

Introduction to Fusion Energy and Plasma Physics Course

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Plasma-Material Interactions I

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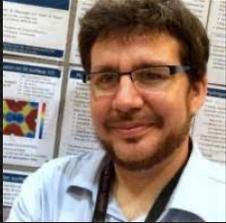
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*A journey across plasma-material interactions in
magnetic fusion plasma and nuclear fusion reactors*

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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General Atomics, San Diego, CA, USA

2008 M.S. Aerospace Engineering
 *ISAE-SUPAERO, France*

2009 M.S. Plasma Physics
 *EPFL, Switzerland*

2009 Visiting Scientist
 *Los Alamos National Lab, USA*

2015 PhD – Plasma Engineering Physics
 *UC San Diego, CA*

2019 Post doctoral Fellow
 *General Atomics, San Diego, CA*

now Staff Scientist
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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!

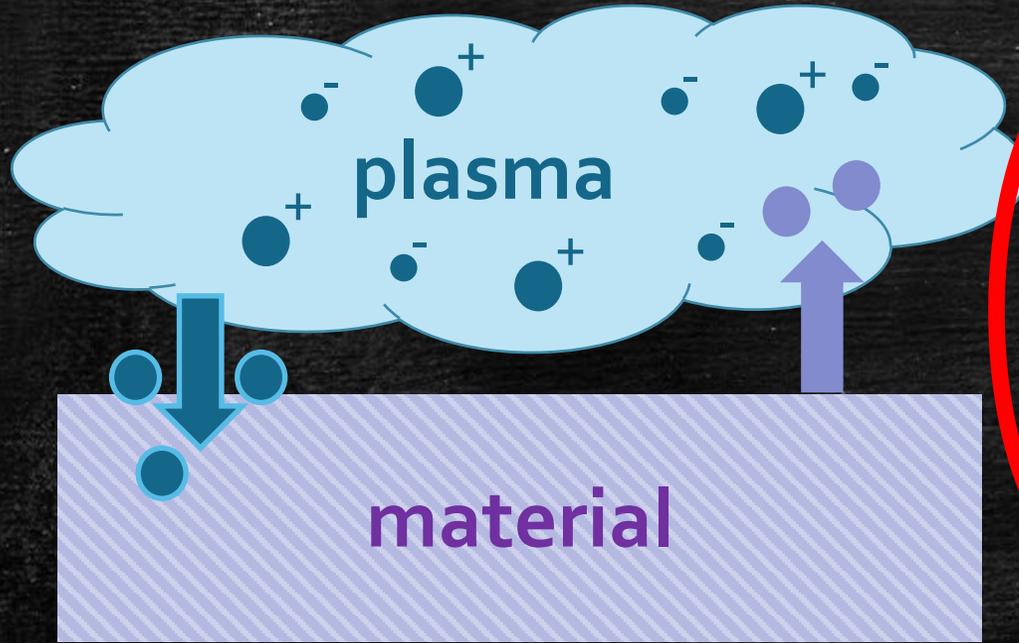
Introduction

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



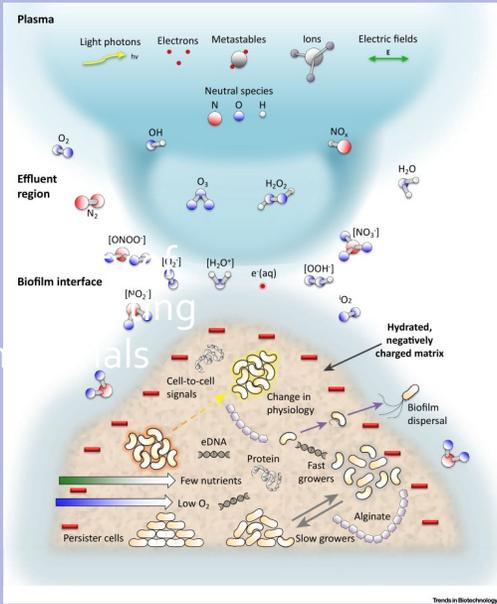
rule of thumb #2

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)

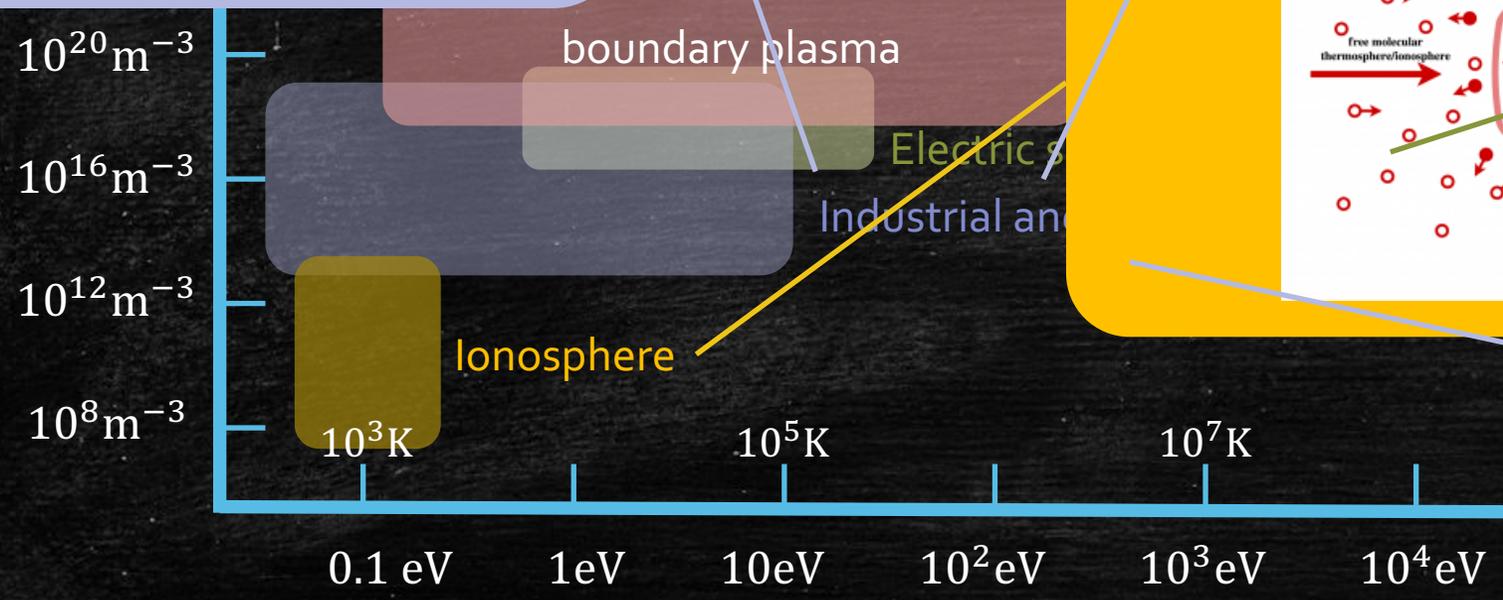


charge plasmas with neutral molecules

Plasma etching
(mainly for microelectronics)

Hall and ion thrusters
(lifetime of thruster components)

atmospheric re-entry
(thermal shielding)



Temperature-dependent plasma-surface interactions

Plasma-material interactions are ... where plasmas are!

