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Fusion and neutron spectroscopy

Gemma Wilson – senior experimental nuclear physicist – Gemma.wilson@ukaea.uk

Introduction to me

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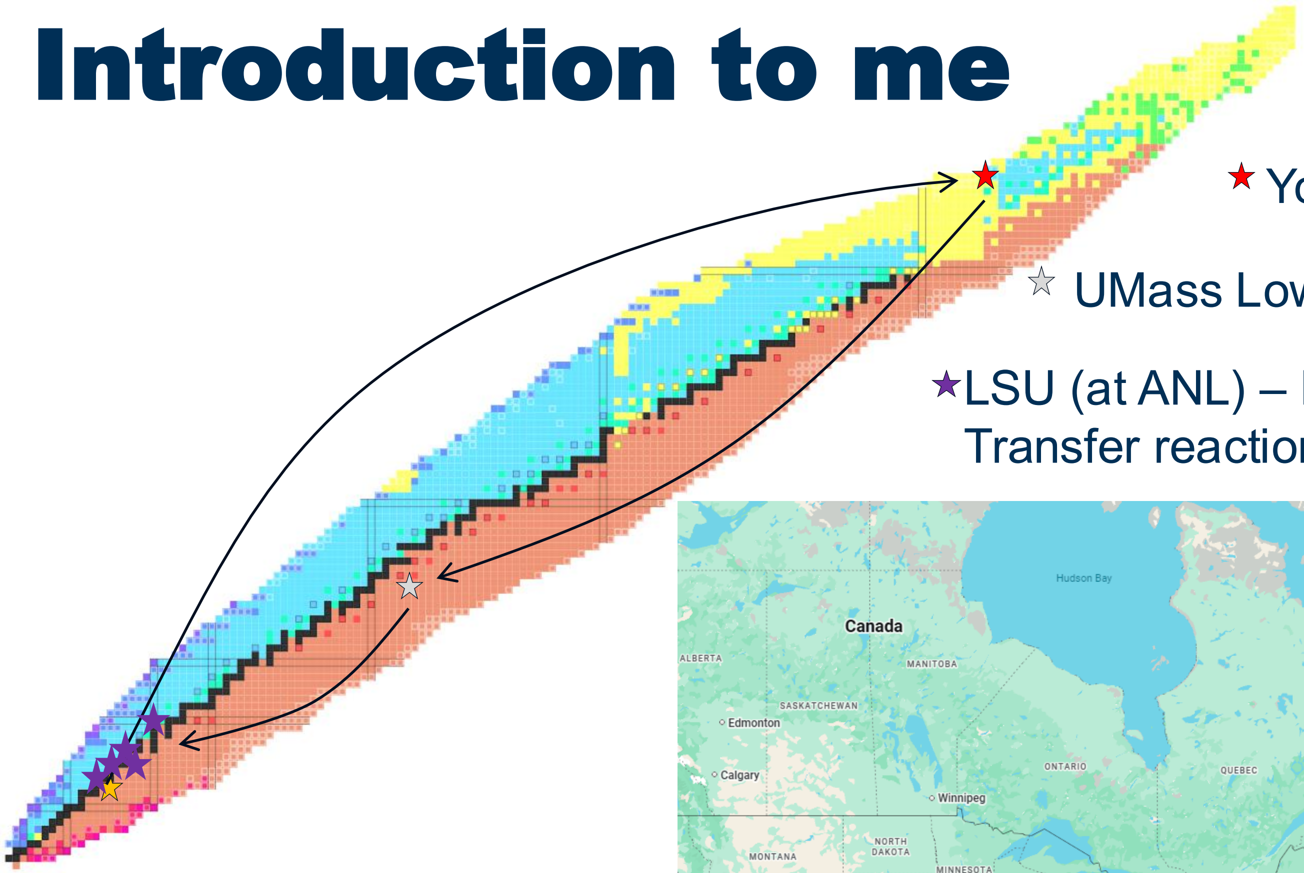

★ Surrey – MPhys, PhD; ^{25}Na(d,p)^{26}Na (2005-2013)

★ York – β-delayed fission of ^{230}Am (2013-15)

☆ UMass Lowell - β-delayed neutron emission from ^{94}Rb (2015-17)

★ LSU (at ANL) – Paul Trap design (β-delayed neutron emission); Transfer reactions; in-flight beam development (2017-2023)

★ UKAEA (2023-present)

Introduction to me

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When getting career advice, remember:

- Everyone has different priorities and circumstances
- What are your deal breakers?
- Where would you/wouldn't you live?
- Postdocs are a great way of exploring but lack security
- So much of this is luck
- Your priorities can change...

April 2025 after two operations, 48 Gy of pelvic radiotherapy and 6 rounds of chemotherapy

Contents

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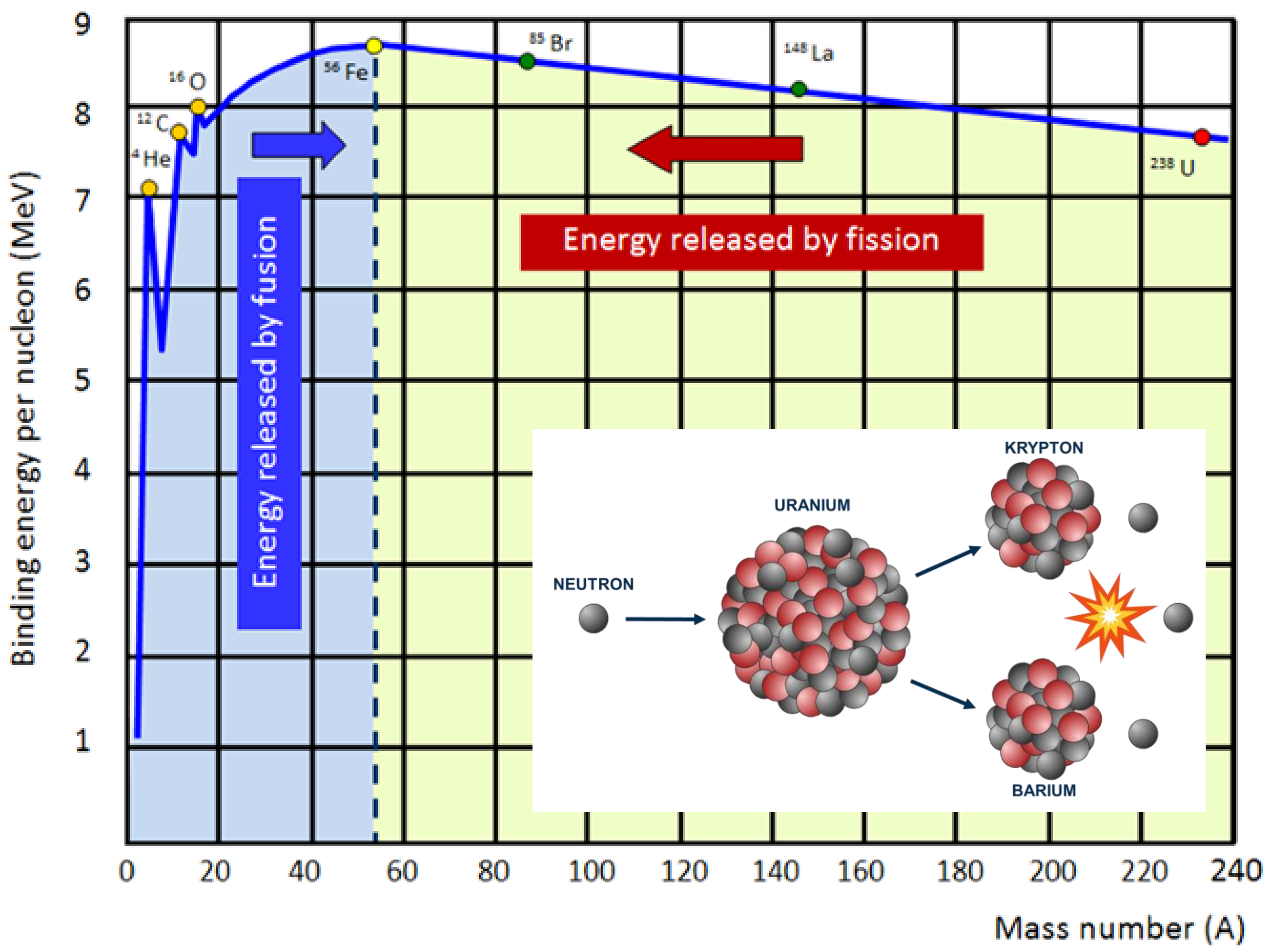
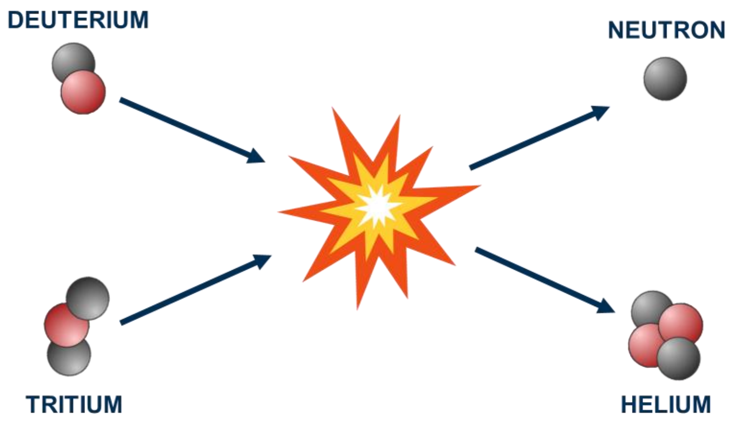
Nuclear reactions





Energy per mole from the DT reaction

Molar masses:

D ~2.013g, T ~3.016g; He-4 ~4.0026g, *n* ~1.0087g

Mass difference:

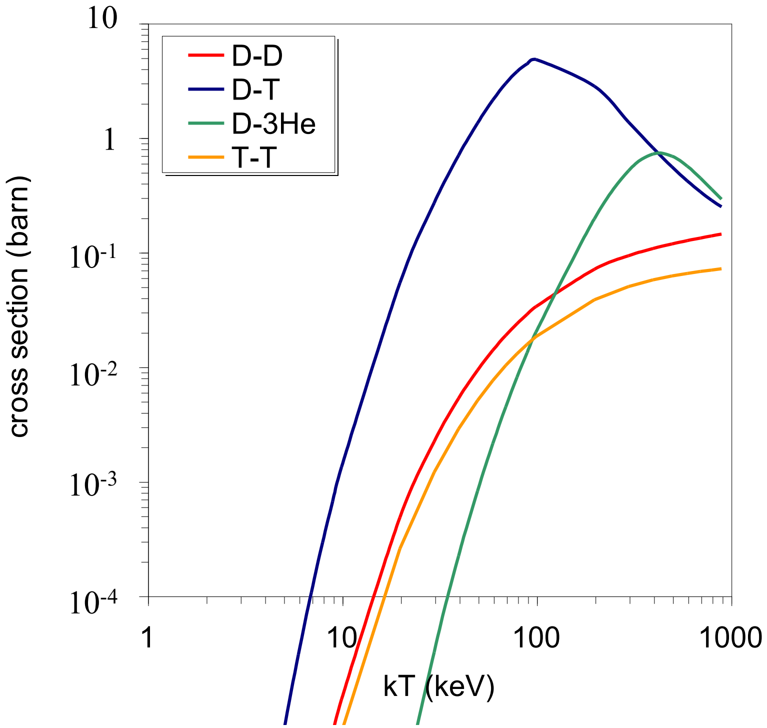
$\Delta m = m_D + m_T - m_{He} - m_n$ ~ 0.018 g per mole

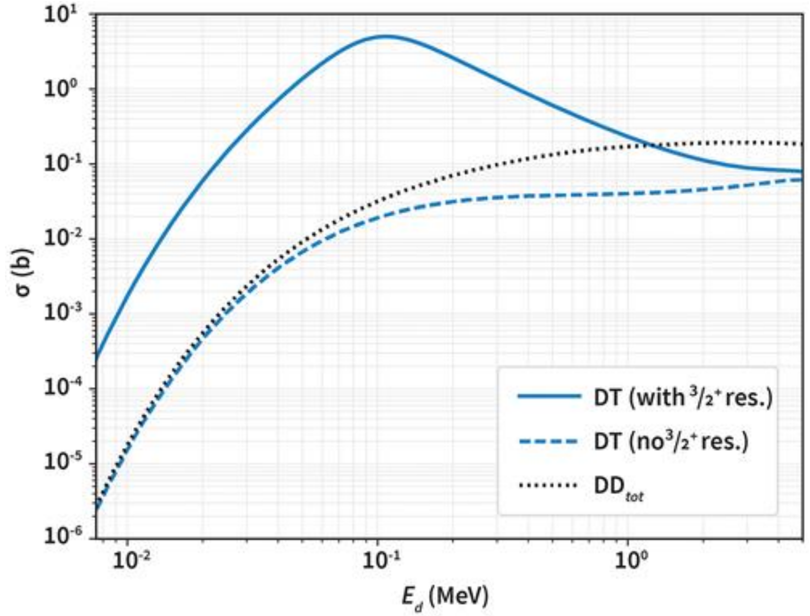
Energy = $(\Delta\, m)c^2$ = 1.6 × 10^{12} J per mole

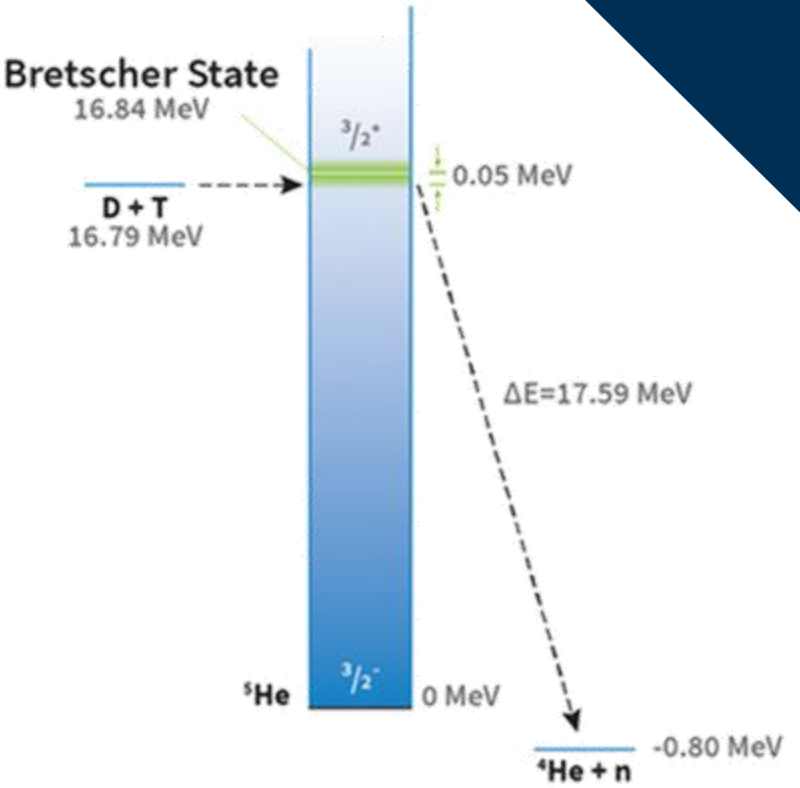
Average energy usage in the EU for 1 person ~ 20kWh/day:
5g of fuel ~ 63 years of energy for one person!

Energy per kg - DT fusion is a factor of between 10 and 14 million times that of coal depending on coal sources

Nuclear fusion on Earth







$^2D + ^2D \rightarrow ^3He + n$ (Q = 3.27 MeV)

$^2D + ^3He \rightarrow ^4He + ^1H$ (Q = 18.3 MeV)

$^2D + ^3T \rightarrow ^4He + n$ (Q = 17.6 MeV)

DT fusion cross section exceeds the deuterium-deuterium (DD) cross sections by a factor of 100, thanks to the A=5 J^{π} 3/2+ **“Bretscher” state**

Several Approaches to Fusion

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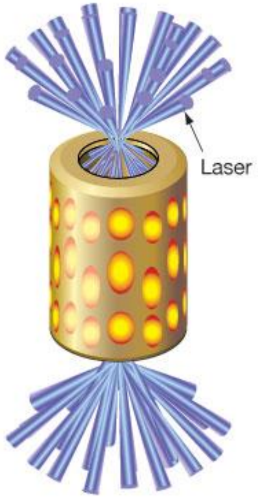
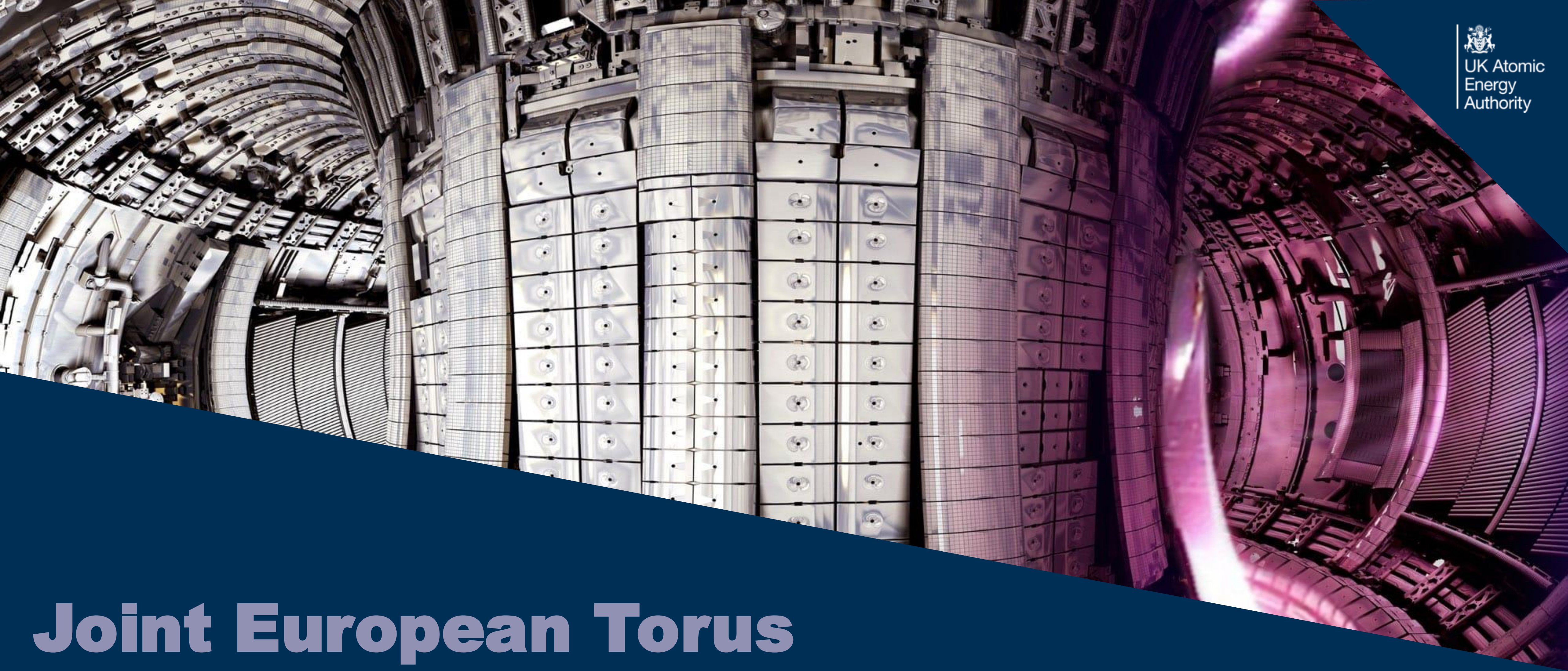
Inertial Confinement



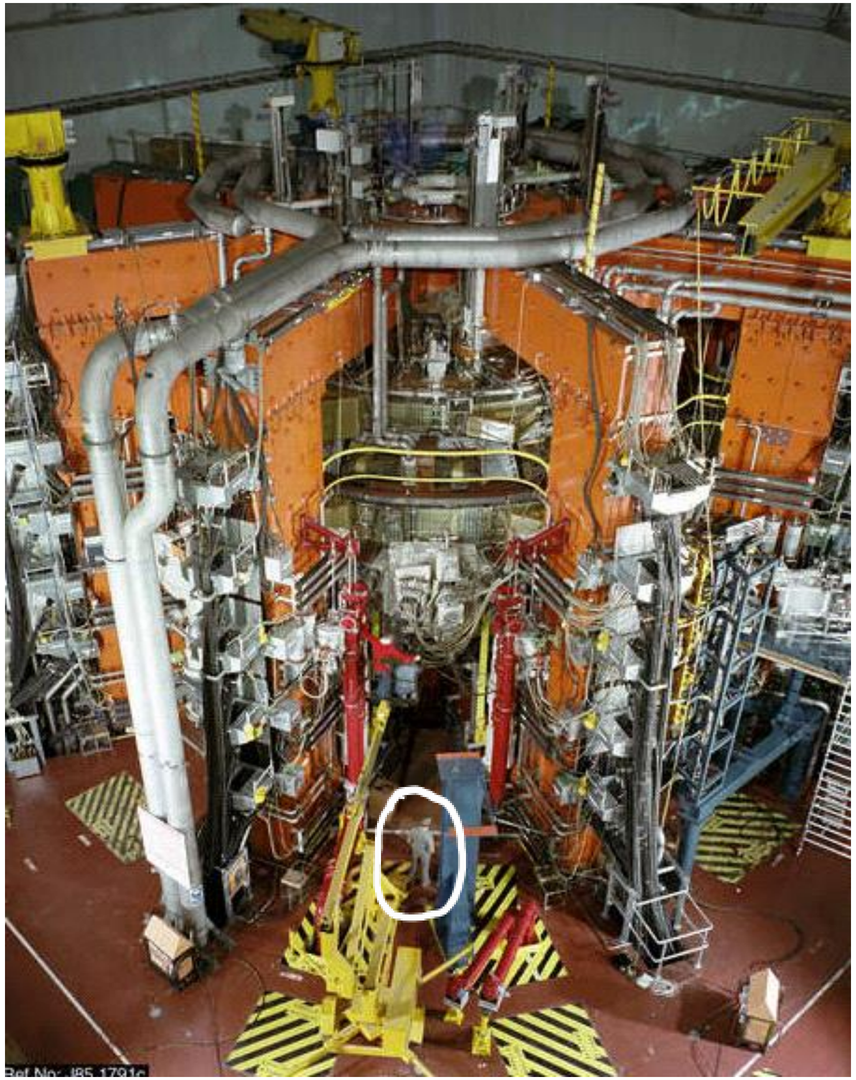
Gravitational Confinement

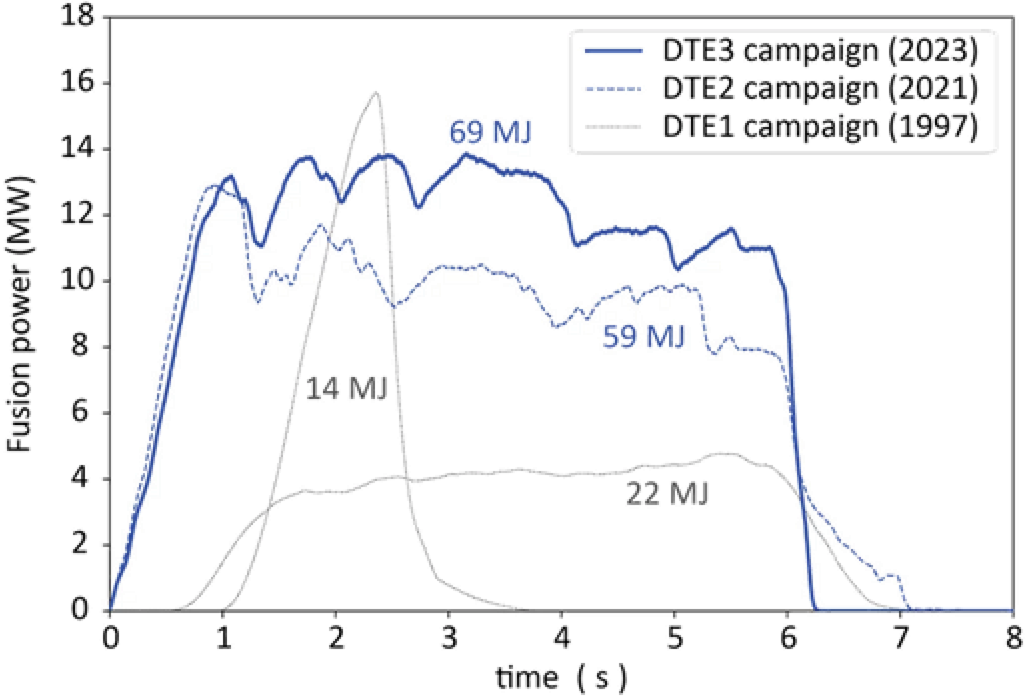
Magnetic Confinement



Joint European Torus (JET)

Joint European Torus (JET)





JET has achieved the largest amount of energy ever achieved in a fusion experiment – using just 0.2 milligrams of fuel.

