8th EIROforum school on instrumentation

Radiation Damages session

ESO/EUROfusion Garching, 13-17 May 2024

Electronics reliability in the nuclear fusion radiation environment of tokamaks

14/05/2024

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Outline

1. Background : nuclear fusion with D-T tokamaks
2. Electronics exposed to radiation in tokamaks
3. Radiation in tokamaks
4. Neutron interactions with material of semiconductor components
5. Radiation effects on electronics in tokamaks
6. How to ensure electronics reliability in tokamaks radiation environment
7. Validation of SER prediction method & models under DD and DT plasma neutrons

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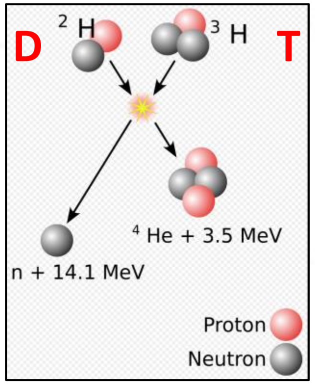
1 – Background : nuclear fusion with D-T tokamaks

1.1 – Deuterium-tritium (D-T) reaction

D-T is the easiest fusion reaction to perform (T ≈ 100 million K "only")

Fusion reaction is intrinsically safe (no divergence). No greenhouse gases. No fission products. No risk of proliferation.

1.1.1 – Energy release



D + T → He + n **$\Delta E = \Delta mc^2$**

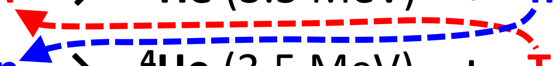
1000g → 996.25g + 94×10^3 MWh ≈ energy for 6000 houses for 1 year (1 house ≈ 16 MWh / year)

15 g D+T = energy for 1 house for 1 human life

1 g D+T = 8 tons of oil

1.1.2 – Fuel and ashes

Because $T_{1/2}$ = 12.3 y, there is no natural resource of tritium => tritium must be produced.



D + T → ^{4}He (3.5 MeV) + n (14.1 MeV) ← Fusion reaction in plasma

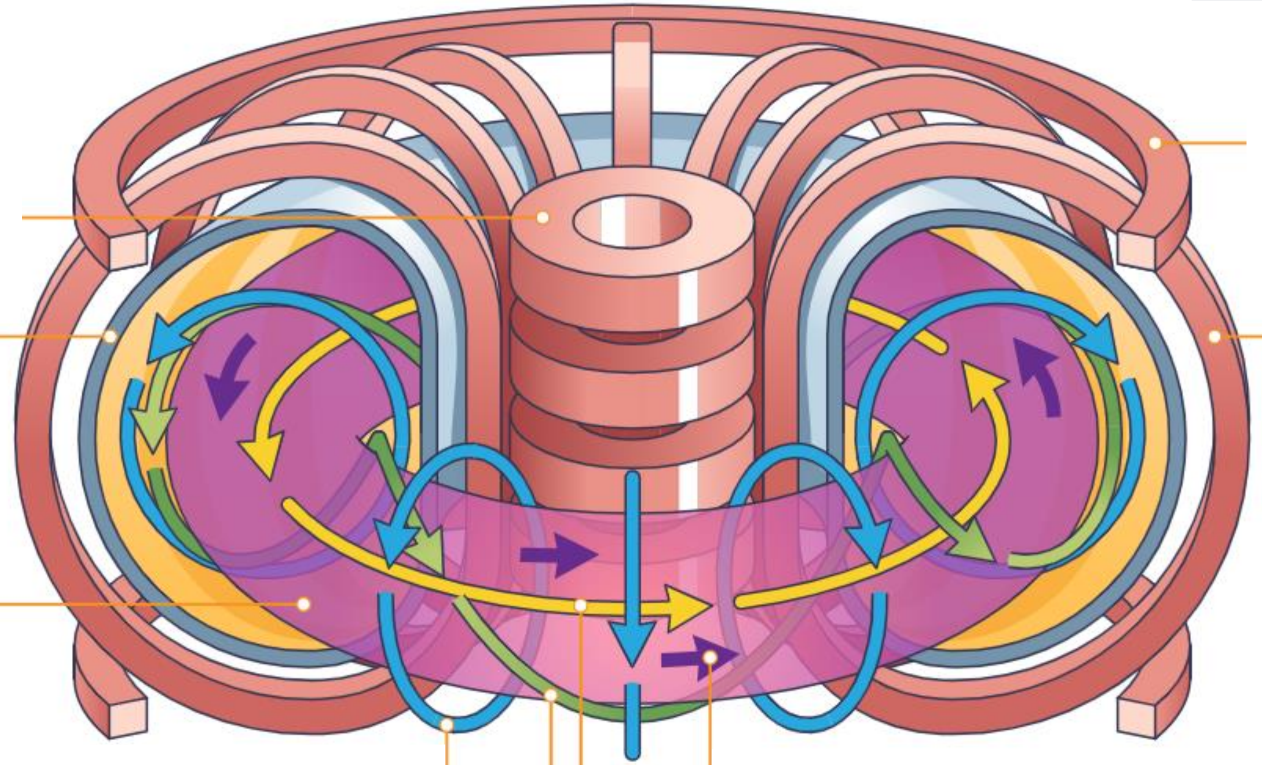
^{6}Li + n → ^{4}He (3.5 MeV) + T ($T_{1/2}$ = 12.3 y) ← Tritium will be produced in breeding blankets in the tokamak

D + ^{6}Li → 2 ^{4}He ← Global reaction

Actual fuel : D (33 g/m^3 sea water => billion years) **and ^{6}Li** (0.17 g/m3 sea water => million years). **Ashes : ^{4}He**

[Figure: Main principles - Nuclear fusion - Energy Encyclopedia Source: ©VectorMine / stock.adobe.com]

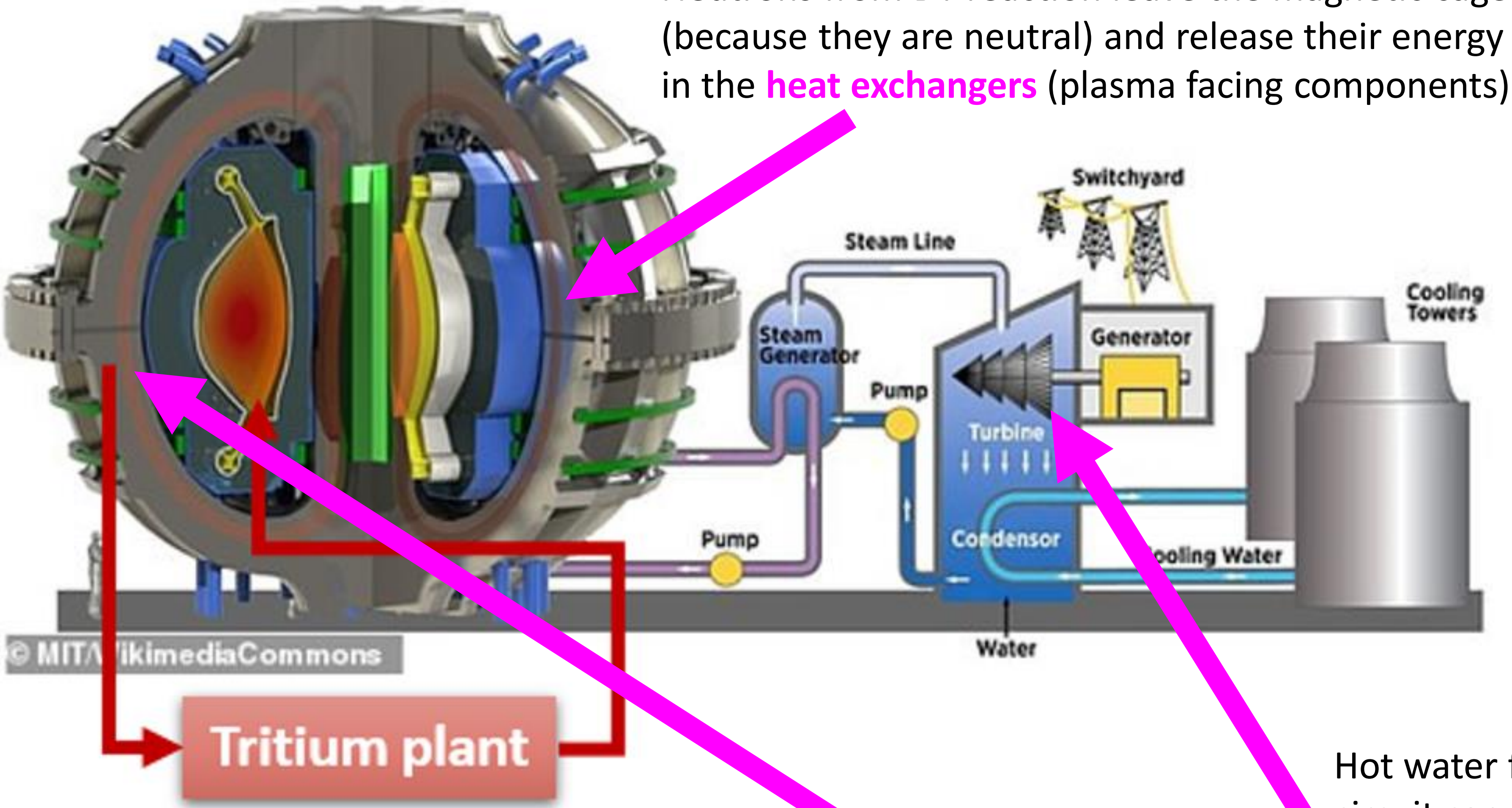
1.2 – Plasma confinement and heating



- Poloidal + toroidal **magnetic field coils** => helical magnetic field on which ions are trapped => **magnetic cage**.
- **Plasma current** is needed for stability
  - ➢ Obtained by **transformer** (primary = poloidal coils, secondary = plasma) => **pulsed mode**
  - ➢ Also obtained by **radiofrequency current drive**. Could be also obtained by "**bootstrap**".
- **Heating: ohmic** (plasma current), then micro-waves and **injection of accelerated ions** (neutralized before entering the plasma)

1.3 – Electricity production by D-T tokamaks

Neutrons from DT reaction leave the magnetic cage which confines the plasma (because they are neutral) and release their energy (4/5 of the energy of the reaction) in the **heat exchangers** (plasma facing components) of the primary cooling circuit.

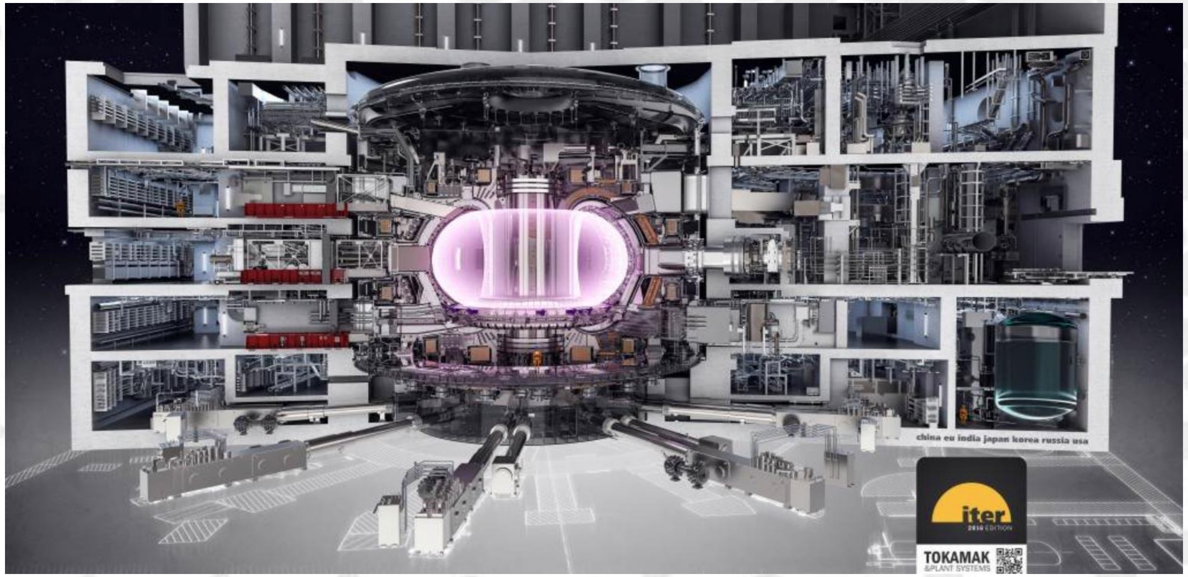


Hot water from the secondary cooling circuit can produce steam to operate **turbines** coupled with alternators to produce electricity.

Neutrons leaving the magnetic cage will hit **breeding blankets** (plasma facing components) to produce Tritium ($^6Li + n \rightarrow {}^4He + T$).

1.4 – ITER

ITER site, September 2023. ©ITER



ITER Tokamak and Plant Systems, 2016. ©ITER

Members: China, the European Union (through Euratom), India, Japan, Korea, Russia and the United States.

Main goals:

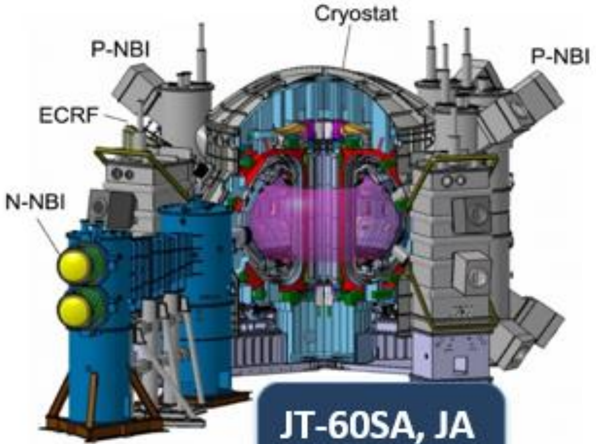
- **DT plasma** with fusion mostly sustained by **internal fusion heating**.
- **500 MW fusion power** in long plasma pulses with **Q=10**
  (ten-fold return on power by the plasma: 500 MW of fusion power from 50 MW of input heating power)
- Contribute to the demonstration of the **integrated operation of technologies** for a fusion power plant.
- Test **tritium breeding**.
- Demonstrate the **safety characteristics** of a fusion device.