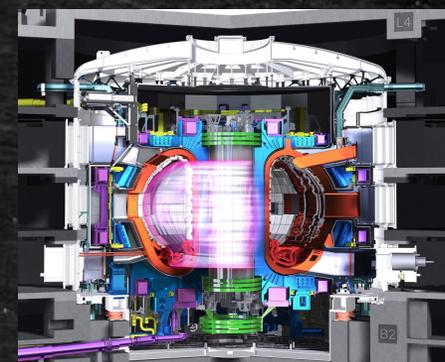
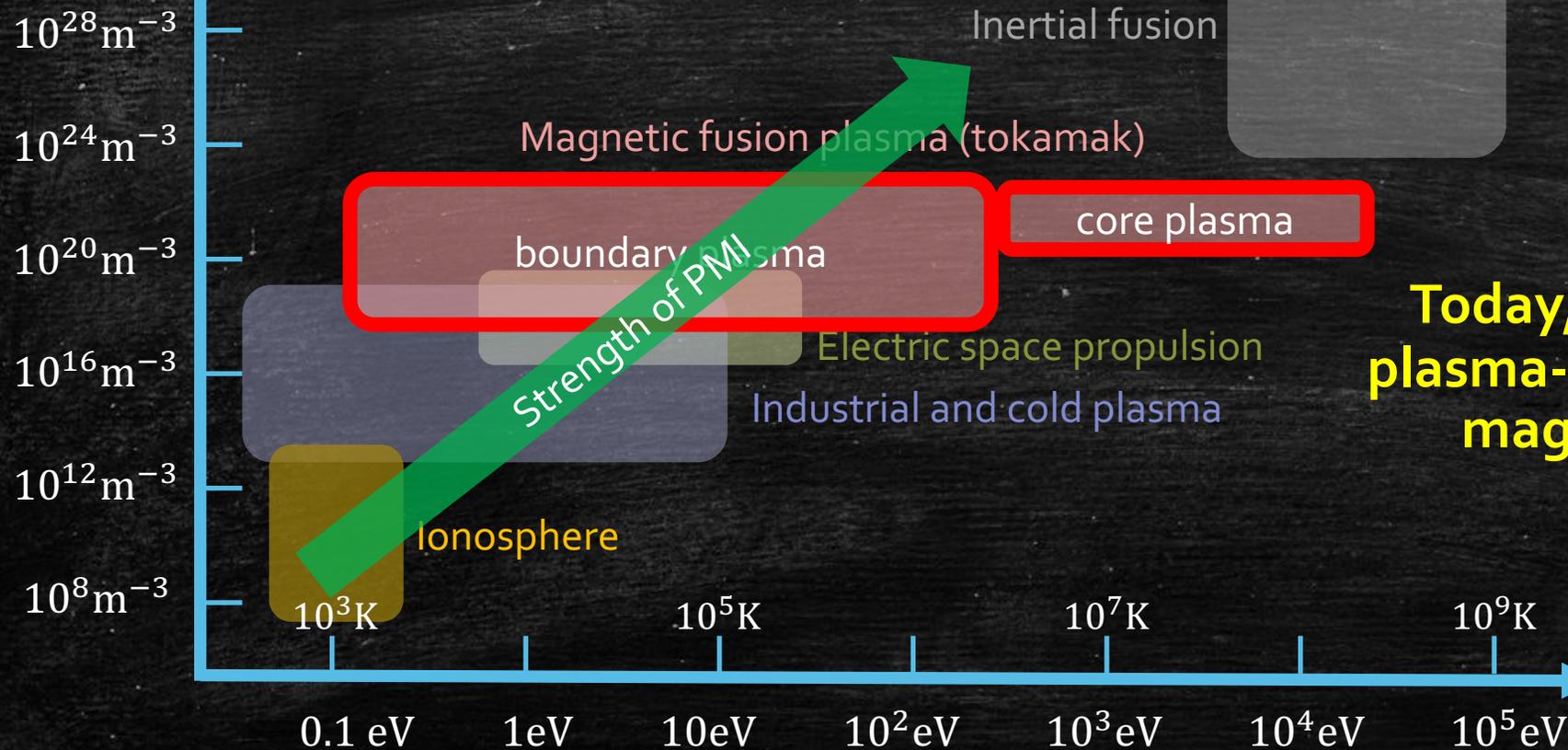


The strength of plasma-material interactions is mainly determined by:

- 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!

