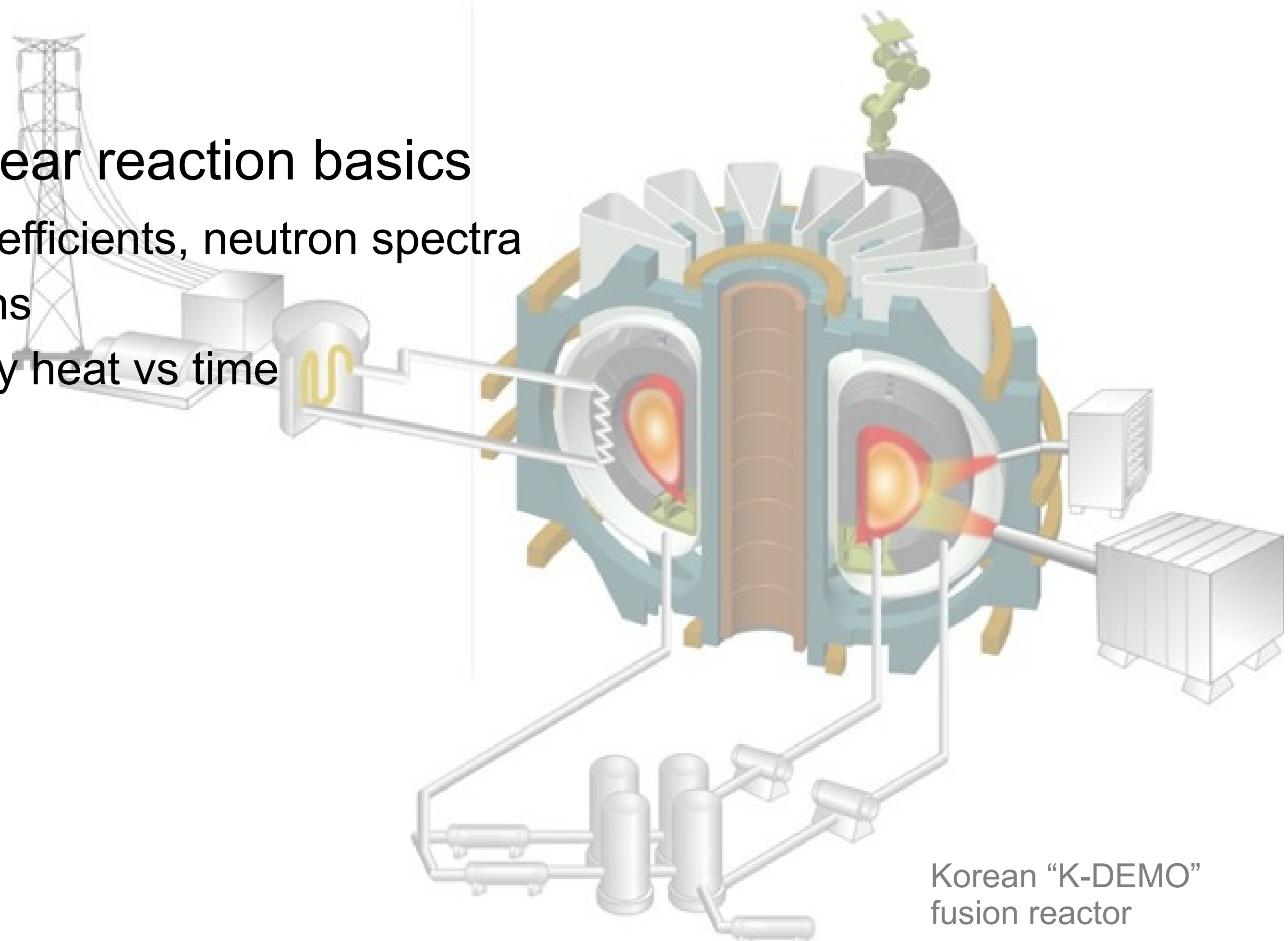
Radiation Effects in Fission and Fusion Power Generation

T N Todd (UKAEA, retired)

Contents

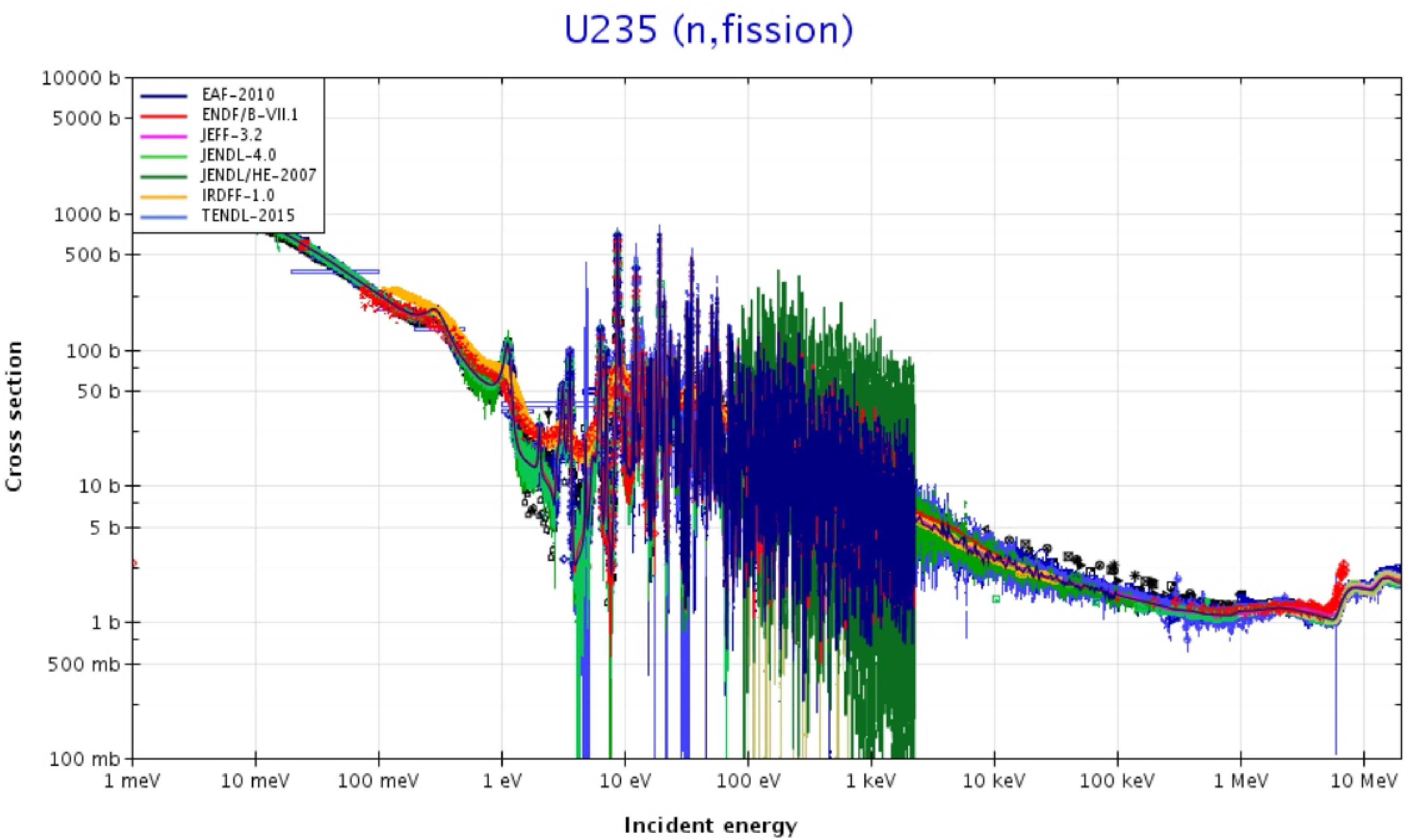
- Power generation nuclear reaction basics
  - Cross-sections, rate coefficients, neutron spectra
  - Activation cross-sections
  - Specific activity & decay heat vs time
- Sources and effects
  - Neutrons
  - Gammas
  - Alphas
  - Protons
  - Betas
- Summary



Korean “K-DEMO” fusion reactor

Fission reaction cross-sections

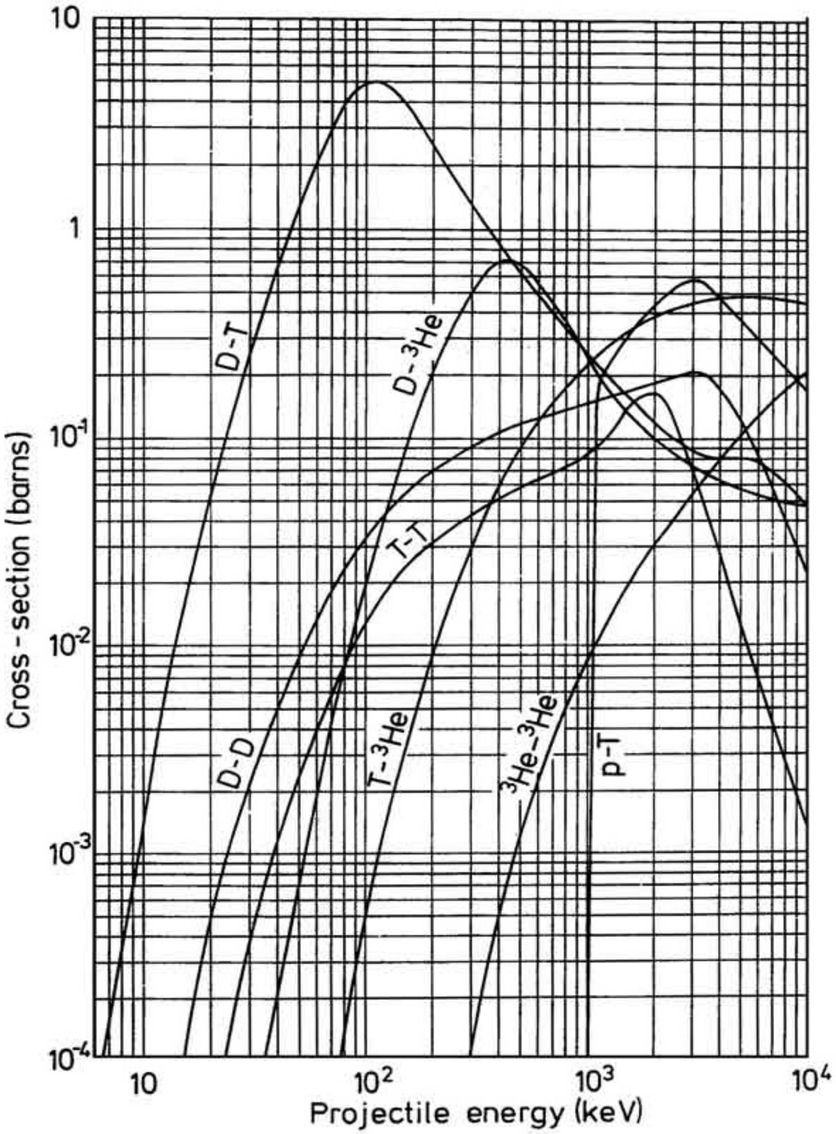
- Fission mainly works on thermal neutrons:

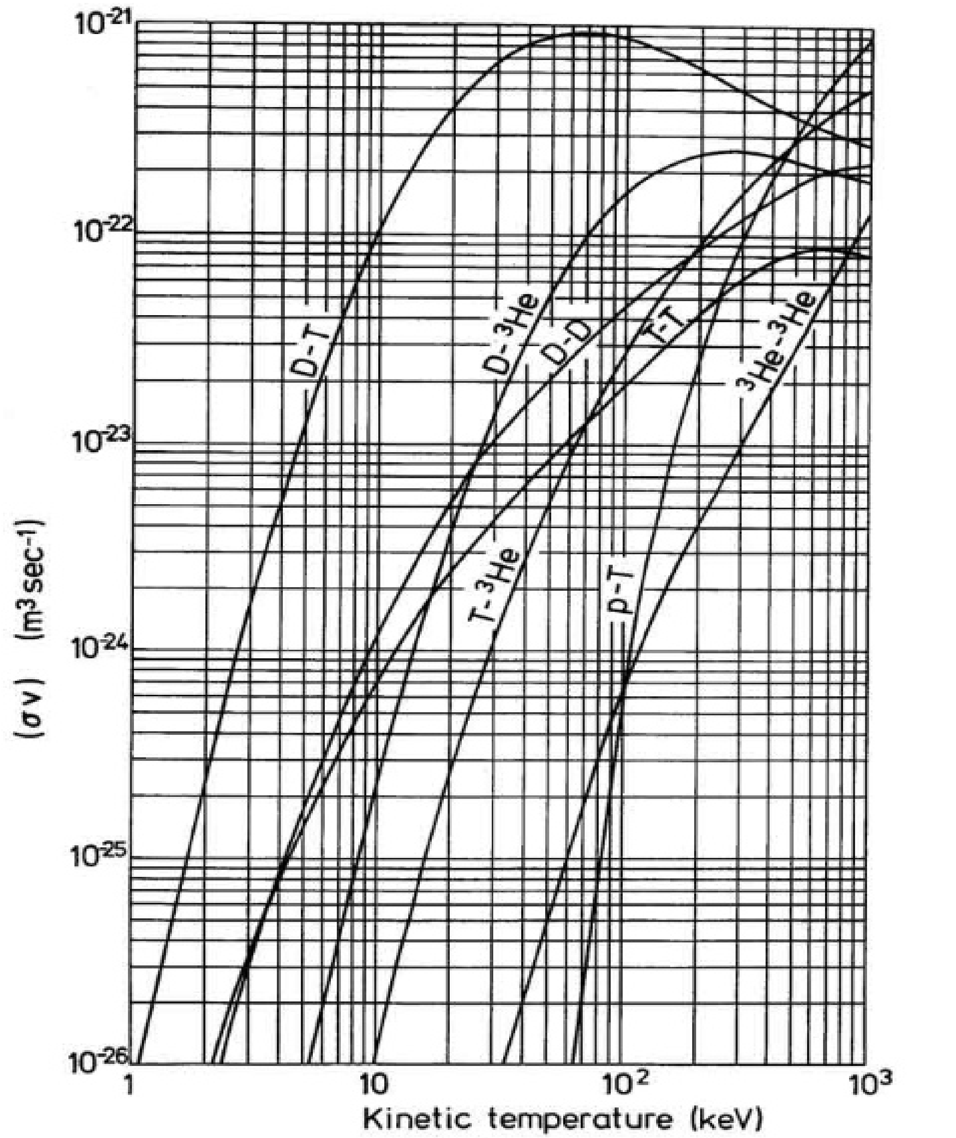


http://www.oecd-nea.org/janis/book/

Fusion reaction cross-sections

- Fusion reactions require high energy H or He isotopes





http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html

Fusion reaction products

- The main fusion reactions yield high energy products:

D + D 50% → T (1.0MeV) + p (3.0MeV)

