wiesen et al. 2008. JET-ITC Report

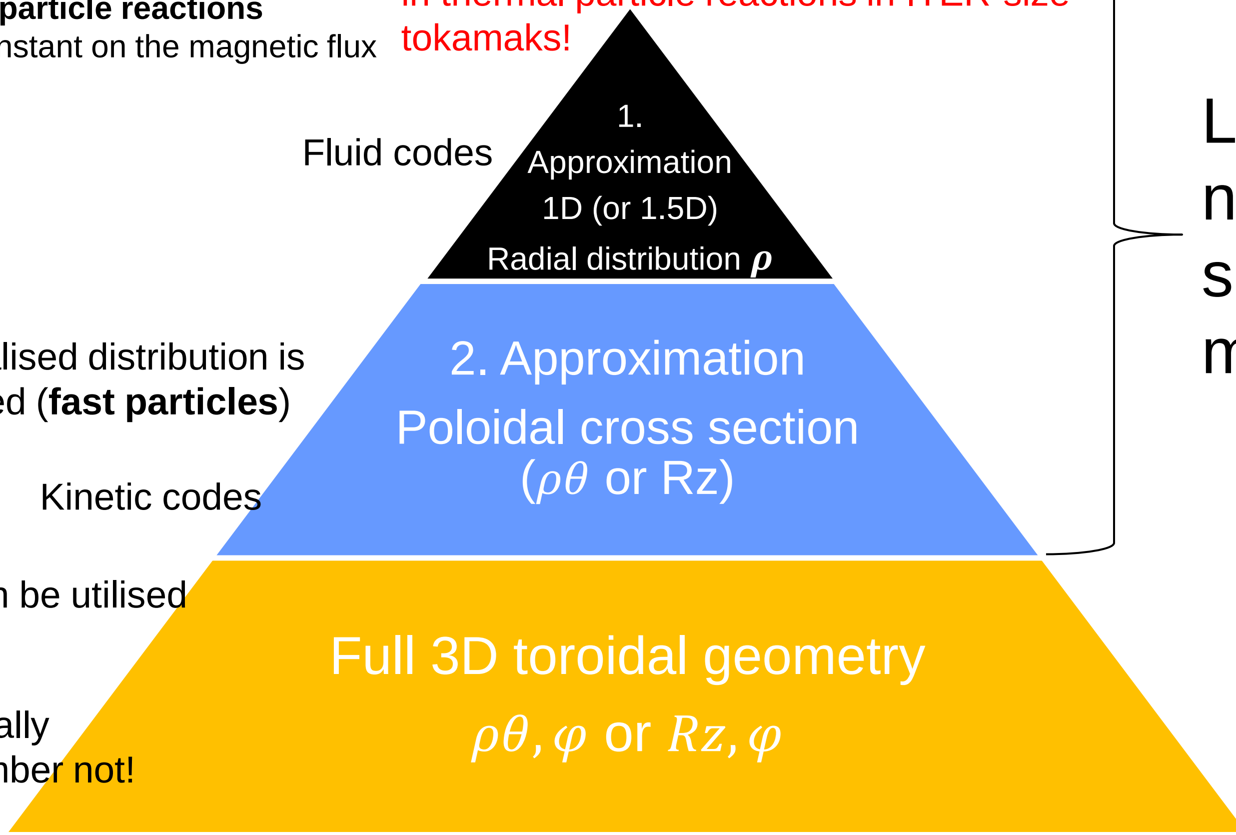
Modelling in tokamak geometry

Major part of neutrons will be produced in thermal particle reactions in ITER-size tokamaks!

Thermal particle reactions
T, n, p constant on the magnetic flux surfaces

Averaging over flux surfaces if needed by different coupled codes

Fluid codes



If localised distribution is needed (**fast particles**)

Kinetic codes

Usually symmetry can be utilised

Plasma is toroidally symmetric, chamber not!

Level of neutron source model

Generating of the neutron source - tools

ASCOT (**A**ccelerated **S**imulation of **C**harged particle **O**rbits in **T**ori)

J. A. Heikkinen et al. 2001 J. Comput. Phys. 173 527-548.
E. Hirvijoki et al. 2014 Computer Physics Communications 185 1310–1321

Fast (minority) particle orbit-following MC code
Developed 1990- at VTT and Aalto University
Powerful and widely used in the analysis (fusion alphas, beam particles) of several fusion devices
Coupled to JINTRAC [1] and ETS [2] code package

Generating a test particle ensemble → Orbit following of test particle by using MC collision operator → Solving Fokker-Planck equation (distribution function) with test particle ensemble

$$\frac{\partial f}{\partial t} = \dot{\boldsymbol{x}} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \dot{\boldsymbol{v}} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

→ $f(v, x)$, $\boldsymbol{v}(x)$

[1] S. Wiesen et al. 2008. JET-ITC Report.
[2] D. P. Coster et al. 2010. E IEEE Transactions on plasma science 38 9.