charge density of plasmas interacting with materials

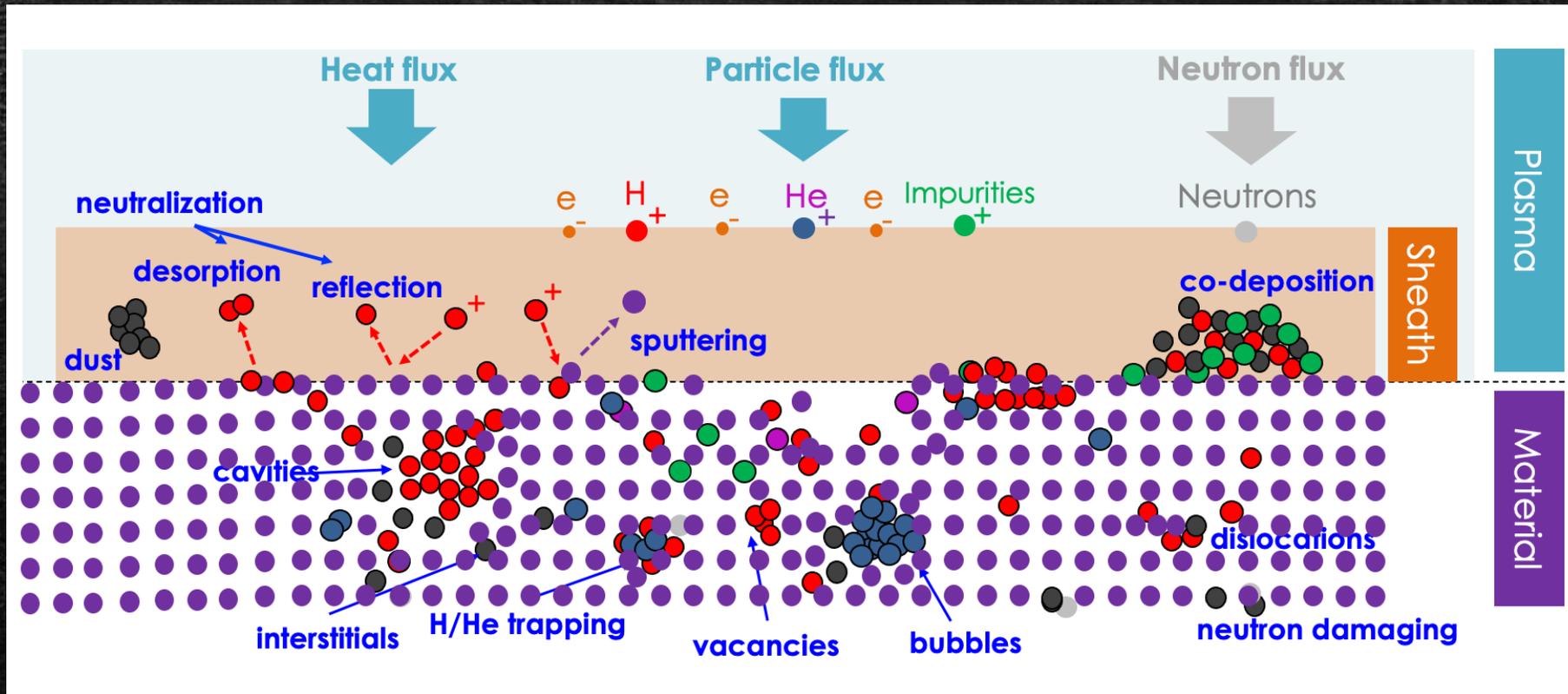


Today, we will focus only on plasma-material interactions in magnetic fusion plasma (tokamak)

temperature of plasma interacting with materials

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!



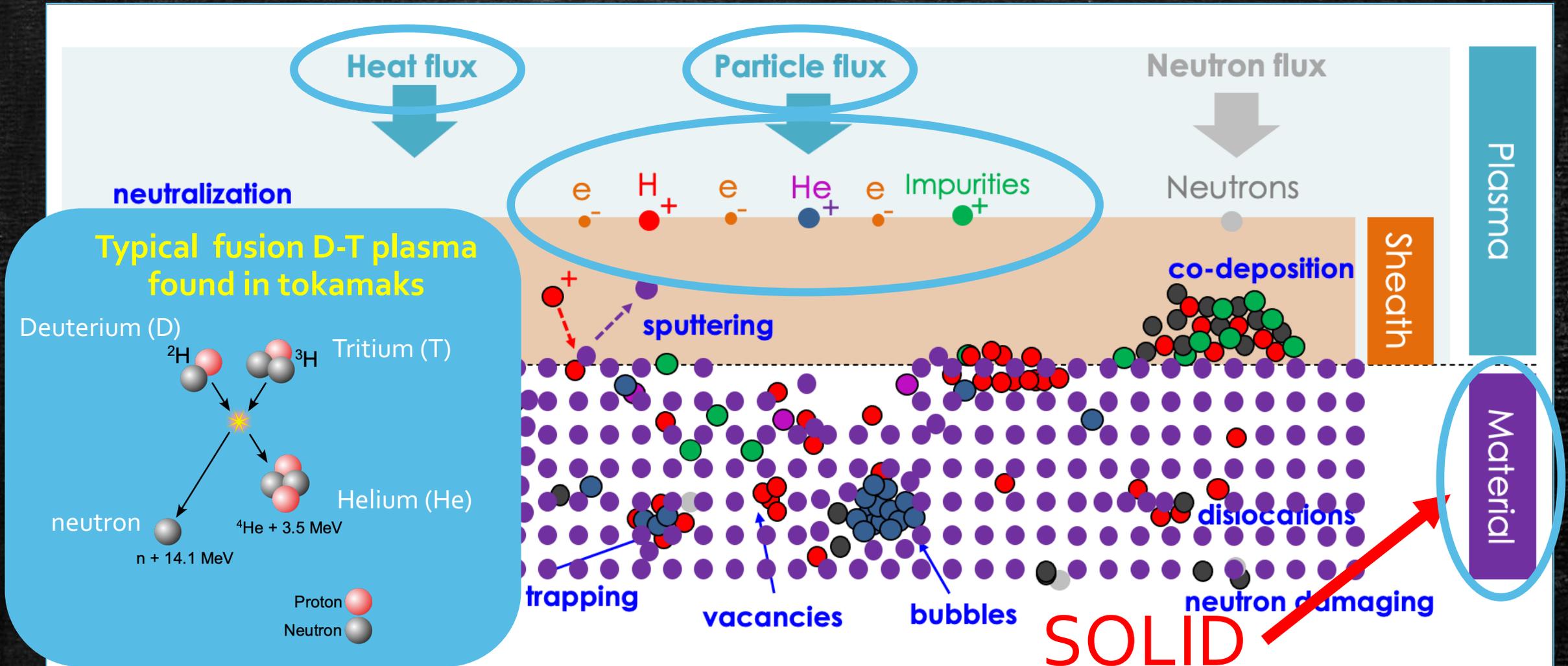
- This zoo of multi-faceted physics mechanisms for D+T magnetic fusion plasma is a good illustration of the complexity of PMI in general

Part I

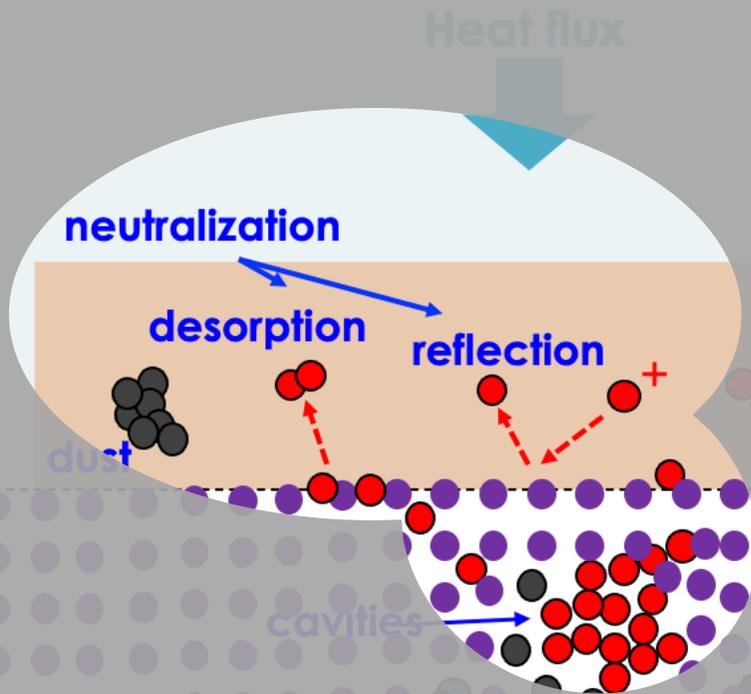
Plasma-material interactions in magnetic fusion plasma

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

PMI fundamentals for D+T fusion plasma in tokamaks



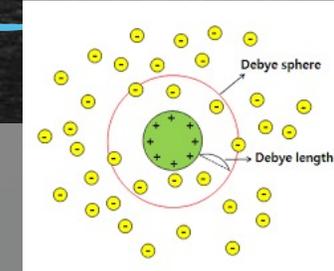
PMI fundamentals: plasma particles interacting with material are recycled as neutrals into the plasma