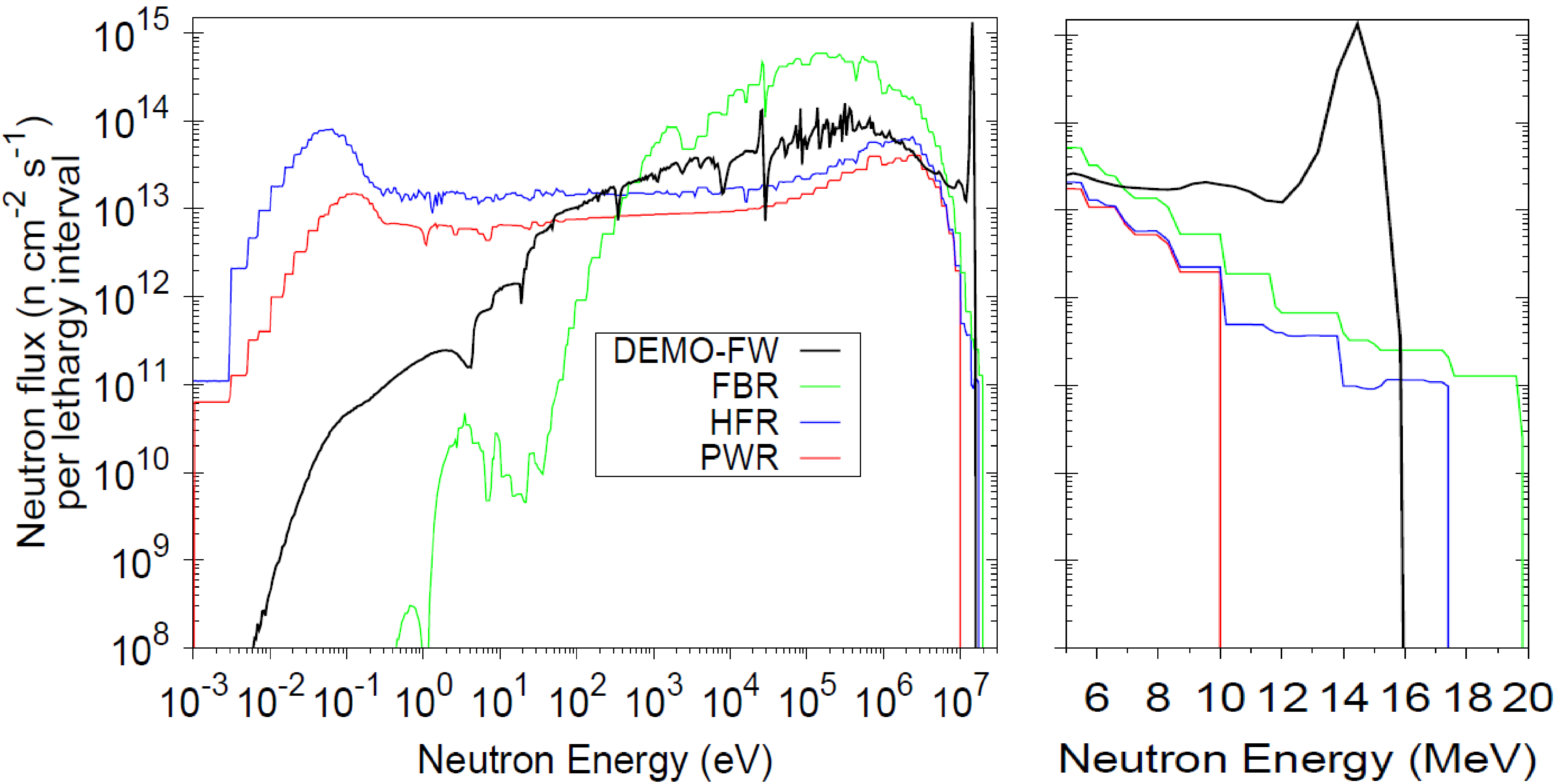
D + D 50% → ^{3}He (0.8MeV) + n (2.4MeV)

D + T → ^{4}He (3.6MeV) + n (14.0MeV)

http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html

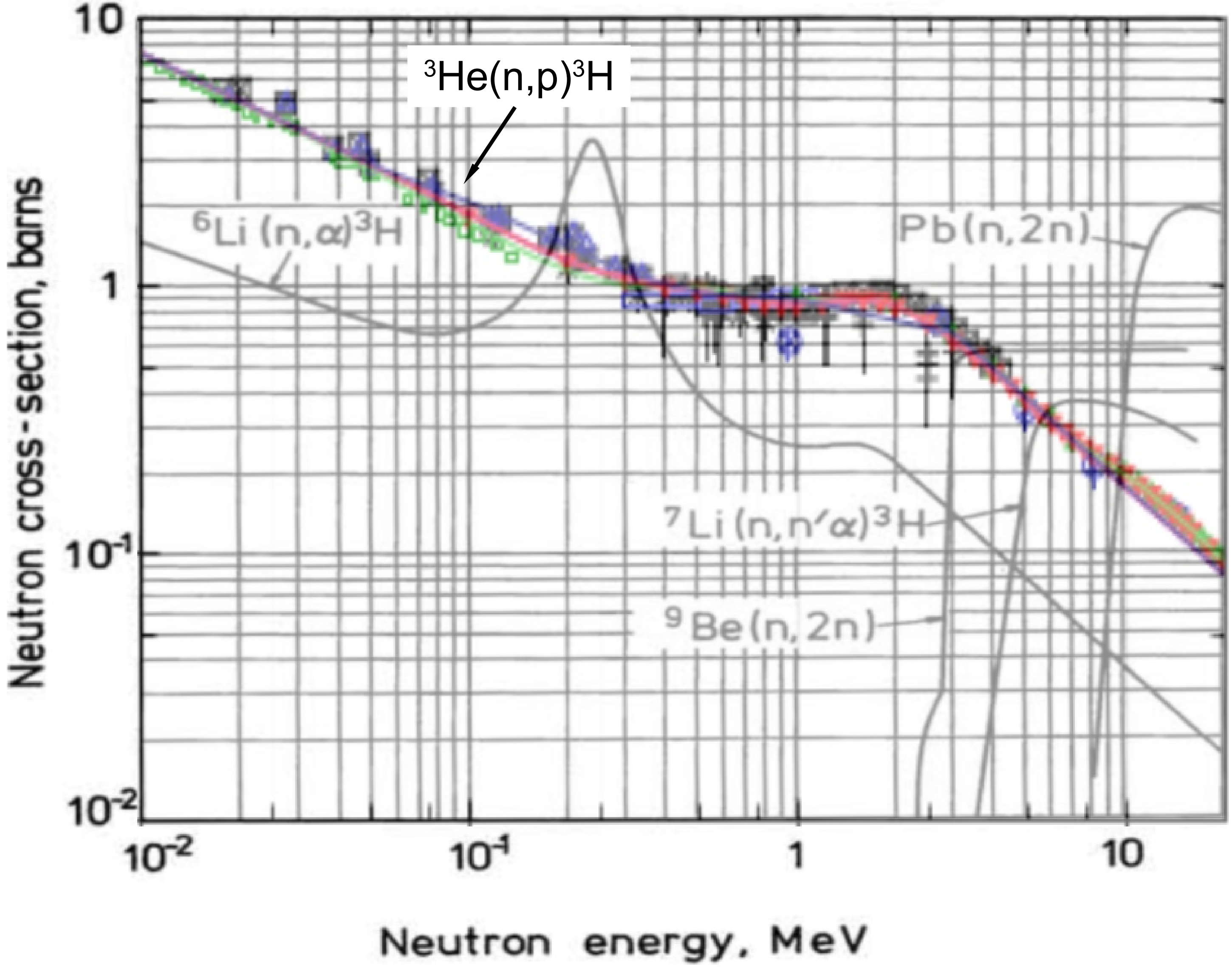
Fission & fusion reactor neutron flux spectra

- Fusion reactors have many more neutrons >10MeV



Fusion reaction cross-sections

Apart from ^6Li, fusion blanket reactions require those fast neutrons:



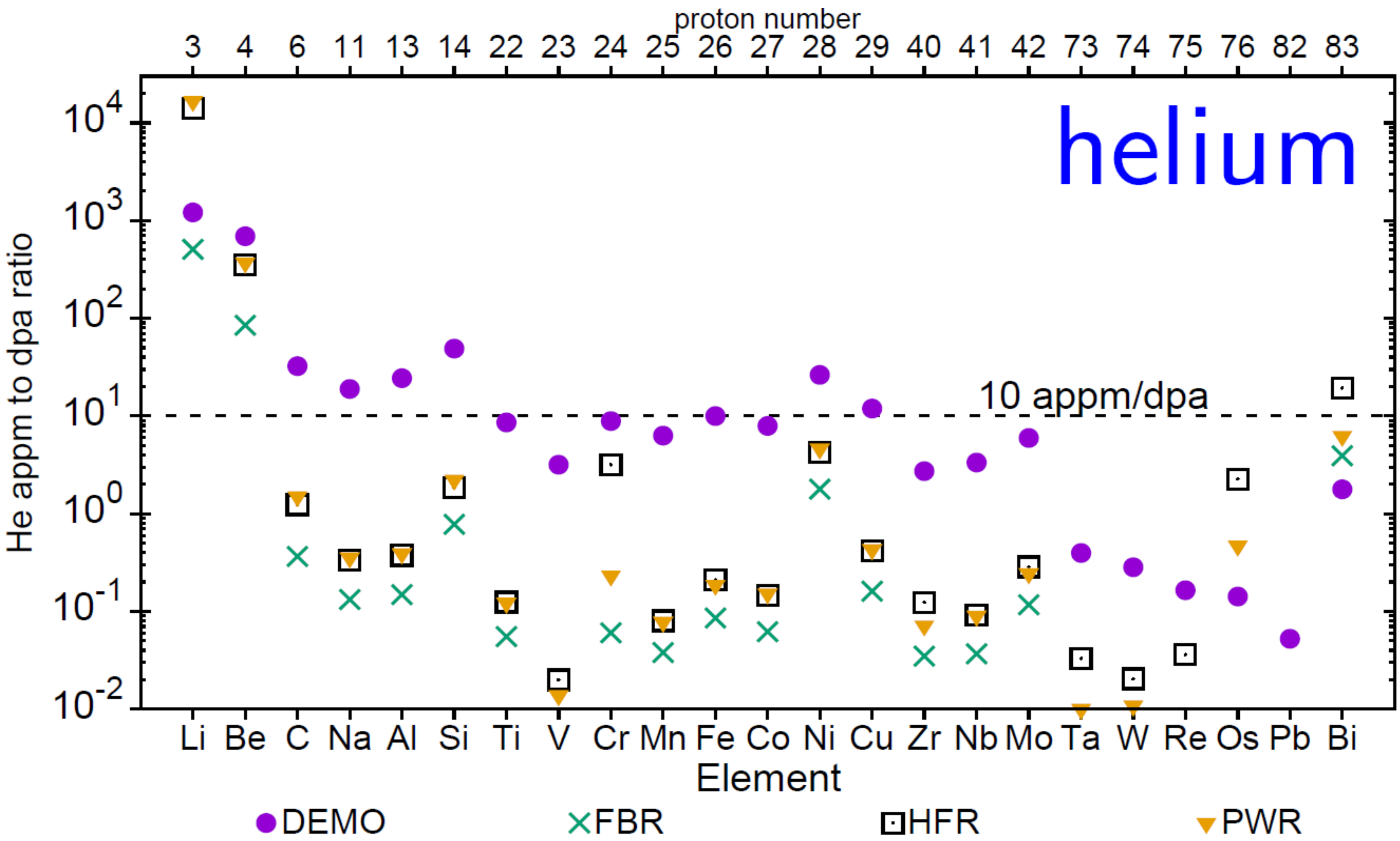
^3He from DD reactions and T decay is usually neglected but is a strong thermal neutron absorber

http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html

http://www.oecd-nea.org/janis/book/

Fission & fusion reactor neutron flux spectra

The fast neutrons create more transmutations and hence gas



M Gilbert *et al*, "Scoping of material damage with FISPACT-II and different nuclear data libraries: transmutation, activation, and PKAs", TM on Nuclear Reaction Data and Uncertainties for Radiation Damage IAEA Headquarters, Vienna, Austria, 13-16 June, 2016

~10x more H is produced than He, but it more readily diffuses out

Fusion radiation in operations

Radiation problems rise with the power and life-time of the machine

Comparison of radiological impacts of JET-ITER-DEMO First Wall (approximate!)

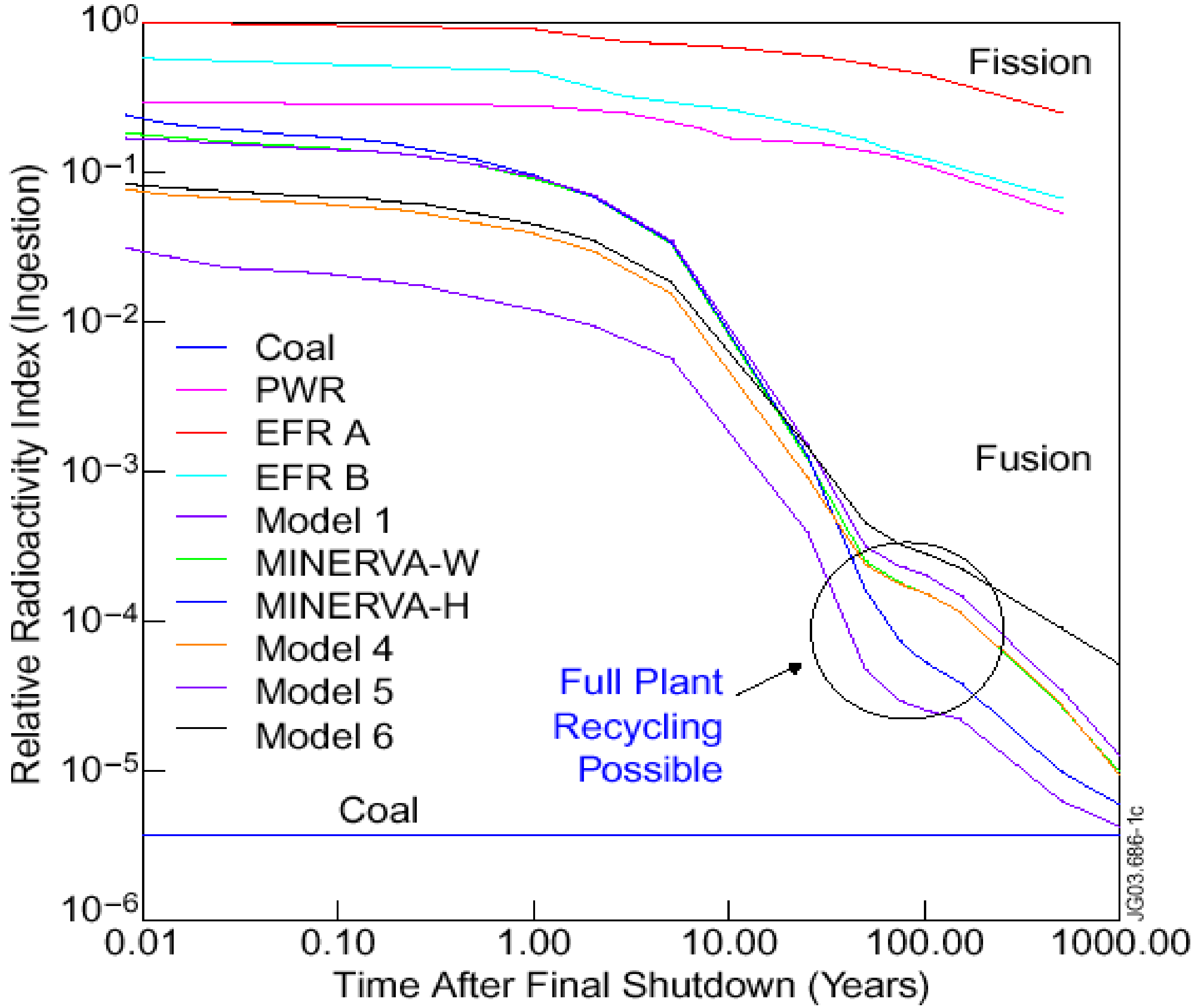
	Site T Inventory, grams	Average $MWyr/m^2$	Peak n/m^2 >0.1MeV*	dpa	He appm	Operating Gy/sec	Shut-down Gy/hr
JET 1997	20	10^{-7}	$1x10^{19}$	10^{-6}	10^{-5}	n: 40 Ɣ: 100	0.01
ITER all life	4000	0.3	$4x10^{25}$	2	20	n: 200 Ɣ: 500	500
DEMO 3 FPY	6000?	6	$8x10^{26}$	50	500	n: 300 Ɣ: 500	10,000

*About 5x the neutron fluence due to virgin 14MeV neutrons alone, due to geometric "Sec(θ)" effects and scattering in the blanket

In epoxy, polyimide, glass, carbon & alumina, there is ~(0.1-1.0)x10^{-15} Gy/(n/m^2)