https://www.euro-fusion.org/devices/jet/

Challenges of Fusion

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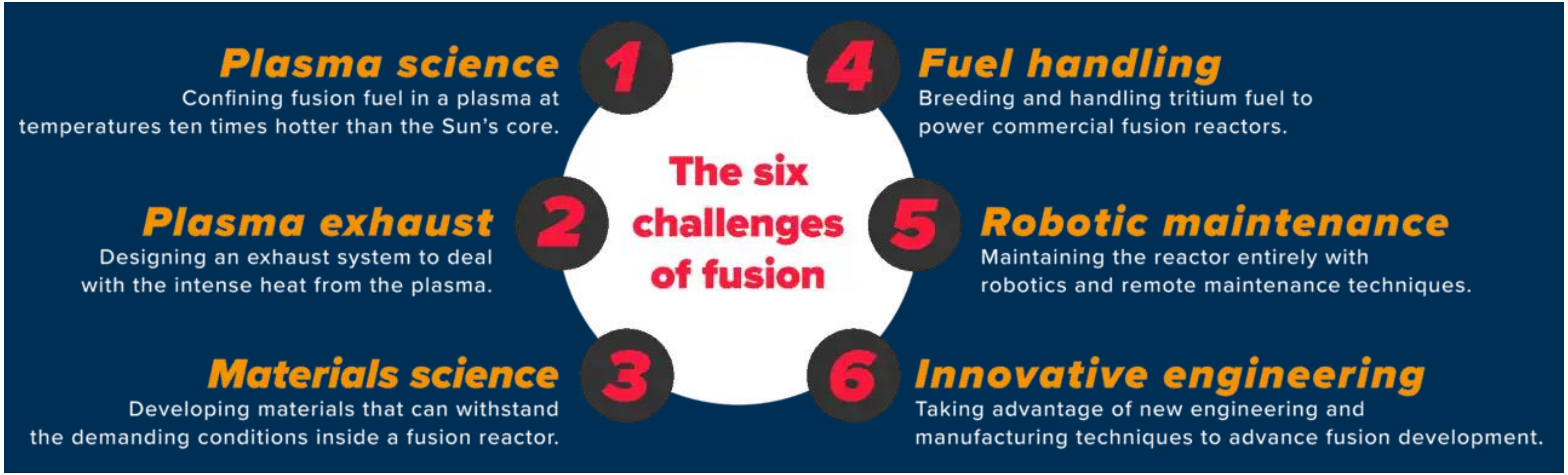
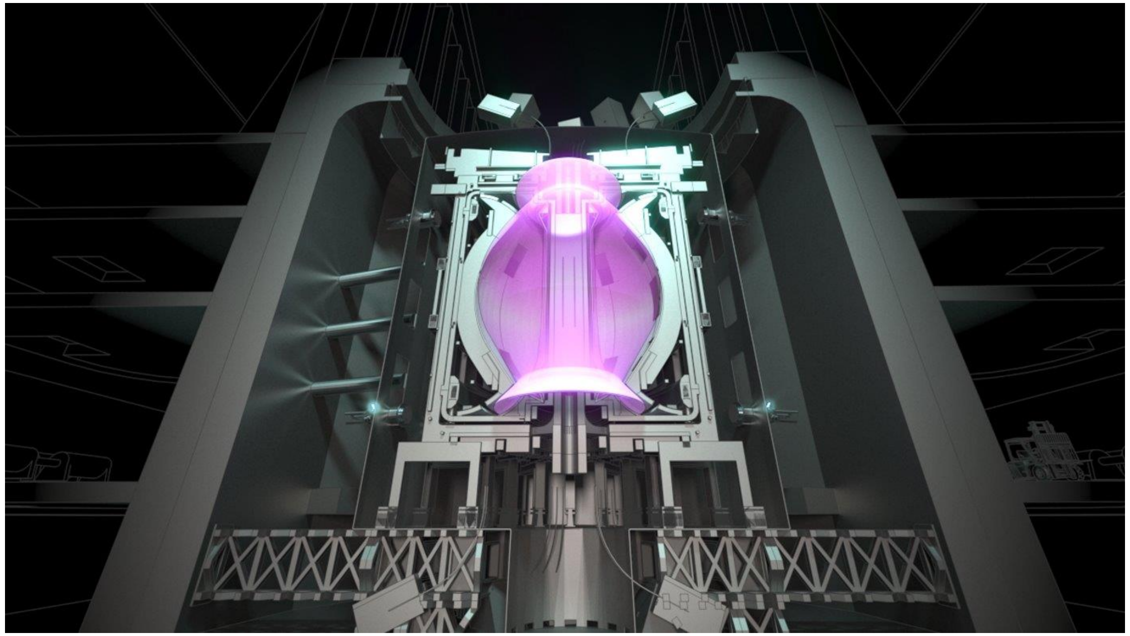
- Requires investment, political will, and skilled, dedicated scientists and engineers to solve technological and materials problems

- Fusion is not a silver bullet – going to need fission and renewables in the mix

- Fusion is moving from the research phase to the delivery phase. Key technologies and materials needed for power plants have not yet been fully tested and demonstrated



STEP



Building a prototype fusion power plant with the aim to demonstrate net energy from fusion targeting 2040.

This will support the potential development of a fleet of future fusion powerplants around the world and seeks to ensure that the UK remains at the forefront of a new technology and emerging industry.

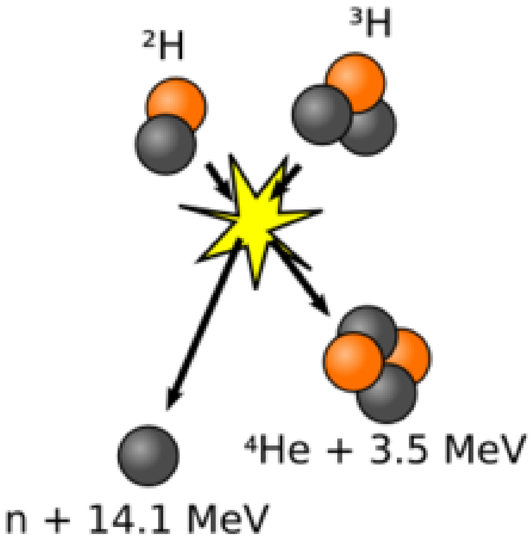
Goals:

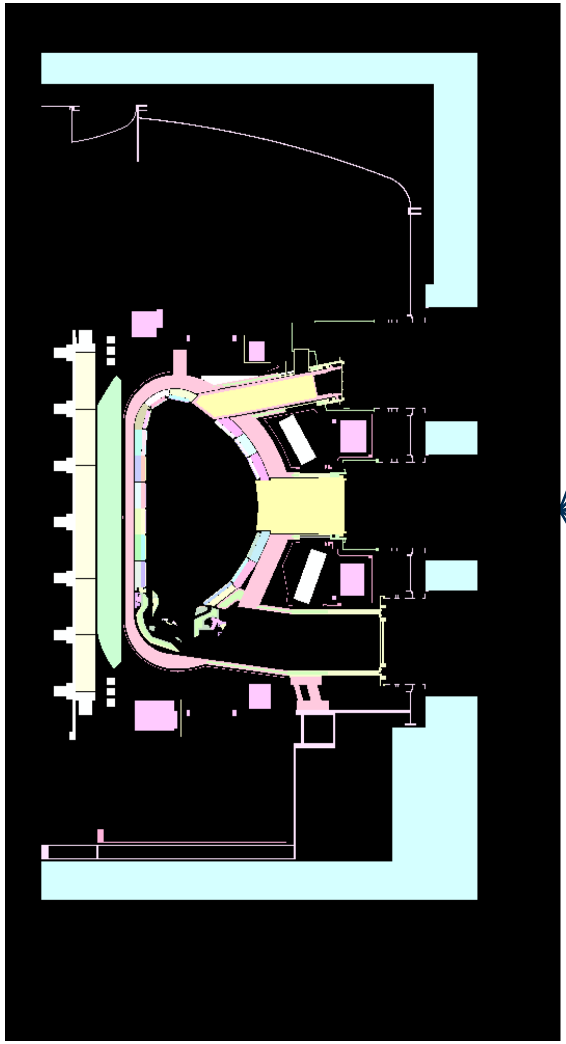
- Demonstrate the ability to put net electricity on the grid.
- Demonstrate how the powerplant can be maintained through its operational life and produce its own fuel.
- Develop UK industry and manufacturing capabilities in preparation for powerplant roll out.

https://step.ukaea.uk/

Neutrons from fusion

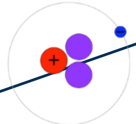
Neutronics is the study of ‘neutrons’ and their interactions.





Radioactivity – Neutrons activate material

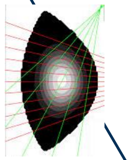
Hazardous - Neutrons are hazardous to health and protection for work force is required.



Produce fuel – Neutrons needed to convert lithium into tritium

Structural integrity – Neutrons cause damage to materials such as embrittlement, swelling etc.

Electricity – 80% of the energy from the fusion reaction is carried by neutrons



Diagnose – Neutrons are important diagnostic of plasma performance

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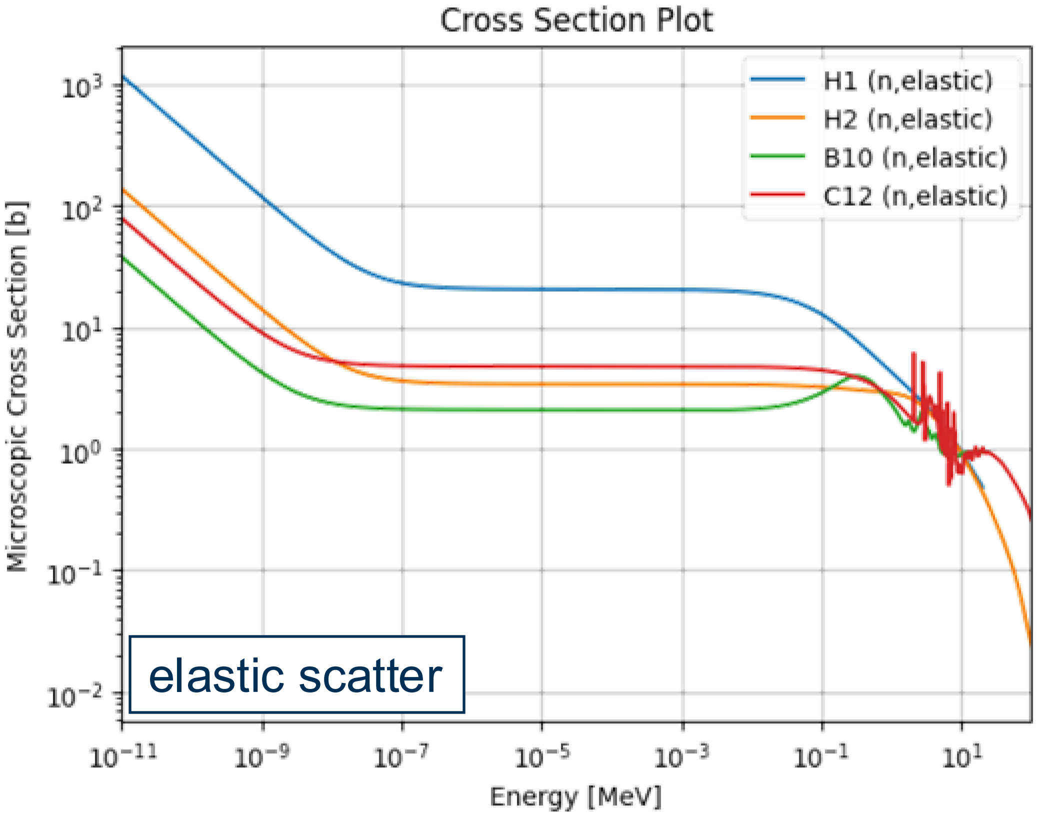
Key cross sections

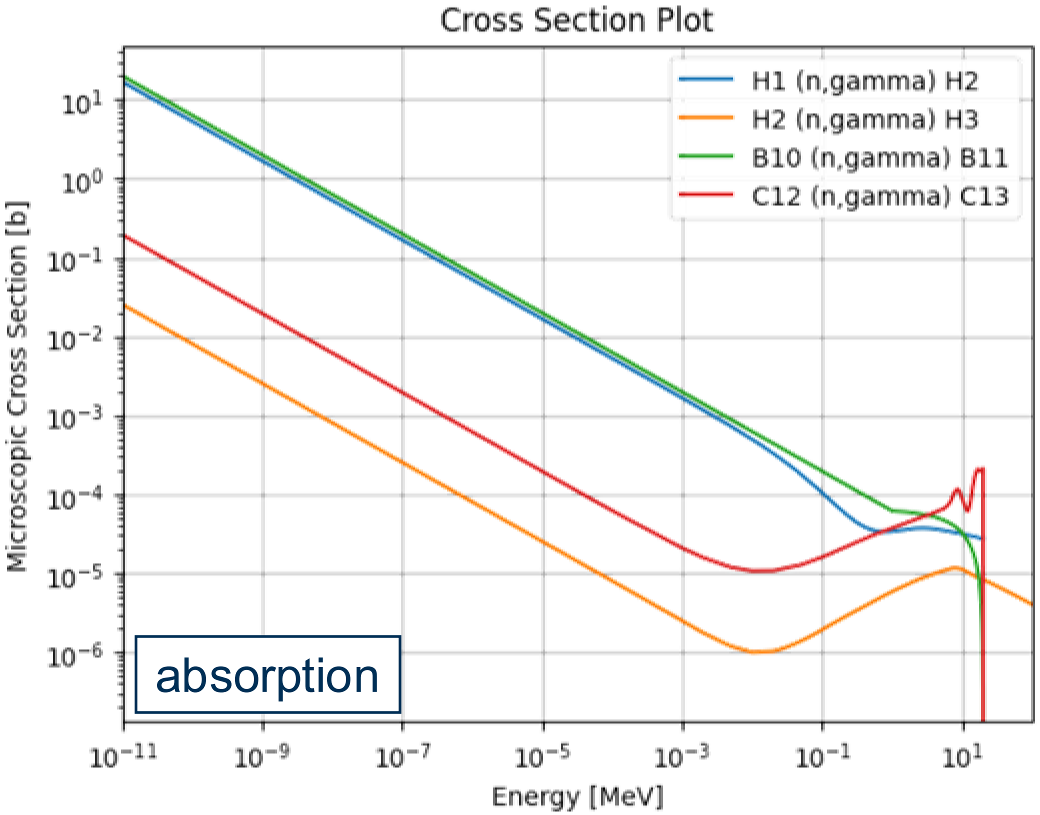
Cross sections are:

- dependent on neutron energy
- dependent on the target isotope
- dependent on material temperature
- compiled into evaluated nuclear data files

$$^{12}C(n,\gamma)^{13}C$$

Target Projectile Product Product





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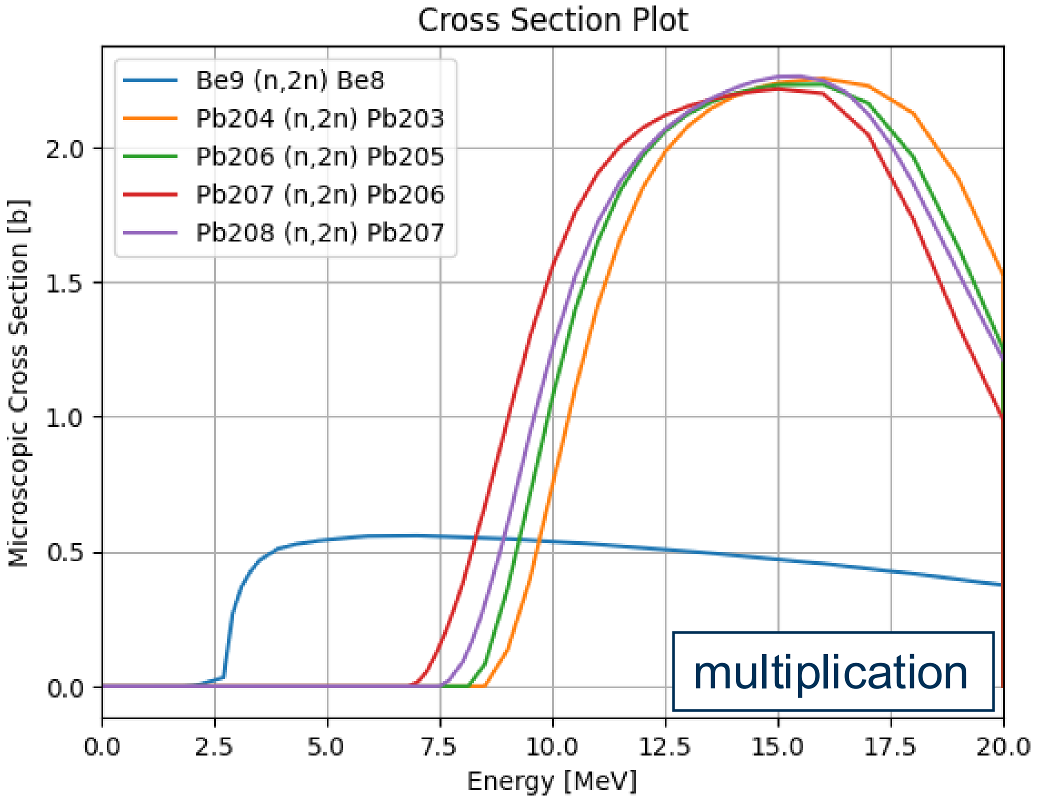
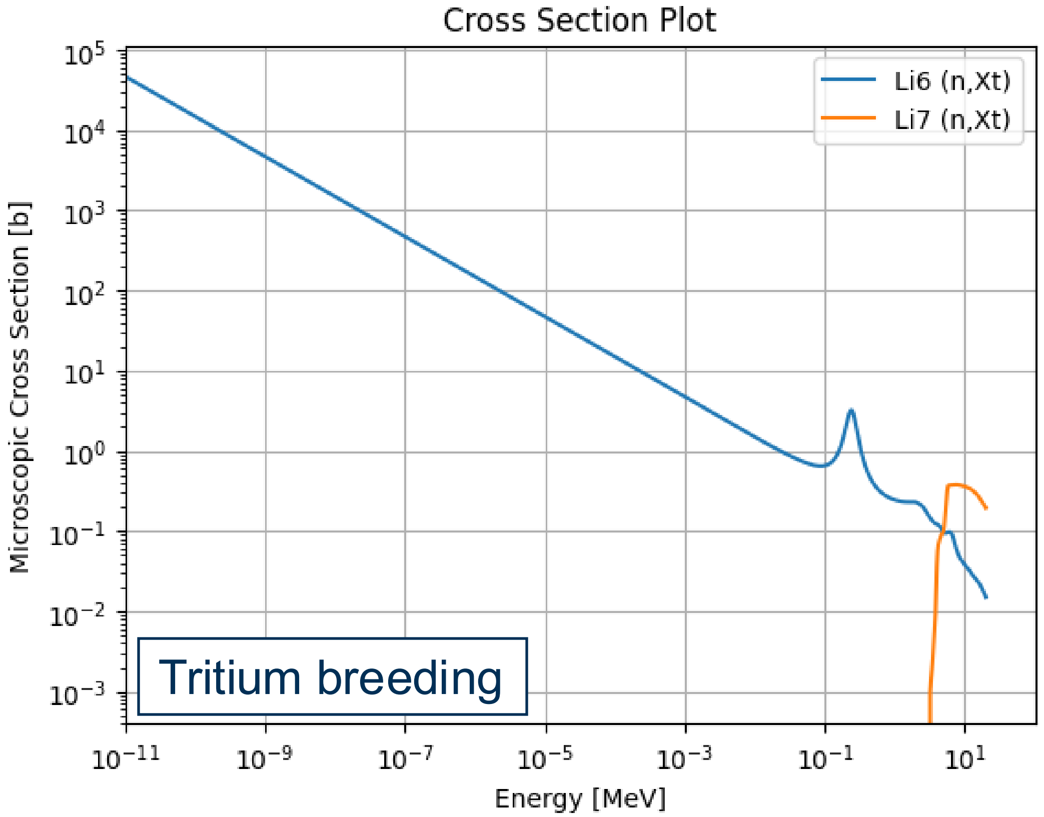
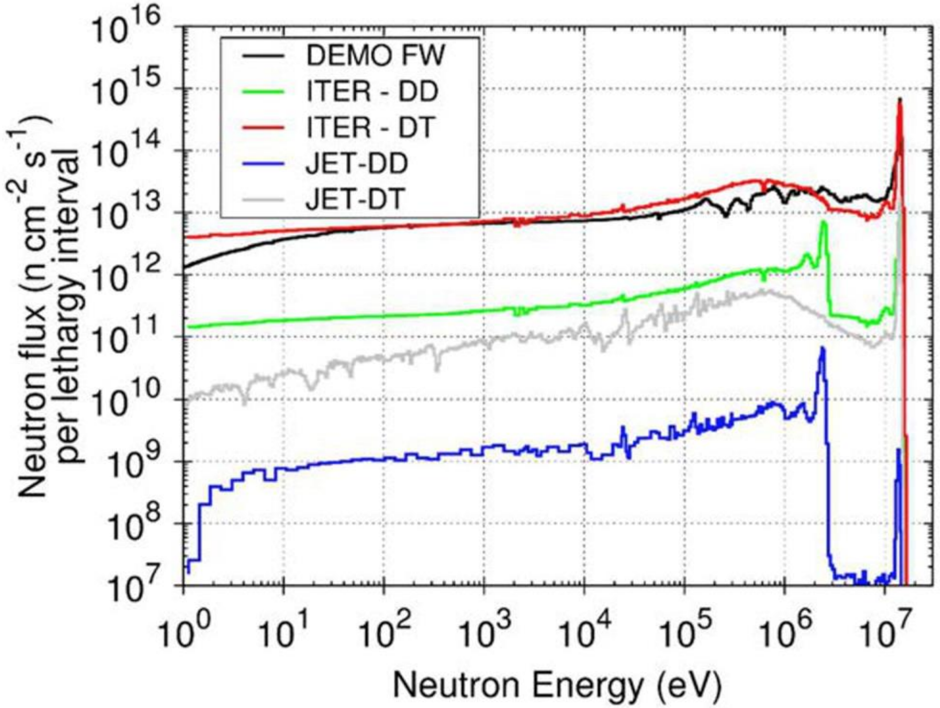
Target | Projectile | Product | Product

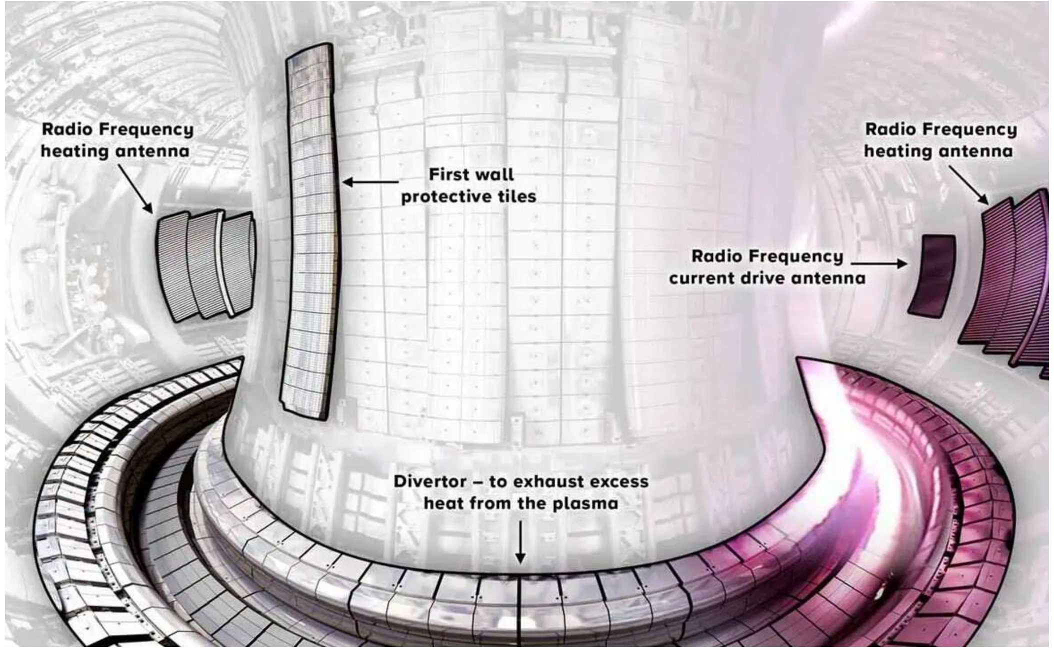




Neutron spectra in tokamaks



- The plasma will produce monoenergetic neutrons either 14 MeV (DT) or 2.5 MeV (DD)
- 14 MeV fusion neutrons lose energy by elastic and in-elastic scattering events with material in the device surrounding the plasma
- Hence even at the first wall there will be a large range of neutron energies



- Measurement of neutrons directly relates to fusion power
- Plasma and fuel parameters can be derived from neutrons
  - fuel ratio (nT/nD)
  - fast ion temperature and alpha energy distribution
  - alpha particle density profile
  - fast ion related MHD instabilities

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Simulation (basic overview)

Power plant design, facility design, radiation safety...

