UK Atomic Energy Authority

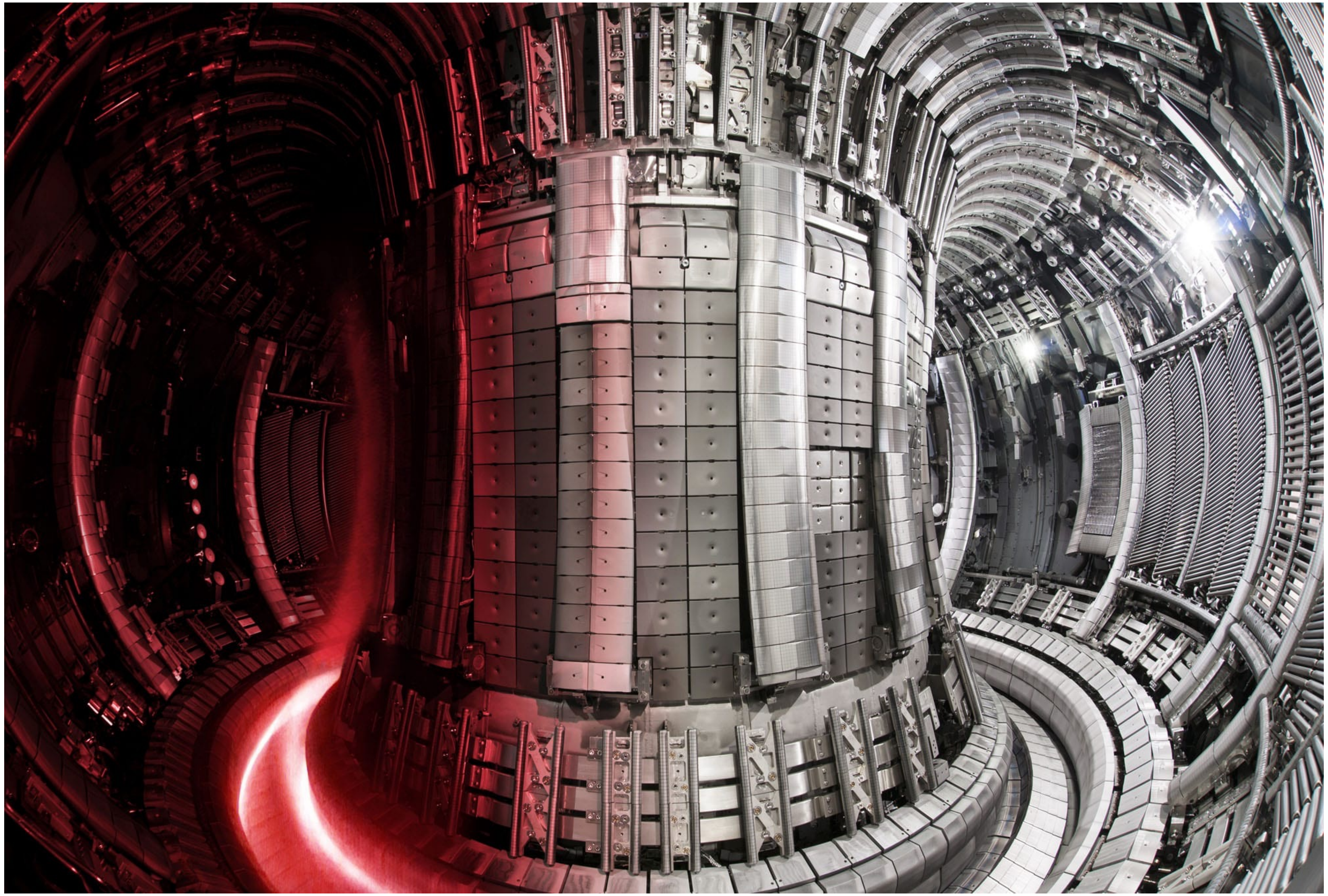
Overview of nuclear fusion

N_TOF winter school 2024

Dr David Foster

Acknowledgments:

- Mark Gilbert
- Lee Packer
- James Hauges
- Greg Bailey
- Jean-Christophe Sublet
- Jessica Hollis
- Trinity Wheeler



Eurofusion

Useful reading

- J. Lilley, ‘Nuclear physics: principles and applications’ (Wiley)
- Chen, ‘Introduction to Plasma Physics and Controlled Fusion’ (Springer)
- G. McCracken, P. Stot,t ‘Fusion – the energy of the universe’ (Elsevier)
- A. Harms, K.F. Schoepf, ‘Principles of fusion energy’ (World Scientific)
- J. Wesson, ‘Tokamaks’ (Oxford Science)
- S. Glasstone and R Lovberg, ‘Controlled thermonuclear reactions’, (Van Nortrand, New York 1960)
- Boyd and Sanderson, ‘The Physics of Plasmas’ (Cambridge 2003)
- Goldstone and Rutherford, ‘Introduction to Plasma Physics’ (IOP 1995)
- K.S. Krane, ‘Introductory Nuclear Physics'

Useful websites:

https://ccfe.ukaea.uk

https://www.euro-fusion.org

https://www.pppl.gov

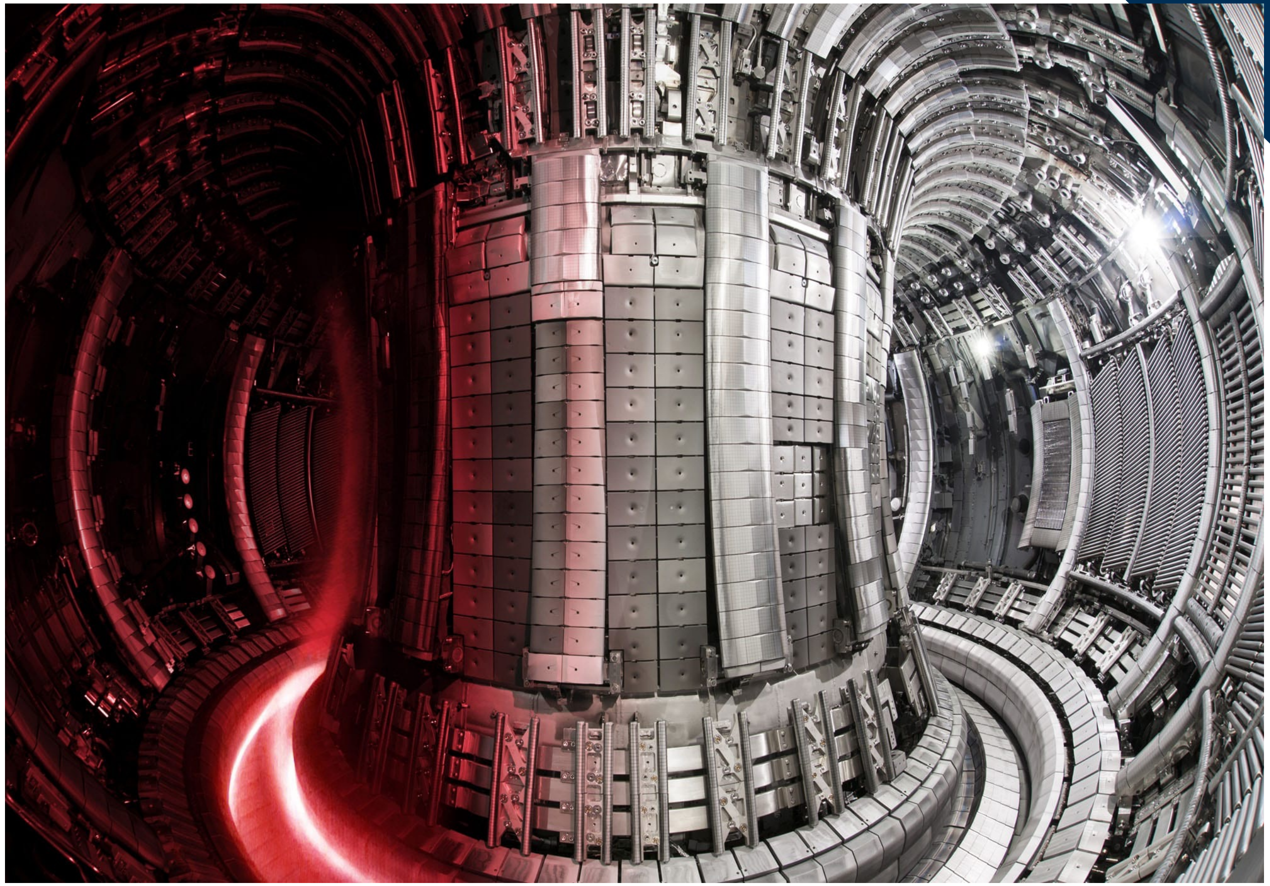
http://www.iter.org

http://fusionforenergy.europa.eu

L Packer

Overview:

- Introduction to nuclear fusion
  - DT reaction and energetic distribution
- Fusion ignition and some devise types
  - Inertial confinement and Magnetic (UKAEA approach)
- Tritium fuel production
- Neutron activation
  - Inventory solutions – my area
- FISPACT-II introduction
- Fusion activation benchmark (FNS)



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Why nuclear fusion

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1. **Clean (at the point of generation)**: helium is the by product of nuclear fusion

2. **'Safe'**: fusion does not rely on a chain reaction and therefore could be stopped rapidly

3. **Fuel abundance**: the fuels are abundant on earth. Deuterium can be found in sea water and tritium can be produced.

4. **Baseload power generation**: does not depend directly on environmental variables

5. **Fuel efficiency**: fusion produces a lot of energy per gram (c^2 is large!)

6. **Shorter lived waste**: fusion power plants are not expected to produce the very long lived, high level radioactive waste associated with nuclear fission

Nuclear fusion:

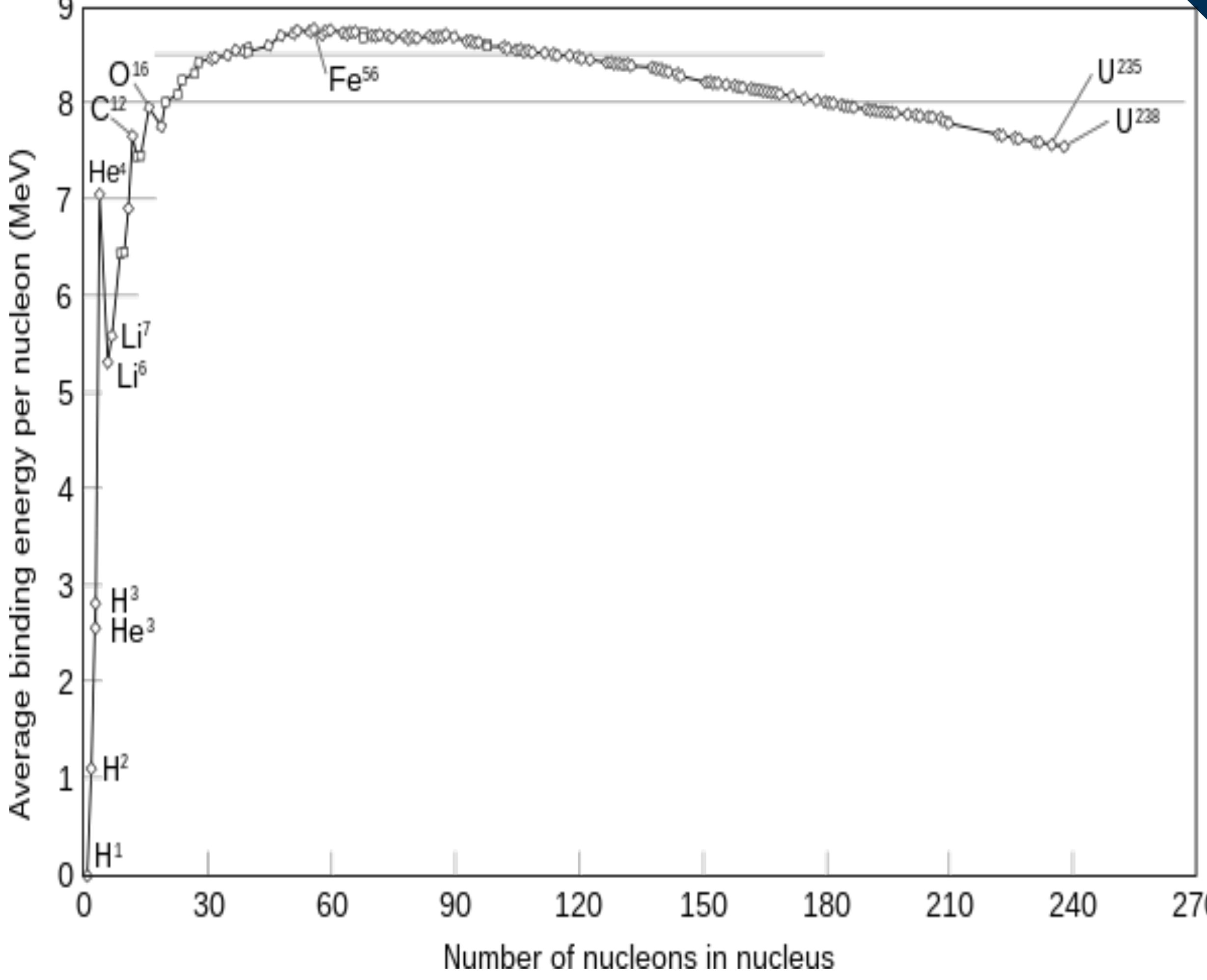
Two nuclei react/merge together to form a single heavier nucleus:

- Reaction releases energy because the sum of masses of the two initial nuclei is greater than the mass of the final nucleus:

$$m_I = \sum_{i=1}^{n} m_i, \quad m_F = \sum_{j=1}^{p} m_j$$

$$\Delta E = (m_I - m_F)c^2$$

energy is distributed between the reaction products.



Wikipedia

Nuclear fusion:

- Many types of nuclear fusion
  -some aneutronic examples

$$\cdot\ {}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{P}(12.9\mathrm{MeV})$$

- low abundance of Helium-3

$$\cdot\ \mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He}(3.67\mathrm{MeV}) + \mathrm{P}(14.68\mathrm{MeV})$$

-low abundance of Helium-3 and high ignition temperature

$$.\ \mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\ {}^4\mathrm{He} + (8.7\mathrm{MeV})$$

-high ignition temperature

*aneutronic is when any neutrons carry away no more than 1% of the energy

Nuclear fusion - UKAEA

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DT (deuterium – tritium) fusion

$$\mathrm{D} + \mathrm{T} = {}^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + n$$

- Greatest cross section
- Deuterium is abundant and can be extracted from water (33 g in every cubic m of sea water)
- Tritium is not abundant, with a half life of ~12.3 years
  - Tritium breeding

Task:
We know the masses:

$$m_D = 2.014u$$

$$m_T = 3.016u$$

$$m_\alpha = 4.003u$$

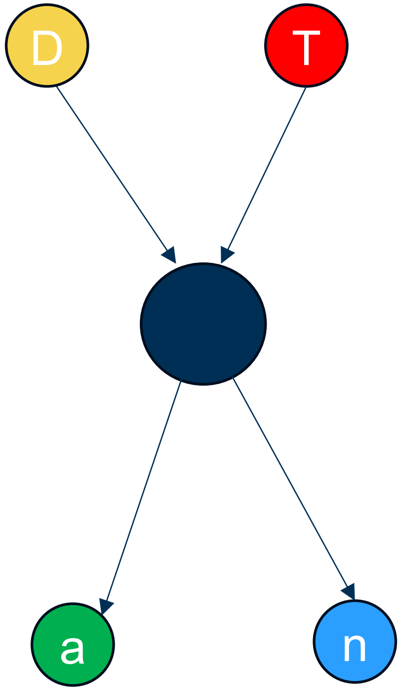
$$m_n = 1.009u$$

What is the energy released per reaction?
Note: Atomic mass unit $u = 1.661 \times 10^{-27}\mathrm{kg}$

DT fusion energy

Energy:

$$
\begin{aligned}
E &= \Delta m c^2 \\
&= (m_D + m_T - m_\alpha - m_n)c^2 \\
&= 2.818 \times 10^{-12} J \\
&= 17.6\text{MeV}
\end{aligned}
$$



This is the Q-value for DT fusion.

DT fusion energy distribution

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Distribution:

- Fusion particles are slow (10 keV) – nonrelativistic
- Kinetic energy $$Q = \frac{1}{2} m_\alpha v_\alpha^2 + \frac{1}{2} m_n v_n^2$$
- Momentum is conserved $$m_n v_n = m_\alpha v_\alpha$$

$$\mathrm{Ke}_n = \frac{m_\alpha}{m_n + m_\alpha} Q \approx 14.1 \mathrm{MeV}$$

DT fusion energy distribution

$$\mathrm{Ke}_n = \frac{m_\alpha}{m_n + m_\alpha} Q \approx 14.1\mathrm{MeV}$$

$$\mathrm{Ke}_\alpha = \frac{m_\alpha}{m_\alpha + m_n} Q = 3.5\mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} = {}^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He}(3.5\mathrm{MeV}) + n(14.1\mathrm{MeV})$$

- Neutrons leave the plasma with 14.1 MeV
- Alphas stay in the plasma and deposit 3.5 MeV

Ignition condition:

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A plasma is defined as ignited when the energy lost is less than the fusion energy.

- Neutrons (to a good approximation) do not heat the plasma
- Alpha interaction heats the plasma:
  - Fusion rate: $f = n_D n_T \langle \sigma \nu \rangle (T)$
  - $\langle \sigma \nu \rangle$ is the Maxwellian average of the cross section multiplied by the relative velocity

$$\langle \sigma \nu \rangle = \int_0^\infty \nu^2 \exp\left(\frac{-m\nu^2}{2kT}\right) \sigma(\nu) \nu d\nu$$

  - n_D, n_T are the deuterium and tritium number densities
  - Alpha-heating rate: $P_H = f V E_\alpha, \quad n_D = n_T = \frac{1}{2} n,$

$$= \frac{1}{4} n^2 \langle \sigma \nu \rangle V E_\alpha$$

Thermal energy lost from the plasma

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Energy in the plasma

$$W = \frac{3}{2}(n_D + n_T + n_e)kT, \quad n_D = n_T = n_e,$$
$$= 3nkT$$

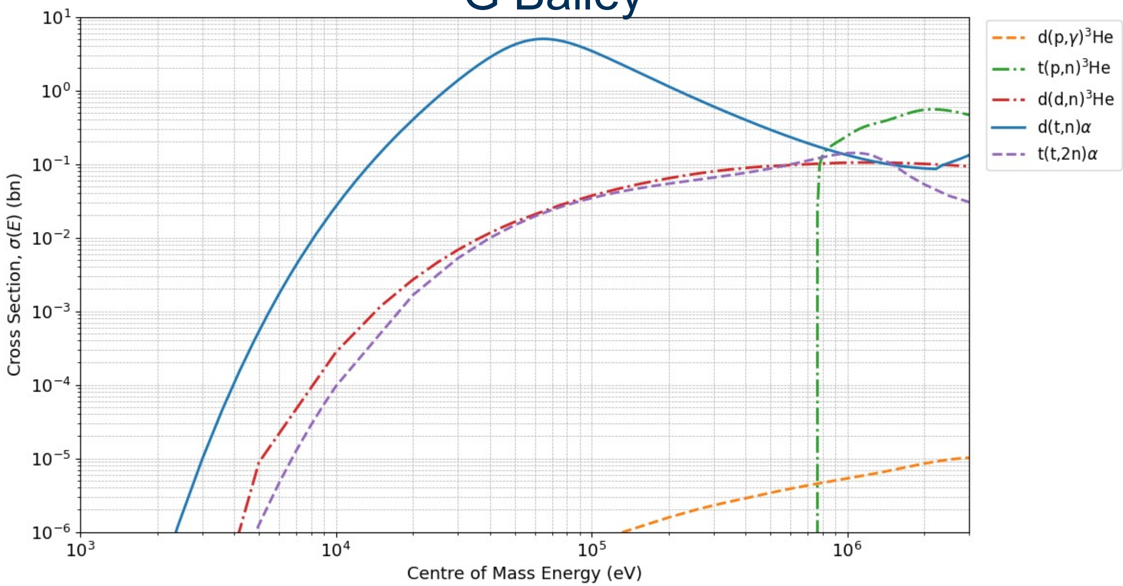
Rate of energy loss from the plasma

$$P_L = \frac{W}{\tau_E}$$

τ_E is the 'energy confinement time'. The time energy is confined in the plasma.

