Introduction to Fusion Energy and Plasma Physics Course

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Plasma-Material Interactions I

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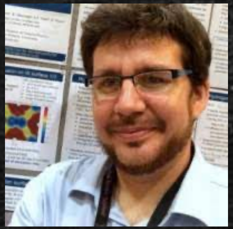
A journey across plasma-material interactions in magnetic fusion plasma and nuclear fusion reactors

Content of the lecture

- **Introduction : What are Plasma-Material Interactions (PMI)?**
- **Part I : Plasma-material interactions in magnetic fusion plasma**
  - Fundamental atomic and plasma physics processes governing PMI in tokamaks
- **Part II : Putting the sun in a sustainable and fusion-friendly box**
  - Constraints imposed by PMI on plasma-facing components in tokamaks
- **Part III : Which materials to build plasma-facing components in a fusion reactor?**
  - Selecting plasma-facing materials compatible with PMI in fusion reactors
- **Part IV: Modeling and simulations of plasma-material interactions**
  - The challenging yet necessary modeling of PMI to design future fusion reactors

Some words about my personal journey in magnetic confinement nuclear fusion



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2009 Visiting Scientist
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2015 PhD – Plasma Engineering Physics
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2019 Post doctoral Fellow
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Two advices from my personal journey

- **Invest in every opportunity** (internship, research project, summer school,…) **to gain experience and build your professional network** (communicate, be curious, talk to people!)
- **Success in research and science depends on several factors that cannot be all controlled**:
  - Work, talent, opportunity, timing, luck, …
  - Focus on what you can control (work ethic, training, professional network, communication,…)
  - There is not a *one-size-fits-all* path in research, especially in nuclear fusion!

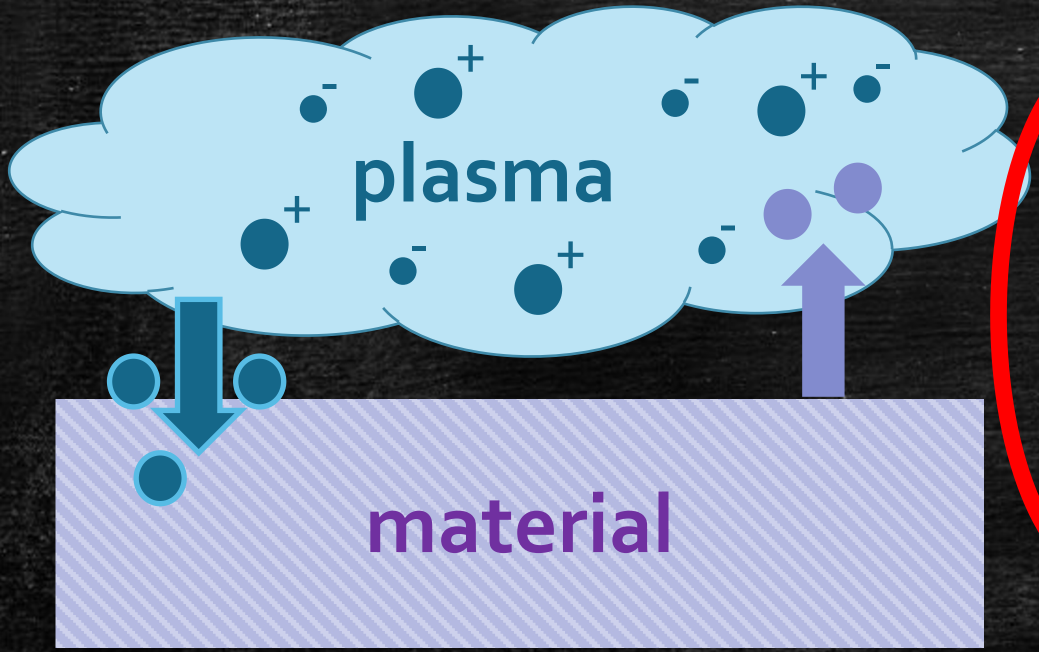
Introduction

What are plasma-material interactions?

Plasma-material interactions govern how plasmas and materials synergistically interact and modify each other

PMI = Plasma-Material Interactions

plasma = ionized gas



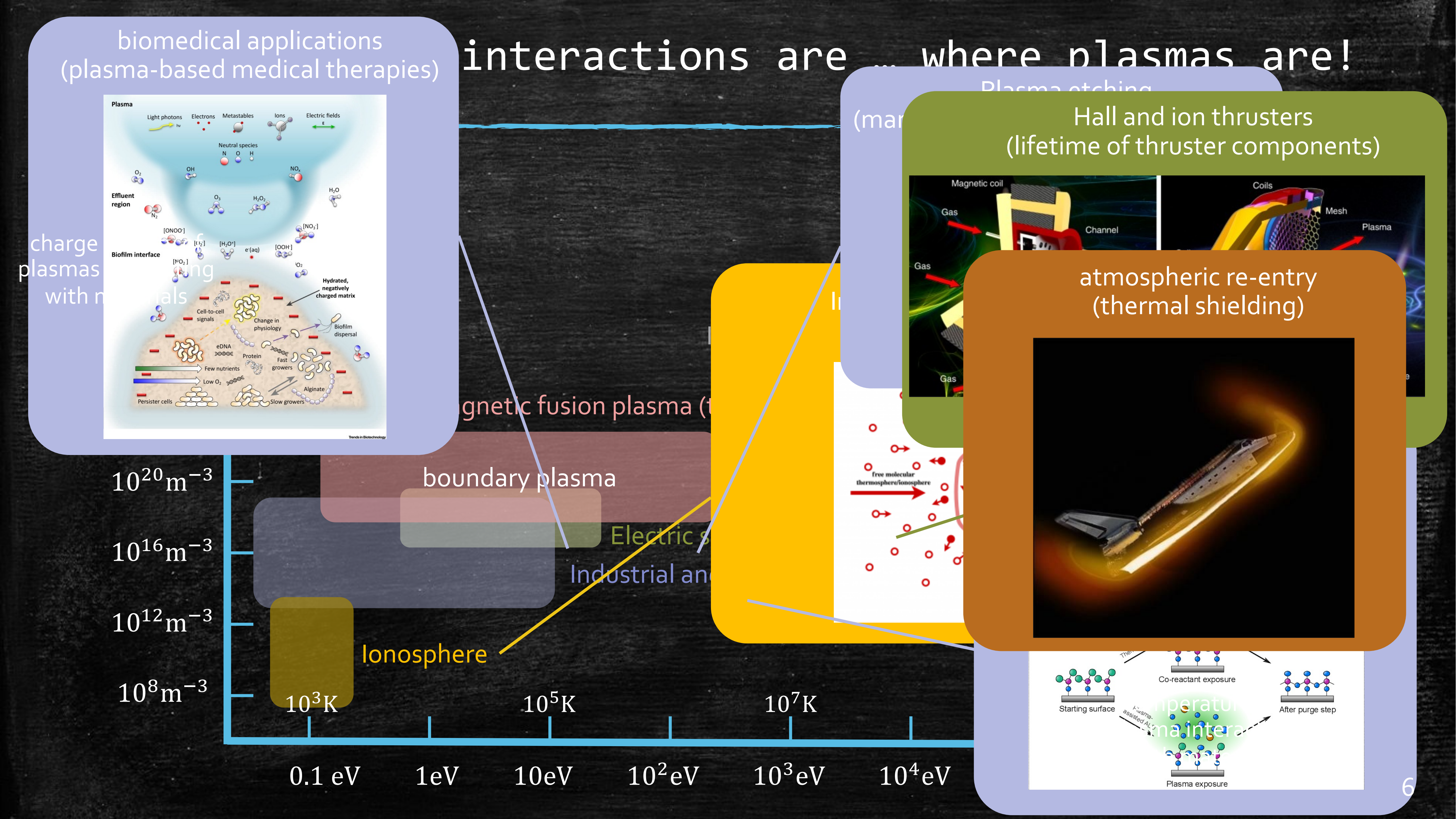
rule of thumb #1

Plasmas interacting with materials are contaminated by charged and neutral species originating from material surfaces

rule of thumb #2

Materials interacting with plasma are degraded or enhanced due to plasma heat and momentum flux and storage of plasma particles in materials

* plasma-material interactions are also often called plasma-surface interactions

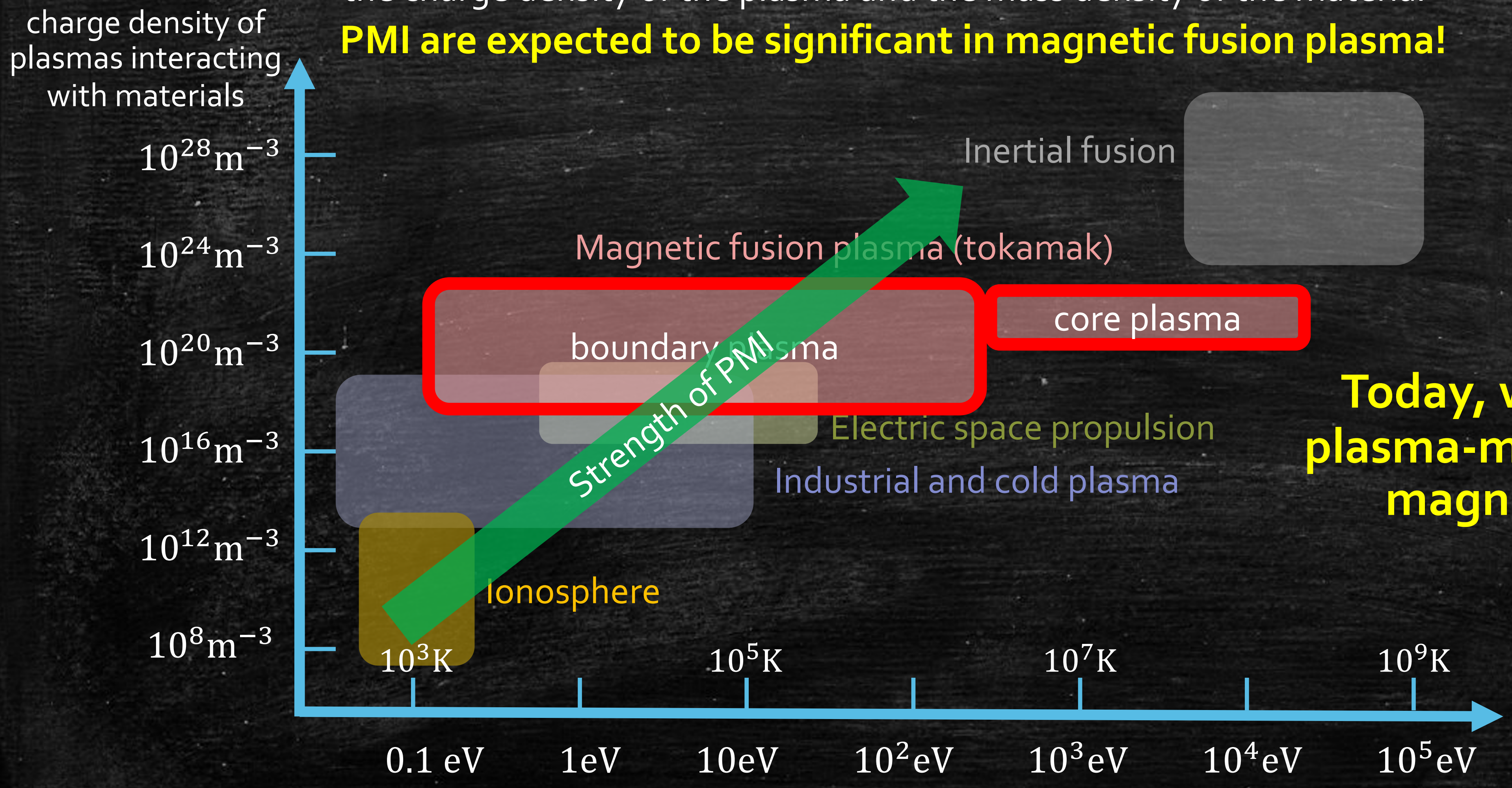

interactions are … where plasmas are!
biomedical applications
(plasma-based medical therapies)
Plasma
Light photons
Electrons
Metastables
Ions
Electric fields
Neutral species
Effluent region
Biofilm interface
Hydrated, negatively charged matrix
Cell-to-cell signals
Change in physiology
Biofilm dispersal
eDNA
Protein
Fast growers
Few nutrients
Low O_2
Alginate
Persister cells
Slow growers
Trends in Biotechnology
charge
plasmas
with
Hall and ion thrusters
(lifetime of thruster components)
Magnetic coil
Gas
Channel
Coils
Mesh
Plasma
atmospheric re-entry
(thermal shielding)
free molecular thermosphere/ionosphere
boundary plasma
Ionosphere
Co-reactant exposure
Starting surface
After purge step
Plasma exposure
$10^{20}m^{-3}$
$10^{16}m^{-3}$
$10^{12}m^{-3}$
$10^{8}m^{-3}$
10^3K
10^5K
10^7K
0.1 eV
1eV
10eV
10^2eV
10^3eV
10^4eV
6

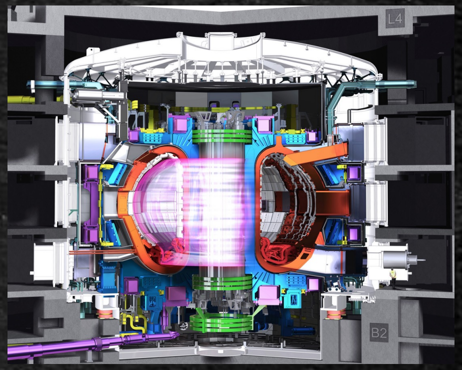
Plasma-material interactions are … where plasmas are!

The strength of plasma-material interactions is mainly determined by:

- the energy (temperature) of the plasma
- the charge density of the plasma and the mass density of the material

PMI are expected to be significant in magnetic fusion plasma!

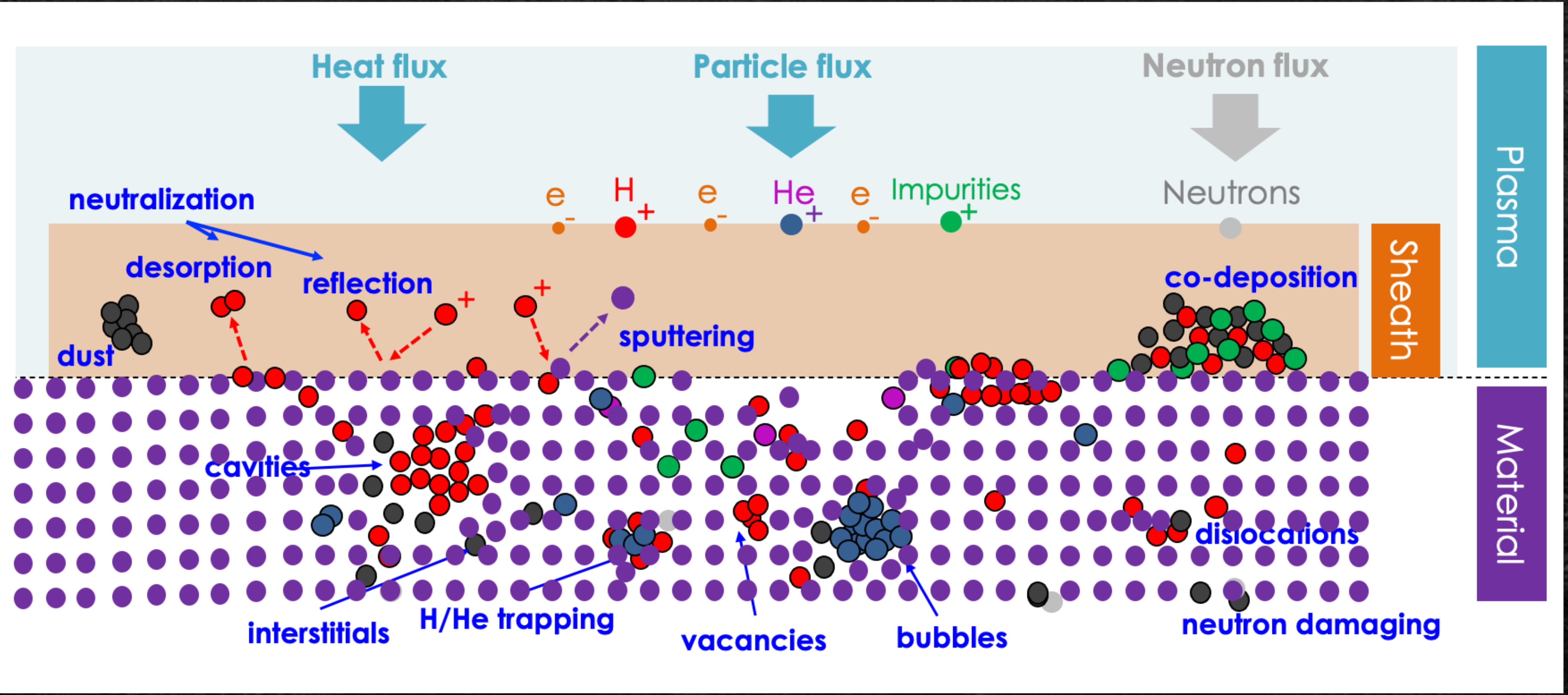




Today, we will focus only on plasma-material interactions in magnetic fusion plasma (tokamak)

Plasma-material interactions are governed by various complex and multi-faceted atomic and plasma processes

- Today, we are only looking at PMI relevant for D+T magnetic fusion plasma…
- Those PMI nevertheless involves a lot of complex multi-faceted physics mechanisms!



