Testing Electronics for Fusion Application

----

focus on neutrons

Jean-Luc Leray, Consulting Engineer

jean-luc.leray@ieee.org or jl.leray@anaxajl.net

SUMMARY

The main scope of this presentation is the test of SEEs induced by neutrons on electronics intended to be operated in a neutron flux near a fusion reactor (DD or DT plasma neutrons).

Regardless of the intensity of the gamma and neutron fluxes, this presentation focuses on the energy spectra of neutrons and its effects, whose energy degradation can vary from one place to another in the reactor building depending on the elastic and inelastic interactions of neutrons with the surrounding structures, such as shields and walls.

Although the neutron fluxes depend on the design of the machine and the building as well as the operation of the reactor, the energy spectra of the neutrons should be quite similar in fusion reactors. Analogies but also differences can be evoked comparing with the case of Fission reactors and with the well described case of the natural atmospheric neutron spectrum.

Outline

- **About Fusion and about Tokamaks. Main types and sizes.**
- **Fusion degraded spectra behind shields**
- **Effects on Electronics**
  - Focus on neutron SEE testing according to degraded spectra behind shields
- **Testing plan in conformity with the required spectrum**
  - Which neutron test beams for which application required degraded spectrum?

Some References Concerning designs and radiations in Fusion Technology

USEFUL JOURNALS, PAPERS and books

Fusion Engineering and Research, Review of Scientific Instruments, IEEE Trans on Nuclear Science, IEEE Trans on Plasma Science

- Cited in this talk in chronology order:
  - **„Diagnostic components in harsh radiation environments: Possible overlap in R&D requirements of inertial confinement and magnetic fusion systems“,** J.-L. Bourgade, Alan Costley, Roger Reichle, J.L. Leray, M. Dentan and coll., Review of Scientific Instruments 79(10):10F304-10F304-5 (2008) DOI: 10.1063/1.2972024
  - **„Generic diagnostic issues for a burning plasma experiment“,** G. Vayakis, E. R. Hodgson, V. Voitsenya, C. I. Walker, Fusion Science and Technology vol. 53 Chapter 12, Feb. 2008, pp 699-750
  - **„Towards Diagnostics for a Fusion Reactor",** Alan E. Costley, IEEE Transactions on Plasma Science, Vol. 38, no. 10, October 2010, 2934.
  - **„Soft Errors, from particles to circuits”**, Jean-Luc Autran and Daniela Munteanu, CRC Press, 2015

- Most recent PhD Thesis: Matteo Cecchetto, **Experimental and simulation study of neutron - induced Single Event Effects in accelerator environment and implications on qualification approach**, CERN & ISE-Montpellier Univ., April 2021

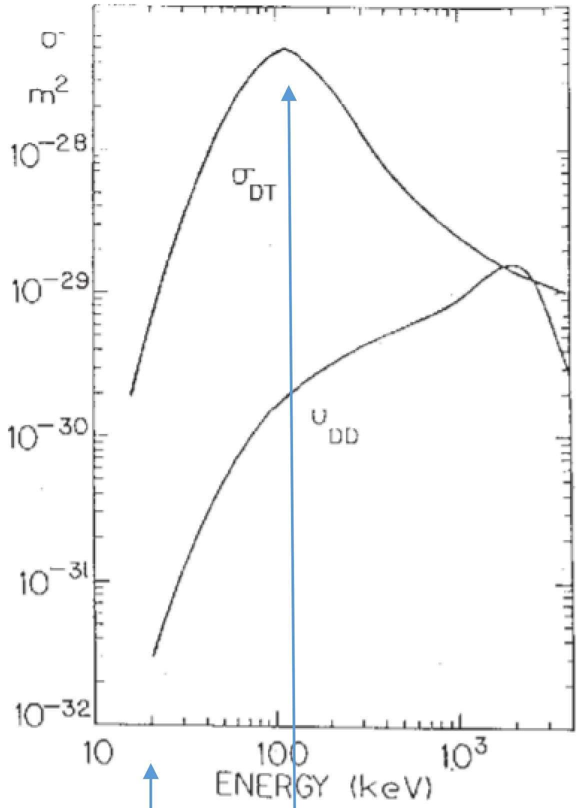
- THE ITER PUBLIC WEBSITE https://www.iter.org/

The ITER Organization provides images and videos on its public website free of charge
for educational and institutional use https://www.iter.org/album/

Early times of fusion

The science and physics of nuclear fusion started in the 1920s

- 1926 British astrophysicist Arthur Eddington suggested that stars draw their energy from the fusion of *hydrogen* into helium (1) => modern theoretical astrophysics (Bethe cycle of fusion in Stars)
- **1934 Rutherford showed the fusion of deuterium, and observed that "an enormous effect was produced" during the process.**
- **His student Mark Oliphant** used an updated version of the equipment **firing deuterium** rather than hydrogen **and discovered helium-3** by D (d, **n**) ^{3}He and **tritium** by D (d, p) **T**, **showing that heavy hydrogen nuclei could be made to react with each other.**



This was the first direct demonstration of fusion in the lab.
Just later Deuteron accelerators in the range of 100 keV were developed
and ARE commonly used BY us to produce n by DD and DT reaction (many instances in our Labs)

DD and later DT plasma (atmospheric pressure) may reach the onset of fusion with large production of energy.

Threshold are ~20 keV (200 megaKelvins),
cross section max at ~100 keV (DT), 2 MeV (DD).

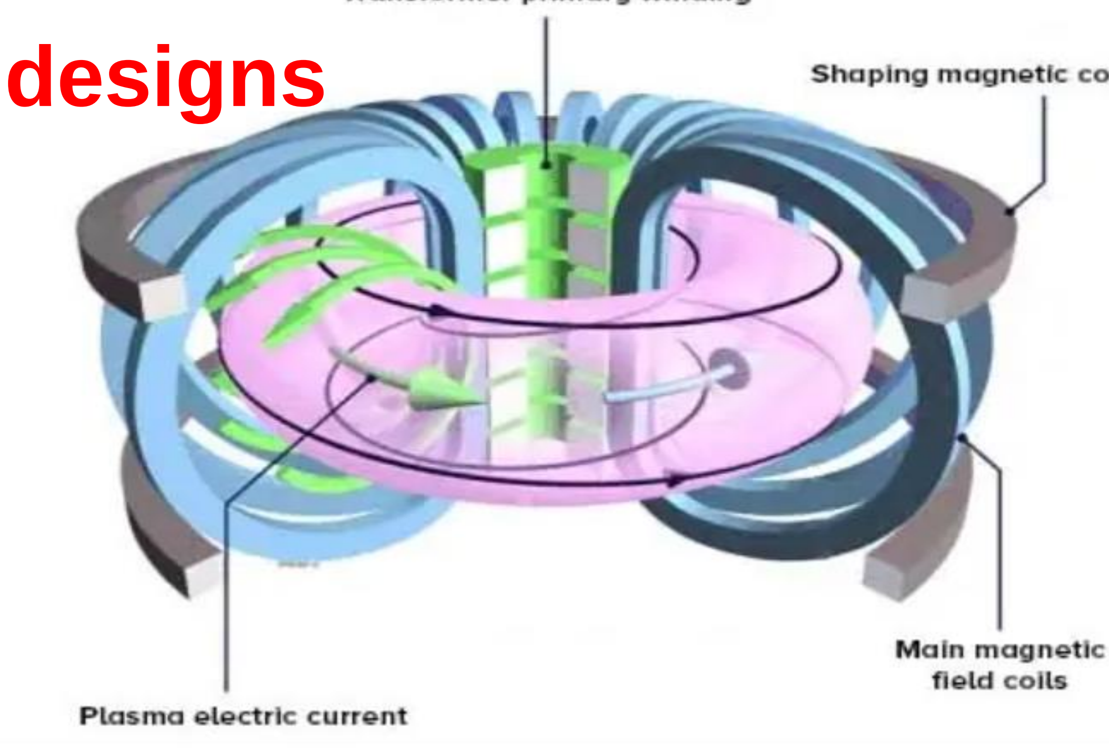
(1) A. Eddington, Internal Constitution of the Stars, 1926

https://www.euro-fusion.org/fusion/history-of-fusion/

As soon as in the 1950s, Machine designs

By the 1950s, ooking at possibilities of
replicating the process of nuclear fusion on Earth.

In 1950 soviet scientists **Andrei Sakharov** and **Igor Tamm** proposed the design for a type of ***magnetic confinement fusion***
=> TOROIDAL device, the *tokamak*.



1968: hydrogen plasma at 10 million degrees, never reached before.

Helicoidal vs toroidal?
Soviet scientist Lev Artsimovich showed that the tokamak was a more efficient concept

Russian acronym Toroidalnaya Kamera c Magnitnymi Katushkami https://ccfe.ukaea.uk/fusion-energy/how-fusion-works/

TOKAMAK with neutron yield (DT) since the 80’s

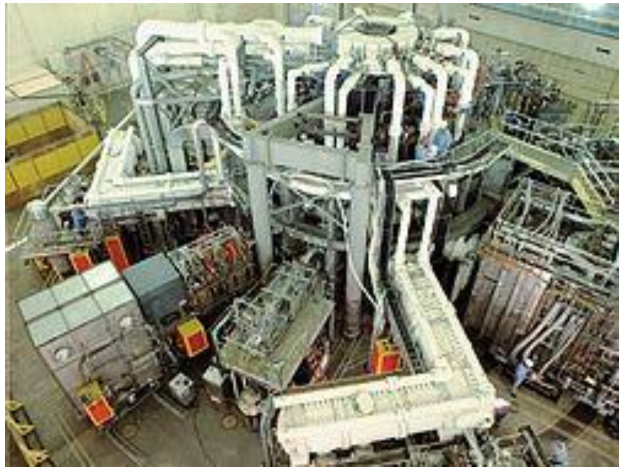
Q= Fusion /Heating (“the gain”

1986: Tokamak Fusion Test Reactor, Princeton, USA, produced the first 'supershots' which **produced many fusion neutrons (0,2)** – decommissioned 2002

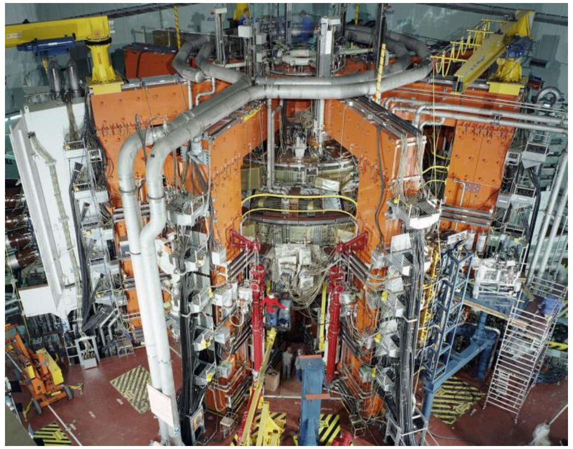
1994, Princeton's Tokamak Fusion Test Reactor (TFTR) produced a world-record **10,7 MW of fusion**

1997: JET, UK near Oxford, several Deuterium-Tritium shots with Fusion (Q=0,7, 16 MW of Fusion power)
- To be renewed in 2021?

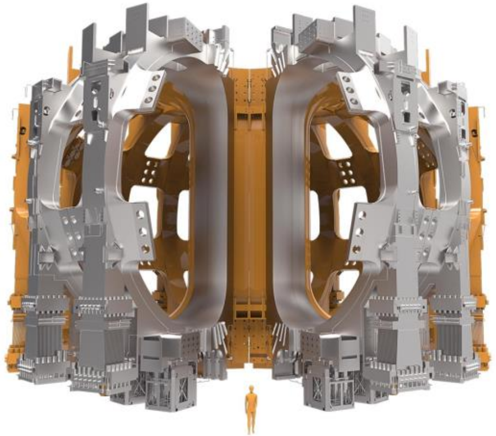
Under construction since 2006 – Iter undertaking in construction, worldwide cooperation
International Thermonuclear Experimental Reactor
2035 and beyond to 500 MW



TFTR, in Princeton



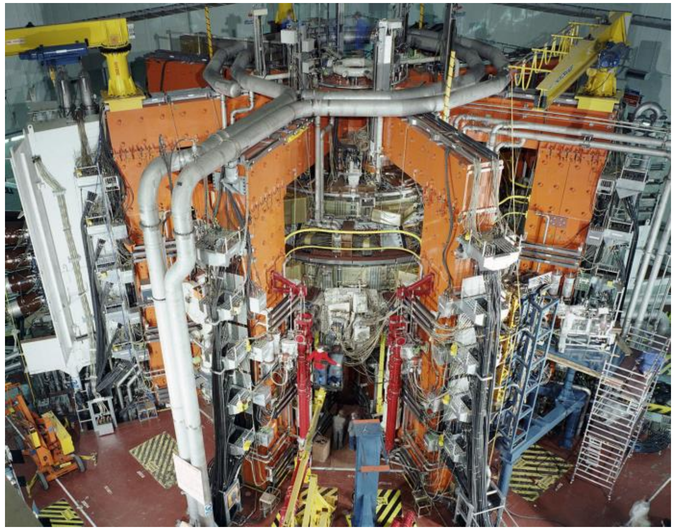
JET, UK in Culham near Oxford



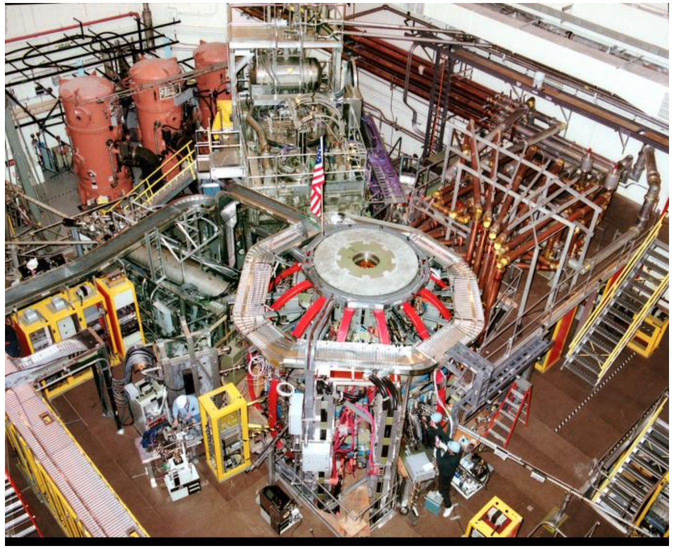
Iter in Aix-En-Provence near Marseilles, France

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

The Way to Fusion
More than 200 TOKAMAKS around the World
Several structures of tokamaks and and related designs

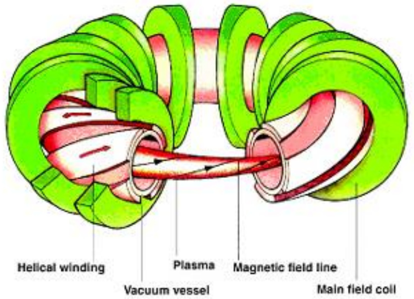


The JET toroid (1991)
Culham, UK
Classical coils



The NSTX Spherical
Princeton, USA since 2002
Classical coils

Wendelstein 7-X helix stellarator
Planck Institut (2011)



15 m diameter
440 t
30 superconducting coils

Fusion for Energy..