More information: ITER - the way to new energy

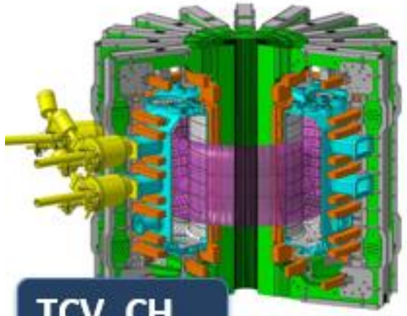
1.5 – Currently operated and future tokamaks in EU or with EU participation

JET, UK

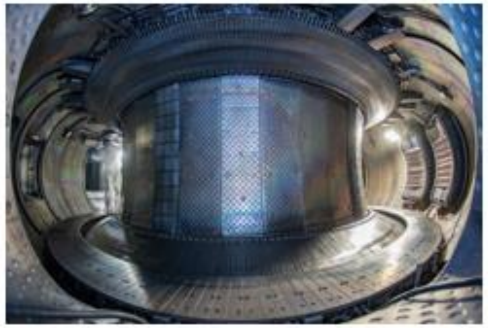
ASDEX Upgrade, Munich, DE



JT-60SA, JA (Start in 2023)

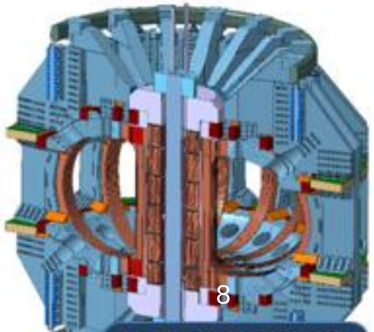


TCV, CH



WEST, FR

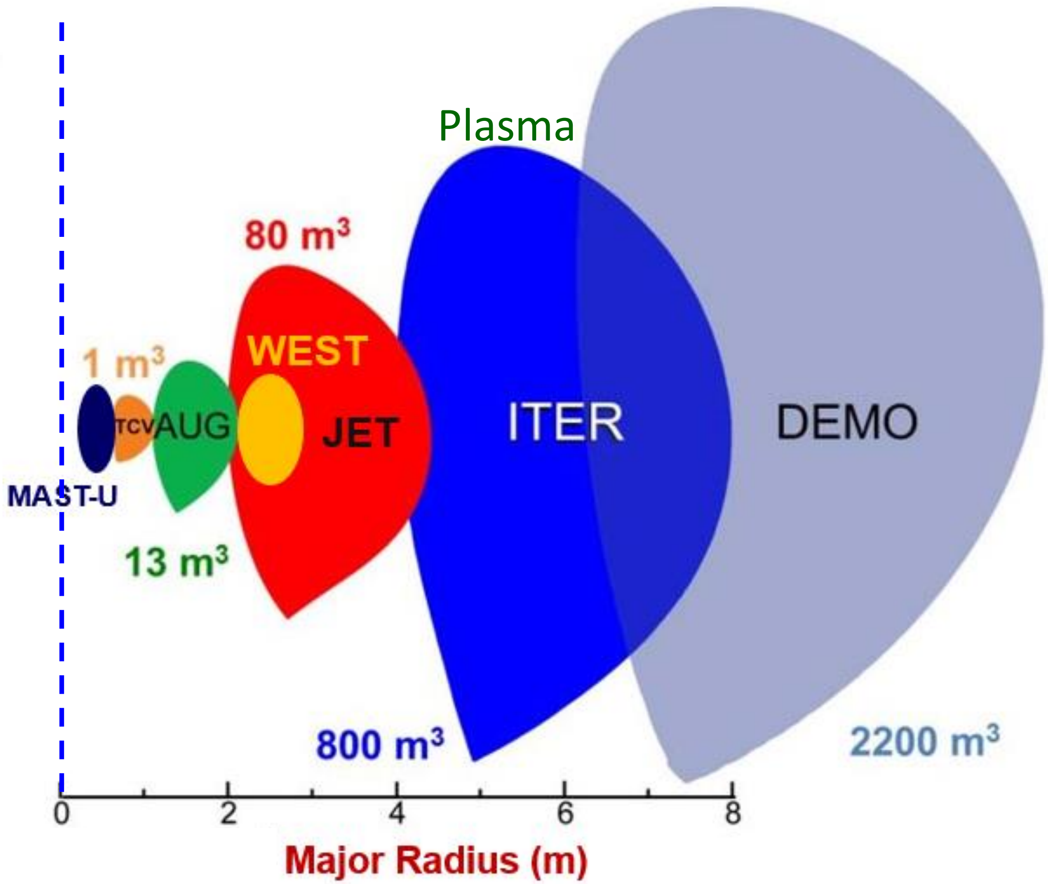
MAST Upgrade, UK

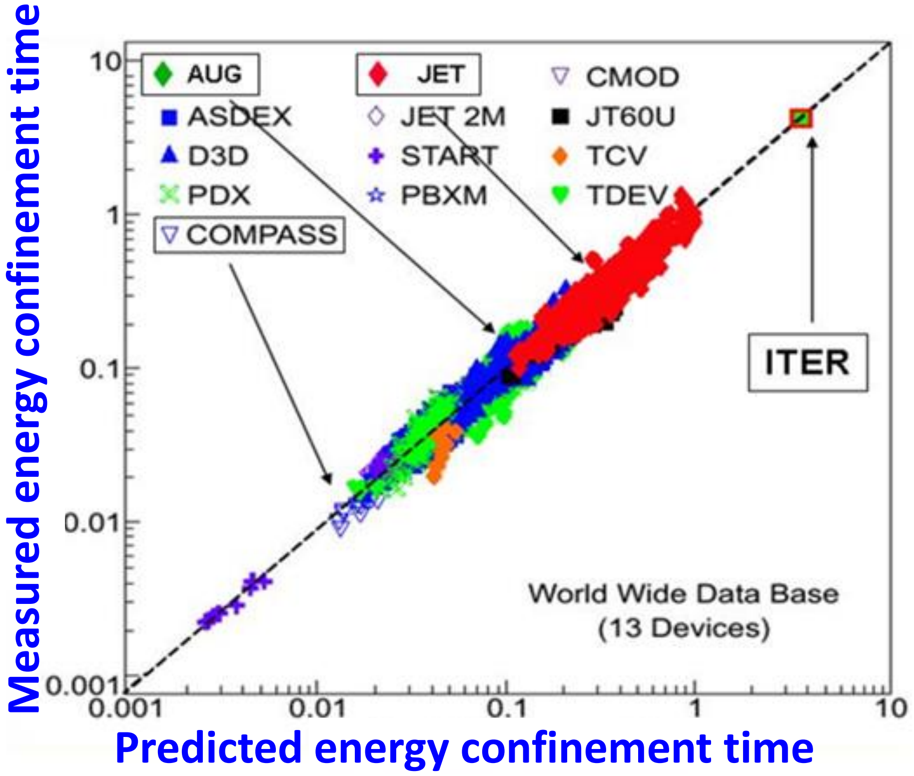


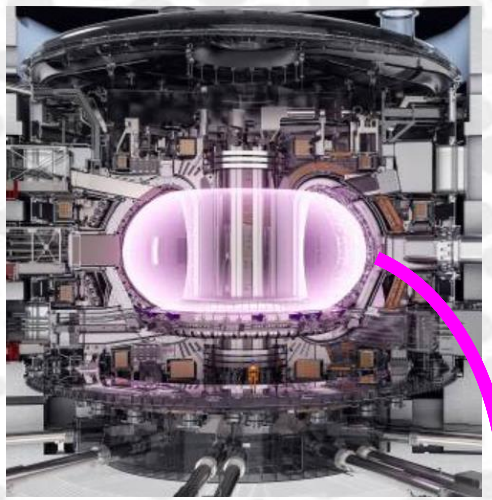
COMPASS-U (Start in 2023)

DTT (Start in 2027)

1.6 – Very different sizes and shapes







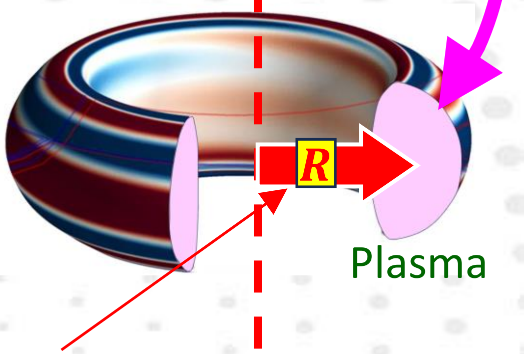
$$\tau_E \propto I_p^2 \; P^{-2/3} \; R^2$$

Energy confinement time

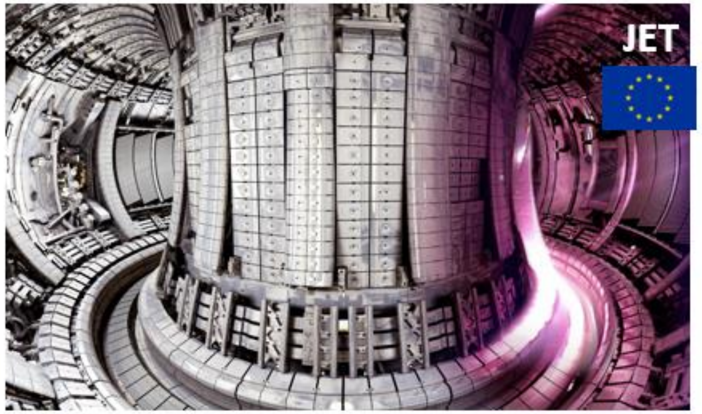
Plasma current

Power

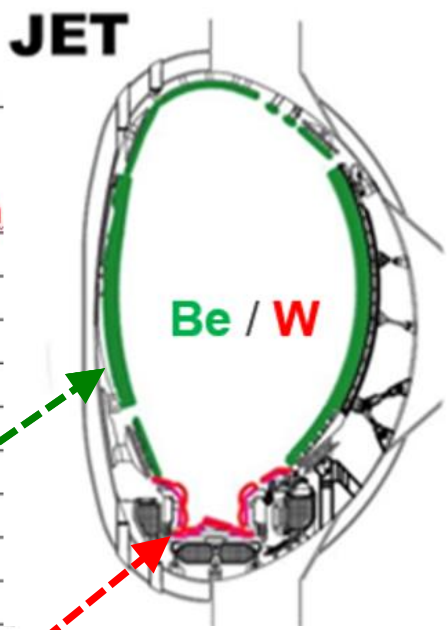
Major radius



1.7 – JET, the tokamak designed to study fusion power



Material of the first wall	Divertor: Solid tungsten and coated tungsten Chamber wall in Berylium
Maximum magnetic field	3.45 T up to 3.9 T
Minor / major radius	0.9m / 2.96m
Volume	80m3
Plasma current	1.0MA - 4.0 MA
Pulse duration	< 10-40 s
Plasma additional heating:	up to ~40 MW
Neutral beam injection	32 MW
Ion-Cyclotron heating	5 MW (25 - 55 MHz)
Specificity	DT operation



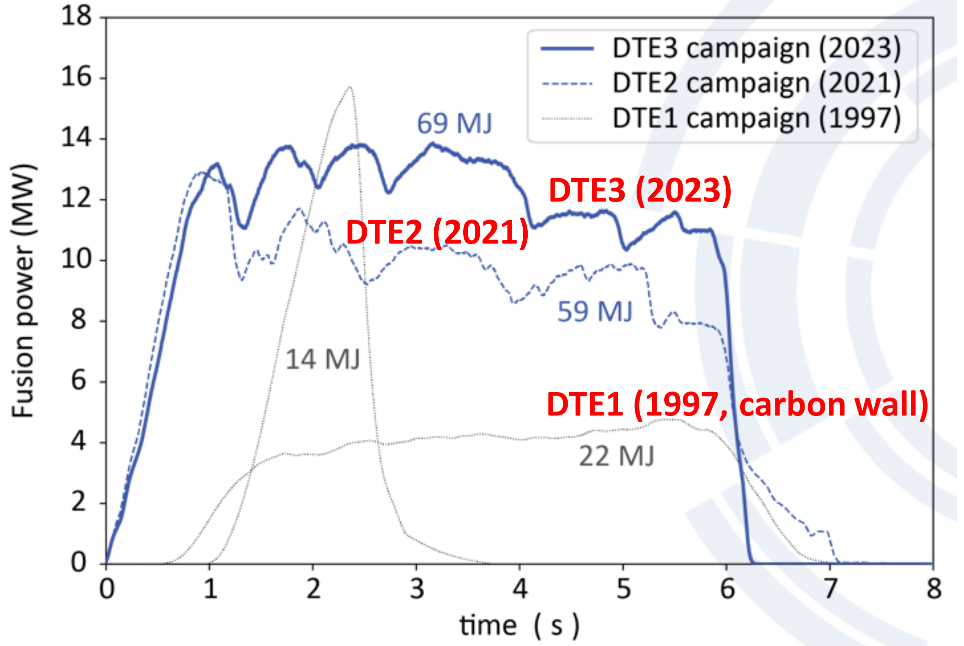
- JET is the largest active tokamak closest to ITER in performance
- Beryllium(*) internal wall and tungsten divertor
- The only tokamak that can carry out DT experiments

(*) *no longer used in ITER*

World records for fusion power:

DTE3 Record Pulse #104522 Tuesday 03/10/2023

- 2.5MA/3.9T
- Ptot = 29.7 MW NBI + 5.5MW RF = 35.2 MW
- Pfus = 13-13.5MW
- Q=0.37-0.38
- Fusion Energy 69.3MJ
- Neutron max 4.9 10^{18} n/s