Lawson Criterion

G Bailey



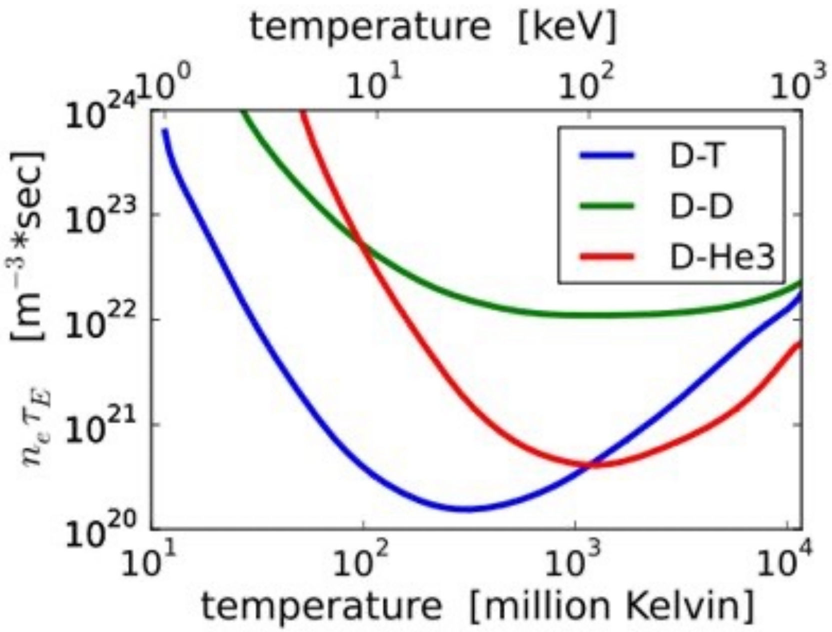
Alpha heating rate needs to be greater than or equal to the energy loss rate by neutrons.

$$P_H \geq P_L$$

Lawson Criterion $$n\tau_E \geq \frac{12nkT}{E_\alpha \langle \sigma \nu \rangle (T)}$$

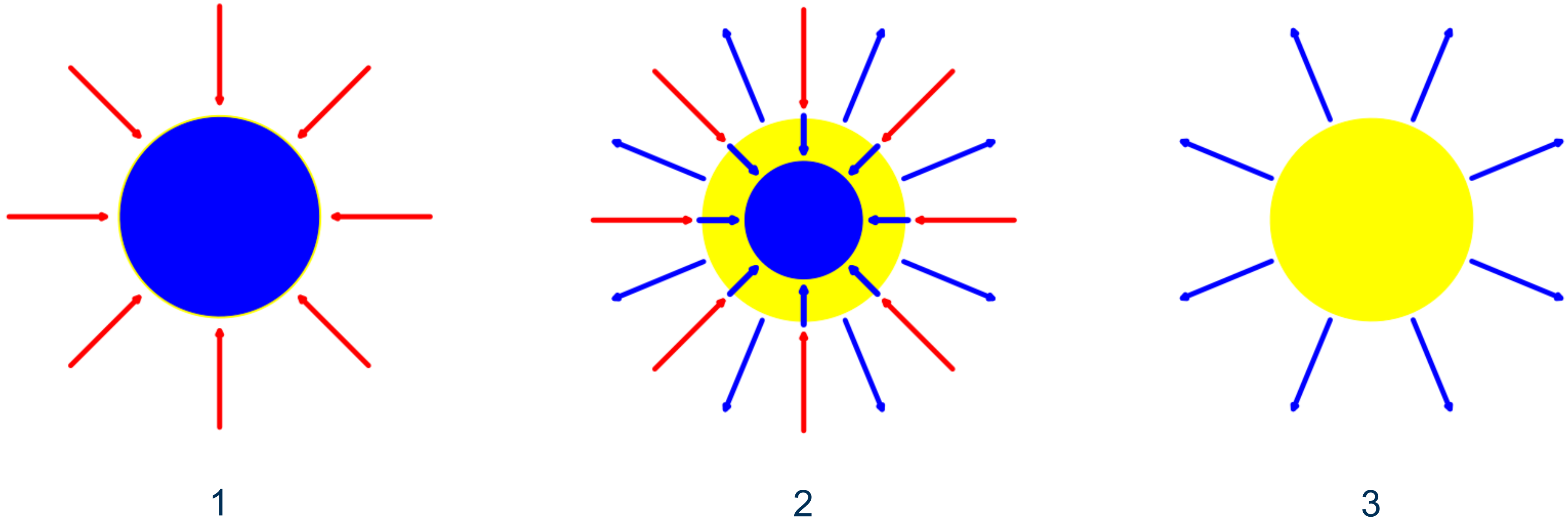
$$E_\alpha = \mathrm{Ke}_\alpha = 3.5\mathrm{MeV}$$

For D-T fusion $n\tau_E \geq 1.5 \times 10^{20} m^{-3} s$



L. Packer

Inertial confinement



1. Laser beam rapidly, uniformly heats the DT cryogenic target surface.
2. Ablation (energetic evaporation, rocket like) of external layer (~10^8 cm/s) generates an imploding shock-wave travelling towards the centre.
3. Thermonuclear DT ignition, producing energy.

Inertial confinement fusion fuel microcapsule

Source: LLNL and L Packer

Inertial confinement fusion

Currently there are two approaches:

- Direct drive:
  - Laser focused directly onto the DT capsule
- Indirect drive:
  - DT fuel is placed in a ‘hohlraum’ – a high Z container
  - Laser is focused inside of the hohlraum, which creates a plasma that produces x-rays

1GW Power plant:

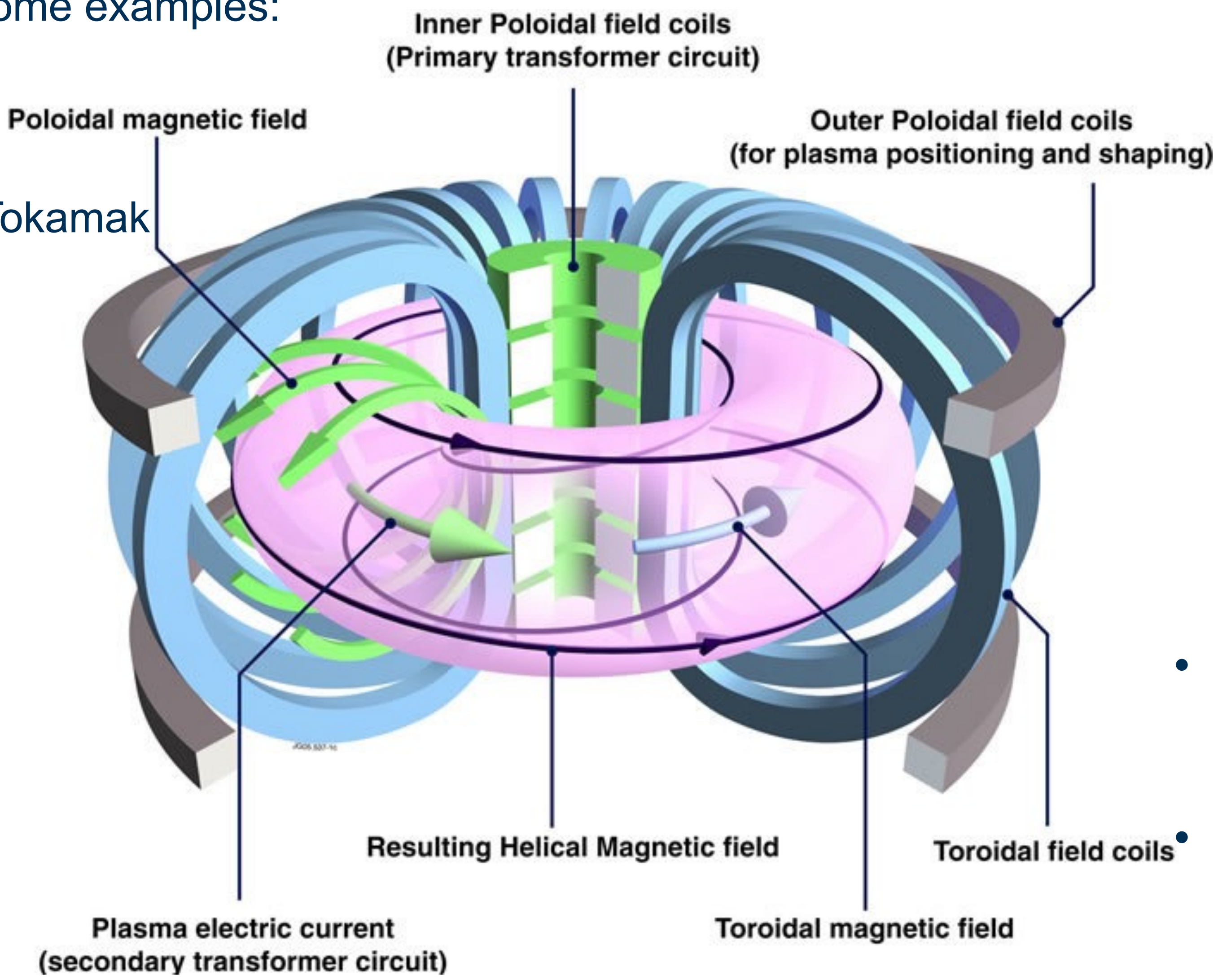
- Require 10 to 20 laser pulses each second
- Heat will produce steam to dive a turbine.

Wire array Z-Pinch is another technique.

Magnetic confinement

Some examples:

Tokamak



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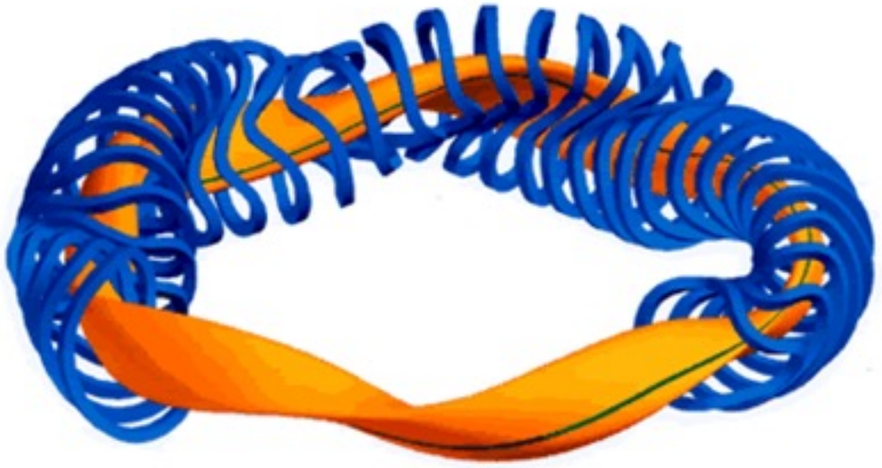
Stellarator

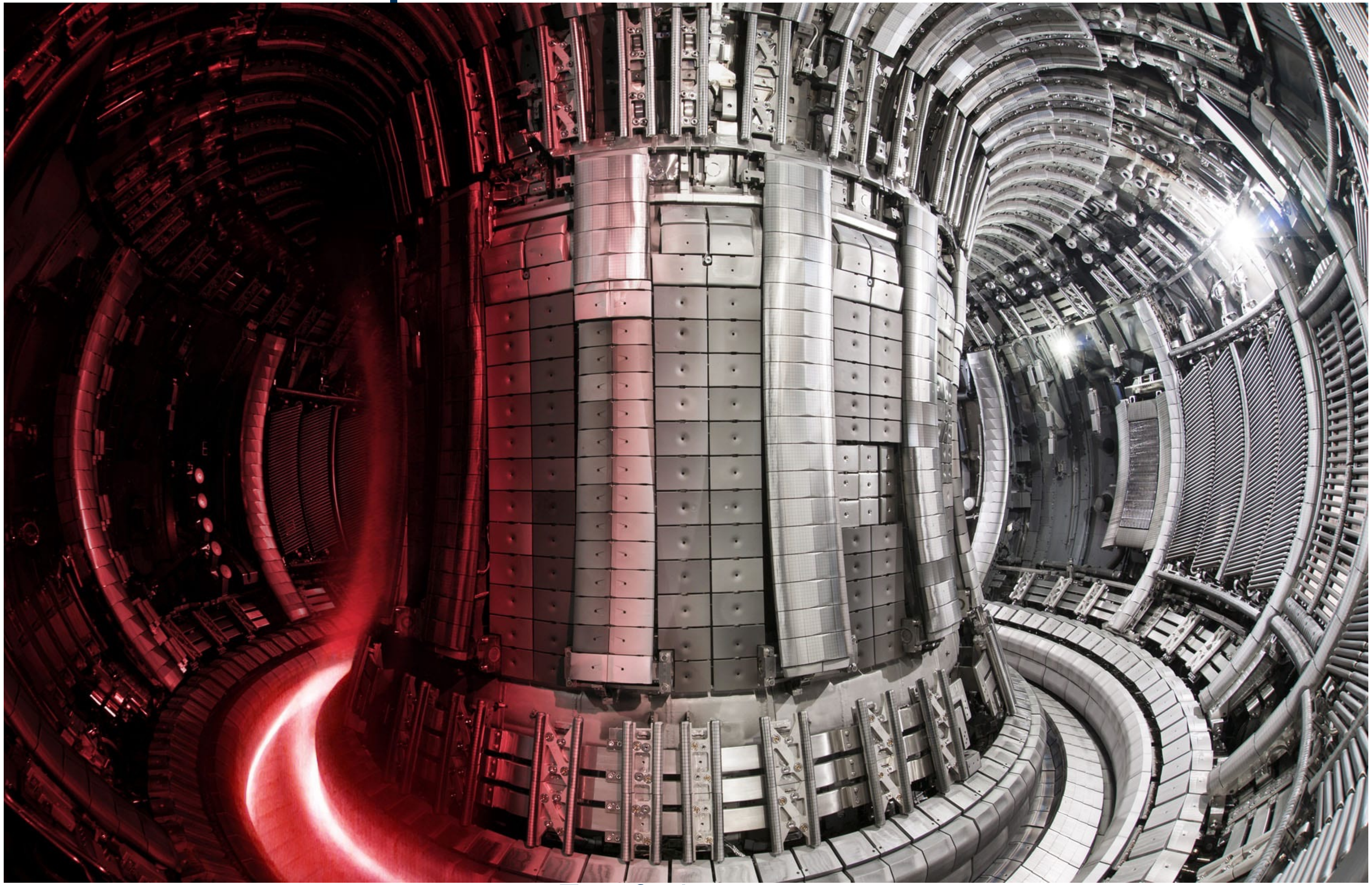


http://www.ipp.mpg.de/16900/w7x

Wendelstein 7-X

- Plasma – a fully ionized homogeneous mix of ions and electrons (electrons no longer bound to nuclei)
- Primary transformer induces a current, which induces a poloidal magnetic field. This with the toroidal field makes a helical magnetic field.
- Fuel spirals along the helical field
- Beam shaped by outer poloidal fields

JET: Joint European Torus



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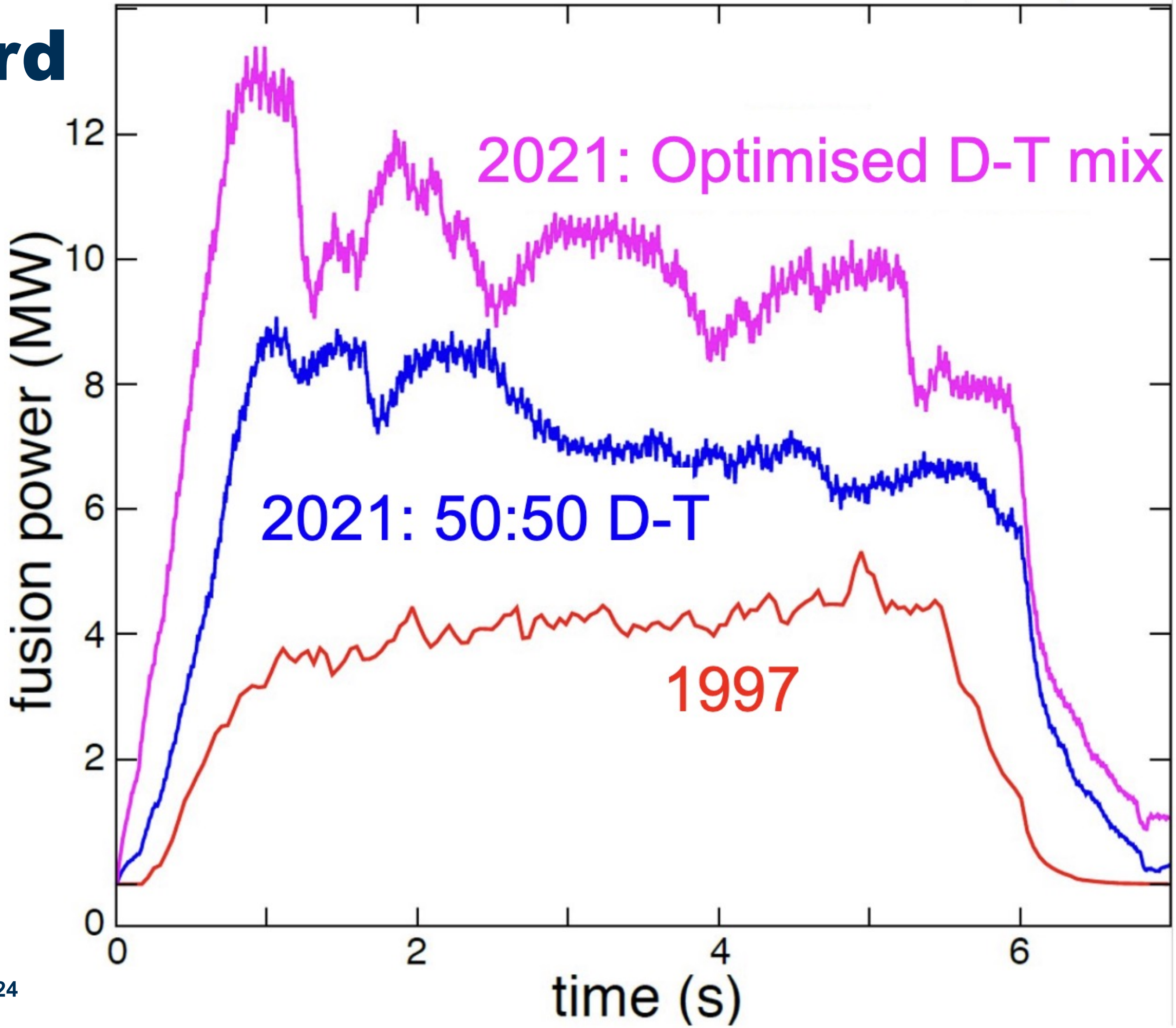
JET
Record-breaking
Pulse 99,971
59MJ fusion energy