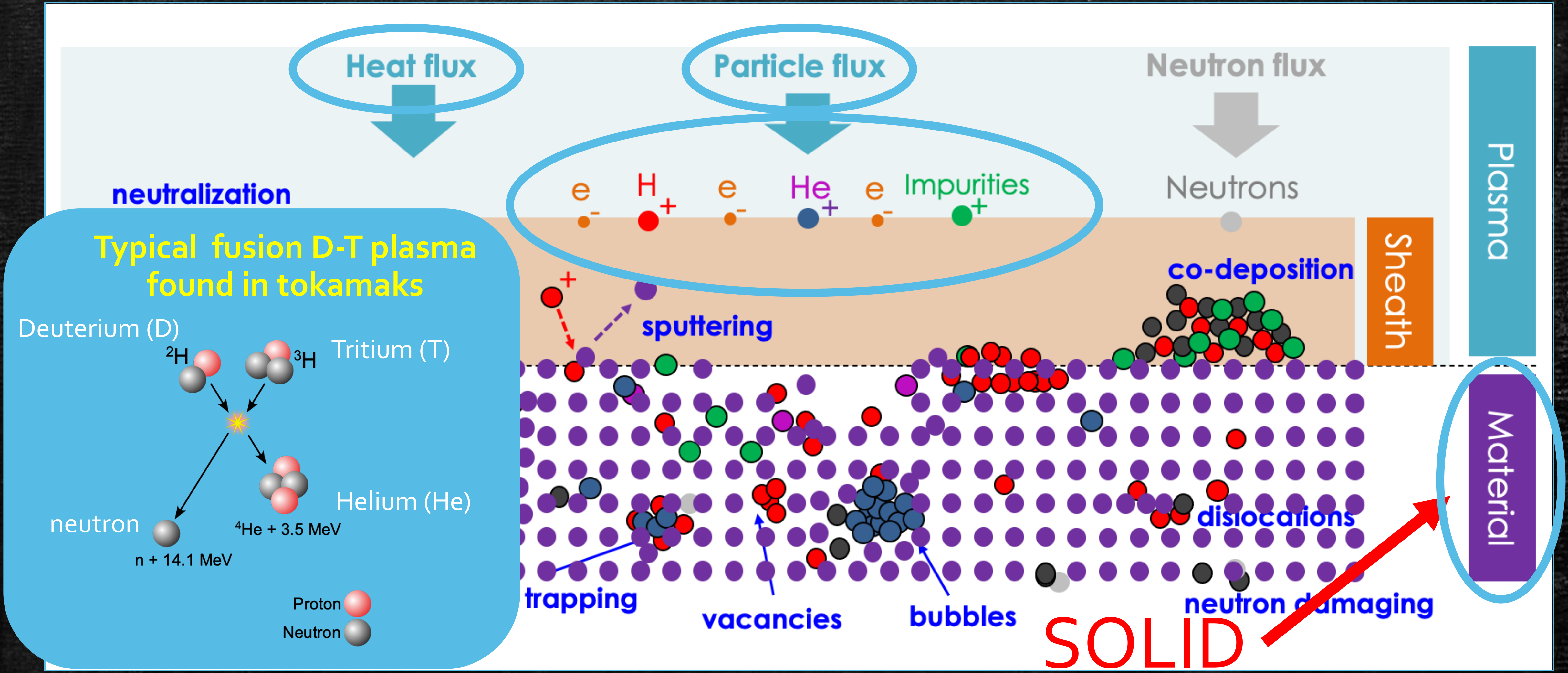
- This zoo of multi-faceted physics mechanisms for D+T magnetic fusion plasma is a good illustration of the complexity of PMI in general

Part I

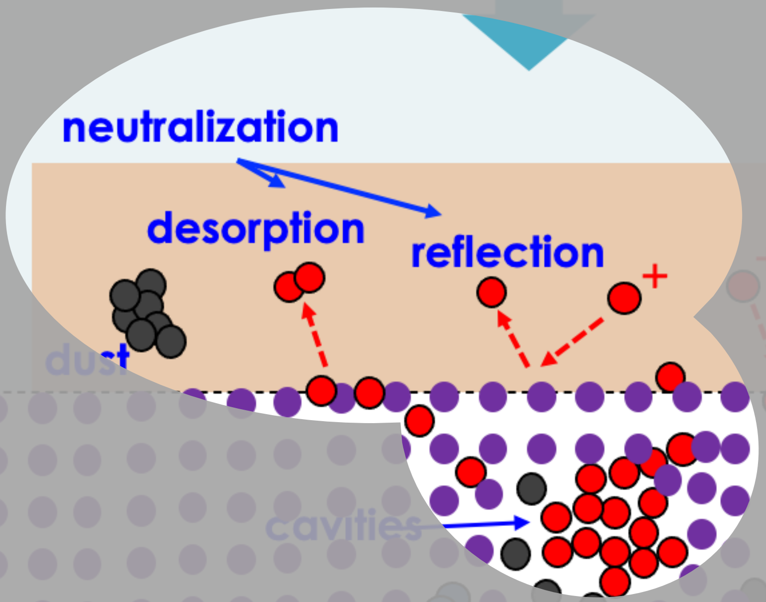
Plasma-material interactions in magnetic fusion plasma

Fundamental atomic and plasma physics processes governing plasma-material interactions in tokamaks

PMI fundamentals for D+T fusion plasma in tokamaks



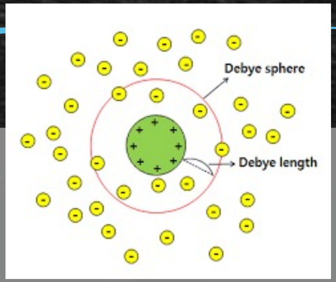
PMI fundamentals: plasma particles interacting with material are recycled as neutrals into the plasma



- **When charged plasma particles hit a solid material surface, they become neutrals:**
  - A fraction of those particles is reflected as atoms (reflection process)
  - The remaining particles are implanted beneath the material surface
  - Almost all particles implanted in the material (>99%) diffuse back to the material surface and desorb into the plasma (desorption process)
- **Most of plasma particles hitting solid material surface are released as neutrals in the plasma and only a small fraction is stored in the material**
  - hydrogenic species (D,T) desorb as molecules (H_2) into the plasma
- The release of plasma particles impinging on material surface back in the plasma as neutrals is called **"recycling"**

Recycling of plasma particles from materials can strongly impact the particle and power balances in plasma

PMI fundamentals: an electric sheath is formed above material surfaces exposed to plasma

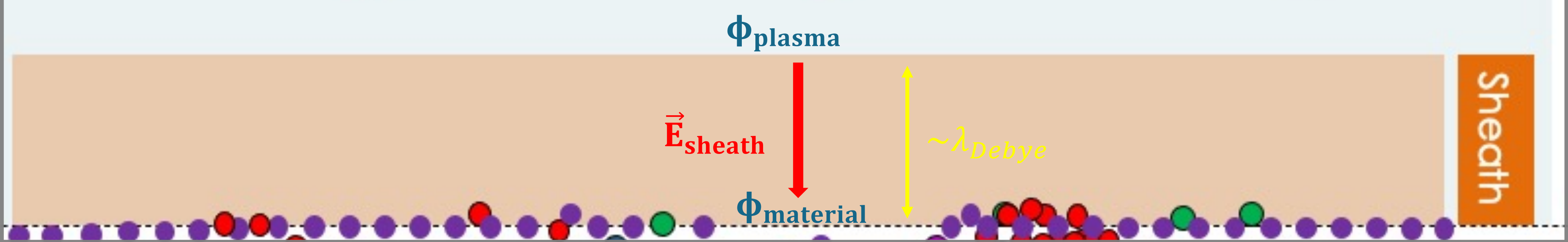


- D+T fusion plasma are weakly coupled plasmas (low density and high temperature):

→ the charge separation between electrons and ions occurs over the Debye length λ_{Debye}

- Plasma species are neutralized once they interact with the material surface:

→ **A charge separation occurs between the plasma and the material surface over a length scale of the order of λ_{Debye}**



- Because electrons are much smaller than ions, they can more easily (faster) reach the material surface:

→ electric potential between material and plasma $\Delta\Phi_{sheath} = \Phi_{plasma} - \Phi_{material} \sim \log\left(\frac{m_{ion}}{m_{electron}}\right) \approx 3\times k_b\times \frac{T_e}{e}$

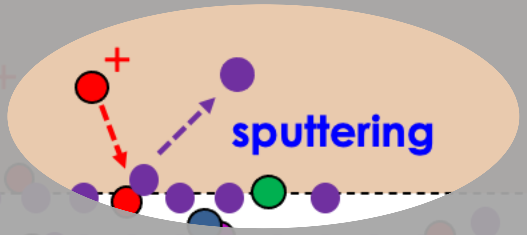
→ **self-consistent electric fieldE_{sheath}** near the material surface which accelerates ions toward the material surface and repels electrons, so that ions and electrons reach the material surface surface at the same rate (ambipolarity)

- **The region where this self-consistent organization takes place is called the sheath**

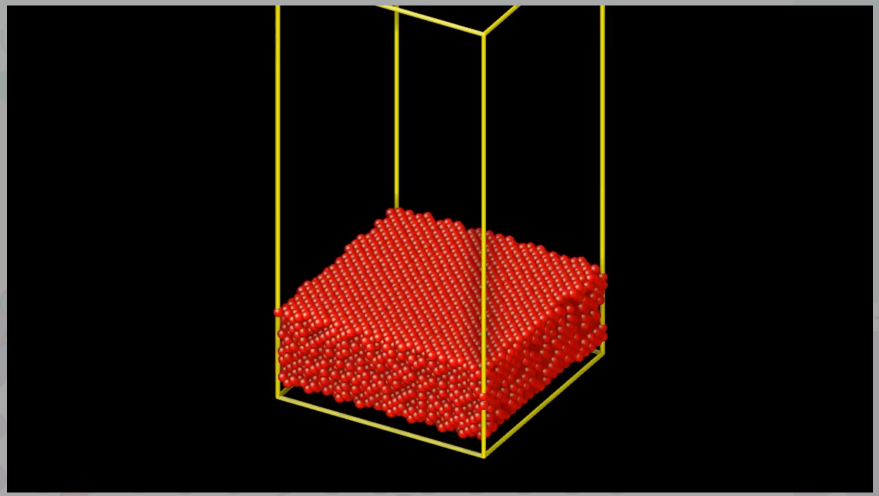
Plasma ions are accelerated toward the material surface by the sheath electric field and gain a kinetic energy $\Delta E_{kin} \sim \sim Q_{ion}\times 3\times k_b\times T_e$ before impinging on the material surface

PMI fundamentals: atoms on material surface are sputtered into the plasma by plasma particles

- Due to the impacts of plasma particles impinging on solid material surface, particles are ejected from the material surface into the plasma
- This phenomenon is called "sputtering" and leads to the material erosion and the damaging of the material surface
- **The electric sheath strongly enhances material erosion by accelerating ions toward the material surface**



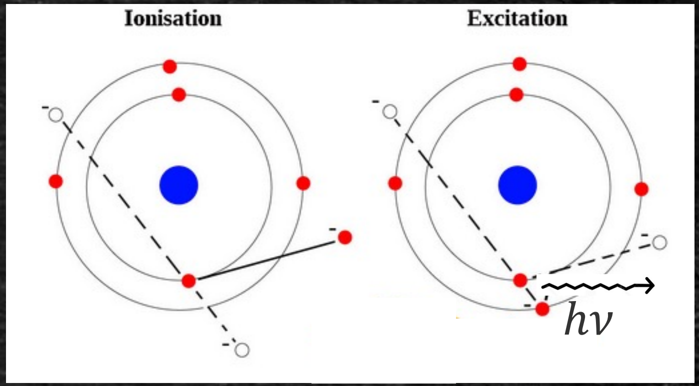
Molecular dynamics simulation of material sputtering



- **The sputtering (erosion) of material due to the impact of plasma particles results in:**
  - **the reduction of the material lifetime**
  - **the pollution of the plasma with impurities**

PMI fundamentals: impurities can significantly cool down the plasma

- Plasma ions/impurities can be ionized and recombine due to collisions with plasma electrons:
  - $D + e^- \rightarrow D^+ + 2e^-$ (ionization)
  - $C^{3+} + e^- \rightarrow C^{2+}$ (recombination)

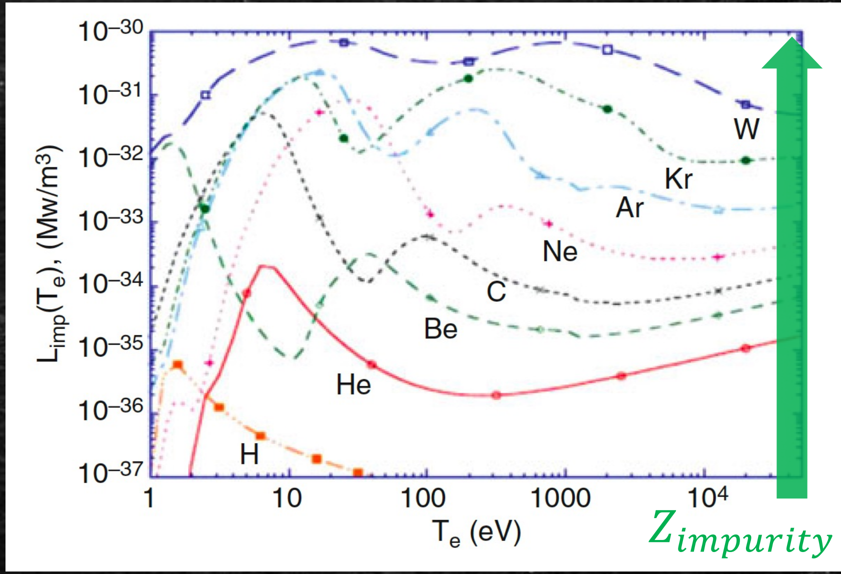


- Electrons in the shell of the plasma ions/impurities can also be excited due to collisions with plasma electrons and radiate power from plasma:

$$P_{rad} = \int dT_e \, L_{imp}(T_e) \times n_e \times n_{imp}$$

cooling rate — plasma electron density — plasma impurity density

- Quantum physics determines the cooling rate L_{imp} :
  - electronic states are quantified
  - the more electronic states available, the easier it is to reach excited electronic states



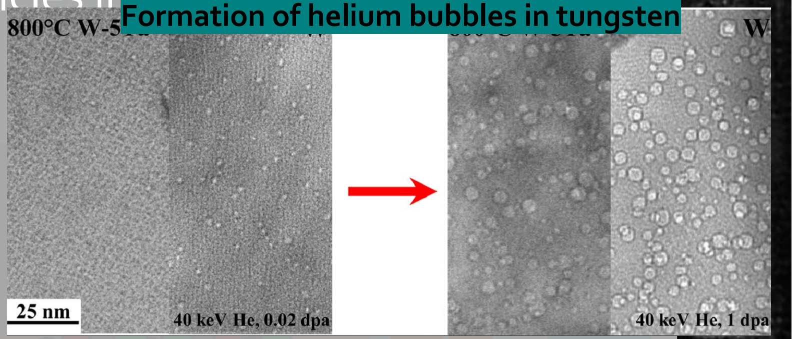
Impurities cool down the plasma by radiating due to collisions with plasma electrons