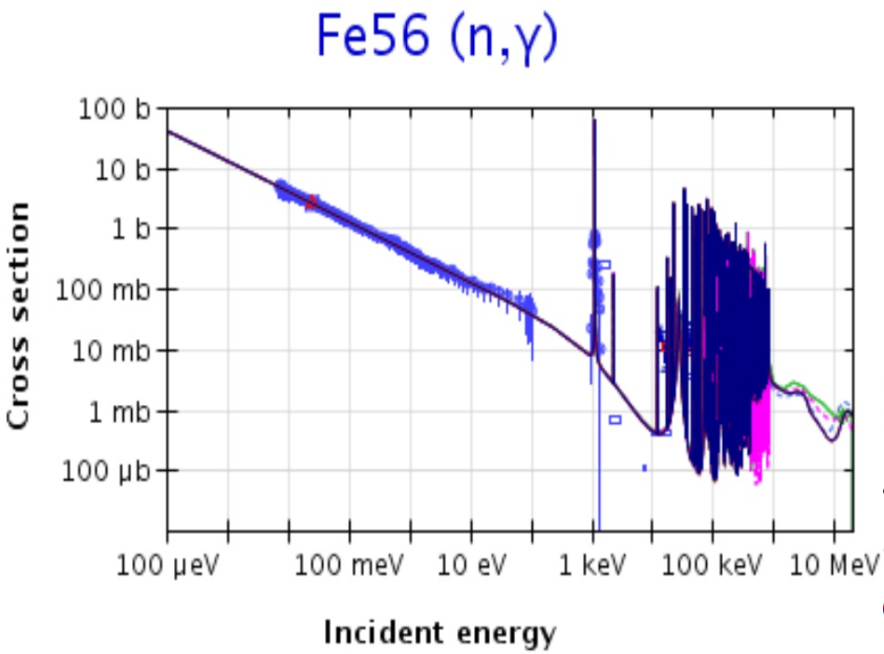
Fission and fusion radwaste decay

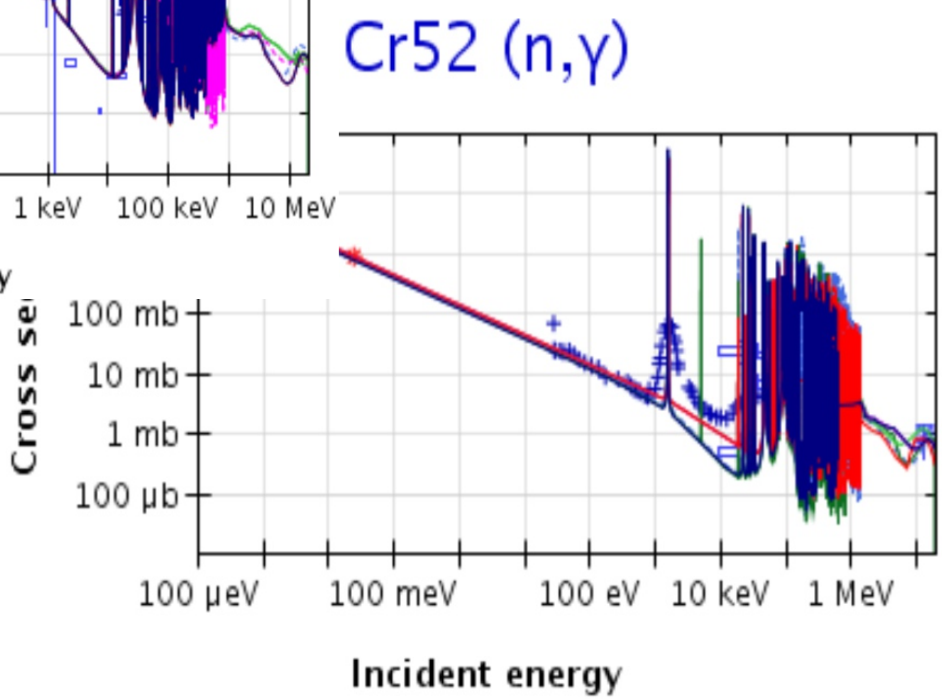
Fusion reaction products are not radioactive, but the reactor structure (steel, tungsten...) becomes activated, as in fission plant

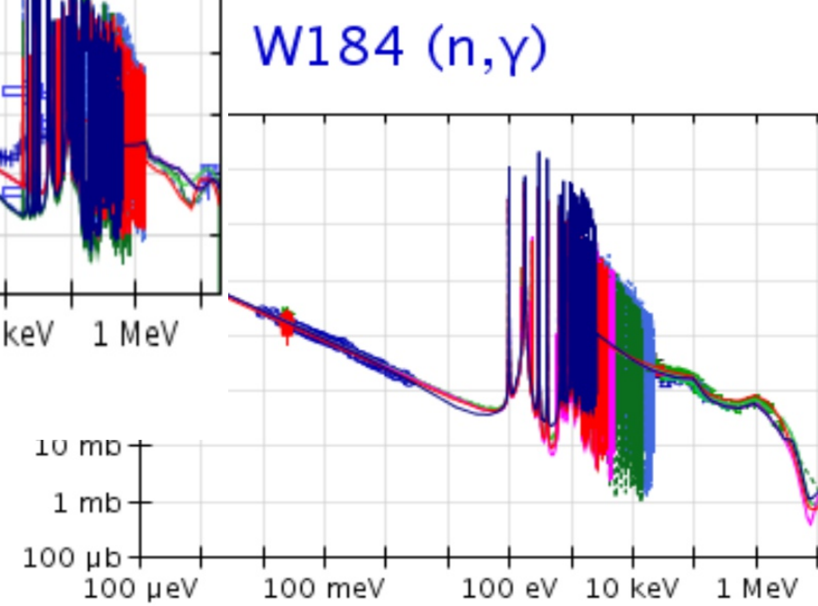


Structural activation cross-sections

- Structural activation is largely sensitive to thermal neutrons:



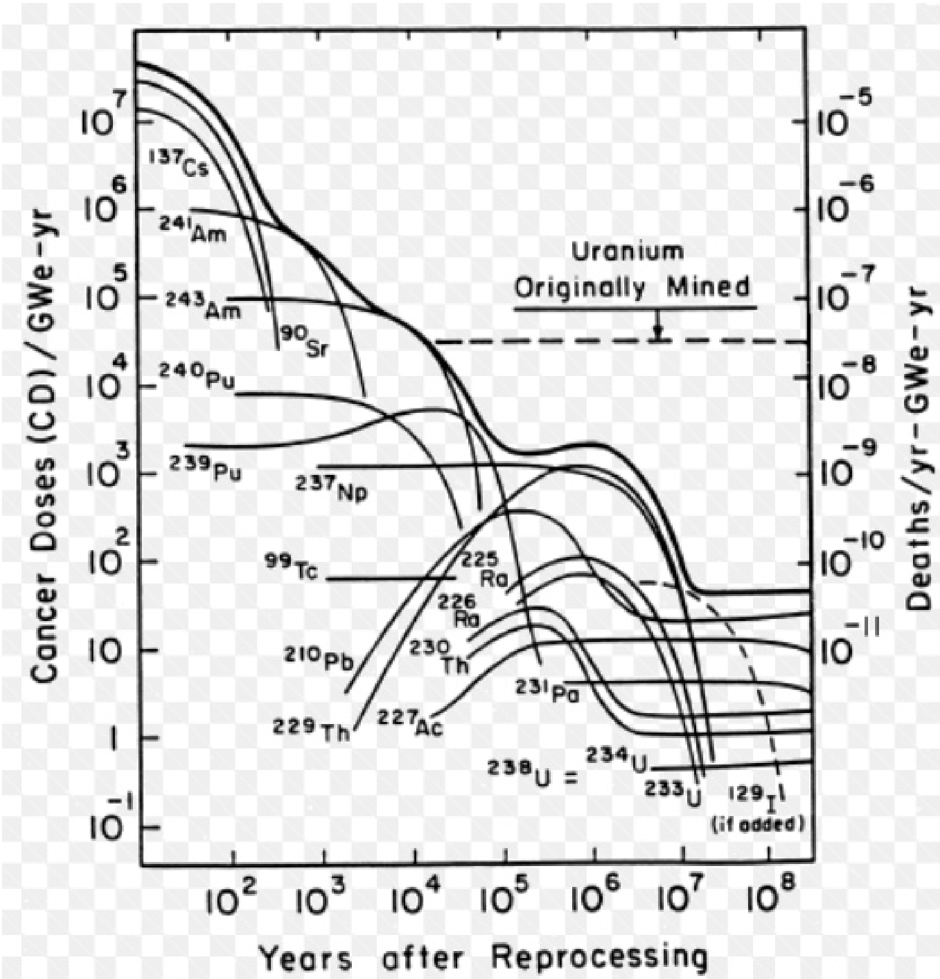




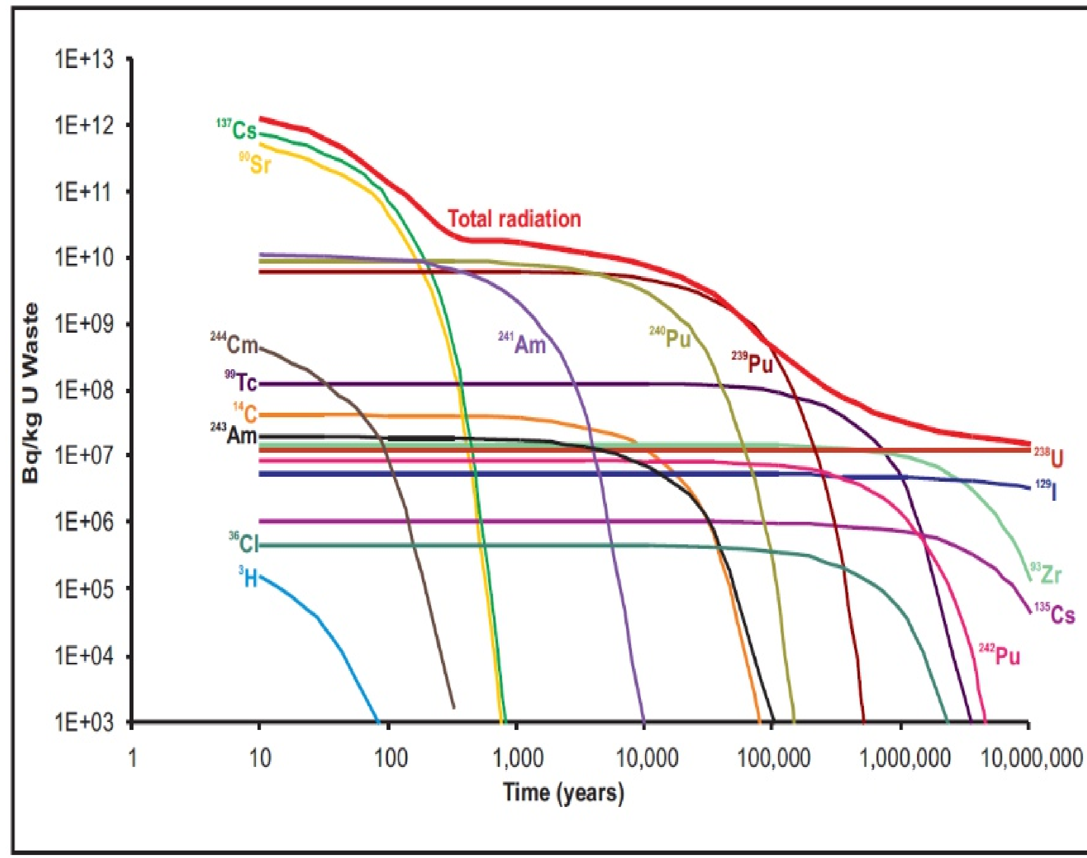
http://www.oecd-nea.org/janis/book/

Fission radwaste decay curves

- Fission PRODUCTS drive much of the fission decay behaviour

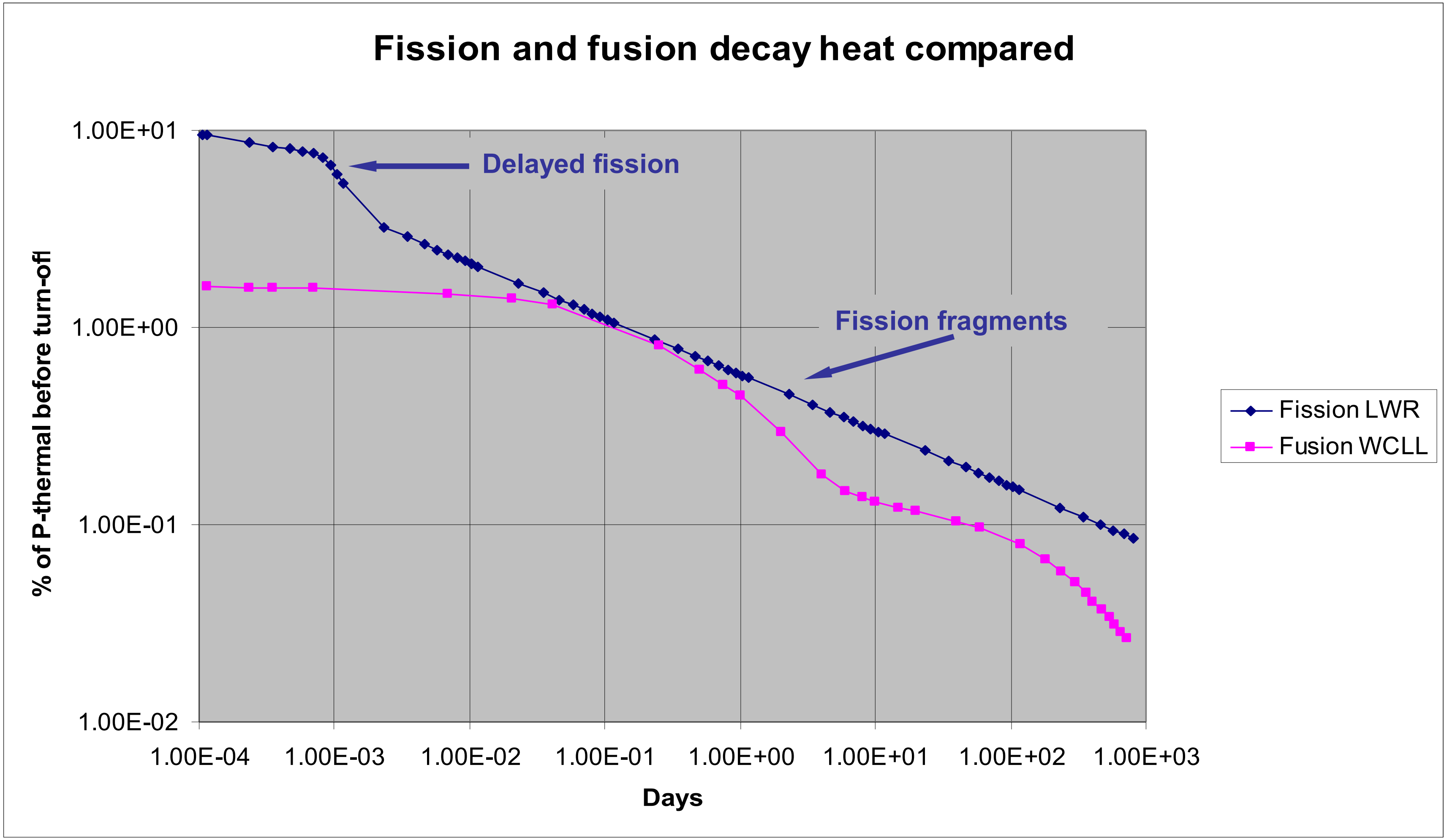


http://www.phyast.pitt.edu/~blc/book/chapter11.html



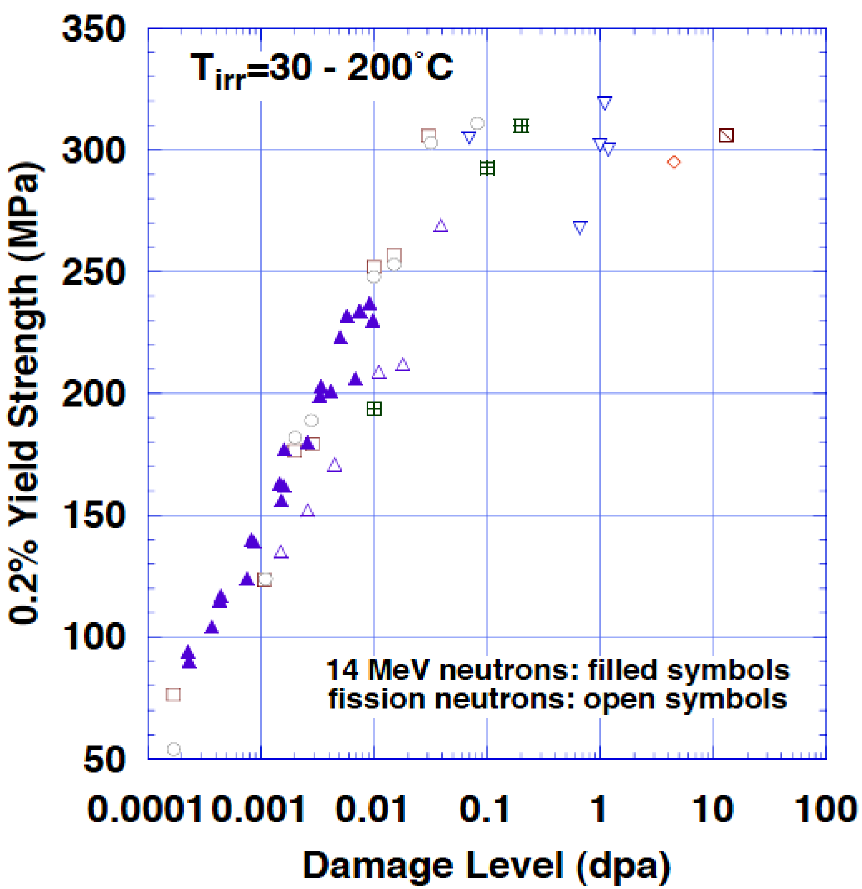
Fusion and fission decay heat

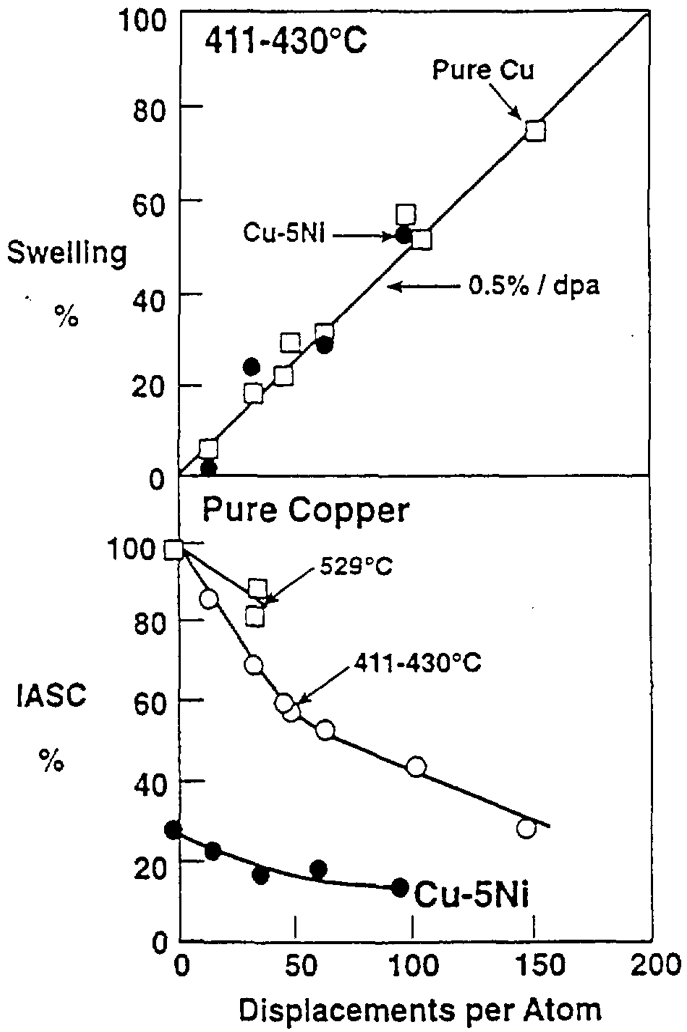
- Over hours to days, decay heat is similar in fusion and fission
- But fusion systems have no solid core, only a large volume of blanket etc. around the plasma region



Neutrons

- Sources are mainly d(d,n)^{3}He at 2.4MeV, d(t,n)α at 14MeV, n(^{7}Li,2n+t)α, n(^{9}Be,2n)2α and n(^{M}Pb,2n)$^{M-1}$Pb where M= 204/6/7/8.
- Material property changes (e.g. hardening, conductivity) mainly scale with dpa, not neutron energy. E.g. copper:

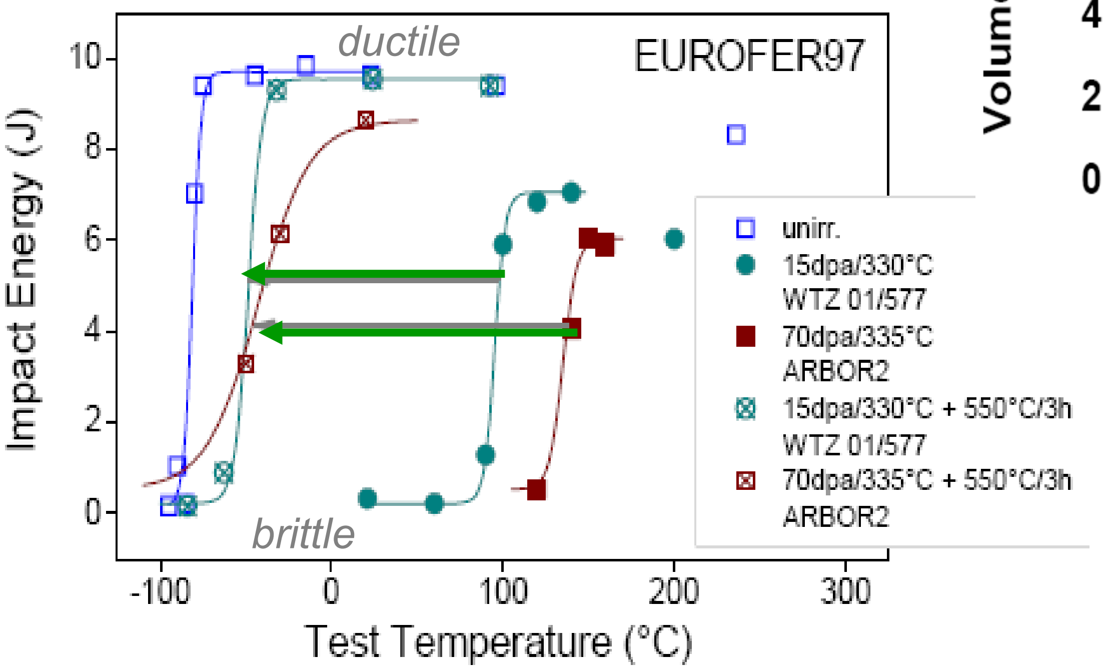


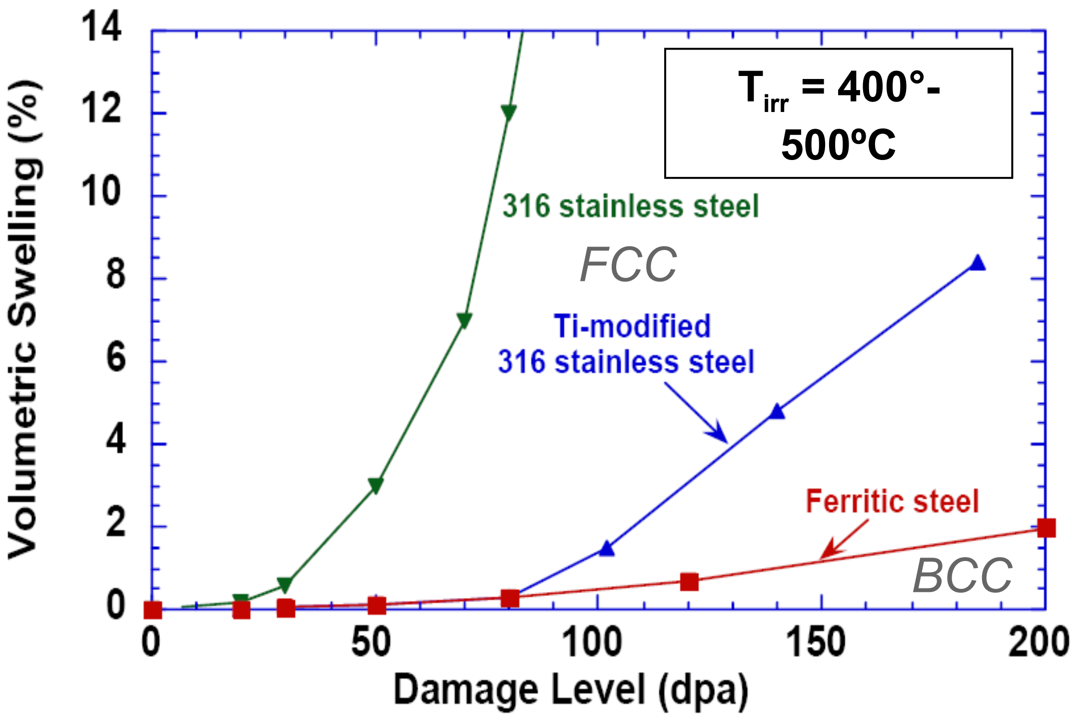


Neutrons

- Material property changes (e.g. hardening, swelling, conductivity) mainly scale with dpa, not neutron energy.

- Steel:

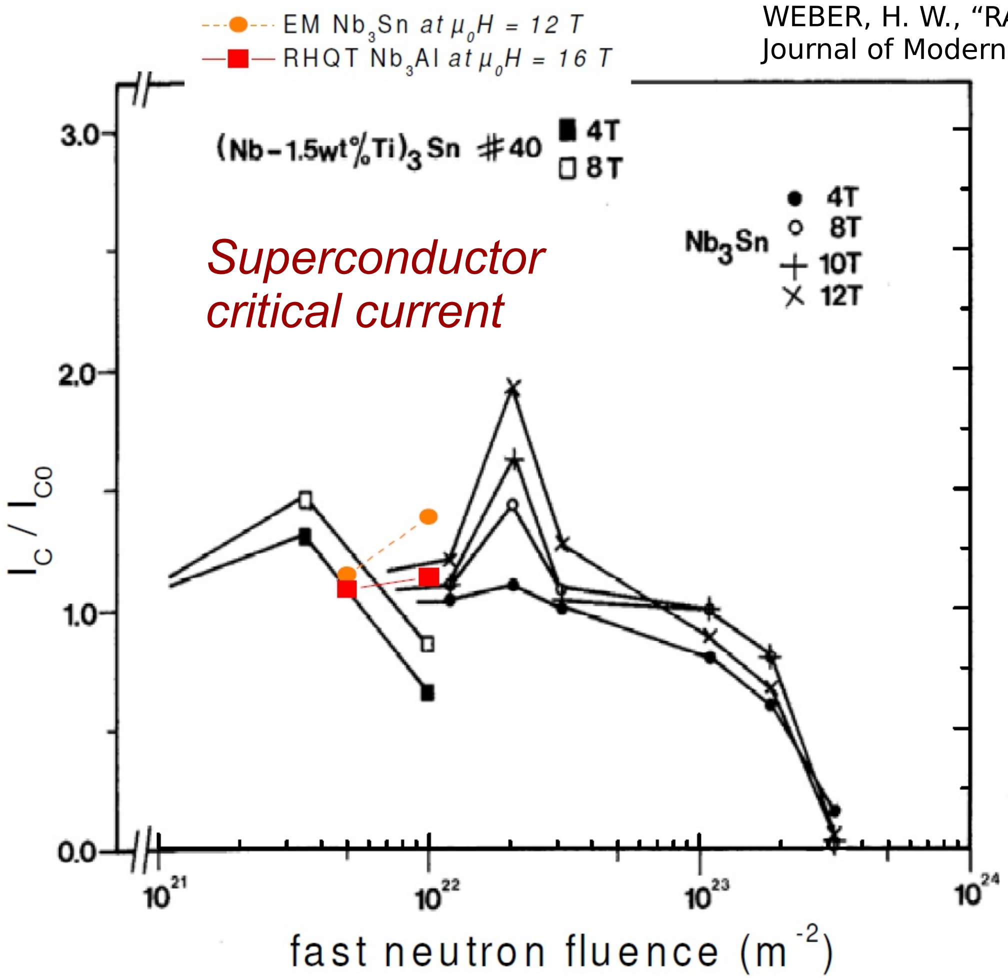


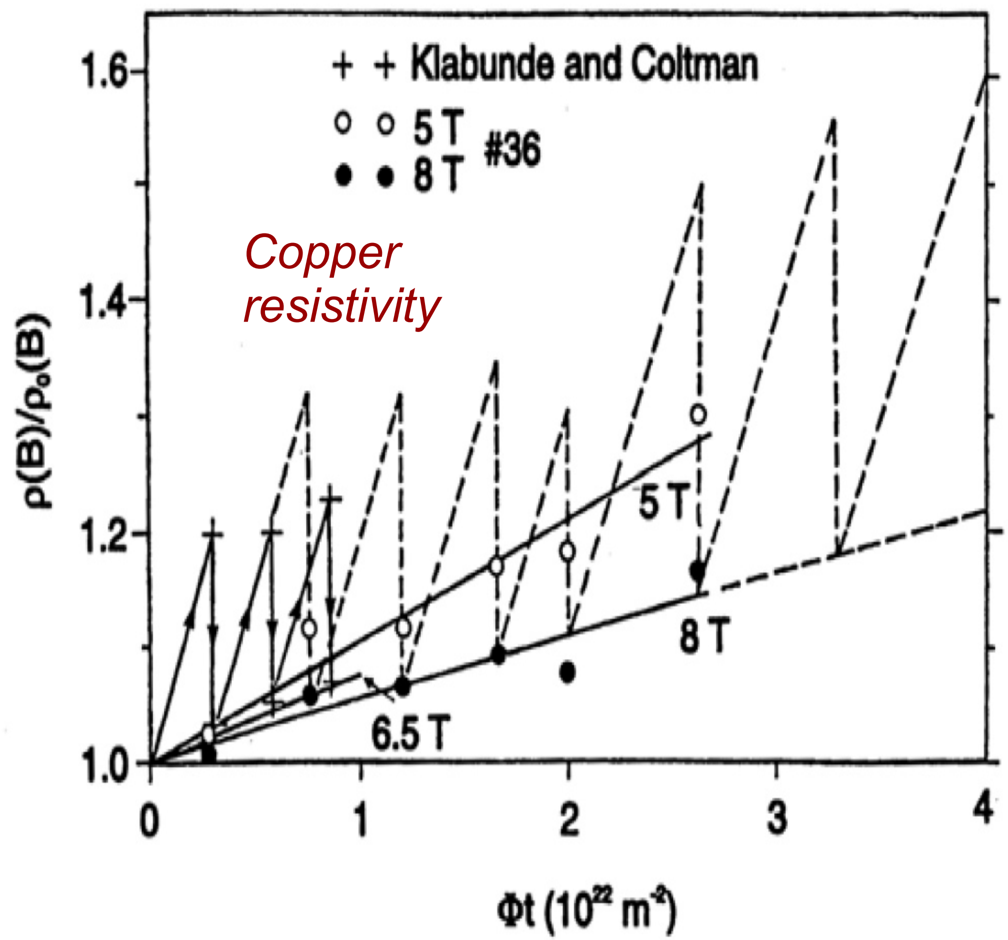


Neutrons

- Fusion reactors need superconducting magnets, which require minimal neutron heating and neutron damage/transmutation.
- Also, the superconductor has a copper “stabiliser” jacket which has to be repeatedly reannealed (to ~20°C) to recover its conductivity (mostly!)