Fusion simulations compared to nuclear physics experiments

- No singular interaction point, like a beam on a target
- Simulating neutrons, and neutron energy loss is different to charged particles
- Huge equipment – more to simulate (on the scale of CERN's ATLAS)
- Huge amount of neutrons generated per second – very computationally expensive

The area I work in:
Neutronics and nuclear data

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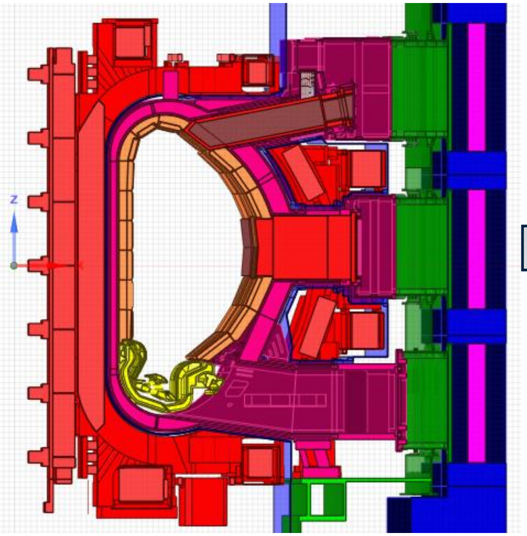
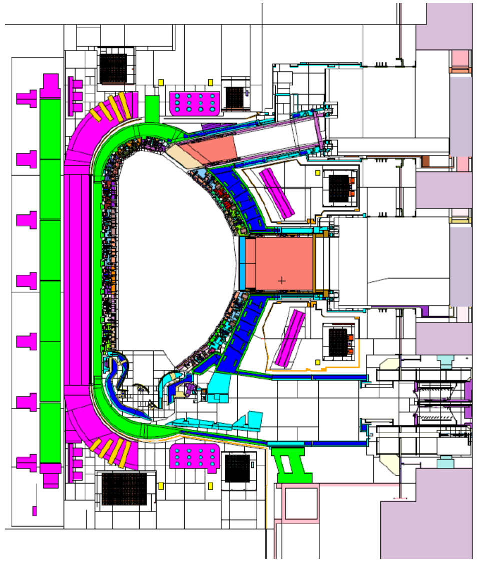
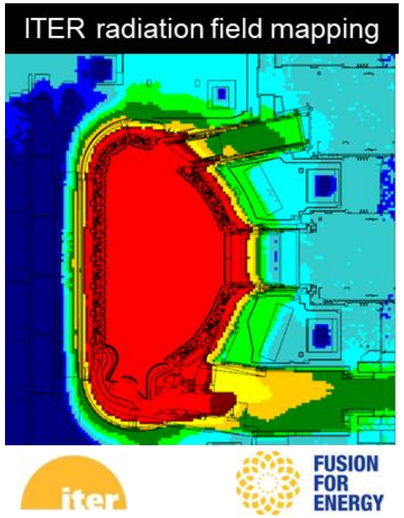
CAD model

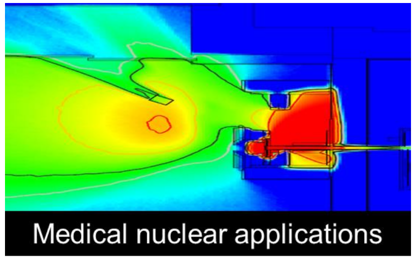


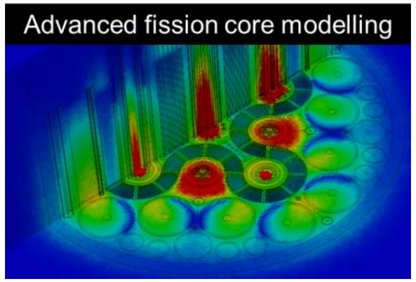
Monte Carlo radiation transport



Nuclear Analysis







Nuclear responses:

- Particle flux
- Dose rates
- Nuclear heating
- Tritium production
- Material damage
- Gas production
- Material activation
- Radiological waste
- Detector responses

The Monte Carlo method

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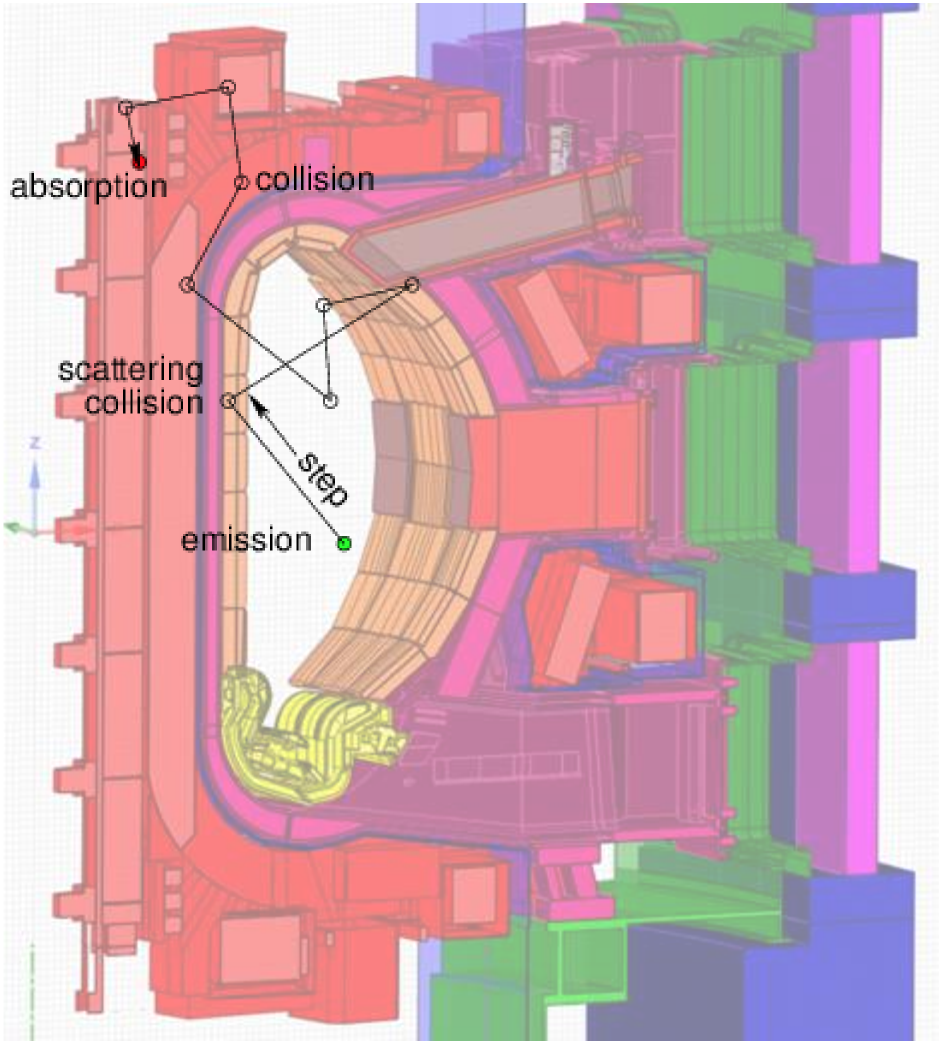
Follow individual particles and track them until their 'death' through e.g. absorption or by escaping the boundaries of the problem

Repeat the process many times and predict the average behaviour of particles in a system



The strength of this method is in its capability to calculate statistical estimates for **integral reaction rates** without explicitly solving for the flux distribution.

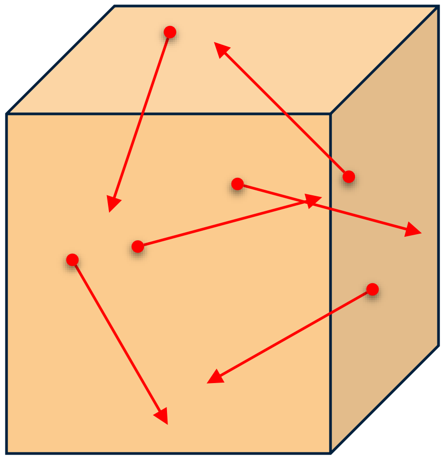
Frequency and outcome of interactions determined by **random sampling** and simulated according to **interaction laws** from particle and nuclear physics

Scalar flux density

- Neutron flux density (ϕ) in units of neutrons cm^{-2} s^{-1}

$$\phi = nv$$

- Where n is the number of neutrons per cm^3 and v is the neutron speed
- Can be thought of as the sum of the path lengths of all neutrons per unit volume



Key term: Microscopic and macroscopic cross section

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- The probability of interaction is characterised by the **microscopic** cross section (σ). It is the expected probability of interaction per unit length per unit number density.
- Measured in barns 1 barn = 10^{-28} m^2 = 10^{-24} cm^2
- **Macroscopic** cross section *(Σ)* corresponds to the total expected probability per unit length of all the nuclei considered (units: cm^{-1}).

$$\Sigma = N_D \sigma$$

*Cross sections are available for scattering, absorption, multiplication, etc. The total cross section is simply a sum of all the others $\Sigma_t = \Sigma_a + \Sigma_s + \Sigma$…

Key term: Reaction rate

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The rate of interaction also known as **reaction rate** (RR) is the total number of neutron interaction per second.

$$\Sigma = N_D \sigma \qquad RR = \phi . \Sigma . V$$

Where:

Σ *is the macroscopic cross section*
N_D is the number density of atoms
σ *is the microscopic cross section*

ϕ *is the neutron flux*
V *is the volume of material irradiated*
λ is the mean free path

Interactions per unit length → $\lambda = \frac{1}{\Sigma}$ ← Interactions per unit length

Moderation – energy loss via scatter

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E_i - Incident energy

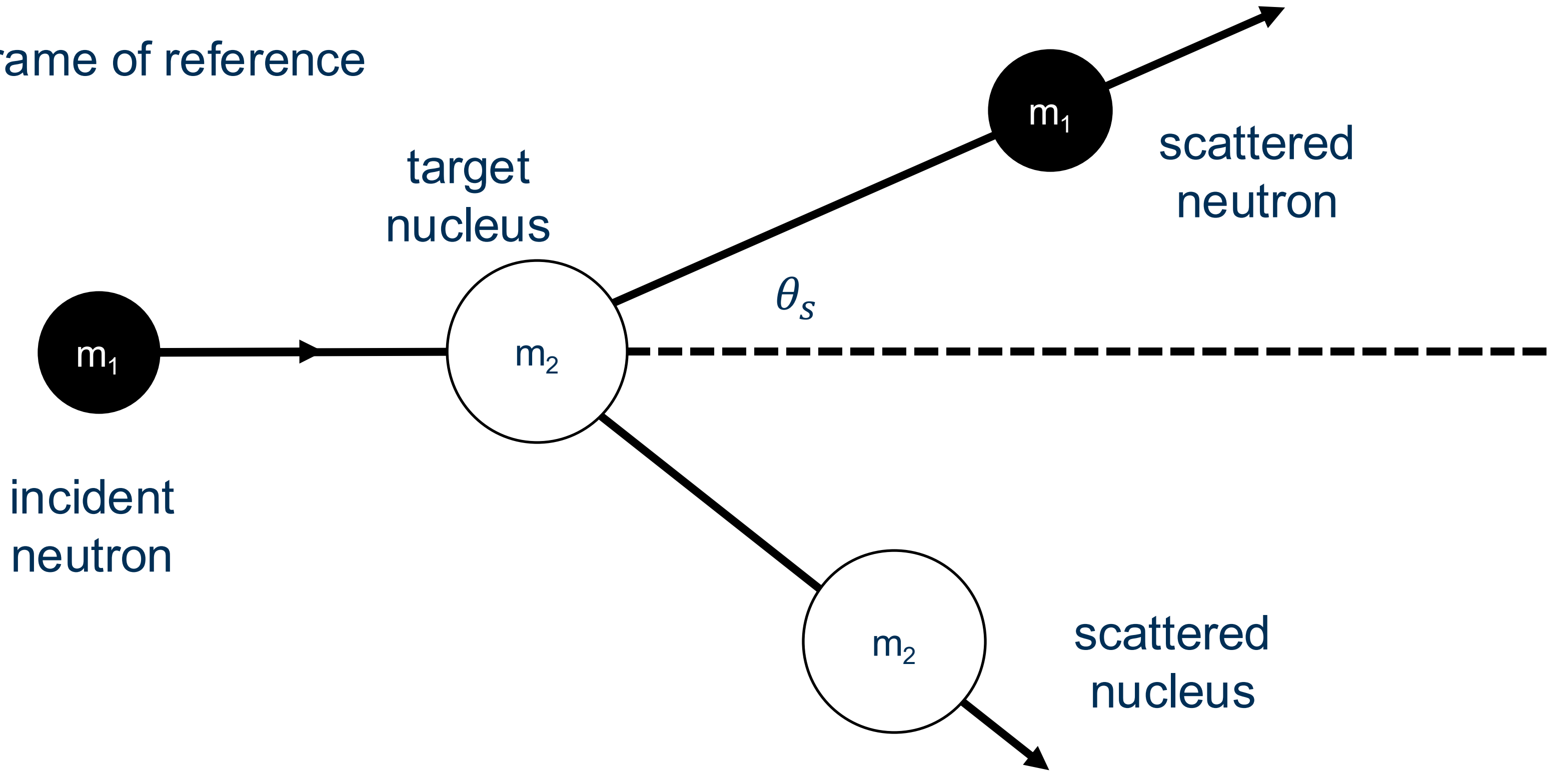
E_s - Scattered energy

θ_s - Scatter angle

A – Mass of target to incident neutron

$$E_s(A, \theta_s, E_i) = E_i \frac{\left(\sqrt{(A^2 - 1 + \cos(\theta_s)^2} + \cos(\theta_s)\right)^2}{(A+1)^2}$$

Lab frame of reference



Full derivation + further information regarding lab/com frame of reference:
https://dspace.mit.edu/bitstream/handle/1721.1/74136/22-05-fall-2006/contents/lecture-notes/lecture14.pdf

Moderation – energy loss via scatter

E_i - Incident energy

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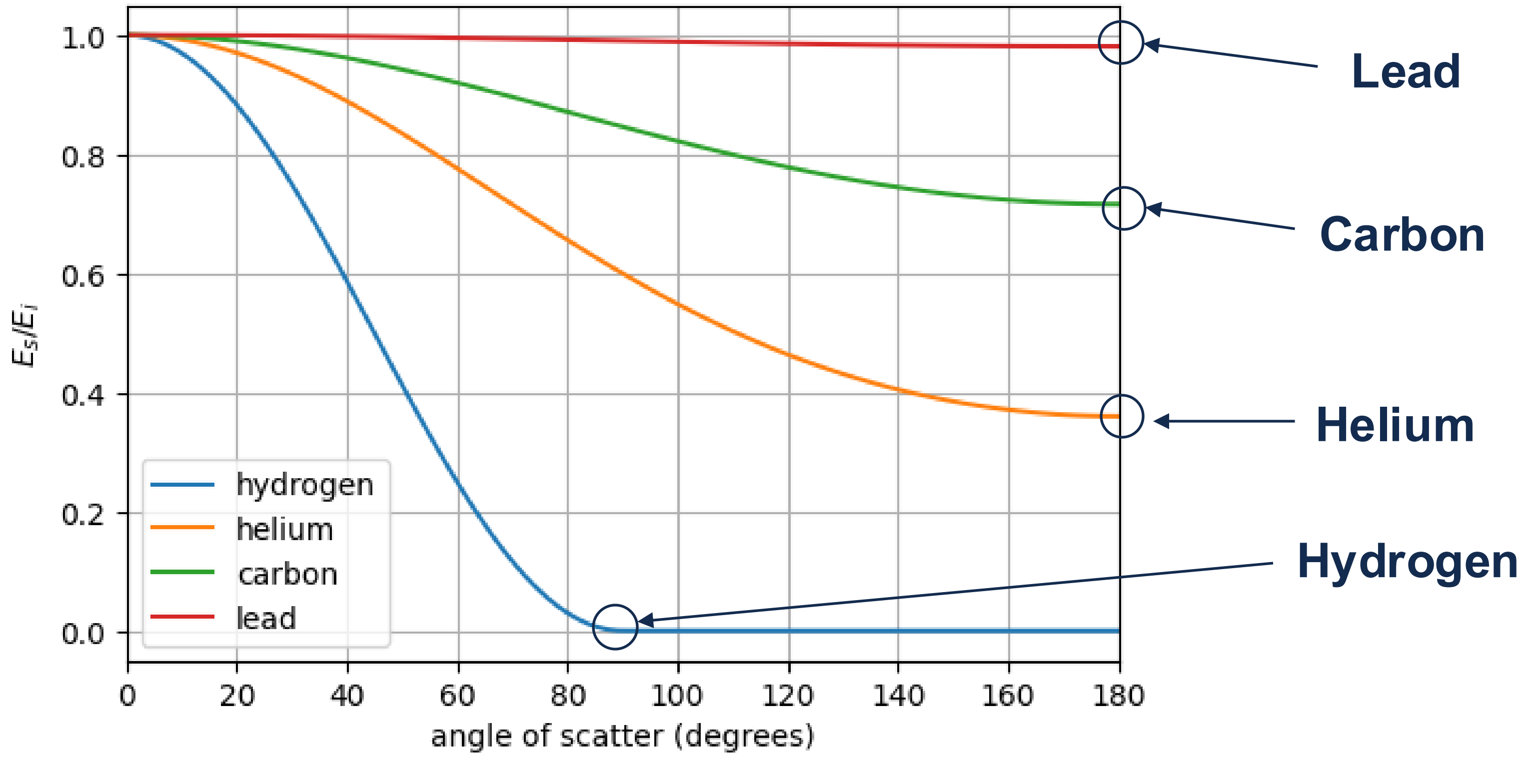
A – Mass of target to incident neutron

$$E_s(A,\theta_s,E_i) = E_i \frac{\left(\sqrt{(A^2-1+\cos(\theta_s)^2} + \cos(\theta_s)\right)^2}{(A+1)^2} \;\Rightarrow\; E_s = \frac{(A-1)^2}{(A+1)^2} E_i$$

θ=180°



Maximum energy loss

$$E_s = \frac{(208-1)^2}{(208+1)^2} E_i = 0.981\ E_i$$

$$E_s = \frac{(12-1)^2}{(12+1)^2} E_i = 0.716\ E_i$$

$$E_s = \frac{(4-1)^2}{(4+1)^2} E_i = 0.360\ E_i$$

$$E_s = \frac{(1-1)^2}{(1+1)^2} E_i = 0\ E_i$$

Full derivation + further information regarding lab/com frame of reference: https://dspace.mit.edu/bitstream/handle/1721.1/74136/22-05-fall-2006/contents/lecture-notes/lecture14.pdf

Moderation – energy loss via scatter

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Often with reactors it is convenient to work with a quantity called the neutron **lethargy** (u)

$$u = \ln\frac{E_0}{E}$$

The **average logarithmic energy decrement** (reduction) per collision (ξ) is related to the atomic mass (A) of the nucleus.

$$\overline{\Delta u} = \xi = 1 + \frac{(A-1)^2}{2A} ln\frac{(A+1)}{(A-1)}$$

The average number of collisions required to reduce the energy of a neutron from E_o to E

$$\mathrm{n} = \frac{1}{\xi}(\ln E_0 - \ln E)$$

However, we should account for the likelihood of scattering.

$$\text{Moderating power} = \xi\Sigma_s$$

Comparing moderators

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	Hydrogen	Deuterium	Beryllium	Carbon	Uranium
Mass of nucleus	1	2	9	12	238
Energy decrement	1	0.7261	0.2078	0.1589	0.0084
Number of collisions to thermalize	1	25	86	114	2172
Moderating power	Depends upon the energy and density.				
Moderating ratio					

- The probabilities of being absorbed are also important. The moderating ratio is a relative measure of a moderator to scatter neutrons without absorbing them.

$$\text{Moderating ratio} = \xi \frac{\sigma_s}{\sigma_a} = \xi \frac{\Sigma_s}{\Sigma_a}$$

Comparing moderators

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	Water	Heavy water	Beryllium	Carbon	Polyethylene (CH_2)
Moderating power	1.28	0.18	0.16	0.064	3.26
Moderating ratio	58	21000	130	200	122

- The moderating ratio is a relative measure of a moderator to scatter neutrons without absorbing them.

$$\text{Moderating ratio} = \xi \frac{\sigma_s}{\sigma_a} = \xi \frac{\Sigma_s}{\Sigma_a}$$

Neutron transport theory

Streaming

Source terms

$$\frac{1}{v}\frac{\partial \Phi}{\partial t} + \underline{\Omega}.\nabla\Phi + \Sigma_t\Phi = \int_{4\pi}\int_0^\infty \Omega_s(E' \to E, \Omega' \to \Omega)\Phi(\underline{r}, E', \Omega', t)dE'd\Omega' + S(\underline{r}, E, \Omega, t)$$

Sink

Imbalance term

- Neutron transport equation is based on the Boltzmann equation as applied across many areas of physics e.g. ions in a plasma and molecules in a liquid.
- A full derivation and application to simple examples can be found here.
- Besides the fusion reaction itself, there are many just as essential:
  - Scattering (elastic and inelastic, where energy is transferred to excited nuclear levels of rest nucleus)
  - Knock-out (matter ejected from rest nucleus) [gas production]
  - Absorption (incident nucleus absorbed)
  - Etc…

For every fusion, many many more scattering and other reactions, which often initiate more subsequent reactions…

How do we simulate neutrons?

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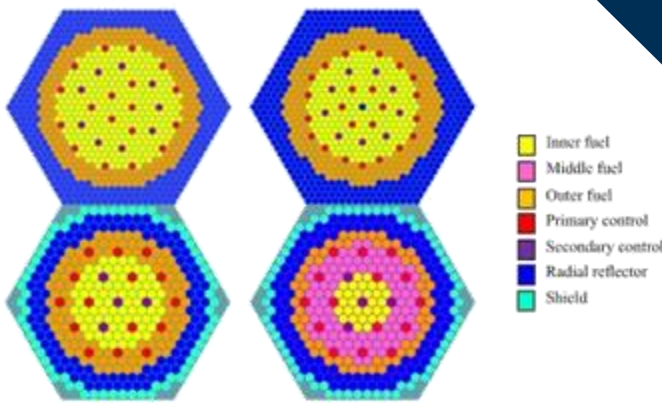
There are two main methods:

- ***Deterministic*** solves the transport equation for a flux solution either through angular (discrete ordinates/Legendre polynomials), energy (multi-group) or space-time simplification

  Pro: Can solve for a whole reactor (as done by industry)

  Con: Each discretization introduces error: energy on cross sections, angular on highly anisotropic, space over curved bodies



- ***Monte-Carlo (Probabilistic)*** uses continuous physics and faithful geometry to follow individual particles one-by-one until enough done to converge

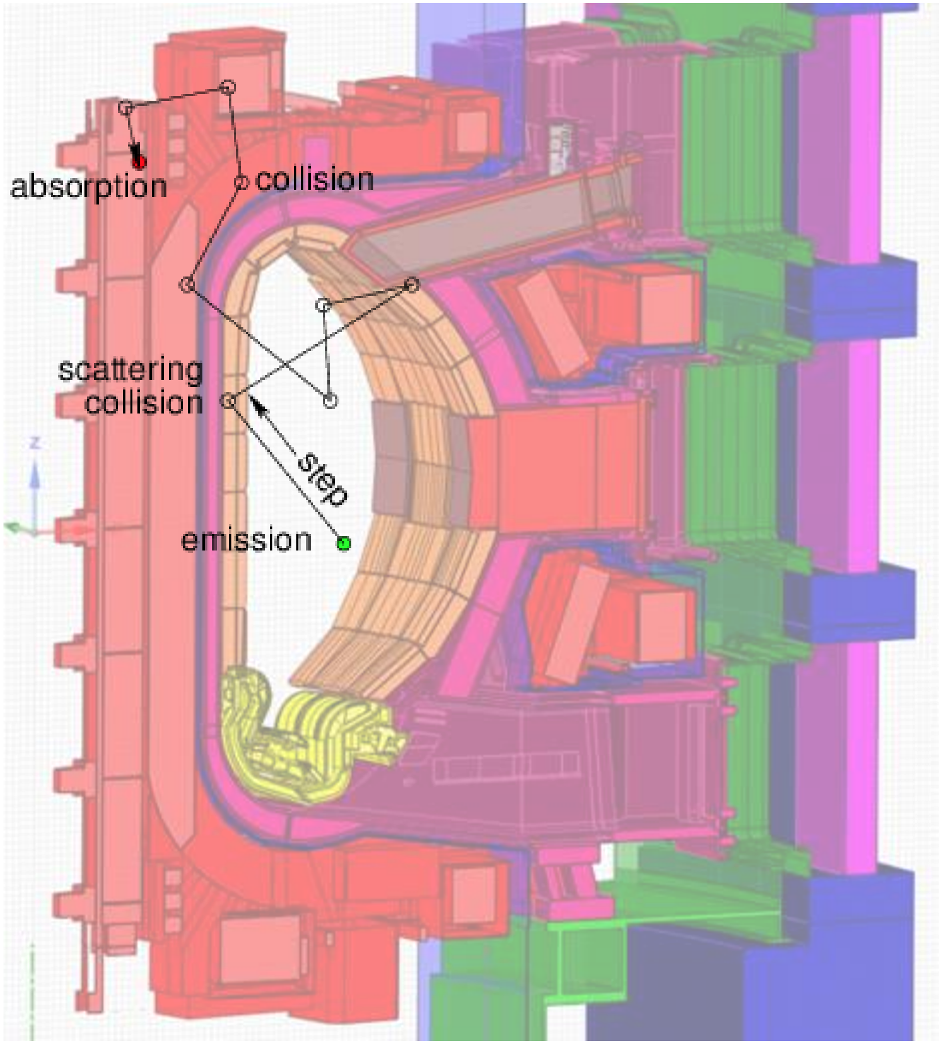
  Pro: As good of a solution as possible with physics knowledge