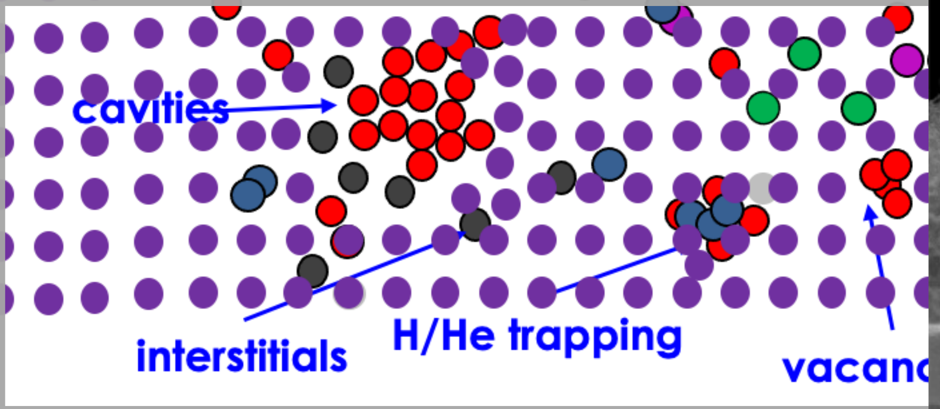
The efficiency of the radiative cooling of plasma by impurities significantly increases with the atomic number Z of the impurity

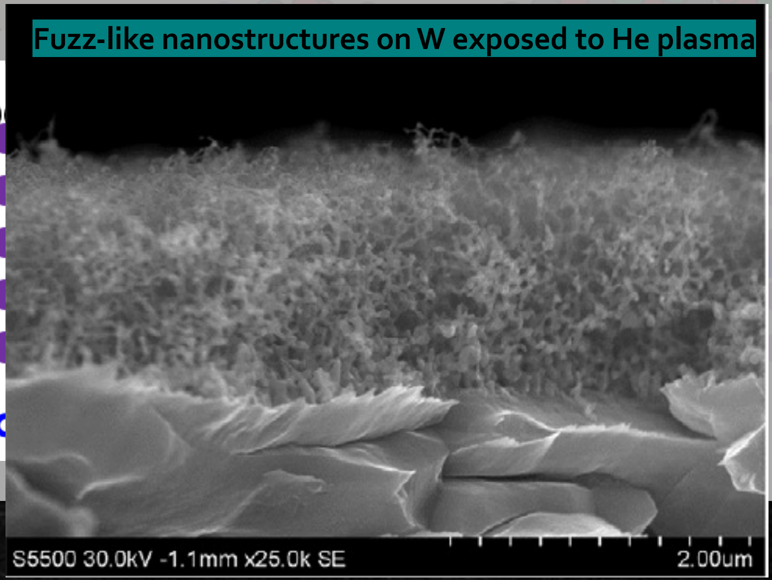
PMI fundamentals: material is damaged by the impacts and the accumulation of plasma particles

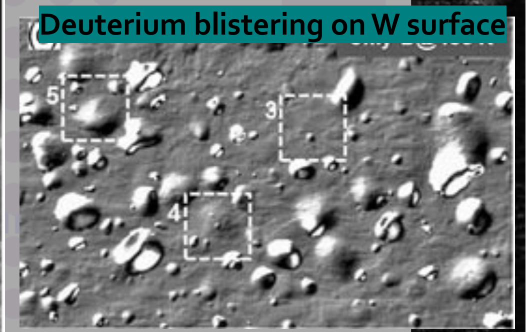
- Implantation of energetic plasma particles in material results in the creation of lattice defects: interstitials atoms, vacancies, voids, …
- These defects favor the accumulation (long-term retention) of plasma particles in the material (blistering, nano-bubbles, nano-fuzz, …)

The accumulation of defects and plasma particles in the material deteriorate the material properties (thermal conductivity, resistance to fatigue, ductility, …) and reduce its operational performances and lifetime


Formation of helium bubbles in tungsten




Fuzz-like nanostructures on W exposed to He plasma

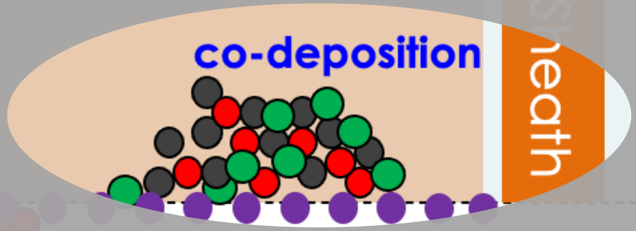

Deuterium blistering on W surface

PMI fundamentals: co-deposition of plasma particles and material impurities

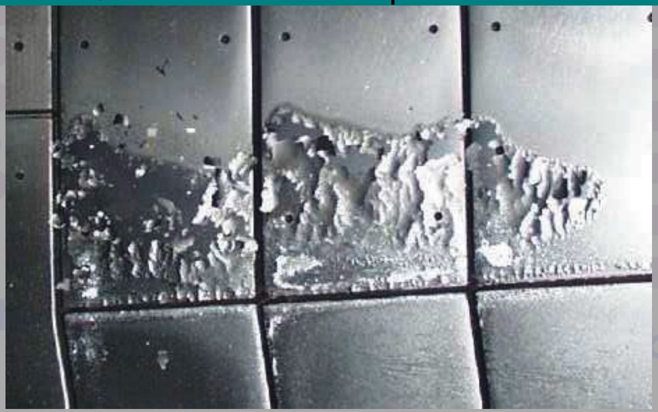
- Codeposition: simultaneous deposition of plasma particles, e.g. hydrogen species, and plasma impurities, .e.g. carbon, resulting in the formation of amorphous (unstructured) layers deposited on material surface

Codeposited layers can become a significant reservoir of particles compared to the structured material beneath

Codeposition of plasma species can have deleterious effects on the plasma due to the sudden recycling of a large amount of particles in the plasma (uncontrollable recycling)



carbon/deuterium codeposit in tokamak



Summary of PMI fundamentals in magnetically confined fusion plasma

- **Plasma particles interacting with material are neutralized: most of them are recycled as neutrals in the plasma and a small fraction is stored in the material**
- An electric sheath is formed above the material surface due to the neutralization of plasma particles and accelerate ions toward the material surface
- Materials exposed to plasma are damaged:
  - Atoms from material surface layers are sputtered into the plasma
  - Plasma particles create defects in the material: vacancies, interstitials, …
  - Accumulation of plasma particles in material can significantly impact material through e.g blistering, bubbles formation, fuzz, …

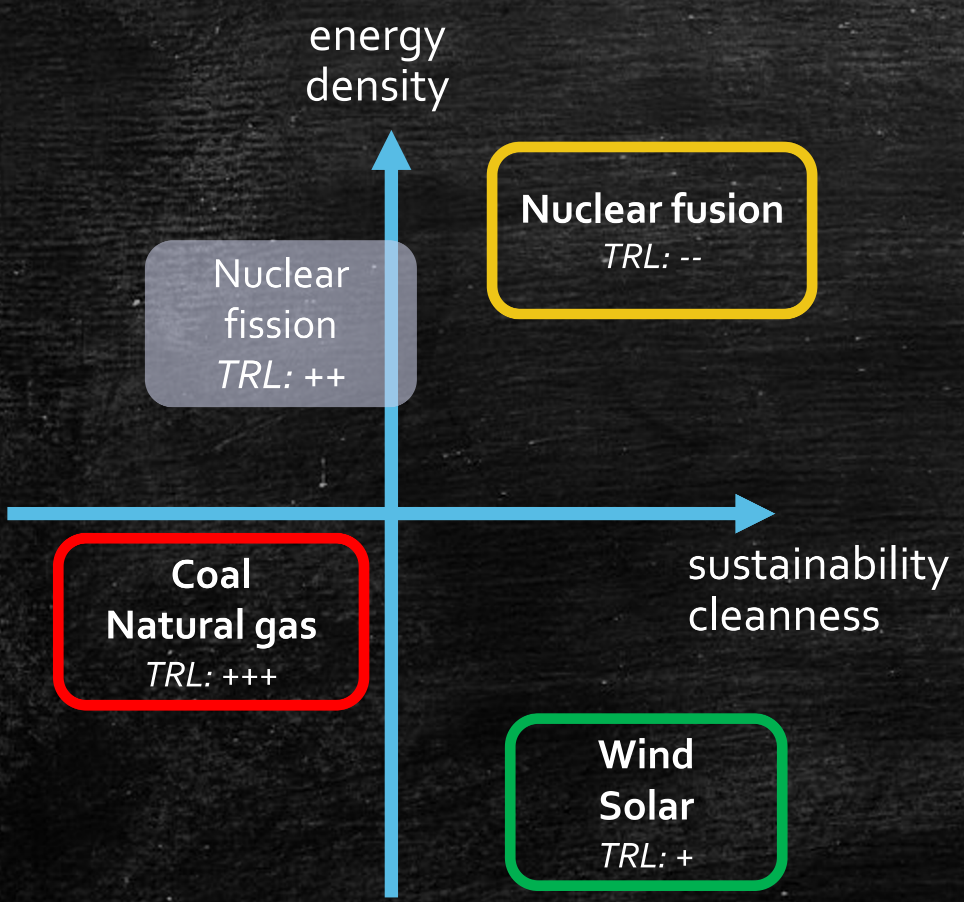
  Those damages can can significantly degrade material properties (thermal conductivity, ductility, resistance to fatigue, …) and reduce material performances and lifetime
- Co-deposition of impurities and plasma particles may result in amorphous layers storing a large amount of particles
- **Material sputtering results in pollution of the plasma by impurities which can cool down the plasma by radiations. The efficiency of the plasma radiative cooling increases with the impurity atomic number Z**

Part II

Putting the sun in a sustainable and fusion-friendly box

Constraints imposed by plasma-material interactions on plasma-facing components in tokamaks

Turning nuclear fusion into a sustainable renewable energy source



(controlled*) nuclear fusion

+ carbon-free footprint
+ abundance and accessibility of fuel
+ absence of high-level radioactive waste
+ safe: no runaway nuclear reaction
- It is very very very very complicated…

Virtually an inexhaustible, safe, environmentally friendly and universally available energy source capable of meeting global energy needs

One of the most challenging areas of experimental and theoretical physics and engineering

Plasma-material interactions are among the main technological challenges !

TRL (technology readiness level): measure the maturity of a ***technology***

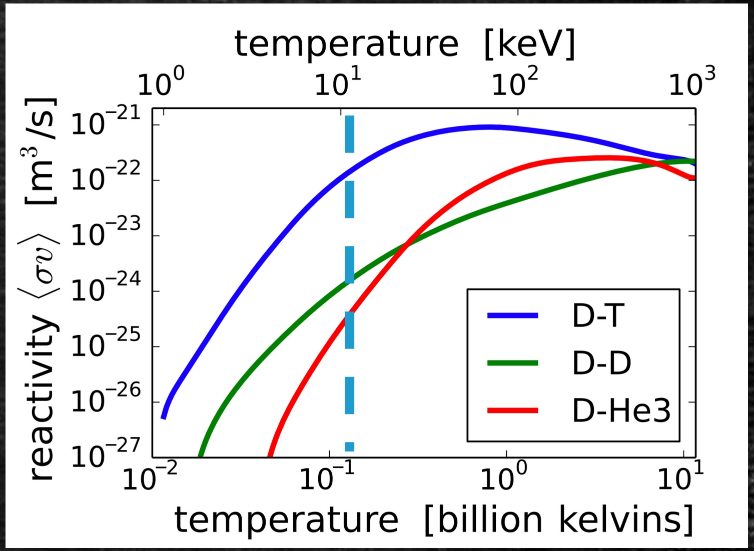
*not a H bomb!

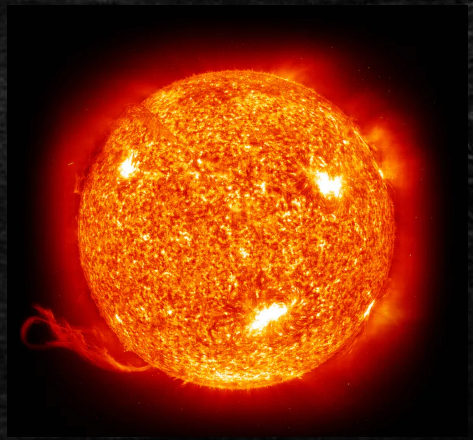
Making a continuous source of nuclear fusion energy requires to confine a very hot plasma

- Thermonuclear* fusion reactions require a very high temperature for their inception to overcome the Coulomb barrier:

  $T > 10\text{keV} \sim 10^9 K$ (it is hot!)

- At those temperatures, matter is its fourth state: a plasma (ionized gas)
- **Obtaining a sustainable source of nuclear fusion energy requires to confine the plasma to prevent plasma particles from running away and cooling down**
- For instance , the sun and the stars are essentially hot plasma balls and shine because of fusion reactions in their core
- The confinement of the plasma in the sun and stars is due to the the large gravitational force resulting from the enormous mass of the sun ~ 10^{30}kg
- **Gravitational confinement of fusion plasma is impossible on Earth!**

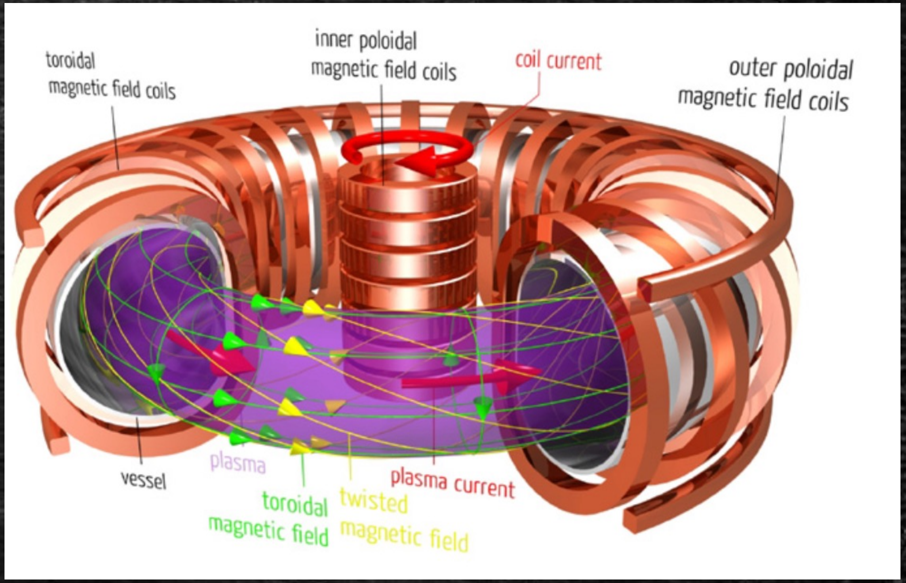


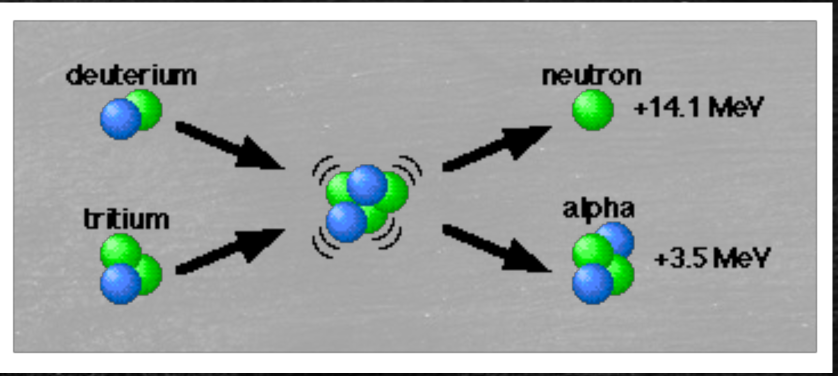


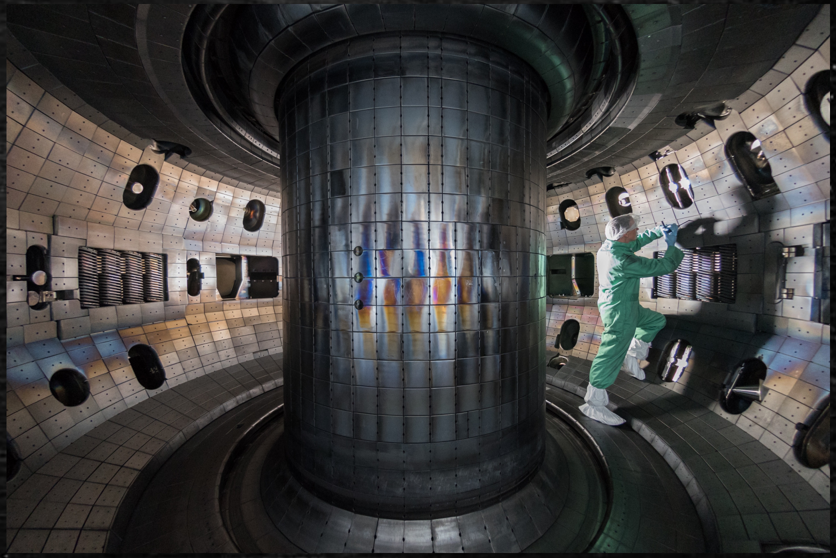
* Thermo = thermalized energy distribution of plasma particles

The most promising and advanced concept for a thermonuclear fusion reactor is the tokamak

- **Tokamak**: confinement of plasma with magnetic field in a torus shape
- Invented by Tamm and Sakharov in the 50's
- Tokamaks are designed to produce fusion. energy via the D-T reaction







How to build a donut-shaped "box" that can contain a D-T fusion plasma?