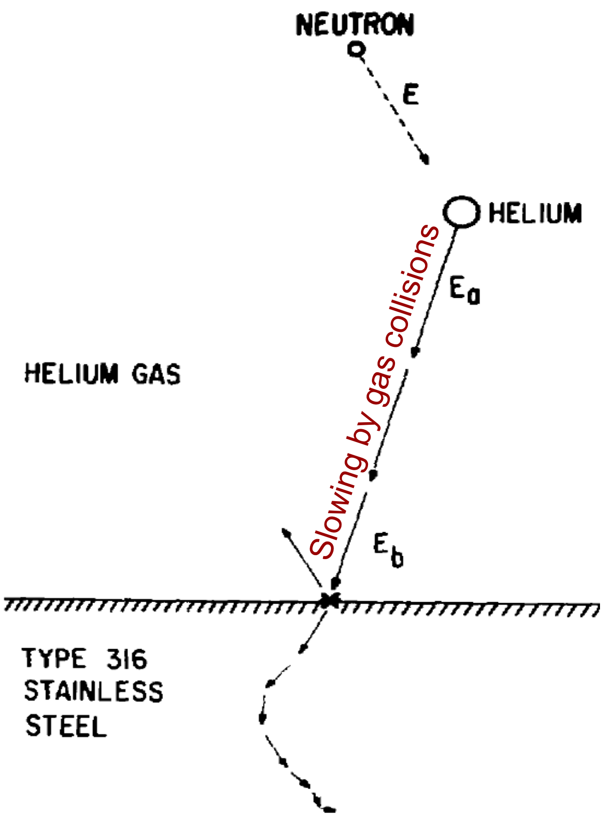
WEBER, H. W., “RADIATION EFFECTS ON SUPERCONDUCTING FUSION MAGNET COMPONENTS”
Journal of Modern Physics E Vol. 20, No. 6 (2011) 1325–1378

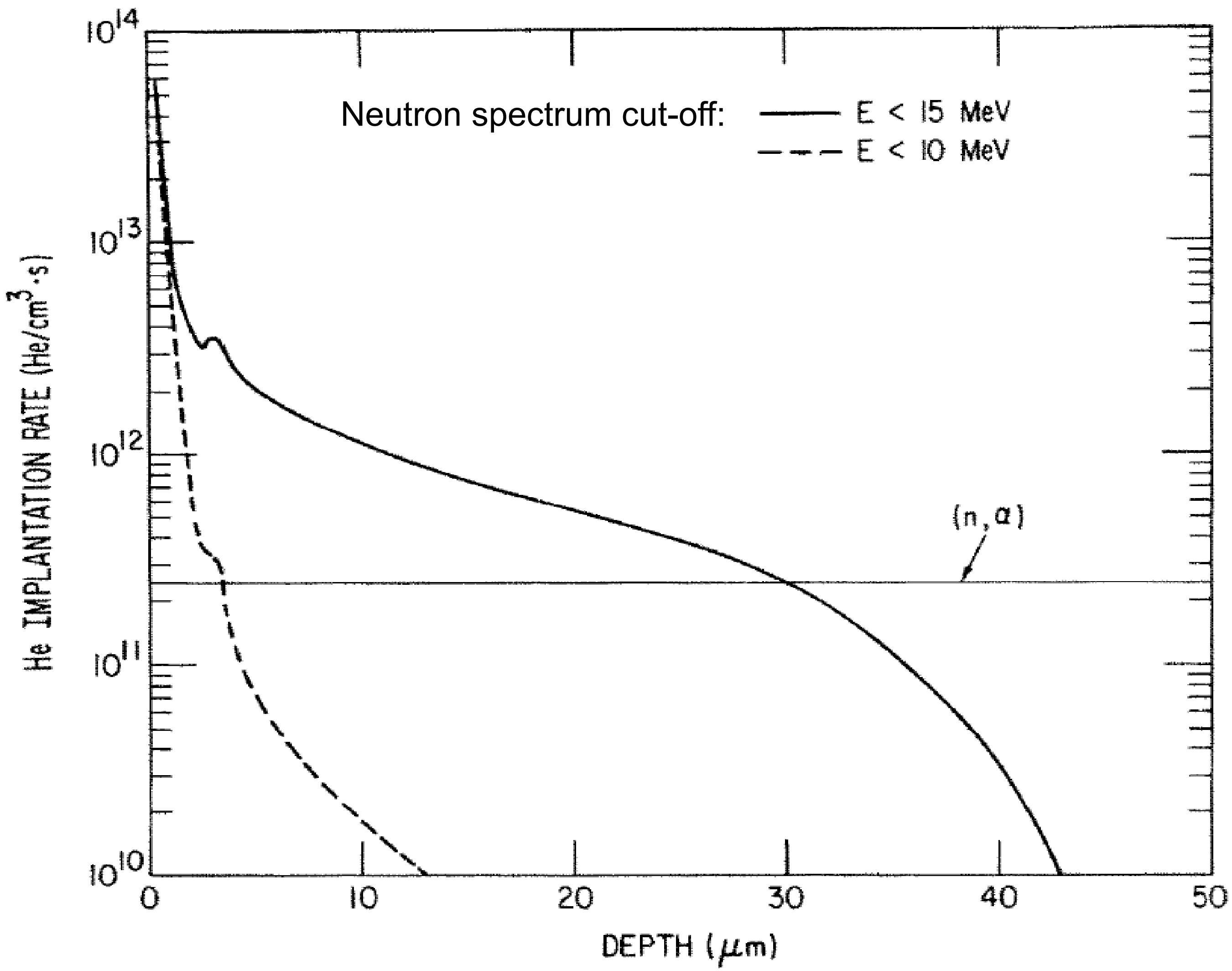




Neutrons – helium recoil in gas coolant

Fusion neutron wall loading 1MW/m^2, He gas at 100bar, 550°C, SS316 pipe wall:



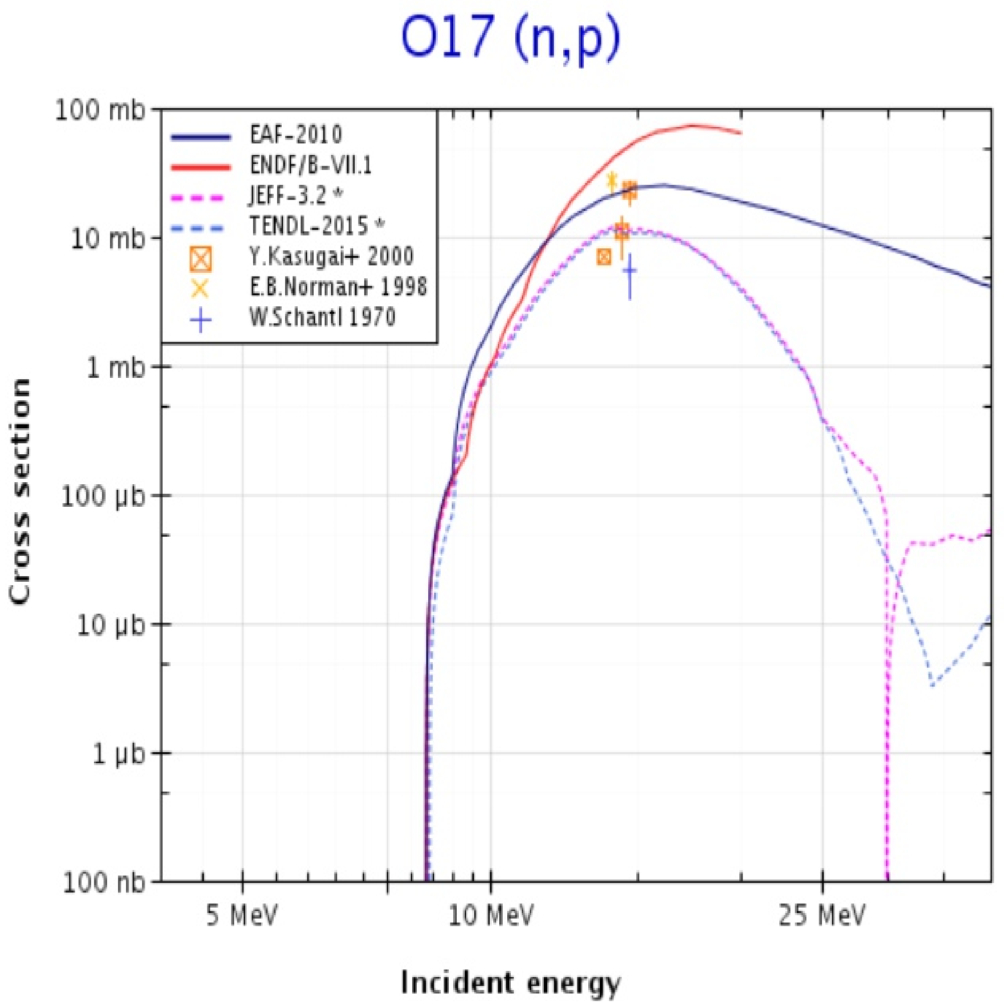


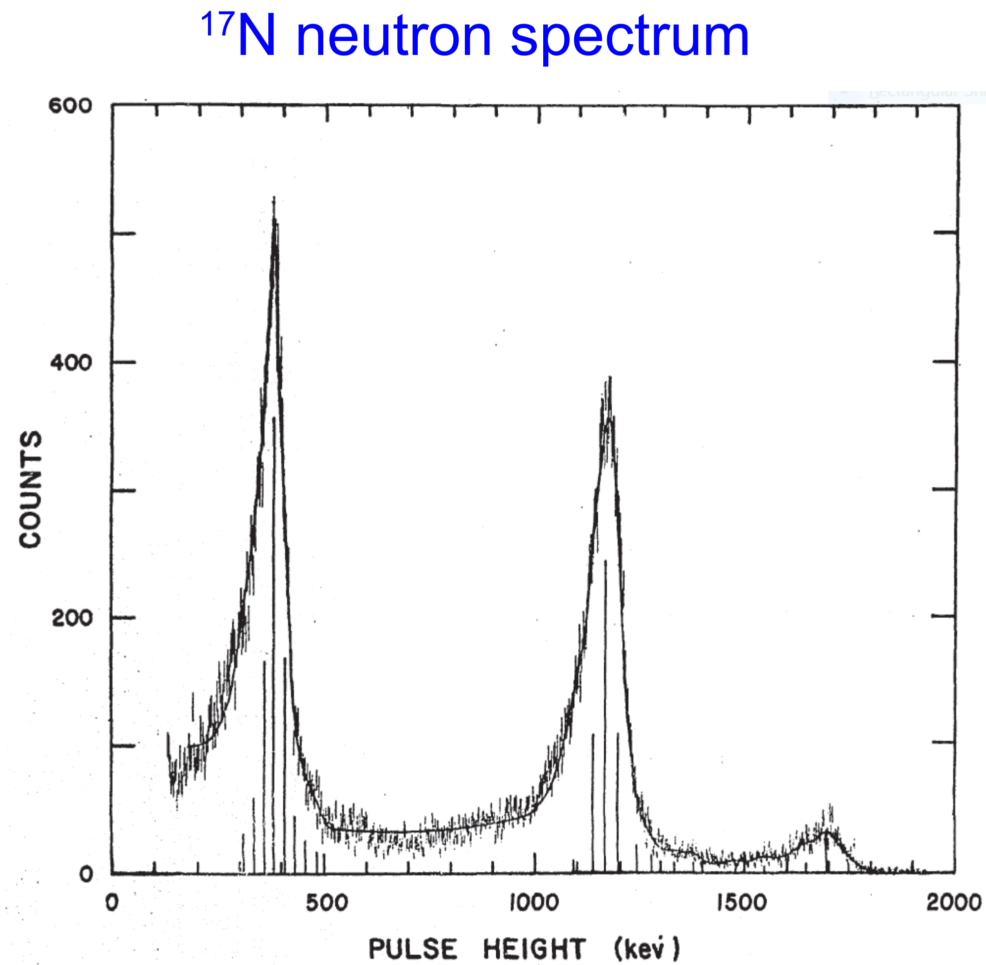
Blistering was predicted
at ~10^{18}/cm^2, after ~3FPY

Yamada, H., "NEUTRON-INDUCED HELIUM IMPLANTATION IN HELIUM COOLANT PIPES OF FUSION REACTORS",
Journal of Nuclear Materials 103 &104 (1981), p 615-618

Neutrons

- Another source of neutrons is ^{17}N (from $^{17}O(n,p)^{17}N$ in the reactor <u>coolant</u>, ^{17}O being ~0.038% of natural O).
- *The 4.17s half-life can allow the ^{17}N to emerge from the reactor hall*

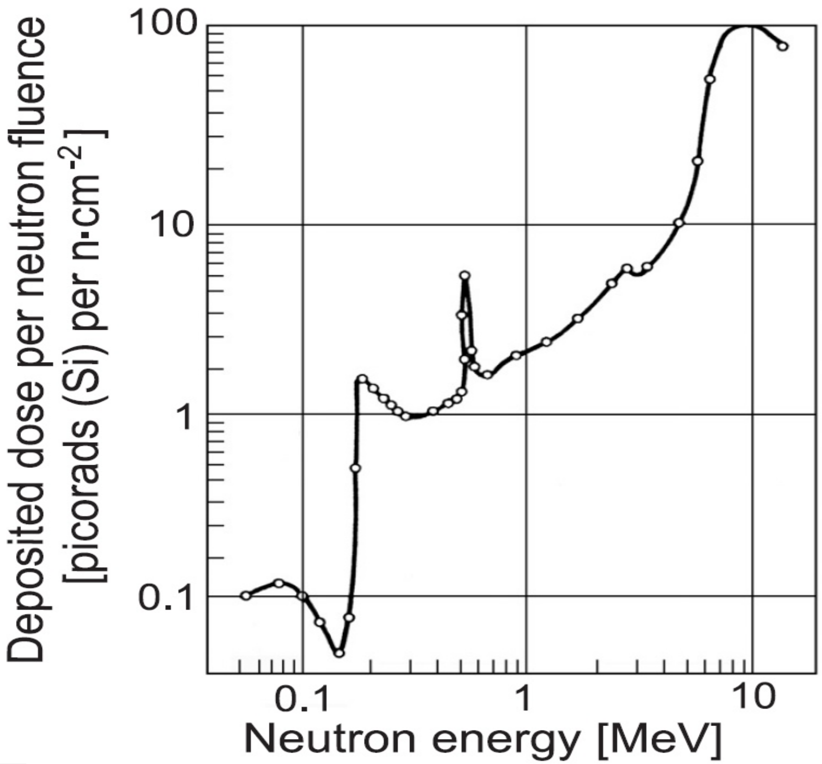


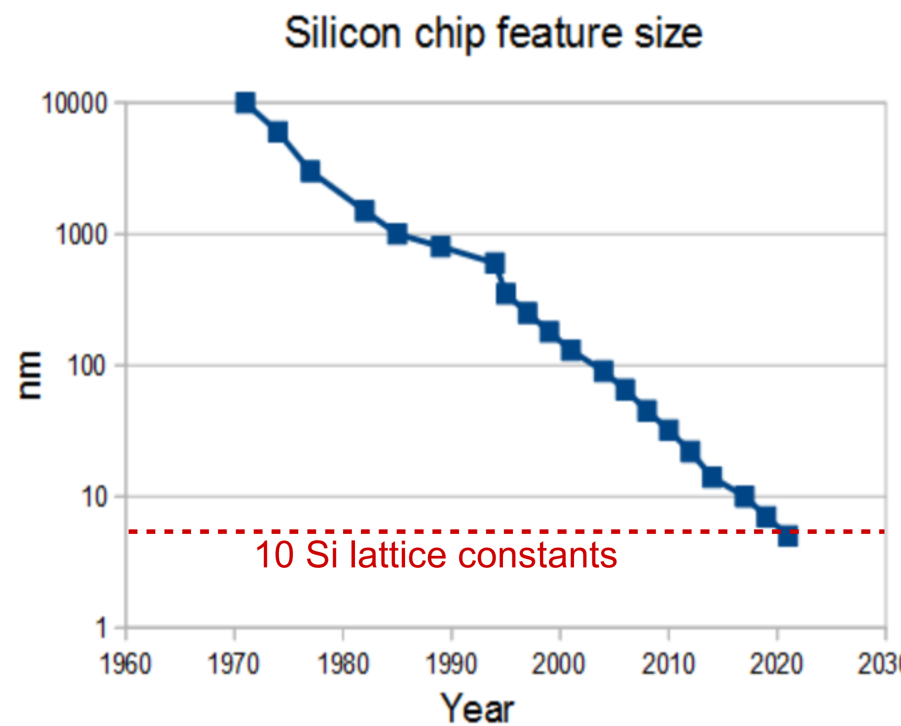


Neutrons

- Even very low fluxes of neutrons impact electronics in detectors, processing electronics and digital logic in personnel access and machine control systems
- E.g. ~6 “Single Event Upsets”/hr from only 0.4n/cm^2-sec above 1MeV in a UAV control system [NASA, memory area ~6cm^2]
  http://www.nasa.gov/sites/default/files/files/SMIII_Problem6.pdf
- They create ionisation by recoil nucleus motion and by activation decay products
- The recoil motion also damages the semiconductor crystal structures (with <14nm scales now appearing in chip design)

Messenger, G. & Ash, M., *The effects of radiation on electronic systems*, Van Nostrand Reinhold Company Inc, 1986