- **The DEMO concept (DEMOnstrator)**

500 MW continuous

Envisaged circa 2100

Needs self sustained balance of energy

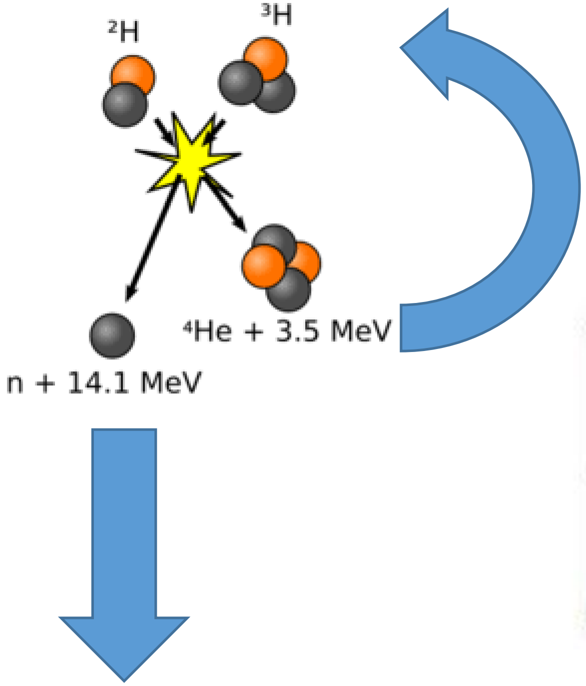
(production = loss + extraction)

Plasma mixture, temperature

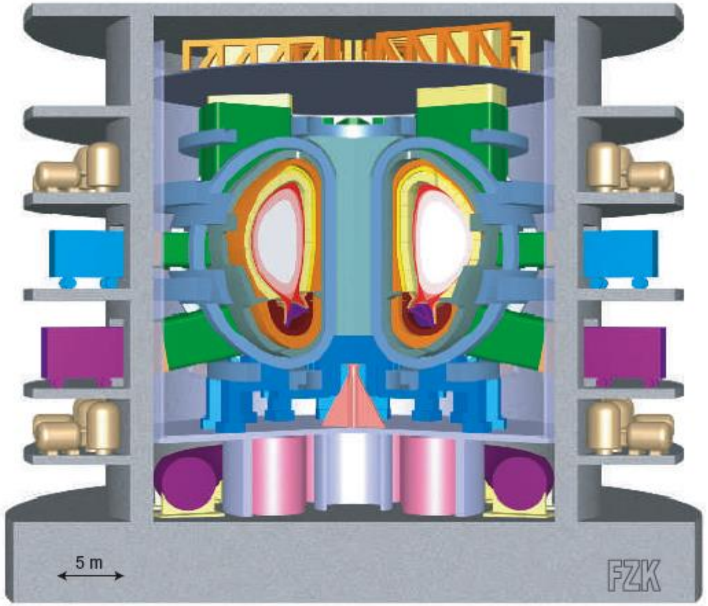
Density, volumes, losses

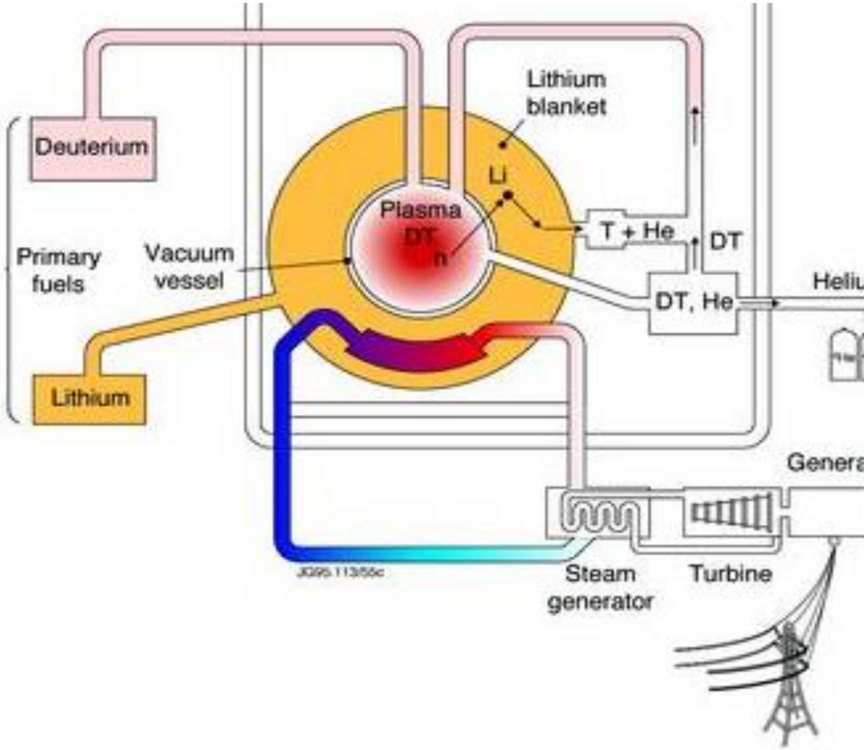
Many steps before

Recycling the energy of the alpha for heating

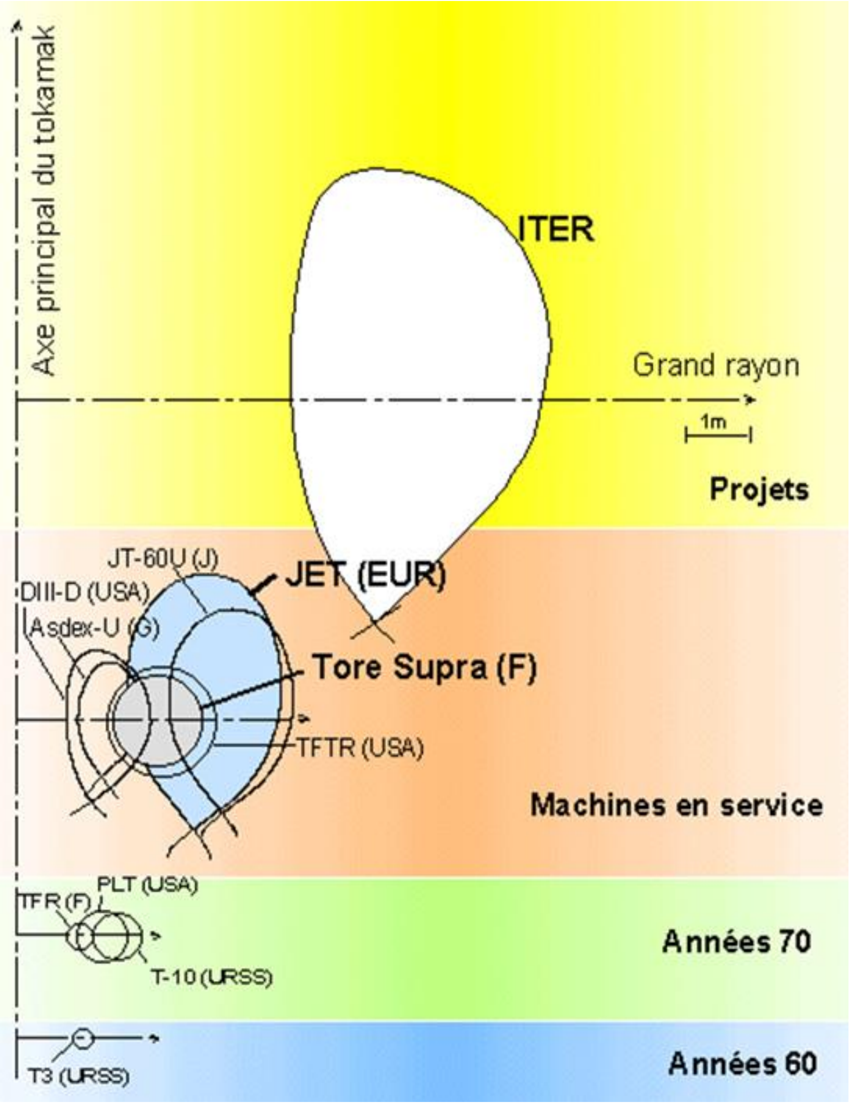


OUTPUT of the neutron energy THROUGH THE WALLS TO THE EXCHANGER





LARGE MACHINES
To improve the GAIN (Q) the balance LOSS/INPUT and increase the stability



- **JET, UK**

  Joint European Tokamak (Cuhlham near Oxford)

  - Q=0,67: 6 MW fusion/24 MW injected, some 10s seconds

- **Iter**

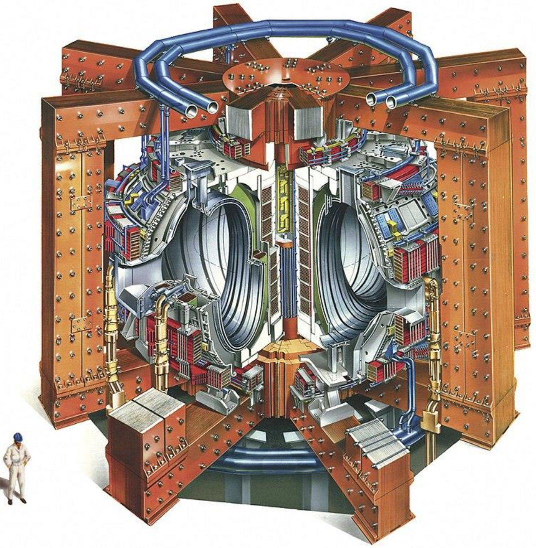
  Cadarache near Aix-En-Provence

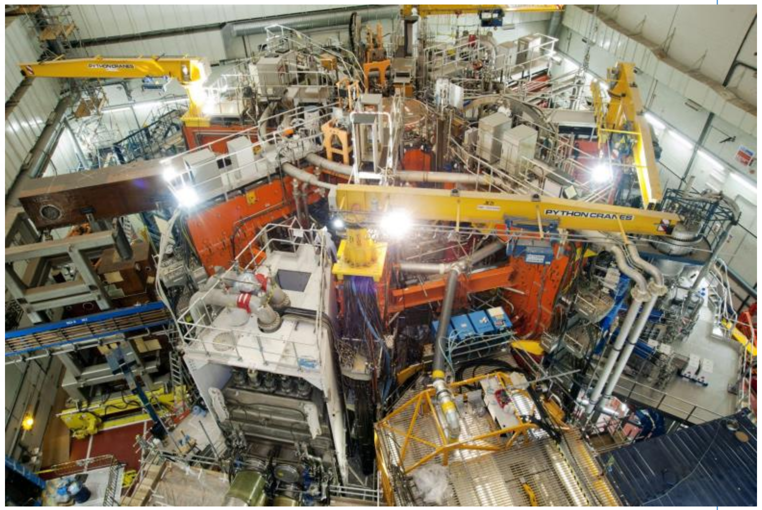
  - Characteristics:
    - Q=10: 500 MW fusion power with only 50 MW external heating
    - Single discharge duration: 500s;
    - ~30 years exploitation
  - Phases
    - 2025 H2
    - 2035 DT
  - Expected accumulated total active plasma burn 0.6 years
    - 20 000 Discharges (shot)
    - accumulated total burn 0.6 years = 4700 h
  - TID, DDD, SEE

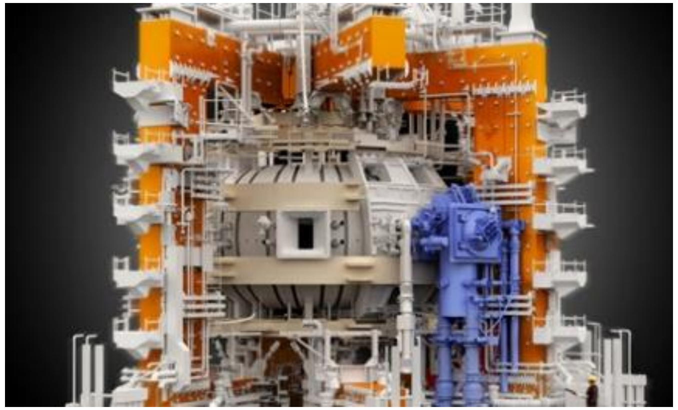
Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

UK fast track: at Culham Centre for Fusion Energy (Oxfordshire)

the JET since 1983 and the STEP (step foward – To 2040)







The UK is also starting the design of a more compact, spherical fusion power plant – the Spherical Tokamak for Energy Production (STEP).