The magnetic confinement of the fusion plasma in a tokamak is not perfect…

- Production of net fusion energy defined by the triple product:

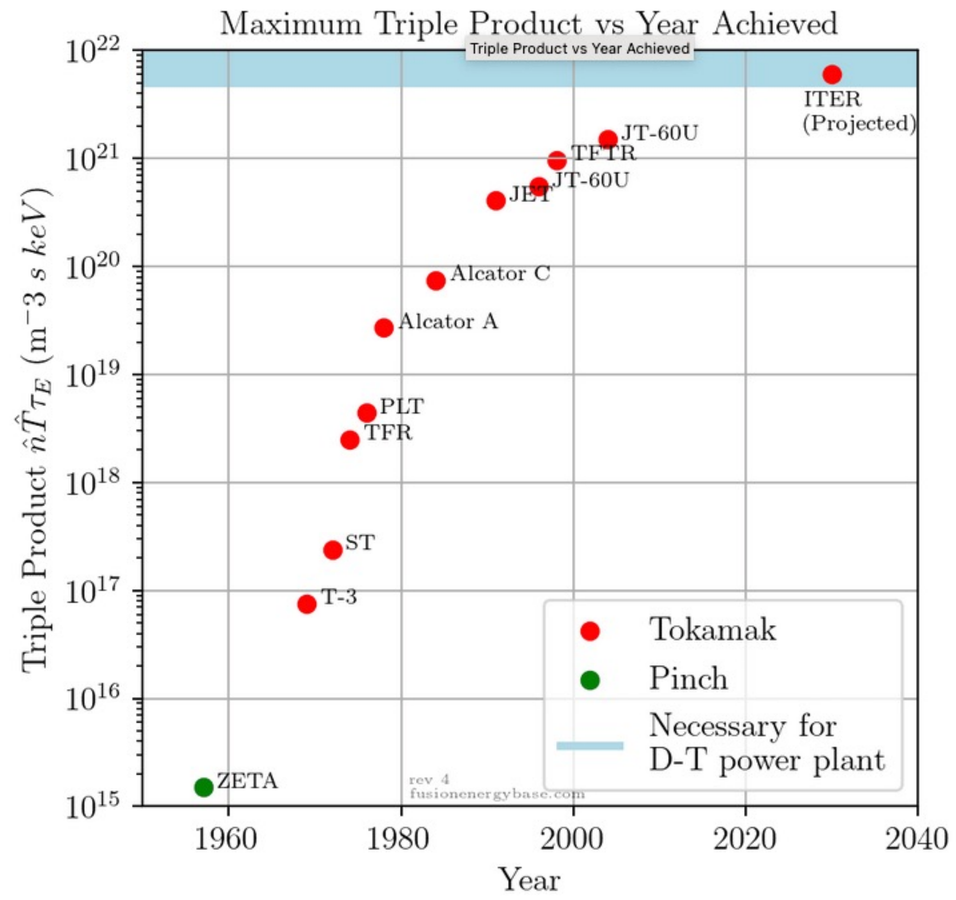
$$n_{core} \times \tau_E \times T_i$$

plasma density → n_{core}; τ_E ← energy confinement time; T_i ← plasma temperature

- Progress toward commercial fusion reactors have been principally made by improving the confinement of the fusion plasma:

$$\tau_E \nearrow$$

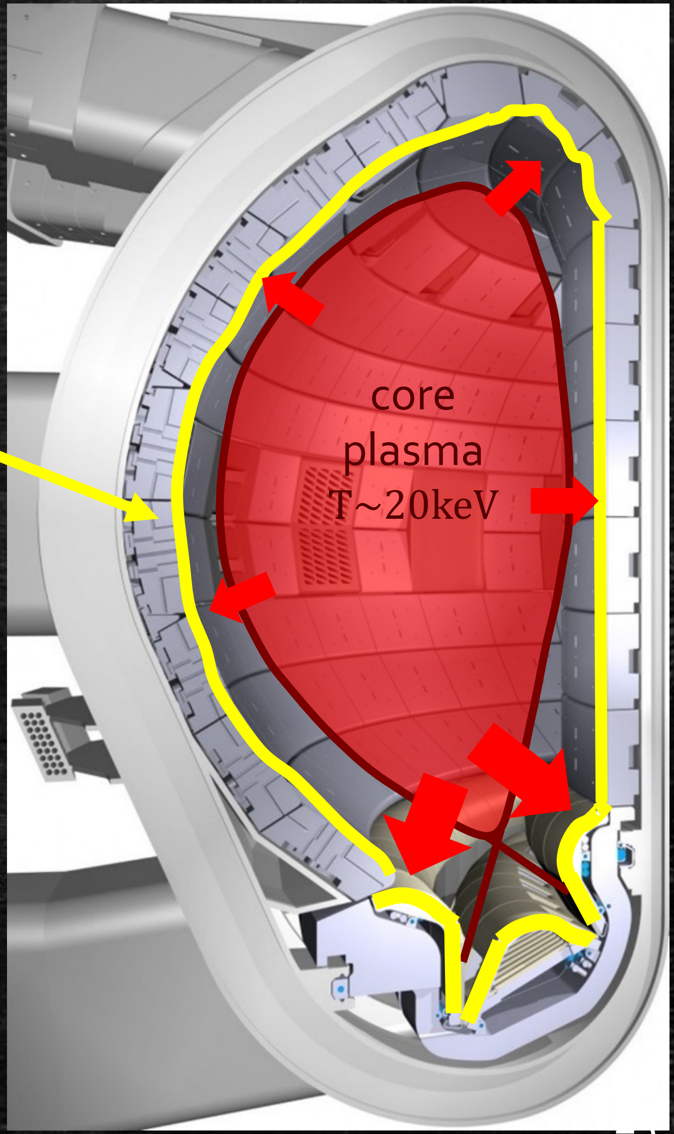
- **But τ_E will always have a finite value!**



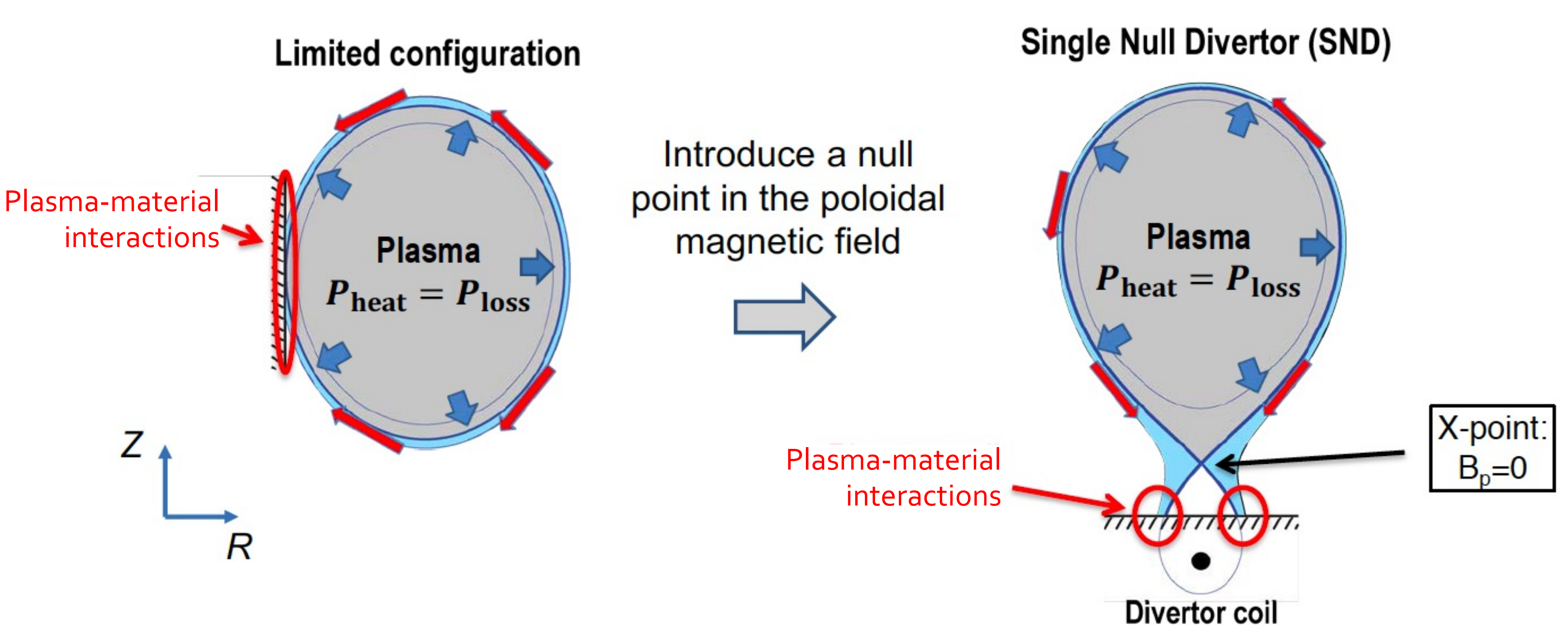
…and particle and energy leaks outside of the core plasma and interact with plasma-facing components

- As a result of the finite confinement of the core plasma, **plasma particle and energy leaks outside of the core plasma region and interact with plasma-facing components**
- **Plasma-facing components**: components exposed to the plasma in a fusion devices
- As we have seen previously, the interactions of the plasma with materials result in:
  - The pollution of the plasma with impurities
  - The modification of the particle and power balance due to the recycling of plasma particles from materials as neutrals
  - The degradation of material performances and lifetime
- PMI will generally reduce performances of the fusion plasma and limit the duration of plasma operations

Engineering and physics solutions must be developed to mitigate deleterious effects of PMI on fusion performances and sustainability



Example: diverting particle and heat fluxes away from the first wall into … a divertor



- Advantage of the divertor configuration:
  - Reduce contamination of core plasma by impurities
  - Reduce sputtering of plasma-facing components
  - Allow better control of the plasma density and removal of He ashes by pumping (high plasma density in divertor)

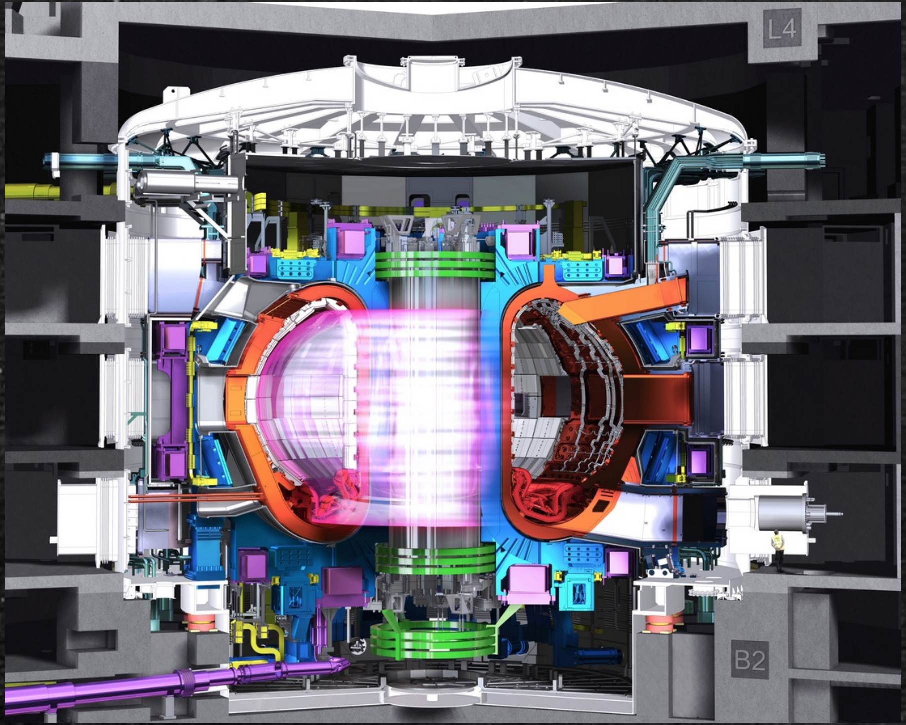
direct result of PMI!

A divertor configuration significantly increases fusion performances in a tokamak!

- **What are the conditions faced by plasma-facing components in this divertor configuration?**

→ Let's take a look at ITER…

ITER will be soon the biggest tokamak ever built and will be a major step toward a commercial fusion reactor