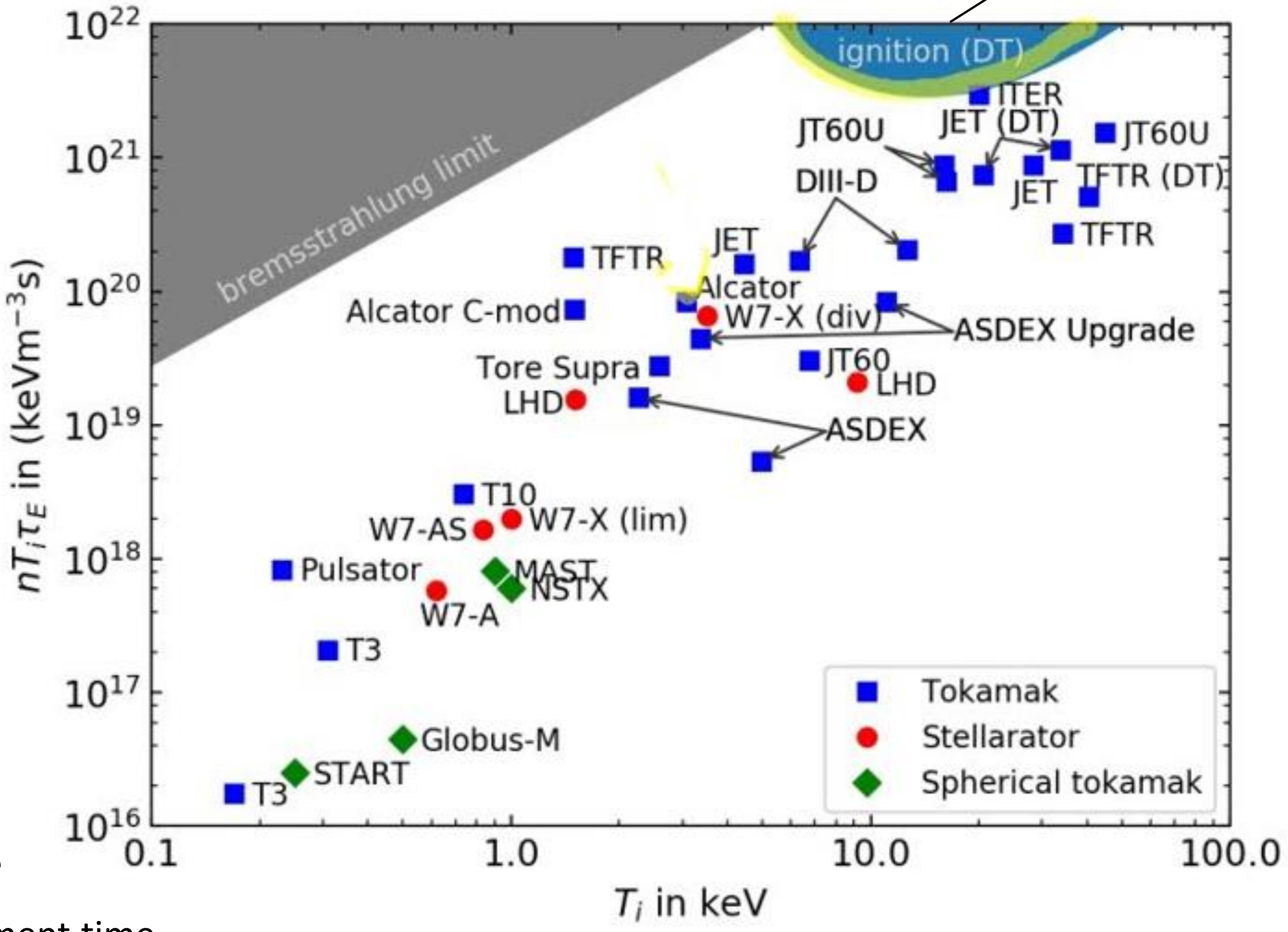


1.8 – Other tokamaks in the world

[Fusion World (remdelaportemathurin.github.io)](remdelaportemathurin.github.io)

Ignition condition (Lawson criteria):
n $T_i \tau_E$ > 10^{21} keV m^{-3} s

1.9 – All these machine pave the way to ITER !



Triple product

n = ion density

T_i = ion temperature

τ_E = energy confinement time

Bremsstrahlung : plasma energy losses, caused by collision of energetic electrons with nuclei, producing X-rays.

1 keV = 11.6 million K

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2 – Electronics in tokamaks

2.1 - Which electronics?

- **Analogue and digital electronics**
  - Control of auxiliary systems

    Vacuum, heating, cooling, magnets, fueling, …
  - Control and readout of diagnostics

    Magnets, neutrons, optical viewing, bolometry, spectroscopy, microwaves, plasma operation, …

2.2 - Integration

- **Embedded in systems**

  Large quantity and diversity

- **Housed in cabinets**

  Several hundreds of cabinets,

  Large quantity and diversity of electronic systems.

  Almost all COTS (Commercial Off The Shelf)

  Several hundreds of Gbits SRAM

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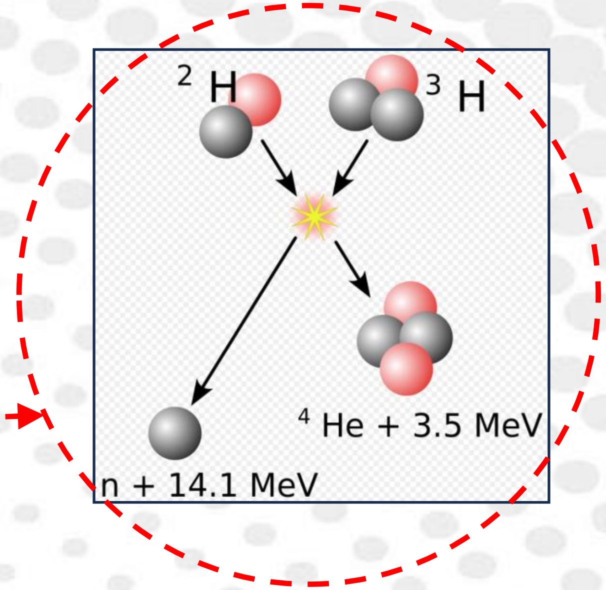
3 – Radiation in tokamaks

3.1 - Main radiation sources during DT plasma operation:

3.1.1 - Plasma neutrons

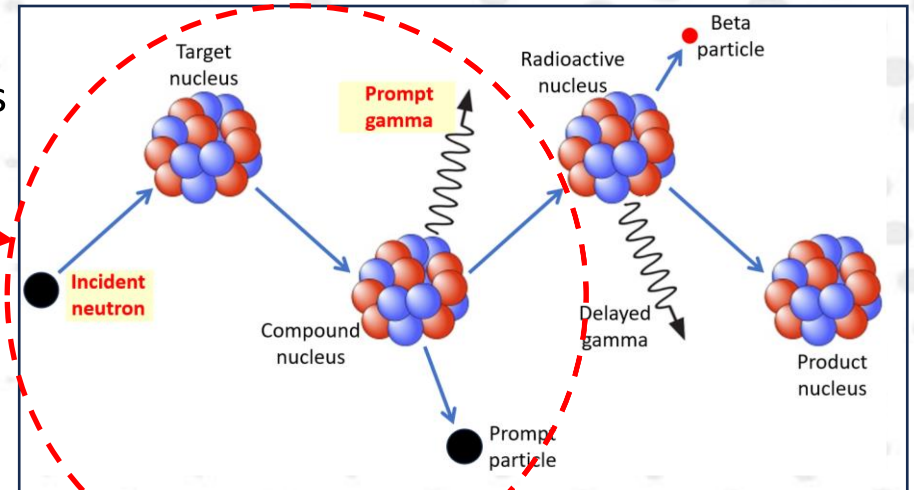
DT nuclear reactions in the plasma produce **14.1 MeV neutrons**

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



3.1.2 - Prompt gammas generated by plasma neutrons

The **de-excitations of excited nuclei** following nuclear interactions between a plasma neutron and the nuclei of an atom of the tokamak structure, generate **prompt gamma**.



Picture adapted from [NAA Technical Overview, https://archaeometry.missouri.edu/naa_technical.html]

3 – Radiation in tokamaks

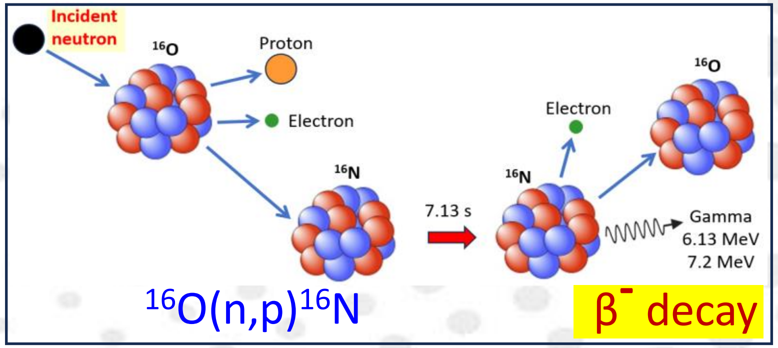
3.1 - Main radiation sources during DT plasma operation:

3.1.3 - Neutrons and photons generated by activated water

High energy neutrons from DT plasma fusion reaction **interact with oxygen isotopes ^{16}O and ^{17}O** from tokamak cooling water, which **creates short live isotopes ^{16}N and ^{17}N**, which then undergoes **beta decay** producing **gammas** and **neutrons**.

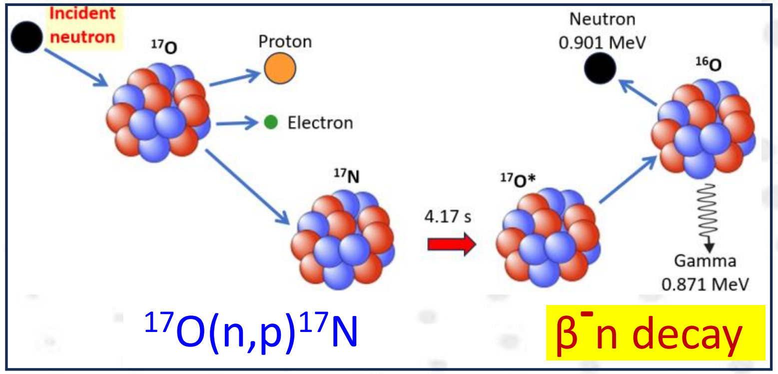
- **^{16}O + n** (12.2 MeV threshold) → **p + ^{16}N**

  β^- decay: **^{16}N** ($T_{1/2}$ = 7.13 s) → **^{16}N + γ** (69% @ 6.13 MeV, 5% @ 7.12 MeV)



- **^{17}O + n** (8.4 MeV threshold) → **p + ^{17}N**

  β^-n decay: **^{17}N** ($T_{1/2}$ = 4.17 s) → **$^{17}O^*$** → **^{16}O + n** (0.901 MeV) **+ γ** (0.871 MeV)



^{16}N and ^{17}N decay times are sufficiently long for water to travel far enough from the activation source (plasma) to cause the presence of activated water all along the cooling water pipework.

3 – Radiation in tokamaks

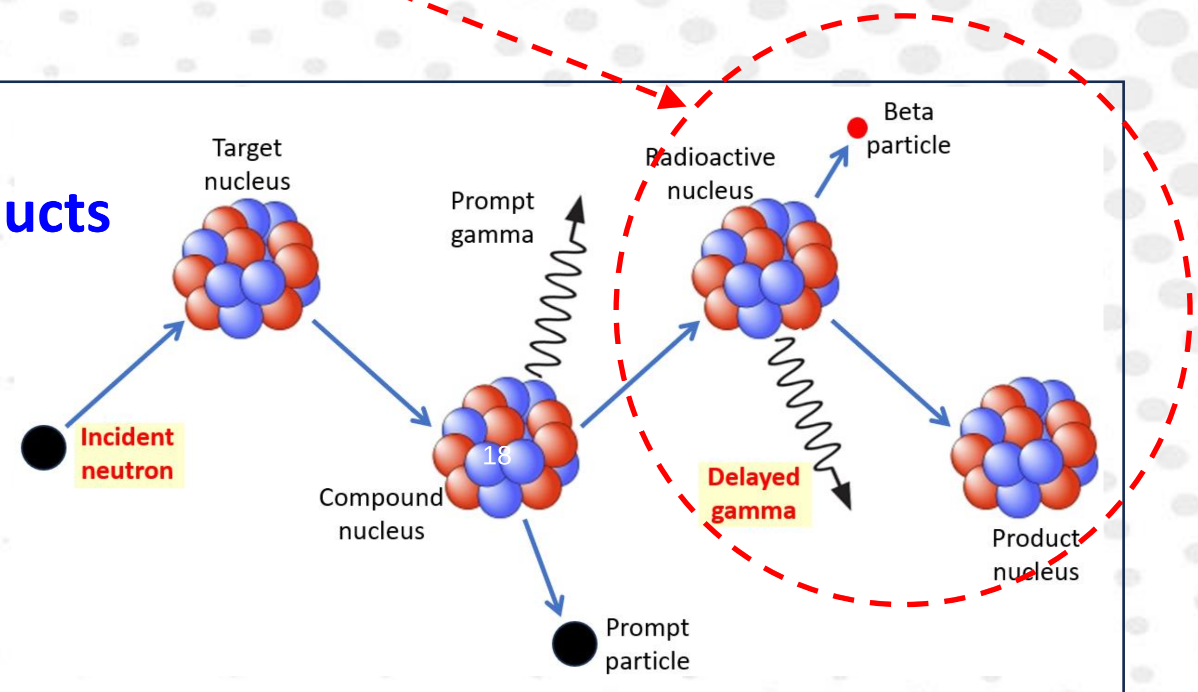
3.2 - Main radiation sources *during maintenance and shutdowns* following DT plasma operation:

3.2.1 - γ emitted by activated materials

- Gammas from **cooling water pipework** activated by neutrons from activated water.
- Gammas from **tokamak structural elements** (vacuum vessel and its content, cryostat, …) activated by plasma neutrons.

3.2.2 - γ emitted by activated corrosion products

- At specific location in cooling water system (e.g. in filters, …).