STEP builds on experience of operating and we are just embarking on a five year initial design phase, in collaboration with UK industry and academia. STEP aims to be generating electricity (>100MW) on a timescale of 2040.

https://ccfe.ukaea.uk/research/joint-european-torus/

LARGE MACHINES

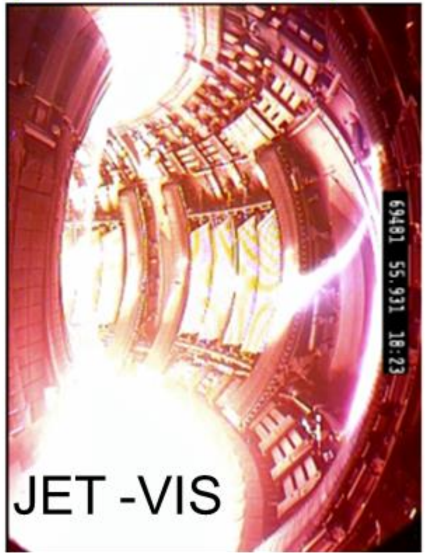
USE OF SUPERCONDUCTING COILS

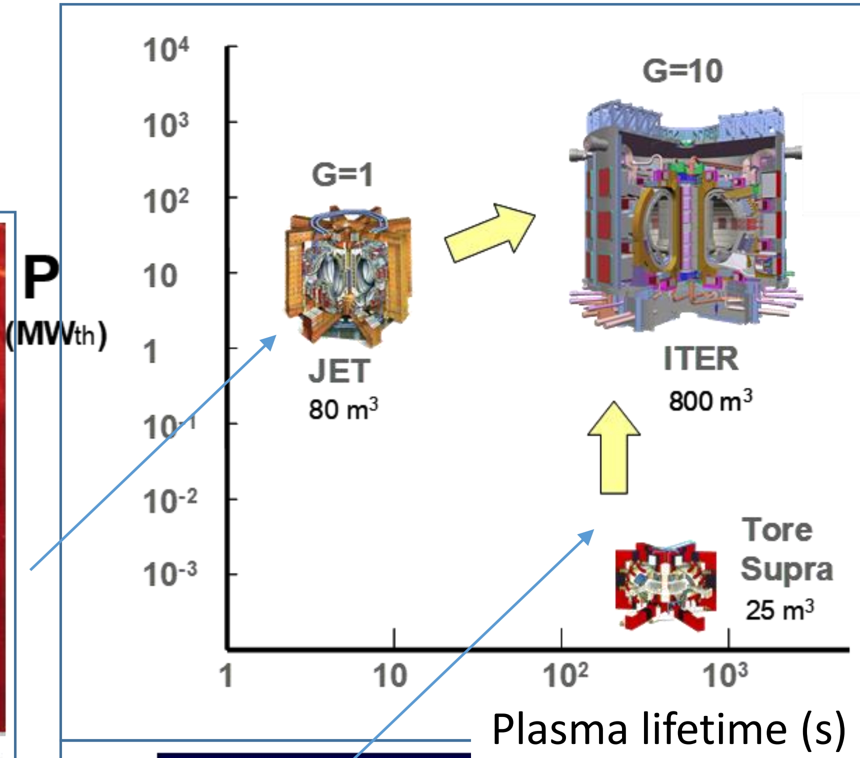
Joint Experimental Thermonuclear
Near Oxford, UK

1 second Deuterium-Tritium fusion
Achieved mid-90’s

You can watch the plasma glow
(**DT burning plasma**)

[E.Gauthier SOFT, 2006]



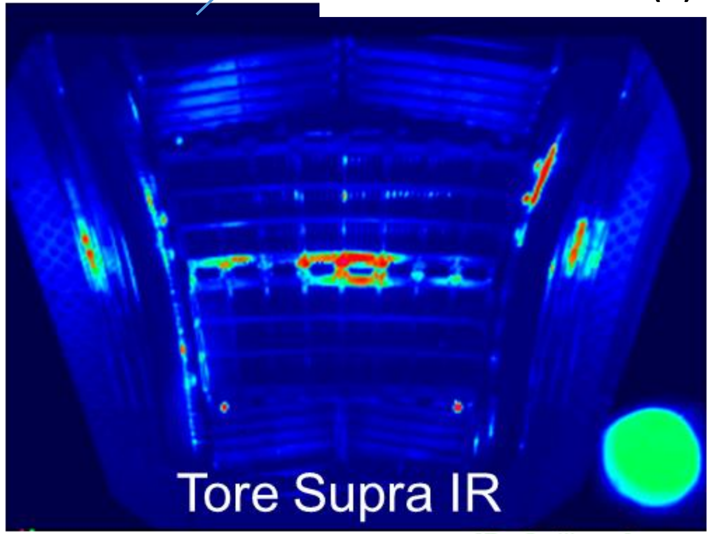


ITER in construction
International
Thermonuclear
Reactor

Near 840 m3 plasma vessel

500 MW thermal power

- 400 seconds
- 4700 plasma cumulated hours



[D. Guilhem]

Tore Supra,
Superconducting wire coils

Cadarache near Marseilles, Fr

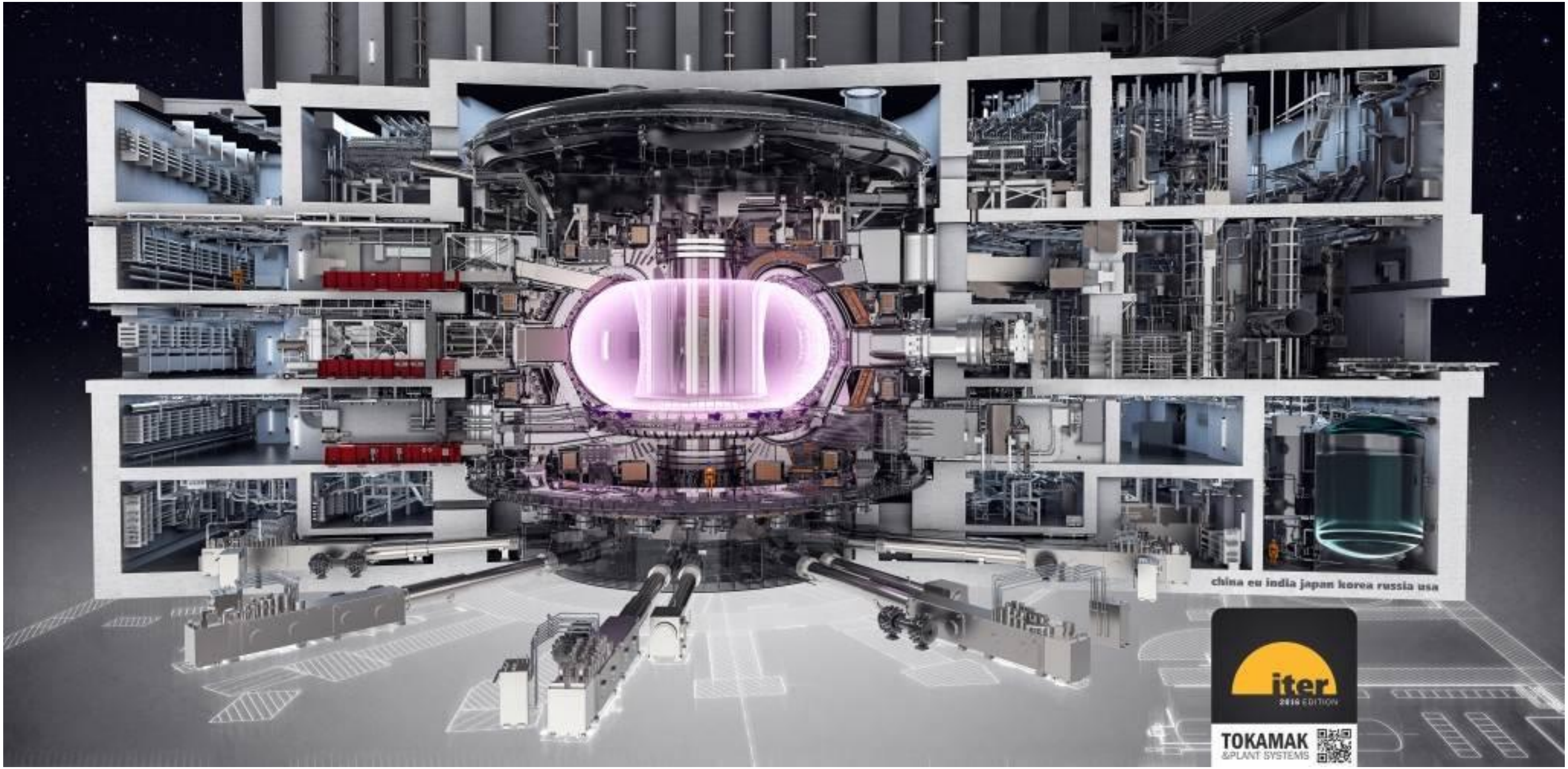
ITER Timeline

- **Recents achievements**
  - In November 2017, the project passed the halfway mark to First Plasma.
  - In July 2020, the project officially launched the machine assembly phase.
  - Today, project execution to First Plasma stands at **71.1 percent** (October 2020 data).

- **Future Milestones**
  - Dec 2025 Commissioning and First Plasma (H2)
  - *2025-2035 Progressive ramp-up of the machine*
  - *2035 DD-DT Operation begins*

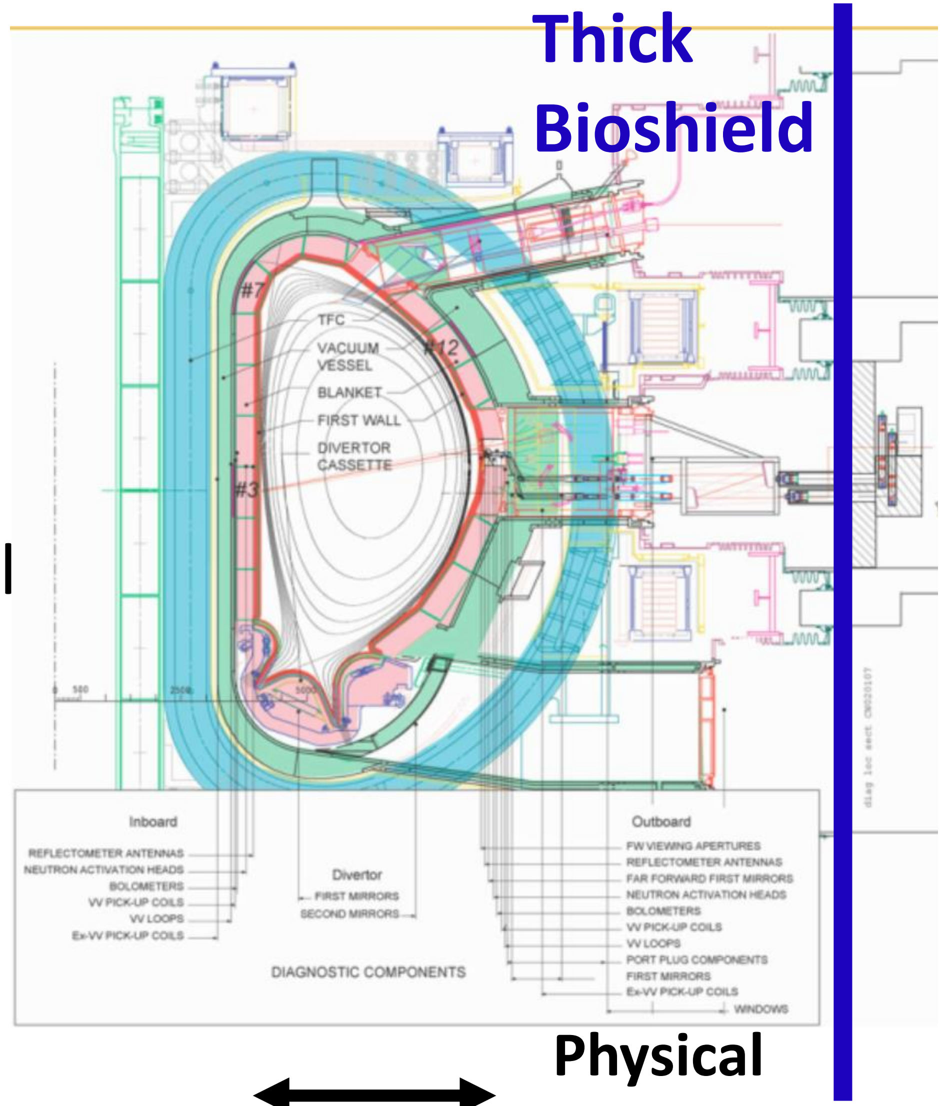
(https://www.iter.org/proj/inafewlines#6 Dec 6th, 2020)

Tightly packed! The technical areas tied to the Port Cells
This design as an example



Generic Sketch

The source region
ie, the plasma
and the 1st wall



Thick Bioshield

Transit of information to the outside

ELECTRONICS

Cables, Optical Fibers…

Physical diagnostics

eg, 4 meters

„Generic diagnostic issues for a burning plasma experiment“, G. Vayakis, E. R. Hodgson, V. Voitsenya, C. I. Walker, Fusion Science and Technology vol. 53 Chapter 12, Feb. 2008, pp 699-750