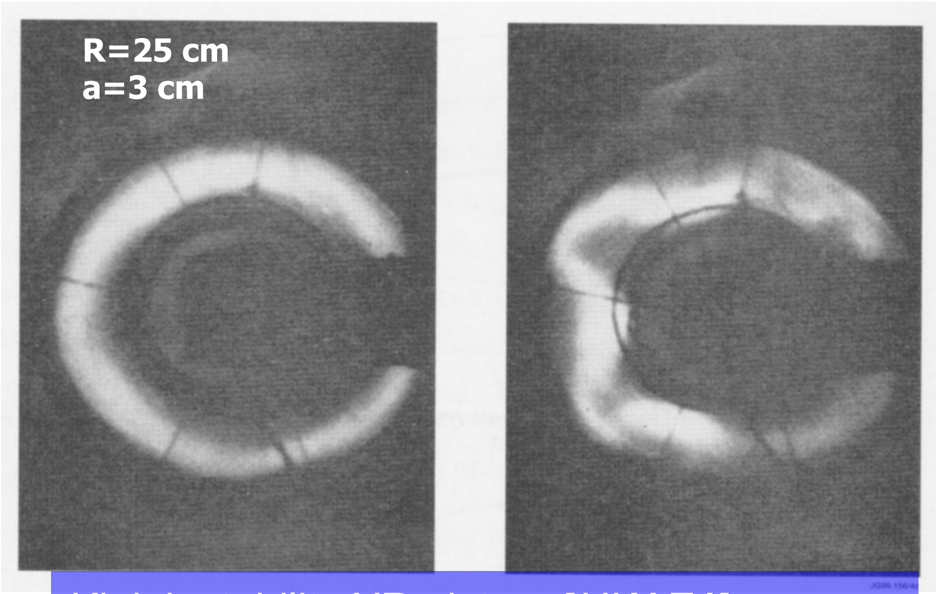
JET record



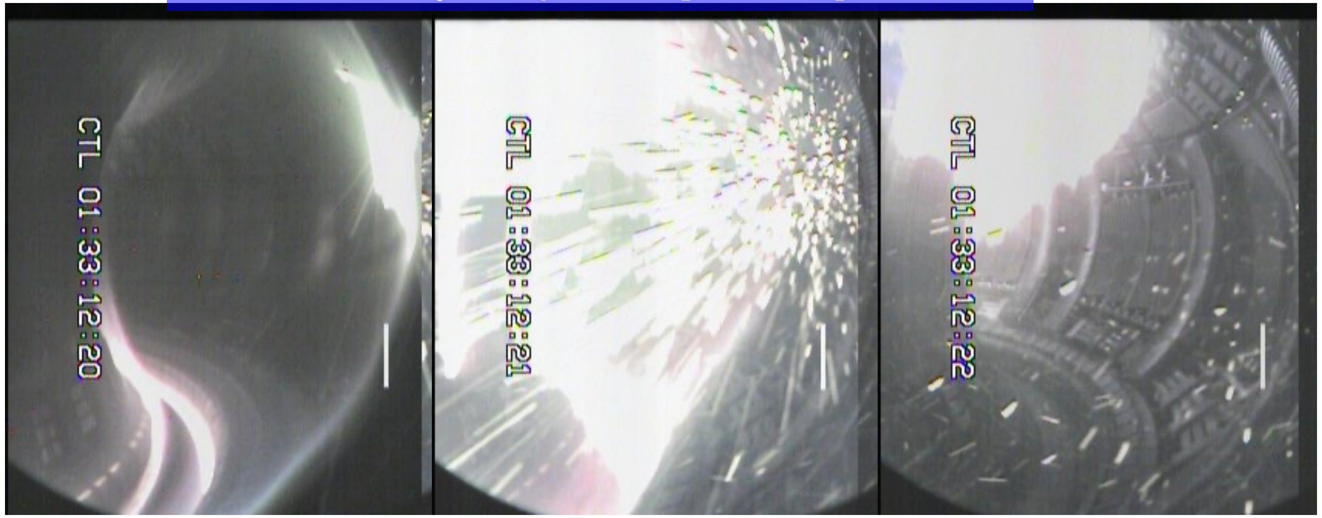
fusion power (MW)
0
2
4
6
8
10
12
0
2
4
6
time (s)
2021: Optimised D-T mix
2021: 50:50 D-T
1997

Tokamak Instabilities

- Current driven instabilities
  - Often the result of the twist being too large in a region
  - Common example is the kink instability
- Density driven instabilities
  - Changes in density cause increase in radiation
  - This causes cooling which in turn changes the conductivity of the plasma, this squeezes the current in the plasma core.
  - The result is to change the twist of the magnetic field causing instability
  - Common examples are ballooning and ELMS
- Micro-instabilities
  - Consequence of turbulence rather than MHD effects



Kink instability XR picture [*UKAEA*].



Plasma disruption at JET [*source: EFDA*].

L. Packer

ELMs

Edge Localised modes (ELMs)

- Analogous to solar flares
- Reduce confinement and damage walls
- First observed on MAST
- Active research area
- Need to mitigate the ELMS

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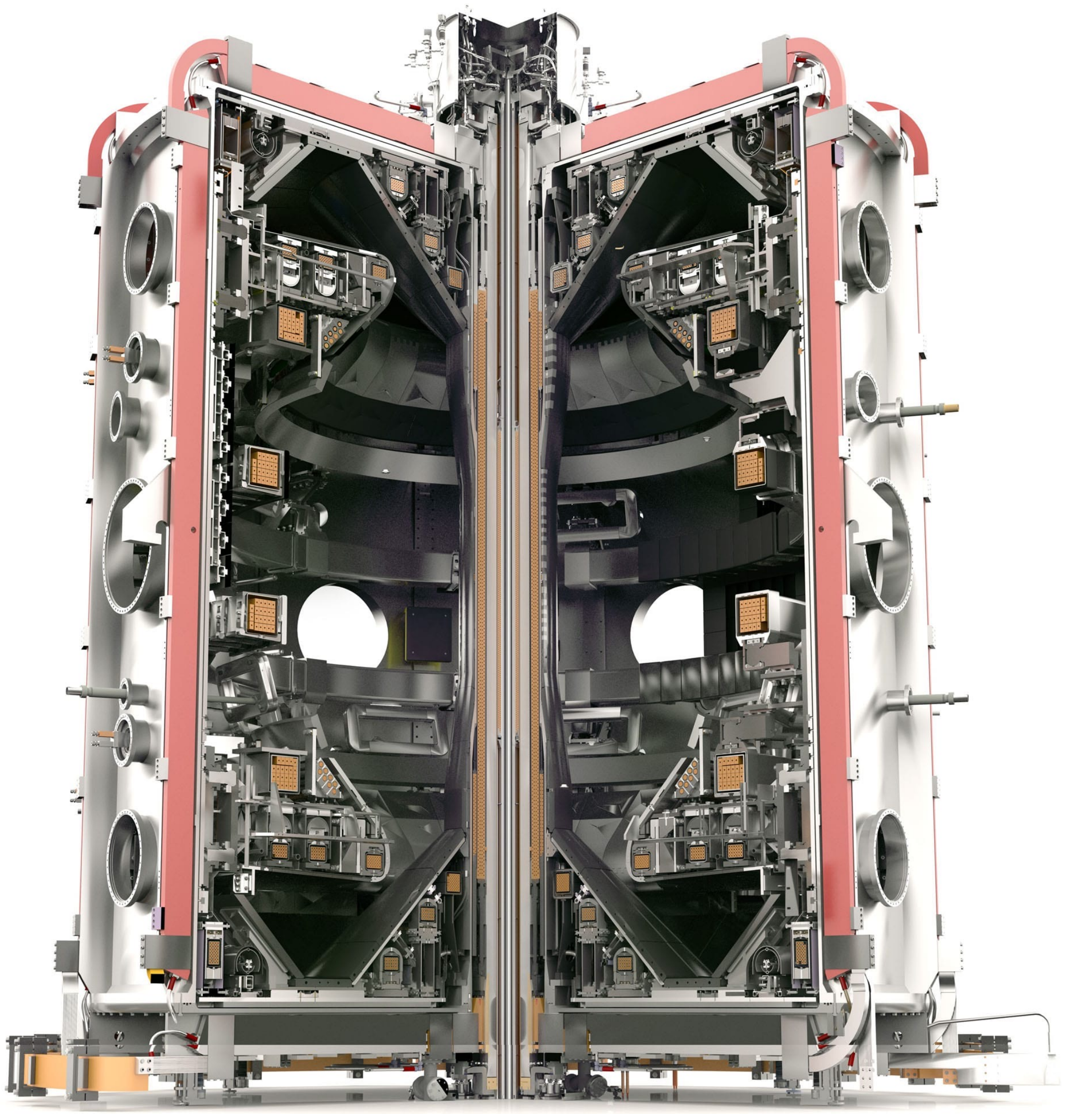

UKAEA Mega Ampere
Spherical Tokamak

Computational approach - UKAEA

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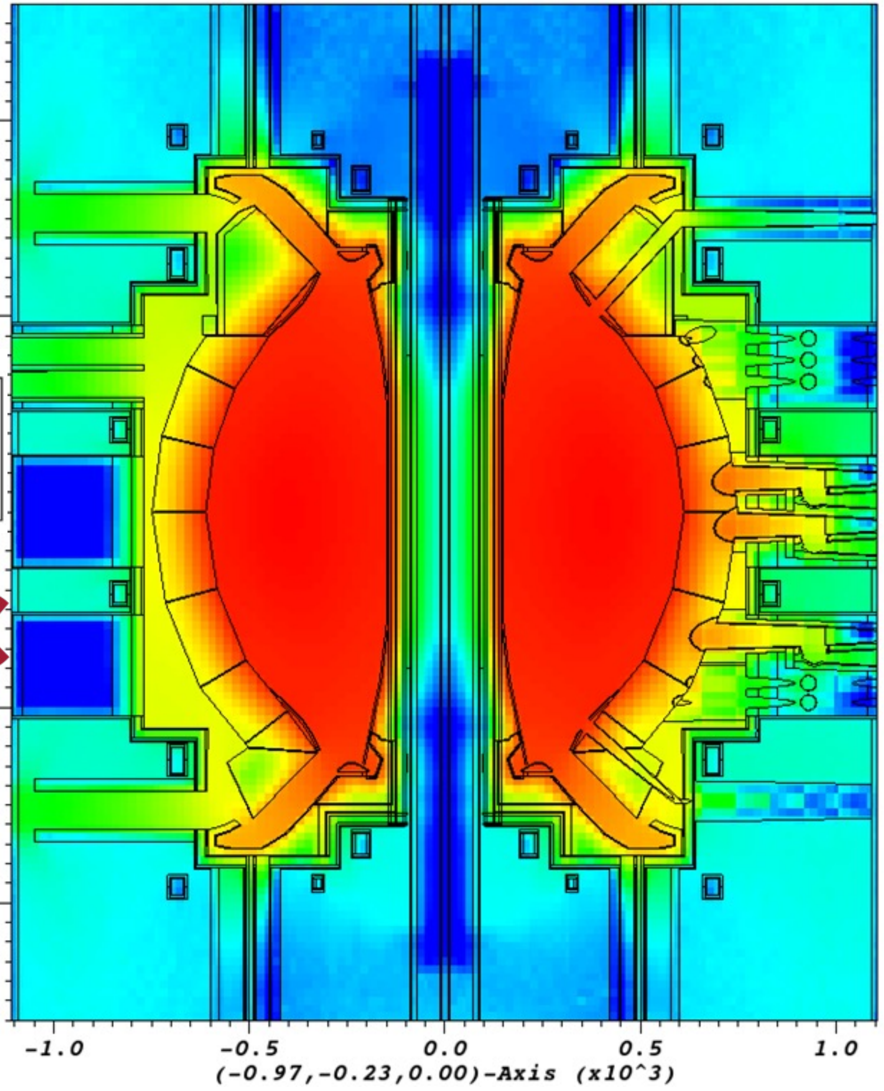
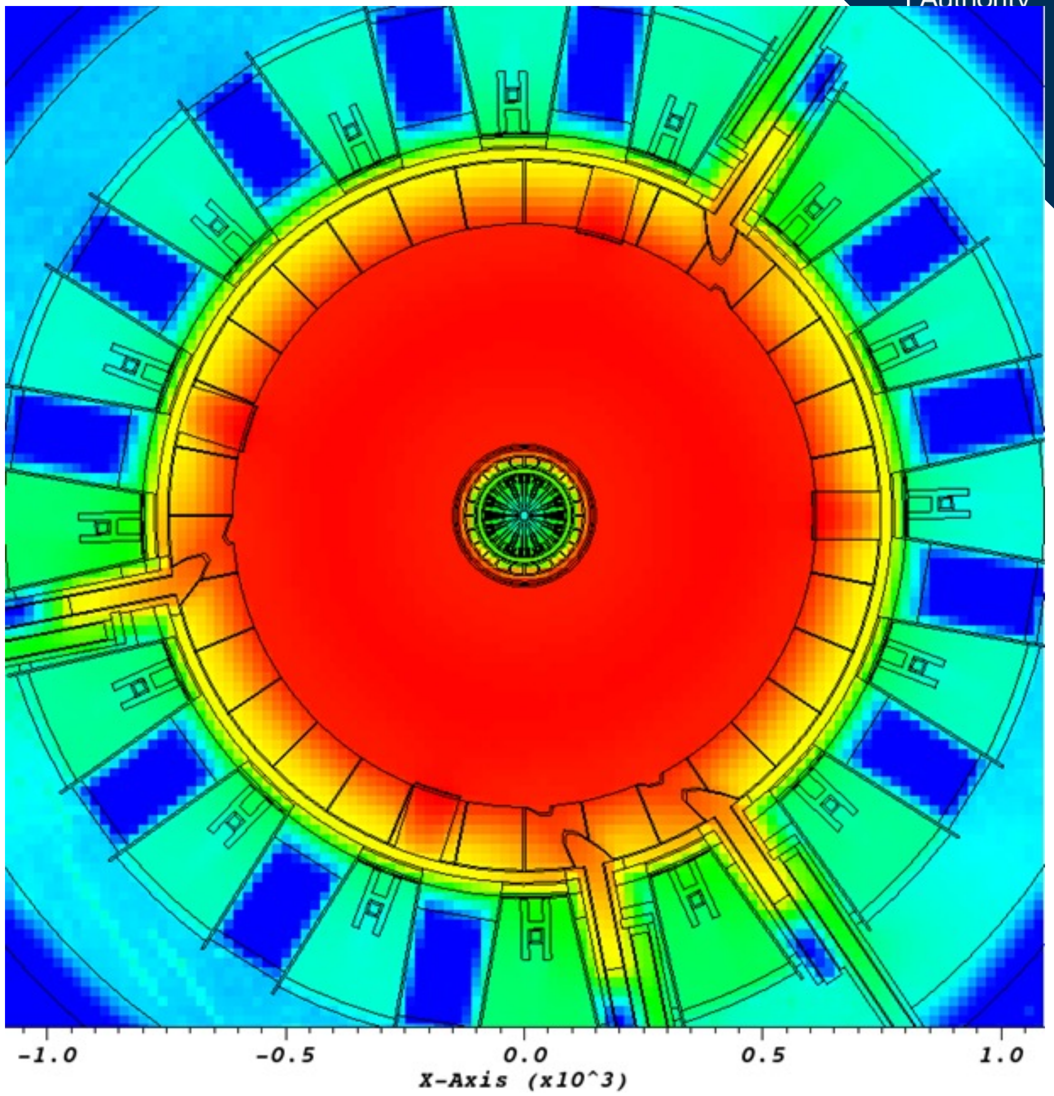
Monte Carlo neutron transport to create the neutron environment.

MCNP6

OpenMC





J Hagues

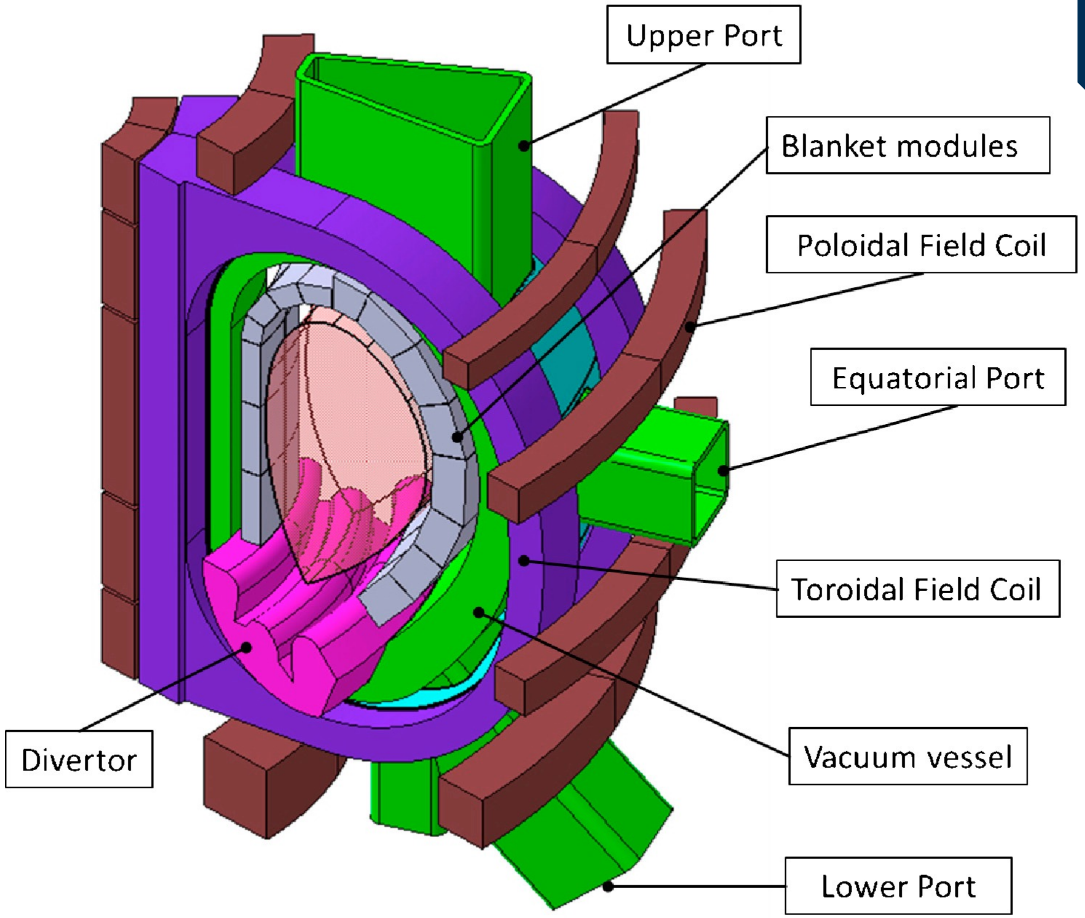
Fuel

The tokamak requires deuterium and tritium.

- Deuterium is stable
- Tritium has a half life of ~12.3 years
    - 1 GW fusion power plant requires **55.6 kg** per full power year

Where does the tritium come from?