Picture adapted from [NAA Technical Overview, https://archaeometry.missouri.edu/naa_technical.html]

3 – Radiation environment in tokamaks

3.3 - Radiation environment impacting electronics reliability:

- Total Ionizing Dose (**TID**)
  Accumulated dose causes **accumulated degradation**
  due to **accumulated charges trapping** in oxides and at oxide-semiconductor interface.

- 1 MeV Equivalent Neutron Fluence (**ENF**)
  Accumulated fluence causes **accumulated degradation**
  due to **accumulated displacement damages** in the semiconductor lattice.

- Total Neutron Flux (**TNF**) with its specific energy spectrum
  An **individual neutron** causes an **instantaneous single event effect (SEE)**
  due to **instantaneous charges deposition** in sensitive nodes of semiconductor devices.

3.4 - Calculation of the radiation environment in a tokamak building

- 3D digital Monte-Carlo simulation using tools such as Geant4, MCNP, etc.
- These simulations take into account :
  - the radiation sources (plasma, activated water, …),
  - the status of the tokamak (DD or DT plasma operation, shutdown/maintenance),
  - the shielding provided by the building structure.

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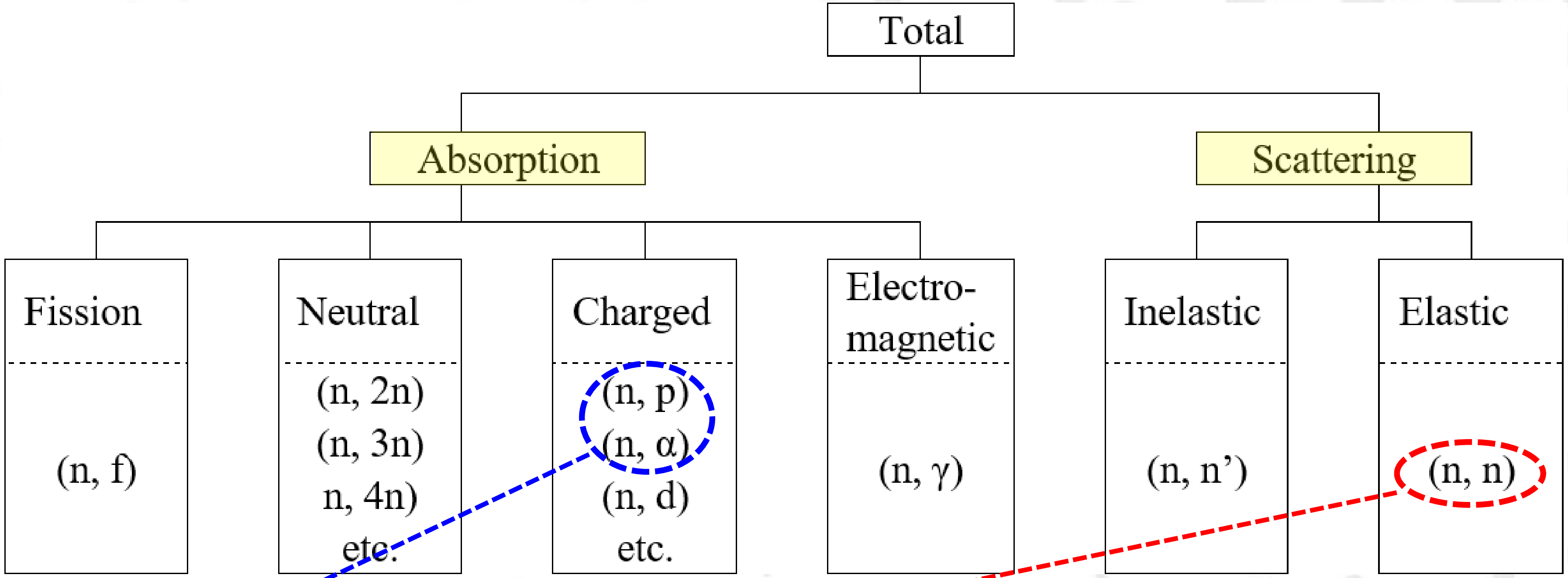
4 – Neutron interactions with atoms of semiconductor components

4.1 - Mechanisms of interaction of incident neutrons with the atoms of the electronic component



Notation, examples:

- ^{28}Si(n,p)^{27}Al represents the charged absorption reaction n + ^{28}Si → p + ^{27}Al
- ^{10}B(n,α)^{7}Li represents the charged absorption reaction n_{th} + ^{10}B → ^{4}He (1.47 MeV) + ^{7}Li (0.84 MeV) + γ(0.48 MeV)
- ^{28}Si(n,n)^{28}Si represents the elastic scattering reaction n + ^{28}Si → n + ^{28}Si

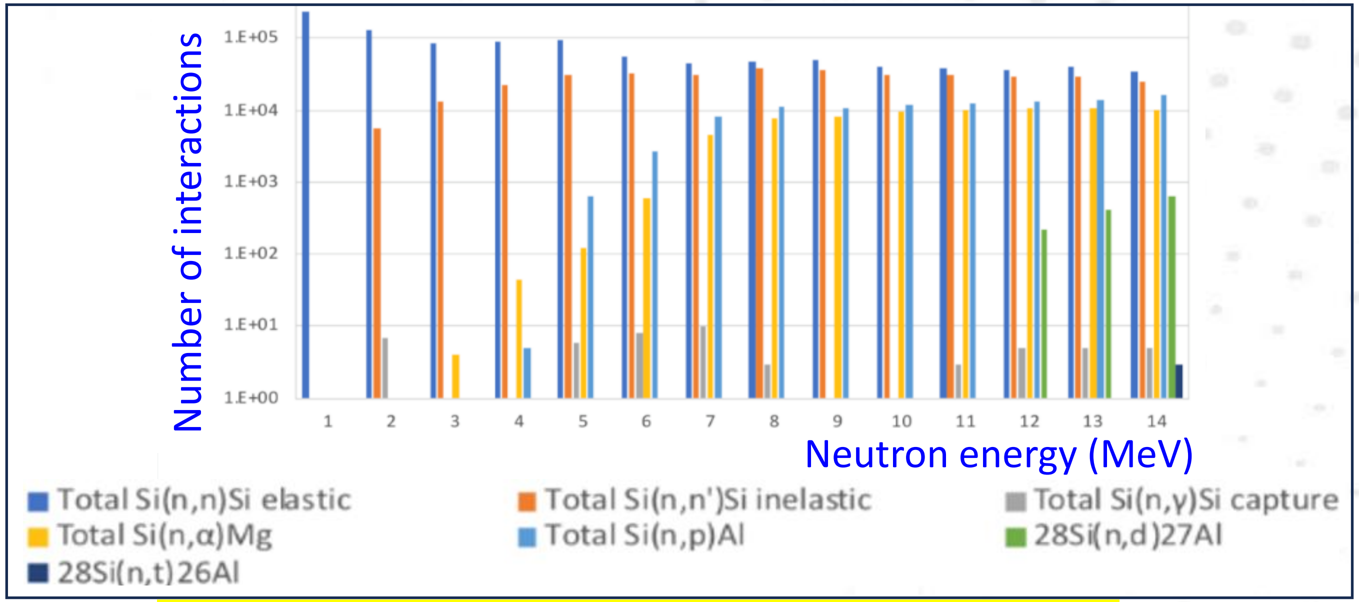
Figure: J.L. Autran, D. Munteanu, "Soft Errors, from Particles to Circuits", CRC Press
Adapted from Rinard P. Neutron interations with matter. Los Alamos Technical Report. Available at: http://www.fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00326407.pdf)

4 – Neutron interactions with atoms of semiconductor components

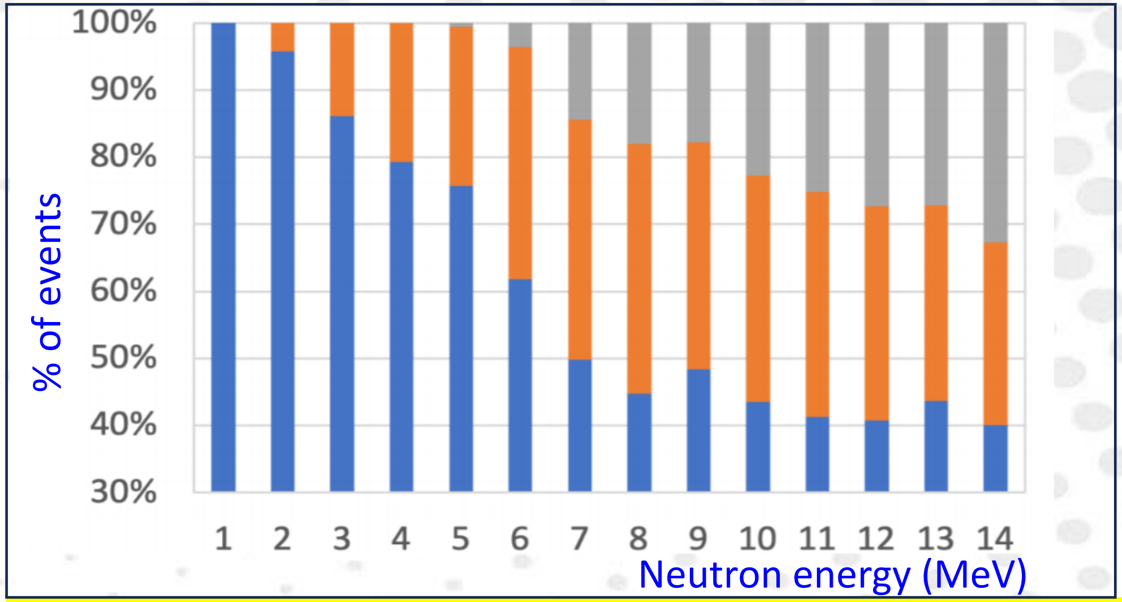
4.2 –Interaction of an incident neutron with an atom of a semiconductor device

There are many possible interactions. The probability of a given interaction depends on:

- The neutron flux and energy (or energy spectrum)
- The composition of the semiconductor device (3D density of constituting atoms)



Example: Number of events caused by 5 x 10^8 n interacting with 1cm^2 x 20 µm Si



For the same example: % of elastic (scattering), inelastic (scattering) and non-elastic (absorption) events

- Below $\sim 5\ MeV$, only elastic scattering and inelastic scattering => only target nuclei recoil.
- Above $\sim 5\ MeV$, non-elastic absorption also occur (producing secondary fragments) => the % of elastic + inelastic decreases.
- At 14 MeV, ~70 % of elastic + inelastic (only target nuclei recoil), and ~30% non-elastic absorption (secondary fragments).

Pictures: Courtesy J.L.Autran, Rennes University / Institut de Physique de Rennes

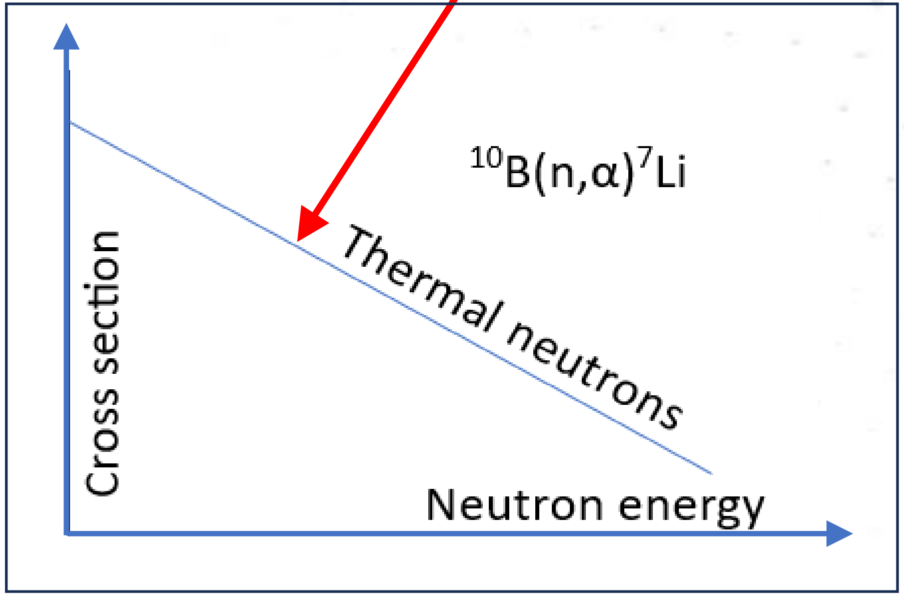
4 – Neutron interactions with atoms of semiconductor components

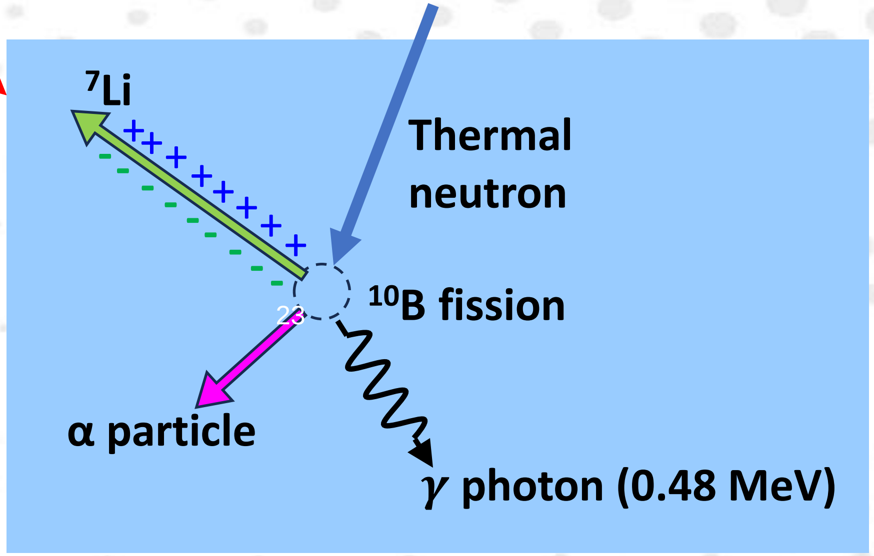
4.3 - Interaction of incident neutrons with ^{10}B

- In integrated circuits, the interconnections are frequently separated by an insulator made of **borophosilicate glass** (**BPSG**) whose natural boron contains 20% ^{10}B.