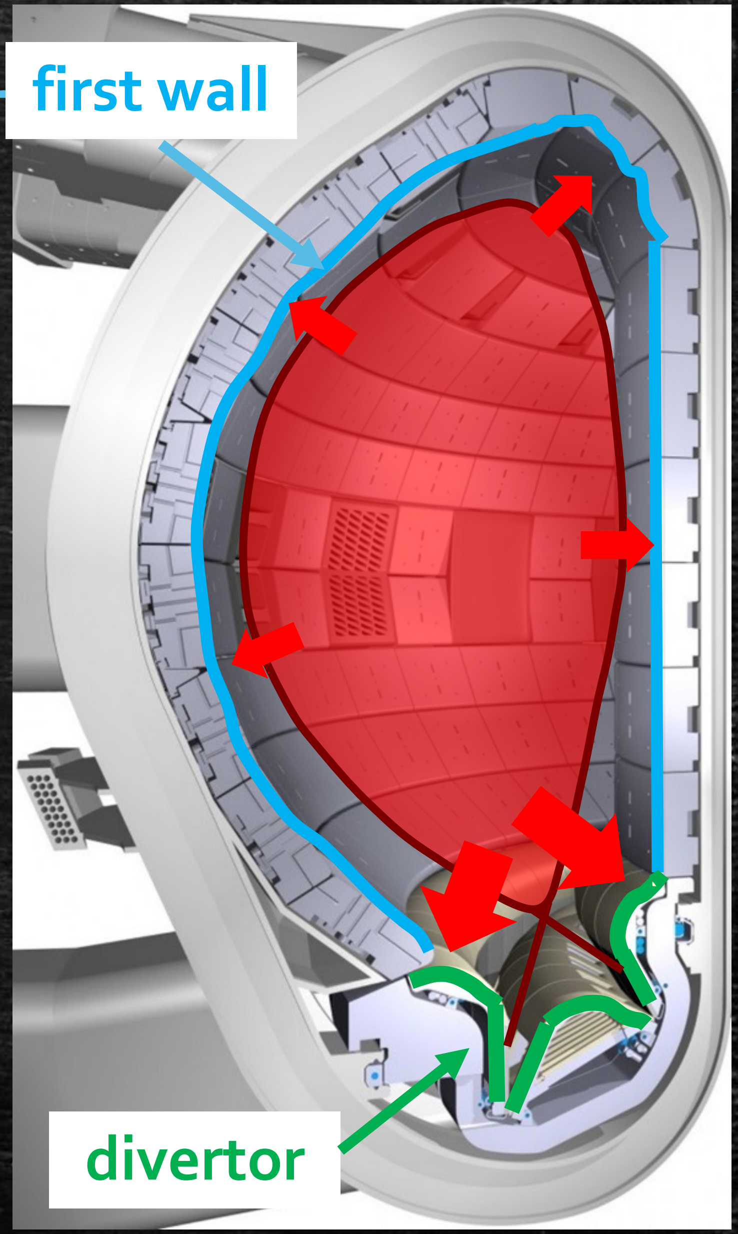


- **ITER will be a major step toward a commercial fusion reactor**

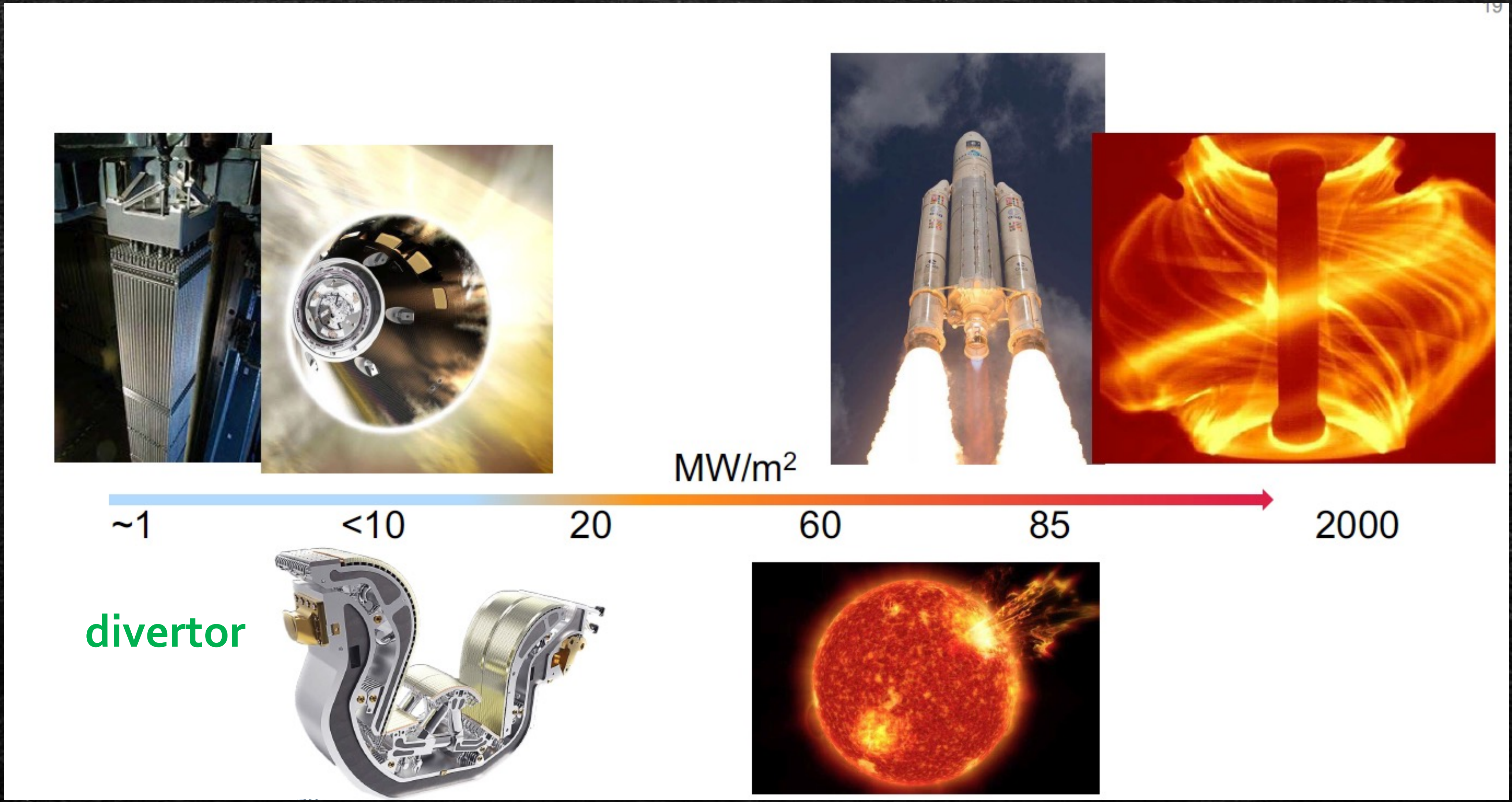
Plasma conditions faced by materials in ITER will be representative of conditions in a commercial fusion reactor

Plasma–facing components in divertor must handle enormous heat and particle fluxes

- ITER baseline scenario: $\mathrm{P_{fus}} = 500\mathrm{MW}$
  – finite core plasma confinement: $\mathrm{P_{core \to boudary}}$ = $100\mathrm{MW}$
- In divertor configuration, heat and particles fluxes leaking from the core plasma are directed toward the divertor
- Plasma-facing components in **divertor** will face extreme plasma conditions:
  – **Very high heat flux ~ $\mathbf{10\ MWm^{-2}}$**
  – **Very high particle flux ~ $\mathbf{10^{24} m^{-2} s^{-1}}$**



Plasma conditions faced by divertor materials are among the most extremes!



Constraints imposed by PMI to build a sustainable and fusion-friendly box to hold the sun

- fusion-friendly:
  - **material erosion and contamination of plasma by impurities must be minimized:**
    - divertor configuration necessary
  - **Long-term retention of fusion fuel in materials must be limited to prevent**:
    - An excessive accumulation of radioactive tritium in the fusion device
    - Uncontrollable recycling from plasma-facing components
  - **Plasma-facing component materials must be available and cost-effective**

- Sustainable:
  - **Plasma-facing component materials must handle large heat and particles fluxes:**
    - Operation at high temperature: $T_{melting} > 2000K$, thermal conductivity > $50W\ m^{-1}K^{-1}$
    - Limited material degradation in time:
      - Must handle accumulation of defects and plasma material
      - Minimal erosion
  - **Low/medium activation by neutrons**

Plasma-material interactions impose very strong constraints on the design of a fusion reactor!

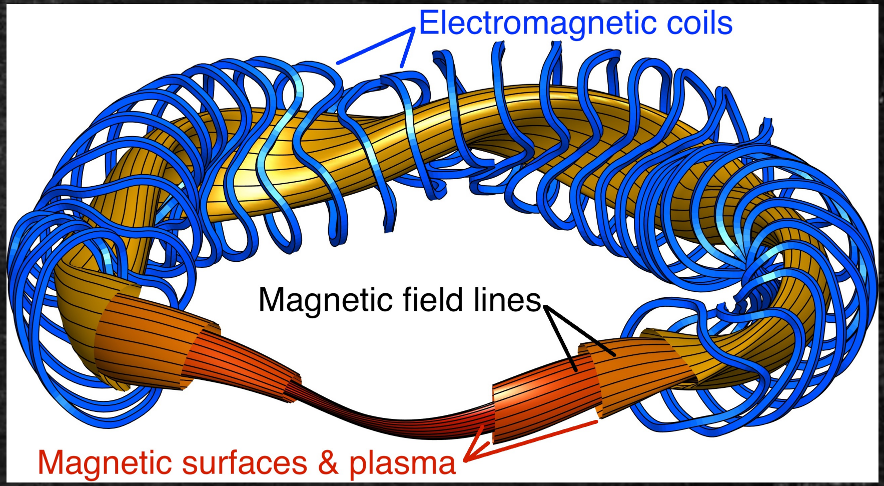
Plasma-material interactions in tokamaks are very similar in other magnetic confinement configurations

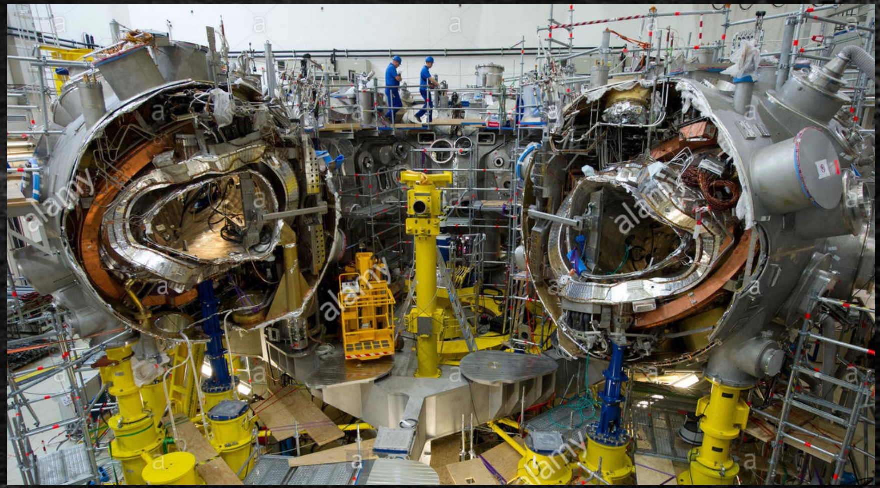
- The tokamak's cousin - the stellarator – is an equally promising concept for nuclear fusion reactors

PMI in tokamaks are generally similar in other magnetic fusion configurations like stellarators …

… and so are the constraints imposed by PMI on fusion plasma

- **By contrast, plasma-material interactions in inertial confinement fusion are very different and are not covered in this lecture.** MFC and IFC are based on very different plasma regimes and rely on very different physics
  - Magnetic Confinement Fusion: low-density plasma and long pulse (>>1 second)
  - Inertial Confinement Fusion high-density plasma and short pulse (<<1 second)





Plasma-material interactions have actually been known issues in tokamaks since day one

Power balance dominated by impurity radiations in the first tokamak T-1 [1]

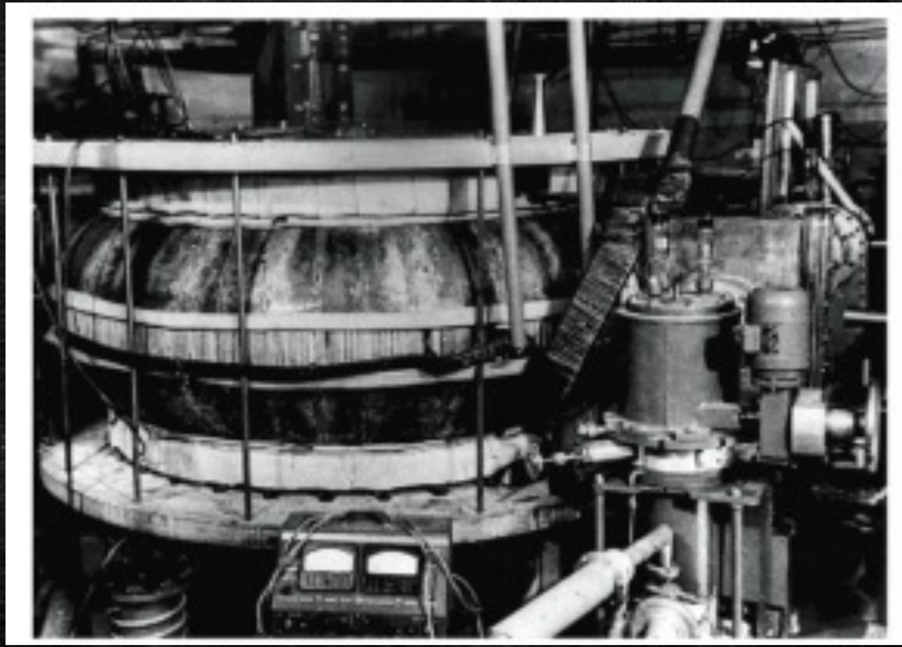
as unity. It is apparent that the radiation from deuterium is only $\frac{1}{15}$ to $\frac{1}{20}$ of the total energy radiated in this region of the spectrum.

Uncontrollable plasma density in first tokamaks due to hydrogen recycling R>1 [2]

Early tokamaks generally had recycling coefficients (box 6.5) significantly greater than unity; the majority of the plasma originated from molecules previously adsorbed on the walls rather than from the filling gas, so that it was impossible to exercise any real control over the plasma density. A

T-1 was the first tokamak

It was an all-metallic device built in Russia in 1958



1 Dolgov-Saveljev Journal of Experimental and Theoretical Physics (1960)

2 Braams & Stott Nuclear fusion: half a century of magnetic confinement fusion research (2002)

Part III

Which materials to build plasma-facing components in a fusion reactor?

Selecting plasma-facing materials compatible with PMI in fusion reactors

Which materials to build a divertor in a fusion reactor?

- ITER baseline scenario: $P_{fus} = 500MW$
  - finite core plasma confinement: $P_{core \to boudary}$ = $100MW$
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  - **Very high heat flux ~ $10\ \mathbf{MW}m^{-2}$**
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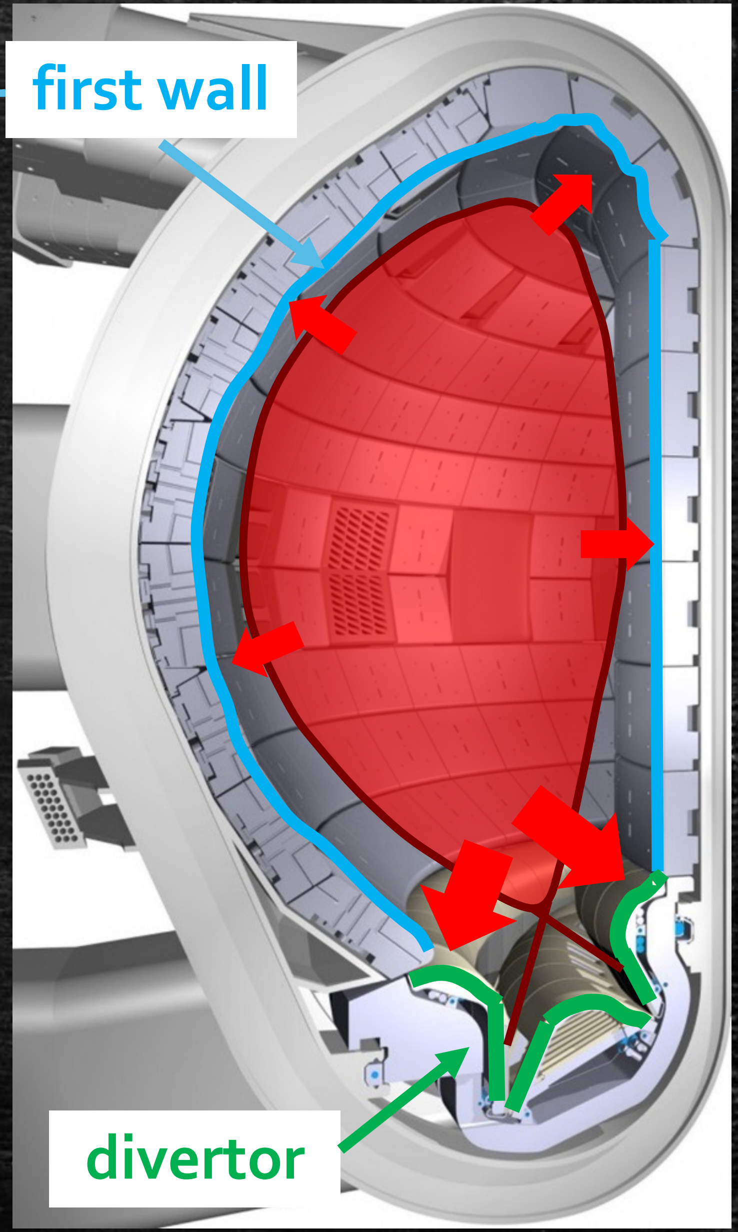

Which materials to build a divertor in a fusion reactor?