AFSI-ASCOT connection
– computing of neutron production rates

ASCOT4

Input:
T, n,
geometry/equilibrium

Output:
Fast particle distributions f_B, v_B,
(beam current density, power depositions…)

AFSI Fusion Source Integrator for tokamak fusion reactivity calculations

Input:
T, n, geometry/equilibrium, fast particle distributions f_B, v_B

Output:
Neutron (or alpha particle) production rates

R_{ij} in different reaction types

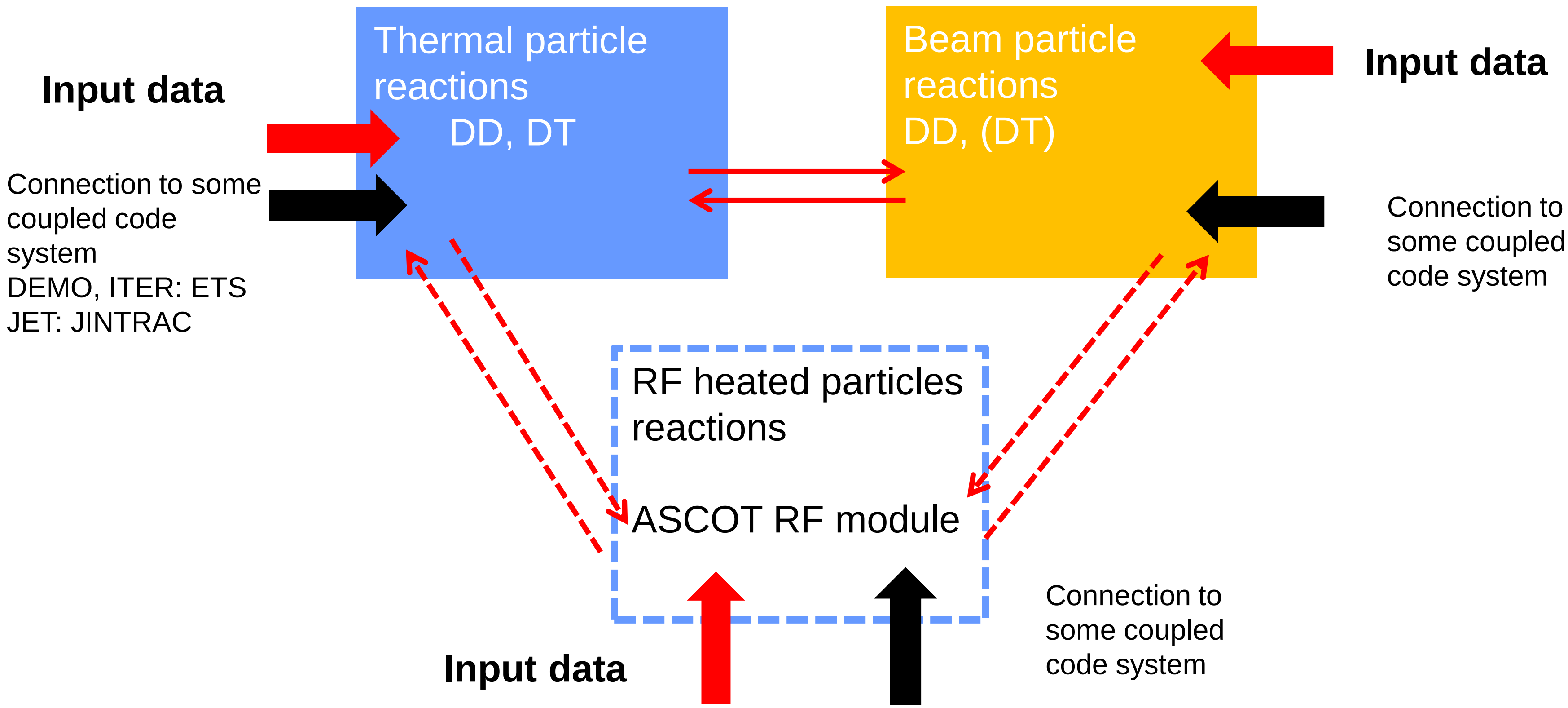
E_n

Example: Fast-thermal (beam-thermal) particle reaction

$$R_{BT} = \iiint_{v_T} \iiint_{v_B} f_T(v_T)(|v_B - v_T|) f_B(v_B)(|v_B - v_T|)\, dv_T\, dv_B$$