- Natural boron with 20% ^{10}B is also present in other places in integrated circuits, e.g. in tungsten plugs.

- The collision cross section of thermal neutrons with ^{10}B decreases with energy as $\mathbf{1/\sqrt{E}}$.

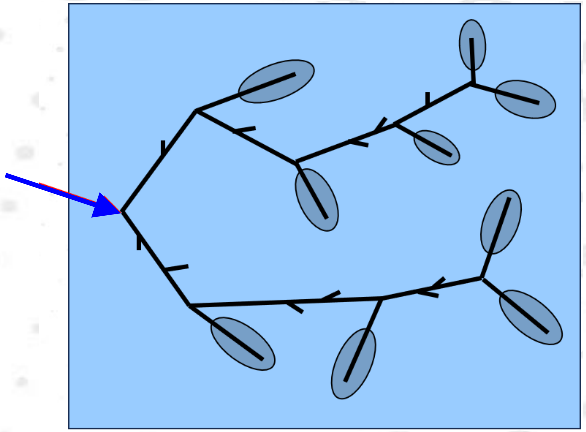




4 – Neutron interactions with atoms of semiconductor components

4.4 – Energy deposition of a recoil particle resulting from neutron-atom interaction

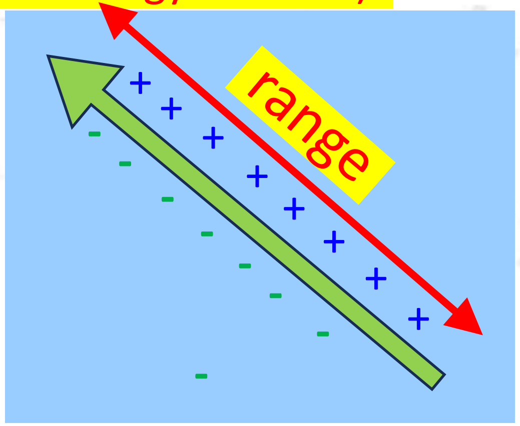
- **Nuclear stopping power** = loss of energy due to **collisions** of recoil atom **with nuclei** of the target material => Cascade of collisions => shower of recoil particles, until their final stop.



- **Electronic stopping power** = loss of energy due to **interactions** of recoil atom **with electrons** of atoms of target material => Ionization => high electron-hole pairs density along the track.

  The electronic stopping power is also called **LET** (Linear Energy Transfer).

$$\text{Weighted LET} = -\frac{1}{\rho}\frac{\Delta E}{\Delta x} \quad (\text{MeV.cm}^2/\text{mg})$$

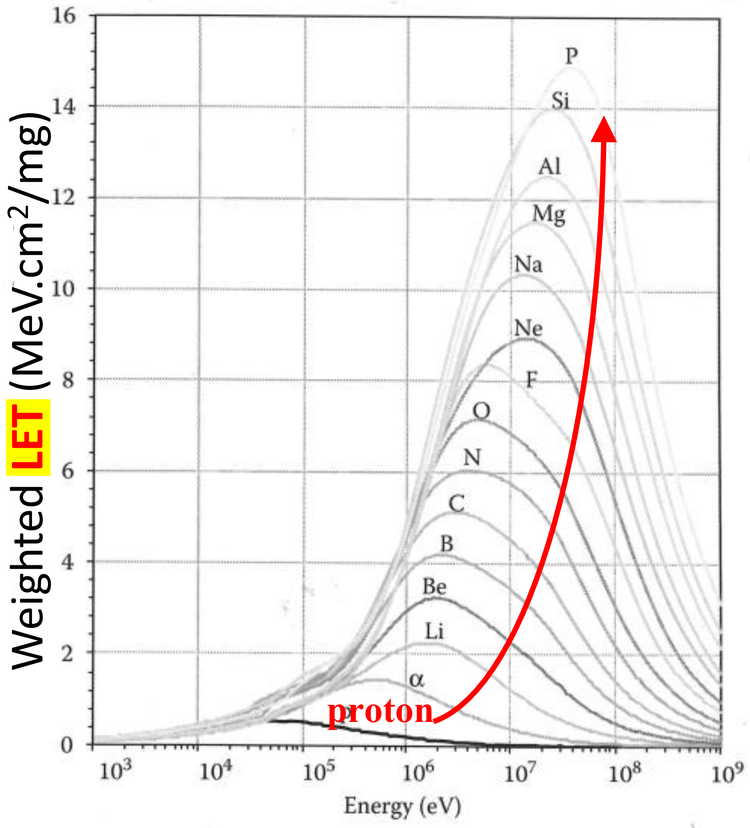


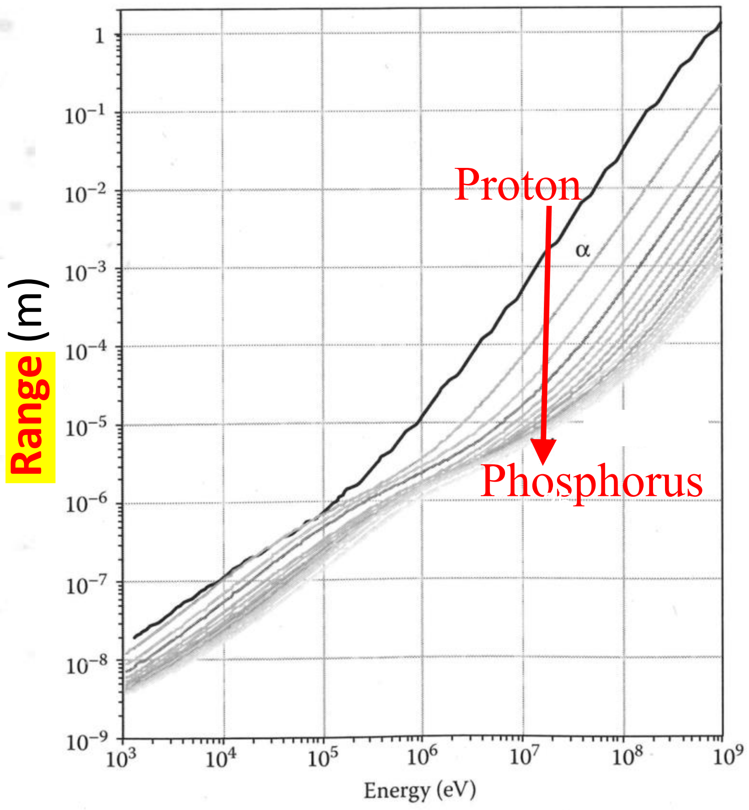
4 – Neutron interactions with atoms of semiconductor components

4.4 – Energy deposition of a recoil particle resulting from neutron-atom interaction

The key parameters that control **single event effects** in semiconductor devices are the **LET** and the **range** of the recoil particle, which depend on the recoil particle and on its energy.

The nature and the energy of the recoil particle depend on the neutron interaction mechanism, which **depend on the target material and on the energy of the incident neutron**.





Figures: J.L. Autran, D. Munteanu, "Soft Errors, from Particles to Circuits", CRC Press

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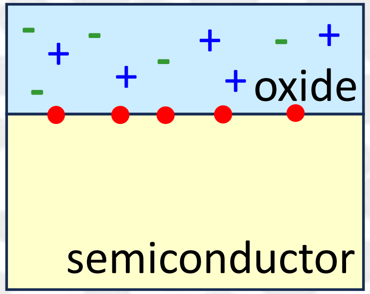
5 – Radiation effects on electronics in tokamaks

5.1 - Accumulated damages caused by Total Ionizing Dose (TID) :

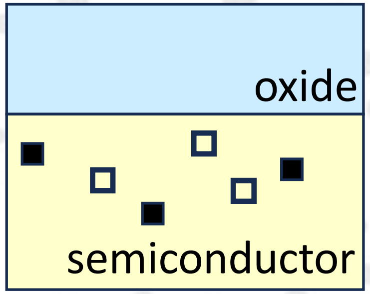


- TID Unit: Gray (Gy). 1 Gy = 1J/kg = 100 rads
- Cumulative effect.
- Effects: Power consumption increase, parametric characteristics shifts, permanent failure.
- No effects reported below 1 Gy.

5.2 - Accumulated damages caused by 1 MeV Equivalent Neutron Fluence (ENF)

- ENF Unit: 1 MeV equivalent neutron fluence (n/cm^2)

  1 MeV neutron fluence producing the same displacement damage than the fluence of the considered neutron environment.
- Impacts diodes and BJTs. No impact on MOS devices.
- Cumulative effect.
- Parametric characteristics shifts, then permanent failure.
- No effects reported below 10 n/cm^2.



5.3.1 - Instantaneous effects caused by Total Neutron Flux (TNF)

- TNF Unit: n/cm²/s
- Individual neutrons causes instantaneous **Single Event Effects (SEE)**, such as e.g.:

Designation	Effects	Correction
Single Event Upset (SEU)	bit-flips in memories, causing abnormal operation, non-operation	Reboot (rewriting memories)
Single Event Latch-up (SEL)	short circuits in parasitic thyristors, causing overconsumption, non-functioning, or destruction	OFF/ON power cycling replacement
Single Event Burnout (SEB)	destruction	replacement
Single Event Gate Rupture (SEGR)	destruction	replacement

- SEUs can cause a single bit upset (SBU), or multiple bit upsets (MBU-2, MBU-3, … MBU-10), depending on the **LET** and **range** of the recoil particle.
- SEUs can have a delayed effect : a bit-flip may cause a **silent data error** which causes an abnormal operation or a failure *only when the corrupted bit is used by the electronic function*.

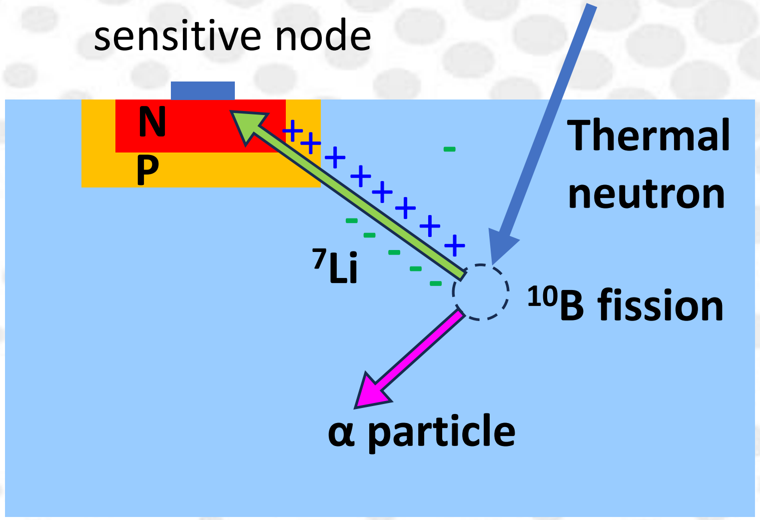
5.3.2 - Neutron-induced SEEs are based on an *indirect* mechanism

- An incident neutron interacts with a nucleus of the material of the electronic component, producing a recoil *ionized* particle.

  Example:

  $n_{th} + {}^{10}B \rightarrow {}^{4}He\ (1.47\ MeV) + {}^{7}Li\ (0.84\ MeV) + \gamma(0.48\ MeV)$

- The recoil ionized particle causes an ionization along its track inside the semiconductor material.
- The ionized track which crosses a sensitive node (e.g. a reverse-biased p-n junction) of a semiconductor device.
- The sensitive node collects a large fraction of the charges of the track (e.g. thanks to the electrical field of the reverse-biased junction).
- The collected charges causes a SEE (see examples in backup slides).



5 – Radiation effects on electronics in tokamaks

5.4 – Neutron-induced single event rate (SER) model:

- $SER = \int \sigma^{SEE}(E) \times \frac{d\phi(E)}{dE} dE$ — *[s^{-1}] (or s^{-1}/bit for memories)*
- $\sigma^{SEE}(E)$ = effective neutron-SEE cross-section — *[cm^2] (or cm^2 /bit for memories)*
- $\frac{d\phi(E)}{dE}$ = differential neutron flux — *[$cm^{-2}.s^{-1}.MeV^{-1}$]*
- E = neutron energy — *Tokamaks : thermal to 14 MeV*

5.4 – Neutron-induced single event rate (SER) model:

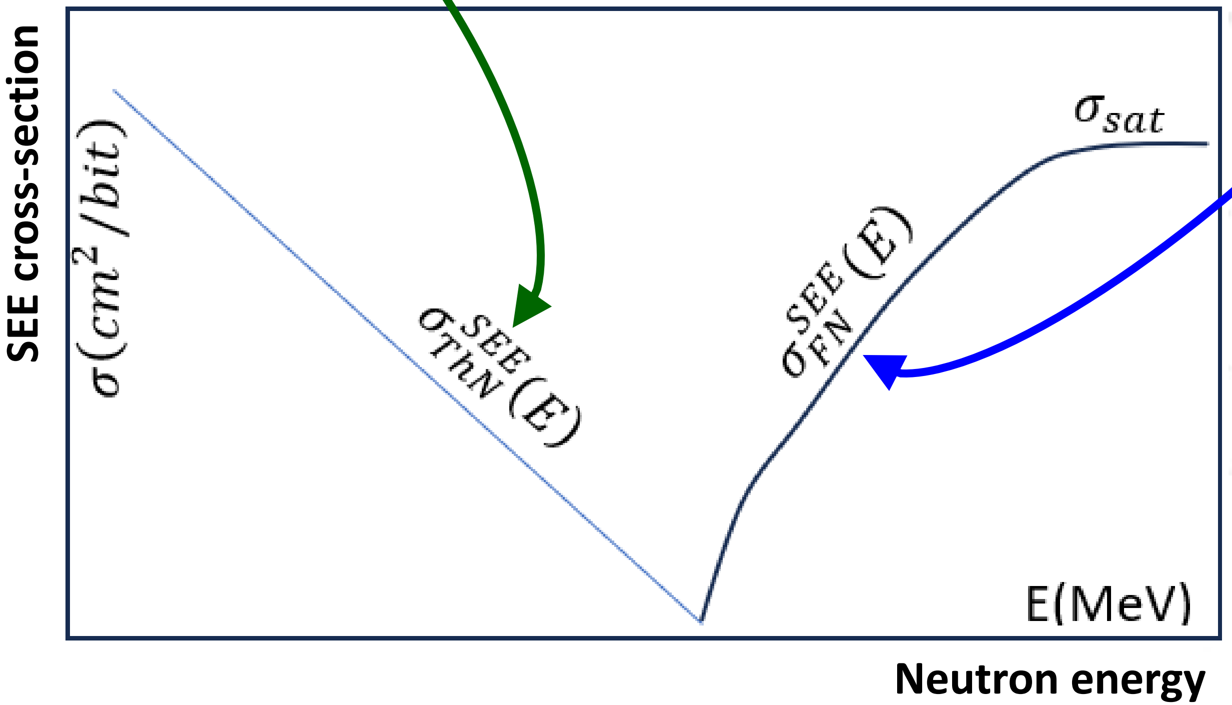
$\sigma^{SEE}(E)$ depends on the energy of the recoil particle, which depends on the neutron-induced SEE mechanism, the energy of the incident neutron, and the struck atom. $\boldsymbol{\sigma^{SEE}(E) = \sigma^{SEE}_{ThN}(E) + \sigma^{SEE}_{FN}(E)}$.