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Constraints for divertor material

- Operate at high temperature
  - $T_{melting} > 2000K$
  - Thermal conductivity > $50W\ m^{-1}K^{-1}$
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- Widely available and cost-effective
- Low/medium activation by neutrons
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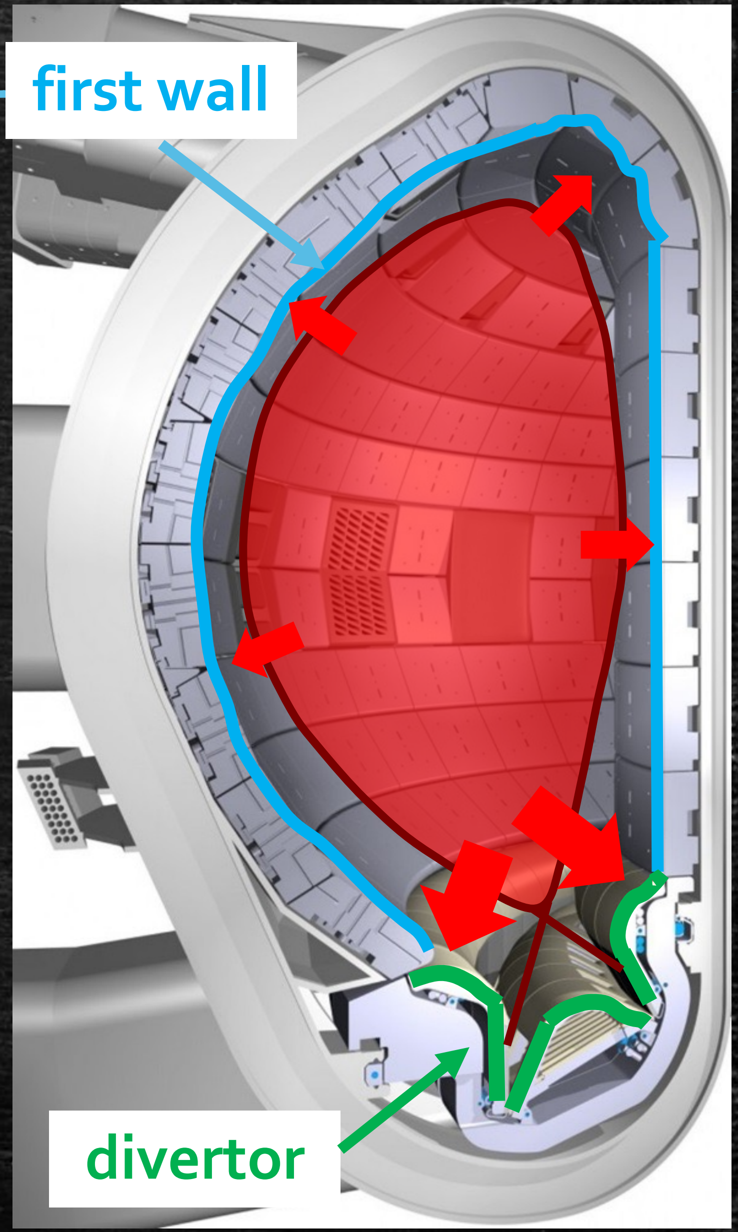

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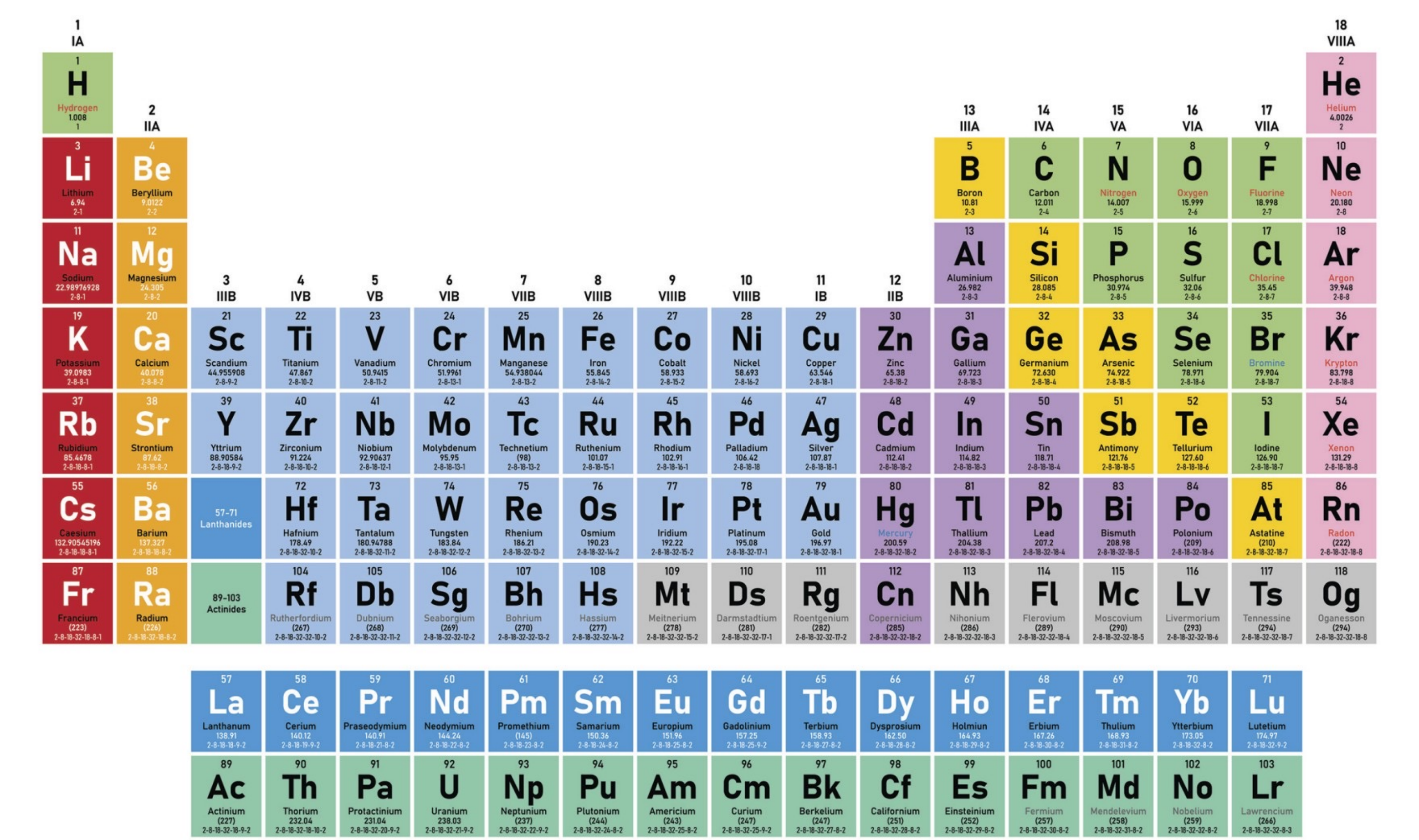

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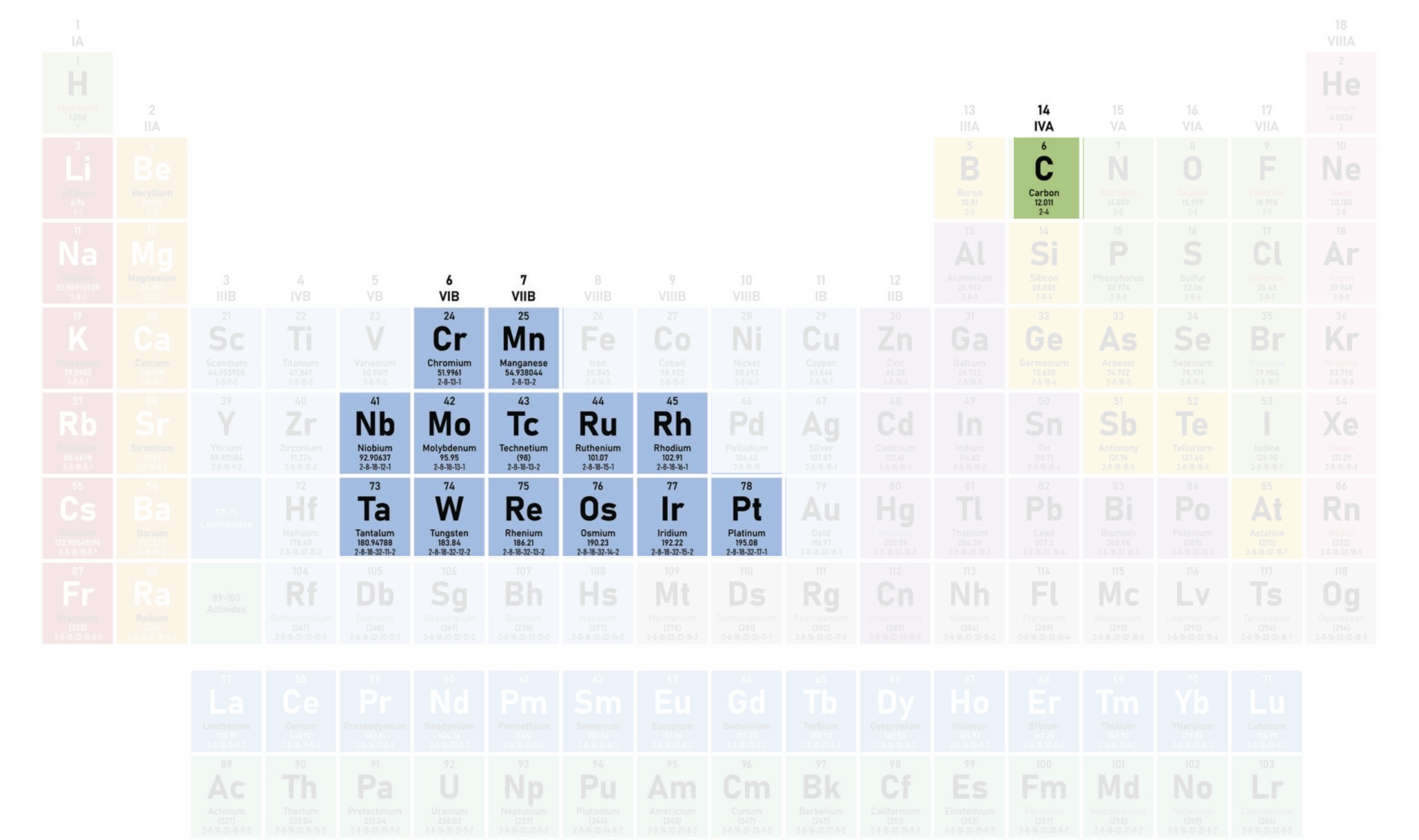

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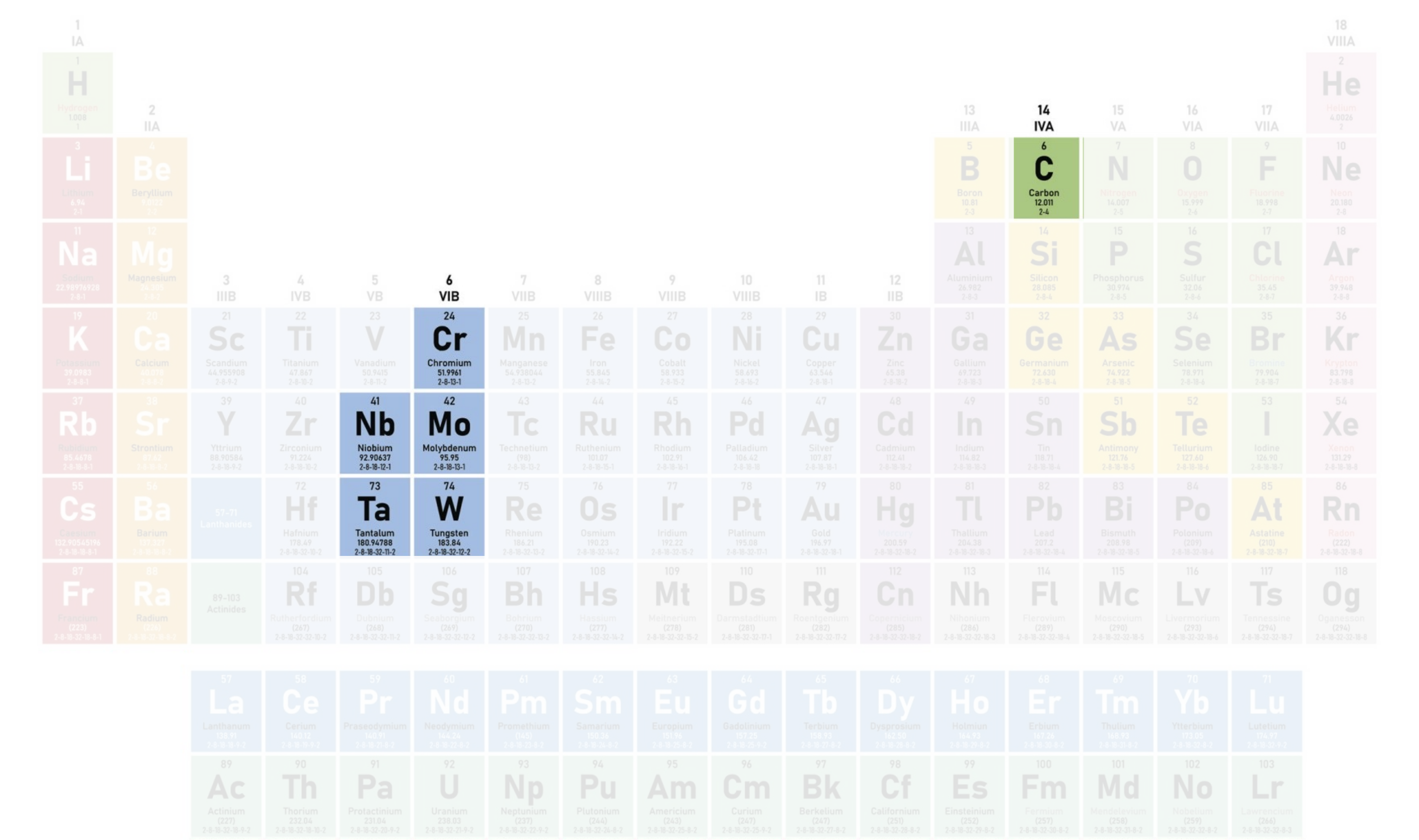

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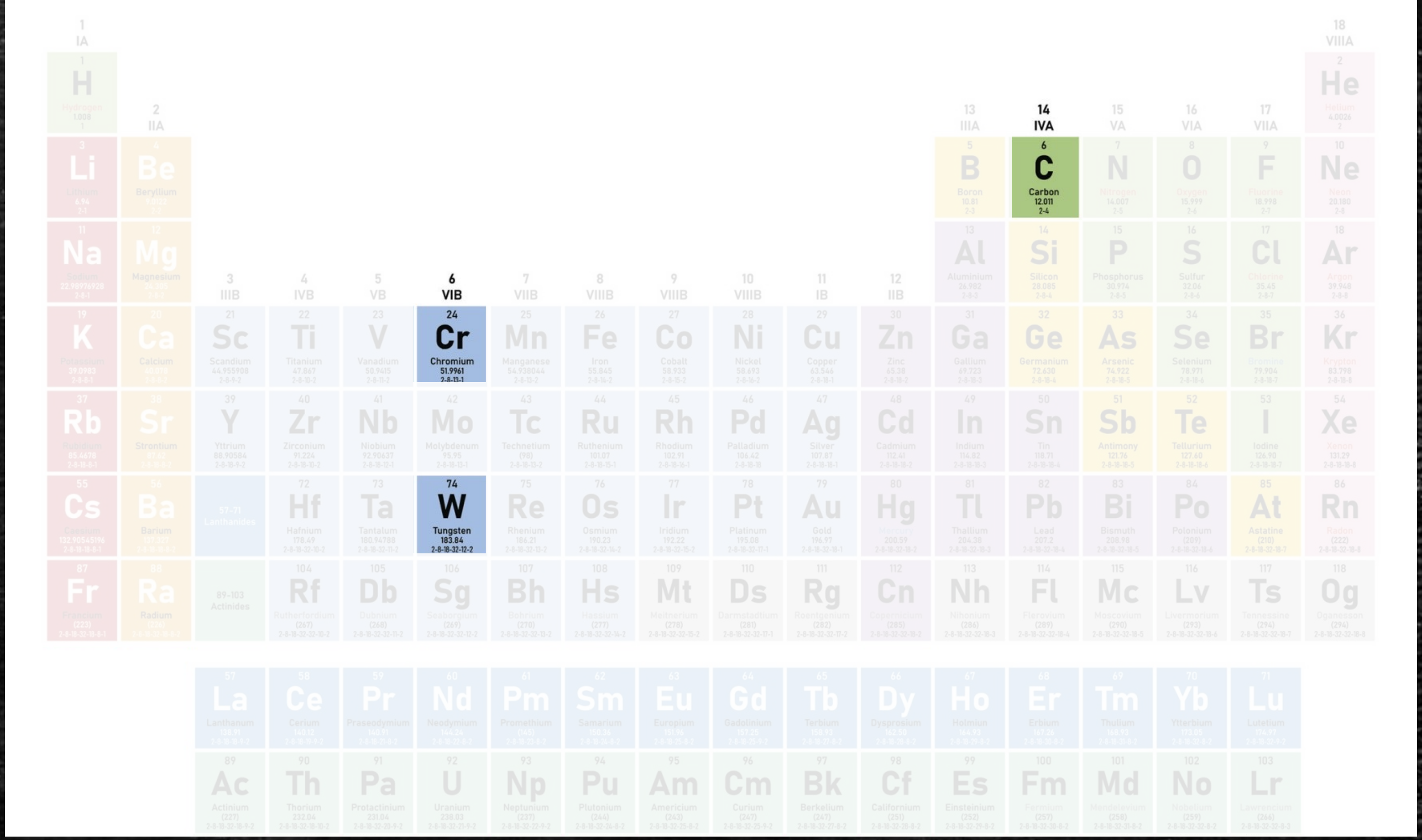