- CANDU reactors produce about 130 g per year (~25kg in stock)
- Need to produce tritium.
    - Breeding blankets



Neutronic performance issues of the breeding blanket options for the European DEMO fusion power plant. U. Fischer et al 2016. Fusion Engineering and Design

Tritium breeding

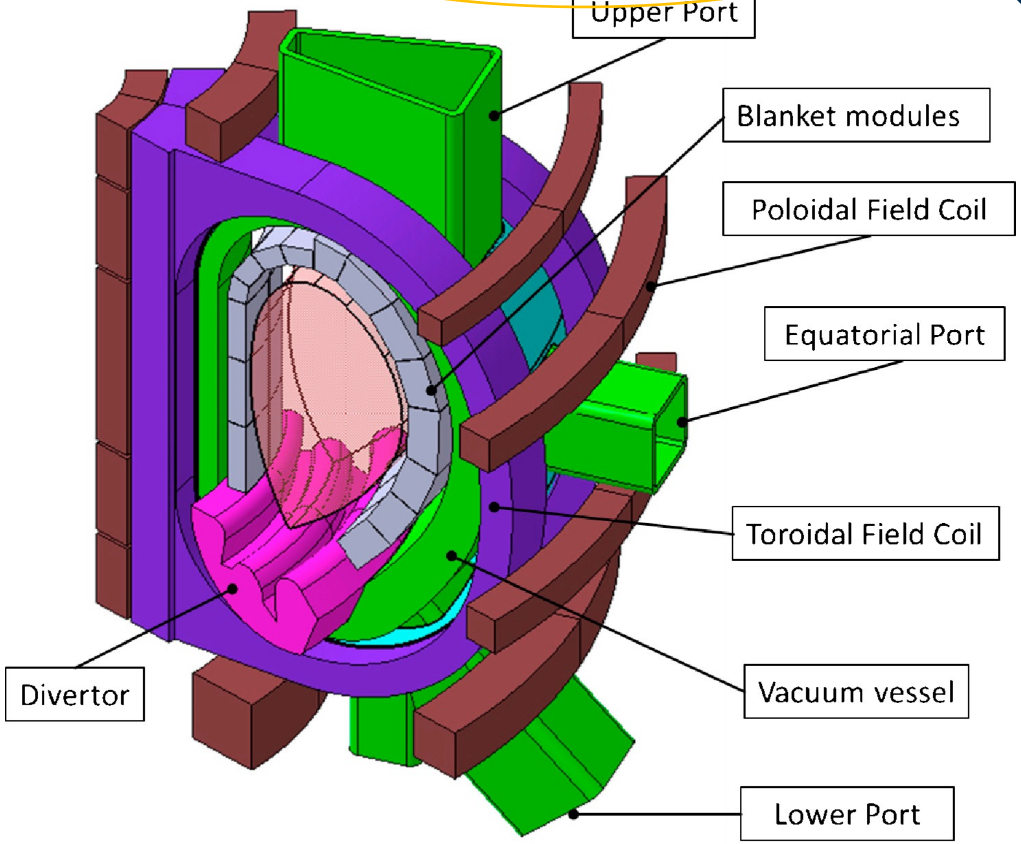
$$\mathrm{D} + \mathrm{T} = {}^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He}(3.5\mathrm{MeV}) + n(14.1\mathrm{MeV})$$

- 14.1MeV neutrons are leaving the plasma

$$^6\mathrm{Li} + \mathrm{n} \rightarrow {}^4\ \mathrm{He} + \mathrm{T} + (4.8\mathrm{MeV})$$

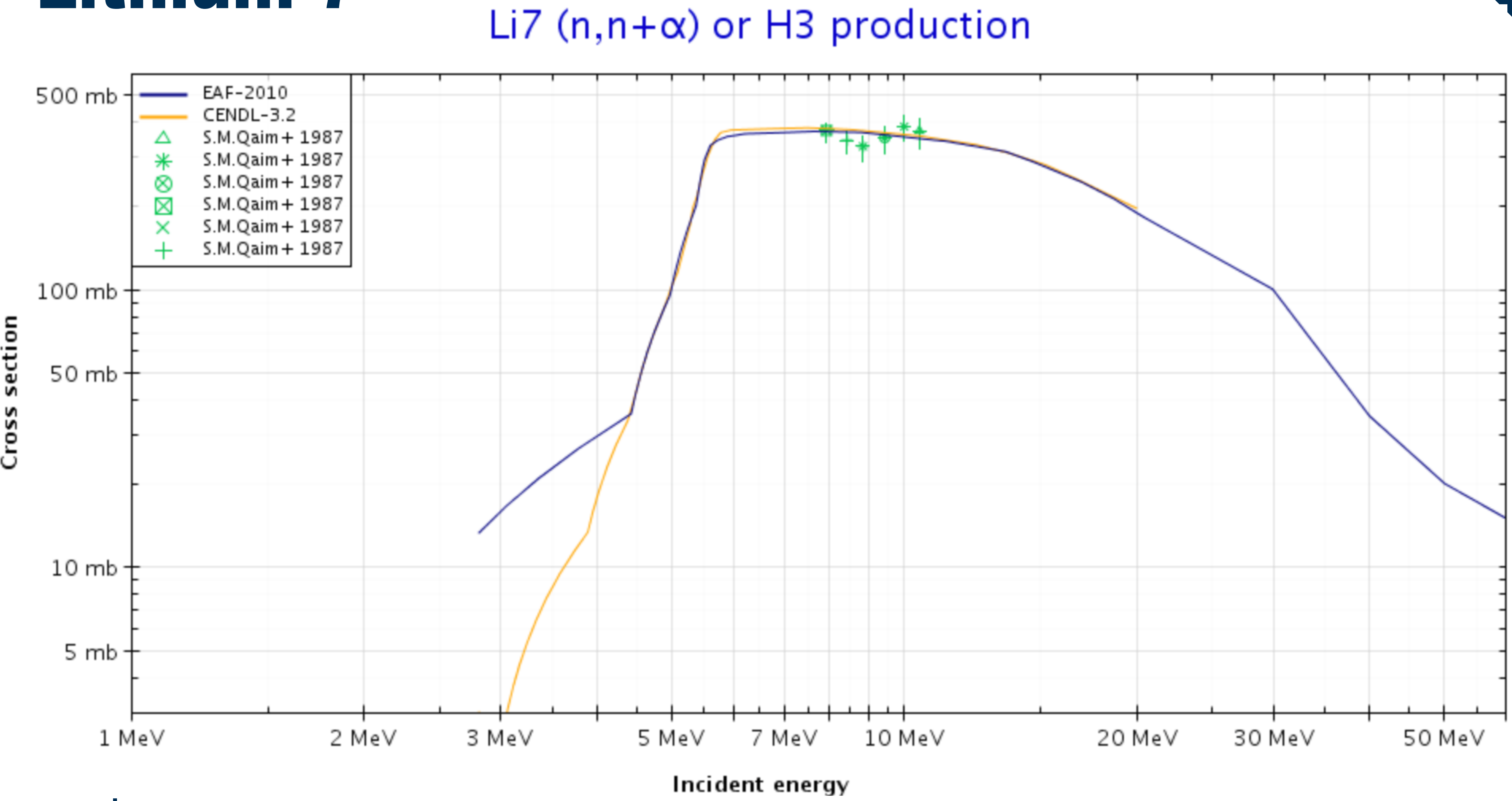
$$^7\mathrm{Li} + \mathrm{n} \rightarrow {}^4\ \mathrm{He} + \mathrm{T} + \mathrm{n}(\text{-}2.3\mathrm{MeV})$$

- Natural lithium ~95% Li-7 and 5% Li-6



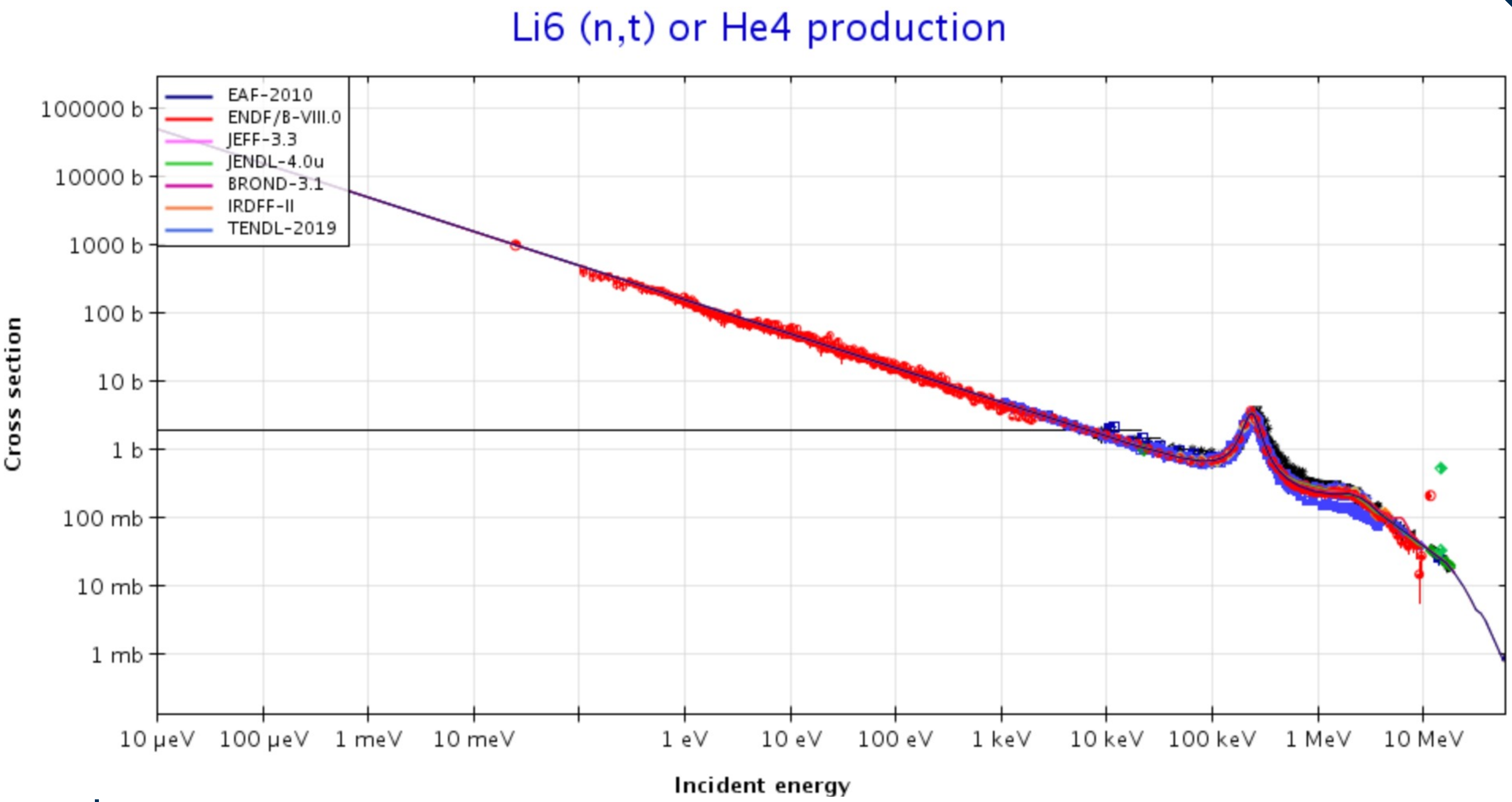
Neutronic performance issues of the breeding blanket options for the European DEMO fusion power plant. U. Fischer et al 2016. Fusion Engineering and Design

Lithium-7



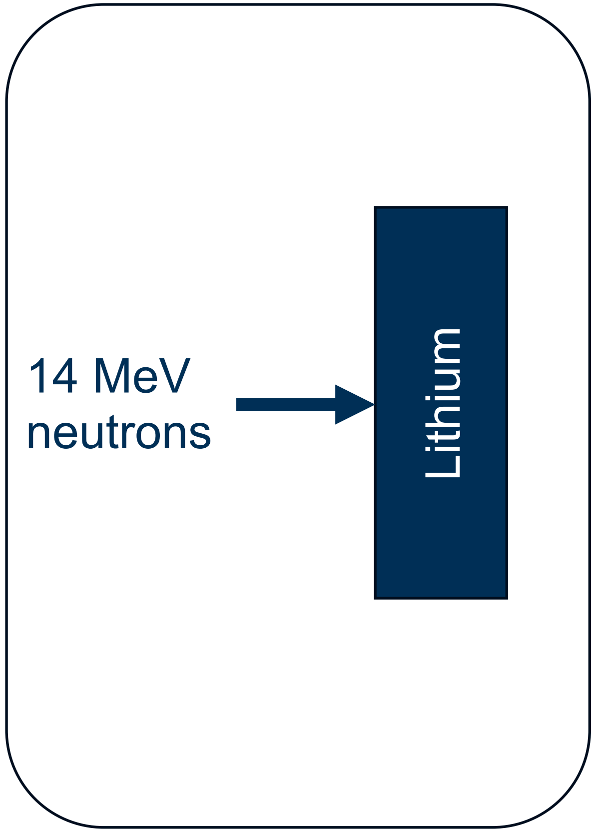
JANISWEB - OECD

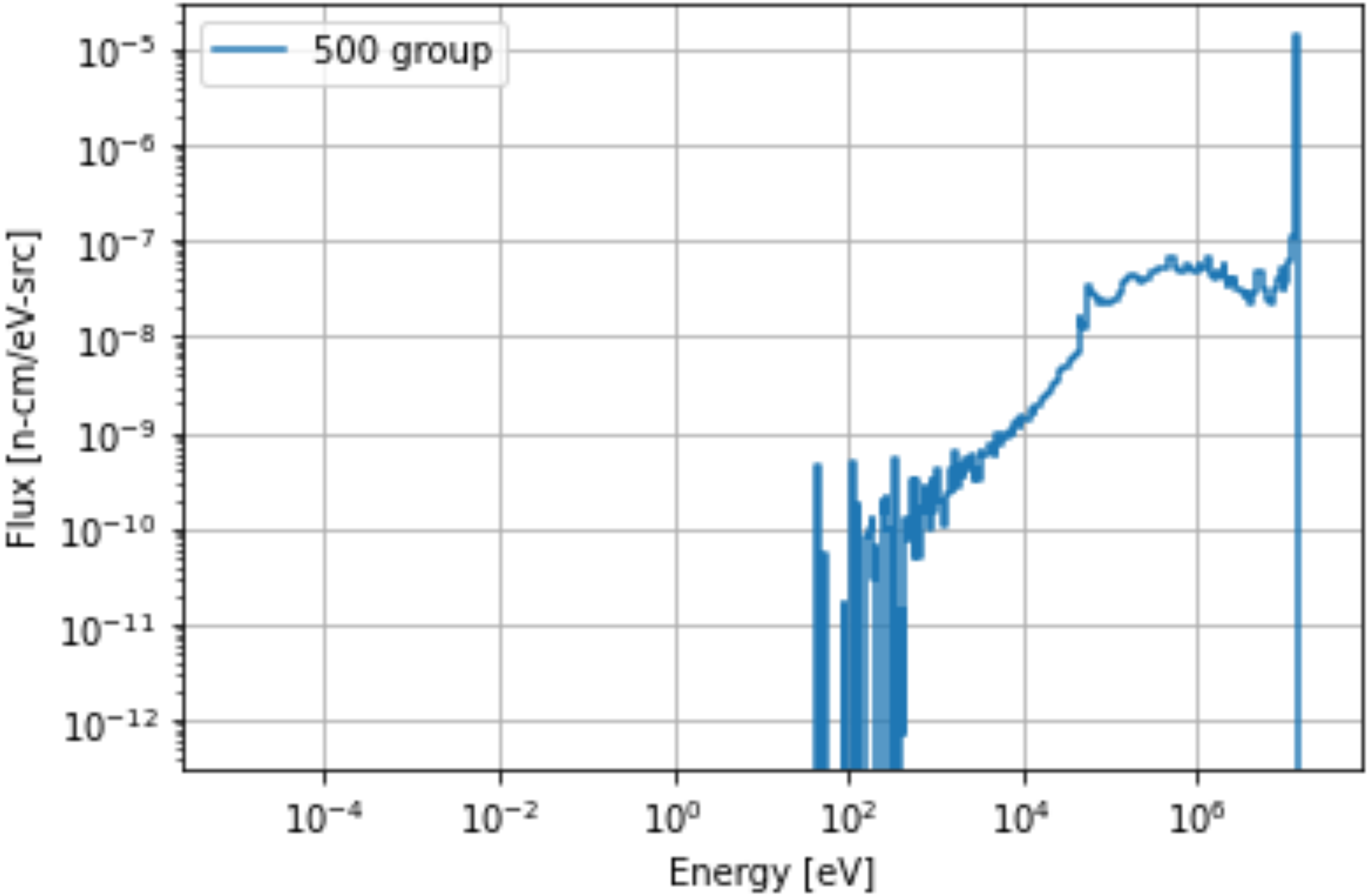
Lithium-6



JANISWEB - OECD

Neutron spectrum inside of Lithium





Simple OpenMC Monte Carlo simulation
- Not a large number of neutron histories

Neutron down scattering by lithium

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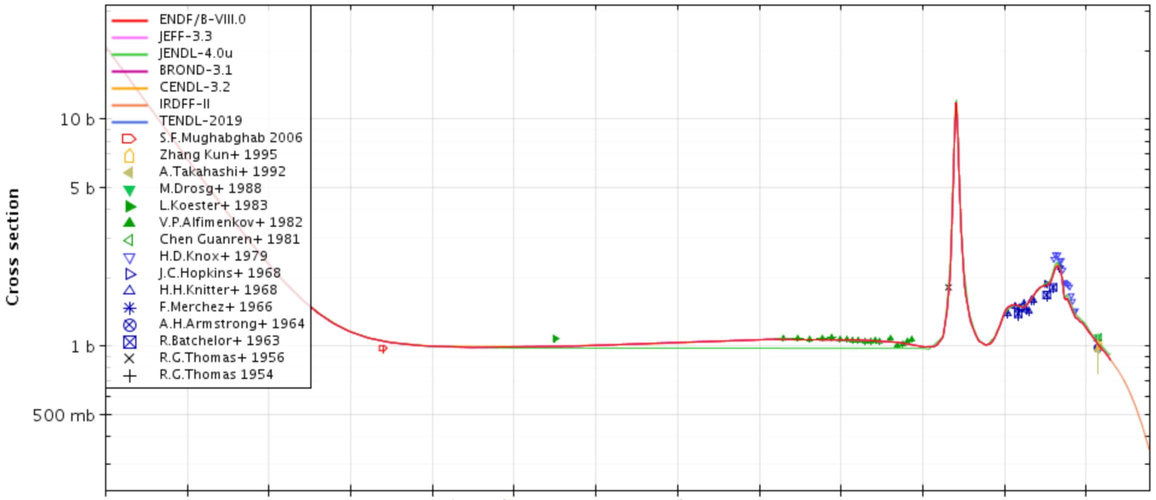
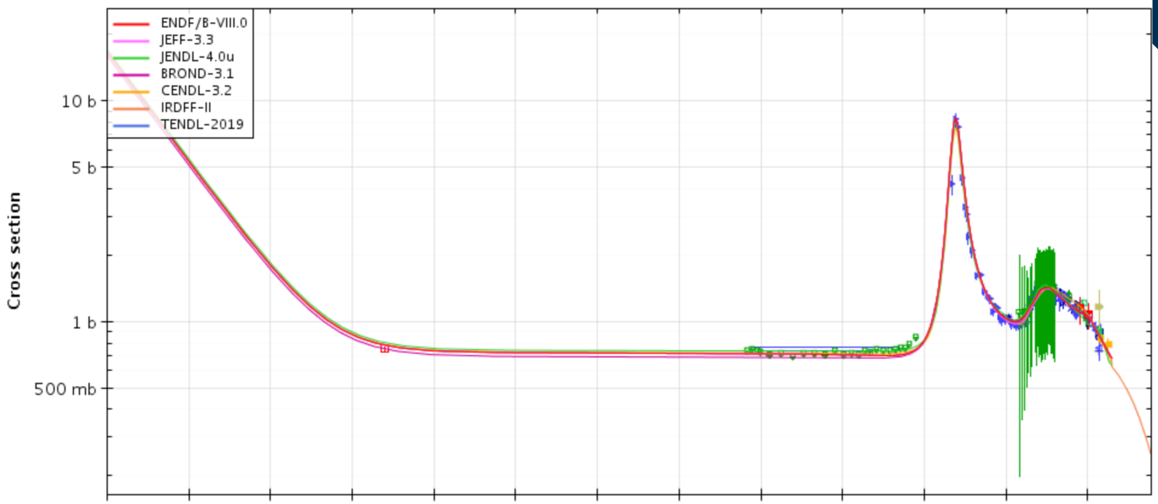
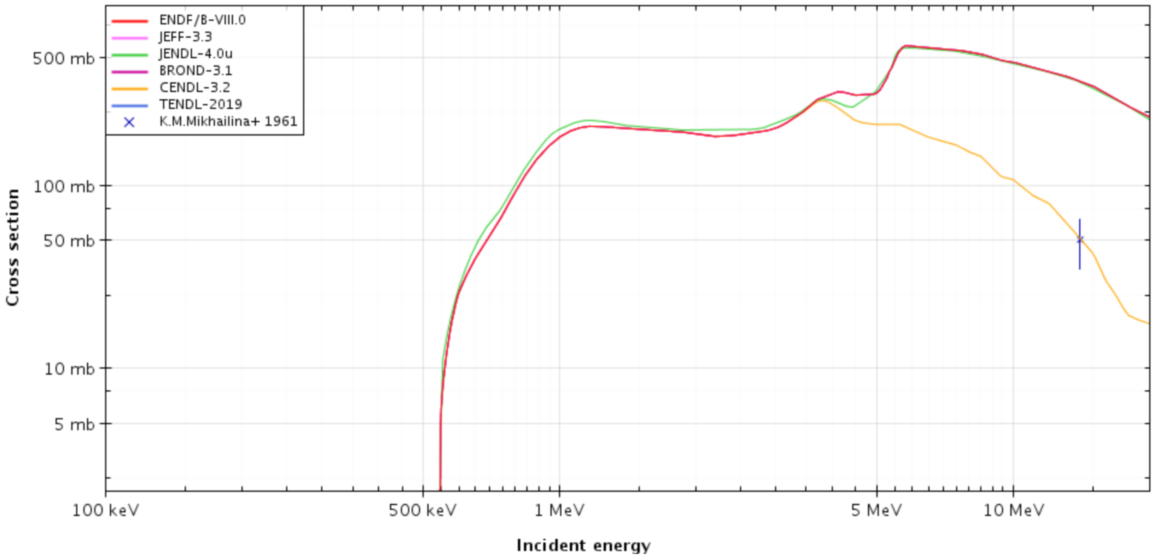
Li7 (n,el)