Thermal neutrons SEE cross-section

$\sigma^{SEE}_{ThN}(E) \sim 1/\sqrt{E}$

Fast neutrons SEE cross-section :

$$\sigma^{SEE}_{FN}(E) = \sigma^{SEE}_{sat}\left(1 - e^{-\left(\frac{E-E_{th}}{w}\right)^{s}}\right)$$



Weibull function's 4 parameters:

- $\boldsymbol{\sigma^{SEE}_{sat}}$ = saturation cross section,
- $\boldsymbol{E_{th}}$ = threshold below which $\sigma^{SEE}_{FN}(E) = 0$,
- $\boldsymbol{w}$ = scale parameter,
- $\boldsymbol{s}$ = shape parameter.

Outline

1. Background : nuclear fusion with D-T tokamaks
2. Electronics exposed to radiation in tokamaks
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6. How to ensure electronics reliability in tokamaks radiation environment
7. Validation of SER prediction method & models under DD and DT plasma neutrons

6 – How to ensure electronics reliability in tokamaks radiation environment

6.1 – Background

6.1.1 - Standards for nuclear electronics:

- **IEC-61508** “Functional safety of electrical/electronic/programmable electronic safety related systems”.

  ⇒ **Requires a reliability demonstration for critical non-safety electronics.**
- **IEC-61511** “Nuclear Power Plants – I&C Important to Safety – General requirements for systems”.

  ⇒ Requires a **reliability demonstration** for safety electronics.

6.1.2 - Reliability units

- **FIT** = Failures in Time (1 FIT = 1 failure / billion hour)
- MTTF = Mean Time to Failure
- MTBF = Mean Time between Failures.

6.1.3 - Reliability defined by manufacturer

- Valid in natural terrestrial ground level environment
- **No longer valid in an artificial environment** more demanding than the terrestrial one.

6 – How to ensure electronics reliability in tokamaks radiation environment

6.1.4 - Radiation qualification of COTS electronics is not possible, for the following reasons:

- The radiation tolerance of non-rad-hard semiconductor devices is fortuitous and varies from batch to batch.
- COTS electronic systems have no traceability of origin of manufacturing batches of constituting semiconductor components

  ⇒ Radiation test results on a specimen are not valid for another identical specimen (same part number).

6.1.5 - Developing radiation-hard electronics for tokamaks is not realistically doable.

- Too complex, too large quantities, too large diversity, too high cost, ….

Alternative approach to demonstrate reliability in the artificial radiation environment :

Replace the *qualification of electronics for its radiation environment* (not doable)
by the *qualification of the radiation environment for general electronics*.

6 – How to ensure electronics reliability in tokamaks radiation environment

6.2 – How to ensure electronics reliability in tokamaks radiation environment

6.2.1 - Critical and safety electronics

- Must be installed in shielded areas ensuring radiation conditions demonstrated equivalent, in terms of impact on the reliability of general modern electronics, to the natural terrestrial environment, in which the reliability established by the manufacturer is valid.
  - TID ≤ 1Gy and ENF ≤ 10 n/cm^2 can be considered as harmless (no reliability impact on electronics reported in any compendium of radiation test results).
  - If TID or ENF during expected life cycle are above these values (e.g. up to x4), periodical replacement could be a solution (if doable).
  - TNF must ensure **RDF ≤ 1** for general modern electronics.

$$\text{RDF (Reliability Degradation Factor)} = \frac{\textbf{\textit{SER}}\ \textit{in}\ \textbf{\textit{artificial}}\ \textit{radiation shielded environment}}{\textbf{\textit{SER}}\ \textit{in}\ \textbf{\textit{natural}}\ \textit{radiation terrestrial environment}}$$

6.2.2 – Non-critical non-safety electronics

- The above requirements can be relaxed *(degraded reliability acceptable)*.
- But they cannot be fully cancelled *(such electronics must work, otherwise no need to install it)*.

6 – How to ensure electronics reliability in tokamaks radiation environment

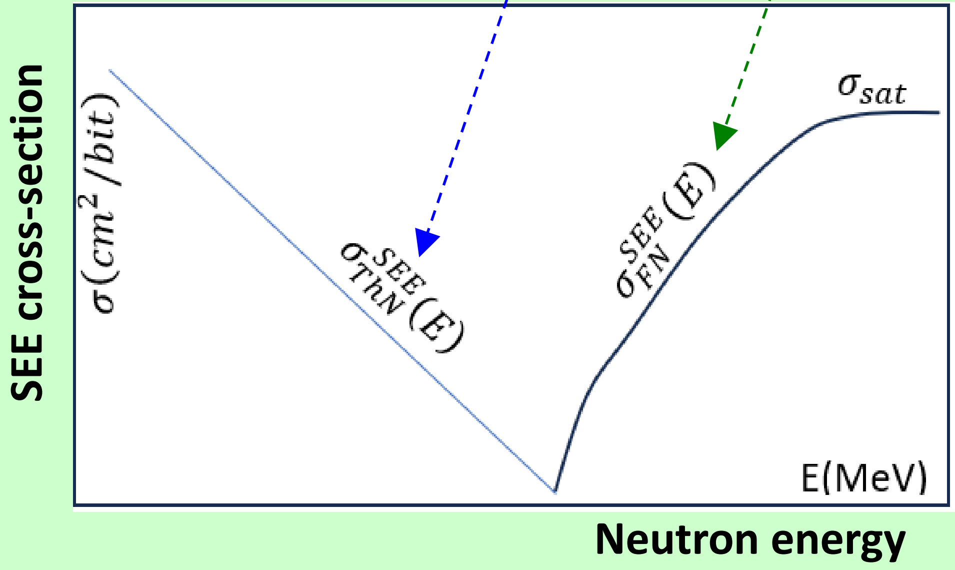
6.3 – Determination of RDF for a given component

$$\mathrm{RDF} = \frac{SER_{artificial}}{SER_{earth}} = \frac{SER^{ThN}_{artificial} + SER^{FN}_{artificial}}{SER^{ThN}_{earth} + SER^{FN}_{earth}}$$

$$SER_{artificial} = SER^{ThN}_{artificial} + SER^{FN}_{artificial}$$

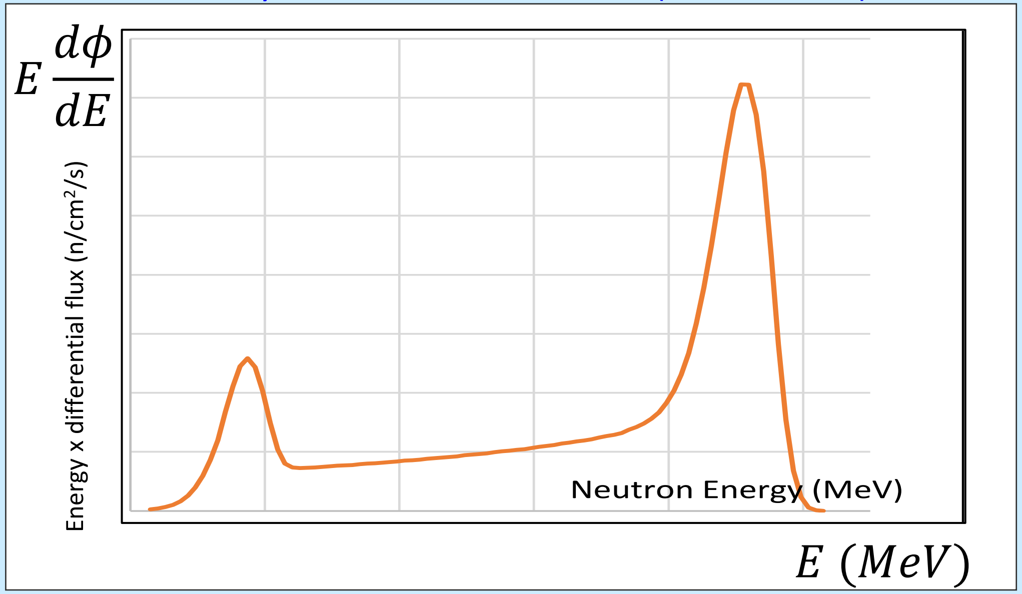
$$= \int \left(\sigma^{SEE}_{ThN}(E) + \sigma^{SEE}_{FN}(E)\right) \times \frac{d\phi}{dE}_{artificial} \, dE$$

$\sigma^{SEU}(E)$ = SEU production cross section by thermal and fast neutrons



Energy spectrum of at electronics location in the tokamak (lethargy representation)

Calculated by Monte-Carlo simulation (or measured)



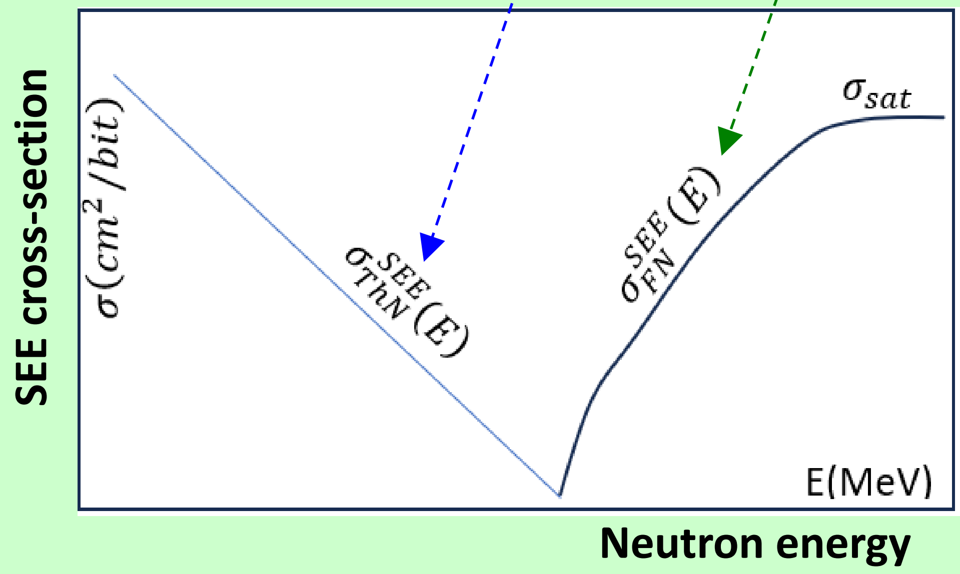
6.3 – Determination of RDF for a given component

$$RDF = \frac{SER_{artificial}}{SER_{earth}} = \frac{SER^{ThN}_{artificial} + SER^{FN}_{artificial}}{SER^{ThN}_{earth} + SER^{FN}_{earth}}$$

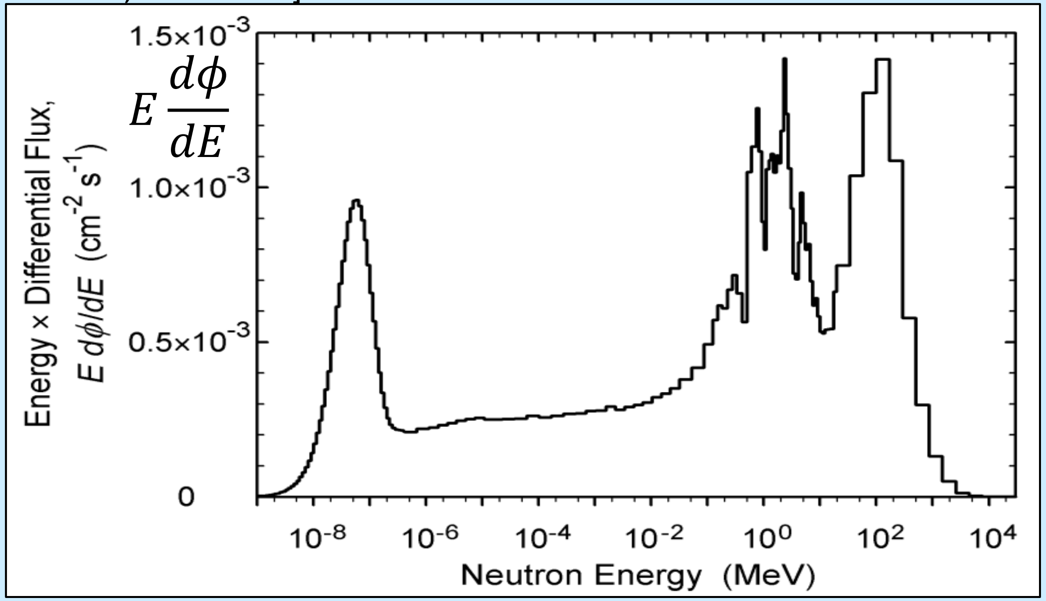
$$SER_{earth} = SER^{ThN}_{earth} + SER^{FN}_{earth}$$

$$= \int \left(\sigma^{SEE}_{ThN}(E) + \sigma^{SEE}_{FN}(E)\right) \times \frac{d\phi}{dE}_{earth} \, dE$$

$\sigma^{SEU}(E)$ = **SEU production cross section by thermal and fast neutrons**



Energy spectrum of natural atmospheric neutrons at sea level (lethargy representation). [M.S. Gordon et Al., IEEE TNS vol. 51 No.6, Dec. 2004] – see also JESD89B standard.