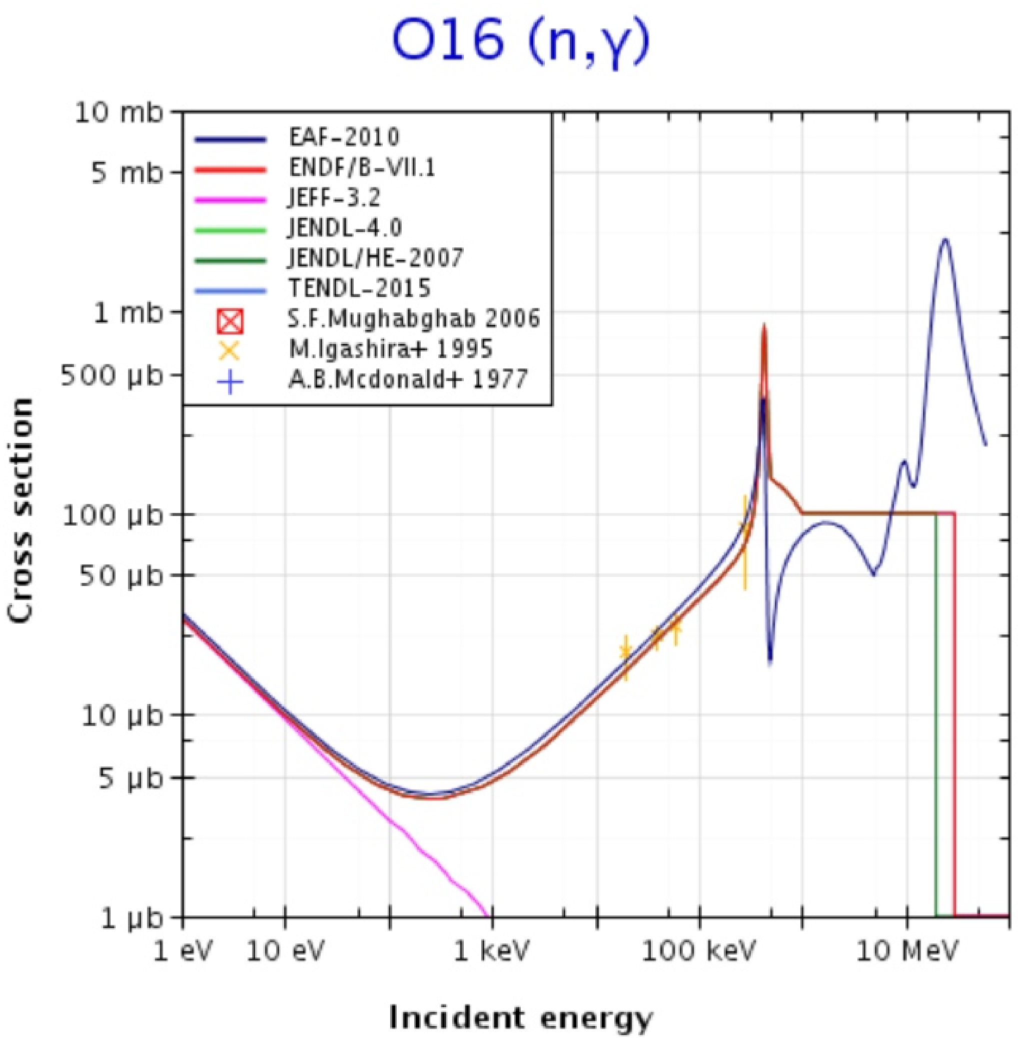
https://en.wikipedia.org/wiki/130_nanometer

Gamma rays

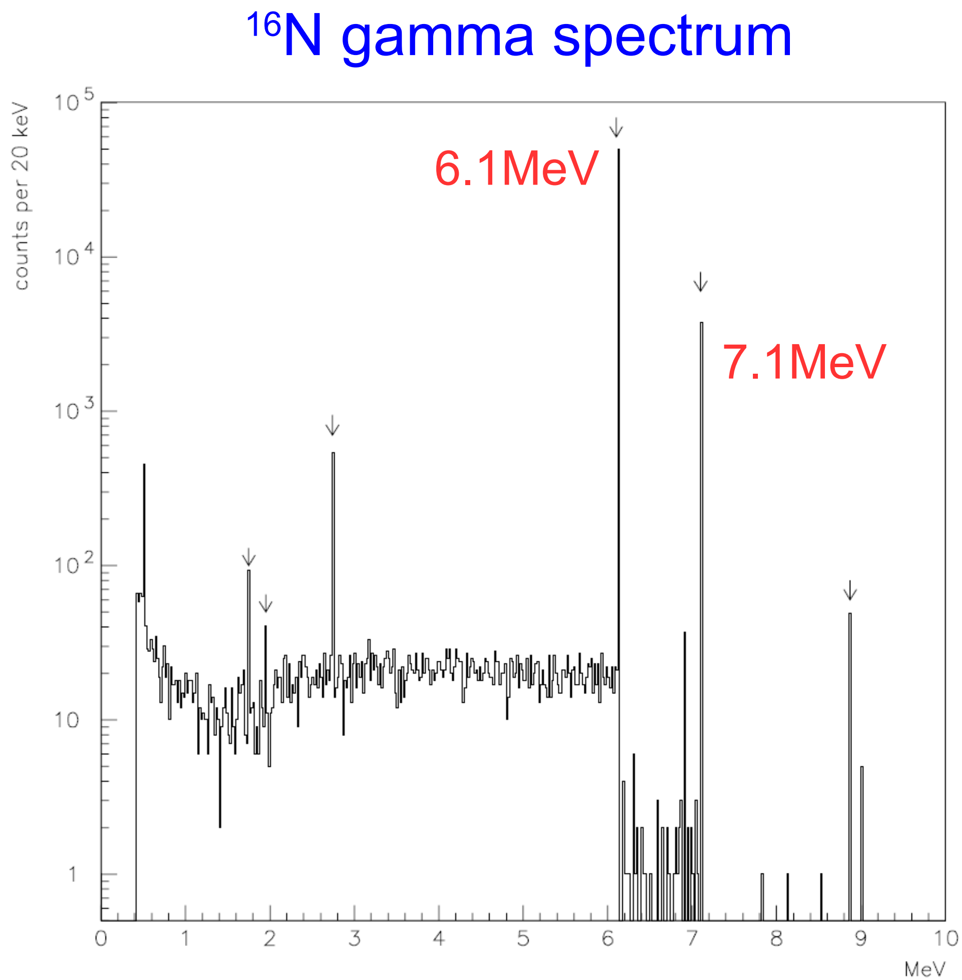
- Gamma rays in fusion systems primarily come from:
  - Low-probability fuel species reactions in the plasma
  - Plasma reactions involving fast fusion products from primary reactions
  - Relativistic electrons hitting metal surfaces at the edge of the plasma
  - Nuclear decay following neutron activation of materials around the plasma
  - Direct bremmstrahlung ("free-free") electron collisions in the plasma
  - De-excitation of inner shell transitions excited by fast electron collisions
- Fluxes in operation are many OOM greater than after shut-down but still present a Health Physics hazard and a radwaste burden, as shown earlier
- Line radiation gamma rays (from nuclear or inner shell electron X-ray transitions of heavy ions) are amongst the most useful plasma diagnostics

Gamma rays

- Another source of gammas is ^{16}N (from $^{16}O(n,p)^{16}N$ in the reactor coolant).
- *The 7.13s half-life can allow the ^{16}N to emerge from the reactor hall, potentially affecting electronics and operations staff*



http://www.oecd-nea.org/janis/book/

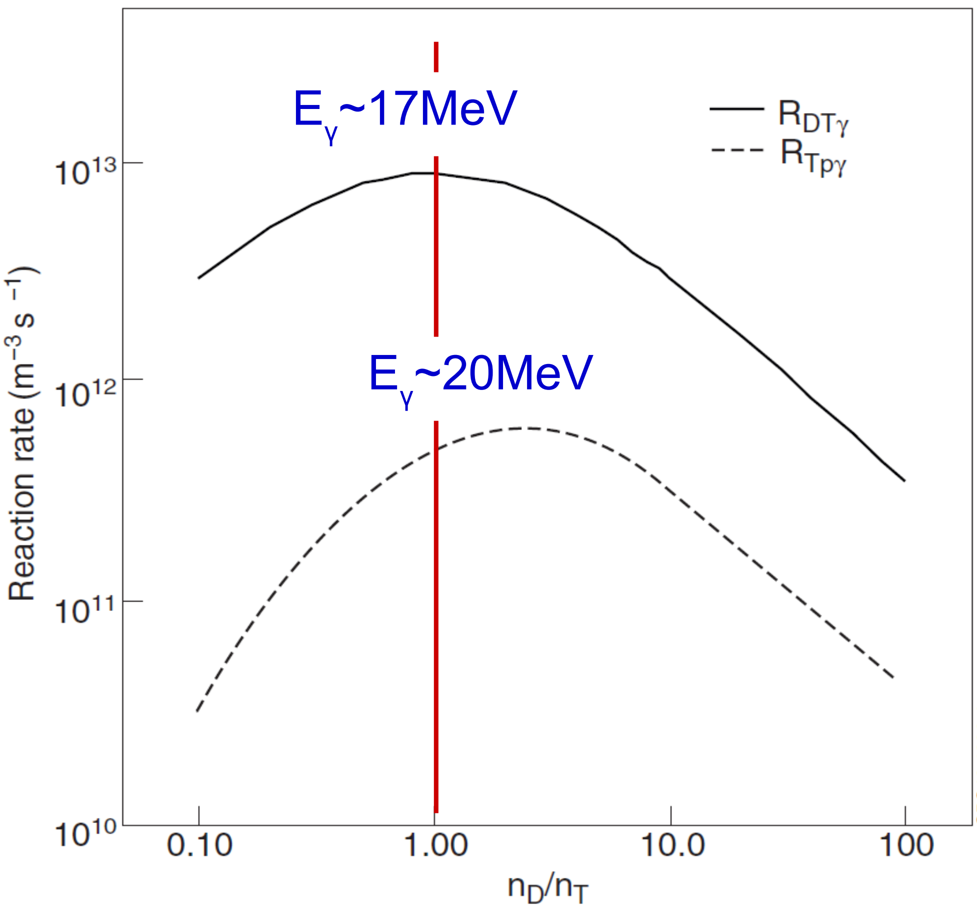


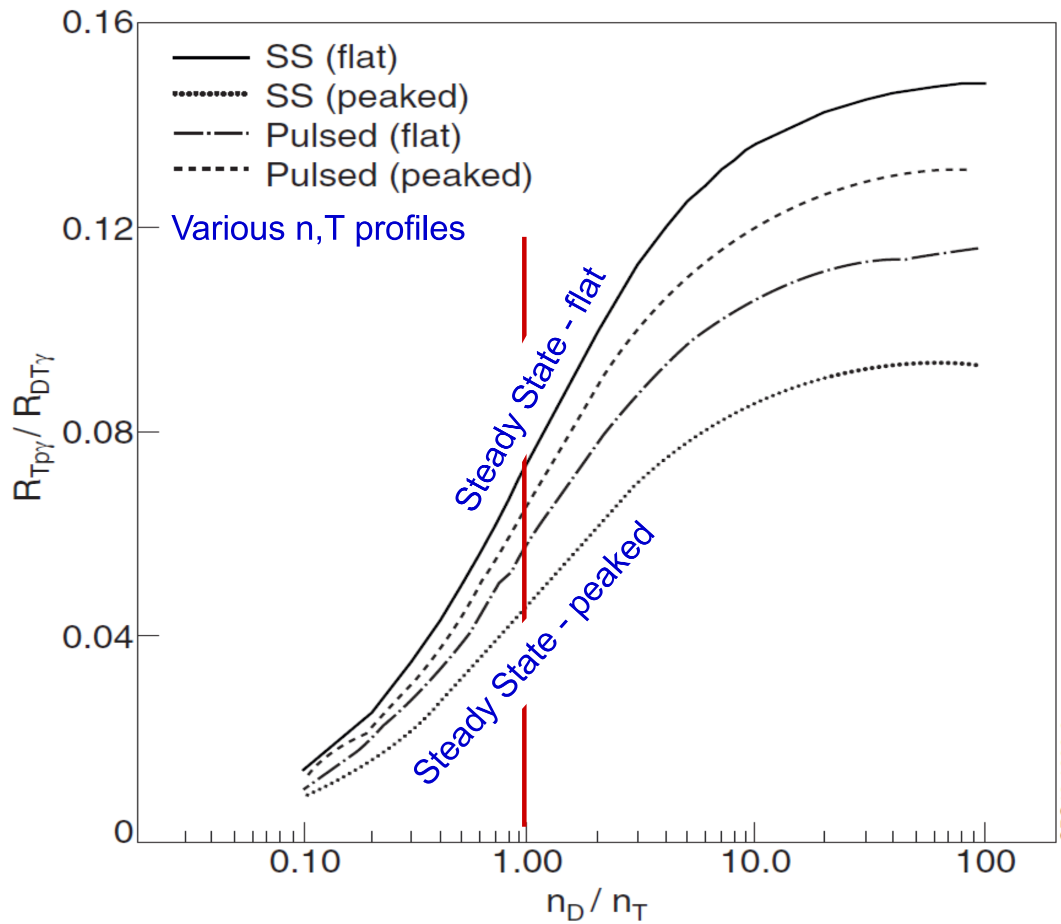
The 16N Calibration Source for the Sudbury Neutrino Observatory
M. R. Dragowsky et al; http://arxiv.org/pdf/nucl-ex/0109011.pdf

Diagnostics – some useful effects

The fusion products create "radiation capture" reactions with other ions in the plasma, producing characteristic gammas useful for core plasma diagnosis.

E.g. D/T ratio from ratio of t(p,γ)^{4}He to d(t,γ)^{5}He (by gamma spectroscopy)

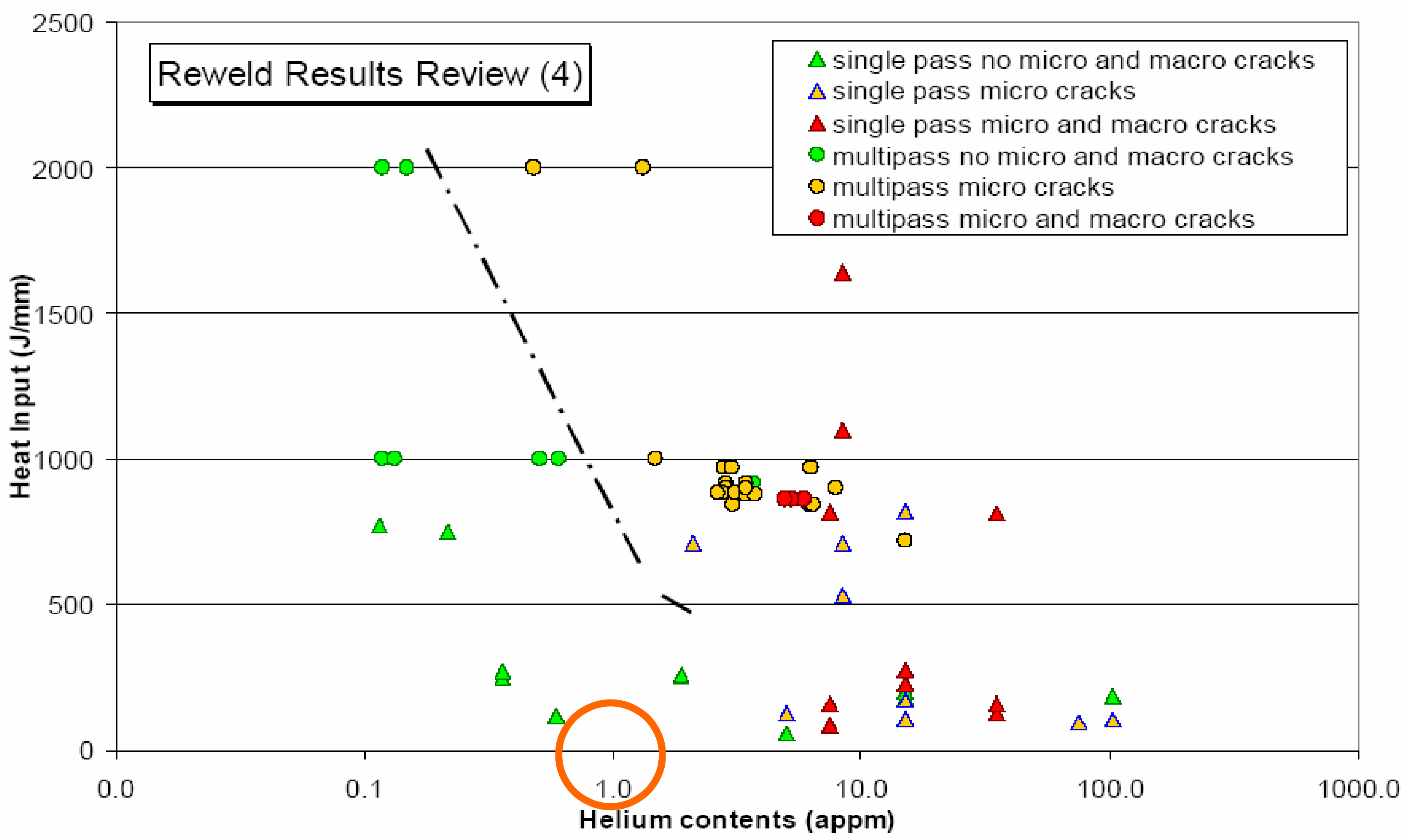




Kiptily, V. G., "On the core deuterium–tritium fuel ratio and temperature measurements in DEMO", Nucl. Fusion 55 (2015) 023008 (7pp)