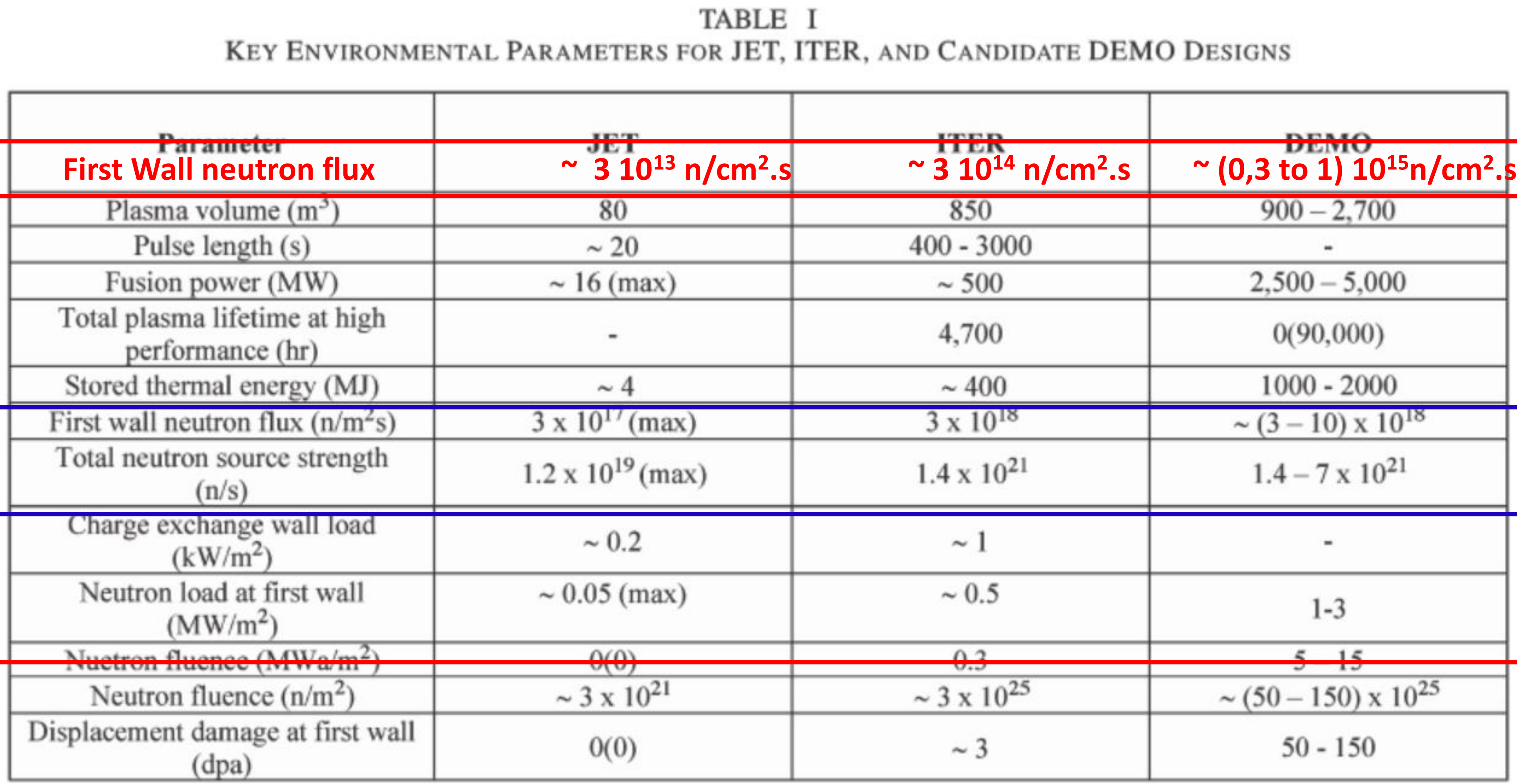


TABLE I
KEY ENVIRONMENTAL PARAMETERS FOR JET, ITER, AND CANDIDATE DEMO DESIGNS

Parameter	JET	ITER	DEMO
First Wall neutron flux	**~ 3 10^{13} n/cm².s**	**~ 3 10^{14} n/cm².s**	**~ (0,3 to 1) 10^{15}n/cm².s**
Plasma volume (m³)	80	850	900 – 2,700
Pulse length (s)	~ 20	400 - 3000	-
Fusion power (MW)	~ 16 (max)	~ 500	2,500 – 5,000
Total plasma lifetime at high performance (hr)	-	4,700	0(90,000)
Stored thermal energy (MJ)	~ 4	~ 400	1000 - 2000
First wall neutron flux (n/m²s)	3 x 10^{17} (max)	3 x 10^{18}	~ (3 – 10) x 10^{18}
Total neutron source strength (n/s)	1.2 x 10^{19} (max)	1.4 x 10^{21}	1.4 – 7 x 10^{21}
Charge exchange wall load (kW/m²)	~ 0.2	~ 1	-
Neutron load at first wall (MW/m²)	~ 0.05 (max)	~ 0.5	1-3
Nuetron fluence (MWa/m²)	0(0)	0.3	5 – 15
Neutron fluence (n/m²)	~ 3 x 10^{21}	~ 3 x 10^{25}	~ (50 – 150) x 10^{25}
Displacement damage at first wall (dpa)	0(0)	~ 3	50 - 150

Alan E. Costley, "Towards Diagnostics for a Fusion Reactor", IEEE Transactions on Plasma Science, Vol. 38, no. 10, October 2010, 2934.

First principles, simple approach, rule of thumb

- **500 MW, 14 MeV**

Assumption of a spherical source, isotropic

Fusion neutrons dn/dt ~ P (W) / 14 MeV / (eV) / (eV/W) ~ 2,2 10^{20} n/s

Flux at a distance d from the “center” $\Phi_n \sim \frac{1}{4\pi\, d^2}$ dn/dt

Φ_n ~ 7 10^{13} n/cm2/s at 5m ~Vessel, First Wall ((Φ_n ~ 2 10^{13} n/cm2/s at 10m)

In 4700 hours, the fluence could be some 10^{21} n/cm2 However, it is not realistic to place Electronics without very thick shielding

Actually, the Bioshield is meters thick to provide sufficient neutron captures, over 1/10^7 in flux (up to 10^{11} and more according to the location)

As a result, a number of gamma comes from in the inner part of the machine (tens of thousand tons) => TID

And, the neutron spectrum suffers reduction by the captures and is softening as well

⇒From 2,45 MeV (DD) or 14 MeV (DT) to thermalization, 1/E white spectrum expected,

⇒LARGE SEE rate and in places significant DDD.

Calculation of the neutron spectrum in every location of the area also is an immense problem.

Spectrum softening along the radial axis

Vayakis et al. GENERIC ISSUES FOR BURNING PLASMA EXPERIMENT

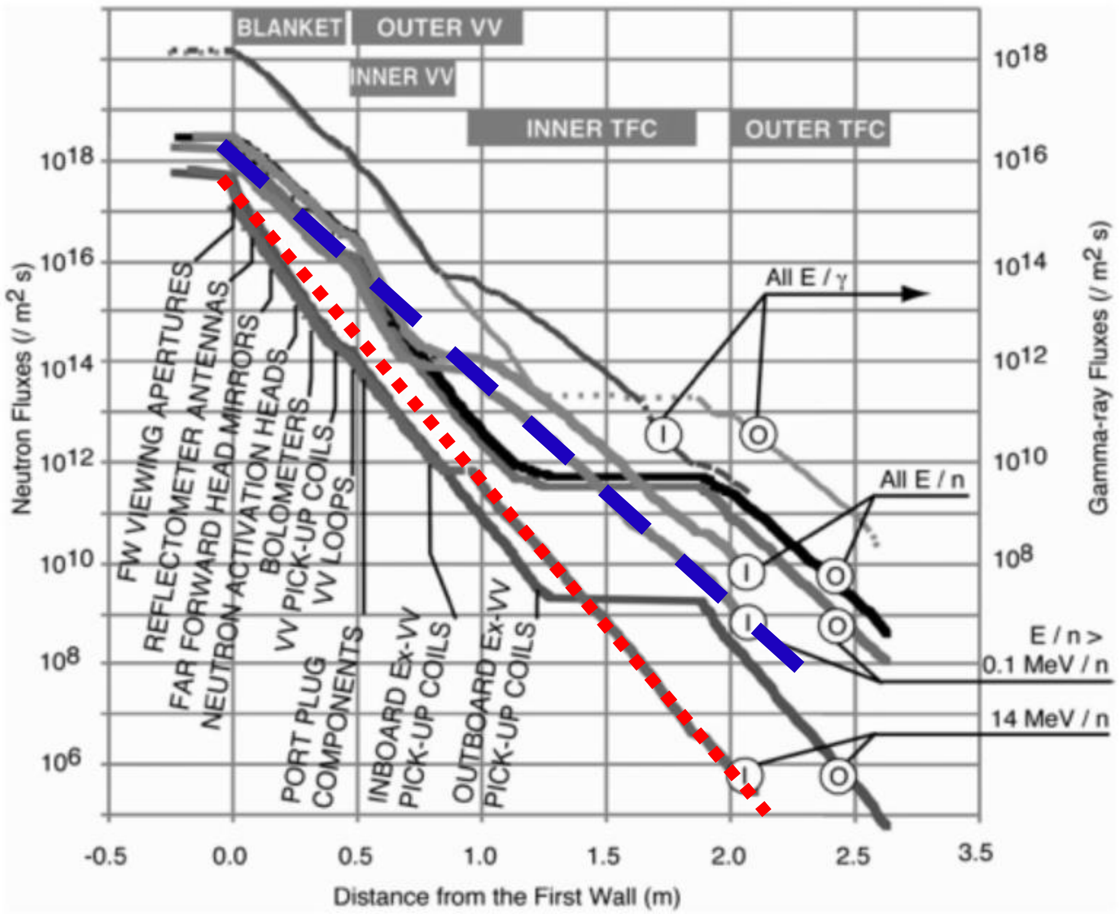


Fig. 2. Neutron and gamma fluxes on diagnostic components during operation for 500 MW. The solid curves are from a simplified 1D equivalent (cylindrical) model of the machine. This averages out the effect of gaps and does not include diagnostic penetrations.

- This early calculation in radial model quantitatively shows the enhancement of >100 keV group with respect to the >14 MeV line
- 3 to 4 decades at 2 meters from the 1st Wall
- Consequently, the SEEs are very sensitive on the actual spectrum at the location of use.
- 1/E slowing spectrum is expected at least at lwer energies, inside bioshield as well as outside in experimental areas

„Generic diagnostic issues for a burning plasma experiment“, G. Vayakis, E. R. Hodgson, V. Voitsenya, C. I. Walker, Fusion Science and Technology vol. 53 Chapter 12, Feb. 2008, pp 699-750

COMPARISON WITH FISSION (conceptual for Single Event Effects)

- **Inside a water-cooled power Fission Reactor, layout consist of submerged fuel rods. Water scatters and array of rods both are a source and an absorber**
- **In a Fusion Reactor, the plasma vessel is surounded by thick absorbers (Li, Water coolant pipes) and thick shield which absorb and scatter.**
- **Both spectra are governed by a Boltzmann equation**

As a result the spectra look rather the same.

In Nuclear Fission engineering, the coarse spectrum is first orderly as this (1) :

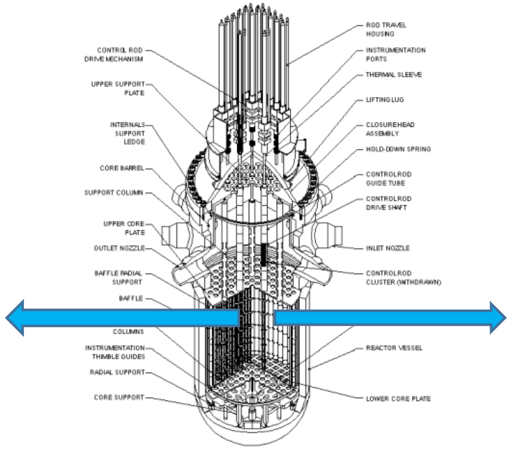
$$\emptyset_E(E) = \begin{cases} C_1 \frac{E}{(kT)^2} e^{-\frac{E}{kT}} & \text{if E<Ethermal} \\ 1/E & \text{if Ethermal< E < Efast} \\ C_2\ \chi(E) & \text{if E > Efast} \end{cases}$$

With Ethermal = 0,5 eV and Efast = 0,5 MeV

The shape of χ(E) is determined by the source and the heavy materials, absorption and density

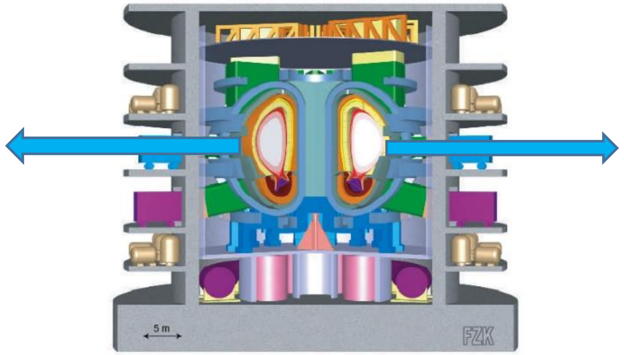
Source = fission spectrum or damped fusion line (14 MeV)