  Con: Potentially huge computational requirement and only local information (where particles are statistically tallied)

The Monte Carlo method

Requires:

- Physics models
- Nuclear data
- Material definitions
- Geometry
- Source distribution
- Tallies



Monte Carlo Particle transport simulation

Requires:

- Physics models
- Nuclear data
- Material definitions
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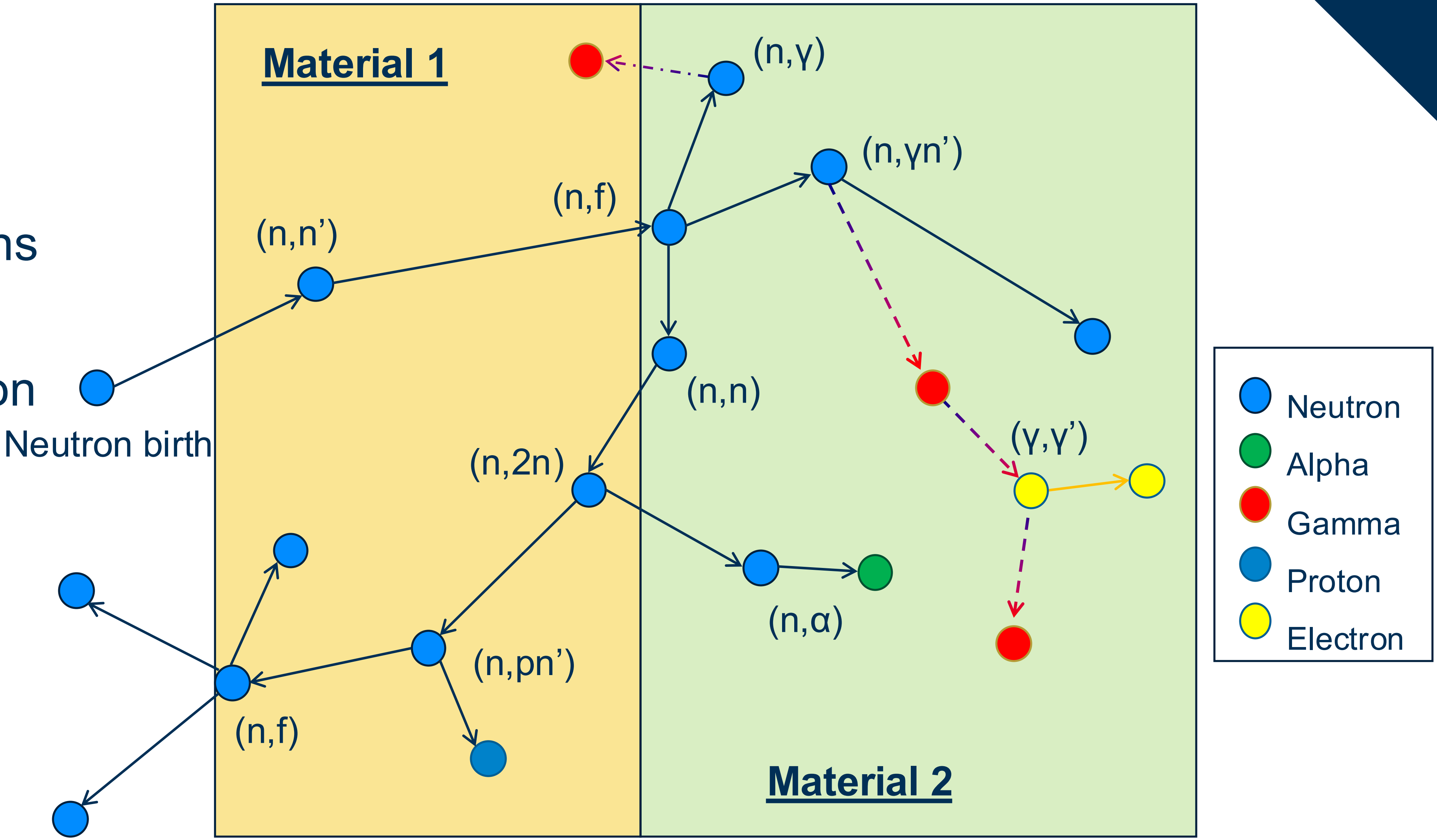
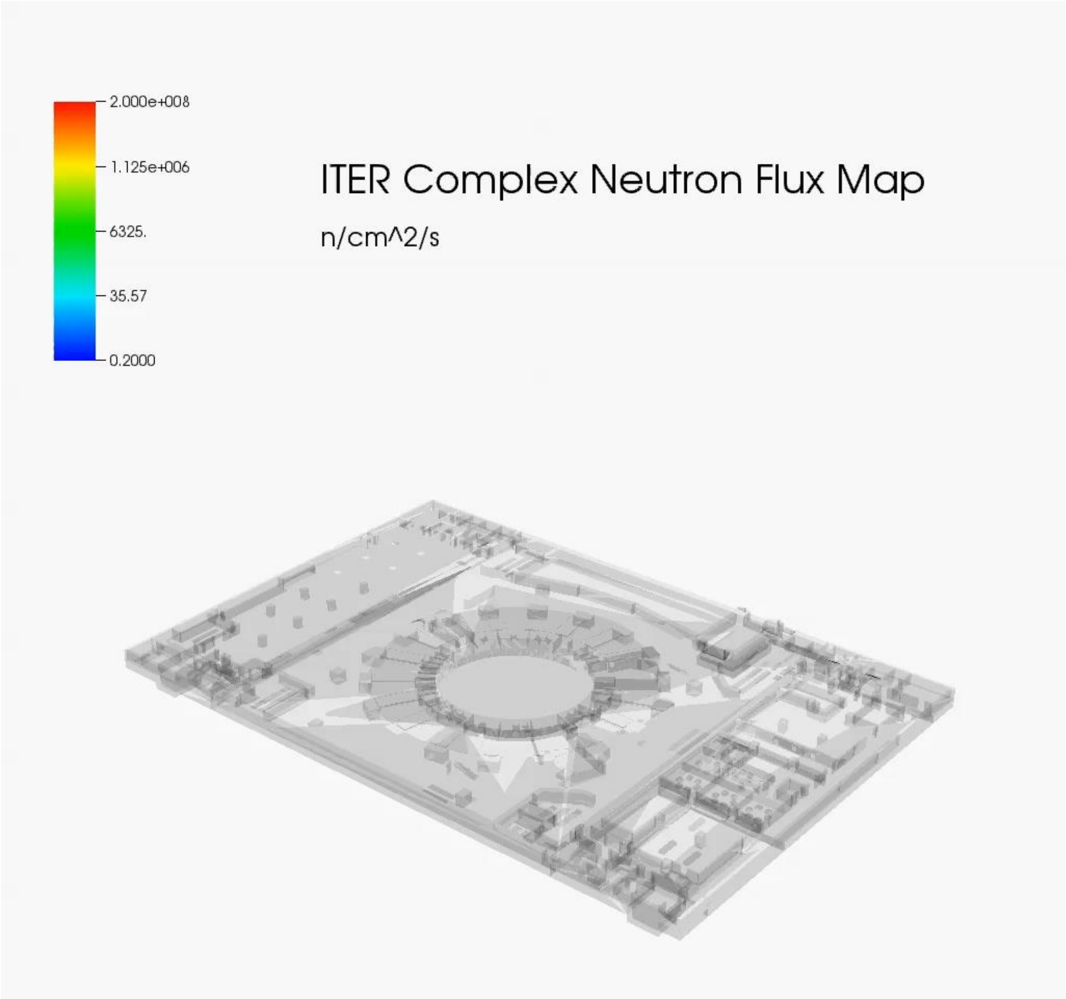
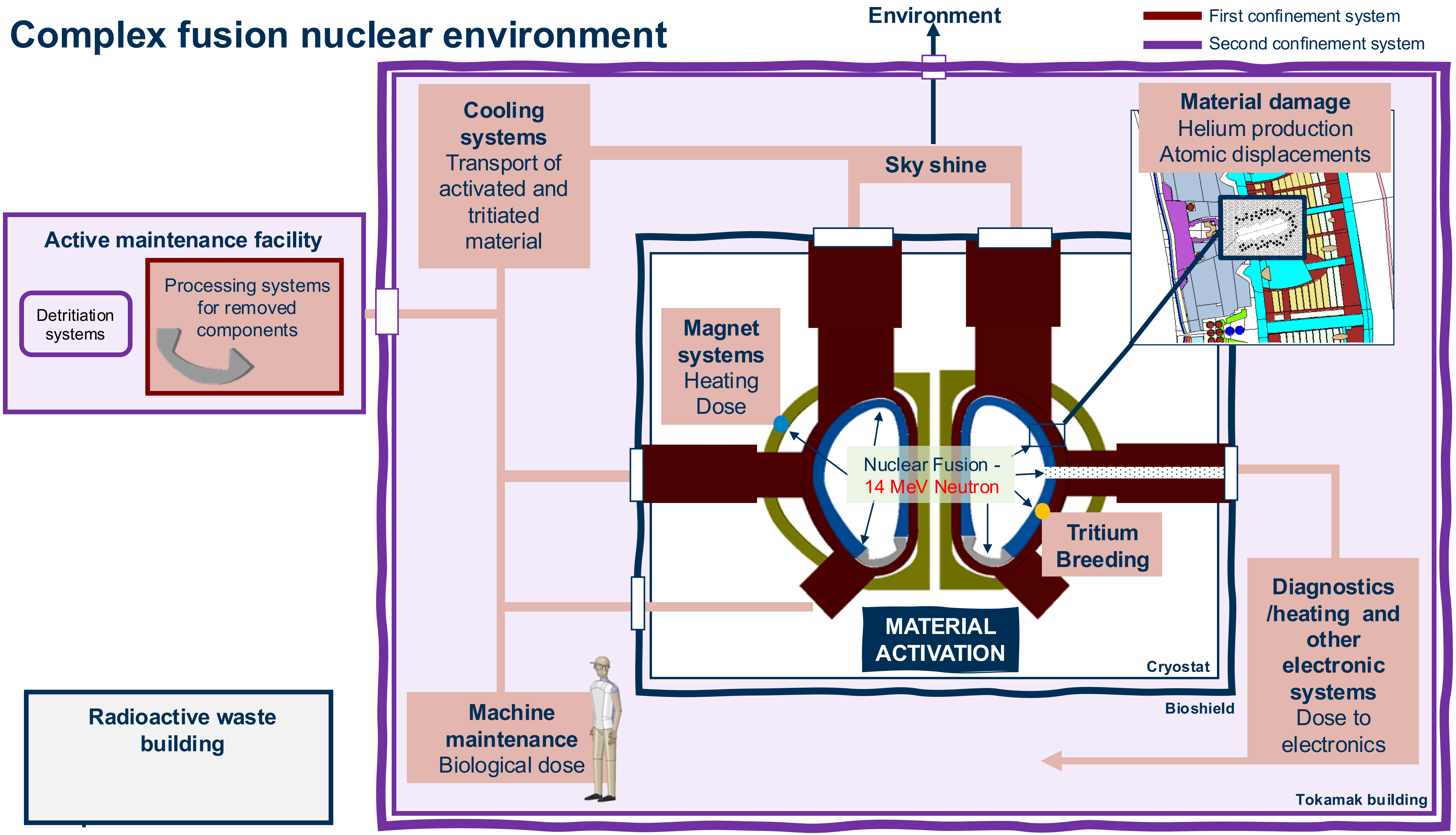


3D neutron flux maps: ITER Complex



Complex fusion nuclear environment



Inventory and shutdown gamma calculations

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$$\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i\phi) + \sum_{j\neq i} N_j(\lambda_{ji} + \sigma_{ji}\phi)$$

loss creation

- Coupled differential equation
  - Inventory solvers such as FISPACT-II using LLSOLDE differential equation solver
  - Couple MC Burnup/inventory calculations in OpenMC using CE/CM method

Modelling with Uncertainty

Due to the complexity of fusion devices, there are multiple competing requirements:

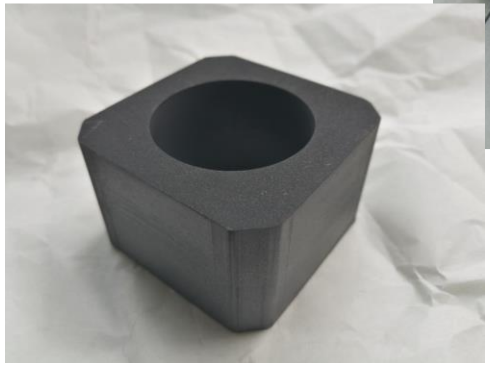
- Cost
- Shielding
- Breeder material
- Cooling capability
- Energy extraction
- Diagnostics
- Maintenance

To make informed decisions on these requirements it is important to understand the underlying uncertainties (e.g., component lifetimes or tritium breeding, and safety factors).

There are many sources of uncertainty in nuclear analysis workflows:

- covariances in nuclear data;
- statistical uncertainty from transport calculations;
- geometric approximations and the design maturity;
- material definitions, particularly for novel materials.

Boron carbide (B4C) validated by ITER as a shielding material for diagnostics.



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iter
china eu india japan korea russia usa

Where to qualify?

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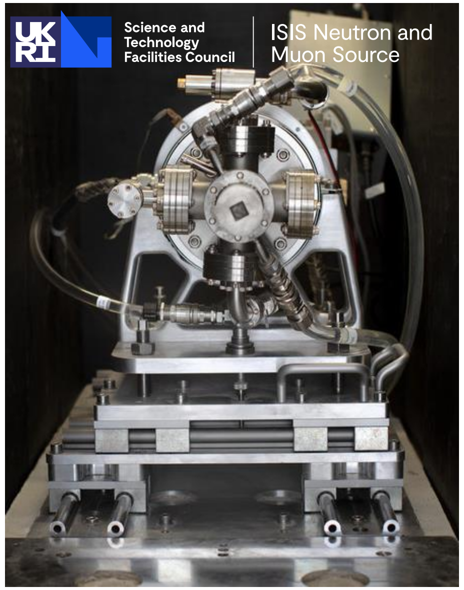
For R&D of novel diagnostics and for demonstrating the effectiveness of shielding for existing diagnostics qualification is required.

The level of qualification is dependent on the application i.e. safety systems will require a higher confidence level.



Neutron Irradiation Laboratory for Electronics (NILE)

DD and DT neutron generator

MC40 Cyclotron

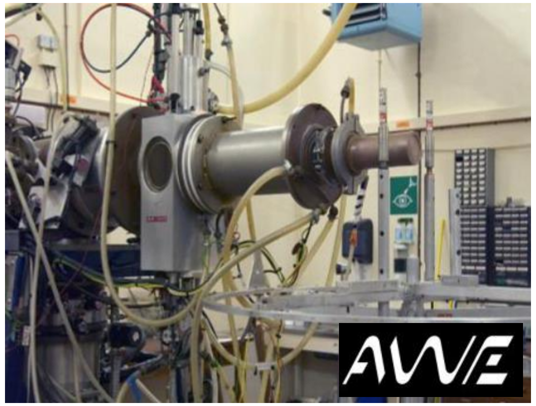
Can produce deuterons up to 20 MeV. Targets can be used to get neutrons of desired energy ranges.

Van de Graaff accelerator

Produces neutrons between 8-17 MeV

ASP Facility

14 MeV DT neutrons, 10^{11} n/s



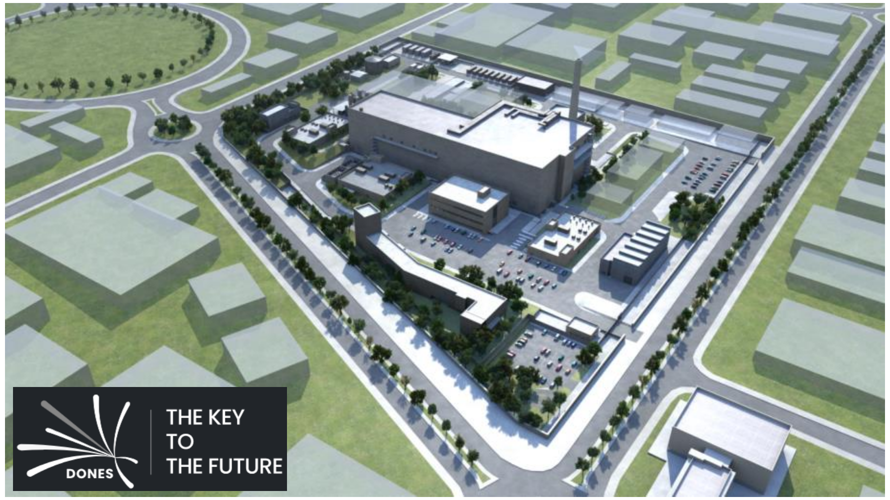
High Flux Accelerator-Driven Neutron Facility (HF-ADNeF)

Protons onto a lithium target. ~1 MeV neutrons, 10^{13} n/s

Future Facilities

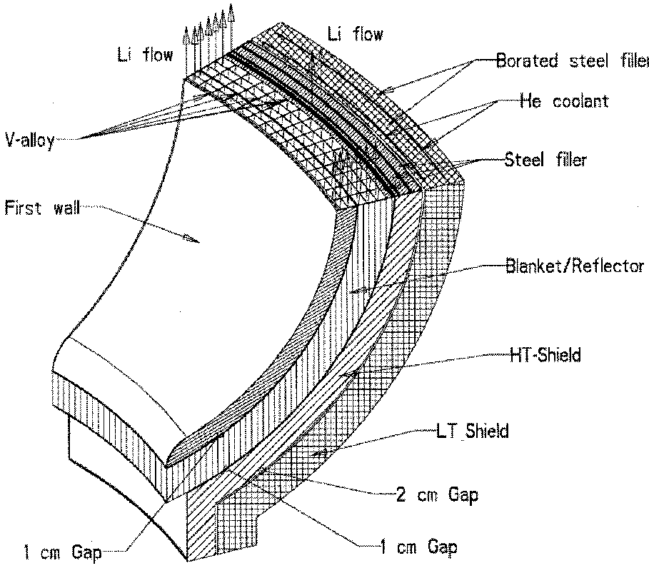
UK Atomic Energy Authority

IFMIF-DONES
International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source



- For testing materials in fusion relevant irradiation conditions.
- Currently in design, planned construction in Granada, Spain.
- Flux in the high flux test module ~10^{14} n/cm^2/s

LIBRTI
Lithium Breeding Tritium Innovation



Breeder blankets are complex components that are critical to the success of fusion.

Many concepts exist, with not many places to qualify at the engineering scale.

- 14 MeV neutrons
- Capacity for large mock-ups to experimentally test key questions that remain about the tritium fuel cycle.
- Also provides an environment to qualify diagnostics.

UK Atomic Energy Authority

Neutron detectors

How do you detect neutrons?

You don't.

- Neutrons are inferred *indirectly*, via the creation of prompt charged particles or radiation
- Detectors contain a target material (for neutron conversion) with the detector technology

n + target → { Reaction products: Recoil nucleus; Fission fragment; α, p, d, t; photons }

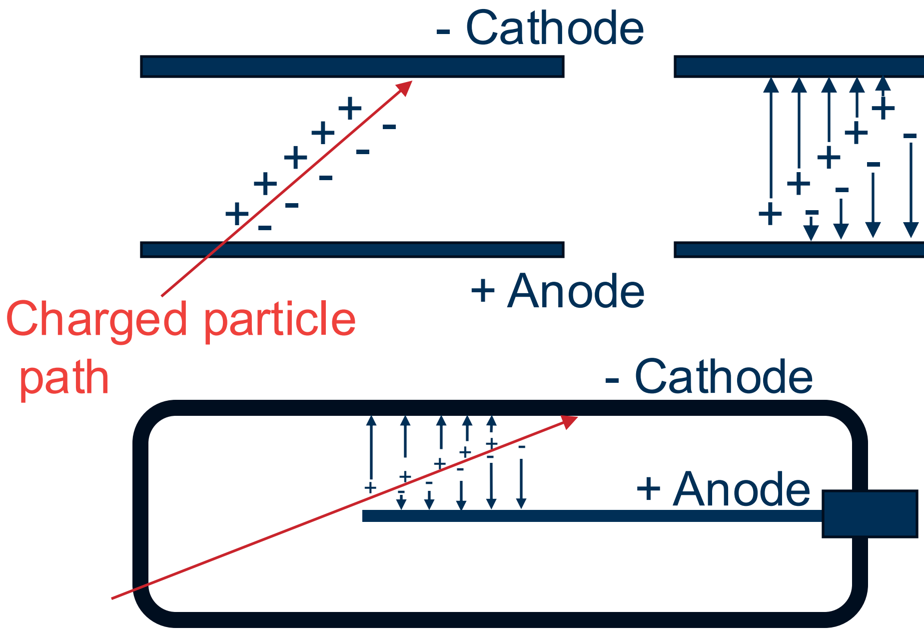
G. F. Knoll, Radiation Detection and Measurement

- Neutron reaction cross-sections are strongly energy dependent
  - Often use different detector types for different neutron-energy regimes

Detector types

	Proportional counters (no neutron energy information)	Spectrometry (energy information inferred)
Active	• Fission chambers • Helium-3 tubes	• Bonner spheres (with Helium-3 tubes) • Proton recoil • Scintillators • Time-of-flight (energy inferred) • Diamond detectors
Passive	• PADC • TLDs • Single activation foils	• Multiple activation foils • Passive neutron spectrometry • Bonner spheres (with foils/TLDs)

Some detector basics



- For incident charged particles: ion pairs created along the path. This charge is swept to the anode/cathode and the resulting pulse is proportional to the energy (in pulse mode)
- Magnitude of signal is proportional to the number of ion pairs created
- For incident photons, they may interact with the cathode and knock off electrons, producing a signal
- Neutrons are not ionising.