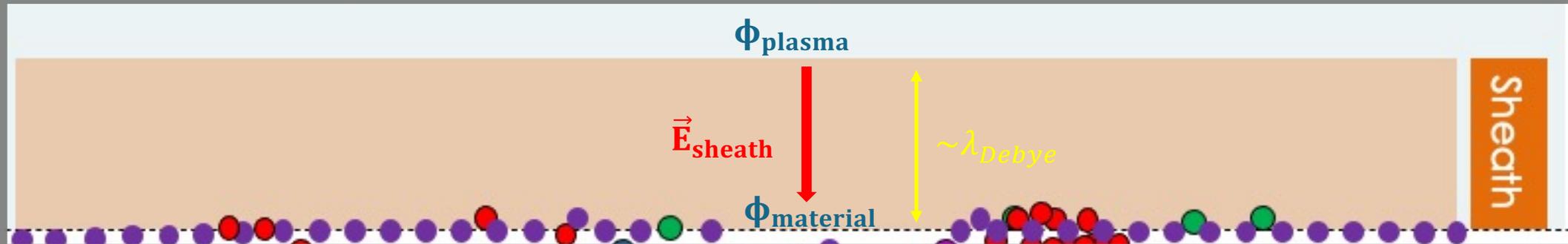
- **When charged plasma particles hit a solid material surface, they become neutrals:**
 - A fraction of those particles is reflected as atoms (reflection process)
 - The remaining particles are implanted beneath the material surface
 - Almost all particles implanted in the material (>99%) diffuse back 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 (H₂) 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}**



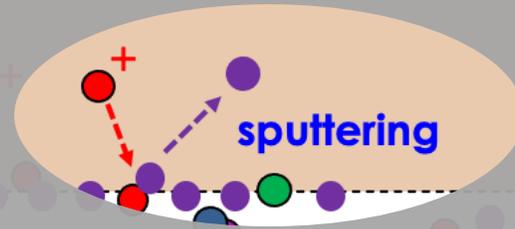
- Because electrons are much smaller than ions, they can more easily (faster) reach the material surface:
→ electric potential between material and plasma $\Delta\Phi_{sheath} = \Phi_{plasma} - \Phi_{material} \sim \log\left(\frac{m_{ion}}{m_{electron}}\right) \approx 3 \times k_b \times \frac{T_e}{e}$
- **self-consistent electric field \vec{E}_{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**



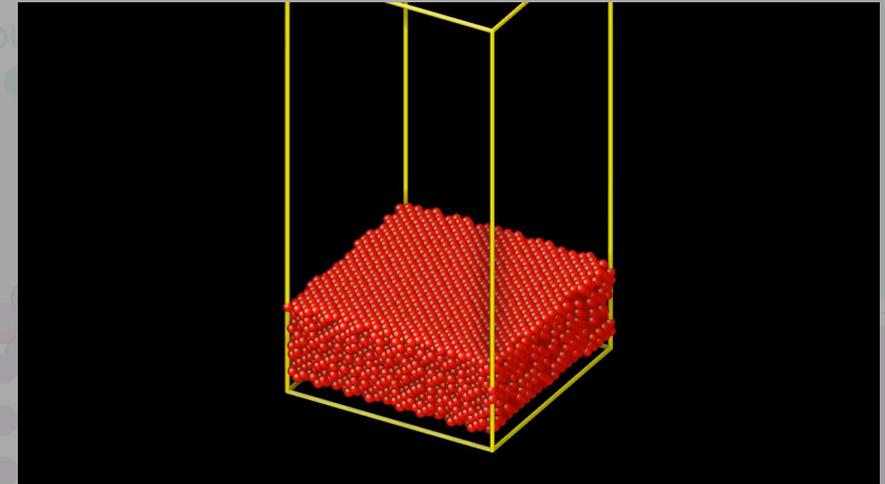
Plasma ions are accelerated toward the material surface by the sheath electric field and gain a kinetic energy $\Delta E_{kin} \sim \sim Q_{ion} \times 3 \times k_b \times T_e$ before impinging on the material surface

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



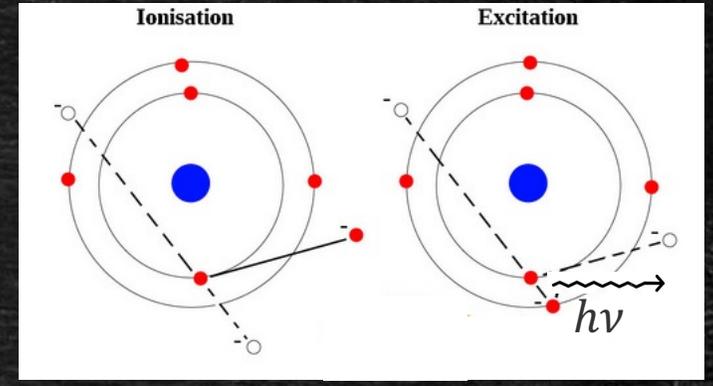
Molecular dynamics simulation of material sputtering



- 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

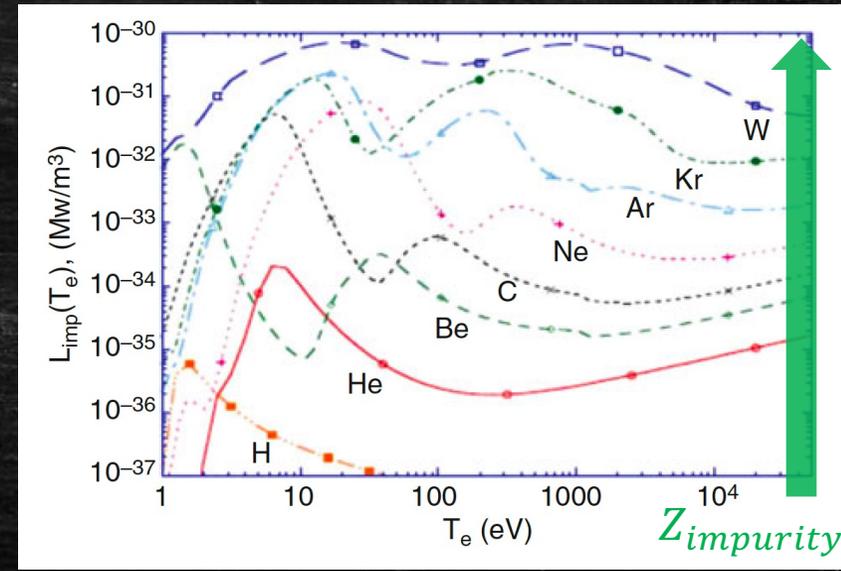
- Plasma ions/impurities can be ionized and recombine due to collisions with plasma electrons:
 - $D + e^- \rightarrow D^+ + 2e^-$ (ionization)
 - $C^{3+} + e^- \rightarrow C^{2+}$ (recombination)
- Electrons in the shell of the plasma ions/impurities can also be excited due to collisions with plasma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