• Fission Reactor (PWR) with its Assemblies



Residual neutron Flux outside the pressurized Vessel, inside the Bldg

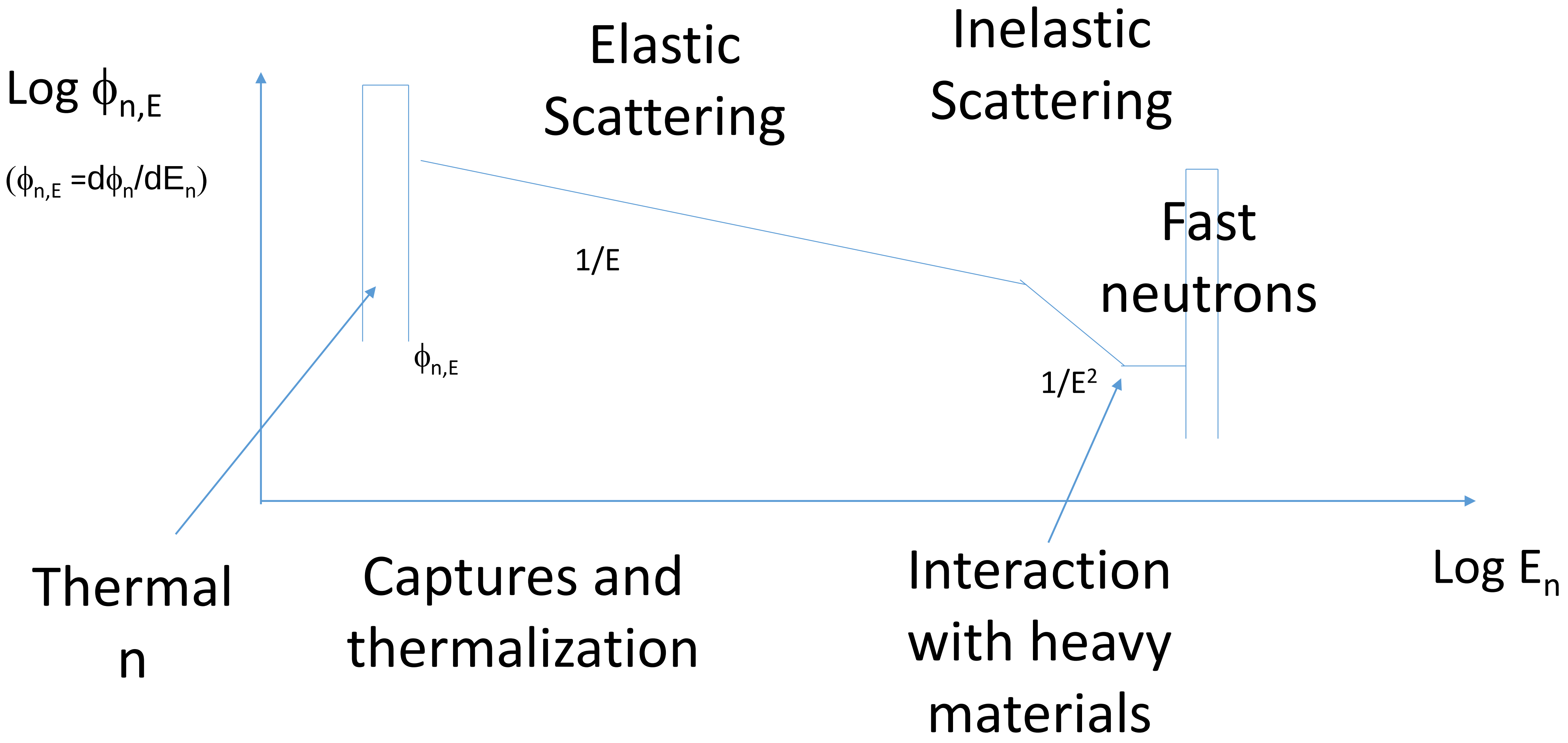
• Fusion Power Reactor with its Shields



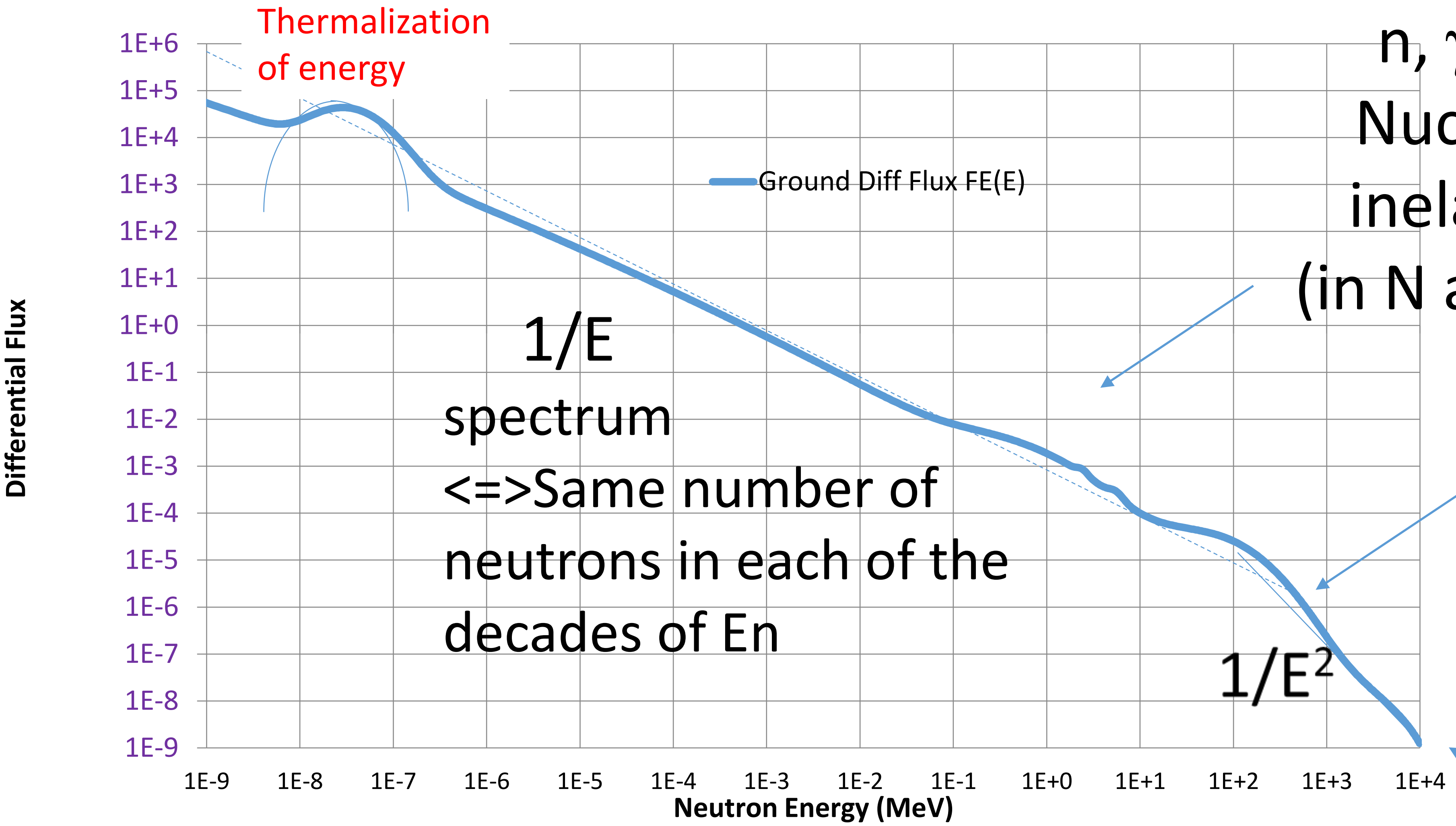
Residual neutron Flux outside the Shield In the technical front areas

(1) From « Neutronics » by R.E. Pevey, chapt 18 in Nuclear Engineering Handbook, Ed by K.D. Kock, CRC Press, 2009, p.586

Modeling the spectrum in broad (coarse) regions (Fusion) Varies with shields design



Comparison with a typical natural neutron spectrum in the atmosphere, at ground level



Thermalization of energy

1/E spectrum <=>Same number of neutrons in each of the decades of En

$1/E^2$

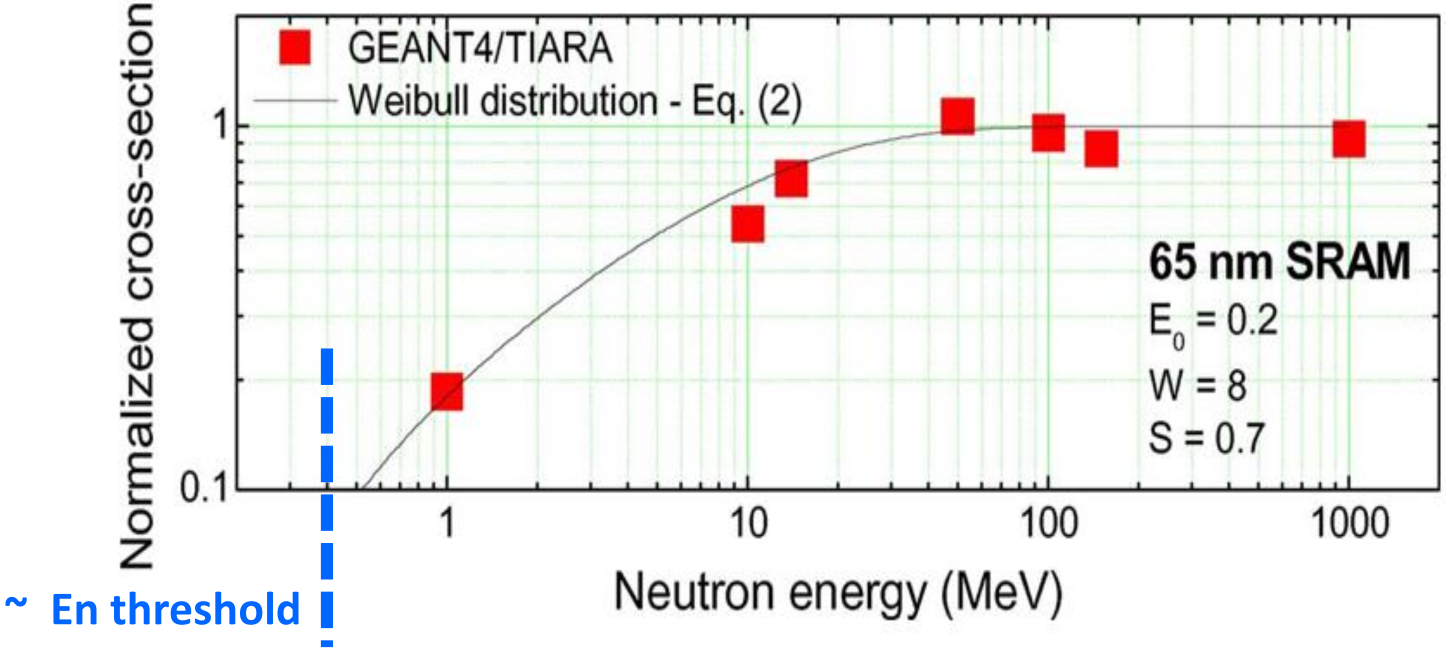
n, γ and Nuclear inelastic (in N and O)

Spallations (on N and O)

Pseudo-neutron source at « some GeV » (cosmic ray hadronic interaction with N and O)

in "SOFT ERRORS", in Jean-Luc Autran and Daniela Munteanu (fig 1.12 p. 20) and M.S. Gordon, P.Goldhagen et Al, IEEE tTNS TNS-51

Shape of the SEU
Modeling (Monte Carlo) by IM2NP, Aix-Marseille University

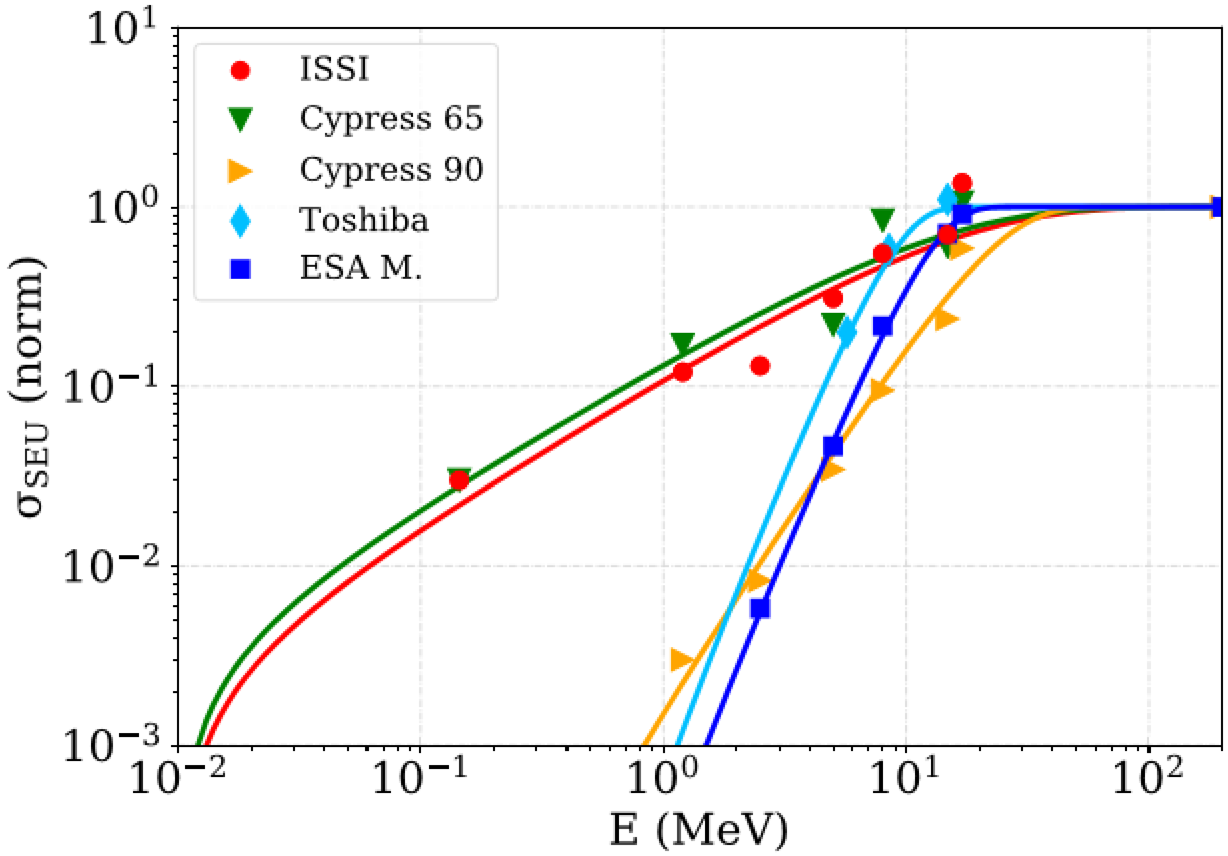


~ En threshold

Fig. 8. TIARA values and normalized Weibull fitting (using (2)) of the 65 nm SRAM cross-section.