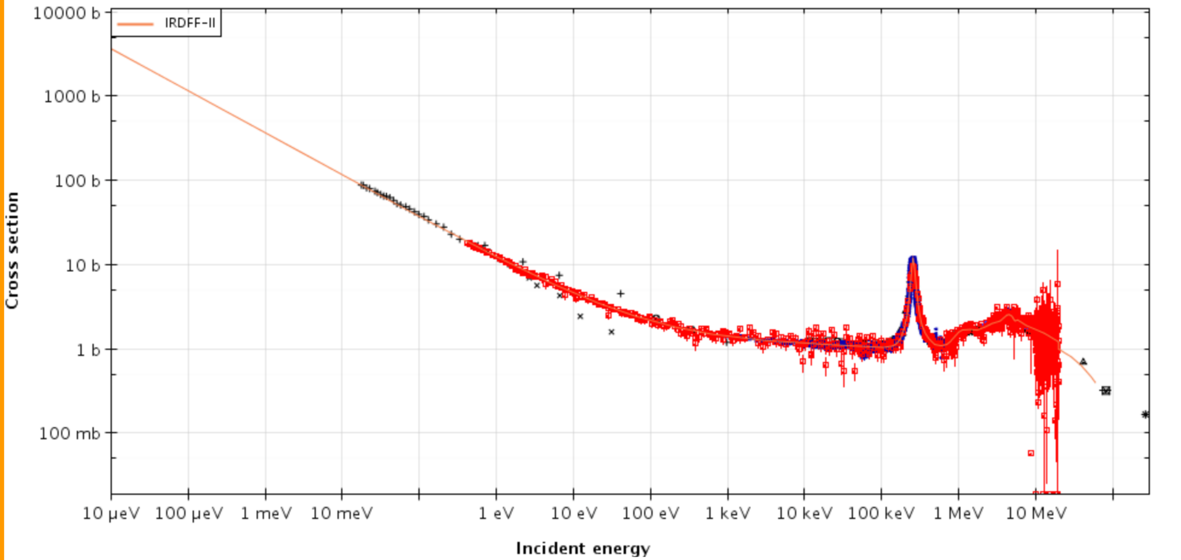
Li6 (n,el)



Li7 (n,n') or Li7 production



LiNat (n,total)



Not all cross sections

JANIS

Tritium production

G Bailey

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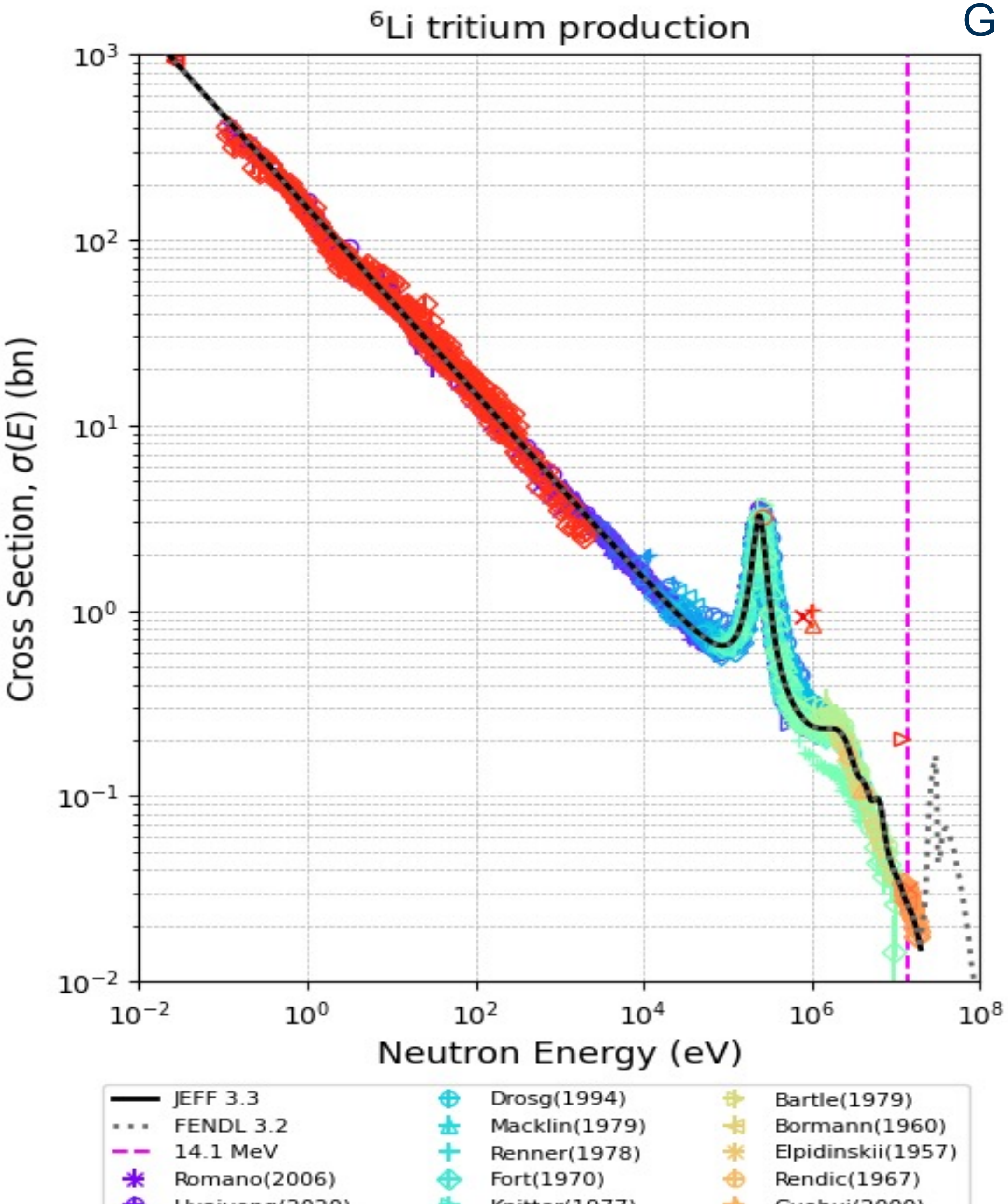
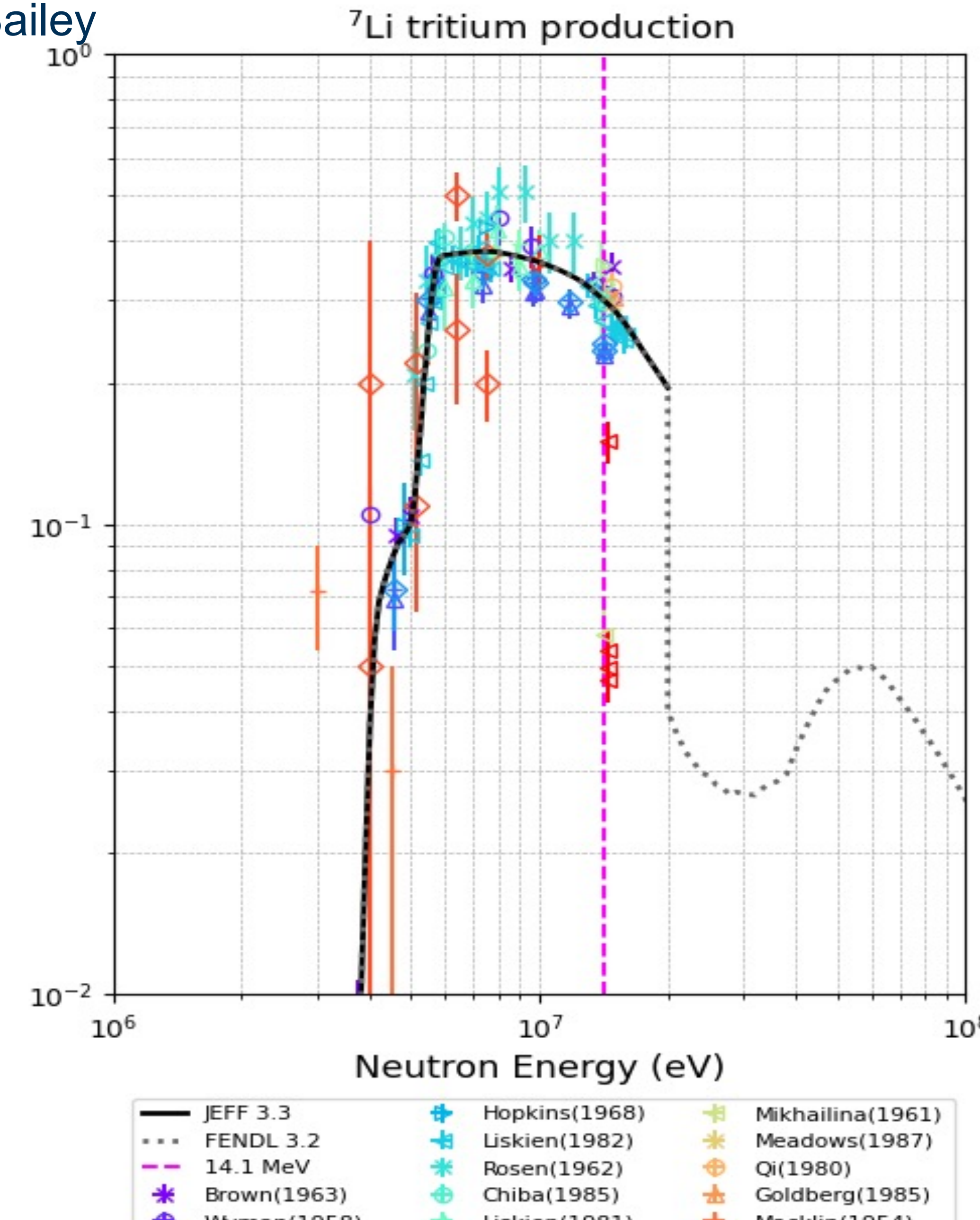
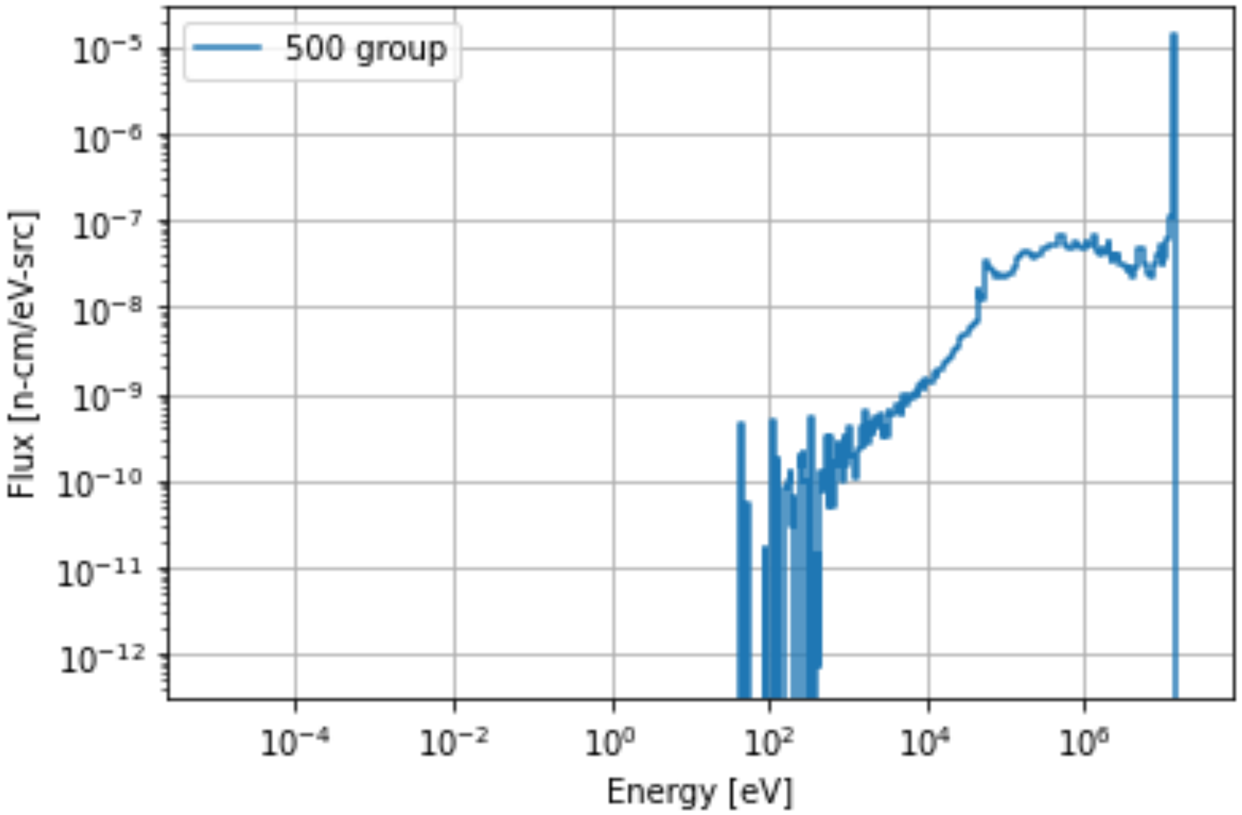
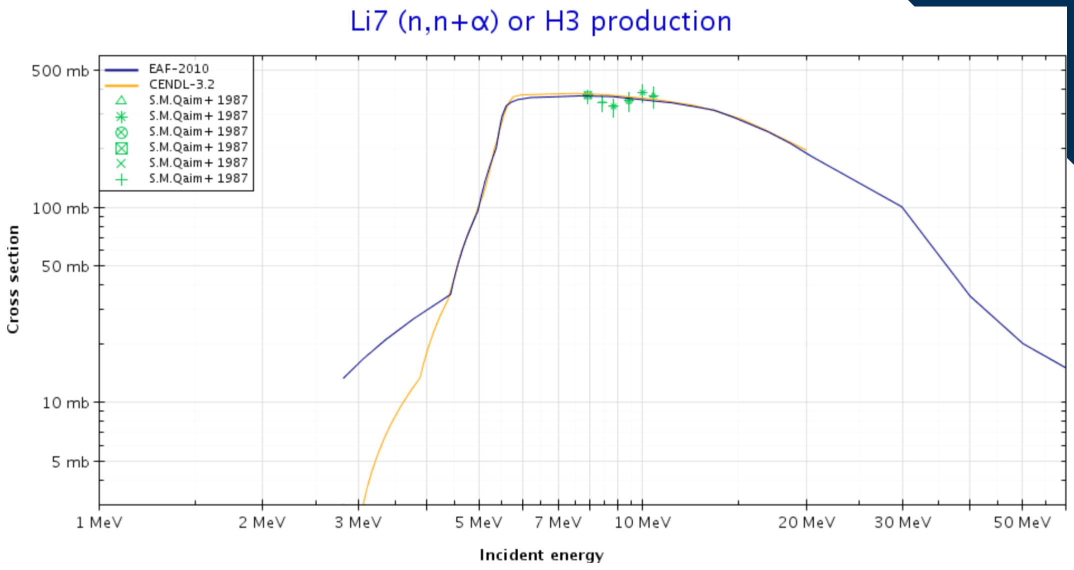
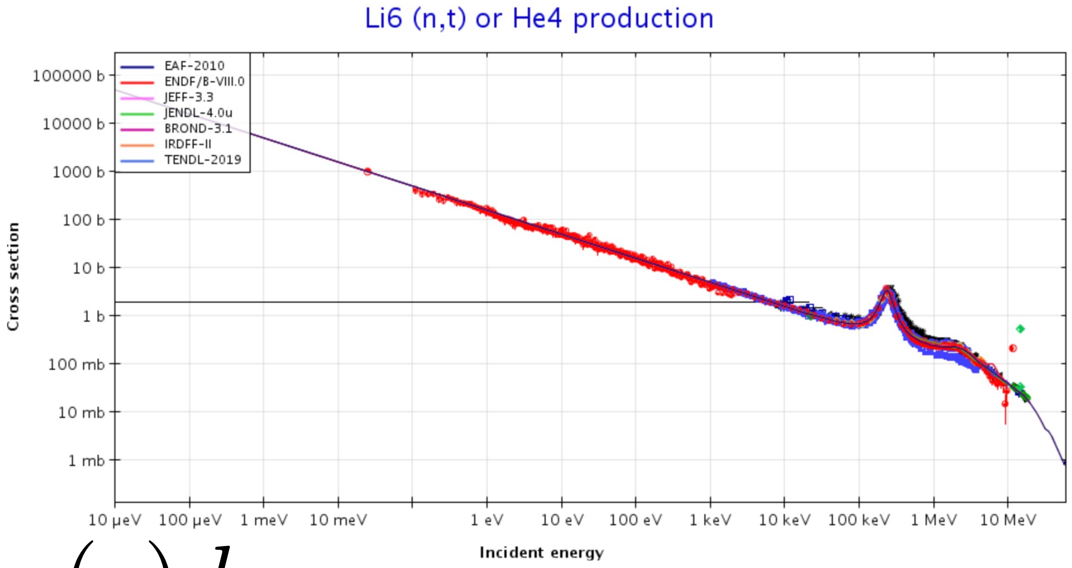