- Current mode:
  - Averages out events
  - Useful with high event rates
- Pulse mode:
  - Records each event
  - Energy and timing information

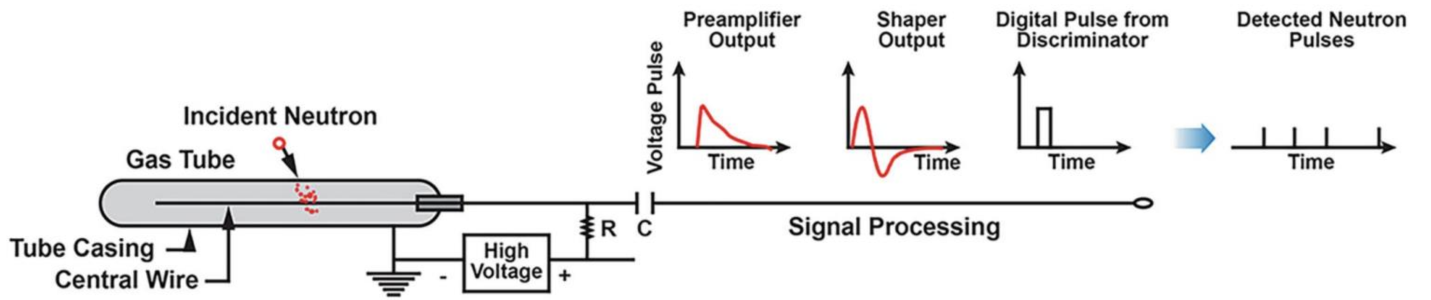


Fig. 15.1 Typical setup for gas-filled neutron detectors   Nondestructive Assay of Nuclear Materials for Safeguards and Security

Diagnostic: PADC

PADC	
Detector type	Proportional
Active/passive	Passive
Time dependence	Integrating
Energy range	0.144 MeV+ [1]
Reaction product	Protons
Hardness	Insensitive to electro-magnetic fields
Cost	Low

PADC dosemeter top, PADC plastic below, before and after processing

[1] https://www.ukhsa-protectionservices.org.uk/cms/assets/gfx/content/resource_2975cs2ef3e50fd7.pdf

- Poly-Allyl Diglycol Carbonate (PADC) – a type of plastic
- Recoil protons induced via neutron scatter -> form voids in plastic
- Fluence to void calculated via optical microscope
- Protons must have linear energy transfer (LET) > 15 keV/μm [2]
- Insensitive to photons and electrons and neutrons < 0.1 MeV [1]

Advantages: cheap, little time dependence

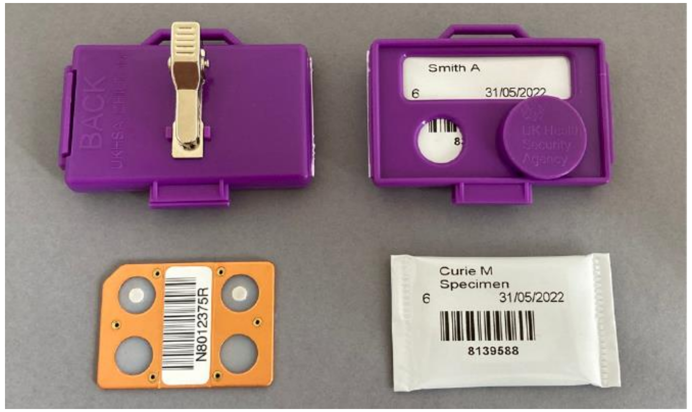
Disadvantages: integrating, need to know neutron spectrum

[2] A Stabilini, Radiation Measurements 141 (2021) 106516

Diagnostic: Thermoluminescent dosimeters (TLDs)

Thermoluminescent dosimeters	
Detector type	Proportional
Active/passive	Passive
Time dependence	Integrated dose up to 1 year.
Energy range	All
Reaction product	Depends on crystal, D,T,P,E
Hardness	Max dose 1.5 Gy, insensitive to electromagnetic fields
Cost	Low

- Crystal lattices with impurities (LiF:Mg,Ti, CaF:Dy, $CaSO_4$, etc...)
- Impurities create electron ‘traps’ at know energy levels
- Traps fill proportionally to energy deposited
- Heating releases trapped electron energy as light in glow curve



https://www.ukhsa-protectionservices.org.uk/cms/assets/gfx/content/resource_2963csb887d8d5e6.pdf

Advantages: cheap, long deployments possible, gamma/neutron discrimination

Disadvantages: low dose rate environments only, fragile to handle, integration of dose only

Diagnostic: Passive neutron spectrometer (PNS)

Activation foils	
Detector type	Spectrometry
Active/passive	Passive
Time dependence	Up to 1 year deployment
Energy range	All energies
Reaction product	T
Hardness	Insensitive to electromagnetic fields / high fluence
Cost	Low

- TLDs placed a different depths of polythene moderator
- Dose response for neutron energy calculated
- Unfolding based inference applied

Advantages: Cheap, rad-hard, portable, information about direction of fluence

Disadvantages: Requires TLD reader, low dose environments only

The Passive Neutron Spectrometer

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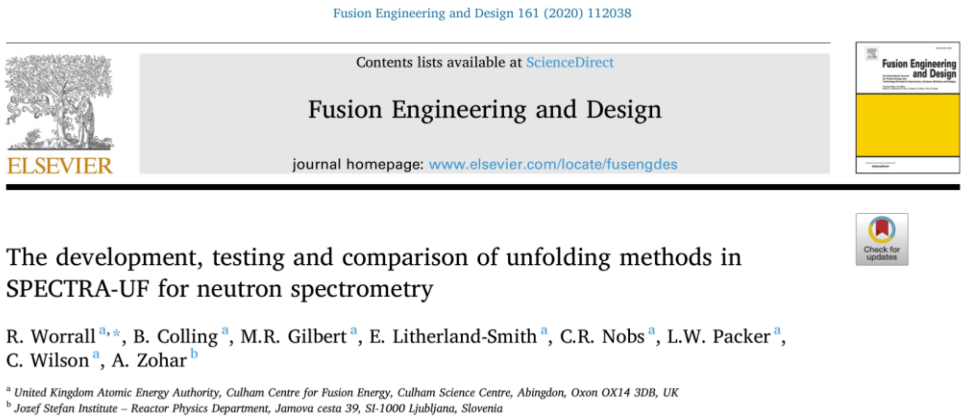
- The Passive Neutron Spectrometer is a 30-cm diameter sphere of HDPE with pairs of TLDs (^{6}LiF, ^{7}LiF) placed at different depths.
- Neutrons lose energy as they are moderated through the plastic, and TLDs will have a response dependent on the depth in the plastic
- The neutron flux as a function of neutron energy is unfolded
- Ross Worrall et al., Fus. Eng. Des. 161 (2020) https://doi.org/10.1016/j.fusengdes.2020.112038

Figures from Ross Worrall



Fusion Engineering and Design 161 (2020) 112038

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journal homepage: www.elsevier.com/locate/fusengdes

The development, testing and comparison of unfolding methods in SPECTRA-UF for neutron spectrometry

R. Worrall[a,*], B. Colling[a], M.R. Gilbert[a], E. Litherland-Smith[a], C.R. Nobs[a], L.W. Packer[a], C. Wilson[a], A. Zohar[b]

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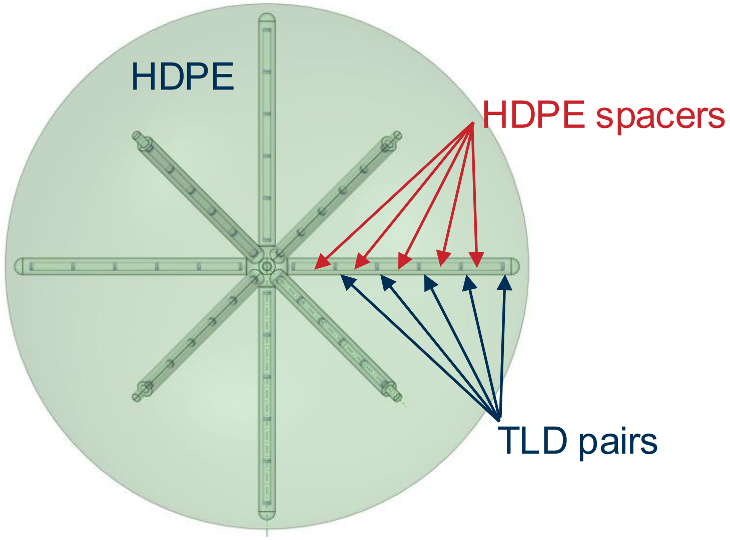
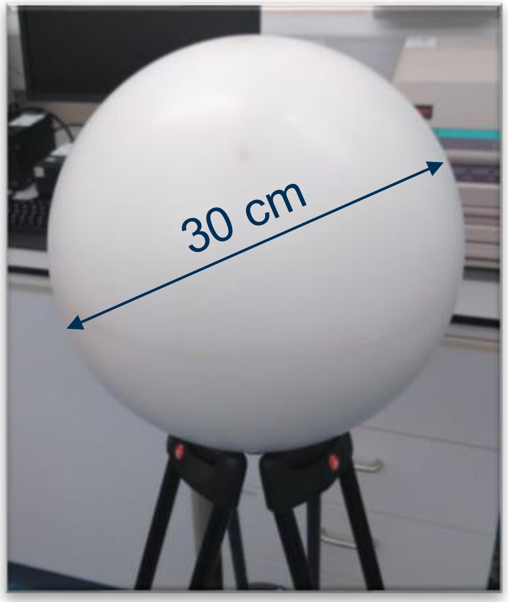




The Passive Neutron Spectrometer

- Light curve extracted for TLDs – after processing, this gives dose as a function of depth
- Neutron energy related to the depth of the TLD
- Need a response function – i.e. the sensitivity of the TLDs to neutrons as a function of energy
- Essentially, unfolding requires solving simultaneous equations:

Figures from Ross Worrall

Measured values

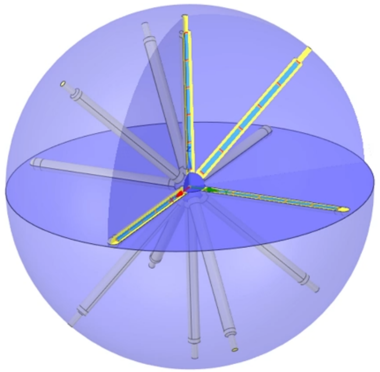
Neutron flux

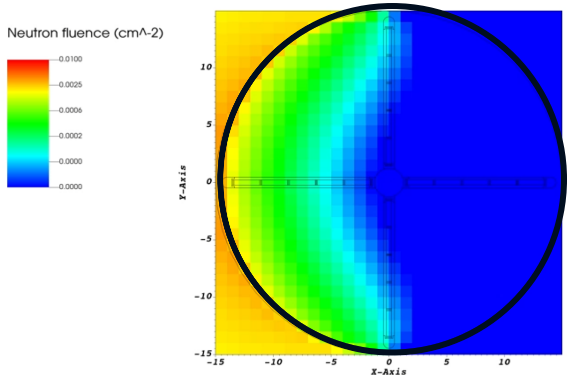
$$Z_0 = \int_0^\infty R_i(E)\varphi(E)dE_i$$

TLD response

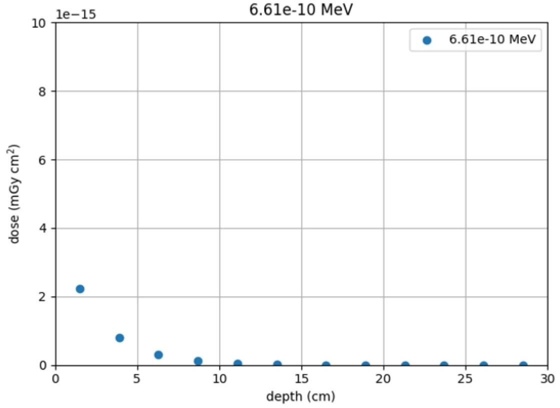
6.61 x 10^{-10} MeV

Neutron energy (from the TLD depth)





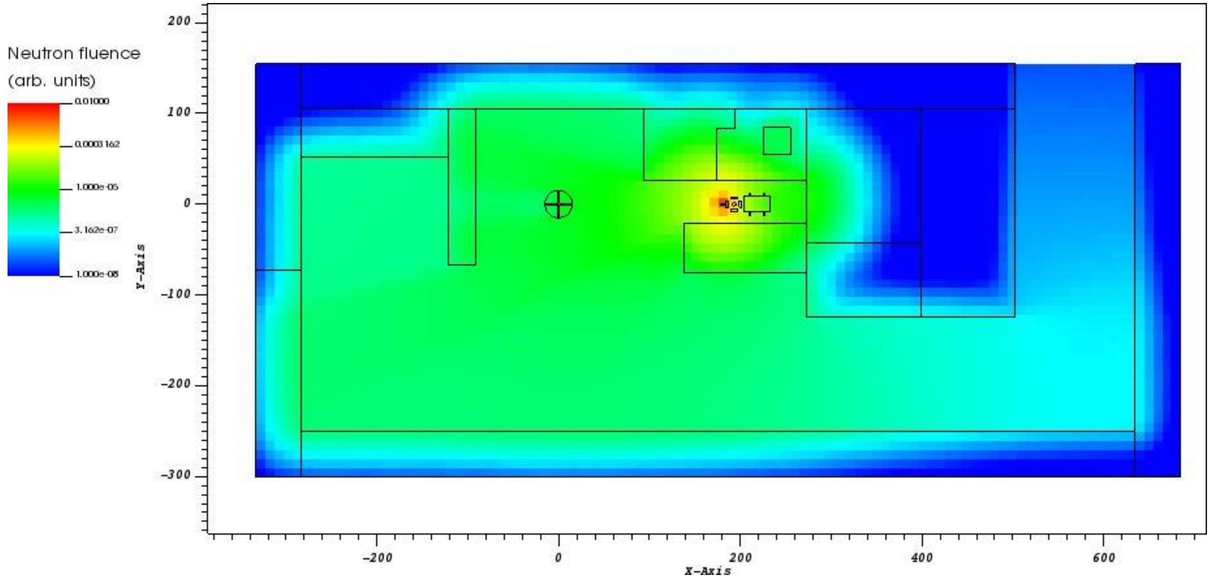
φ(E) across the PNS

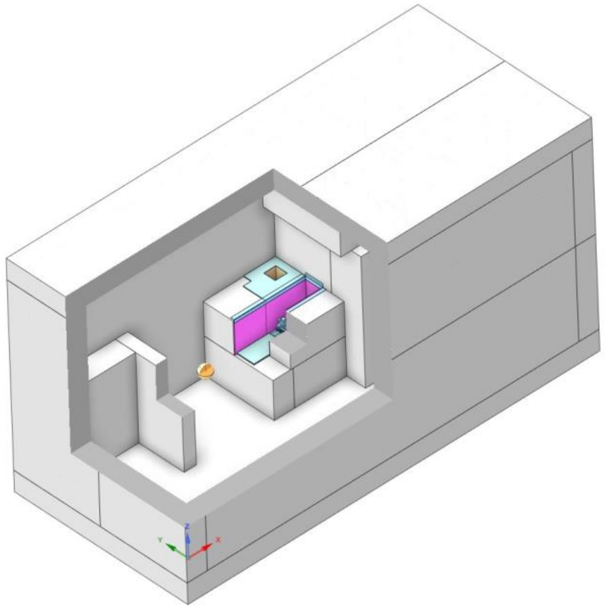


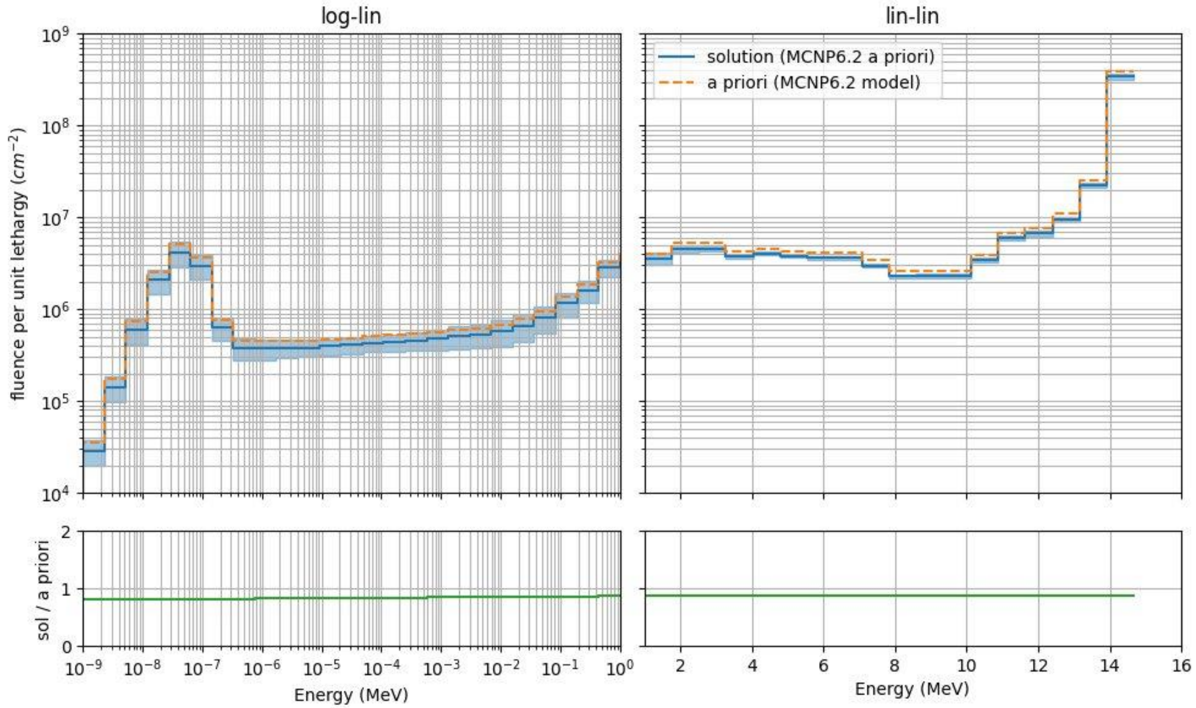
Dose as a function of depth

Deployment at NILE

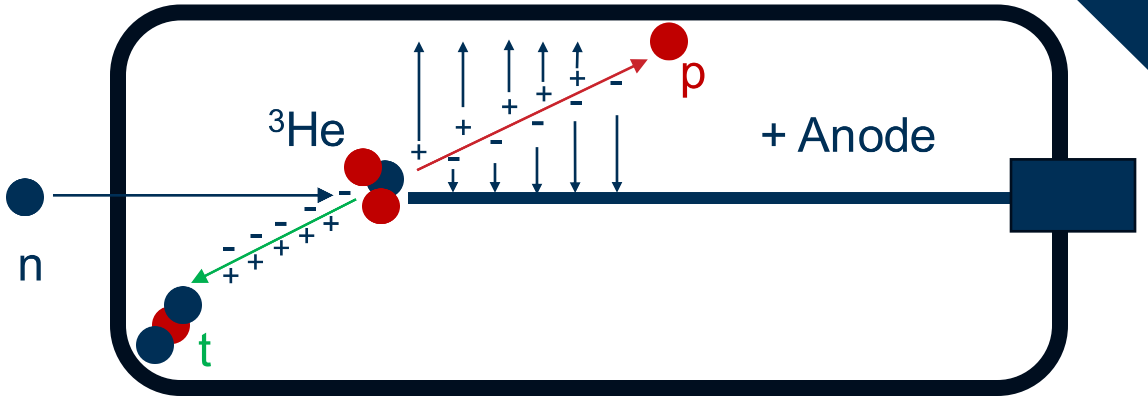
UK Atomic Energy Authority







Diagnostic: Gas tubes (thermal n)



Gas tubes	
Detector type	Proportional
Active/passive	Active
Time dependence	Integrating
Energy range	Thermal
Reaction product	*t*, *p* / α, ^{7}Li recoil
Hardness	Good in high temperature/γ fields
Cost	Medium

For ^{3}He tubes: $${}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p} + 0.764\ \mathrm{MeV}$$

For BF_3 tubes: $${}^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\mathrm{He} + 2.31\ \mathrm{MeV}$$

- Difference in the Q value makes γ discrimination harder in ^{3}He than BF_3
  - BF_3 useful for n detection in high γ-ray fields
- Additive gases (Ar, CO_2) can reduce pile-up in high flux environments by speeding up electron drift

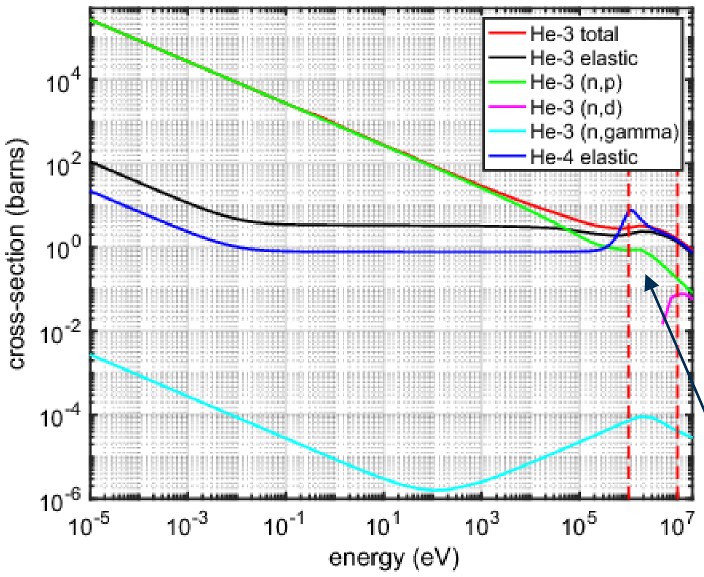
Advantages: high efficiency

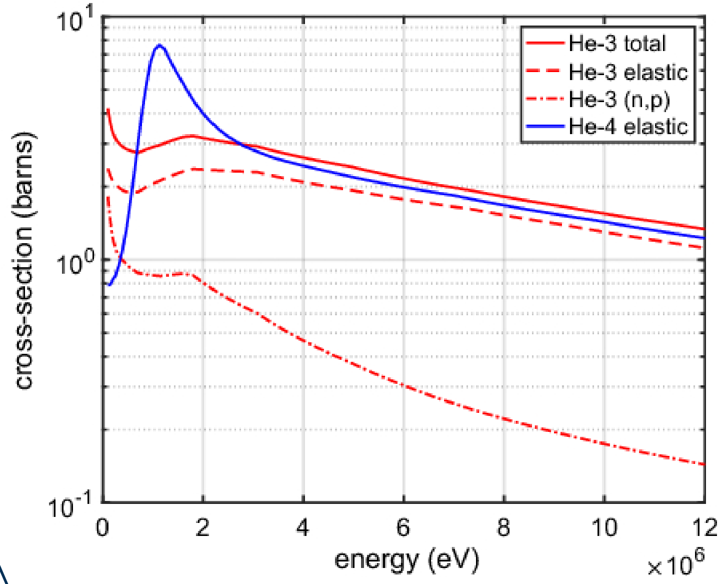
Disadvantages: ^{3}He shortage, BF_3 toxicity

Diagnostic: ^{3}He tubes (fast n)

^{3}He tubes	
Detector type	Spectroscopic
Active/passive	Active
Time dependence	None
Energy range	fast
Reaction product	*t*, *p*, ^{3}He indirectly
Hardness	Insensitive to γ (produces pileup)
Cost	Medium

F. Piscitelli et al, Eur. Phys. J. Plus (2020) 135:577





It is also possible to use ^{3}He tubes spectroscopically for fast neutrons, thanks to the kinematics of elastic scattering

For fast neutrons, ^{3}He elastic scattering dominates, making spectroscopy possible (a maximum of $\frac{3}{4}E_n$ is transferred to the recoiling ^{3}He nucleus), but this requires spectrum unfolding

Advantages: Can cover wide energy range, rugged

Disadvantages: ^{3}He shortage, requires unfolding

Diagnostic: Fission chambers

Fission chambers	
Detector type	Proportional
Active/passive	Active
Time dependence	Integrating
Energy range	All
Reaction product	Fission fragments
Hardness	Insensitive to γ
Cost	High (£100k)

- Variation on gas-filled counter (90:10 Ar:CH_4) with very thin coating on the walls:
  - ^{233}U, ^{235}U, ^{239}Pu coatings for thermal neutron detection
  - ^{237}Np and ^{238}U coatings for fast neutron detection

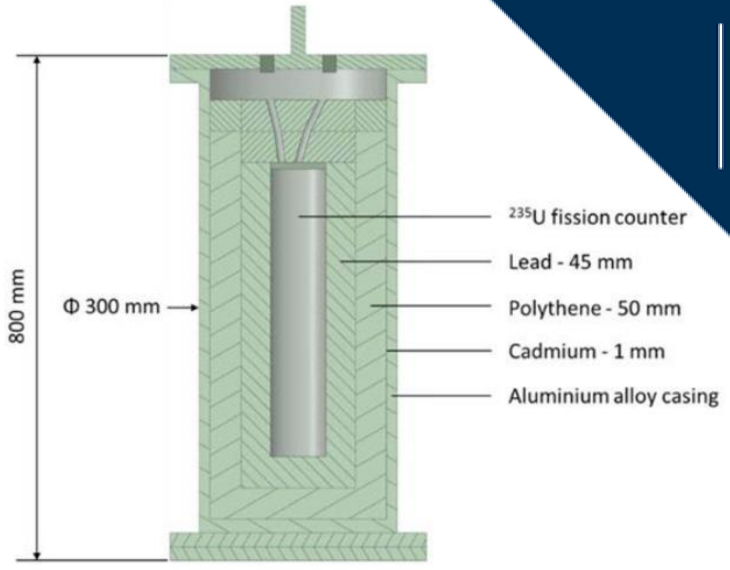


FIG. 5. Schematic showing the U-235 based fission yield counter used at JET.