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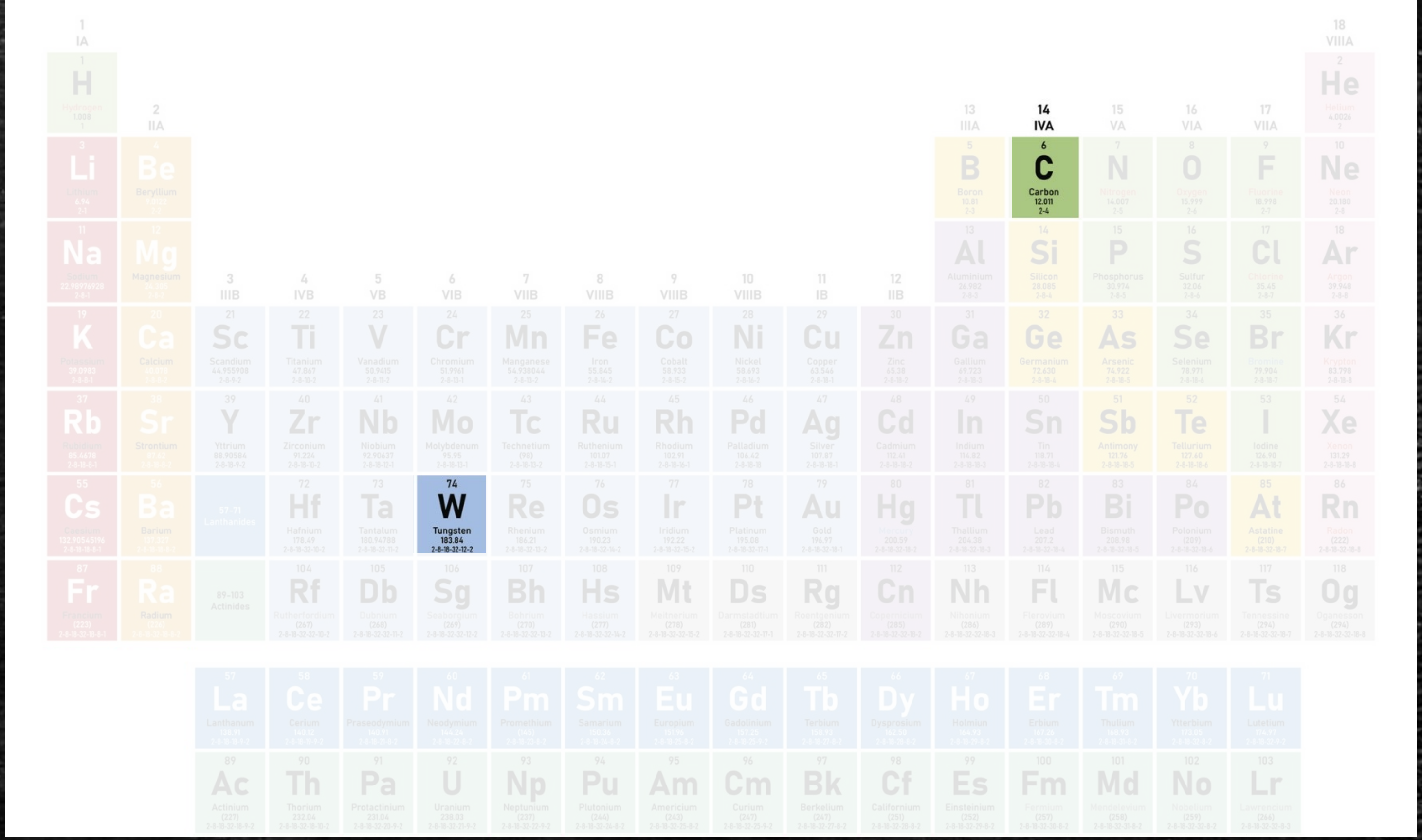

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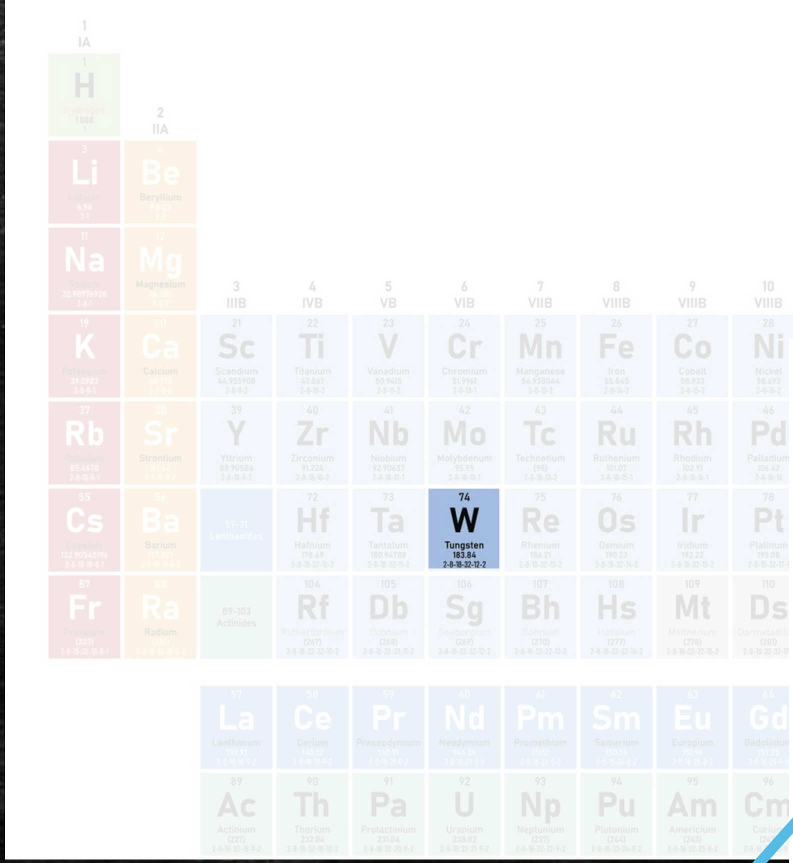

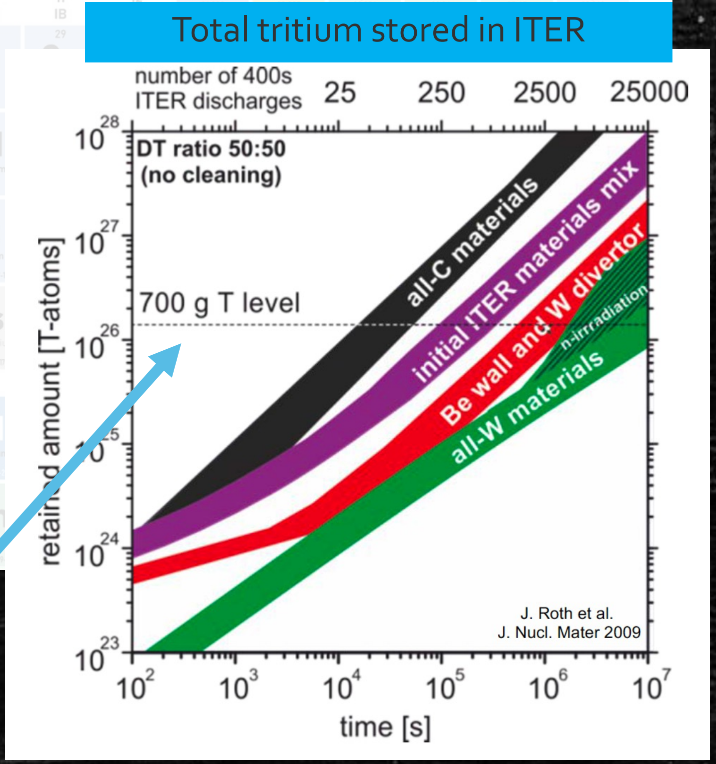

Regulatory limit on the total tritium content in ITER

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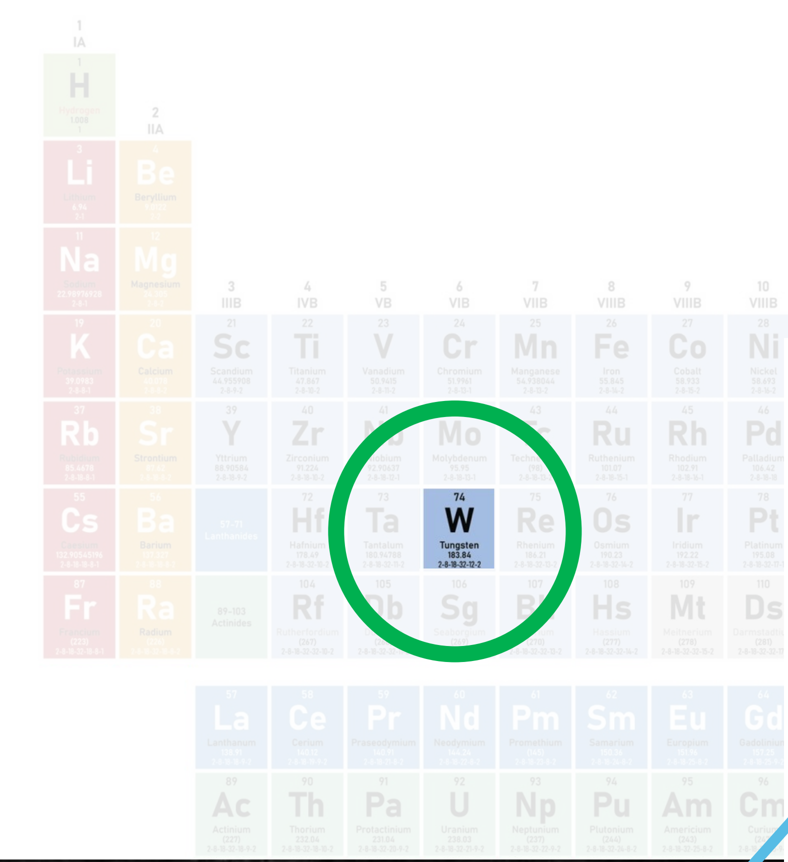
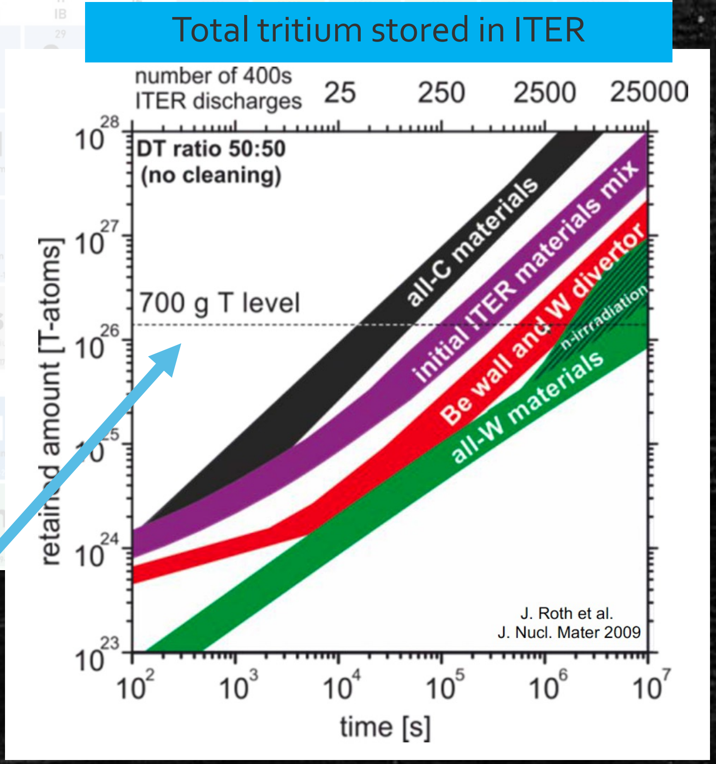


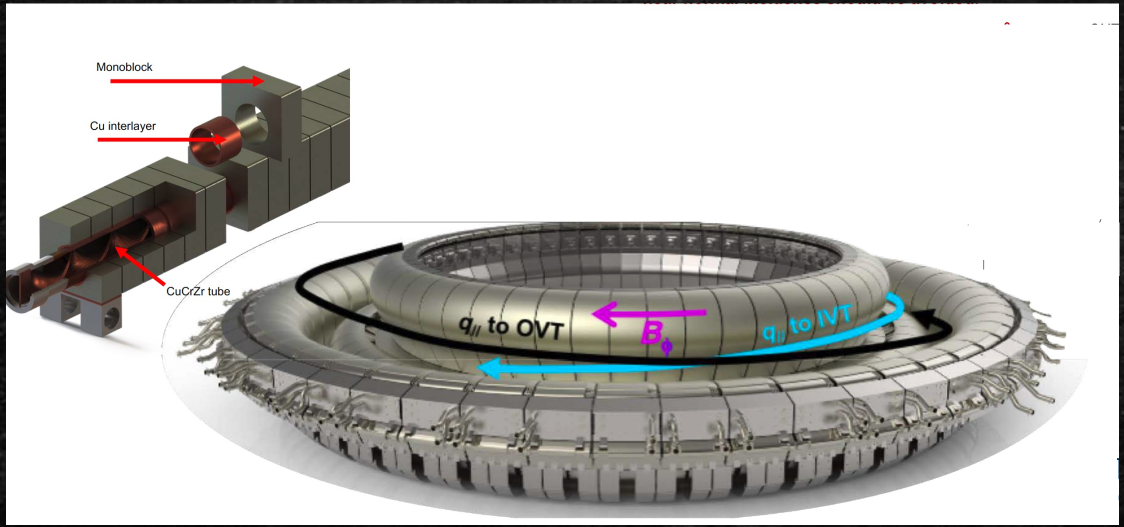


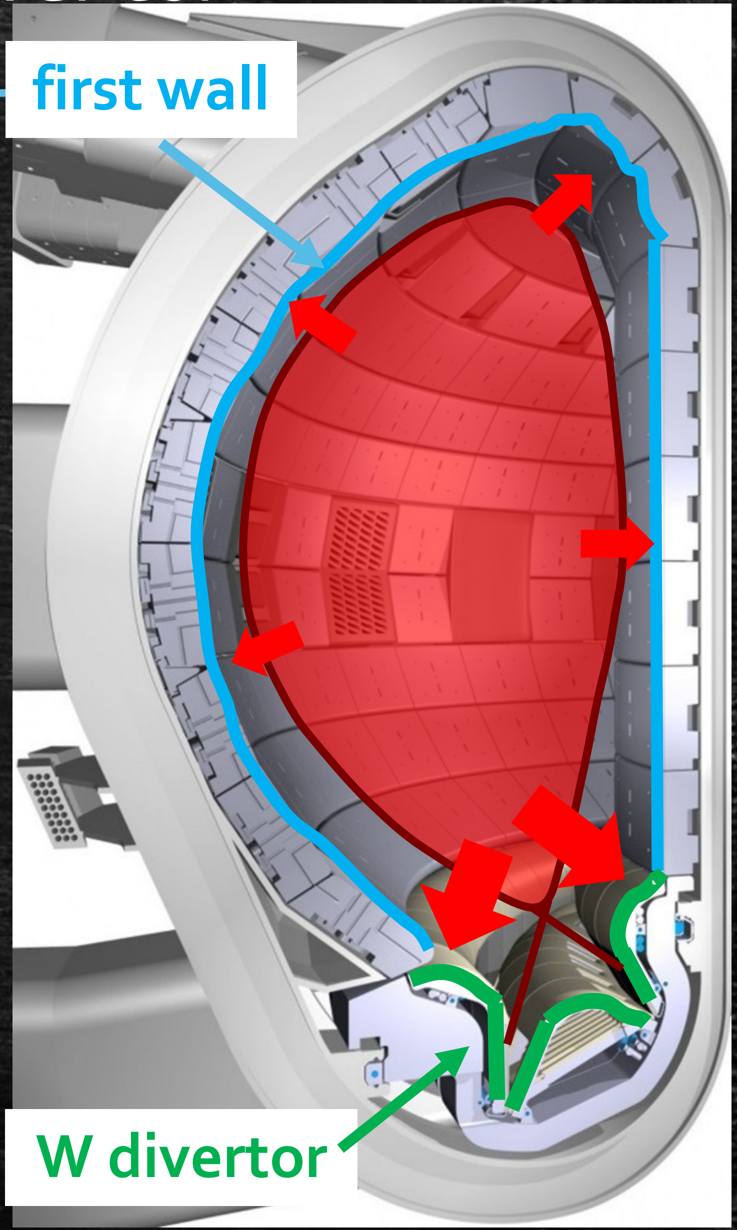
Regulatory limit on the total tritium content in ITER

ITER will operate with a tungsten divertor

- It is therefore no surprise that ITER divertor will be made of tungsten !

Tungsten is now considered as the material of choice for divertors of future fusion reactors





ITER will operate with a tungsten divertor and a beryllium wall!

- It is therefore no surprise that ITER divertor will be made of tungsten !