Tritium production



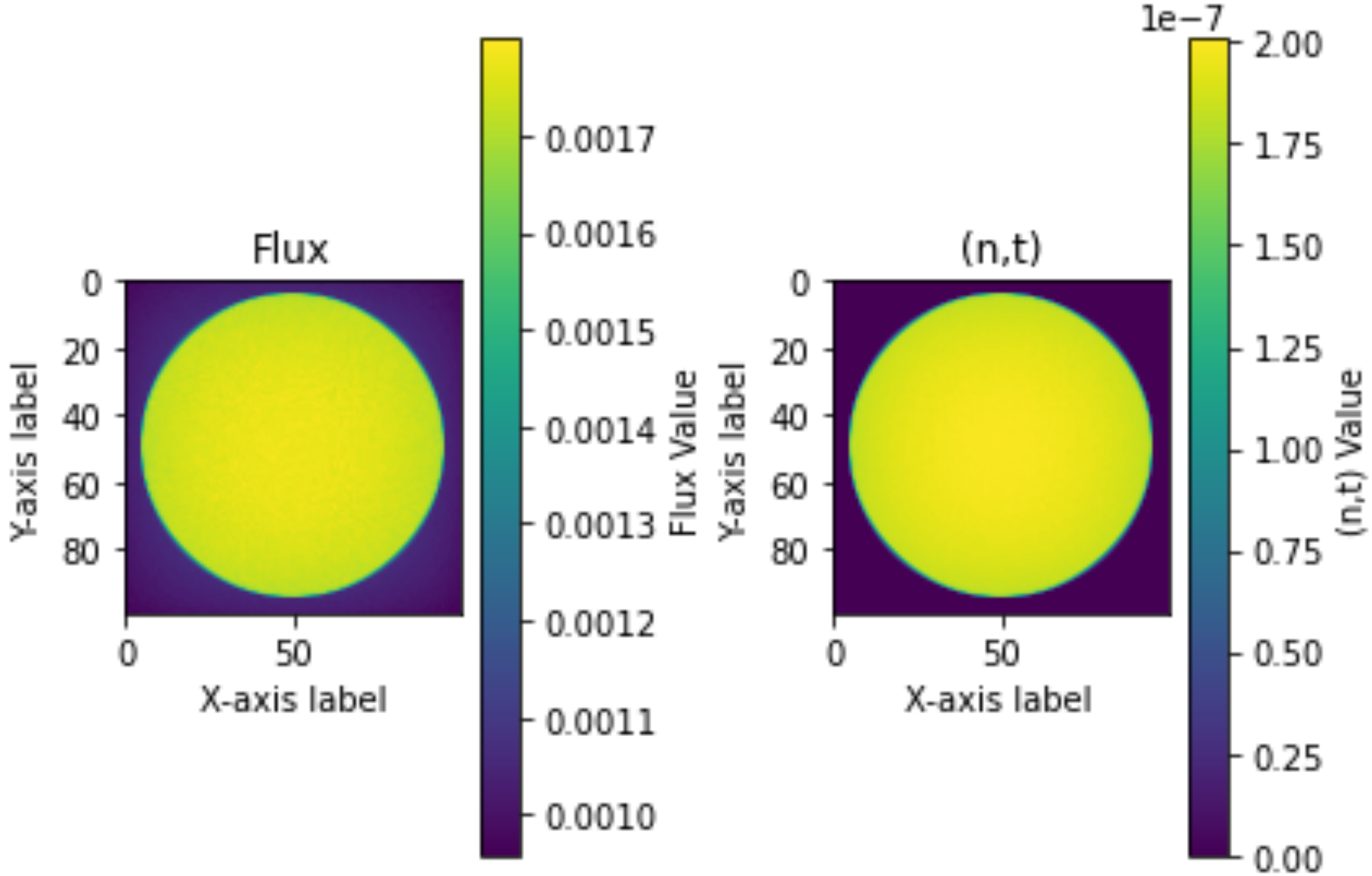




$$R = \int_0^\infty \phi(e)\sigma(e)de$$

Lithium

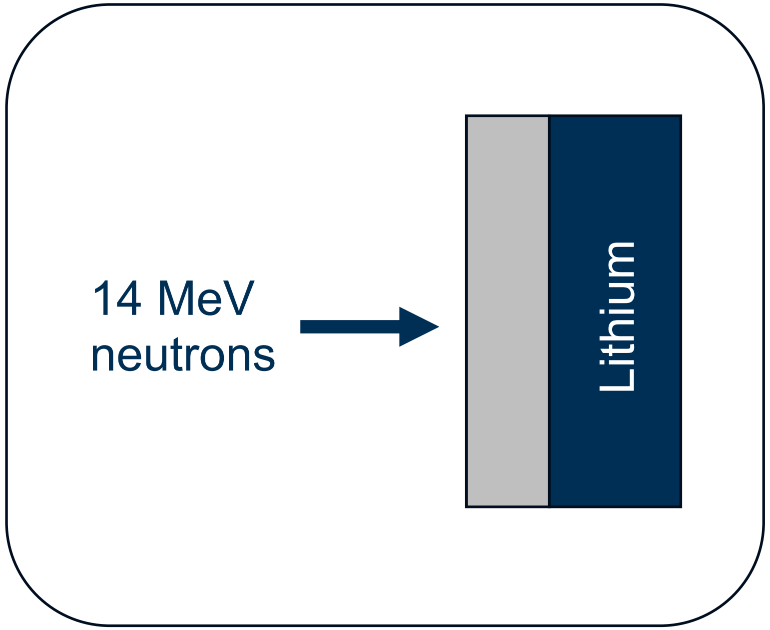
- Natural lithium ~95% Li-7 and 5% Li-6
    - Approximately 19 times more Lithium-7 than Lithium-6
    - Down scattering is dominated by Lithium-7 due to its natural abundance
    - Down scattered neutrons are ‘mopped-up’ by ~200keV Li6(n,a)T peak.

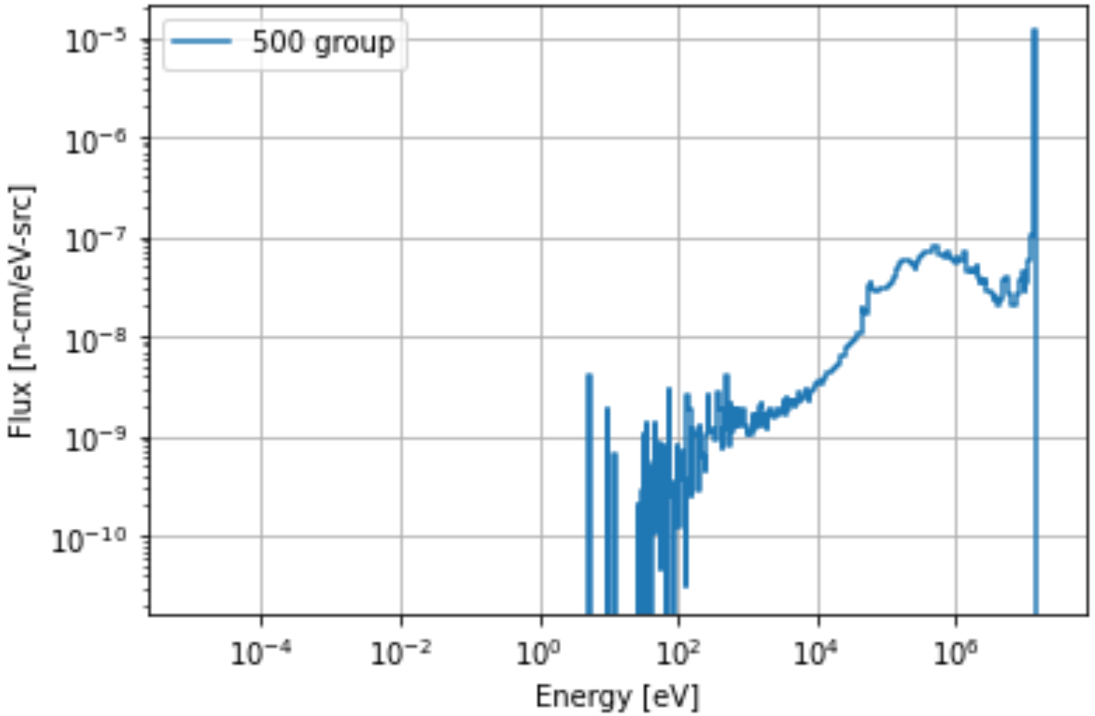


Tritium production

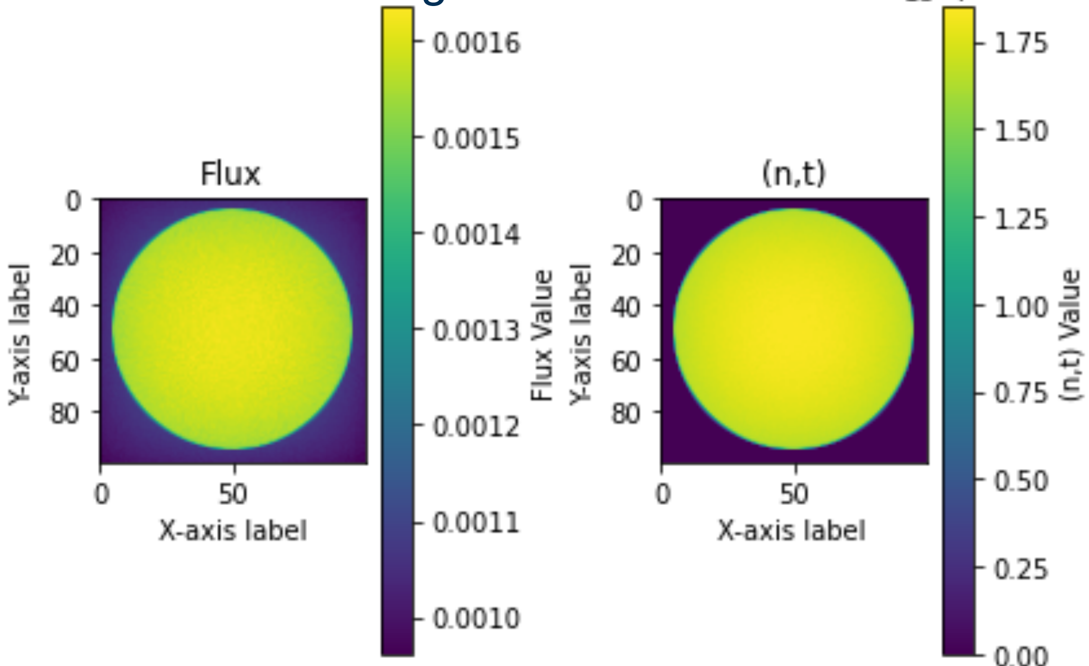
When the lithium is behind a shield.

- Tungsten shield
- Increase thermalization
- Reduced neutron flux





- Not a large number of neutron histories



LIBRTI

Lithium Breeding Tritium Innovation (LIBRTI) Program

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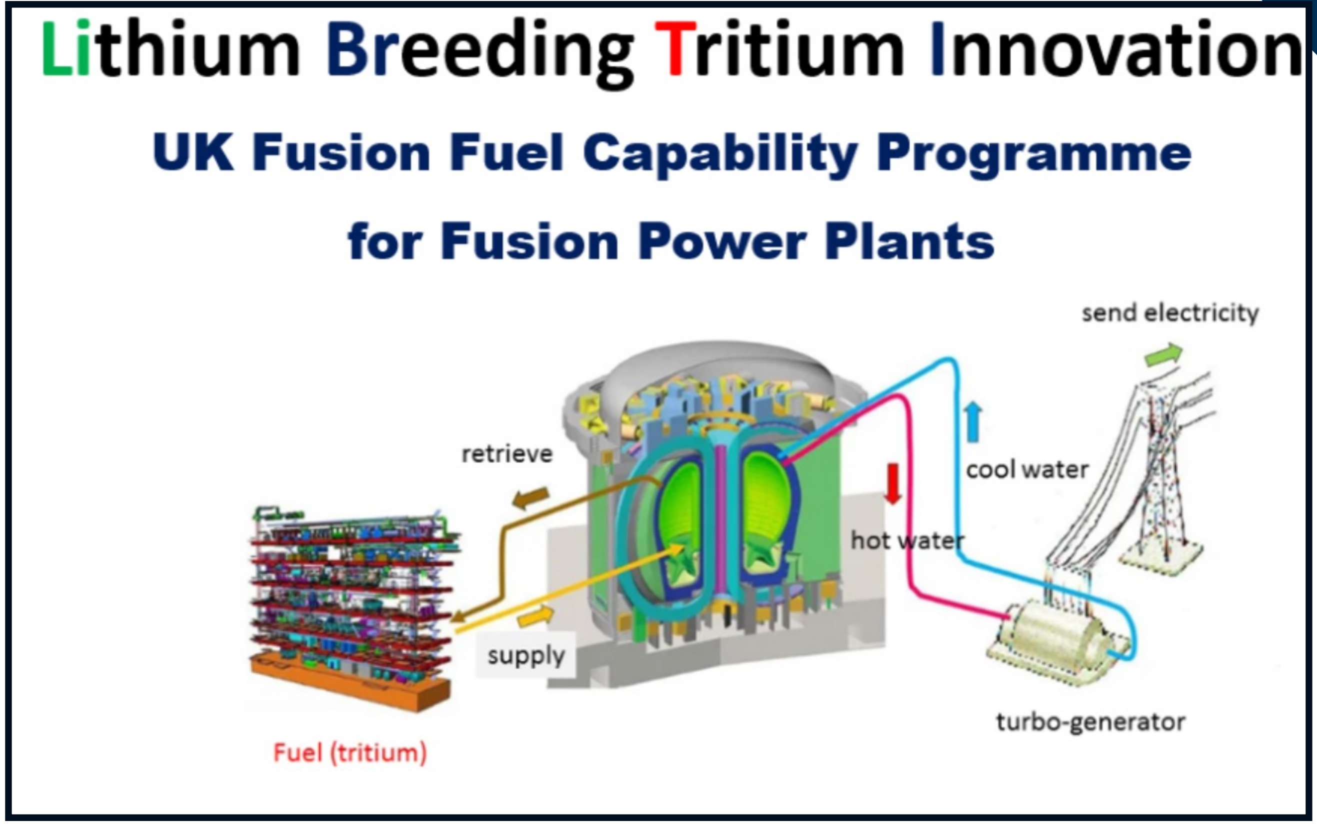
- Facility (building, active gas handling, shielded bunker, neutron source, cooling loops and diagnostics)
- **portfolio of research projects** under parallel workstreams
    - **physical and digital experiments**
- **portfolio of research projects** under parallel workstreams

LIBRTI aims to pave the way for fusion powerplant-scale tritium breeding. It will demonstrate that for a given neutron flux and lithium substrate, the amount of bred tritium can be quantitatively predicted and accurately, and reproducibly, achieved.

- PhD and Postdoc positions in the future



Neutron activation

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We have discussed that neutrons can transmutation Lithium to produce tritium.

Neutrons can transmute other materials, causing activation.

$$\frac{dN_i}{dt} = -N_i\lambda_i - N_i \sum_s \int \sigma_{is}(E)\phi(E)dE + \sum_{k\neq i} N_k \left(\lambda_{ki} + \int \sigma_{ki}(E)\phi(E)dE\right)$$

Where

$N_i(t)$ is the number of nuclides of type i

$\sigma_{is}(E)$ is the cross section for i to j, as a function of energy

λ_i is the decay constant

$\phi(E)$ is the neutron flux, as a function of energy

Neutron activation – solutions

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- Inventory equation can be rewritten in the form:

$$\dot{N}(t) = A(\phi, \Lambda, \lambda)N(t)$$

  - Where N is a vector of nuclides
  - A is a matrix of coefficients
  - Collapsed cross section

$$\Lambda = \int_0^\infty \phi(e)\sigma(e)de$$

- Solution would be of the form:

$$N(t) = N(t=0)e^{At}$$

- How do we calculate the matrix exponential

Bateman solution

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$$A \xrightarrow{\lambda_1} B \xrightarrow{\lambda_2} C$$

The inventory equation can be solved with a **Laplace** transformation yielding the Bateman type solutions.

$$N_n(t) = N_1(t=0)\left(\prod_{i=1}^{n-1}\lambda_i\right)\left(\sum_{i=1}^{n}\frac{e^{-\lambda_i t}}{\prod_{j=1,j\neq i}^{n}(\lambda_j - \lambda_i)}\right)$$

- expansion of exponentials
- here lambda can be decay or reaction (collapse of cross section with spectrum)

Inventory equation solutions

Decay solutions:

$$A \xrightarrow{\lambda_1} B \xrightarrow{\lambda_2} C$$

$$\dot{N}_A(t) = -\lambda_1 N_A(t)$$

$$\dot{N}_B(t) = -\lambda_2 N_B(t) + \lambda_1 N_A(t)$$

$$\dot{N}_C(t) = \lambda_2 N_A(t)$$

Task

What is the Bateman solution for this system?

$$N_n(t) = N_1(t=0)\left(\prod_{i=1}^{n-1}\lambda_i\right)\left(\sum_{i=1}^{n}\frac{e^{-\lambda_i t}}{\prod_{j=1,j\neq i}^{n}(\lambda_j - \lambda_i)}\right)$$

Inventory equation solutions

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$$A \xrightarrow{\lambda_1} B \xrightarrow{\lambda_2} C$$

$$\begin{aligned} N_B(t,\lambda_1,\lambda_2) =& \frac{\lambda_1}{\lambda_2-\lambda_1} N_A(t=0)(e^{-\lambda_1 t} - e^{-\lambda_2 t}),\\ =& \frac{\lambda_1}{\lambda_2-\lambda_1} N_A(t=0)e^{-\frac{(\lambda_1+\lambda_2)}{2}t}(e^{\frac{\lambda_2-\lambda_1}{2}t} - e^{\frac{\lambda_2-\lambda_1}{2}t})\\ =& 2\frac{\lambda_1}{\lambda_2-\lambda_1} N_A(t=0)e^{-\frac{(\lambda_1+\lambda_2)}{2}t}\sinh\left(\frac{\lambda_2-\lambda_1}{2}t\right). \end{aligned}$$

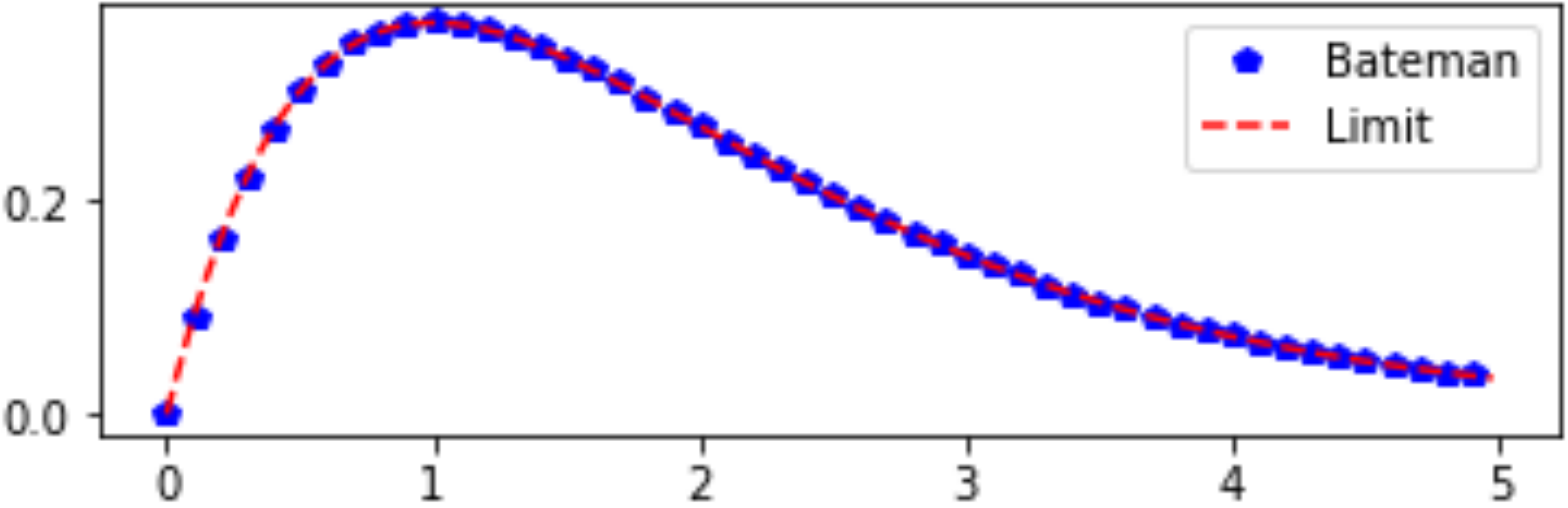
Caution if $\lambda_1 = \lambda_2$

$$b = \frac{\lambda_2-\lambda_1}{2}$$

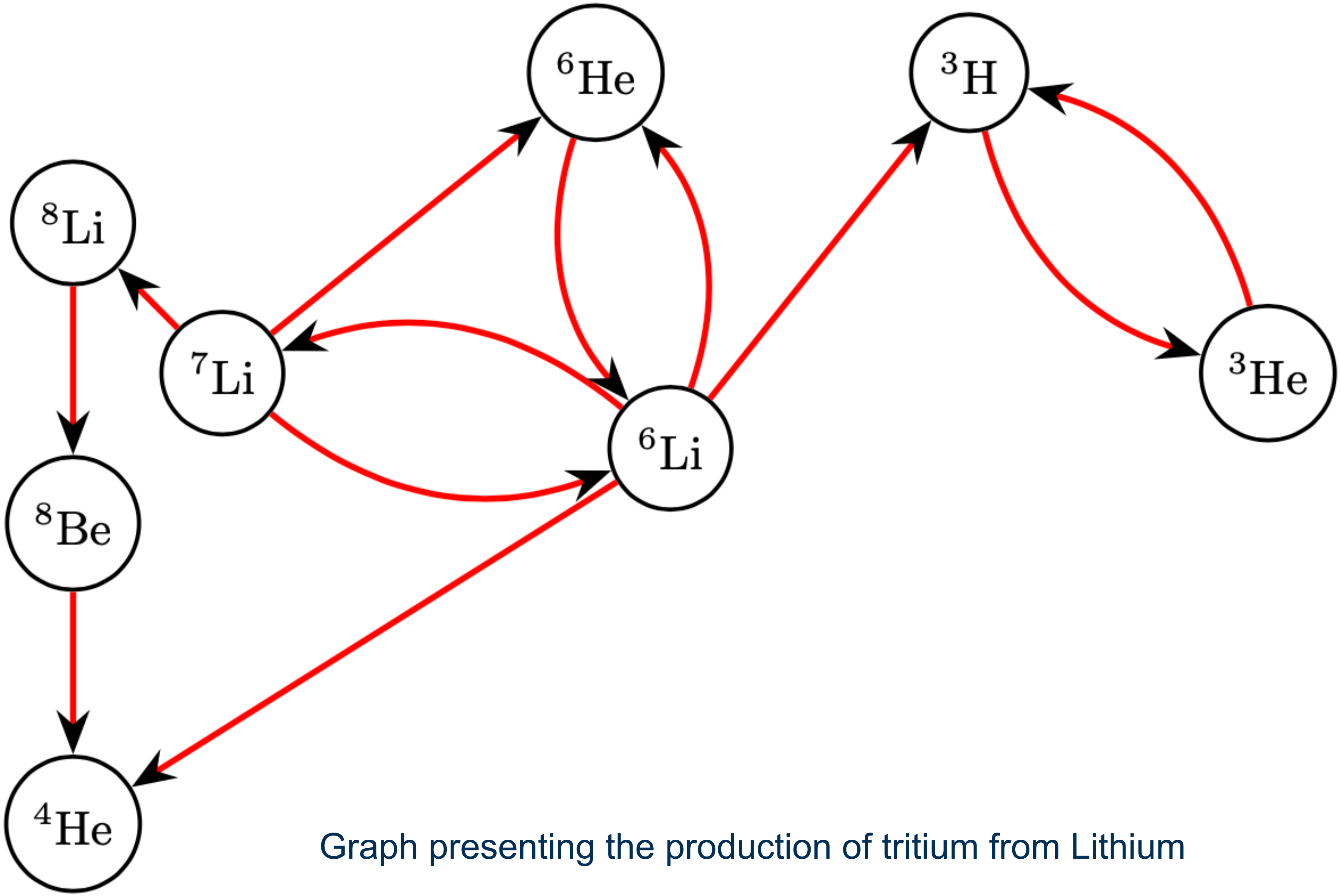
$$\lim_{b\to 0} N_B(t,\lambda_1,b) = N_A(t=0)\lambda_1 e^{-\lambda_1 t} t$$