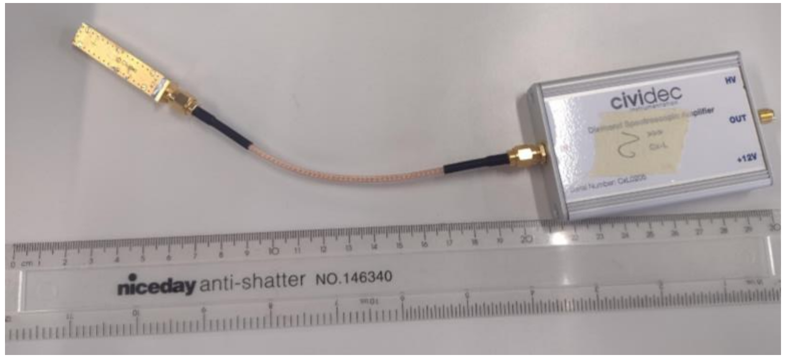
L. Packer et al., IAEA-TECDOC-1935, 2017

- Two fission fragments share ~160 MeV, which ionises the gas
- Large signals – higher than competing reactions
  - Low background measurements, can operate at low counting rates
  - α decay background that can be discriminated out
- Operates in pulse mode, current mode or Campbelling mode

Advantages: Robust, wide energy range

Disadvantages: Low intrinsic efficiency (~1%), integrating, burn up of material

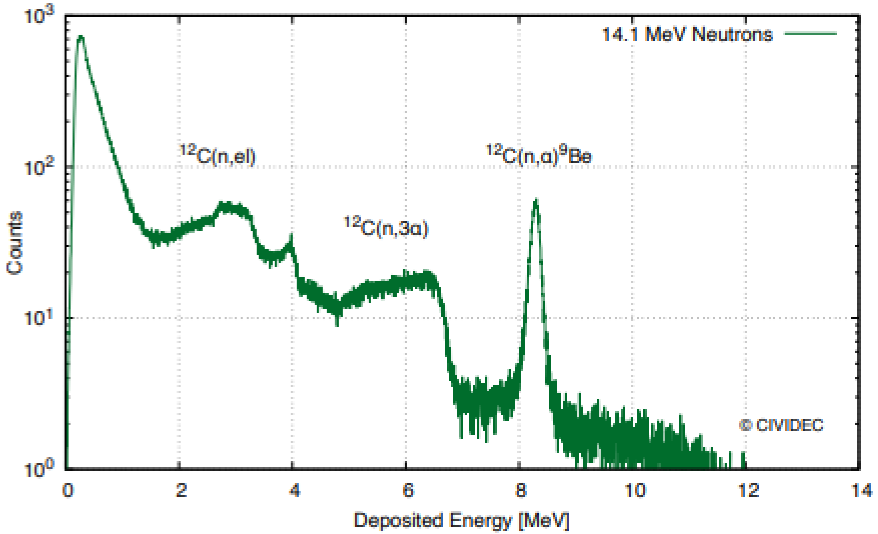
Diagnostic: Diamond



Diamond	
Detector type	Spectrometry
Active/passive	Active
Time dependence	None
Energy range	Thermal or >1MeV
Reaction product	α, *p*, *d*, *t*
Hardness	Very rad hard
Cost	Medium (~£10k)

- Diamond is both the target material and the detection material
- Fast neutrons induce reactions on ^{12}C and ^{13}C (eg (n,α), (n,n'), (n,p))

- Thermal: eff = 0.5% @ 25meV
- Fast: eff = 1%



CIVIDEC Instrumentation - CVD Diamond Technology applications

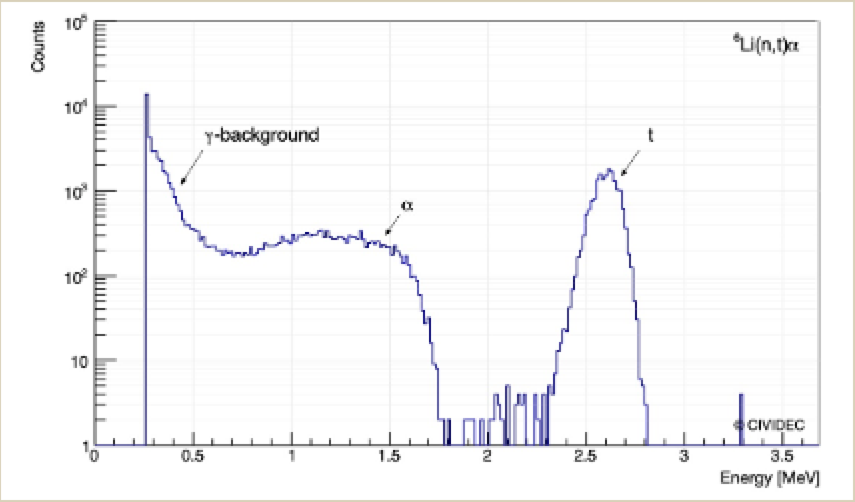
Advantages: fast, compact, rad hard

Disadvantages: small surface area, low efficiency

Diamond detectors

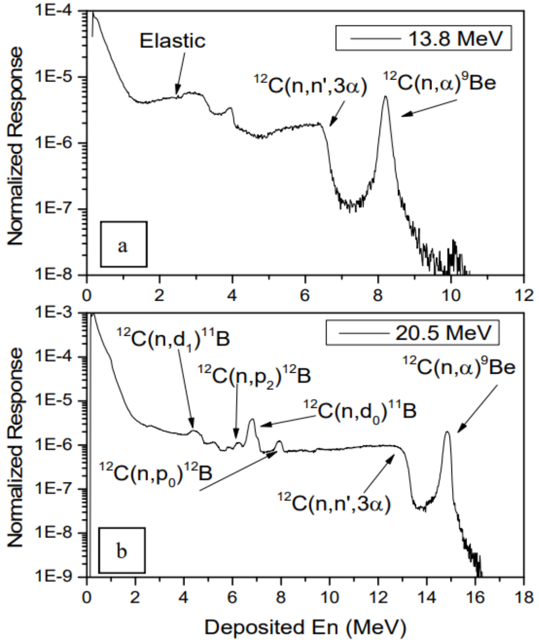
For thermal neutrons, a ^{6}LiF layer is mounted in front of the diamond to convert the neutrons via the ^{6}Li(n,t)α reaction

Thermal neutron spectrum (from interaction with ^{6}LiF)



CIVIDEC Instrumentation - CVD Diamond Technology applications

Fast neutron spectrum (from interaction with ^{12}C, ^{13}C†)



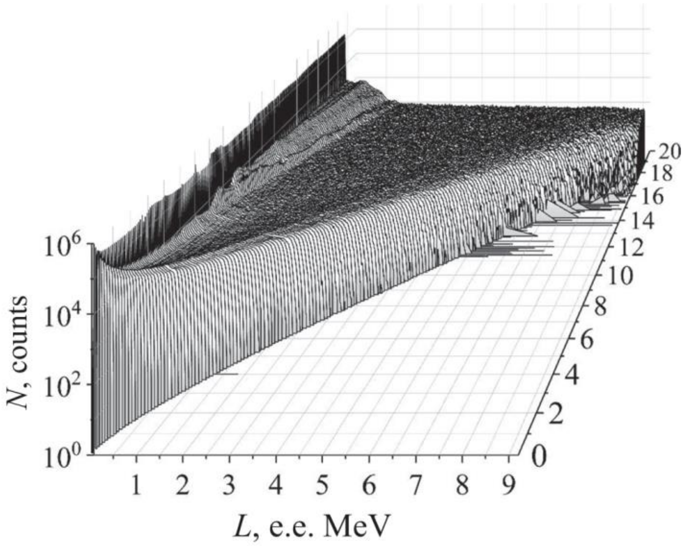
M. Angelone, IAEA-TECDOC-1935, 2017

Reaction	*Q*-value (MeV)
^{12}C(n,α)^{9}Be	-5.701
^{12}C(n,n')3α	-7.275
^{12}C(n,n')^{12}C	0
^{12}C(n,p)^{12}B	-12.587
^{12}C(n,d)^{11}B	-13.732
^{13}C(n,α)^{10}Be	-3.835

† ^{13}C has 1.1% abundance

Diagnostic: Scintillator

Diamond	
Detector type	Spectrometry
Active/passive	Active
Time dependence	None
Energy range	> 0.1 MeV
Reaction product	*p*
Hardness	PMT + electronics sensitive to EM
Cost	Medium (~£10k)



- Neutrons of a given energy produce a light spectrum response
- Pulse shape discrimination for neutrons and photons
- Unfolding base inference used to calculate the incident neutron fluence

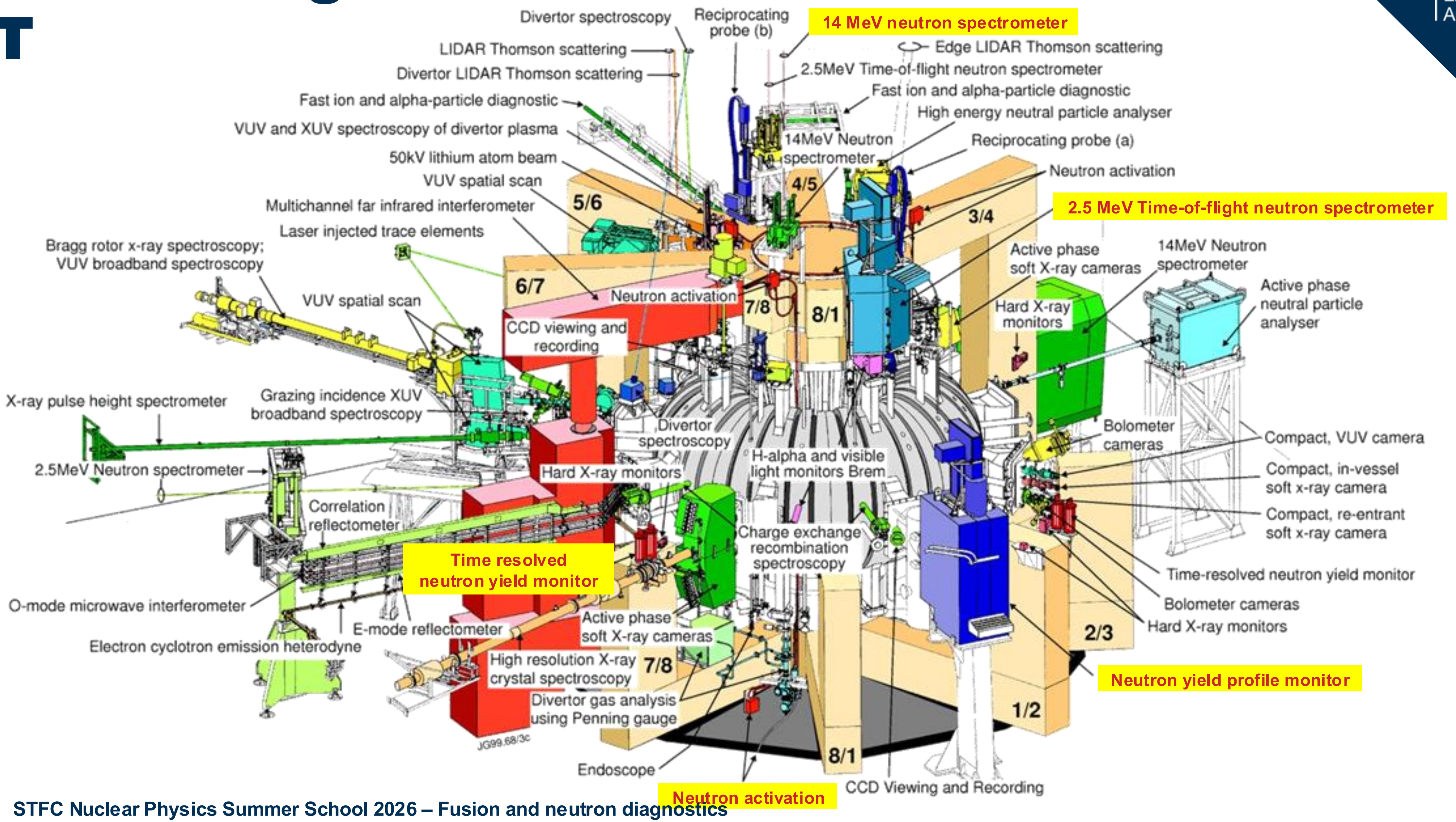
Advantages: high resolution spectormetry

Disadvantages: small surface area, low efficiency

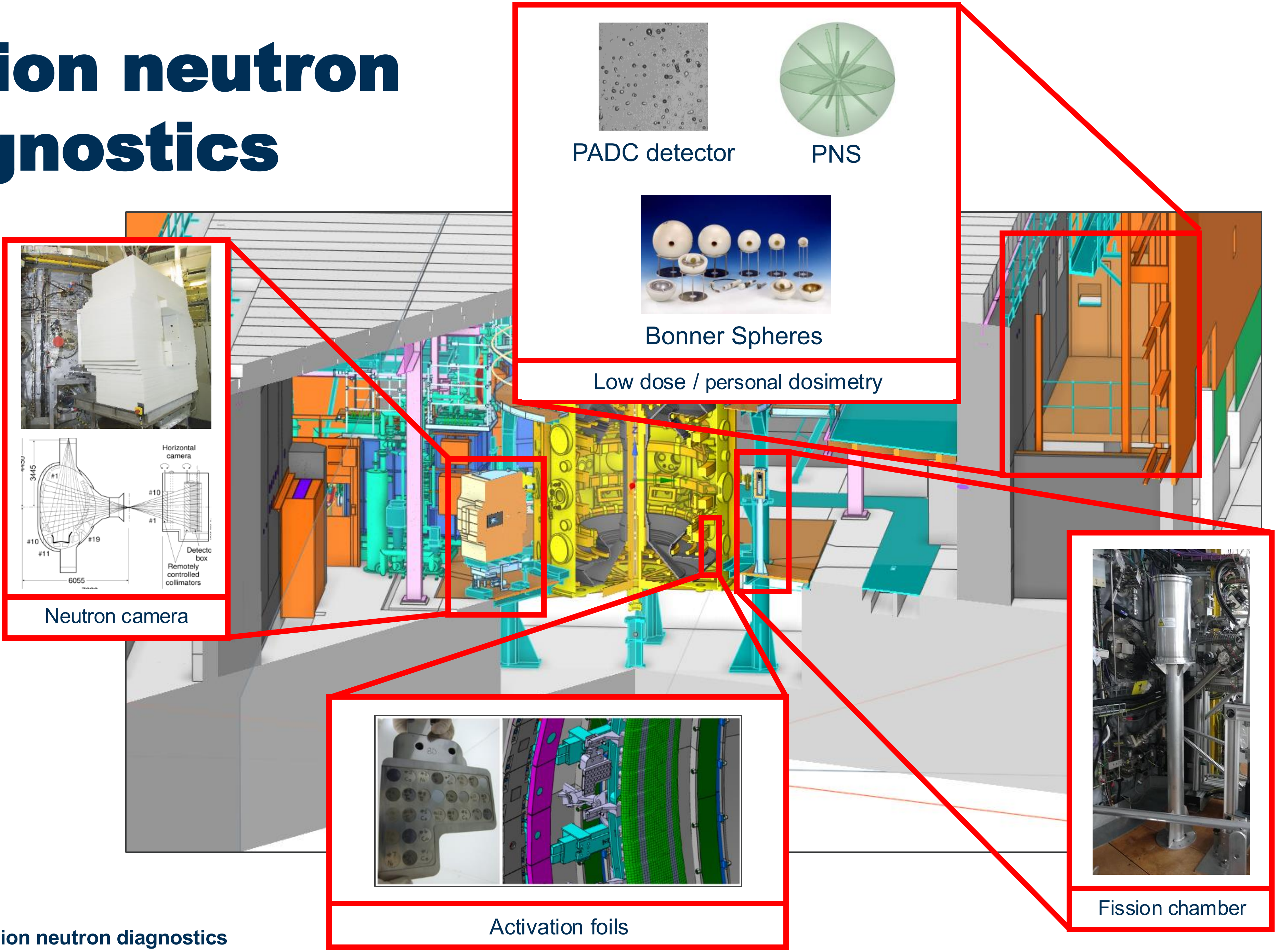
Response matrix simulation for a fast neutron spectrometer based on an organic scintillator, R. F. Ibragimov et. Al. 2024.

Tokamak diagnostics
JET

UK Atomic Energy Authority



Fusion neutron diagnostics



Environment gets more intense

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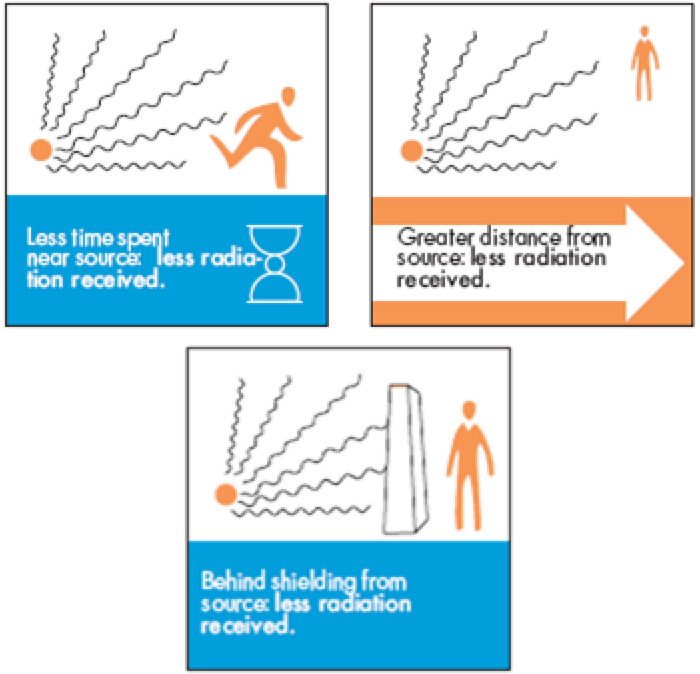
- Temperatures ranging from 100-450 degrees (at diagnostics locations - tritium breeding module environments particularly challenging).
  JET: Approximately 50-100 degrees
- Magnetic fields ranging from 1-10 Tesla
  JET: ~3 Tesla
- Neutron flux 10^{12}-10^{16} n/cm^2/s
  JET: 10^{9}-10^{10} n/cm^2/s
- Also, gamma radiation, vibrations, dust, etc.
  JET: less intense, diagnostics more easily accessed, shorter operations



Ethos:

- **Move diagnostics further away** – while minimising lines of sight
- **Shield** – while minimising perturbation of the field
- **Redesign** – takes time and requires qualification
- **Use as little as possible –** diagnostics on power plants will be minimal, aiming at control (not science)

Challenge:
We don't know the exact environments or requirements for future machines but may be required to provide solutions quickly to inform design/planning.

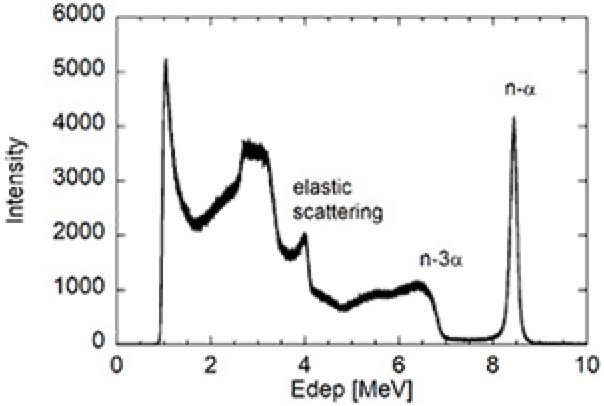
Diamond detectors

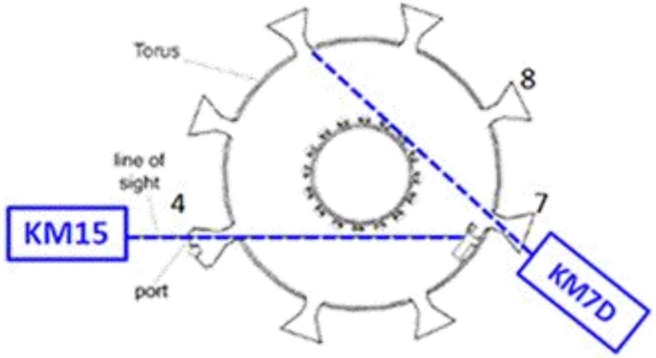
DTE2 saw an enhancement of the nuclear diagnostics used on JET, including the use of single crystal diamond-based detectors along collimated lines of sight to measure 14 MeV neutron yield.

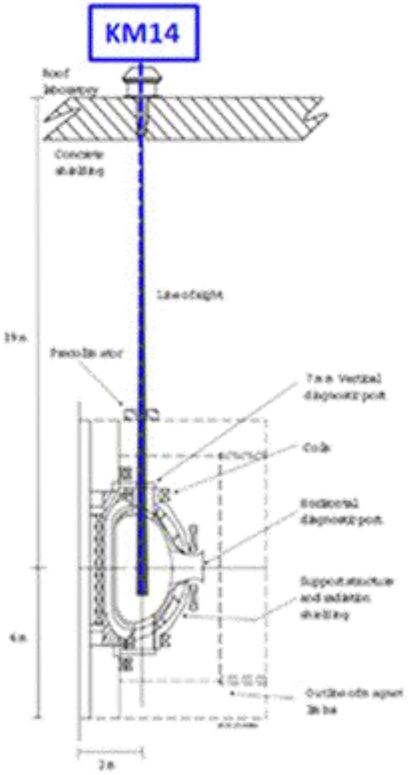
The best production technique is the chemical vapor deposition (CVD) which can grow electronic grade single crystal diamonds detectors, suitable for radiation detection purposes.

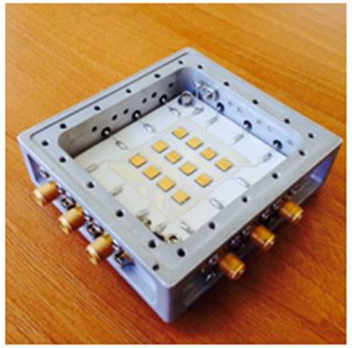
Electron–hole pairs are generated by the charged particles produced via neutron-induced nuclear reactions with the carbon and the charge associated is proportional to the energy of the neutron, the key reactions are:

- $^{12}C(n,n')^{12}C$
- $^{12}C(n,n')3\alpha$
- $^{12}C(n,\alpha)$







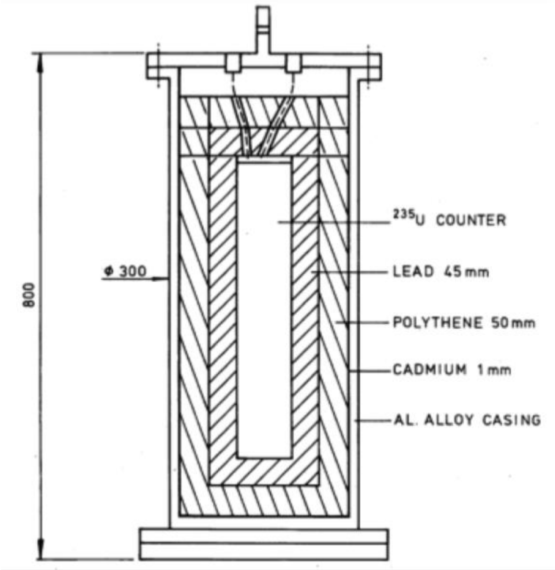


https://iopscience.iop.org/article/10.1088/1741-4326/ad0a49

Time resolved neutron yield monitor

KN1 Fission Chambers

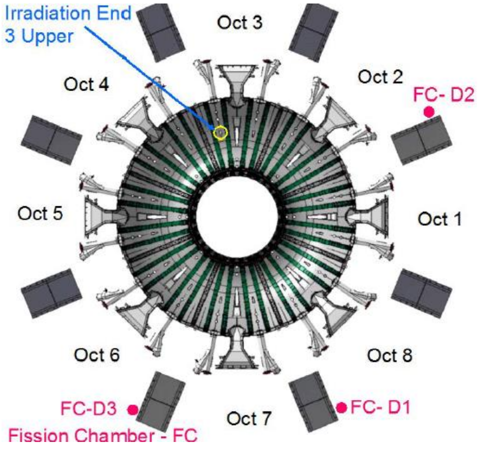
UK Atomic Energy Authority



- Incoming neutrons must be thermalised, in this case using polythene and lead
- Thermal neutrons interact with a thin layer of highly enriched uranium (HEU) producing fission fragments with high kinetic energy and causing ionizing radiation.
- The uranium layer must be thin enough for the fission fragments to escape and enter the filling gas between the electrodes.
- A voltage is applied between the anode and the cathode, and the produced electric current is proportional to the neutron flux.

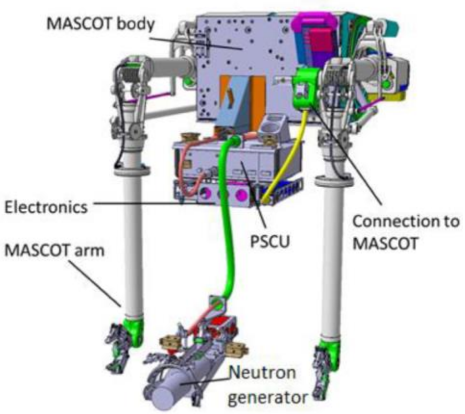
- Three U-235/U-238 pairs of fission chambers located around JET to monitor the time evolution of the neutron emission rate
- Neutron yields can be measured ranging from 10^{10} to 10^{20} n/s

- Fission chambers are insensitive to neutron energy
- Intensive Monte Carlo codes need to be run to determine the fraction of scattered/direct neutrons in order to apply a correction coefficient to the measurements.



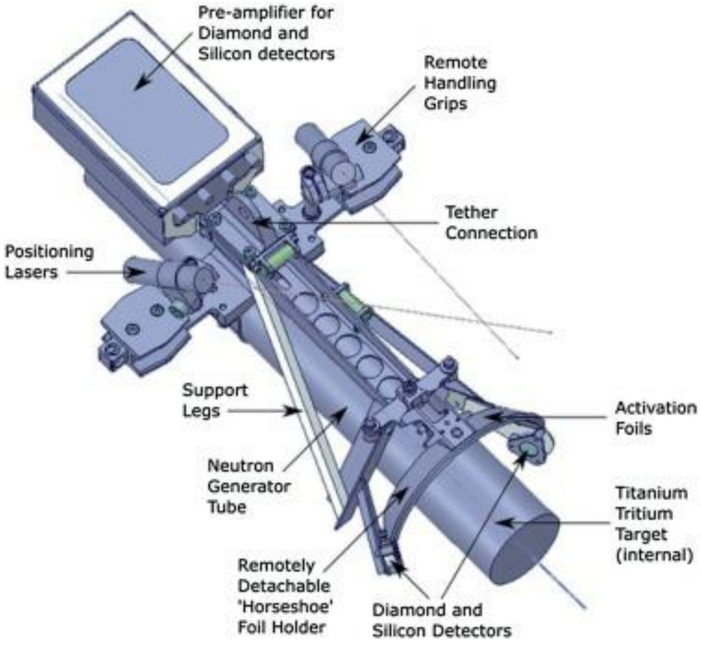
https://scipub.euro-fusion.org/wp-content/uploads/2014/11/EFDP11011.pdf

Calibrating the fission chambers



The KN1 fission chambers are located ex-vessel - this means neutrons born in the plasma have scattered on a variety of materials prior to detection.

To calibrate the diagnostics and verify the Monte Carlo simulations DT neutron generators were deployed using MASCOT.