Alphas

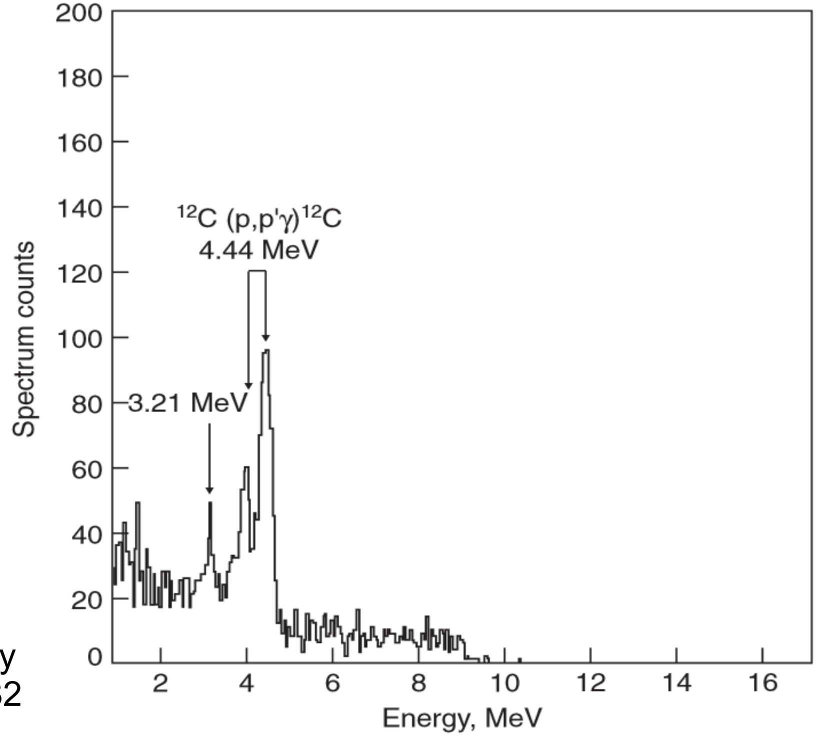
- Alpha particles produced by radioactive decay in the structure become trapped in crystal vacancies and develop into bubbles, contributing to embrittlement of alloys such as SS316 and aggravating their reweldability:



K. Asano, J. van derLaan, “Reweldability of Stainless steel 316L(N)-IG” MAR, 2001v

Protons

- 2.45MeV protons come from DD fusion reactions, but are not as bad as 3.45MeV He (from DT reactions) for wall damage if the fast particles are lost from the plasma before thermalising.
- Protium (^{1}H) is a common transmutation product but it readily diffuses out of the host material and so is generally not a problem (although it adds to the demand on the isotope separation system of the T fuel cycle).
- The fast protons can be useful for radiation capture reactions, as described above for monitoring the plasma core D:T ratio. Others include:
  - $d(p,\gamma)^{3}He$
  - $^{12}C(p,\gamma)^{13}N$ and $^{12}C(p,p'+\gamma)^{12}C$
  - $^{9}Be(p,\gamma)^{10}B$



Kiptily, V. G. et al, "Gamma ray diagnostics of high temperature magnetically confined fusion plasmas", Plasma Phys. Control. Fusion 48 (2006) R59–R82

Betas

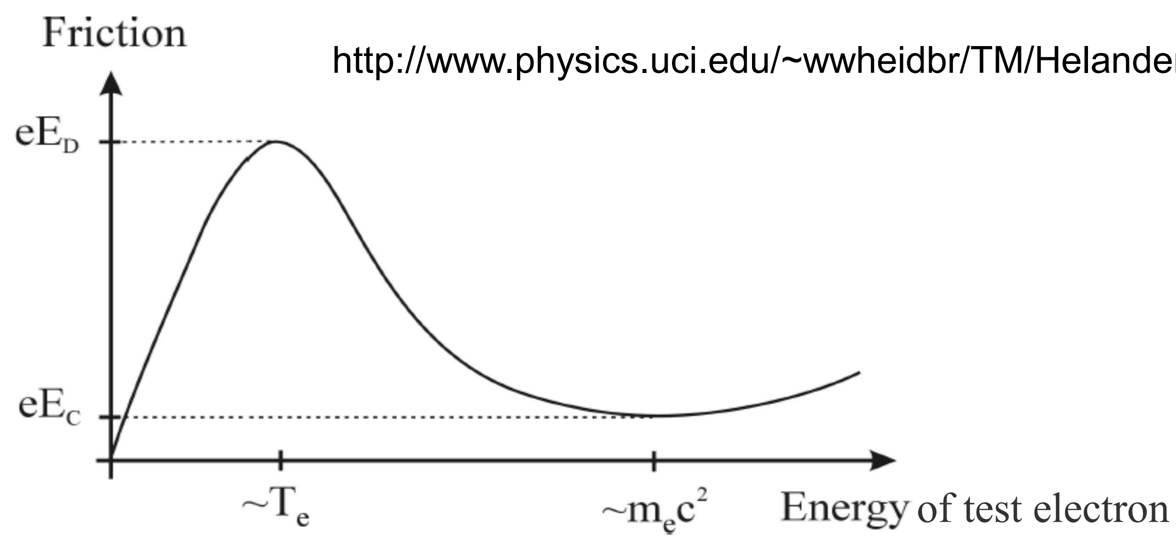
- β emission from T → $^3He = \beta^-$ ($t_{½}$ = 12.3yrs, 360TBq per gram, ~4kg expected fusion reactor site inventory) is the most important issue for fusion Health Physics and the potential environmental impact.
- It also provides energy for chemistry in substances permeated by the T, enhancing T diffusion through plastics and e.g. drawing C out of steel as heavy methane.
- β emission from neutron-activated elements in the blanket and structure mainly just contributes to decay heat
- However the tokamak is usually sustained by an electric field acting on the plasma, so we can unintentionally create very energetic “runaway electrons” if the ratio of electric field to plasma density is too high...

Betas - created in the tokamak

- Frictional drag competes with the electric field acceleration:

  - Non-monotonic function of velocity

http://www.physics.uci.edu/~wwheidbr/TM/Helander.PDF



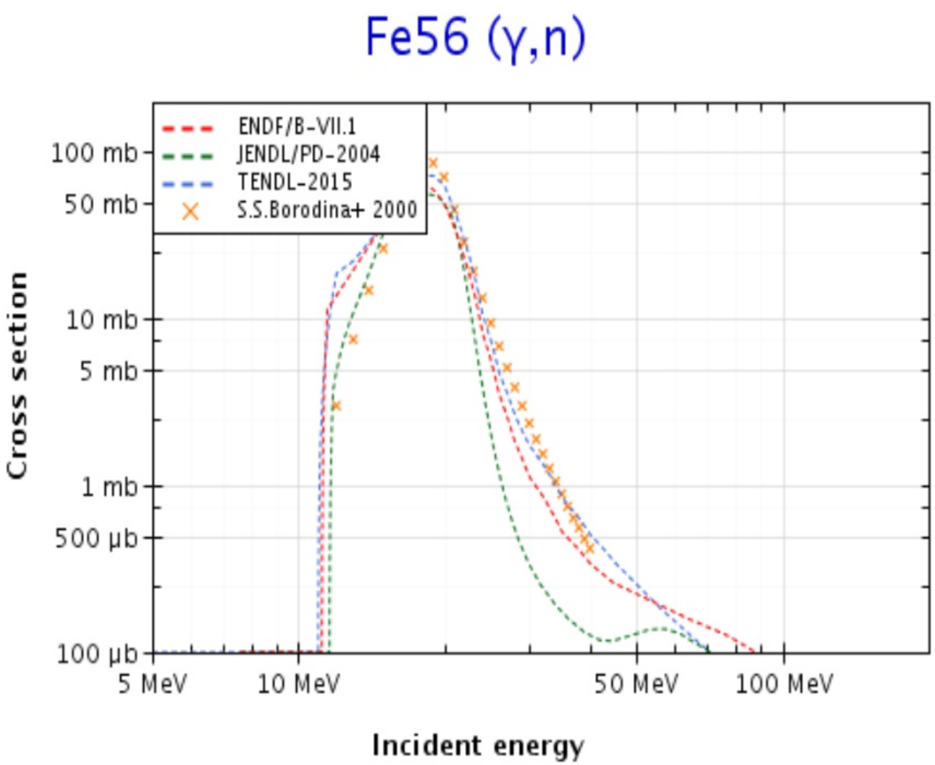
  - Runaway acceleration of some electrons if $E > E_C$
  - Massive runaway if $E > E_{Dreicer}$

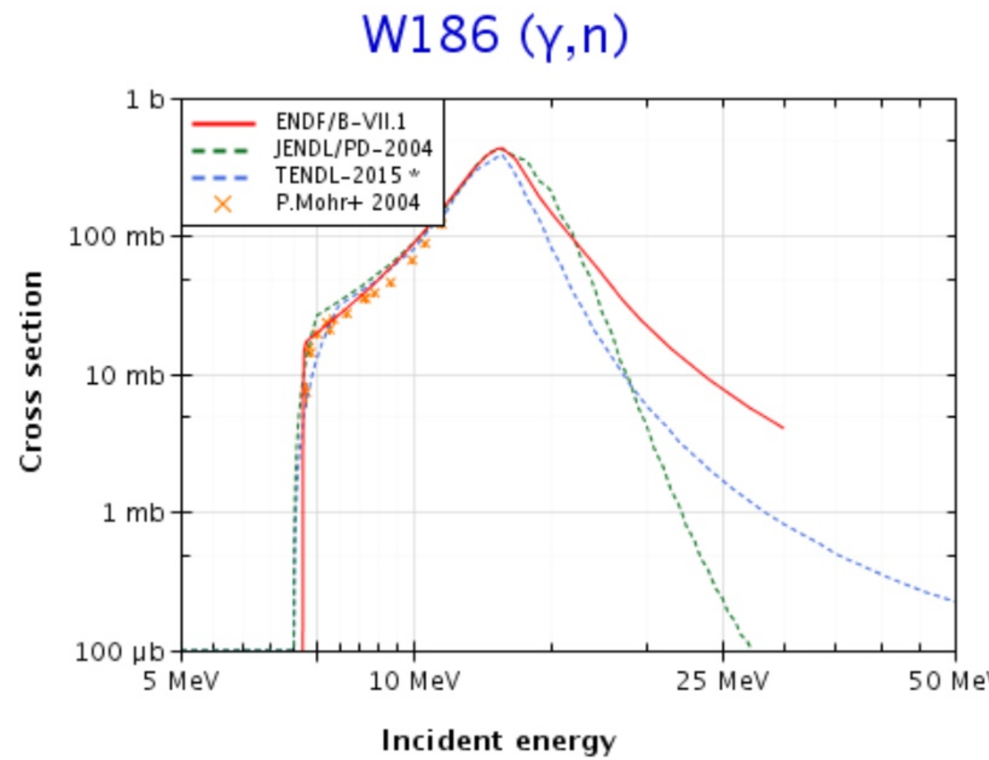
$$E_D = \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0^2 T_e}, \qquad \frac{E_c}{E_D} = \frac{T_e}{mc^2} << 1$$

- This creates electron motion essentially along the magnetic field lines, but in a tokamak these are curved...

Betas - created in the tokamak

- “Curvature drift” displaces the fast electron orbits from the magnetic surfaces defining the plasma shape, resulting in a critical energy above which they cannot stay in the plasma, E_{max} ~50MeV per MA of plasma current I_P
- Since quite small tokamaks have I_P>0.5MA, and bremsstrahlung creates gammas from the betas hitting the wall (as in an X-ray tube), interesting activation reactions occur even in “non-nuclear” tokamaks:





http://www.oecd-nea.org/janis/book/

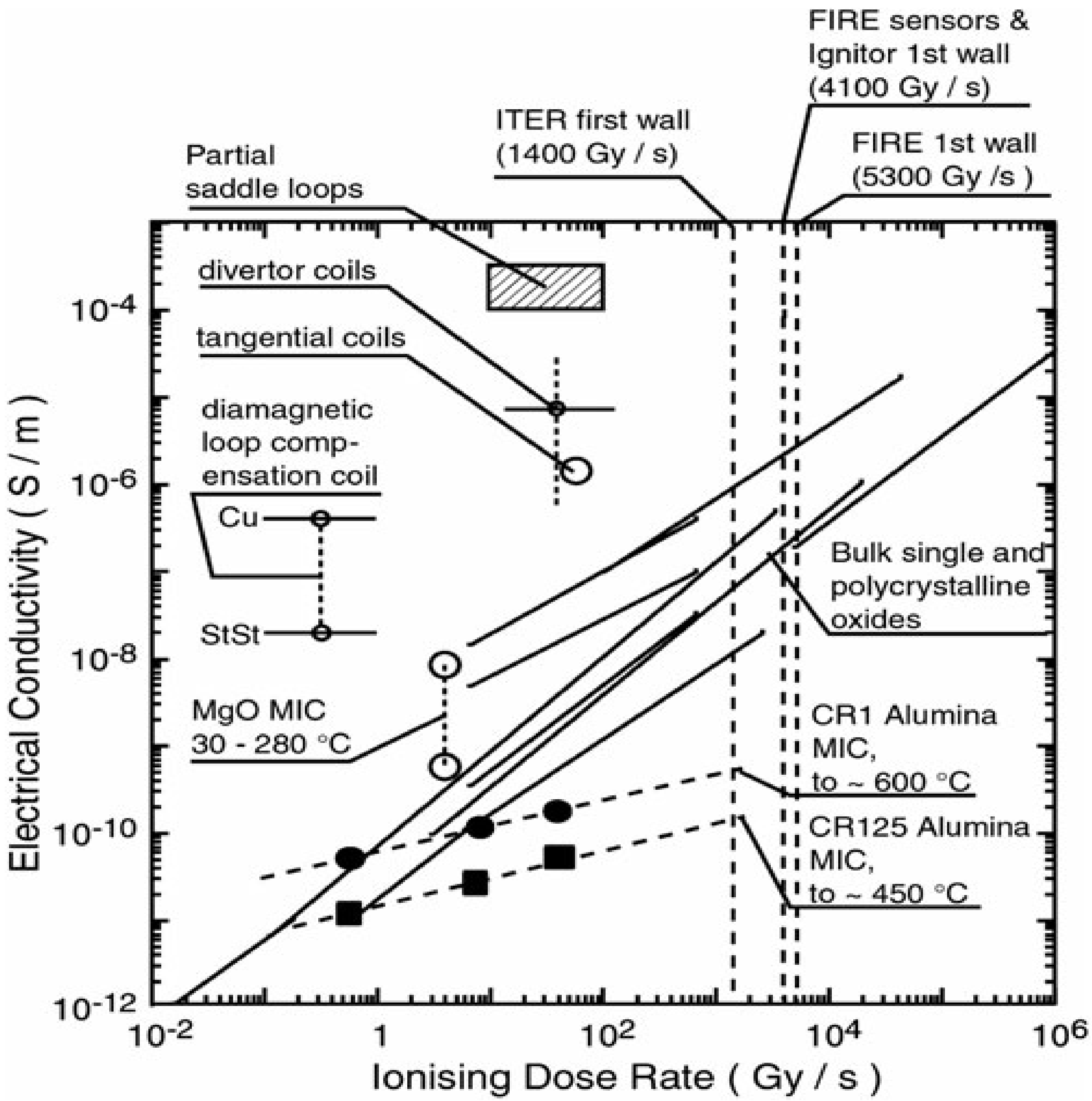
These multi-MeV β effects (mainly γ) create the dominant radiation hazard in small fusion devices.