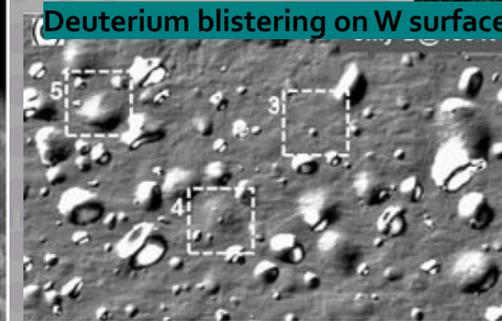
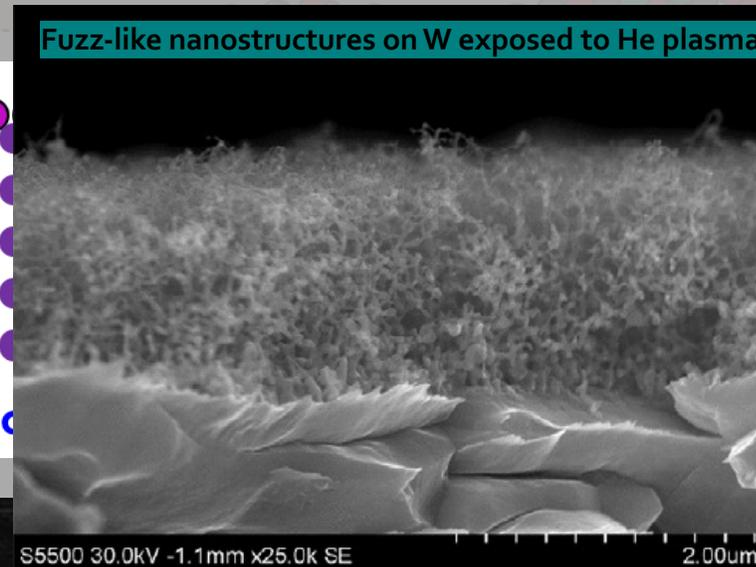
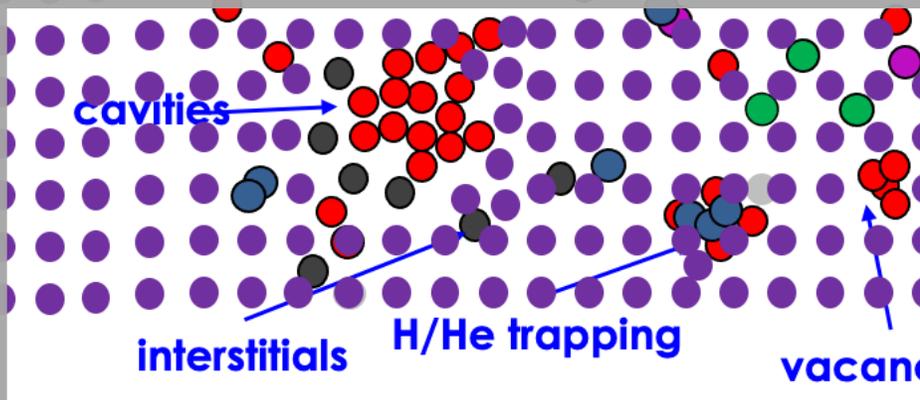
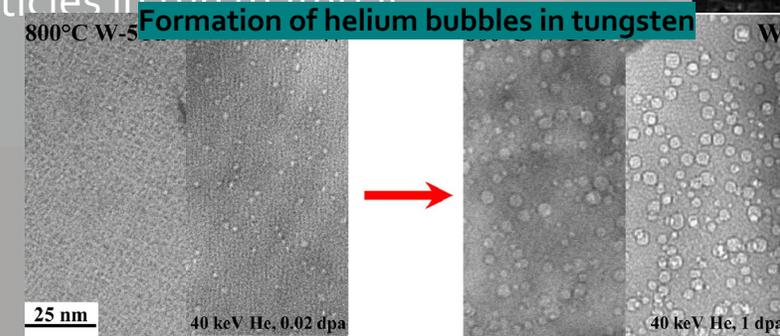
The efficiency of the radiative cooling of plasma by impurities significantly increases with the atomic number Z of the impurity

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

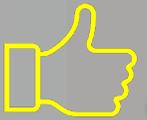


PMI fundamentals: co-deposition of plasma particles and material impurities

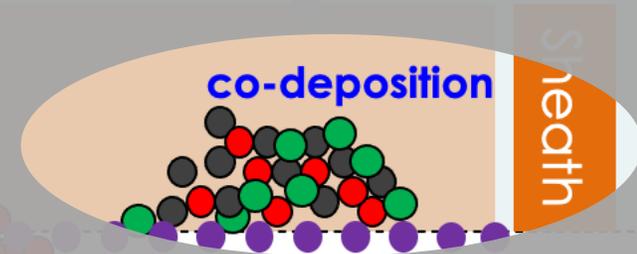
- Codeposition: simultaneous deposition of plasma particles, e.g. hydrogen species, and plasma impurities, e.g. carbon, resulting in the formation of amorphous (unstructured) layers deposited on material surface



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, ...

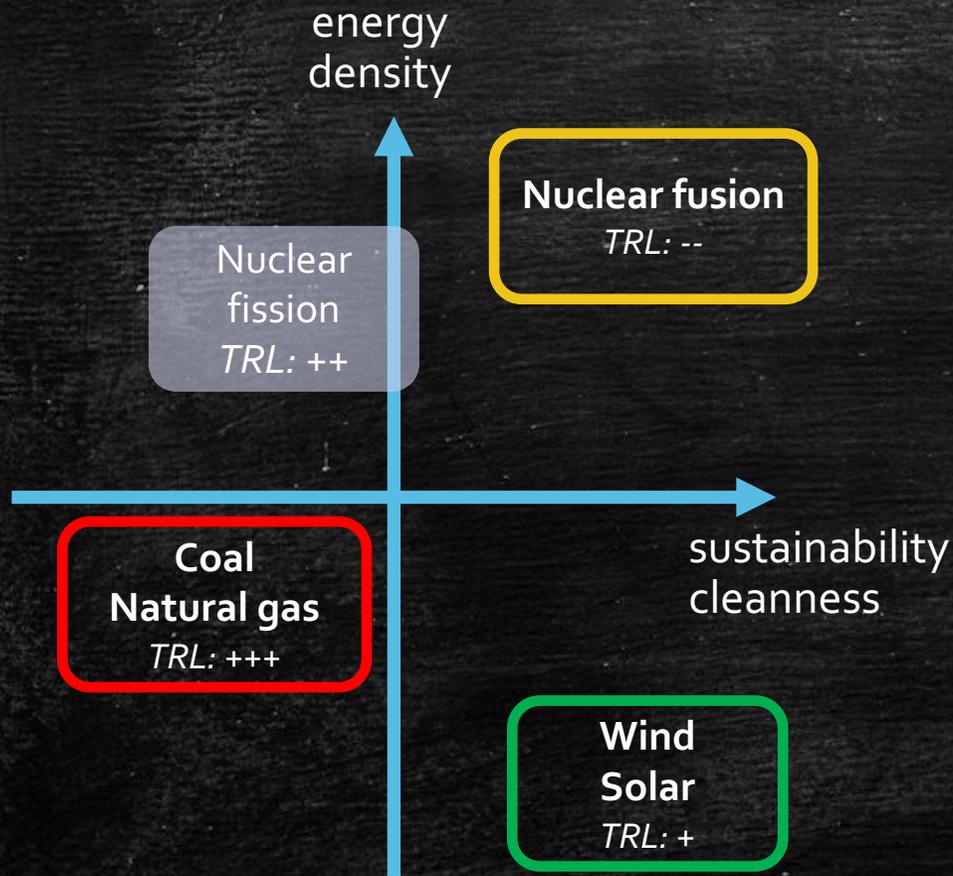
Those damages can significantly degrade material properties (thermal conductivity, ductility, resistance to fatigue, ...) and reduce material performances and lifetime
- Co-deposition of impurities and plasma particles may result in amorphous layers storing a large amount of particles
- **Material sputtering 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