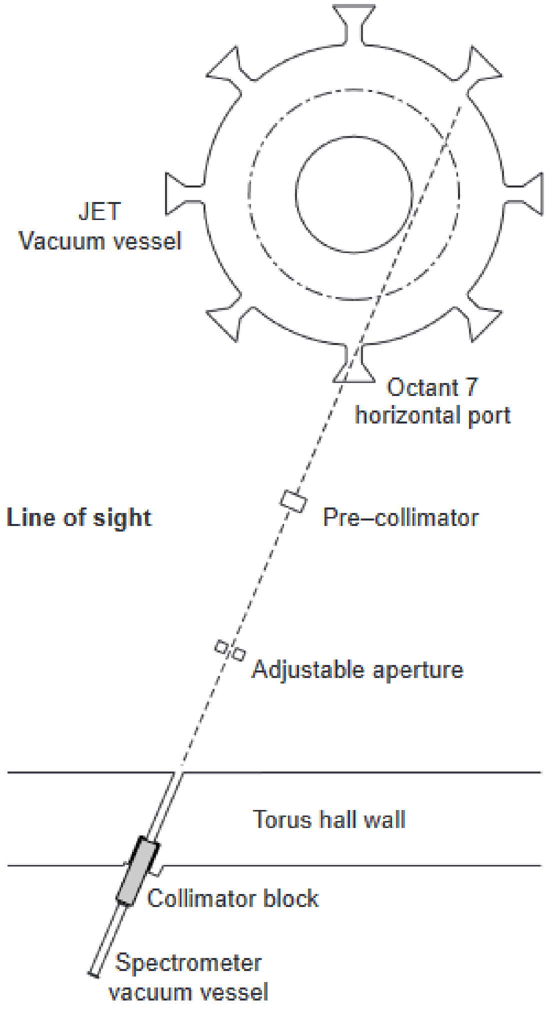
The neutron generators were characterised prior to deployment at the National Physical Laboratory (NPL, Teddington) and was modified to include a "horseshoe" of activation foils, diamond detectors and silicon detectors to verify the output of the neutron source and the angular distribution of the neutrons emitted.

Once the output was well known the generator was deployed in JET and the fission chambers could be calibrated from this well characterised output.

https://www.sciencedirect.com/science/article/pii/S0920379618300978
https://race.ukaea.uk/programmes/jet/

14 MeV neutron spectrometer

Magnetic Proton Recoil (MPR) spectrometer



Based on the principle of the proton recoil telescope, initially for 14 MeV neutrons.

- Collimated neutrons scatter elastically on hydrogen nuclei (protons) in a thin plastic foil
- The energy distribution of the ejected protons is measured in a semiconductor detector.
- The neutron spectrum can then be deduced from the proton spectrum, given knowledge of the geometry of the instrument.

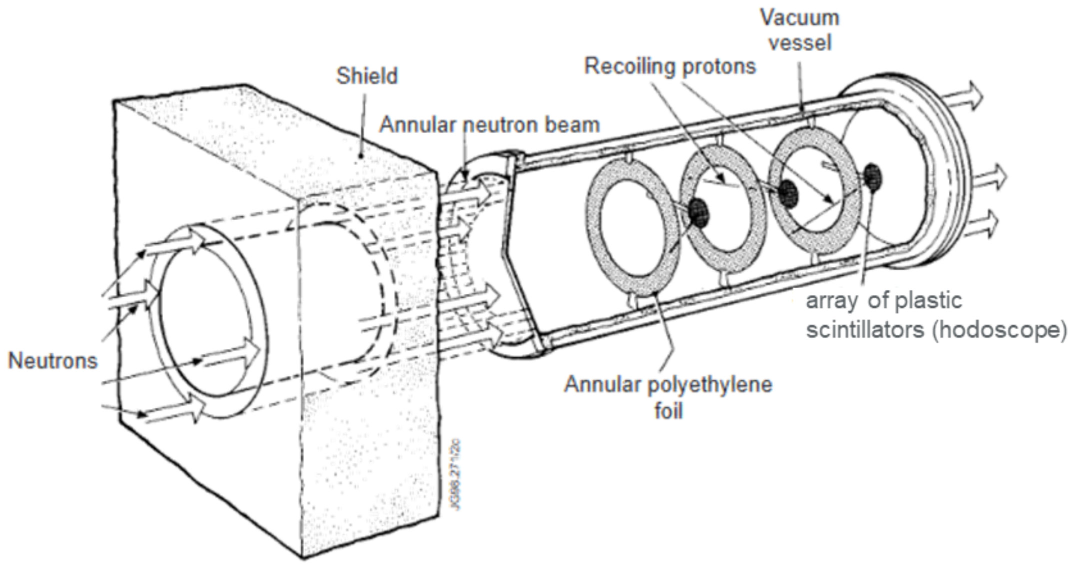
Three identical telescope modules arranged one behind the other, to increase efficiency without worsening resolution.

- Horizontal line of sight to the plasma
- The detector is physically shielded

MPRu

To access 2.5MeV (DD) neutrons.

Each element of the hodoscope has a fast plastic scintillator facing the incoming protons as the top layer and a second thicker slow scintillator. The different timing properties makes pulse shape discrimination possible.



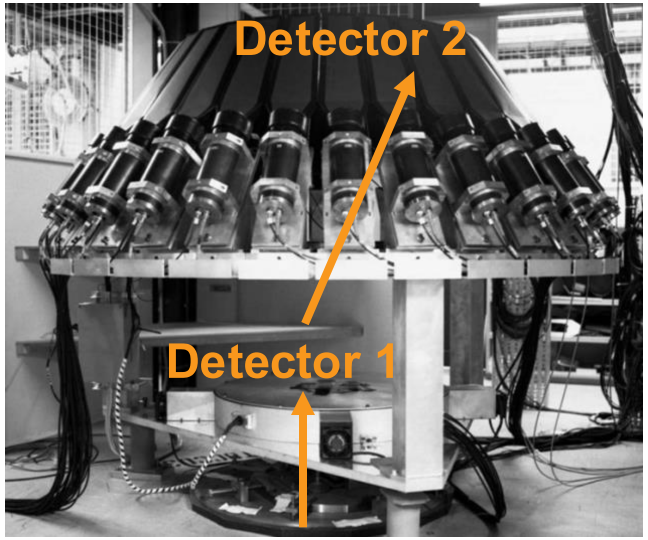
https://scipub.euro-fusion.org/wp-content/uploads/2014/11/JETP98030.pdf
https://scipub.euro-fusion.org/wp-content/uploads/2014/11/EFDC060108.pdf

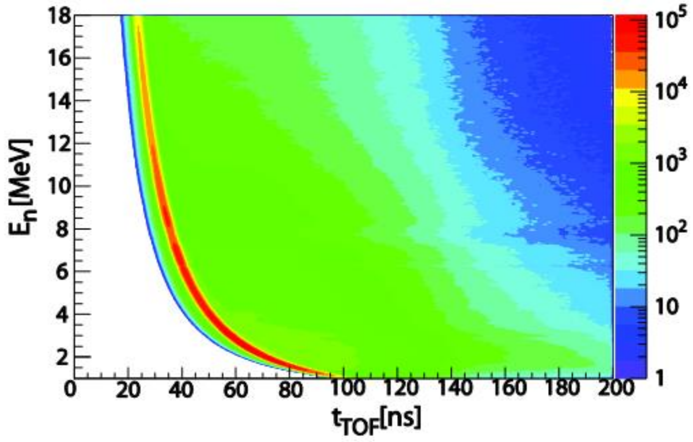
2.5 MeV Time-of-flight neutron spectrometer

Time Of Flight neutron spectrometer Optimized for high count Rate (TOFOR)

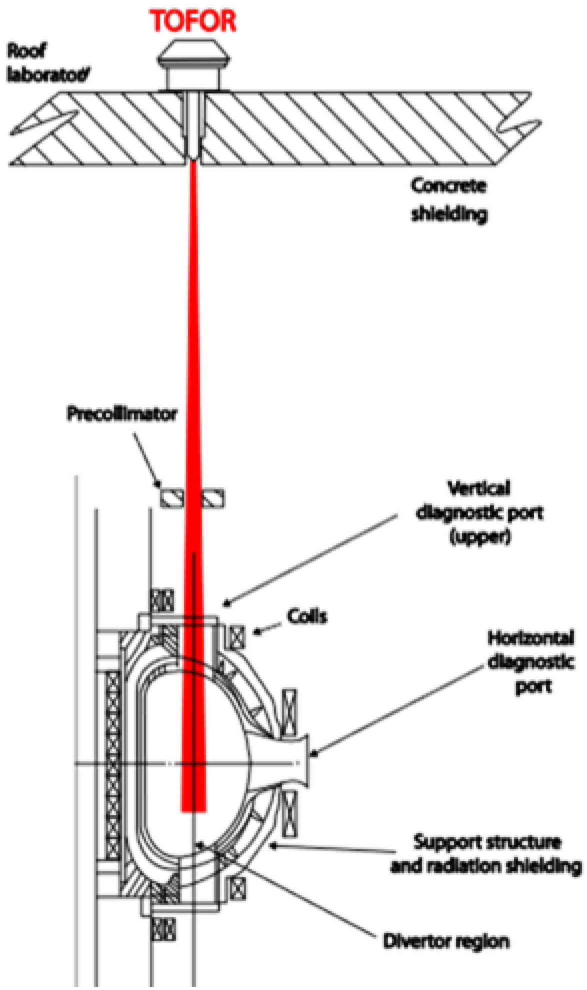
- Requires direct lines of sight to the plasma (vertical in JET)
- Neutrons leave the plasma through a vertical port through a collimator.

- Neutrons enter TOFOR through a small scintillation detector, where they scatter on hydrogen giving a signal in the first detector.
- The scattered neutron then travels to an upper detector array resembling an umbrella.
- The time between the first and the second pulse gives a measure of the neutron energy.





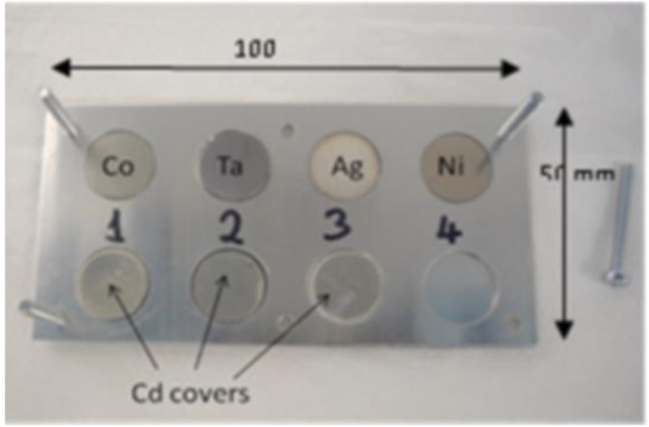
These devices are large, complex and manpower-intensive.



https://scipub.euro-fusion.org/wp-content/uploads/2014/11/EFDC060101.pdf

Diagnostic: Activation foils

Activation foils	
Detector type	Proportional or Spectrometry
Active/passive	Passive
Time dependence	Require removal based on half-life
Energy range	Depends upon materials/reaction
Reaction product	gamma
Hardness	Insensitive to electromagnetic fields / high fluence
Cost	Low



R Villari et al, Fus. Eng. Des **136** (2018) 1545-9

- Foils become neutron activated via a variety of reactions with different threshold energies
- Foils selected on several factors: neutron field expected, half-life and gamma rays emitted by the product, unfolding limitations
- After activation, foils are analysed by gamma-ray spectroscopy
- Removing the activated foils needs to be considered from health physics perspective
- Information gained: flux and some limited energy information, based on threshold energies of reactions

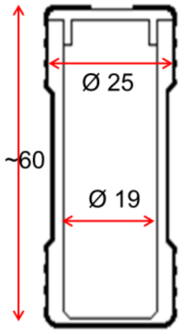
Advantages: Cheap, rad-hard, portable

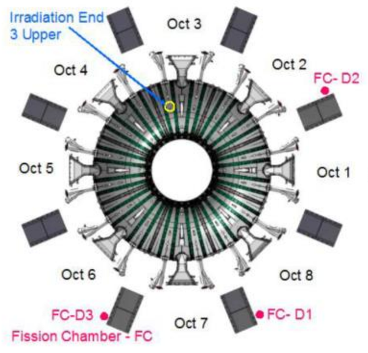
Disadvantages: Requires gamma spec, time constraints, needs high flux

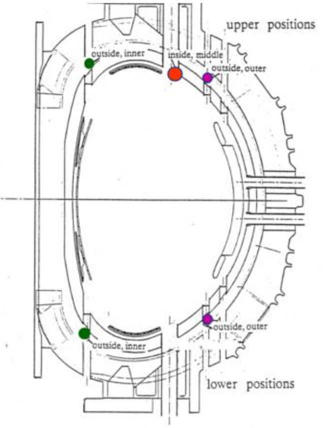
Neutron activation (KN2)

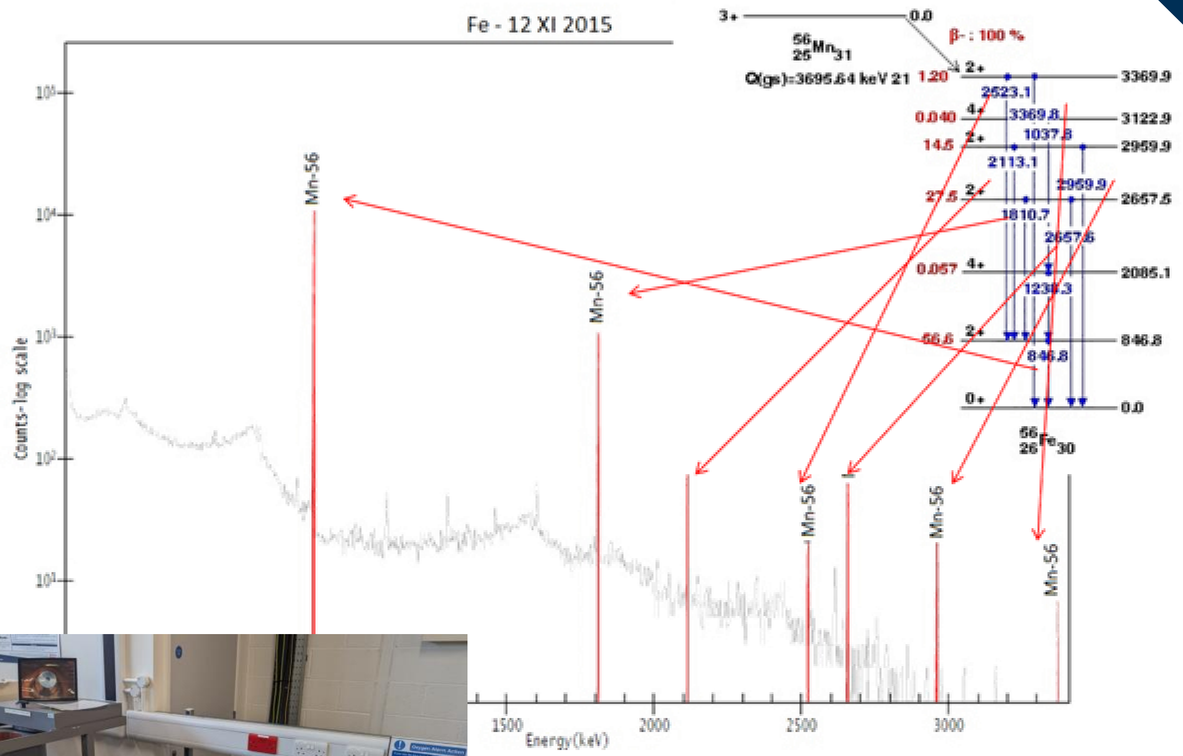
Usually, the 115In(n,n')115mIn activation reaction is used for DD neutrons and 28Si(n,p)28Al, 63Cu(n,2n)62Cu, 93Nb(n,2n)92mNb reactions for DT neutrons

Short term irradiation (8 ends in total, 2 are used)

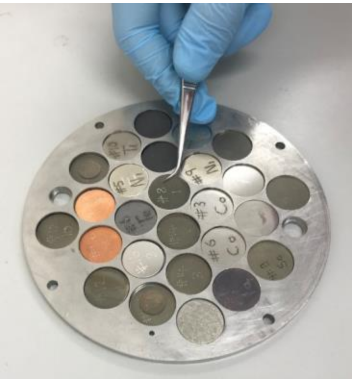








Long term irradiation



Neutron yield profile monitor

UK Atomic Energy Authority

Requires direct lines of sight to provide neutron emission as a function of both position and time.

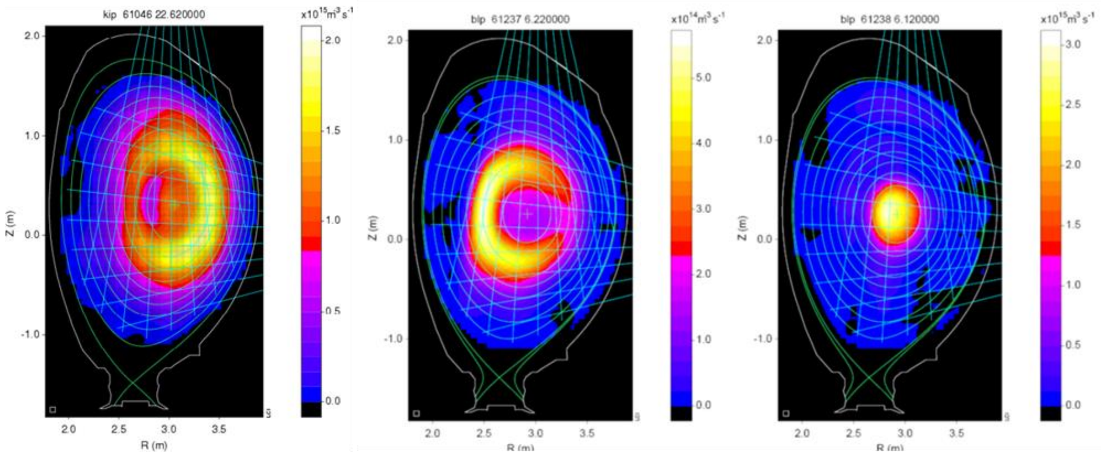
The neutron profile monitor consists of two concrete shields which each provides a fan-shaped array of collimators. There are two neutron detectors, NE213 liquid scintillators and BC418 plastic scintillators, pulse shape discrimination can be used to distinguish neutrons of different energies.

The ratio of the 2.5–14 MeV neutron yields provides a measure of the ratio of the densities of deuterium and tritium in the plasma. Used (1999) to study the transport of tritium into a magnetically confined plasma

Off-axis T-beam $n_e(0) \approx 4.5\times10^{-19}$ m^{-3}

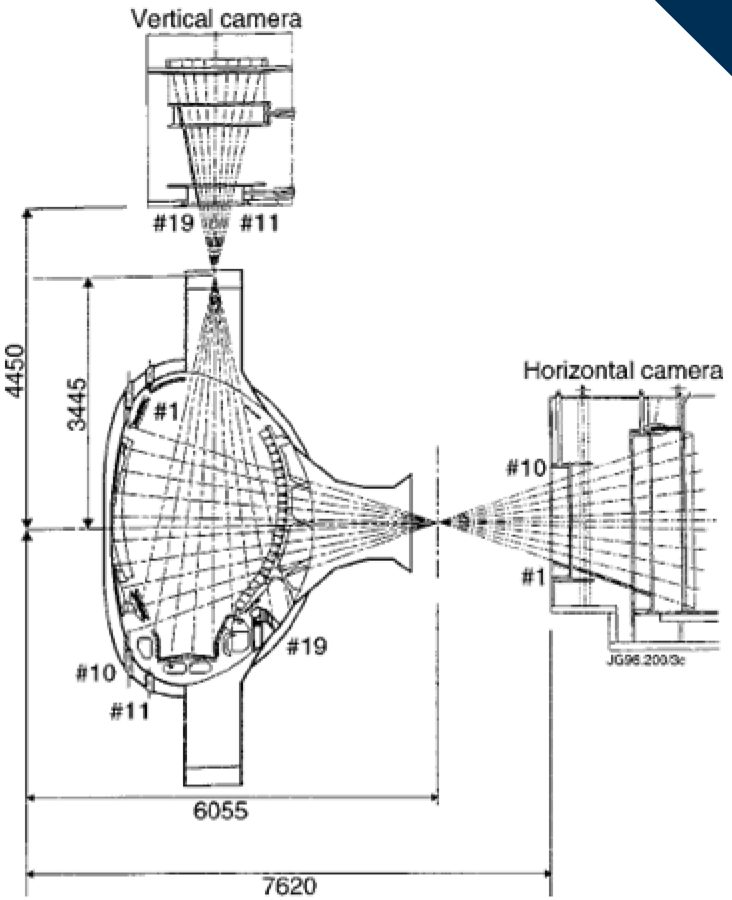
Off-axis T-beam $n_e(0) \approx 1.8\times10^{-19}$ m^{-3}

On-axis T-beam $n_e(0) \approx 4.4\times10^{-19}$ m^{-3}



Also used for taking preventive or mitigating actions against impending disruptions by monitoring the radiated power in different plasma regions.

Computationally intensive task typically performed using machine learning.



https://www.researchgate.net/publication/253863077_Neutron_profile_measurements_for_trace_tritium_experiments

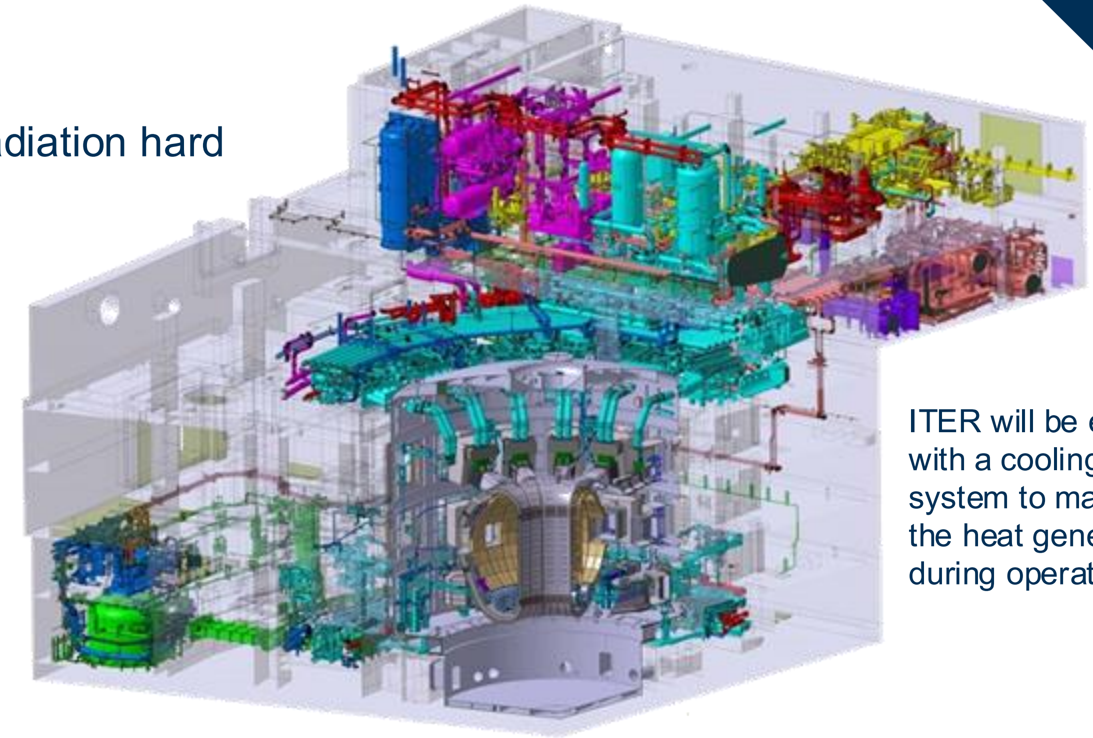
Resilient diagnostics

Radiation, temperature, magnetic field

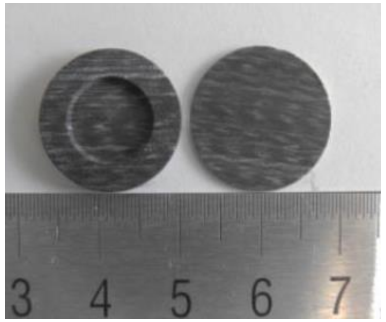
1. Making better use of diagnostic systems that are inherently radiation hard
   - Activation foils – encapsulation and machine learning
   - Coolant systems – intentional dopants
   - Diamond detectors
   - Hollow core fibres

2. Shielding diagnostics to make them radiation hard
   - Can perturb the results
   - Adds to cost and reduces space
   - Makes maintenance potentially more challenging
   - Requires re-qualification

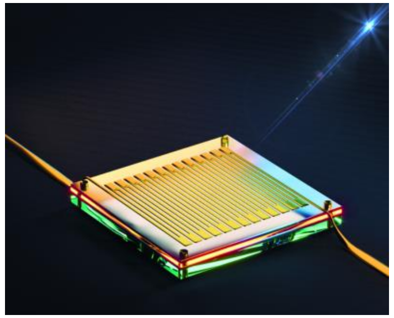
3. R&D to make diagnostics radiation hard
   - Understanding failure modes
   - Require appropriate testing environments
   - Takes time



ITER will be equipped with a cooling water system to manage the heat generated during operation.



Optical fibres



Optical fibres are a great way to transmit information – potentially allowing us to place electronics further from the harsh environment of the machine.