AFSI - Further development steps

Neutron production rate and energy distribution in 2D for different reaction types



Neutron source - geometrical distribution 1/2

2D distribution (poloidal cross section)

***ρθ* grid**

Radial position (normalised radial coordinate) *ρ*
Poloidal angle *θ*

Simple to scale geometrical features (R, a, ellipticity, triangularity, inverse aspect ratio…) of source plasma

- Sensitivity tests
- ITER/DEMO prospects
- Fluid code input (ρ) -> 1D approximation

***Rz* grid**

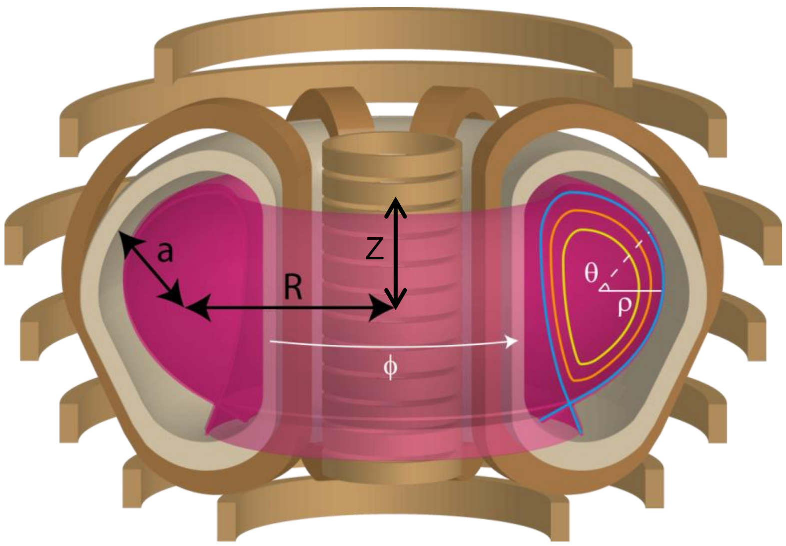
Position in Rz matrix

Better accuracy of local distribution (**fast particle reactions** & energy distribution!)

Both of these will be implemented to the neutron source model!

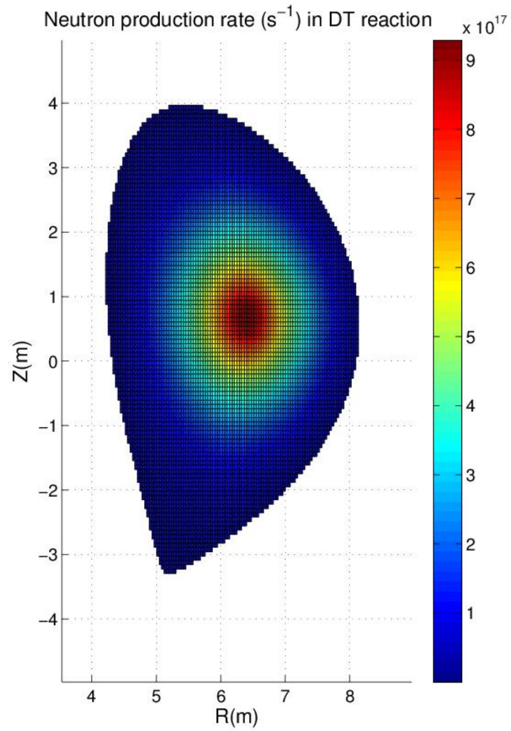
Geometrical distribution 2/2

3D distribution



- Radial position (normalised radial coordinate) ρ
- Poloidal angle θ
- Toroidal angle φ

or R, z (applies to ρ and θ)



Example case: Neutron production in thermal DT reactions in ITER baseline Q=10 plasma with D/T mix (50%/50%) computed by AFSI

Neutron source practically: Defining of probability distributions

Example cases:

JET (DT 70/30) #42976 t = 12.3 s (thermal particle reactions)

ITER (DT 50/50) baseline Q=10 (thermal particle reactions)

JET:

1. Probability of reaction **DD: 20.44%, DT: 79.56%**
2. Probability of radial position
   $$P_{DD}(\rho) = \frac{n\,production\,rate\,in\,DD\,at\,\rho}{total\,n\,production\,rate\,in\,DD}$$
   $$P_{DT}(\rho) = \cdots$$
3. Probability of location in the poloidal flux surfaces **isotropic**
4. Probability of toroidal angle **isotropic**
5. Probability of energy **discrete DD: 2.45 MeV, DT: 14.08 MeV**

ITER:

1. Probability of reaction **DD: 0.3%, DT: 99.7%**
2. Probability in Rz grid
   $$P_{DD}(Rz_i) = \frac{n\,production\,rate\,in\,DD}{total\,n\,production\,rate\,in\,DD}$$
   $$P_{DT}(Rz_i) = \cdots$$
3. Probability of toroidal angle **isotropic**
4. Probability of energy **discrete DD: 2.45 MeV, DT: 14.08 MeV**

Serpent neutron source data structure

General data

- Magnetic axis
- Plasma boundary coordinates
- Coordinate system
- Number of reactions
- Number of time points
- Link to reaction data

Reaction (1) data

Reaction (2) data

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Reaction (n) data

- Probability per reaction
- Time
- Energy (size of grid, values, probability distribution)
- Link to geometrical data

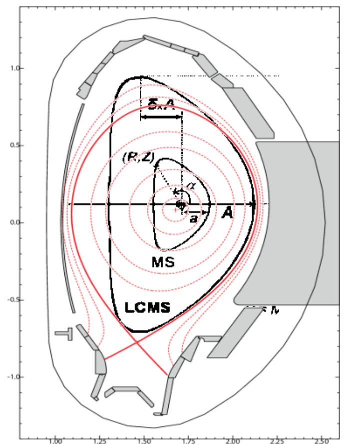
Geometrical data

Geometrical distribution (size of grid, grid, probability distribution)
$\rho\theta\varphi$ grid or
$Rz\varphi$ grid

Plasma related effects in modelling which could affect neutronics results

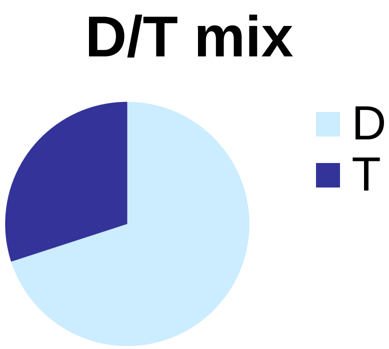
Plasma geometry

(D-shape model vs. Grad-Shafranov solver)



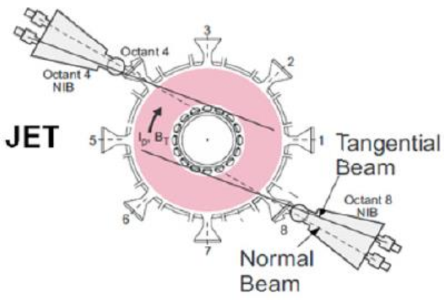
Mix of fuel

(Ratio of 2.45 MeV and 14.08 MeV neutrons)



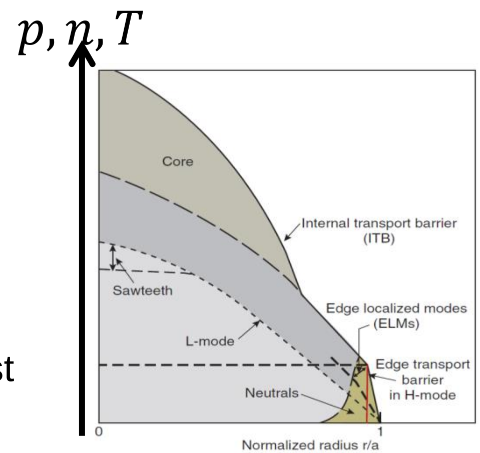
Heating (NBI) system

(beam alignment, power -> Fast particle distributions)



Temperature, density profiles

(total neutron production, production peaked to the centre, interaction with fast particles…)



Time-dependent neutron source

Example case: time-independent neutron source
Data profiles (n, T) from one time point are used
Good approximation in flat-top phase for baseline plasmas

In time-dependent simulations, probabality distributions should be updated

Source is strongly peaked near the magnetic axis in advanced tokamak plasmas

effect on the neutron energy distribution and the total amount of produced neutrons

Routines to use time-dependent source are available in Serpent (if data is available)!

Conclusions, challenges & Open questions

Current status of neutron source:

ITER 15 MA NBI-heated DT plasma

Distribution of neutrons produced by thermal particle reactions is defined based on AFSI - ASCOT simulations

Realistic fast particle reaction distributions will be inplemented to AFSI in the next phase

JET DT record shots #42976, #42974

Neutron source calculated by JINTRAC-ASCOT(AFSI) simulations

Neutrons from thermal and beam particle reactions included

Collaboration in the developing of neutron source model is very limited. (Collaboration with CCFE neutronics is existing but not in plasma physics-neutronics coupling).

Model validation

Serpent calculations with fusion plasma neutron source will be validated with the data from existing device (Work under JET DT campaingn?).

What is the real role of the modelling of plasma physics and neutron source in the complete analysis of neutronics? How important is it practically (heat deposition, material damage, activation etc)?