„Soft Errors, from particles to circuits”, Jean-Luc Autran and Daniela Munteanu, CRC Press, 2015

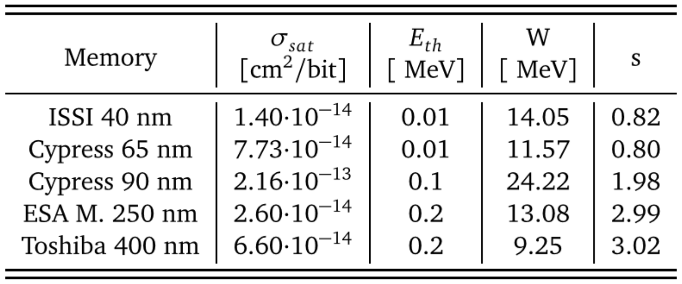
Matteo Cechetto's Thesis and publications (Apr 2021)



(b)

Matteo Cecchetto, Experimental and simulation study of neutron - induced Single Event Effects in accelerator environment and implications on qualification approach, CERN & ISE-Montpellier Univ., PhD Thesis April 2021, p.145

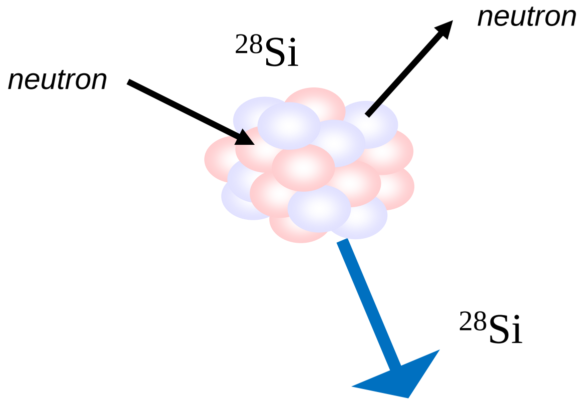
Table 7.5: Weibull fit parameters of the tested memories and those of the Toshiba reference (from [10]) for the HEHeq calculation.



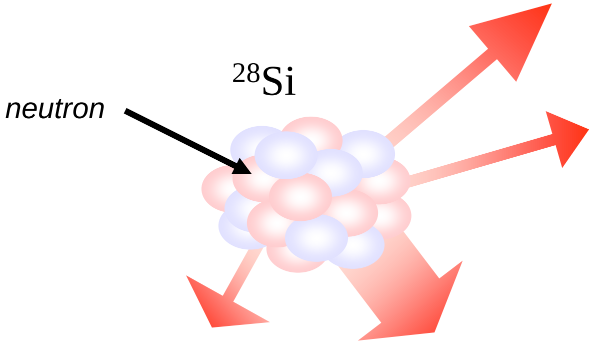
Memory	σ_{sat} [cm^2/bit]	E_{th} [MeV]	W [MeV]	s
ISSI 40 nm	$1.40{\cdot}10^{-14}$	0.01	14.05	0.82
Cypress 65 nm	$7.73{\cdot}10^{-14}$	0.01	11.57	0.80
Cypress 90 nm	$2.16{\cdot}10^{-13}$	0.1	24.22	1.98
ESA M. 250 nm	$2.60{\cdot}10^{-14}$	0.2	13.08	2.99
Toshiba 400 nm	$6.60{\cdot}10^{-14}$	0.2	9.25	3.02

Back to the nuclear interaction: example of neutron in silicon Capture, quasi fission, or scatering

- Neutron scattering, silicon recoil



- Exothermic nuclear silicon break-up



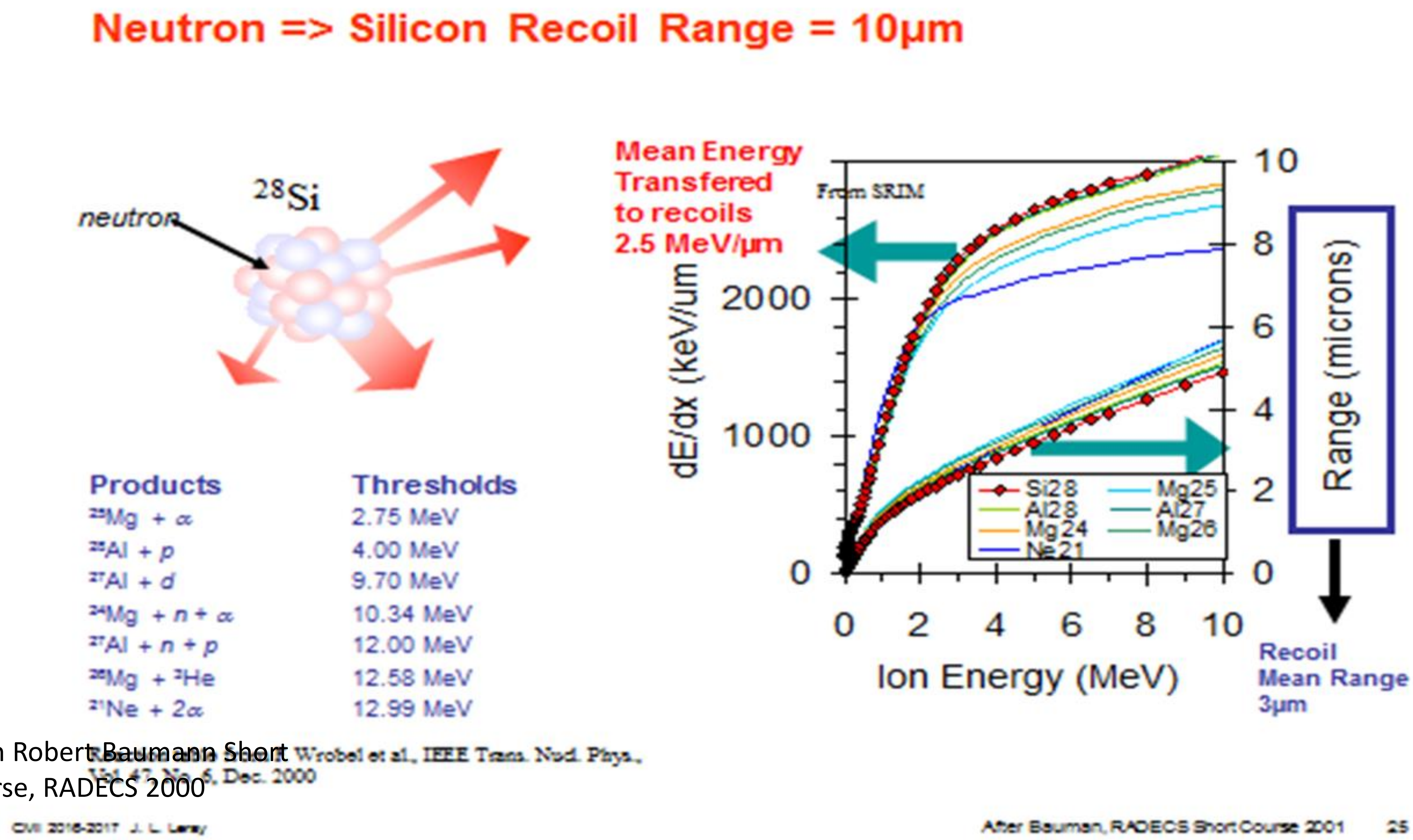
- No threshold
- Cross section

Sketch from Robert Baumann Short Course, RADECS 2001

By-products (recoils)	n energy thresholds	cross section
^{25}Mg + α	2.75 MeV	
^{28}Al + p	4.00 MeV	
^{27}Al + d	9.70 MeV	
^{24}Mg + n + α	10.34 MeV	
^{27}Al + n + p	12.00 MeV	
^{26}Mg + ^{3}He	12.58 MeV	
^{21}Ne + 2α	12.99 MeV	

Reaction table from F. Wrobel et al., IEEE Trans. Nucl. Phys., Vol. 47, No. 6, Dec. 2000

What effects of one neutron in silicon?



Neutron => Silicon Recoil Range = 10µm

Products	**Thresholds**
^{25}Mg + α	2.75 MeV
^{28}Al + p	4.00 MeV
^{27}Al + d	9.70 MeV
^{24}Mg + n + α	10.34 MeV
^{27}Al + n + p	12.00 MeV
^{26}Mg + ^{3}He	12.58 MeV
^{21}Ne + 2α	12.99 MeV

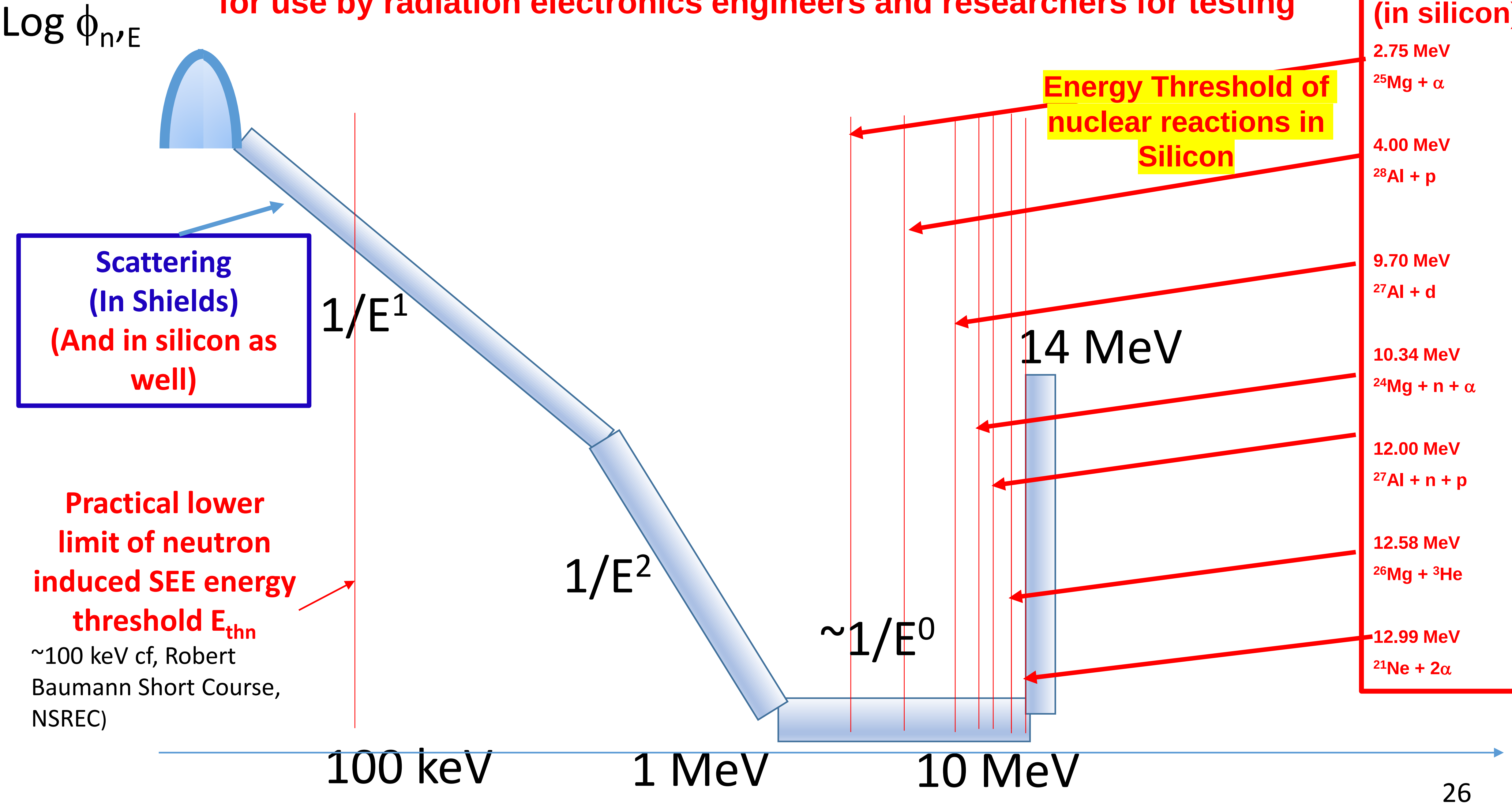
Wrobel et al., IEEE Trans. Nucl. Phys., Vol. 47, No. 6, Dec. 2000