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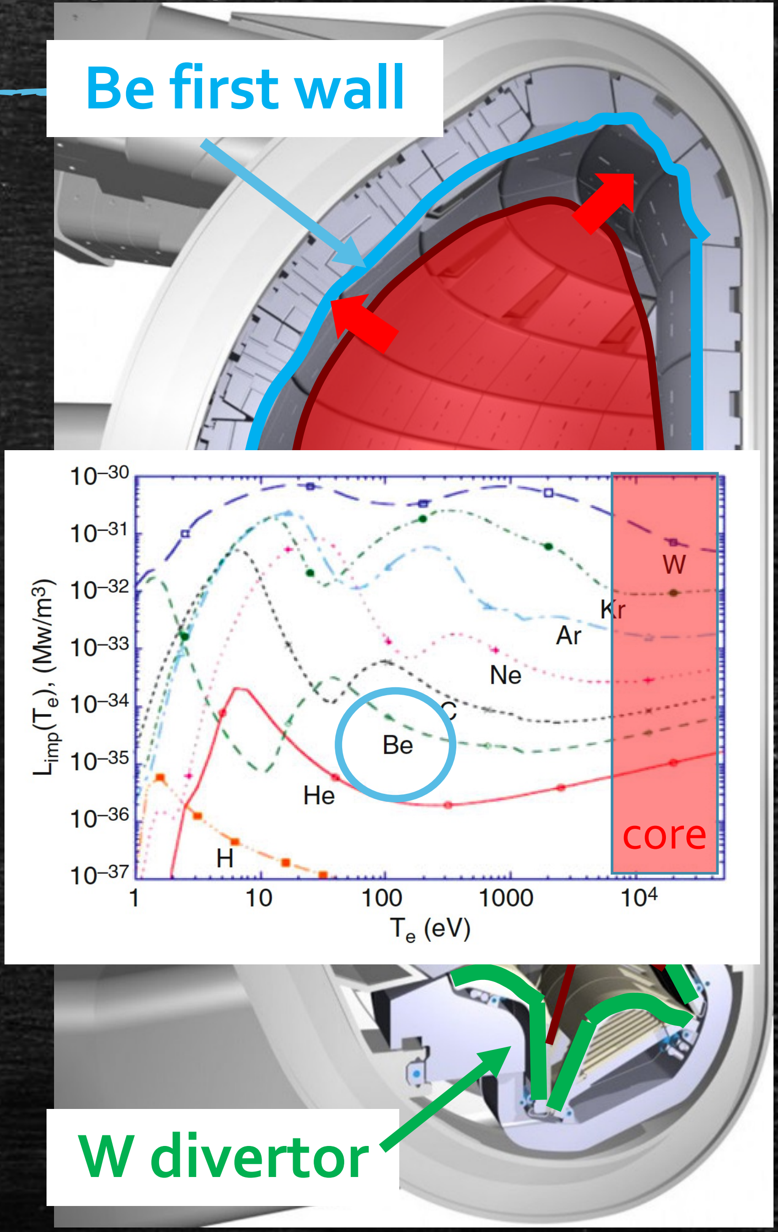
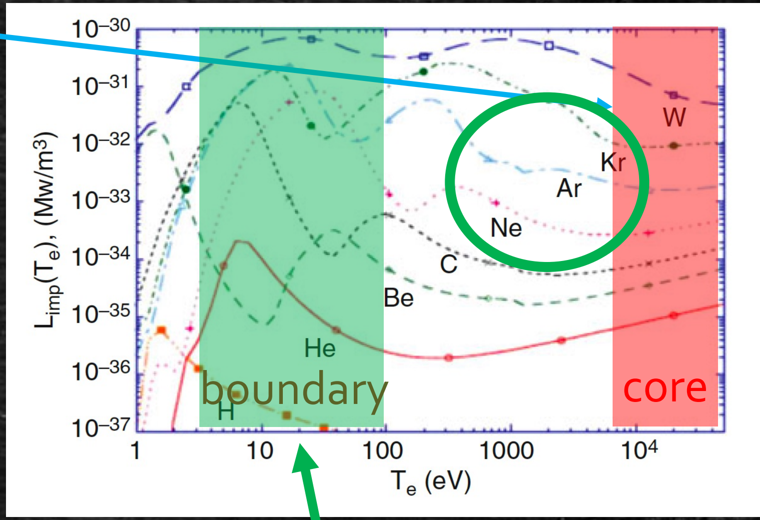
- ITER first wall will be made of beryllium
  - Beryllium (Be): Z = 4

- **Why a low-Z material for the first wall?**
  - Particle and heat fluxes onto first walls are orders of magnitude lower than in the divertor (this is the goal of the divertor)
  - Low-Z impurities do not significantly cool the core plasma
  - Be is also an excellent oxygen getter (capture oxygen present initially in plasma)
  - Co-deposition of Be with tritium and deuterium is much lower than with carbon



Wait a minute!

- Isn't tungsten (W) a high-Z material that can cool down and kill fusion plasma ?
- Yes! This is a compromise imposed by PMI…
  - Tungsten concentration in the core must remain very low ($< 10^{-5}$)
  - Erosion of tungsten in divertor must be strongly mitigated
  - Temperature of plasma hitting tungsten divertor must be below 5eV



- **In addition, the heat flux deposited on tungsten divertor is expected to exceed the engineering limit of $10\mathrm{MWm}^{-2}$**

→ Plasma must be significantly cooled down before reaching divertor plasma-facing components :
  - **Can be achieved by introducing mid-Z impurities that radiate power only in the boundary plasma**
  - When the temperature of plasma is below 5eV, plasma ions recombine into neutrals and the divertor plasma become detached from the divertor surface: **this process is called "detachment"**
  - **How such detachment can be achieved in a fusion reactor remains an open question!**

Finding sustainable power and particle exhaust solutions in tokamaks remains one of the biggest challenges to achieve fusion energy!

Part IV

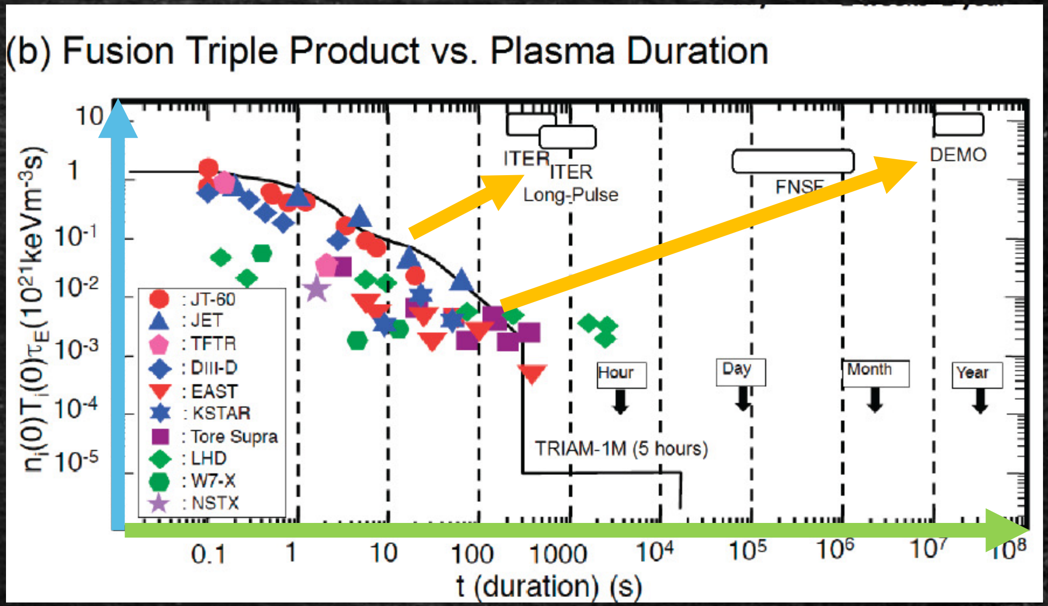
Modeling and simulations of plasma-interactions in tokamaks

The challenging yet necessary predictions of PMI needed to design future fusion reactors

Modeling and simulating of plasma-material interactions are critical to design future fusion reactors

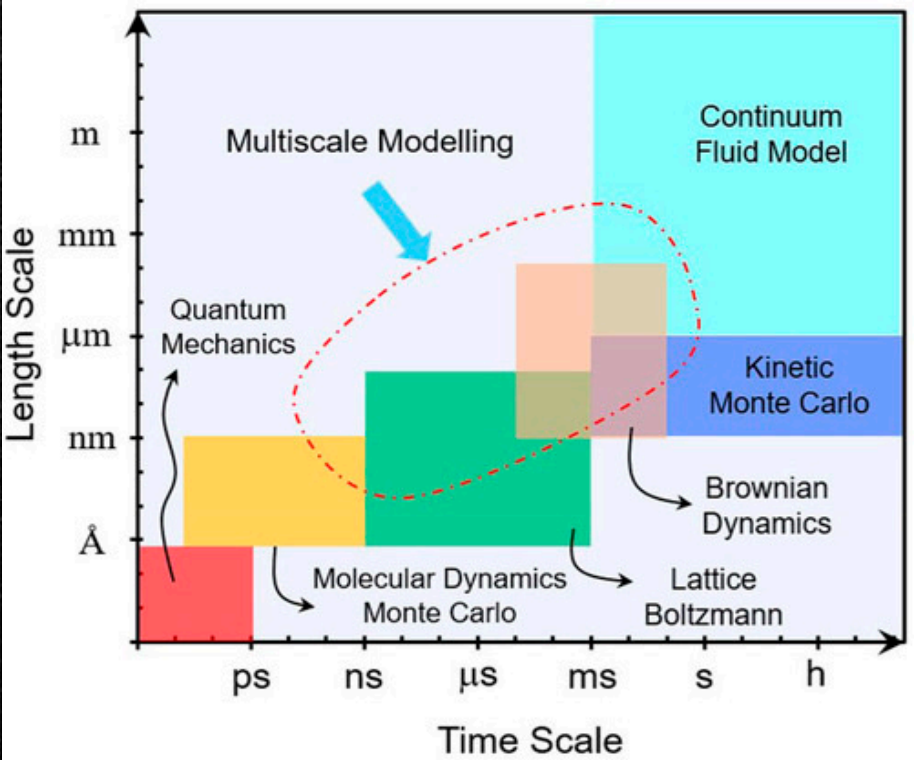
- We have seen that PMI very heavily constrain the feasibility and the sustainability of magnetic fusion reactors (tokamaks)

- It is however virtually impossible to build an experimental device to study simultaneously all aspects of PMI relevant for a commercial fusion reactor:
    - fusion devices are costly (ITER > $20B)
    - long-pulse plasmas require superconductor magnets
    - radioactive tritium
    - toxic beryllium
    - activation of materials by neutrons



- **Modeling and simulating PMI in tokamaks are therefore essential to design and build future fusion reactors by bridging the gap with existing experiments through:**
    - **Extrapolation of PMI in current experiments to the relevant duration of operations in commercial fusion reactors**
    - **Extrapolation of PMI effects on fusion performances to commercial fusion reactors**

Modeling and simulating PMIs in tokamaks is an enormous challenge due to the multiscale and complex nature of PMI



- PMI in tokamaks are governed by a variety of complex material and plasma which take place on time and space scales spanning over several orders of magnitude!
- Comprehensive modeling and simulations of PMI in tokamaks require to solve a hierarchy of material and plasma models and to couple them
- Start-of-the art high performance computing methods on the most powerful computers in the world are necessary to tackle this challenge!

The multiscale and complex nature of material and plasma processes governing PMI in magnetic fusion devices makes the modeling and the simulations of PMI:

- extremely challenging
- very interesting as it covers almost all aspects of modern physics!

Summary

- **Plasma-material interactions are governed by various complex and multi-faceted atomic and plasma processes**
- **PMI impact the plasma through:**
  - the recycling of plasma particles as neutrals from the material surface into the plasma
  - the sputtering of material atoms into the plasma, resulting in the contamination of the plasma by impurities which can radiate a large amount of power
- **PMI impact material through:**
  - Accumulation of defects and plasma particles into material
  - Large heat flux carried by plasma particles
- **PMI impose strong constraints on the sustainability and the performances of a fusion reactor:**
  - Plasma-facing components must sustain very high particle and heat flux during a long time (t ~ weeks)
  - Plasma-facing components must be able minimize the accumulation of radioactive tritium particles and handle significant neutron flux
  - Fusion performances (power and confinement) must not be significantly reduced by the contamination of fusion plasma with material impurities and by the recycling of plasma particles as neutrals

Summary

- **Designing a fusion reactor which can handle those PMI constrains is one of the biggest challenges in developing of viable fusion reactors to makes fusion energy available to the mankind**
- Only a few materials can handle all PMI constraints, e.g. tungsten(high-Z) and graphite (low-Z)
- The divertor in ITER will be made of tungsten , which is now considered as the material of choice for divertors of future fusion reactors
- However, even with tungsten, boundary plasma in fusion reactors must be significantly cooled down before reaching divertor plasma-facing components, e.g with detachment of the plasma
- **Finding sustainable power and particle exhaust solutions in tokamaks remains one of the biggest challenges to achieve fusion energy, and requires to model and simulate PMI in tokamaks to bridge the gap with existing experiments**
- Modeling and simulating PMI is extremely challenging due to the the multiscale and complex nature of PMI
- **Experimental studies of PMI are critical to inform those models!**

$\Rightarrow$ **How to experimentally assess PMI and build plasma-facing components of divertor and first walls in fusion reactors?**

This is the topic of the next lecture!

Opportunities for internships and PhD projects available at General Atomics, San Diego, CA


General Atomics


San Diego, CA

Opportunities for internships and PhD projects on plasma-material interactions available at General Atomics on the San Diego campus!

Contacts:

- **Theory and simulations:** guterlj@fusion.gat.com
- **DIII-D experiments**: abramst@fusion.gat.com


DIII-D tokamak at General Atomics

Some references to go further

- F. Chen, *An indispensable truth: how fusion power can save the planet*. Springer Science & Business Media, 2011.
- J. Wesson, *Tokamaks*. Vol. 149. Oxford university press, 2011
- D. Naujoks, *Plasma-material interaction in controlled fusion*. Vol. 39. Springer Science & Business Media, 2006.
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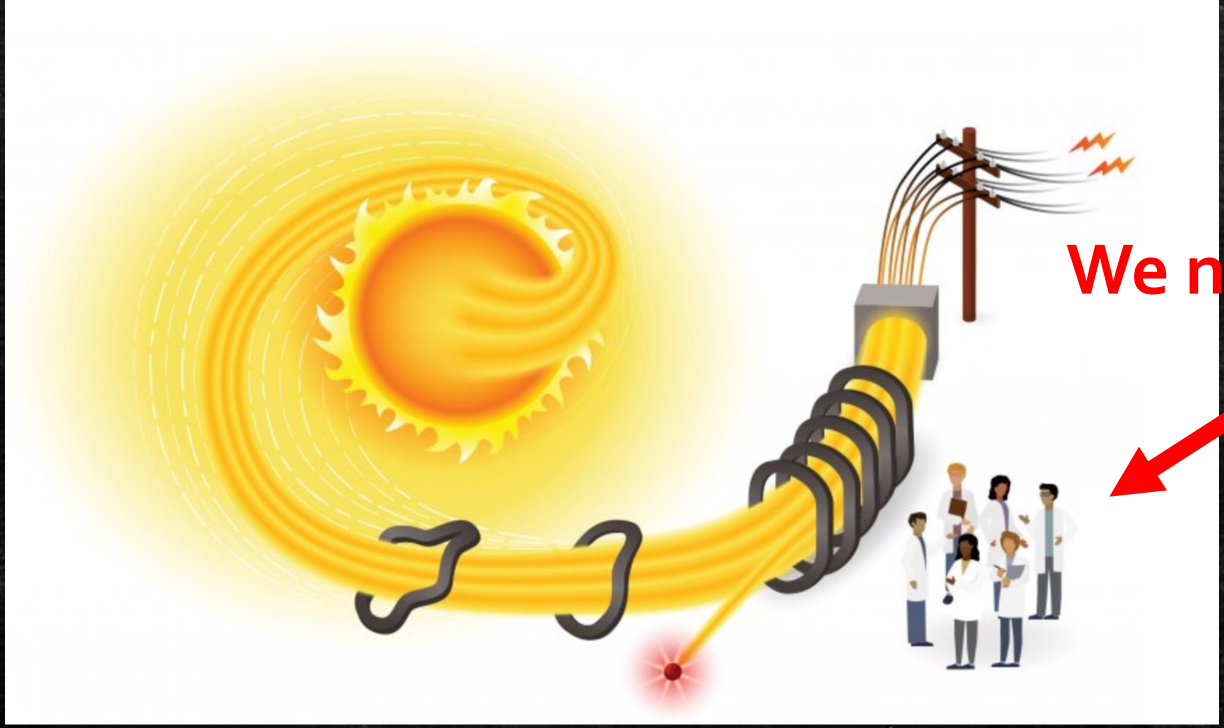
- S.I. Krasheninnikov, *On the Edge of Magnetic Fusion Devices*. Springer International Publishing, 2020

A last word...

- Fusion energy is nowadays getting significant traction in the US and around the world ...
- ...but achieving fusion power on the grid will require a lot of talented and dedicated scientists and engineers!



We need you there!