Neutrons and gamma rays

- **Neutrons and gamma rays are very bad for close-in plasma diagnostics!**
- Both types of radiation are ionising and therefore generate conductivity $\propto$ flux (Radiation Induced Conductivity)...
- ...and radioscintillation in optical media (lenses, fibre-optics, detector windows)
- They create heating sufficient to require active cooling provisions, even in ITER
- The neutrons create displacements per atom (dpa), which:
  - Create defects in optical components (lenses, fibre-optics), hence darkening
  - Derange nano-structures in detectors and electronics
  - Precipitate metals in ceramics (Radiation Induced Electrical Degradation)
  - Create trapping sites for helium (hence swelling)
  - Embrittle ductile conductors
- The neutrons activate and transmute atoms in the sensors and cables etc., which:
  - Creates thermocouples in same-alloy connectors (Radiation Induced EMF)
  - Alters doping in sensors and electronics

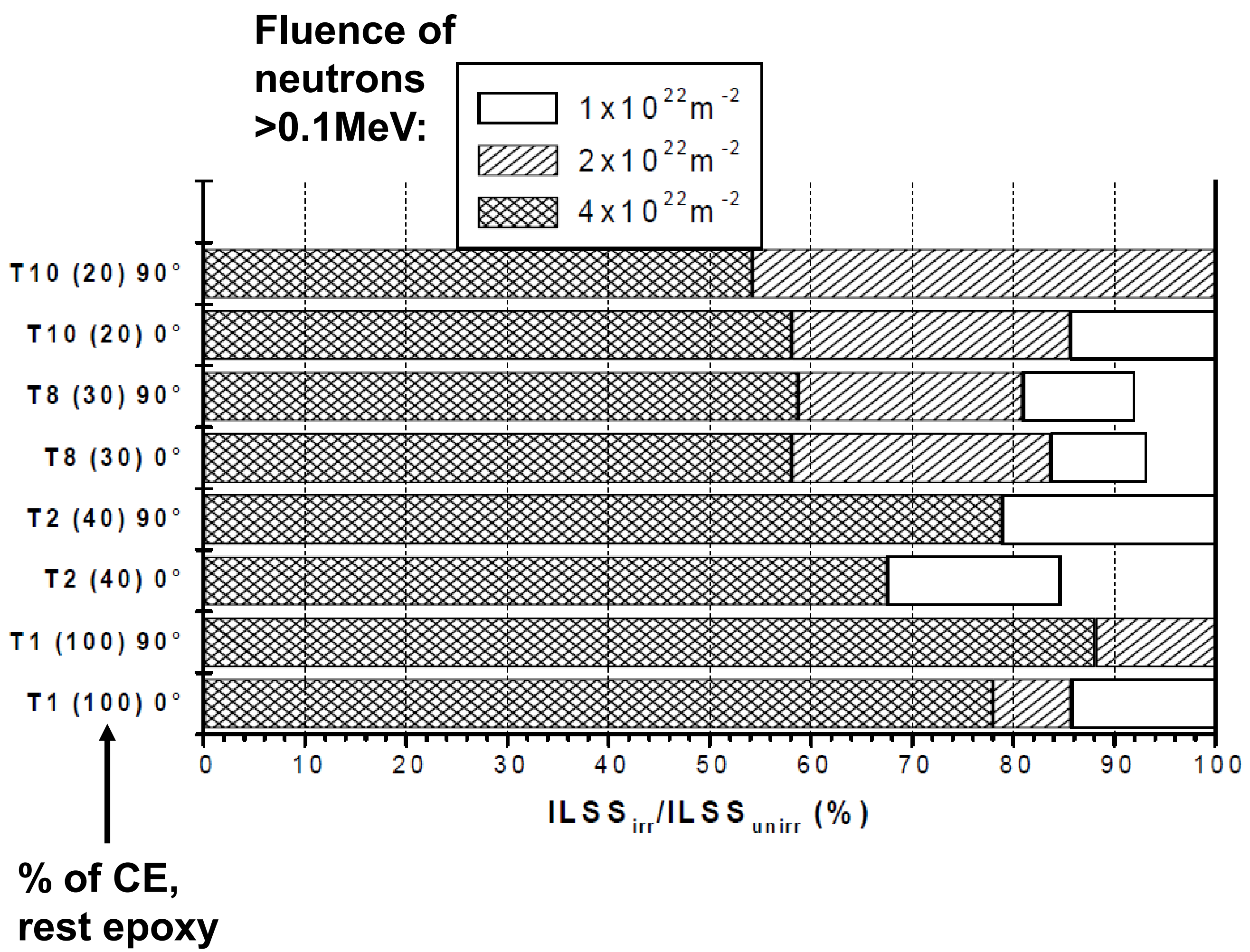
Gamma rays

- Gamma radiation lifts electrons from closed shells into conduction band, making insulators become conductive (a flux effect, not fluence)



Gamma rays

At doses ~100MGy, or ~10^{23} n/m^2, so a fluence effect, the mechanical strength of epoxy insulation is severely degraded, although cyanate ester is less so.



Prokopec, R., *et al* – Mechanical behaviour of cyanate ester/epoxy blends after reactor irradiation to high neutron fluences, ICMC Proceedings Volume 986; Chattanooga (Tennessee), 16-20 July 2007, p.182-189

Neutrons

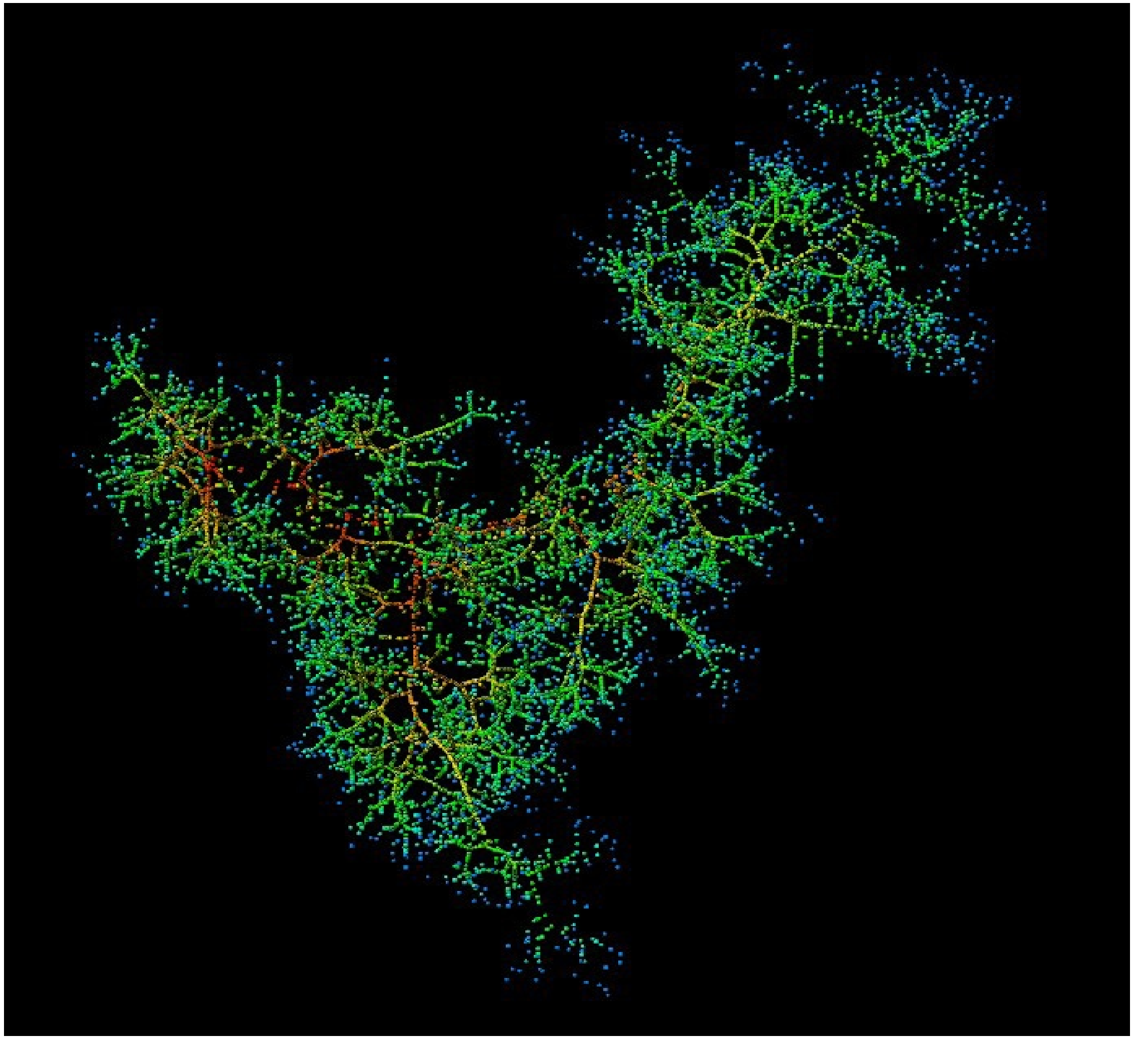
Fast neutrons can produce very energetic recoil ions in the materials they encounter

Example of Fe lattice damage caused by one cascade induced by a 150keV Fe ion recoiling from a single neutron impact.

Size of simulation cell: 475 Å; 6.75 million atoms

Nearly all the displacements are Frenkel Pairs (vacancy + interstitial atom) which recombine rapidly (faster with higher temperature), but still hundreds remain, together with more complex crystal defects.

K. Nordlund, TEKES –
University of Helsinki: December 2012



Fe has an atomic separation of 2.87Å, SiO_2 (1.62 - 2.62)Å and Si 5.43Å.

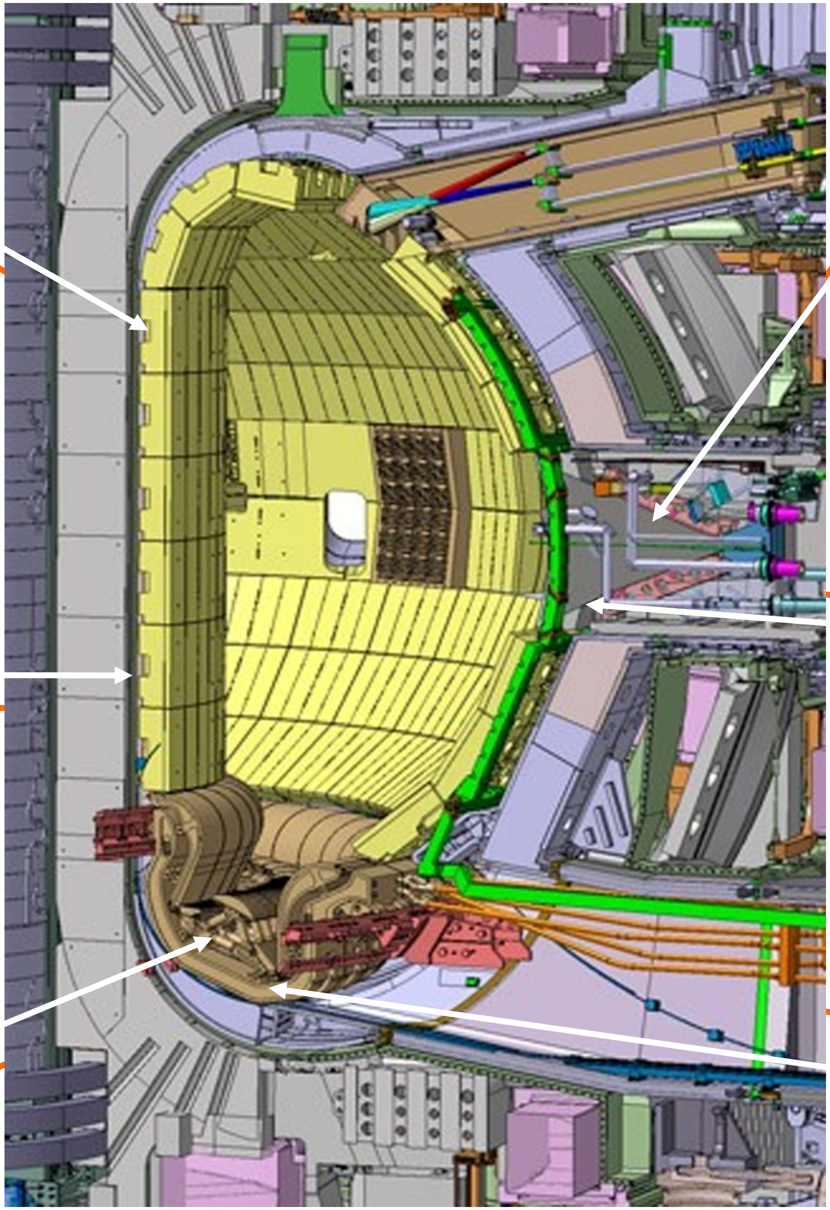
Neutrons and gamma rays

Example problems for plasma diagnostics in ITER (DEMO-like flux, but small fluence)

Magnetic coils
Radiation Induced Conductivity (RIC)
Radiation Induced Electric Degradation (RIED)
Radiation Induced Electromotive Force (RIEMF)
Any integrators must be ultra-low drift

Bolometers
RIC
Nuclear Heating
Sputtering
Contact degradation
Differential swelling and distortion

Pressure gauges
RIC
RIED
Filament aging



Neutron cameras
Noise due to γ-ray, proton, α
Radiation damage on solid state detectors

Optical diagnostics
Mirror
Deposition, erosion
Swelling, distortion
Window
Permanent transient absorption
Radioluminescence
Swelling, distortion

Impurity monitoring
Mirror and windows
same as above
Fibers
Permanent transient absorption
Radioluminescence

Vayakis, G., - The ITER radiation environment for diagnostics, N 55 RI 38 04-05-06 W 0.1, SRD-55 (Diagnostics) from DOORS (ITER_D_28B39L v3.1)

Diagnostics – some useful effects

- The energetic radiation from the plasma is of course useful for diagnosing some of its key properties...
  - The (thermalised) neutron flux is measured with passive microfission chambers, providing a measure of fusion power.
  - Neutron spectroscopy provides plasma ion temperature.
  - Neutron tomography provides plasma (ion) pressure profile
  - Poorly confined charged fusion products are detected near the plasma edge and yield information on the plasma confinement physics.
  - Gamma ray spectroscopy yields densities of species interacting with fusion reaction products.
  - X-ray Doppler spectroscopy of line radiation (photon energy ~ few keV) provides impurity ion temperature and velocity in the plasma core.
  - *We try not to make Runaway Electrons but their presence is detected by relativistic cyclotron emission from the plasma core and gamma ray emission from their hitting the walls.*

Summary (1/2)

- Fusion requires very energetic fuel species nuclei (~50keV, ~500M°C) and generates much faster neutrons than fission (~3MeV - 14MeV)
- The harder neutron spectrum permits a greater range of transmutation reactions and activation, of interest in minimising radwaste, and it also creates ~30x more He appm/dpa in the surrounding structure, bad for swelling, rewelding, embrittlement, conductor resistivity...
- ...and it is more aggressive in activating any oxygen isotopes in the reactor coolant, producing short-life radioactive ^{16}N and ^{17}N which leave the reactor hall with the coolant and require flow delay features and shielding to protect staff and electronics
- But the fast neutrons are necessary to achieve neutron multiplication and hence tritium breeding ratio >1, vital for the reactor function
- Fusion has no long-lived radioactive daughter products but the activation of the structure makes low activation materials attractive, to reduce radwaste and decay heat
- The neutrons have to be well shielded from the near-by superconducting magnets, to prevent degradation of the superconductor and excessive resistance rise in the associated copper stabiliser jacket

Summary (2/2)

- Fusion also creates very energetic charged products, important for heating the plasma but not significant as a radiation hazard
- These fast reaction products (p, d, t, ^{3}He, ^{4}He) can be lost from the plasma if born in unfavourable orbits, creating some damage to the first wall, but the loss flux is measurable and informative for the machine operation
- The fast products can undergo secondary reactions with characteristic gamma ray emission, also useful for plasma diagnosis
- Beta emission is of most significance as radiation from the tritium fuel, which drives most of the reactor safety case analyses.
- Beta emission in the activated structure contributes to decay heat but gamma radiation dominates Health Physics for maintenance and radwaste issues
- Tokamaks can unintentionally produce Runaway Electrons at tens of MeV, creating significant gamma rays and activation even in "non-nuclear" fusion devices
- The energetic neutron and gamma radiation is extremely bad for most plasma diagnostic systems, but can be characterised in spectrum and emission profile to assist machine control