Business from technology

Generating of the fusion plasma neutron source

Workshop in Fusion Neutronics, Cambrigde 2015

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Motivation – Why fusion neutronics?

Neutrons in fusion power plant

80% of extracted heat

Activation

Material and equipment damage

Safety aspects
Biological shielding

Need for extensive studies!

Connection between plasma physics and neutronics

Experimental data

- T
- n
- Plasma geometry (ψ, F, ρ)
- NBI system geometry
- Tokamak wall geometry

Computational fusion reaction rates

- Neutron production rates in different reaction types
- AFSI [1], ASCOT [2,3]
- JETTO [4]

Neutron source

- Source neutrons
- x, y, z
- E
- φ

Serpent [5]

[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] G. Genacchi, A. Taroni. Rapporto ENEA RT/TIB/88/5
[5] J. Leppänen et al. The Serpent Monte Carlo code: Status, development and applications in 2013, Annals of Nuclear, 2014, available online 8.9.2014

Computational fusion neutron source - generally

Neutron production rate per reaction

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

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

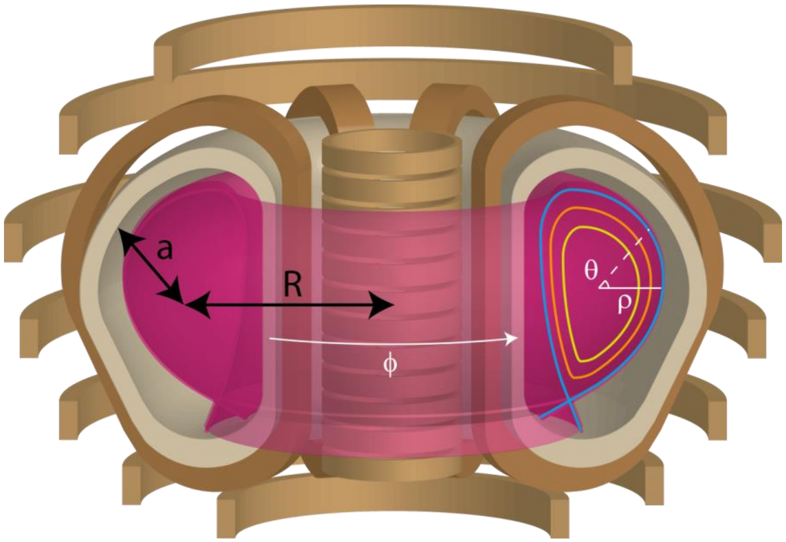
Different reaction types

- 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

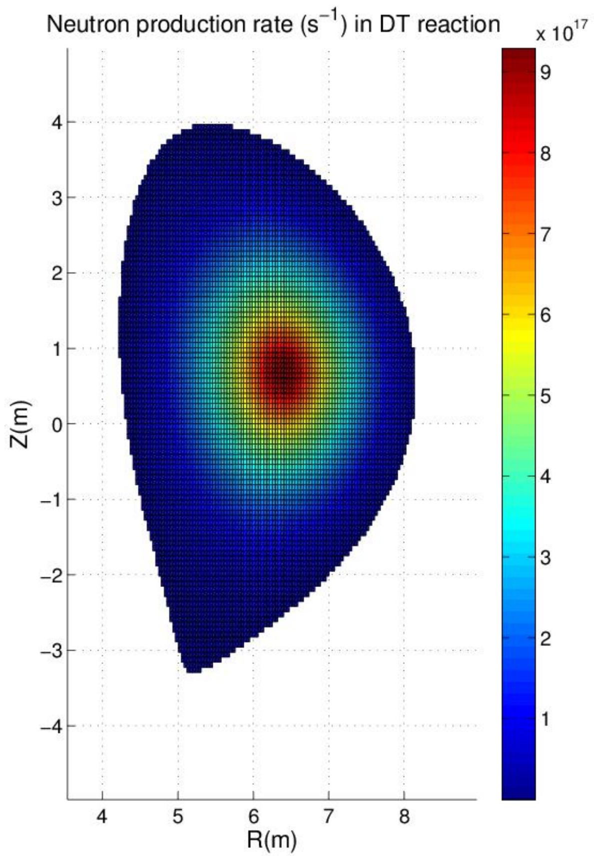
Neutron is defined:

- Location
- Energy
- Direction

Geometrical (3D) distribution



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



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

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 in the magnetic flux surfaces

Averaging over flux surfaces if needed by different coupled codes

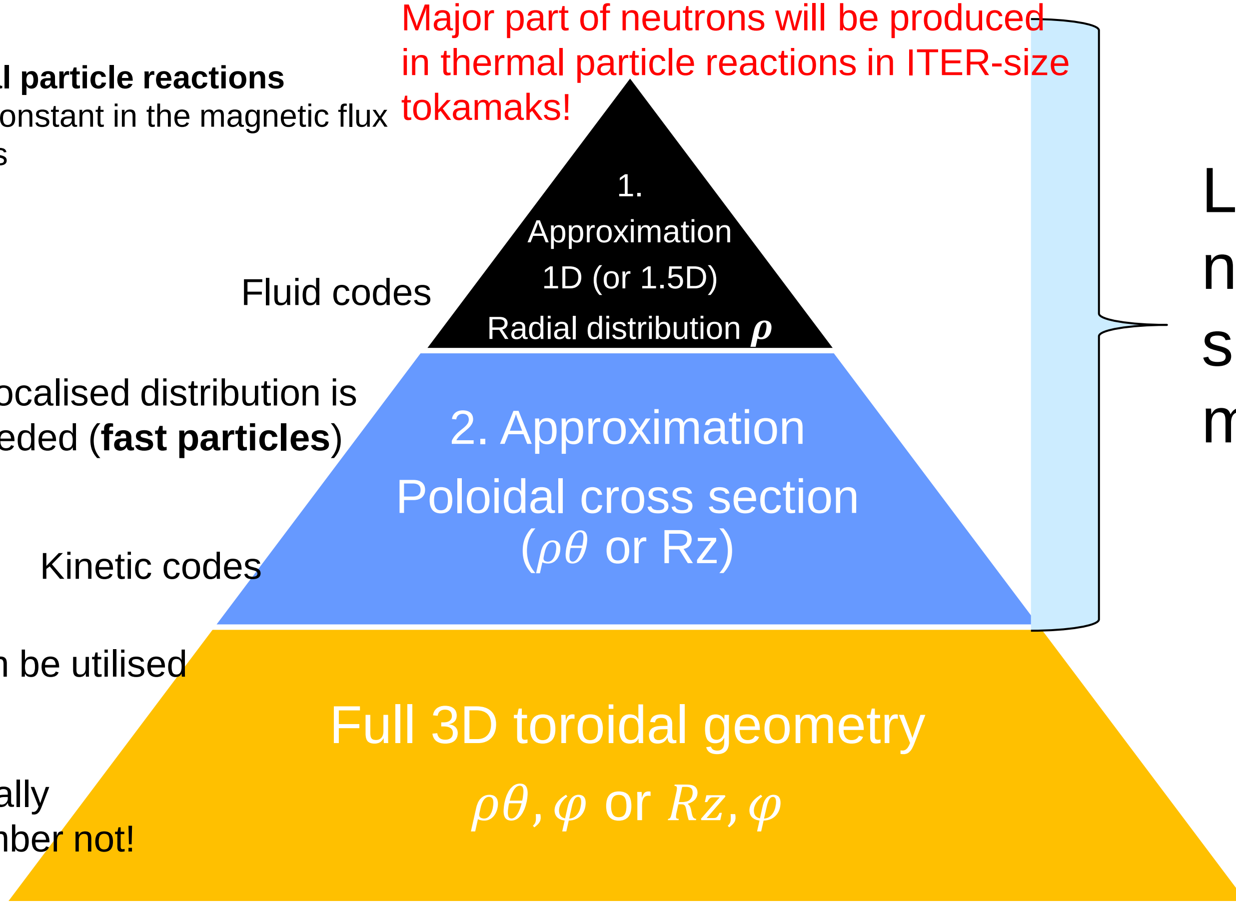
Fluid codes

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

Geometrical distribution

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!