Inventory equation solutions

$$\lim_{b\to 0} N_B(t, \lambda_1, b) = N_A(t=0)\lambda_1 e^{-\lambda_1 t} t$$



Deviations from chains

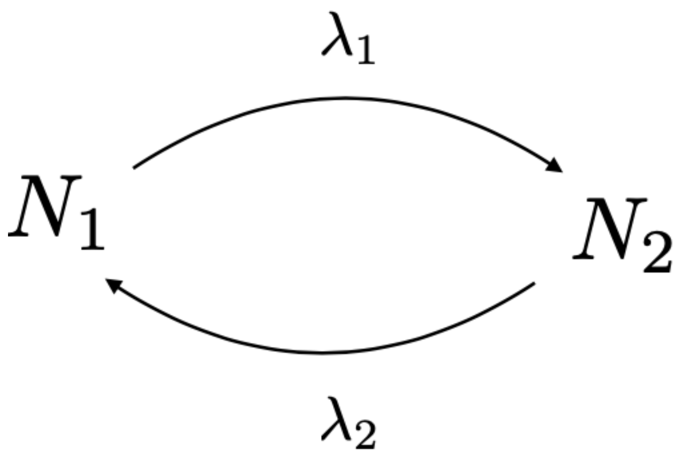


Graph presenting the production of tritium from Lithium

Activation loop

$$\dot{N}_1(t) = -N_1\lambda_1 + \lambda_2 N_2$$

$$\dot{N}_2(t) = -N_2\lambda_2 + \lambda_1 N_1$$



$$\dot{N}(t) = AN(t)$$ where $$A = \begin{bmatrix} -\lambda_1 & \lambda_2 \\ \lambda_1 & -\lambda_2 \end{bmatrix}$$

$$\sigma_1 = 0, v_1 = (\lambda_2, \lambda_1)$$

$$\sigma_2 = -(\lambda_1 + \lambda_2), v_2 = (-1, 1)$$

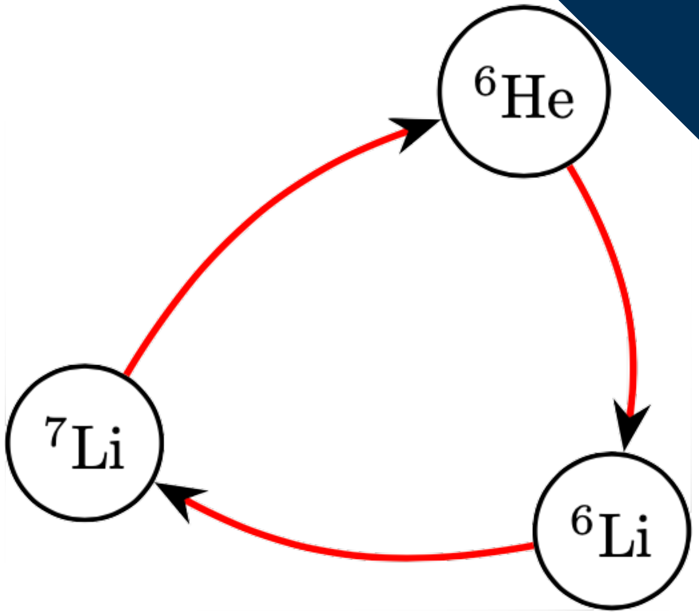
$$Av = \sigma v$$

Eigen equation

$$N(t) = c_1 v_1 e^{\sigma_1 t} + c_2 v_2 e^{\sigma_2 t}$$

$$N(t) = \frac{n_1 + n_2}{\lambda_1 + \lambda_2}\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} + \frac{\lambda_2 n_2 - \lambda_1 n_1}{\lambda_1 + \lambda_2} e^{-(\lambda_1+\lambda_2)t}\begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

Activation triangles



$$PA^{\text{sub}}P^{T} = \begin{pmatrix} -a & 0 & c \\ a & -b & 0 \\ 0 & b & -c \end{pmatrix}$$

$$\sigma = \{\sigma_i | Av_i = \sigma_i v_i\}$$

Which has one complex eigenvalue if a≈b and c<<1

- This is significant for initial time step estimate and error propagation of a numerical integrator
- Deviates away from conventional Bateman type solution

$$N(t) = c_1 v_1 e^{\sigma_1 t} + c_2 v_2 e^{i\omega t}$$

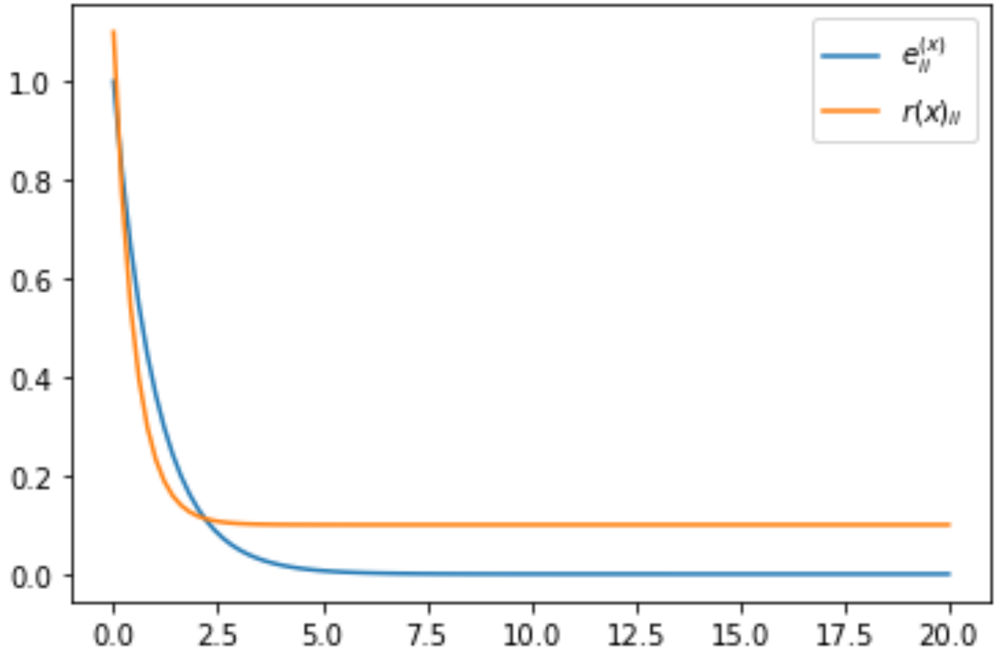
Computational inventory approaches

$$\dot{N}(t) = AN(t)$$

- Linear chains
  - Automate the Bateman linear chains solution
- CRAM (CHEBYSHEV RATIONAL APPROXIMATION METHOD)
  - Approximates exp(At) on the the negative comple plan.

$$\epsilon_{k,k} = \sup_{x\in\mathbb{R}^-} |r_{k,k}(x) - e^x| = \inf_{r_{k,k}\in\pi_{k,k}} \left(\sup_{x\in\mathbb{R}^-} |r_{k,k} - e^x| \right)$$

$$\hat{r}_{kk}(z) = \alpha_0 + \sum_{i=1}^{k} \frac{\alpha_i}{z - \theta_i}$$



- Used in the fission industry
- Assumes eigen values of A are distributed near the negative real axis.
- Coefficients are available in **M. Pusa's** thesis *'Numerical methods for nuclear fuel burnup calculations'* (Recommend to read)

UKAEA Inventory approach FISPACT-II

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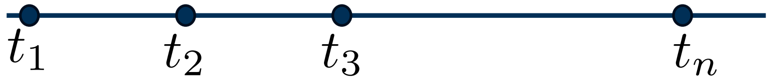
FISPACT-II performs a full finite difference numerical integration of the inventory equation:

- Variable is discretized on a lattice
  - FISPACT-II discretizes in time



$$y'(t) = f(t, y)$$

- Differentials are represented as a truncation of Taylor series on the lattice

$$\sum_{k=0}^{s} a_k y_{n+k} = h\beta f(t_{n+s}, y_{n+s})$$

- Backwards differential approximation
  - A-stable
    - Stable for large spectral range
  - Coefficients are available online
  - Further details in the FISPACT-II manual

FISPACT-II

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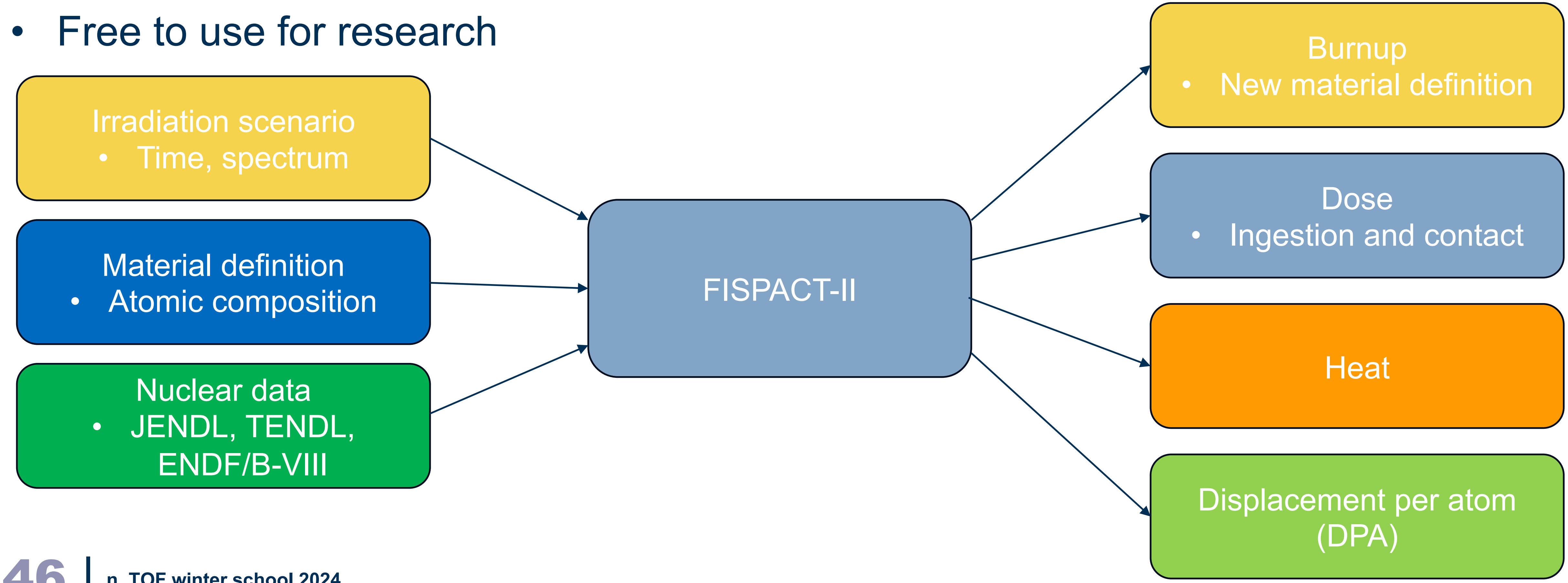
- UKAEA nuclear burnup code
- Availed to download from the NEA-DB
- Free to use for research



FISPACT-II

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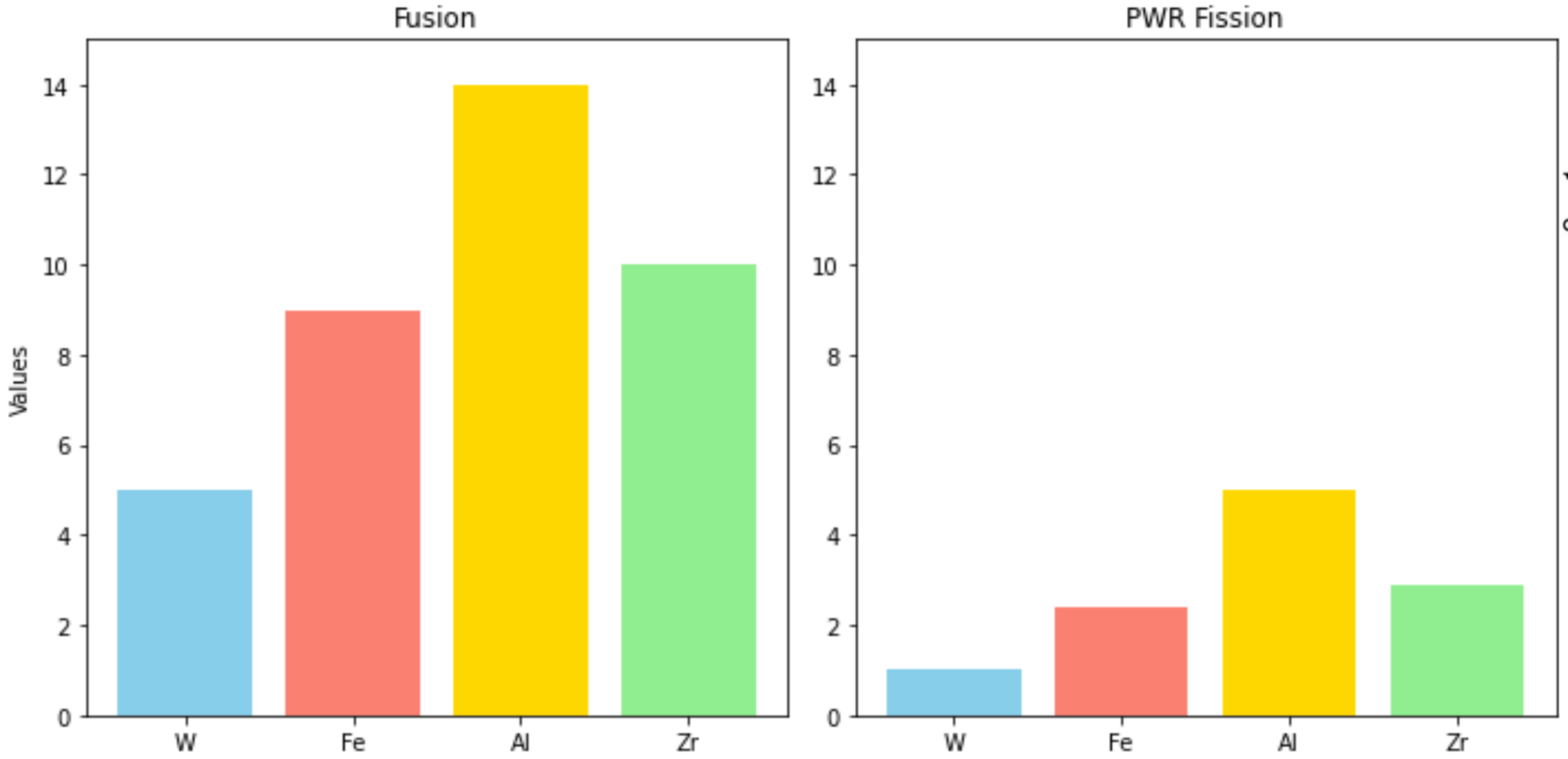
```
  Fe 60       1.53061E+06   1.523E-16   2.241E-08   1.835E-25   0.00E+00   0.000E+00   0.000E+00
  Co 57       6.76163E+08   6.393E-14   1.996E+01   5.849E-17   0.00E+00   4.004E-16   1.857E-10
  Co 58       9.86721E+16   9.493E-06   1.117E+10   6.141E-08   0.00E+00   1.747E-06   2.780E+00
  Co 58m      1.92475E+16   1.852E-06   4.164E+11   1.486E-06   0.00E+00   1.212E-07   1.108E-01
  Co 59    #> 1.02186E+25   1.000E+03   0.000E+00   0.000E+00   0.00E+00   0.000E+00   0.000E+00
  Co 60       3.03394E+15   3.019E-07   1.264E+07   1.960E-10   0.00E+00   5.072E-09   9.199E-03
  Co 60m      9.84923E+12   9.802E-10   1.087E+10   9.696E-08   0.00E+00   1.182E-08   1.478E-02
  Co 61       1.91280E+04   1.935E-18   2.232E+00   1.668E-16   0.00E+00   3.468E-17   2.633E-11
  Ni 59       1.88628E+04   1.846E-18   5.451E-09   4.037E-27   0.00E+00   2.222E-27   1.903E-21
  Ni 60    #  5.75910E+12   5.731E-10   0.000E+00   0.000E+00   0.00E+00   0.000E+00   0.000E+00
  Ni 61    #  1.85560E+05   1.877E-17   0.000E+00   0.000E+00   0.00E+00   0.000E+00   0.000E+00
0  TOTAL NUMBER OF NUCLIDES PRINTED IN INVENTORY =   36
0  TOTAL CURIES    TOTAL ALPHA    TOTAL BETA     TOTAL GAMMA
                   CURIE-MeV      CURIE-MeV      CURIE-MeV
   1.26502E+01   0.00000E+00   9.09757E-01   1.66822E+00
0  ALPHA BECQUERELS = 0.000000E+00  BETA BECQUERELS = 4.081865E+10  GAMMA BECQUERELS = 4.272379E+11
0  TOTAL ACTIVITY FOR ALL MATERIALS     4.68057E+11 Bq
   TOTAL ACTIVITY EXCLUDING TRITIUM     4.68057E+11 Bq
0  TOTAL ALPHA HEAT PRODUCTION          0.00000E+00 kW
   TOTAL BETA  HEAT PRODUCTION          5.39309E-06 kW
   TOTAL GAMMA HEAT PRODUCTION          9.88929E-06 kW            TOTAL HEAT PRODUCTION 1.52824E-05 kW
0  INITIAL TOTAL MASS OF MATERIAL       1.00000E+00 kg            TOTAL HEAT EX TRITIUM 1.52824E-05 kW
0  TOTAL MASS OF MATERIAL               1.00000E+00 kg
   NEUTRON  FLUX DURING INTERVAL        1.00000E+11 n/cm^2/s
0  NUMBER OF FISSIONS                   0.00000E+00               BURN-UP OF ACTINIDES  0.00000E+00 %
0  Total Displacement Rate (n,Ddiss) =  1.64178E+14 Displacements/sec  =  1.60666E-11 Displacements Per Atom/sec  =  5.07023E-04 DPA/year
   Total Displacement Rate (n,Dinel) =  4.46510E+14 Displacements/sec  =  4.36958E-11 Displacements Per Atom/sec  =  1.37893E-03 DPA/year
   Total Displacement Rate (n,Del  ) =  5.64248E+14 Displacements/sec  =  5.52178E-11 Displacements Per Atom/sec  =  1.74254E-03 DPA/year
   Total Displacement Rate (n,Dtot ) =  2.28961E+15 Displacements/sec  =  2.24063E-10 Displacements Per Atom/sec  =  7.07090E-03 DPA/year
0  KERMA RATE (n,Kktot) =  5.94800E+18 eV/sec = 9.52974E-04 kW/kg = 8.48147E-06 kW/cm^3
```

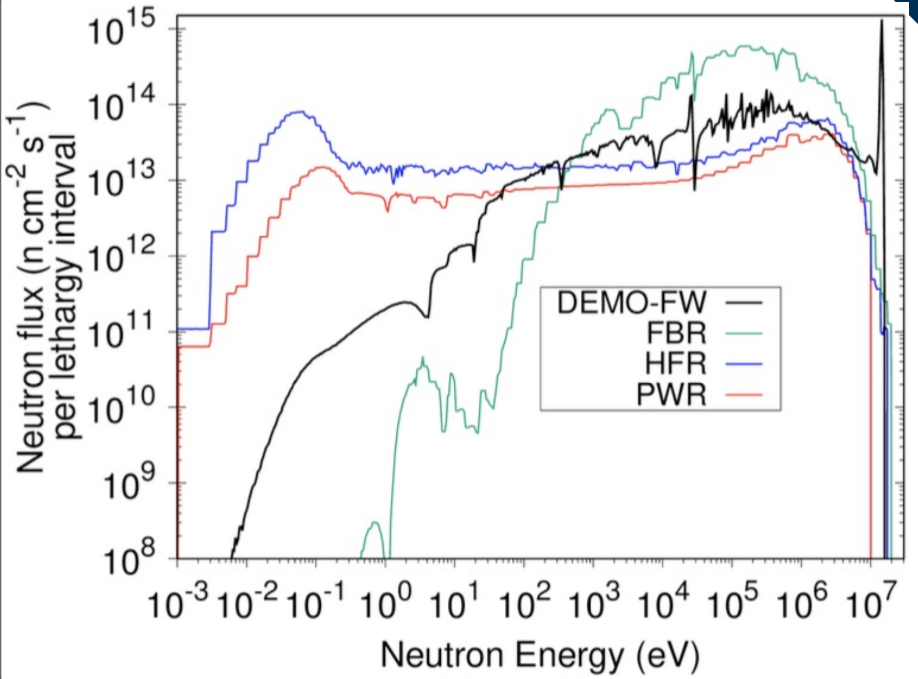
Irradiation of Cobalt
Much more outputs

DPA

Materials

The energy delivered to materials by the neutron bombardment is more severe than from fission





- Displacements per atom (DPA/dpa) is an atomic-level measure of neutron dose
- DPA is an integral measure that loses much of the information available from nuclear data?