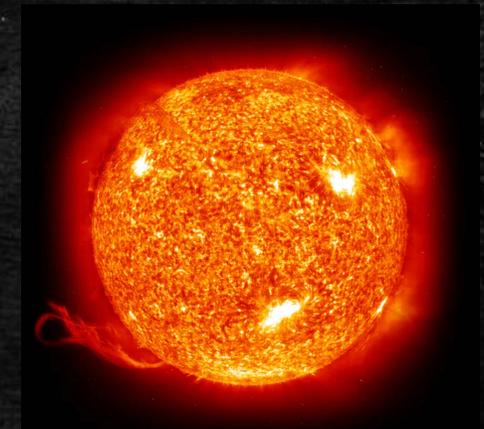
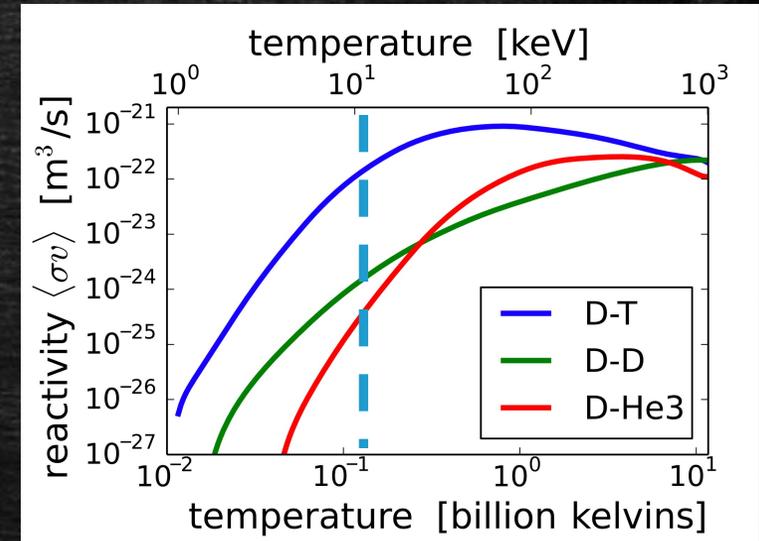
Plasma-material interactions are among the main technological challenges !

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:

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

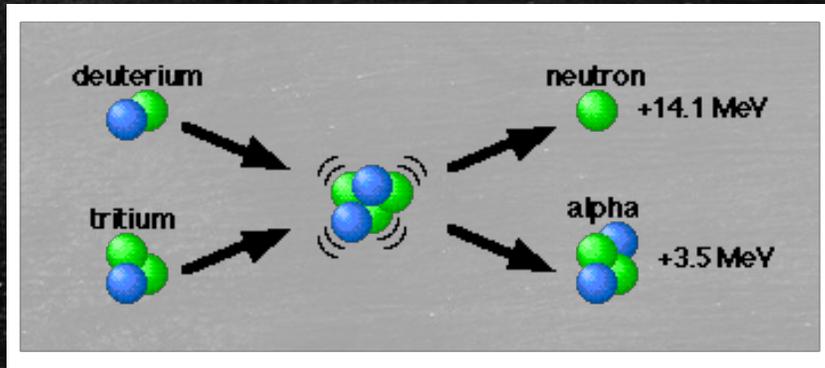
- At those temperatures, matter is its fourth state: a plasma (ionized gas)
- **Obtaining a sustainable source of nuclear fusion energy requires to confine the plasma to prevent plasma particles from running away and cooling down**
- For instance , the sun and the stars are essentially hot plasma balls 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 $\sim 10^{30}\text{kg}$
- **Gravitational confinement of fusion plasma is impossible on Earth!**



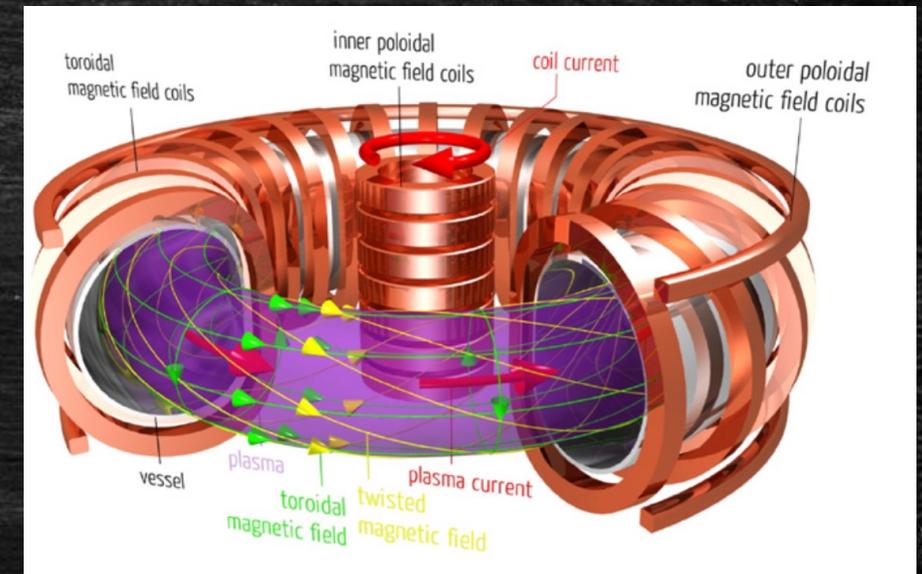
* Thermo = thermalized energy distribution of plasma particles

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:

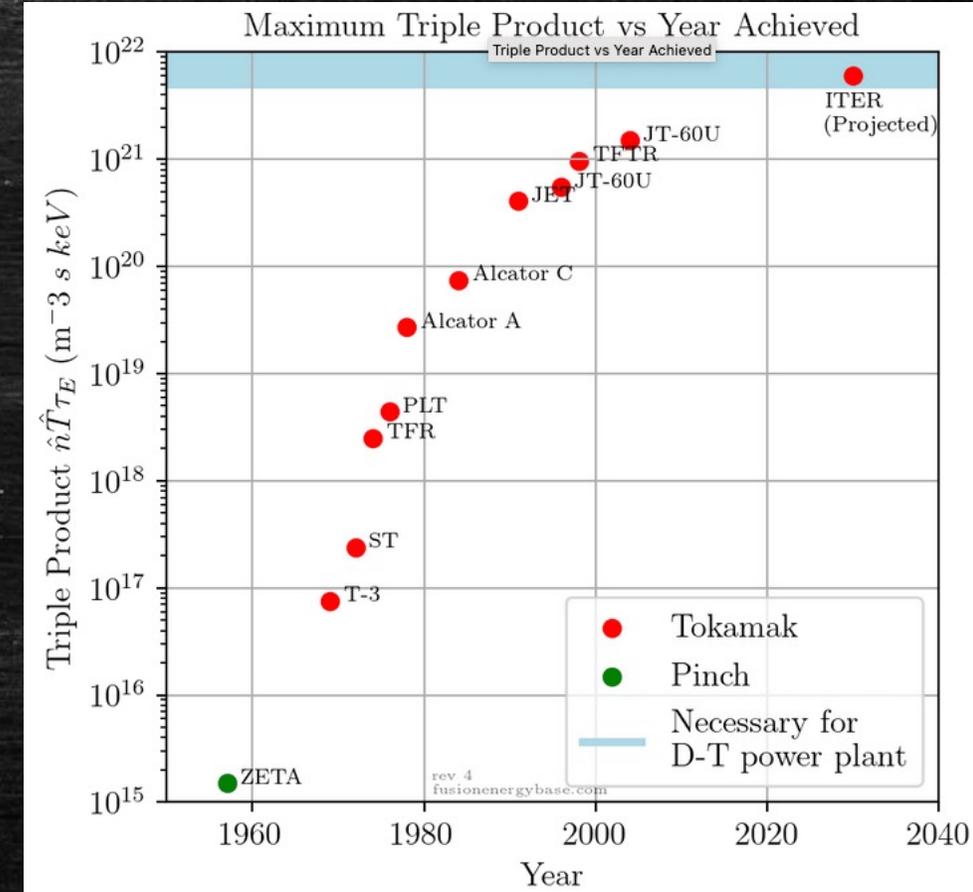
$$n_{\text{core}} \times \tau_E \times T_i$$

plasma density \rightarrow n_{core} \times τ_E \times T_i \leftarrow plasma temperature
 \uparrow
 energy confinement time