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- in 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*), ***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_T

Output:
Neutron (or alpha particle) production rates

R_{ij} in different reaction types

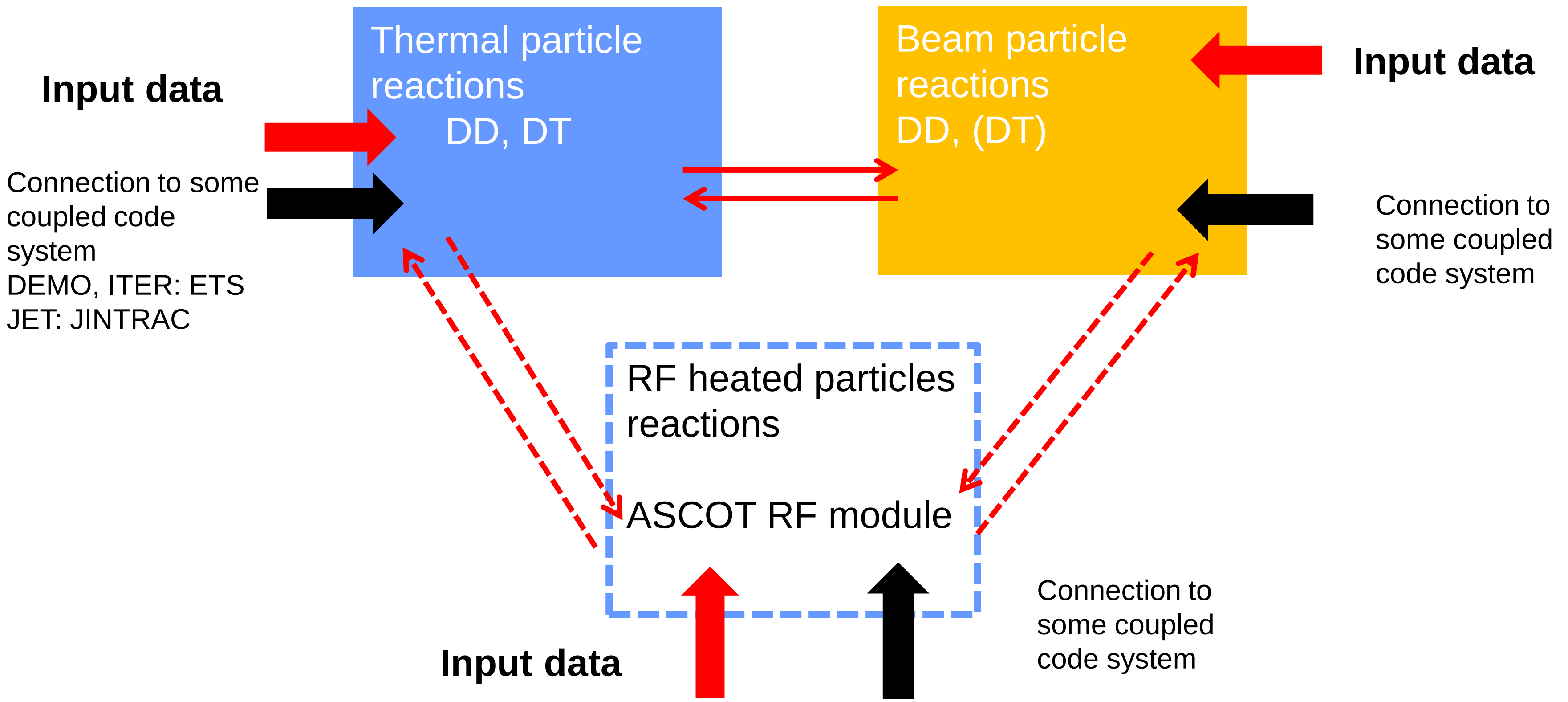
E_n

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 practically: Defining of probability distributions

Example cases:

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

ITER (DT) 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, RZ**
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**

Conclusions: Current status of neutron source

ITER 15 MA NBI-heated DT plasma

- Distribution of neutrons produced by thermal (and fast (NBI) particle reactions will be soon added) is defined based on AFSI - ASCOT simulations

- Energy distribution includes two discrete values (DD,DT)
  Realistic distribution will be inplemented to AFSI in the next phase

- ITER plasma neutron source works succesfully with realistic CAD model in Serpent calculation → ITER-relevant neutronics modelling can begin

Future plans

- RF heated plasmas will be included in the analysis (with ASCOT RF module)

Challenges & Open questions

Collaboration in the developing of neutron source model is very limited.

Model validation
Serpent calculations with fusion plasma neutron source will be validated with the data from existing device (JET?).

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)?

In DEMO case, input data is very limited available. Need for integrated modelling with plasma physics?