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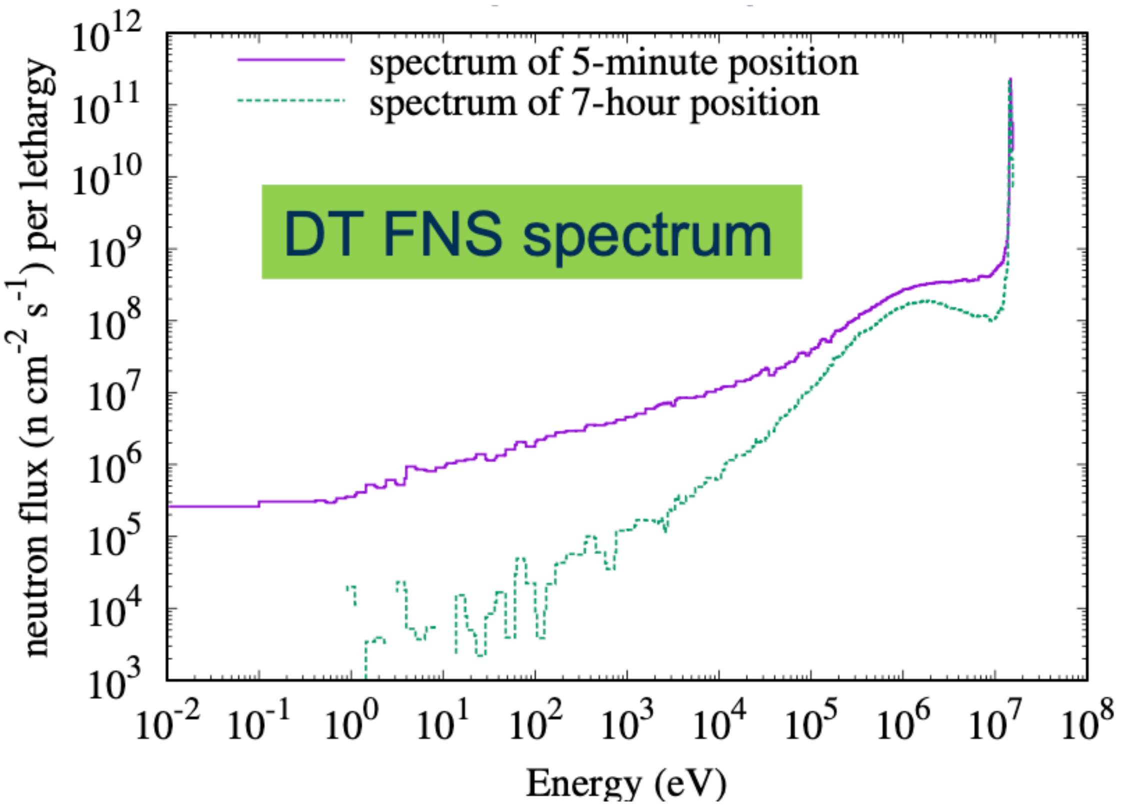
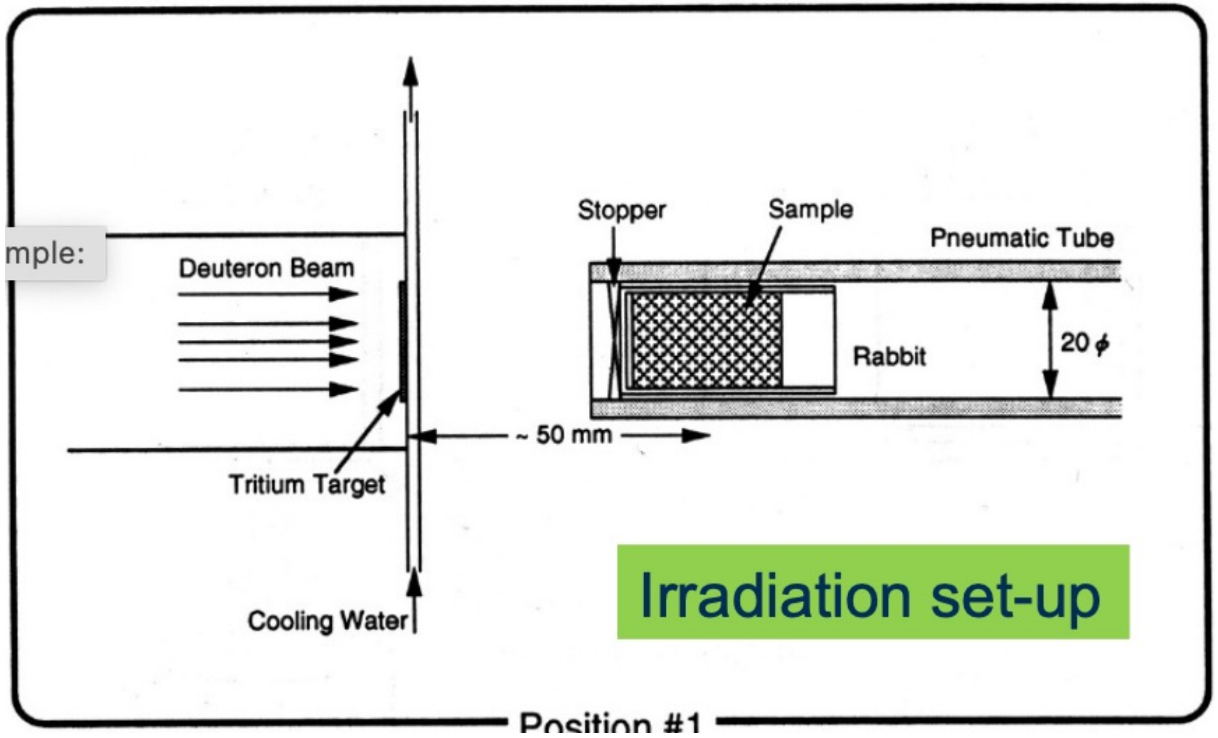
FNS decay-heat

- The Japan Atomic Energy Agency (JAEA) used their Fusion Neutron Source (FNS) to irradiate several materials.
- 2 mA deuteron beam onto a tritium target producing a fusion neutron flux (14MeV peak) ~10^10 n/cm2/s



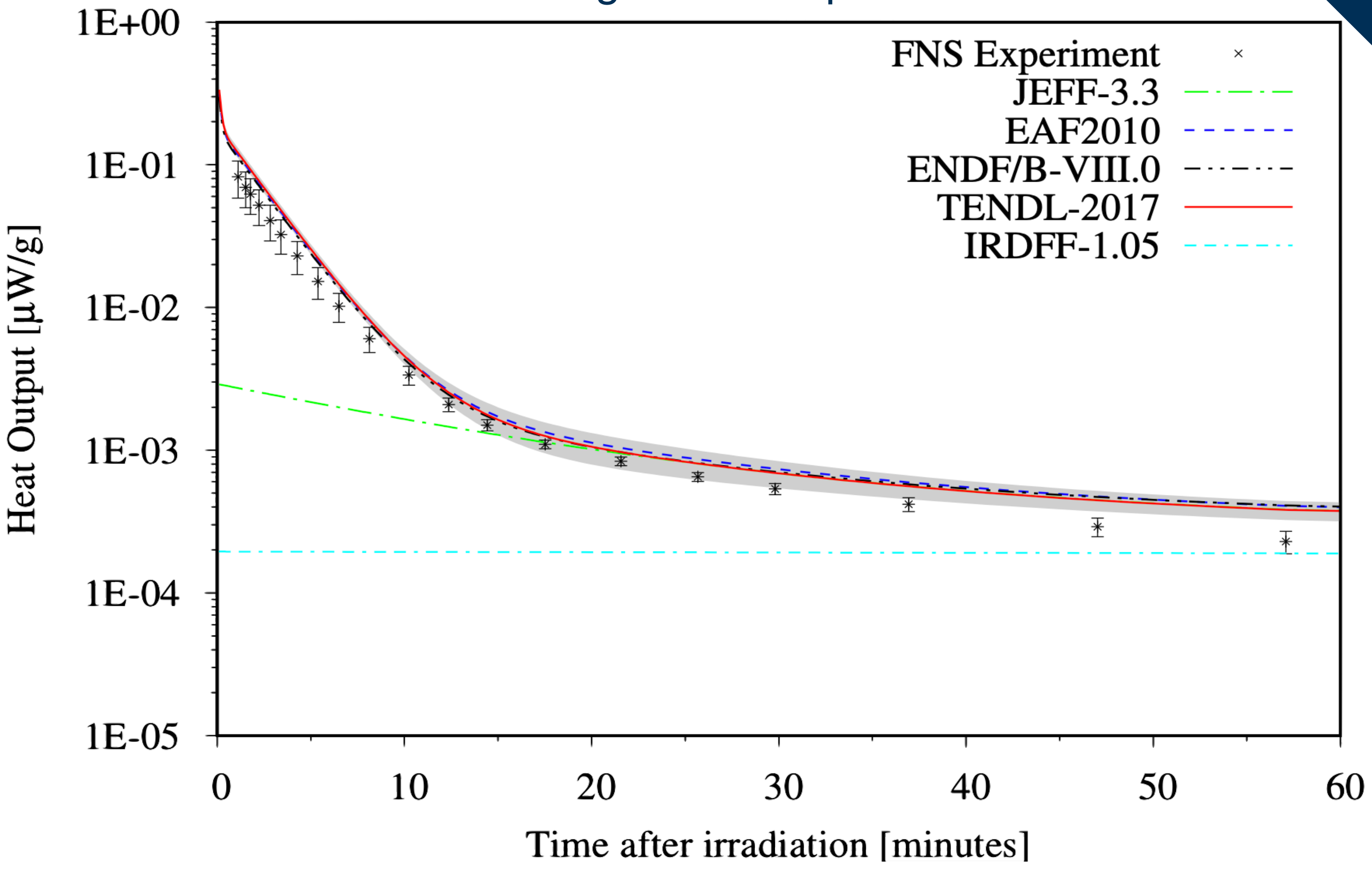


FISPACT-II FNS benchmark

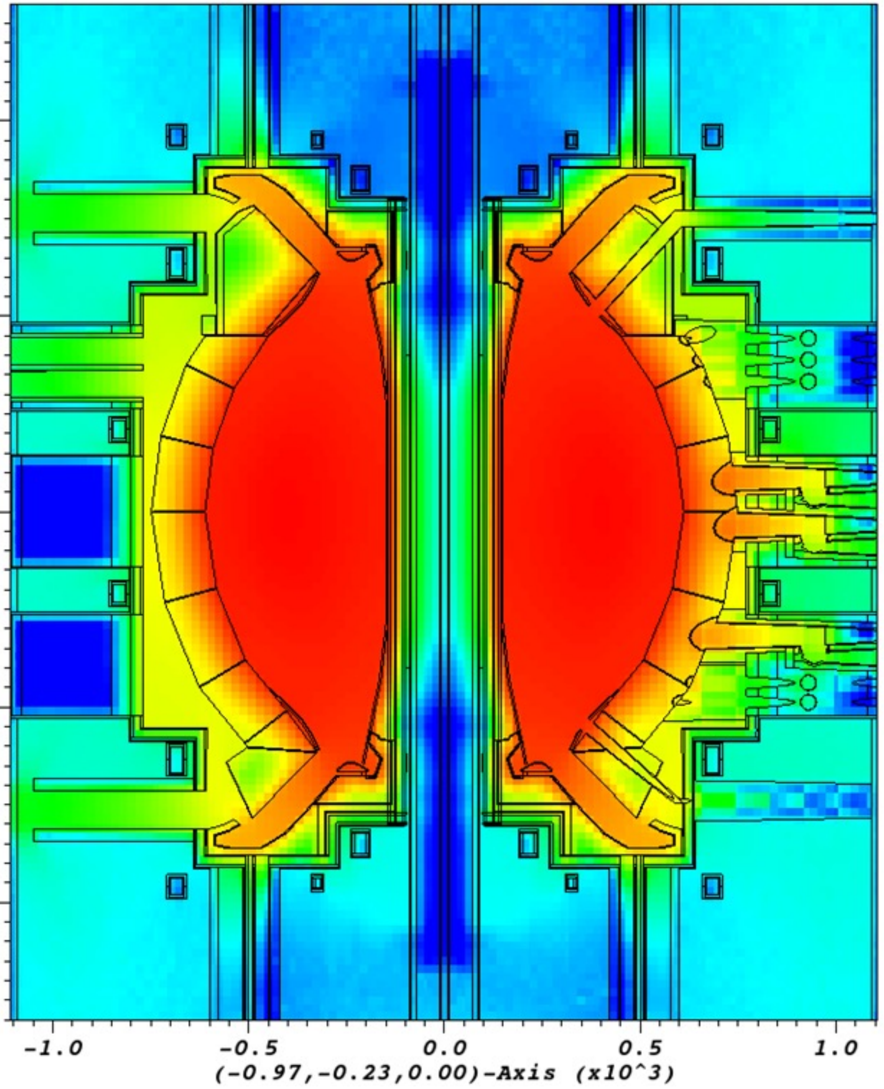
M. R. Gilbert and J.C. Sublet (2018) used the FNS heat results to validate FISPACT-II for 73 materials.

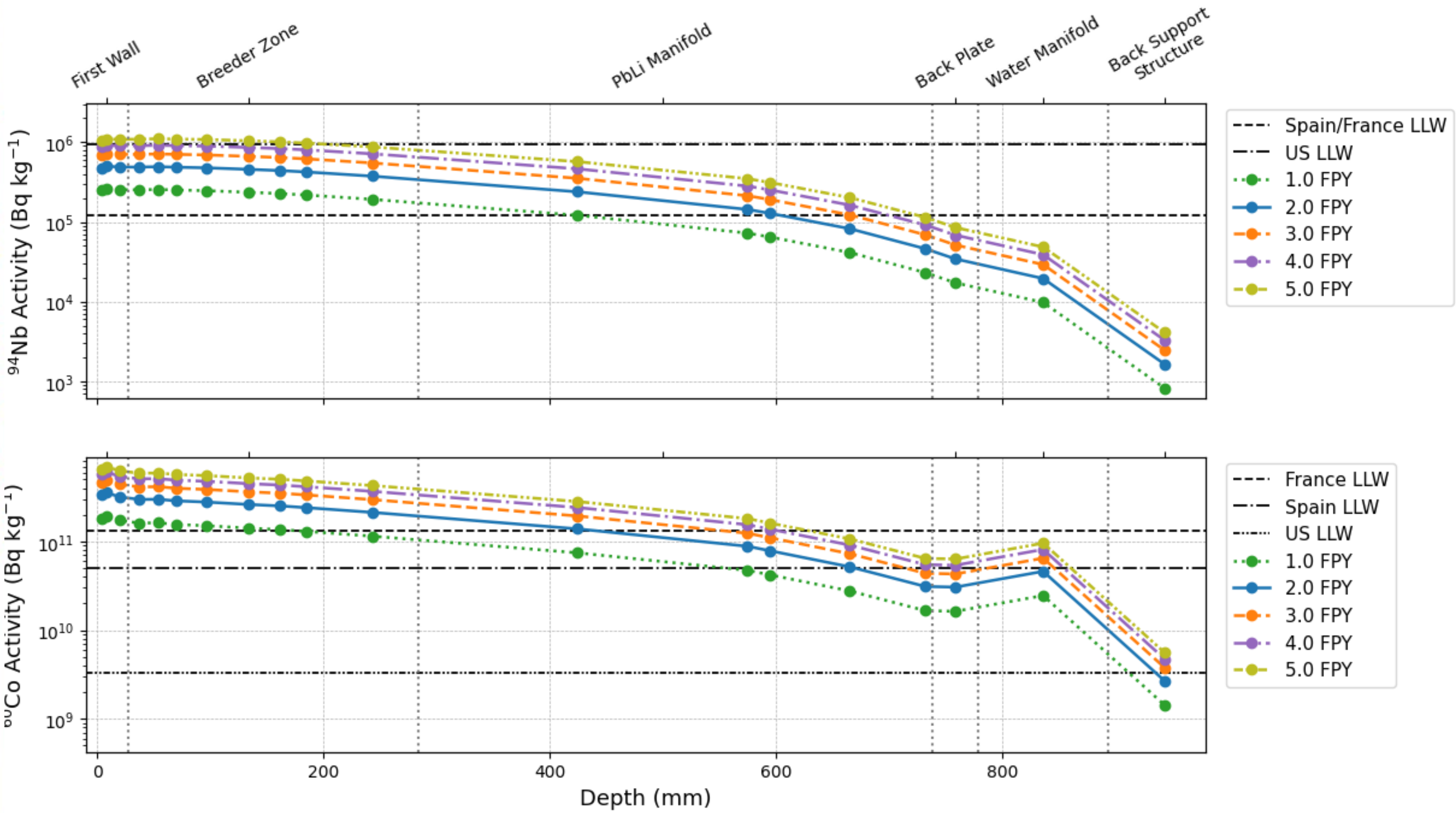
- 73 different materials
- Developed into a simulation benchmark
  - Tests:
    - FISPACT-II
    - Nuclear data libraries
- Fundamental for nuclear engineering
  - Waste predictions
  - Material performance
  - Service schedule
    - Technician dose
  - Tritium production

Tungsten example



Complex example:





Latest Insights From EU-DEMO Activation Assessments, FEC 2023. G. Bailey et al

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Summary

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- Introduction to nuclear fusion
  - DT reaction and energetic distribution
- Fusion ignition and some devise types
  - Inertial confinement and Magnetic (UKAEA approach)
- Tritium fuel production
- Neutron activation
  - Inventory solutions – my area
- FISPACT-II introduction
- Fusion activation benchmark (FNS)

Thank you very much