Sketch from Robert Baumann Short Course, RADECS 2000

CMI 2016-2017 J. L. Leray

After Bauman, RADECS Short Course 2001 25

Need for of a simple parametrizable neutron spectrum for use by radiation electronics engineers and researchers for testing



Scattering
(In Shields)
(And in silicon as well)

Practical lower limit of neutron induced SEE energy threshold E_{thn}

~100 keV cf, Robert Baumann Short Course, NSREC)

Energy Threshold of nuclear reactions in Silicon

Effects (in silicon)

2.75 MeV
^{25}Mg + α

4.00 MeV
^{28}Al + p

9.70 MeV
^{27}Al + d

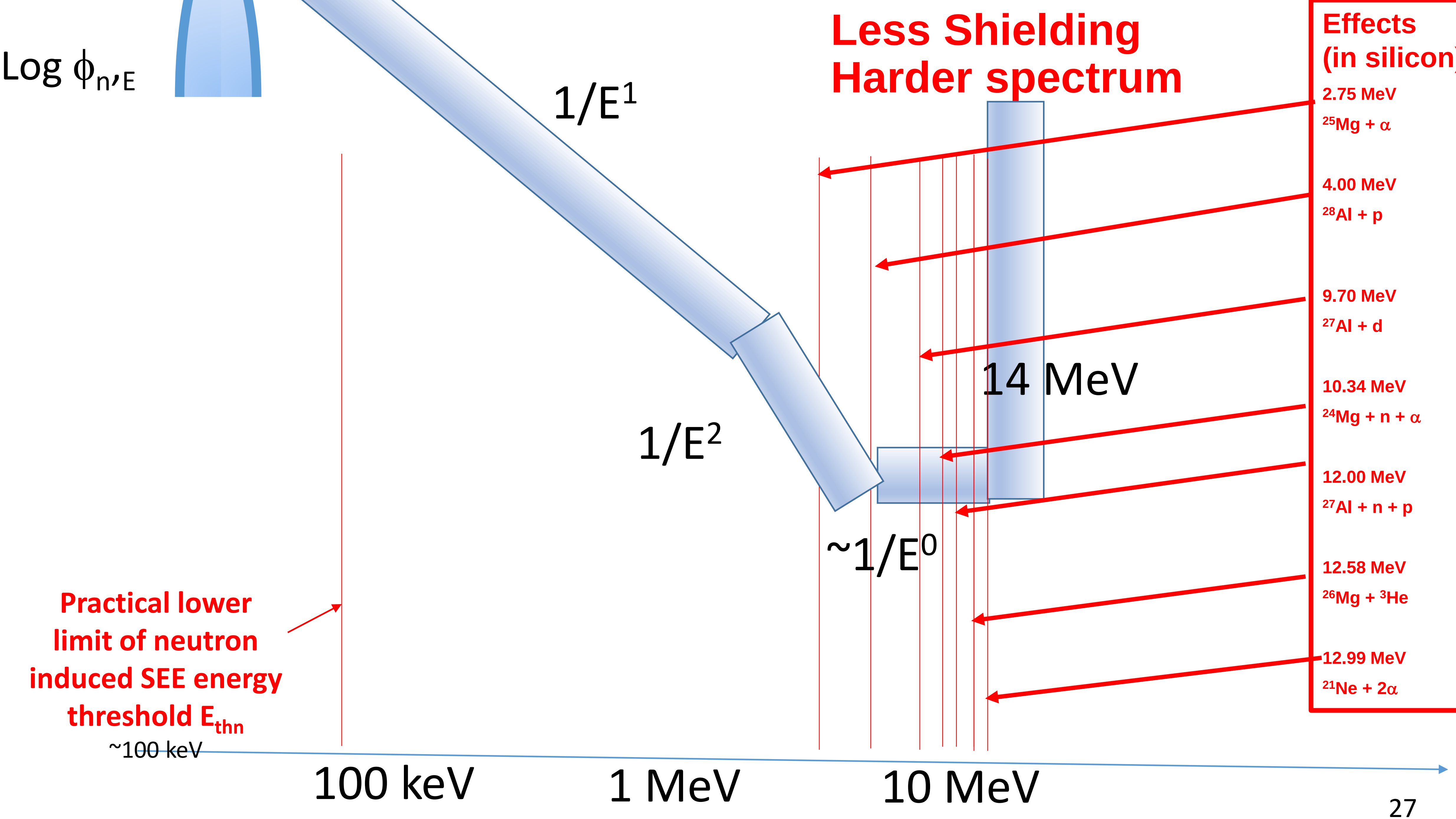
10.34 MeV
^{24}Mg + n + α

12.00 MeV
^{27}Al + n + p

12.58 MeV
^{26}Mg + ^{3}He

12.99 MeV
^{21}Ne + 2α

Less Shielding
Harder spectrum



Effects (in silicon)

2.75 MeV
$^{25}\text{Mg} + \alpha$

4.00 MeV
$^{28}\text{Al} + p$

9.70 MeV
$^{27}\text{Al} + d$

10.34 MeV
$^{24}\text{Mg} + n + \alpha$

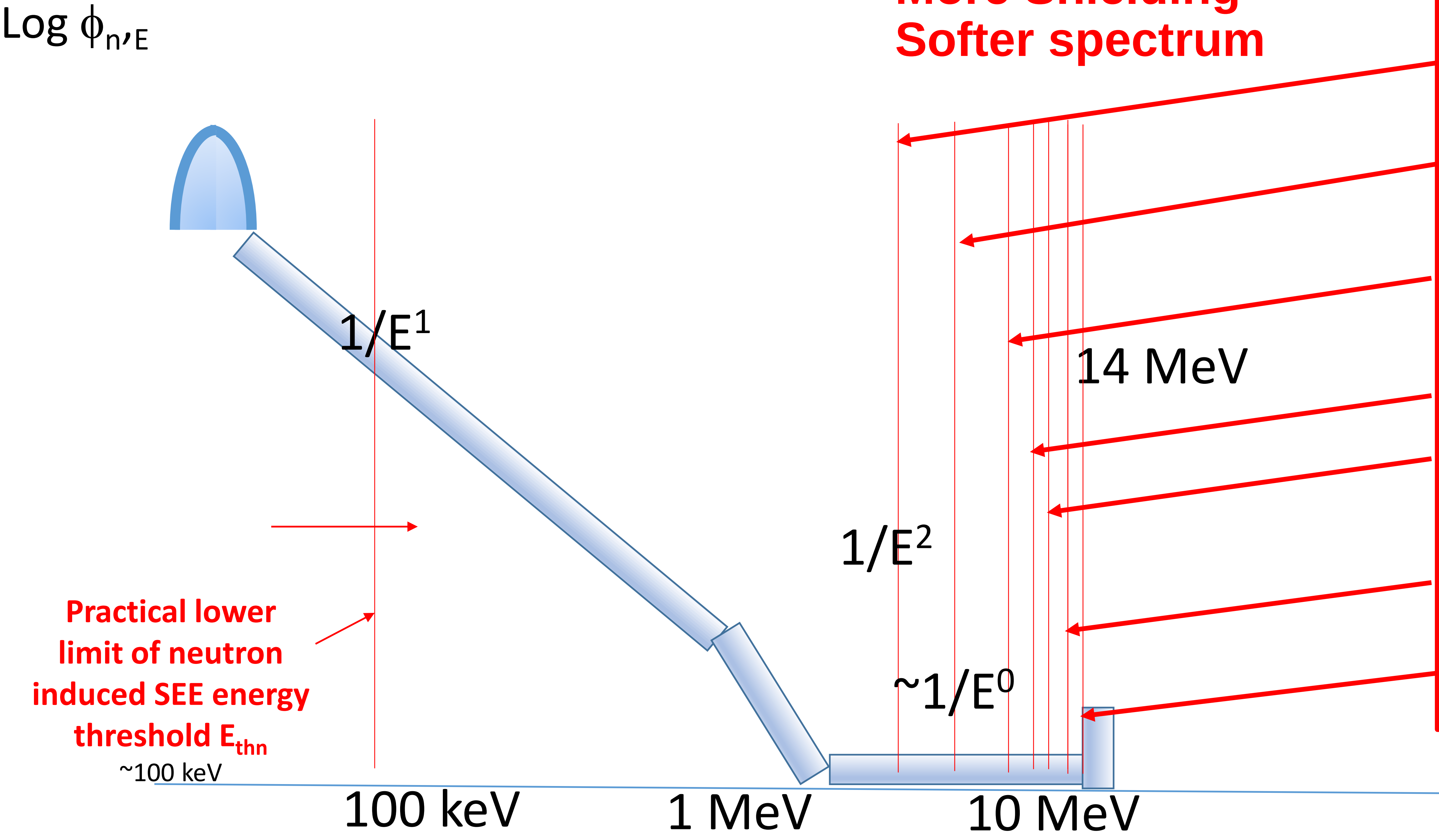
12.00 MeV
$^{27}\text{Al} + n + p$

12.58 MeV
$^{26}\text{Mg} + {}^{3}\text{He}$

12.99 MeV
$^{21}\text{Ne} + 2\alpha$

Practical lower limit of neutron induced SEE energy threshold E_{thn}

More Shielding
Softer spectrum



Practical lower limit of neutron induced SEE energy threshold E_{thn}

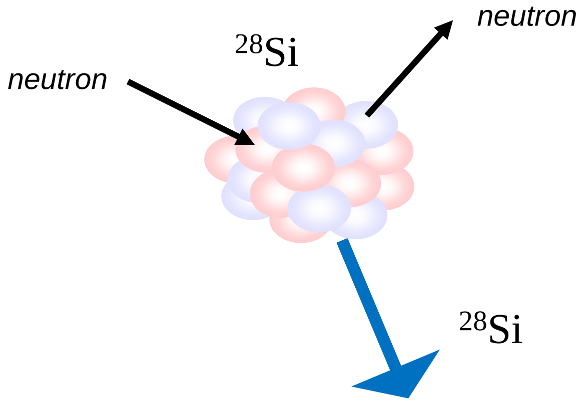
~100 keV

Effects (in silicon)

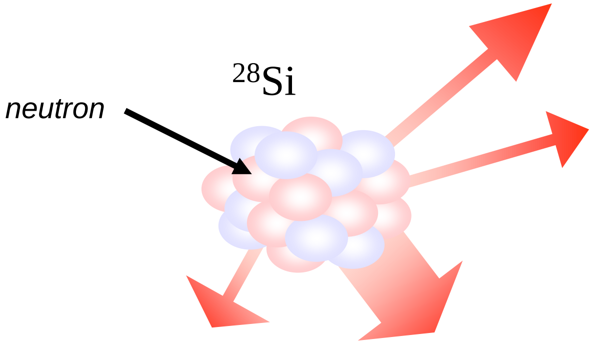
- 2.75 MeV $^{25}Mg + \alpha$
- 4.00 MeV $^{28}Al + p$
- 9.70 MeV $^{27}Al + d$
- 10.34 MeV $^{24}Mg + n + \alpha$
- 12.00 MeV $^{27}Al + n + p$
- 12.58 MeV $^{26}Mg + {}^{3}He$
- 12.99 MeV $^{21}Ne + 2\alpha$

Back to the nuclear interaction: One neutron in silicon

- Neutron scattering, silicon recoil



- Exothermic nuclear silicon break-up



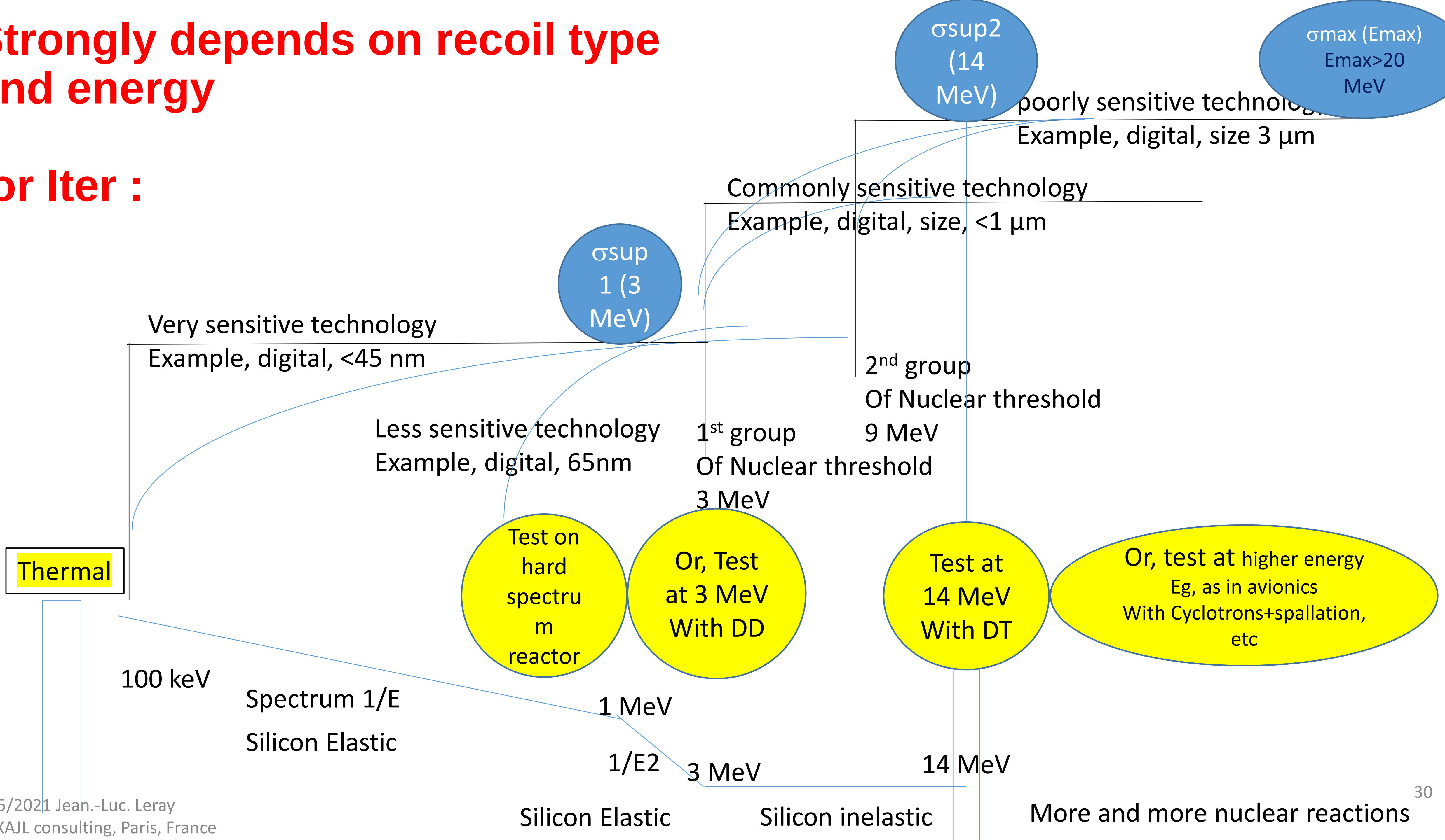
- No threshold
- Cross section

By-products (recoils)	n energy thresholds	cross section
^{25}Mg + α	2.75 MeV	
^{28}Al + p	4.00 MeV	
^{27}Al + d	9.70 MeV	
^{24}Mg + n + α	10.34 MeV	
^{27}Al + n + p	12.00 MeV	
^{26}Mg + ^{3}He	12.58 MeV	
^{21}Ne + 2α	12.99 MeV	