However, traditional solid fibres suffer from an effect known as darkening, a loss of the propagating optical signal leading to decreased power at the output end. This can be influenced by:

- Radiation
- Glass composition
- Operating wavelength
- Dose rate and total accumulated dose
- Temperature
- Power propagating through the core

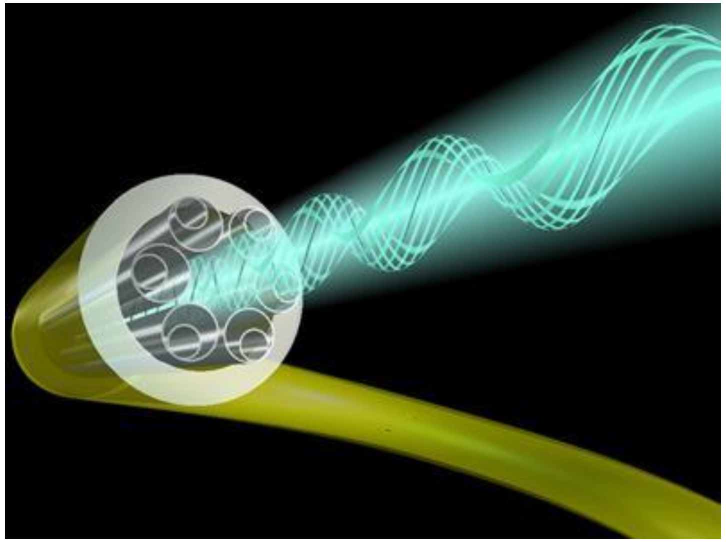
Untapped area: Quantum sensors

Capable of extracting information from a single photon, making these darkening effects less problematic.

Alternative: Hollow core fibres?

- Demonstrated with promising tolerance to gamma and some neutron fields
- Requires more research to explore applications for fusion in neutron diagnostics, also magnetic field sensors and tritium detectors.

CERN



University of Southampton

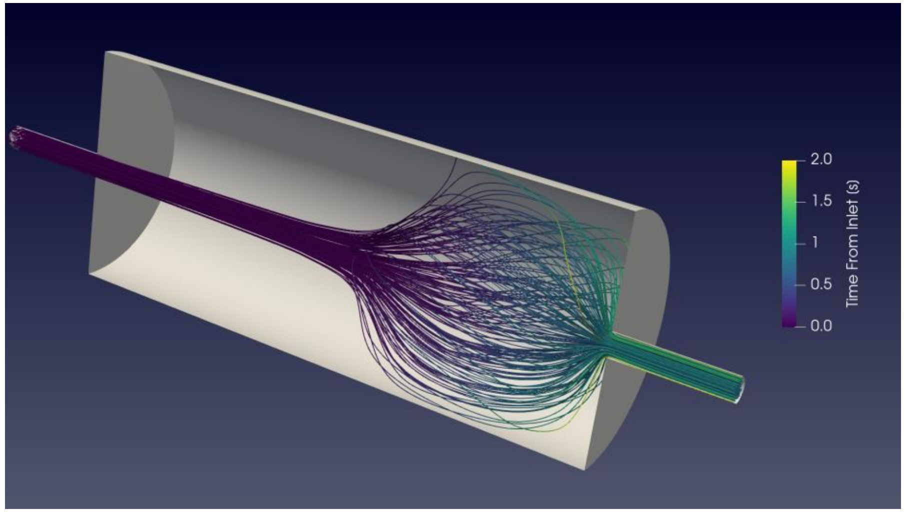
Fluid Activation and ACPs

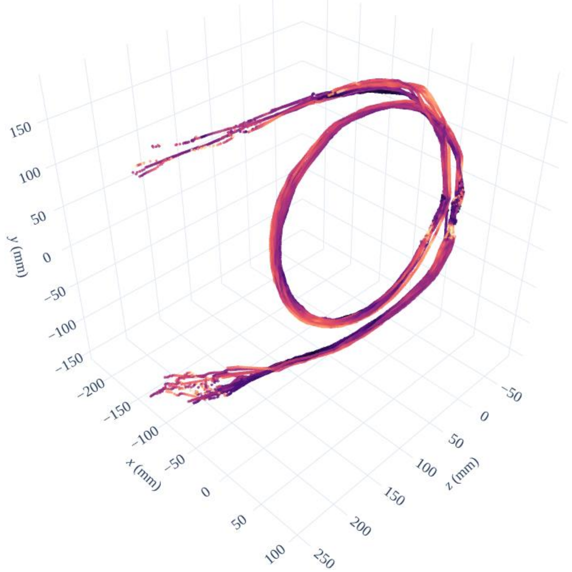
UK Atomic Energy Authority

- Movement of fluids around coolant/tritium breeding circuits are an important consideration in fusion reactors
    - Can take activated fluids outside of the biological shielding posing risk to personnel
    - Can cause issues with the positioning of safety important sensitive equipment
    - Can affect the overall activity/decay heat of material inside the reactor

- When passing through radiation areas the fluids will become activated, and in non-radiation areas the activation products will decay.

- Predicting the dose rate from activated fluids is complicated, you must consider:
    - Fluid dynamics – how the fluid moves through the network of pipes, and this depends on the type of fluid, the geometry of the pipes, the temperature/density which could vary depending on location in the system.
    - ACPs – activated corrosion products. Corrosion products will enter the system and could become activated in radiation areas, these not only add to the dose of the fluid but can deposit and accumulate within the pipe network.





PEPT imaging techniques can be used for validation

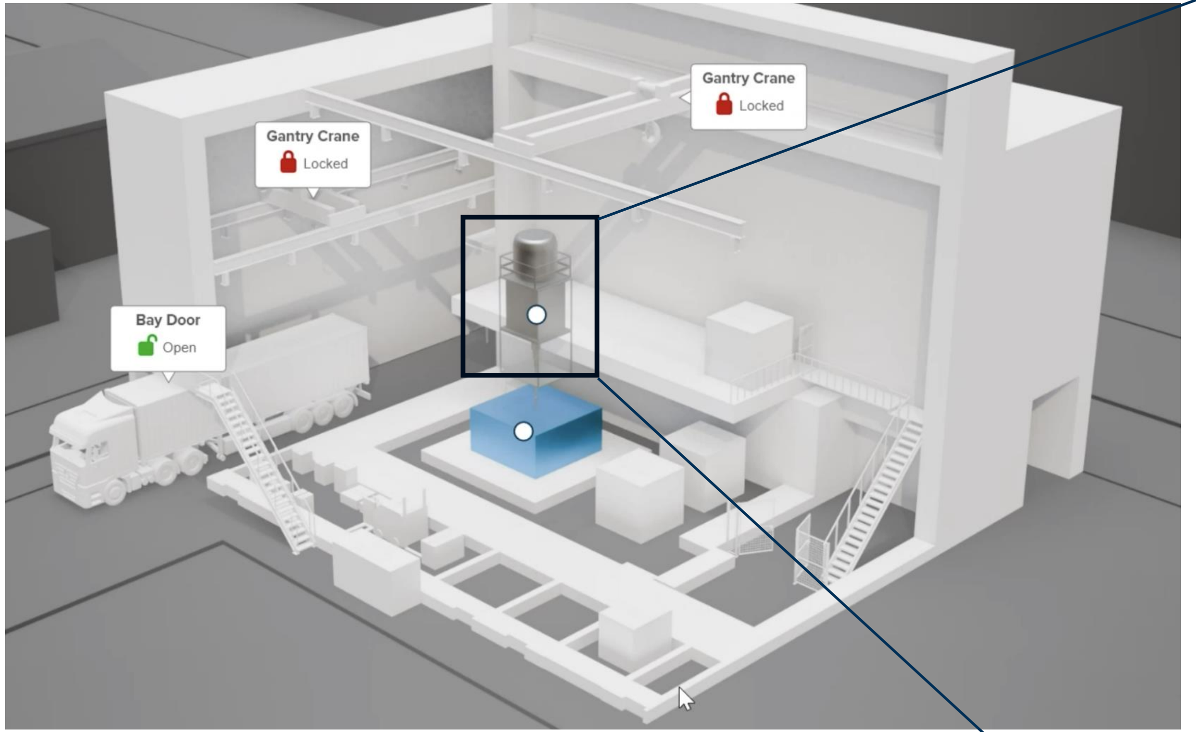
UNIVERSITY OF BIRMINGHAM

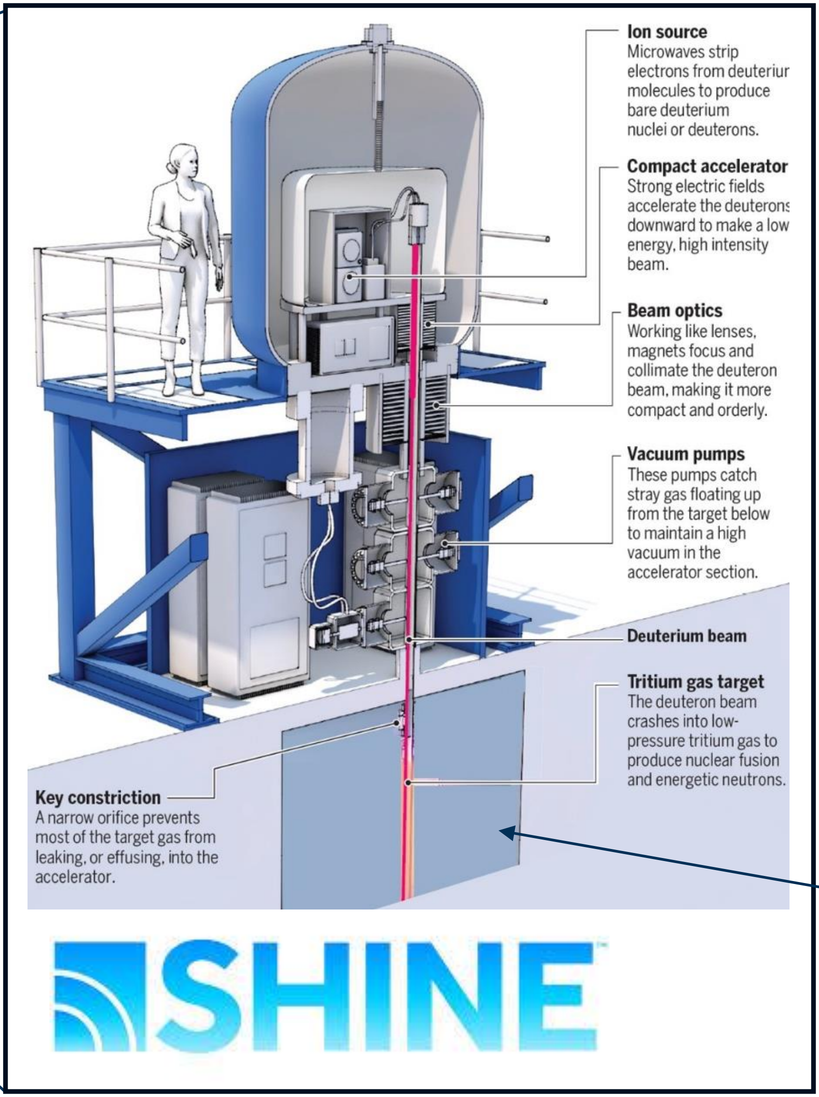
https://www.sciencedirect.com/science/article/pii/S0920379621006700

LIBRTI – LIthium BReeding Tritium Innovation

A unique testbed for benefit to fusion powerplant design & construction

UK Atomic Energy Authority

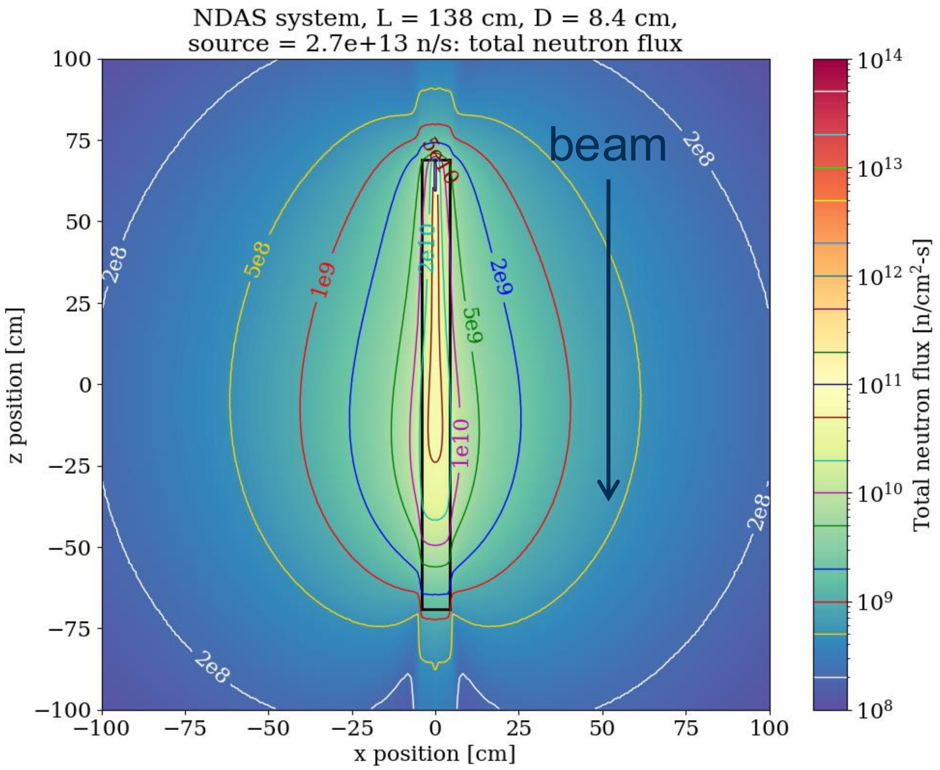


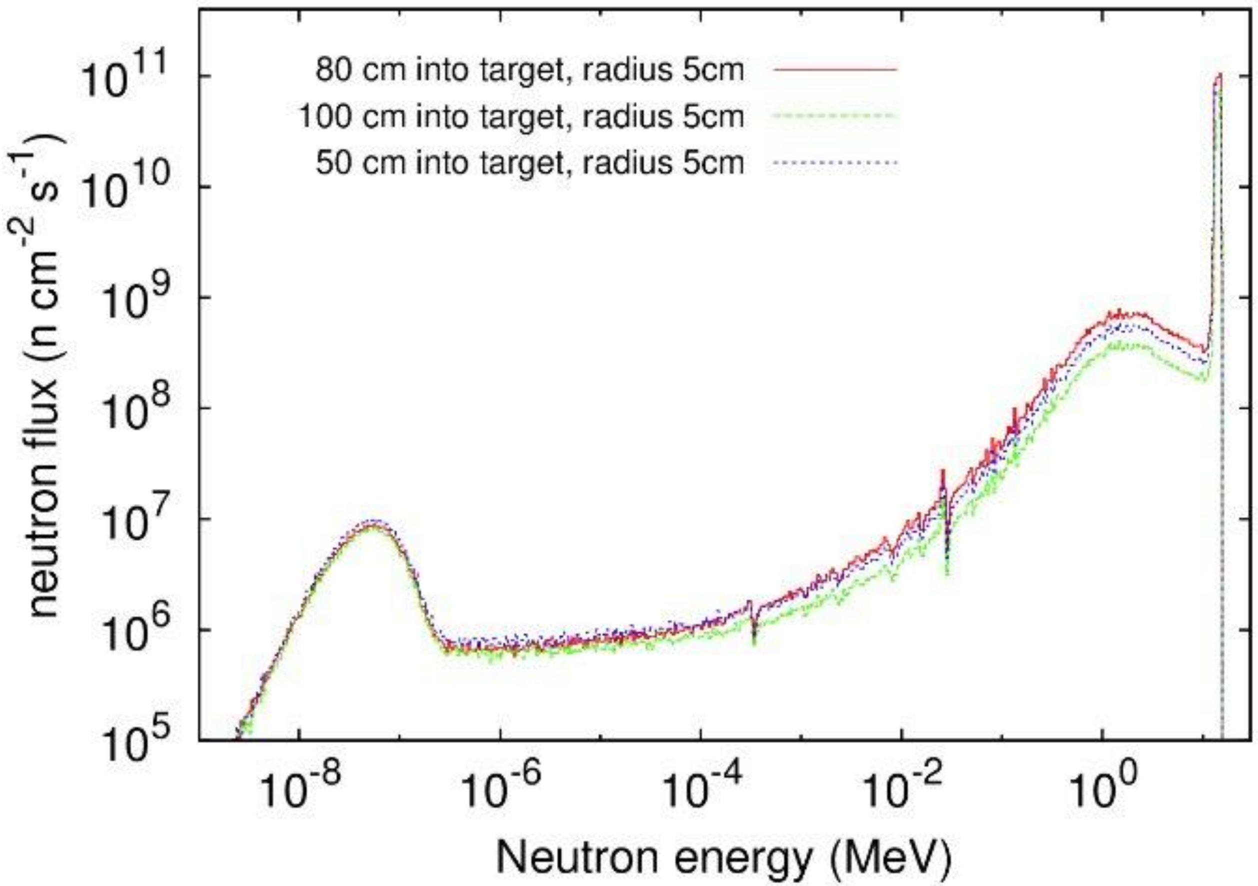


- 125 kW system
- 75 mA deuteron beam injection
- ~300 keV deuterons
- Up to 5×10^{13} n/s total DT-neutron output

- Predict and reproducibly achieve Tritium production
- **Science simulation underpinned by experiments**

The SHINE neutron source profile





Why are we measuring neutrons?

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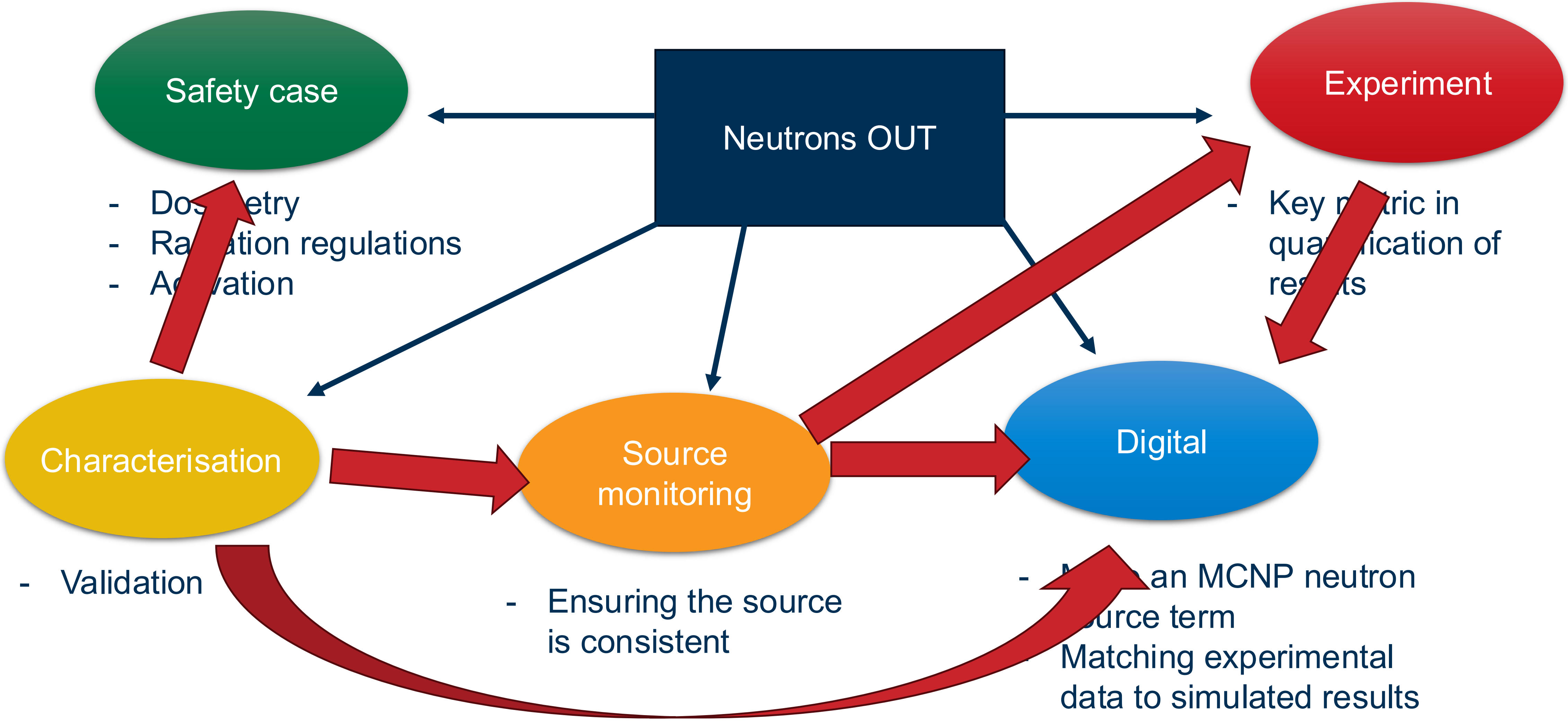

The need for characterisation

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- Factory Acceptance Testing – does it work as anticipated?
- Recharacterise after major maintenance – is everything performing as it should?
- A key performance indicator of a breeder is the *tritium breeding ratio*

$$\text{Tritium Breeding Ratio (TBR)} = \frac{\text{Tritium produced}}{\text{Tritium consumed}}$$

Directly related to neutron flux

- Knowing the source output as a function of time is key
- Use characterisation to cross-calibrate diagnostics around the neutron source
- Better handle on errors and how it affects the measured TBR

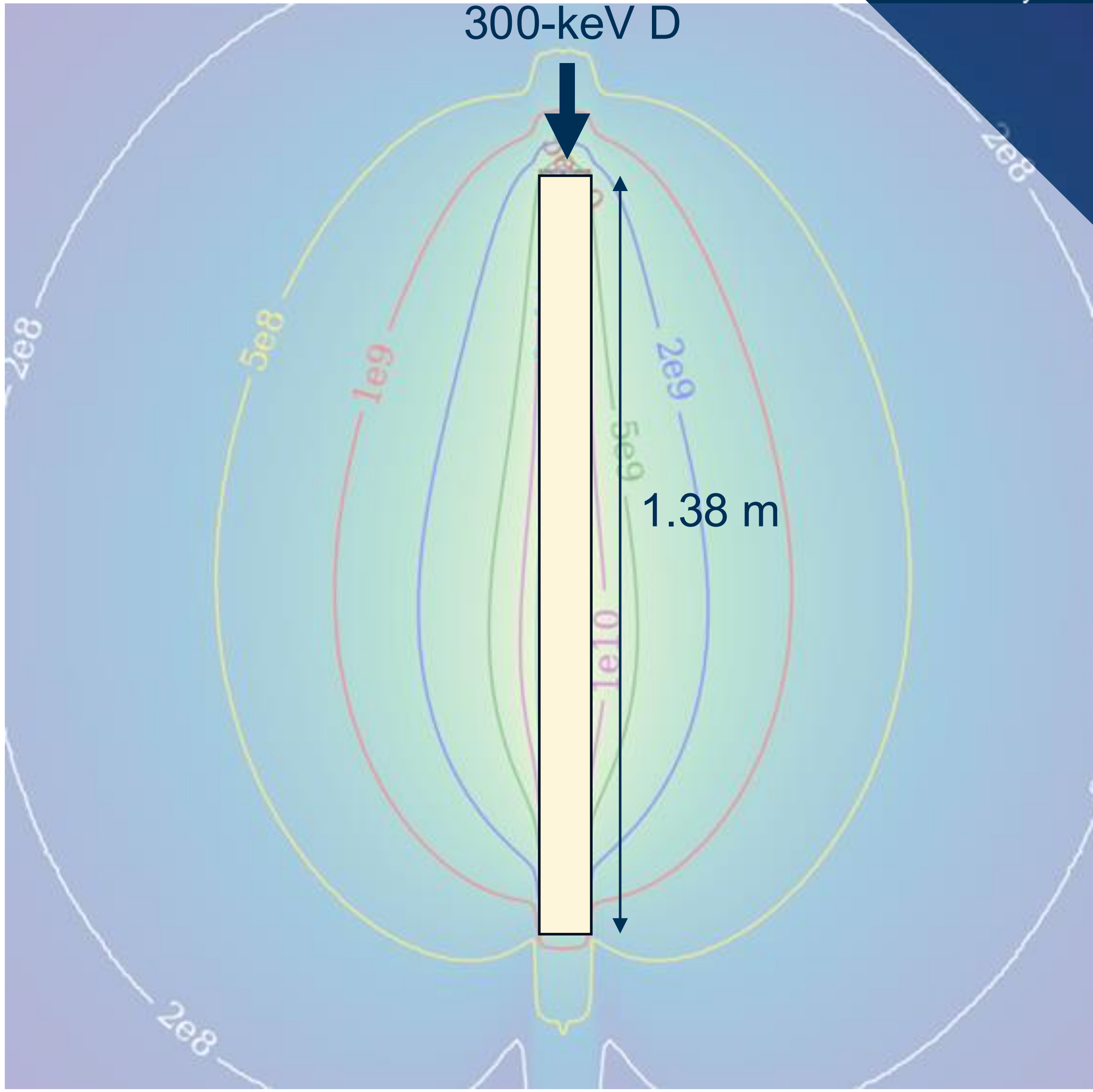
The need to do it a bit differently

Many other DT facilities are ^{2}H beam on solid TiT target

- Use Associated Alpha Detection, foils, fast/thermal neutron detection
  - Can also measure their reaction products (eg medical isotopes) – trickier with ^{3}H

We have:

- Volume source, high source strength
- The need for multiple measurements (to change beam/target settings, etc)
- Don't want to activate too much



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Nuclear fusion needs for nuclear physics

We need nuclear physicists!

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- Reaction cross-sections (neutron induced on relevant fusion materials)
- Data libraries often lacking
- Radiation hard diagnostics
  - High temperature, magnetic fields, high flux, gamma background
  - Electronics, or solutions for electronics far away
  - Diagnostics for a range of neutron energies
- irradiated materials in fusion-relevant environments

Adjacent:

- Material science (embrittlement etc)
- Tritium measurements