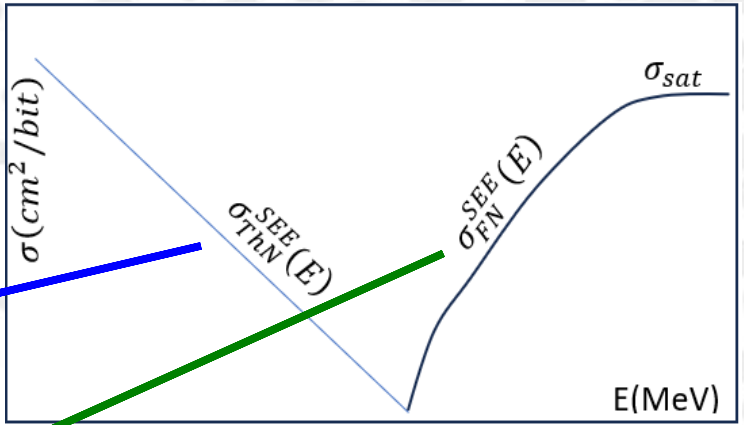
6 – How to ensure electronics reliability in tokamaks radiation environment

6.3 – Determination of RDF for a given component

$$RDF = \frac{SER_{artificial}}{SER_{earth}} = \frac{SER^{ThN}_{artificial} + SER^{FN}_{artificial}}{SER^{ThN}_{earth} + SER^{FN}_{earth}}$$

$$SER_{artificial} = \int \left(\sigma^{SEE}_{ThN}(E) + \sigma^{SEE}_{FN}(E)\right) \times \frac{d\phi}{dE}_{artificial} dE$$

$$SER_{earth} = \int \left(\sigma^{SEE}_{ThN}(E) + \sigma^{SEE}_{FN}(E)\right) \times \frac{d\phi}{dE}_{earth} dE$$



$$\sigma^{SEE}_{ThN}(E) = \sigma^{SEE}_{25meV} \times \sqrt{\frac{0.025\ eV}{E[eV]}}$$

$$\sigma^{SEE}_{FN}(E) = \sigma^{SEE}_{sat}\left(1 - e^{-\left(\frac{E-E_{th}}{w}\right)^{s}}\right)$$

For a given component σ^{SEE}_{25meV} is determined by SEE measurements under **thermal neutrons**

For a given component, the 4 parameters σ^{SEE}_{sat}, E_{th}, w and s are determined by SEE measurements under **mono-energetic fast neutrons** at several energies

6 – How to ensure electronics reliability in tokamaks radiation environment

6.4 – Determination of worst-case RDF for general modern electronics in a given artificial environment

A – Determination of parameters of $\sigma_{ThN}^{SEE}(E)$ and $\sigma_{FN}^{SEE}(E)$ models for general modern electronics by SEE measurements on a panel of components representative of general modern electronics

Constituents of the panel:

- Only semiconductor *components* (no electronic *systems*), the most basic possible, known to be sensitive to neutron-induced SEEs,
- Several device types (memories, power devices, …),
- Several technologies,
- Several technology nodes,
- Several manufacturers.

B – Determination of the worst-case RDF at electronics location in the tokamak for general electronics

- Calculation of RDF at electronics location for each component of the panel
- Determination of the worst-case RDF (RDF_{GE}), deemed to be representative of general electronics (**GE**).

6.5 – Shielding improvement to ensure electronics reliability in a tokamak radiation environment

6.5.1 – Targets

- **For critical/safety electronics:**

  $RDF_{GE} \leq 1$

  TID ≤ 1 Gy

  ENF ≤ 10 n/cm^2

- **For other electronics**, determine acceptable values, e.g.

  $RDF_{GE} \leq 10\text{-}100$

  TID ≤ 10-50 Gy

  ENF ≤ 100-500 n/cm^2

6.5 – Shielding improvement to ensure electronics reliability in a tokamak radiation environment

6.5.2 – Shielding incorporated in building structure (e.g. shielded walls, shielded slabs)

- Against gamma photons,
- Against fast neutrons.

Not recommended against *thermal* neutrons
because the remaining fast neutrons will thermalize at electronics location.

6.5.3 – Local shielding on electronics cabinets

- Recommended against *thermal* neutrons (**light, thin B_4C panels** – requires careful 3D design and digital Monte-Carlo simulation to optimize shielding of openings for heat removal and of cables penetrations).
- Not recommended against photons or fast neutrons
(would require steel/concrete: too bulky, too heavy, limited effectiveness).

Outline

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7 – Validation of SER prediction method & model under DD and DT plasma neutrons

To illustrate the above section 6, this section 7 presents a preliminary study currently being conducted by **CEA-IRFM**, **CERN**, **Aix-Marseille University** and **University of Rennes** in collaboration with **STMicroelectronics,** aiming at **replacing the radiation qualification of the electronics (not doable) by the qualification of the radiation environment at electronics location in tokamaks and in particle accelerators**.

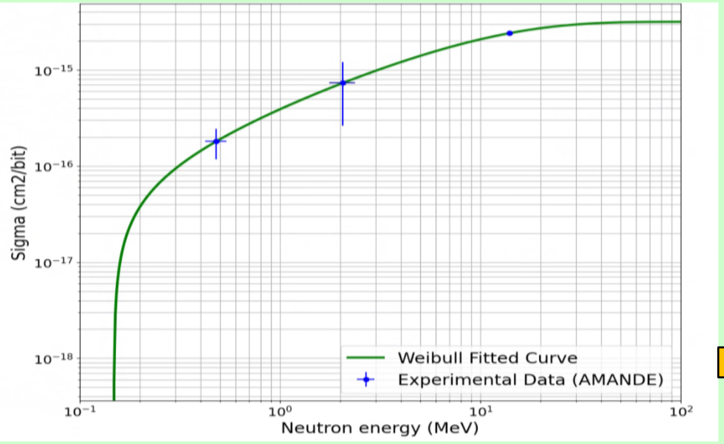
7.1 – Validation at WEST tokamak (CEA/IRFM) under D-D plasma neutrons

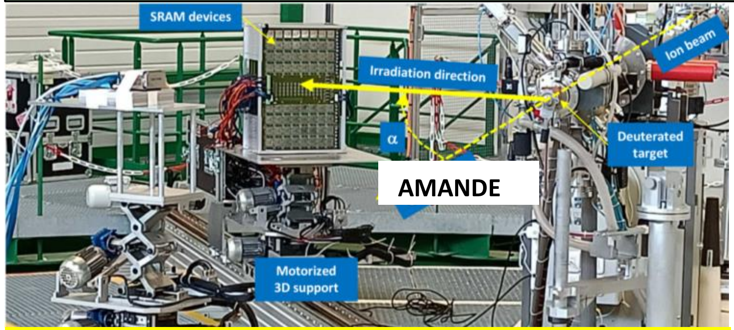
Real Time Soft Error Rate test bench from AMU/IM2NP:

384 memory chips (65 nm bulk SRAM from STM, BPSG-free, 3,226 Gbits in total.

DIAMON neutron spectrometer from Raylab : energy range = from thermal to 20 MeV.

SEE measurement under mono-energy neutrons at GENESIS(1) and AMANDE (2)

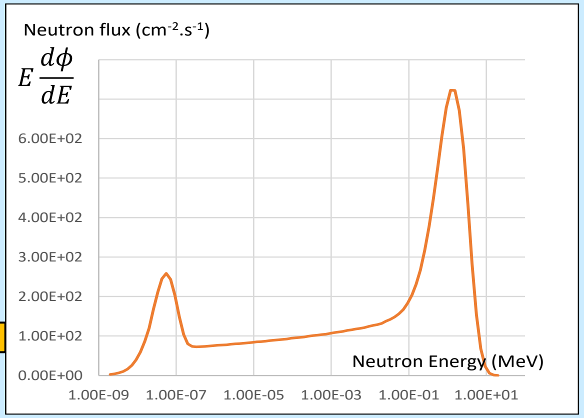




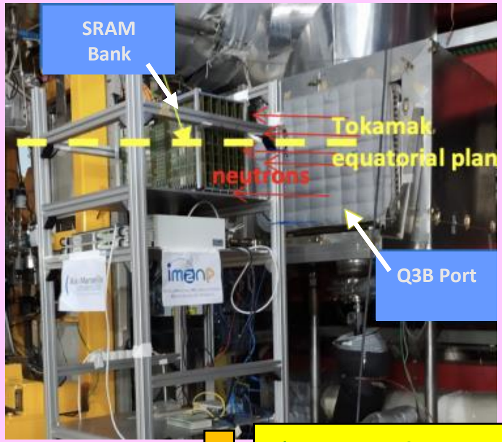
(1) GENESIS neutron test facility from LPSC in Grenoble.
(2) AMANDE neutron test facility from IRSN in Cadarache

Neutron spectrum and SEE measurement under D-D neutrons at WEST

Neutron spectrum measured at the location of the RTSER test bench



Bit flip SER* measured on RTSER at WEST during C5 campaign



**SER = Soft Error Rate (bit flip rate)*

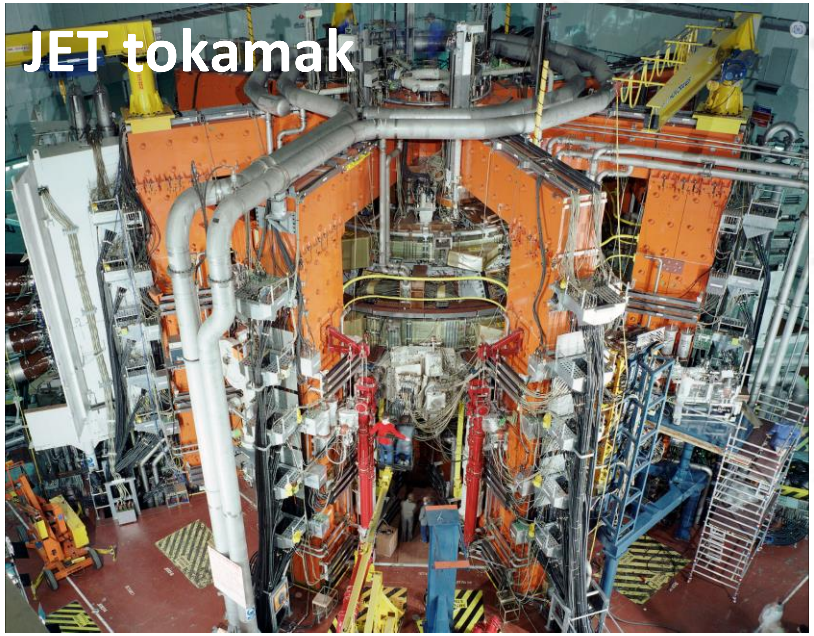
predicted SER → $\frac{\textbf{predicted } SER}{\textbf{measured } SER} = 0.63$ ← measured SER

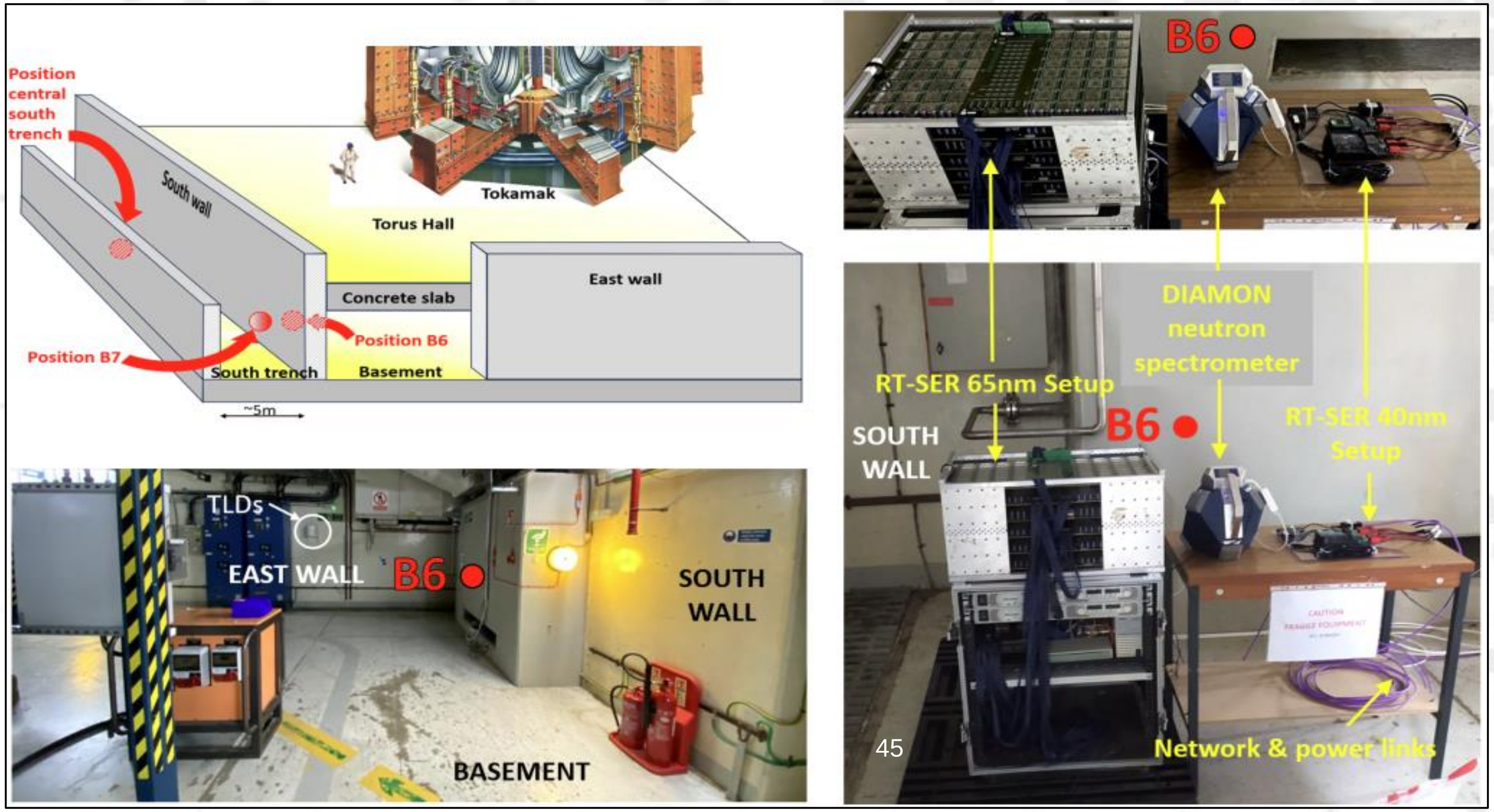
Method validated for D-D fusion plasmas

The slight underestimation (30%) of predicted SER is attributed to the fact that thermal neutrons are not considered in this preliminary analysis (partially justified by BPSG-free process)

[M. Dentan et Al., "Preliminary Study of Electronics Reliability in ITER Neutron Environment" RADECS 2022 proceedings / IEEE / DOI:10.1109/RADECS55911.2022.10412483]

7.2 – Validation at JET tokamak (EUROfusion and UKAEA) under D-T plasma neutrons





$$\frac{predicted\ SER}{measured\ SER} = 0.64$$

Method validated for D-T fusion plasmas

Ratio almost identical to that obtained under D-D plasma neutrons at WEST

[M. Dentan et Al., "Real-Time SER Measurements of CMOS bulk 40 nm and 65 nm SRAMs Combined with Neutron Spectroscopy at the JET Tokamak during D-D and D-T Plasma Operation", to be published in IEEE TNS / Proceedings of NSREC 2024 Conference]

The results of the preliminary study conducted at WEST then at JET validate the SER prediction methods and models.