Reaction table from F. Wrobel et al., IEEE Trans. Nucl. Phys., Vol. 47, No. 6, Dec. 2000

Strongly depends on recoil type and energy

for Iter :



σmax (Emax)
Emax>20
MeV

σsup2
(14
MeV)

poorly sensitive technolog
Example, digital, size 3 µm

Commonly sensitive technology
Example, digital, size, <1 µm

σsup
1 (3
MeV)

Very sensitive technology
Example, digital, <45 nm

2nd group
Of Nuclear threshold
9 MeV

Less sensitive technology
Example, digital, 65nm

1st group
Of Nuclear threshold
3 MeV

Thermal

Test on hard spectrum reactor

Or, Test at 3 MeV With DD

Test at 14 MeV With DT

Or, test at higher energy
Eg, as in avionics
With Cyclotrons+spallation,
etc

100 keV

Spectrum 1/E

Silicon Elastic

1 MeV

1/E2

3 MeV

14 MeV

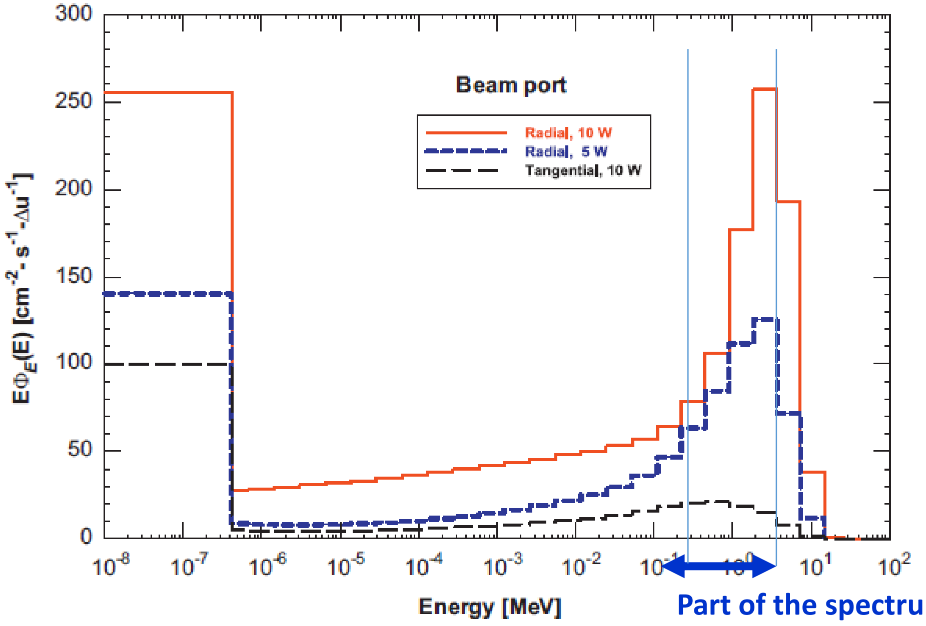
Silicon Elastic

Silicon inelastic

More and more nuclear reactions

Test at higher flux or larger beam for PCB

Example of a Triga fission reactor
(neutron 3 MeV-peaked latency spectrum)



Part of the spectrum
of interest
200 keV-3 MeV

Fig. 3. Beam ports neutron spectra.

H.R. Vega-Carrillo et al. / Applied Radiation and Isotopes 83 (2014) 252–255, Elsevier
National Institute of Nuclear Research in Mexico

Suited for

- **Bin B3a = 200 keV – 3 MeV**

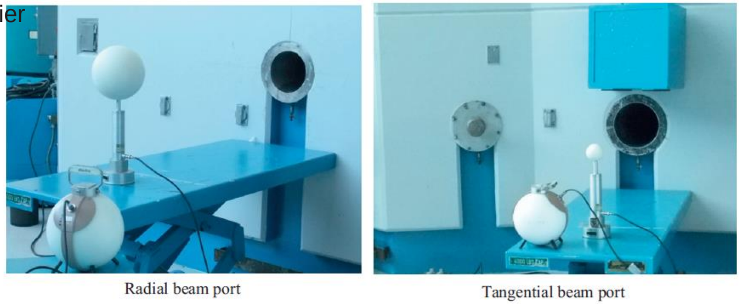
with filters to block below 1 keV (100 keV…?)

Optionally suited for

- ***Bin B1 = thermal if such a line exists at the same location : with classical thermalizer and filters and spectrum characterization + dosimetry***

Table 1
Integral features of neutrons at the TRIGA Mark III beam ports.

Beam port	ϕ [cm^{-2} s^{-1}]	E_{Av} [MeV]	$H(10)$ [μ Sv h^{-1}]
Radial, 5 W	1073 ± 63	0.6906	505 ± 30
Radial, 10 W	2085 ± 122	0.8166	934 ± 55
Tangential, 10 W	537 ± 31	0.1853	106 ± 6



Radial beam port

Tangential beam port

Fig. 1. TRIGA Mark III beam ports.

SEE TEST PROCEDURE
for the Iter-specific neutron radiation

ITER-CERN
RHE WORKSHOP
23/MAY/2018

SUMMARY on RADIATION (neutron)

- **Unmitigated**
  - The neutron flux is expected to a very high ceiling near the Vessel
  - Thanks to the cooling system and very efficient bioshield, the radiation levels are expected to decrease significantly as one moves further away.
- **Mitigation**
  - In some places the electronics can be forbidden.
  - However, for non-critical applications, the use of Commercial-Off-The-Shelf components and modules is foreseen.
  - Electronics is likely to be relocated outside as much as possible

- **TESTING TO NEUTRON MUST TAKE EXTREME CARE OF THE SPECTRUM : the one at the proper location and the one of the TEST MACHINE**
- **COMPLIANCE RULES MUST BE SET TO ALLOW COMPLIANCE OF THE TEST SPECTRUM WITH THE DESTINATION NEUTRON SPECTRUM**

Similarities and differences in TESTING between Avionics and Fusion

(Similarities: 1/E spectrum down to thermal energy)

avionics

- Apparent Neutron source is at « some GeV »
- Testing
- **JEDEC/JESD89 standard is the reference for testing devices**
- High Energy Test is recommended between 10 MeV and 1 GeV
- The opinion of JESD89 members (IEEE/NSREC Conference 2018) is that the component of Single Event Rate below 10 MeV is of minor interest
  - Because there are few neutrons compared to neutrons above 10 MeV)
- Test at high energy
  - Either using a naturel spectrum on mountains
  - Or a spallation spectrum (cyclotrons), and/or p+ at higher energy
  - Or a synthetic formula of 4 monoenergetic tests between 10 and 100 MeV and 14 MeV n

fusion

- Neutron source energy is at 14.1 MeV or 2,45 MeV
- Testing
  - Specific method between 14 MeV down the thermal energy
  - With suitable sources
  - But such sources are not easily adjustable in energy

Thank you for your attention

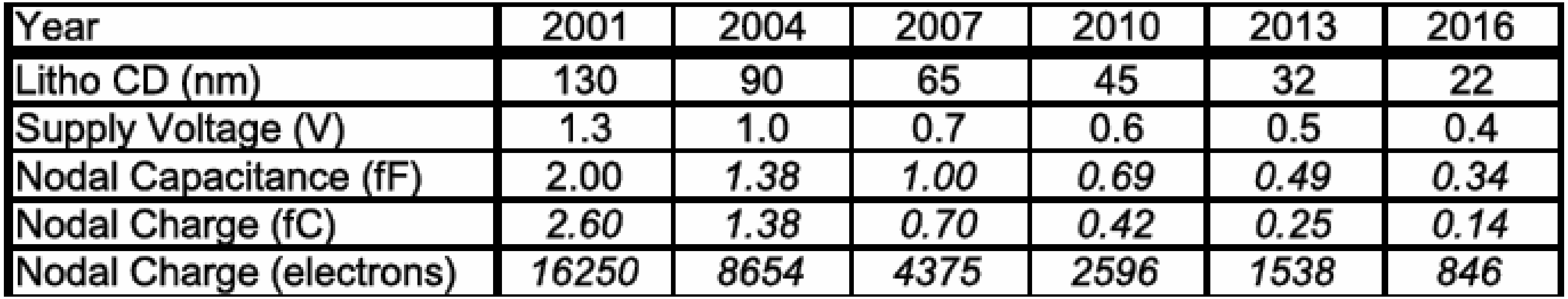
We have
- Described spectrum-specific issues in fusion
- Compared with the Atmospheric neutron case (avionics)
- Proposed testing method bases on three neutron energy lines , thermal, 3 MeV, 14 MeV
- Provided caveats for other neutron sources use and method for estimating the SER boundaries

Remarks?

Suggestions?

Jl.leray@anaxagoras2k.fr

BACK-UP SLIDES



Year	2001	2004	2007	2010	2013	2016
Litho CD (nm)	130	90	65	45	32	22
Supply Voltage (V)	1.3	1.0	0.7	0.6	0.5	0.4
Nodal Capacitance (fF)	2.00	*1.38*	*1.00*	*0.69*	*0.49*	*0.34*
Nodal Charge (fC)	*2.60*	*1.38*	*0.70*	*0.42*	*0.25*	*0.14*
Nodal Charge (electrons)	*16250*	*8654*	*4375*	*2596*	*1538*	*846*

Lawson citeria for the onset of fusion

In 1955, John D.Lawson (4 April 1923-15 January 2008) demonstrated that the conditions for fusion reactions relied on three vital quantities: temperature (T), density (n) and confinement time (τ).

rate of fusion energy produced by the plasma - loss

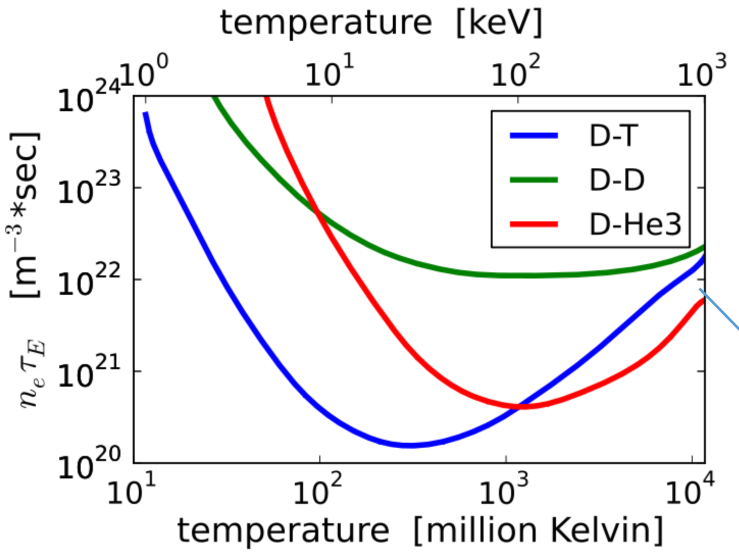
- Fusion rate = Number density of fuel A × Number density of fuel B × Cross section(Temperature) × Energy per reaction
- **Net power = Efficiency × (Fusion − Radiation loss − Conduction loss)**

- The Lawson criterion requires that fusion heating exceeds the losses
  figure of merit used by today's fusion scientists, the triple product, to get an energy gain >1.

$n\ \tau = f(T)\ \approx \geq 10^{20}\ m^3 s$

(n density, τ lifetime, temperature)

τ is linked to the nuclear fusion cross section and to the temperature



For D-T, the minimum of the product occurs near 200 10^6 K (20 keV)
Minimum minimorum is 30 million degrees (2.6 keV)

Inertial
n > 200 gram/cm3
τ < 0.1 nanosecond

https://en.wikipedia.org/wiki/Lawson_criterion

Magnetic
n 1 gram/dm3 (1 bar and > 1 Tesla)
τ > 1 second … 1000 second ?