Next steps:

- Determination of parameters of $\boldsymbol{\sigma_{ThN}^{SEE}(E)}$ and $\boldsymbol{\sigma_{FN}^{SEE}(E)}$ models for general modern electronics by SEE measurements on a panel of components representative of general modern electronics.
- Determination of the worst-case **RDF**$_{GE}$ at electronics location in the artificial environment of a tokamak and of an accelerator.
- Shielding improvement to ensure electronics reliability in the artificial radiation environment of tokamaks and accelerators (worst-case **RDF**$_{GE}$ ≤1 for critical electronics)

Back-up slides

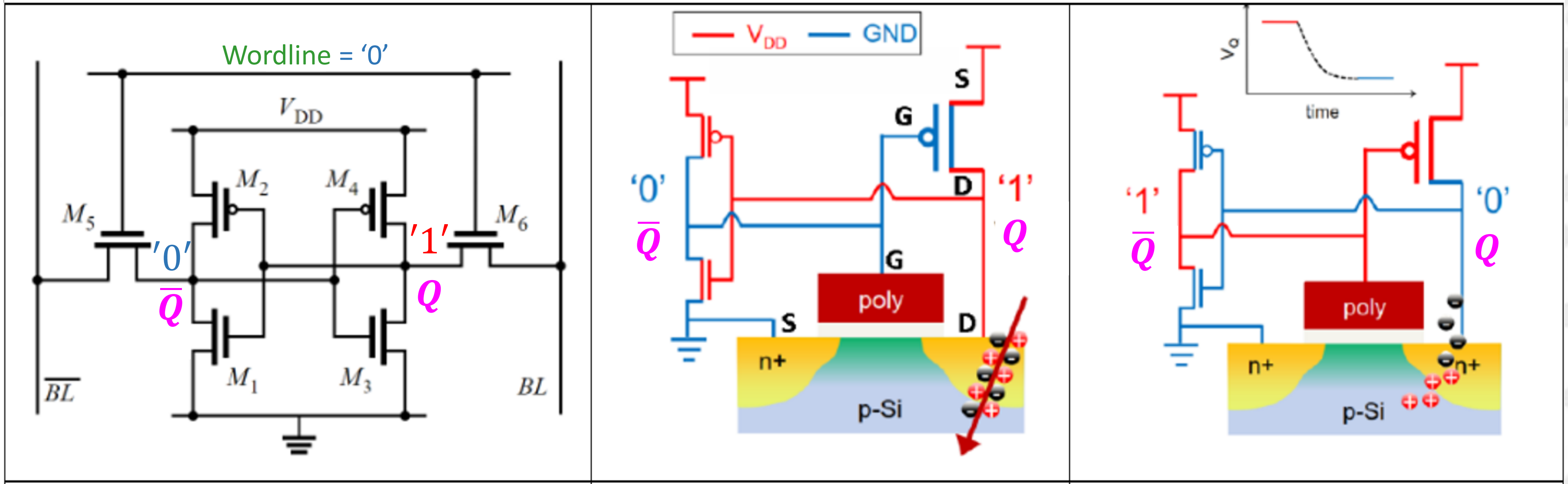
14/05/2024

Martin DENTAN

CERN Project Associate

5 – Radiation effects on electronics in tokamaks

5.2.1 - Example of neutron-induced SEE : SEU (bit-flip) in 6 MOSFET SRAM memory cell



(a) 6-MOSFET SRAM architecture | (b) Ionization | (c) Bit flip

[S. Gerardin "Corso di qualita e affidabilita pin elettronica: Single Event Effects«, 2015-2016]

When Wordline = '0', no access to transistors => the cell is holding its stored data using the back-to-back inverter configuration.

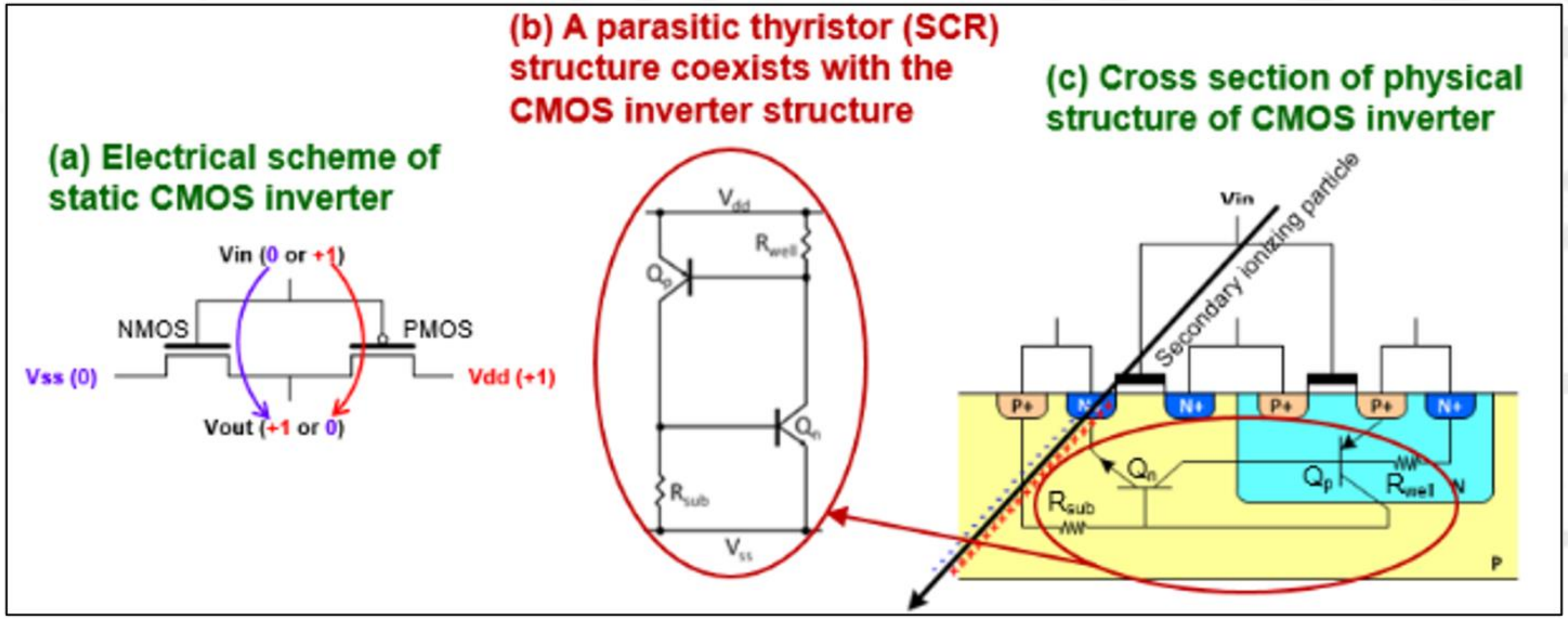
(a) Initially, node $\overline{Q}$ = '0' and node Q = '1' (+Vdd).

(b) an ionized particle crosses the drain of transistor M_3.

(c) Negative charges are collected on the drain of M_3 => a transient current propagates through the inverter and changes the state of node $\overline{Q}$ from '0' to '1'. This change propagates backwards through the inverter and changes of state of node Q from '1' to '0' => the two nodes have flipped ($\overline{Q}$ = '1' and Q = '0'), and the memory cell now stores a false value.

5 – Radiation effects on electronics in tokamaks

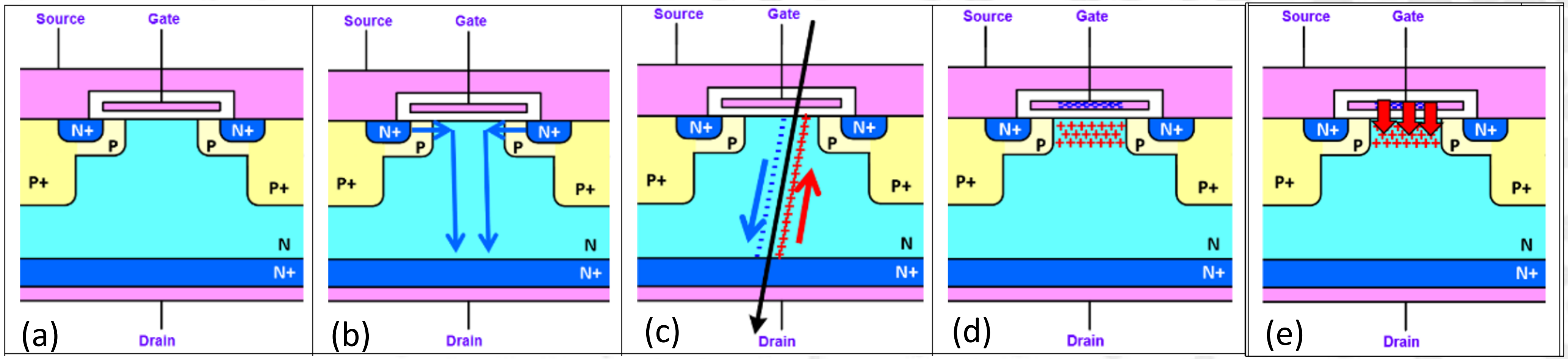
5.2.2 - Example of neutron-induced SEE : single event latch-up (SEL) in the parasitic thyristor of CMOS pair

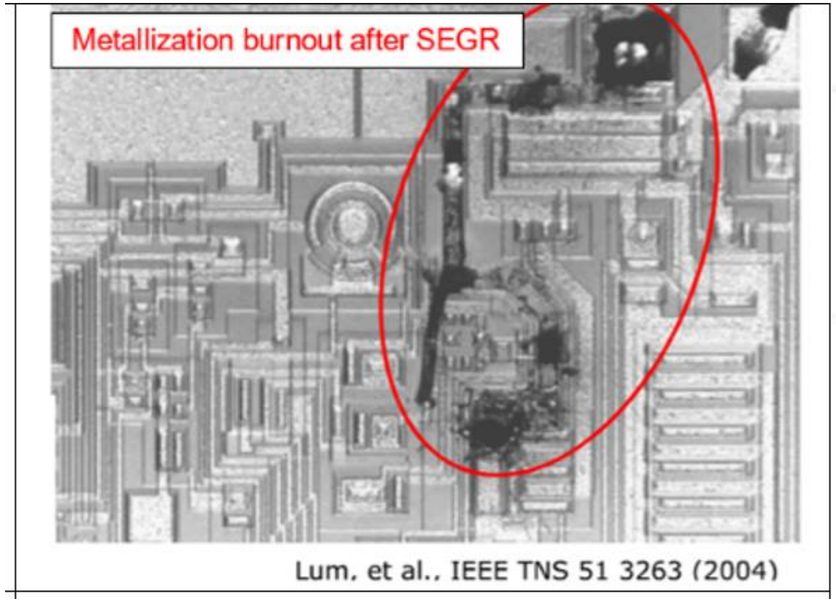


- In normal operation, the parasitic thyristor in OFF (the parasitic transistors Qn and Qp are both OFF)
- An individual recoil particle from neutron interaction creates electron-hole pairs along its track.
- This ionized track crosses a sensitive node of Qn, which puts it in ON mode. This conductive mode of transistor Qn is propagated to transistor Qp through the parasitic thyristor structure, and transistor Qp goes to conductive mode, which stabilizes the conductive mode of transistor Qn.
- With both Qn and Qp in conductive mode, the thyristor is in conductive mode. This conductive mode is stable and remains as long as the inverter is supplied with power.

5 – Radiation effects on electronics in tokamaks

5.2.3 - Example of neutron-induced SEE : single event gate rupture (SEGR) in a power MOSFET structure





[Photo: G. K. Lum et Al., IEEE TNS Vol. 51, No.6, Dec. 2004 (3263-3269)]

(a) Schematic view of power MOSFET cross section.

(b) ON mode. Current flows from source to drain. No electrical field in N/N+ drain junction.

(c) OFF mode. An ionized track crosses the structure. High electrical field in N/N+ drain junction separates its (+) and (-) charges.

(d) The (+) charges accumulate below gate oxide, and image (-) charges accumulate above gate oxide.

(e) This causes a high electrical field through the gate oxide, which causes a **gate rupture**.