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

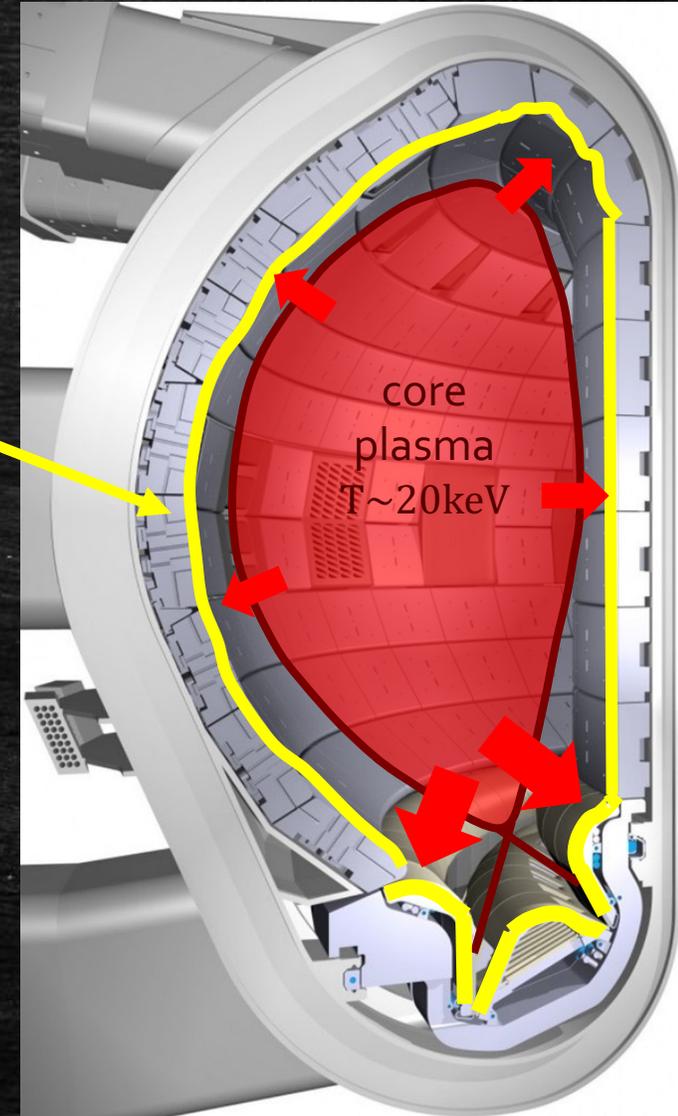
$$\tau_E \nearrow$$

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



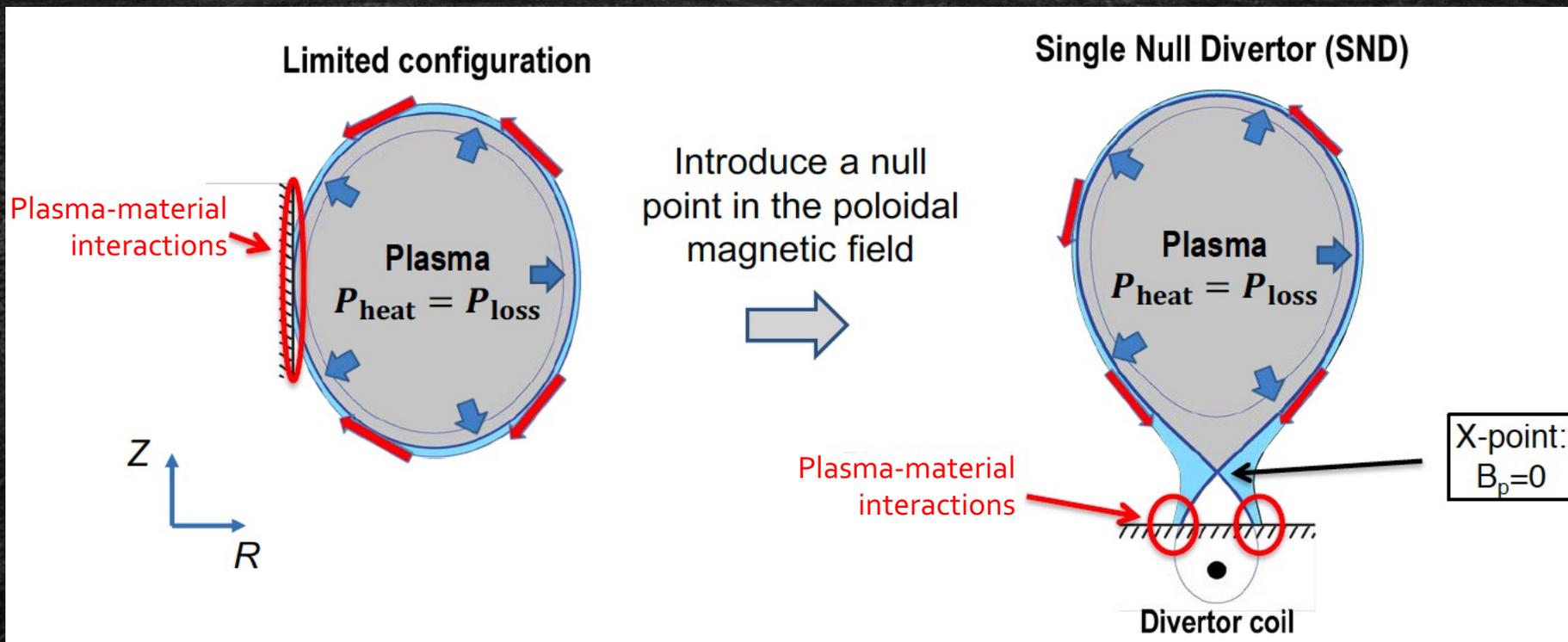
...and particle and energy leaks outside of the core plasma and interact with plasma-facing components

- 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)

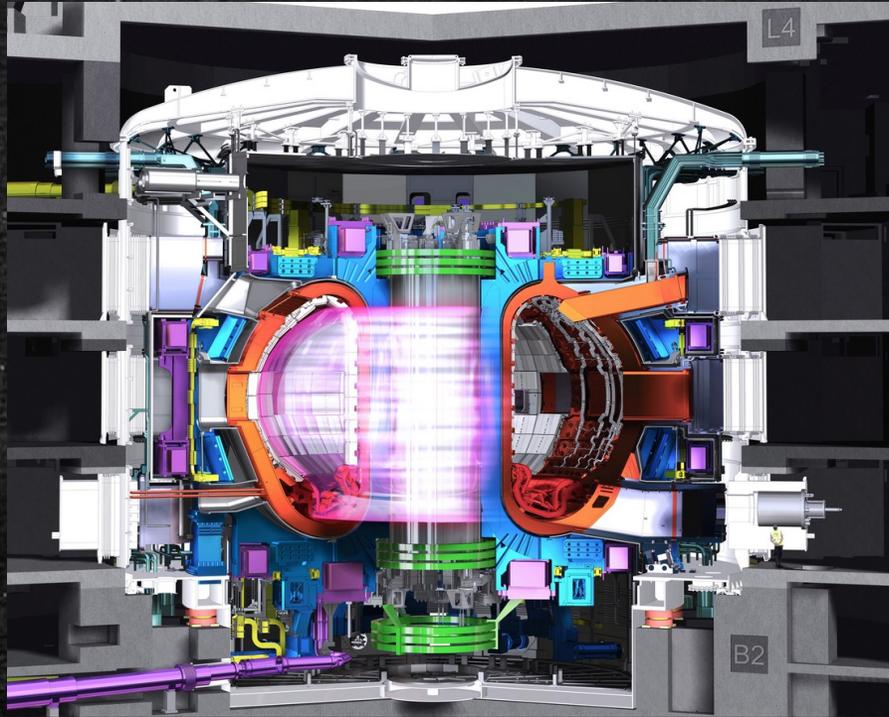
direct result of PMI!

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



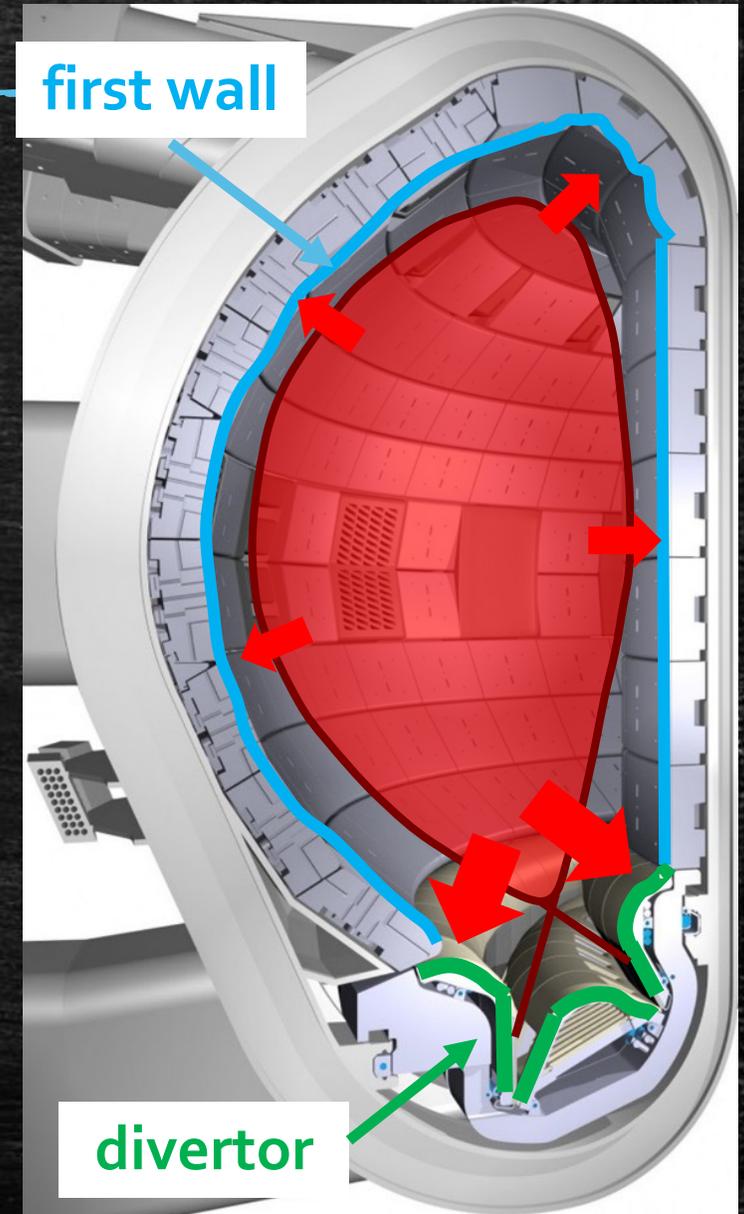
- ITER will be a major step toward a commercial fusion reactor

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

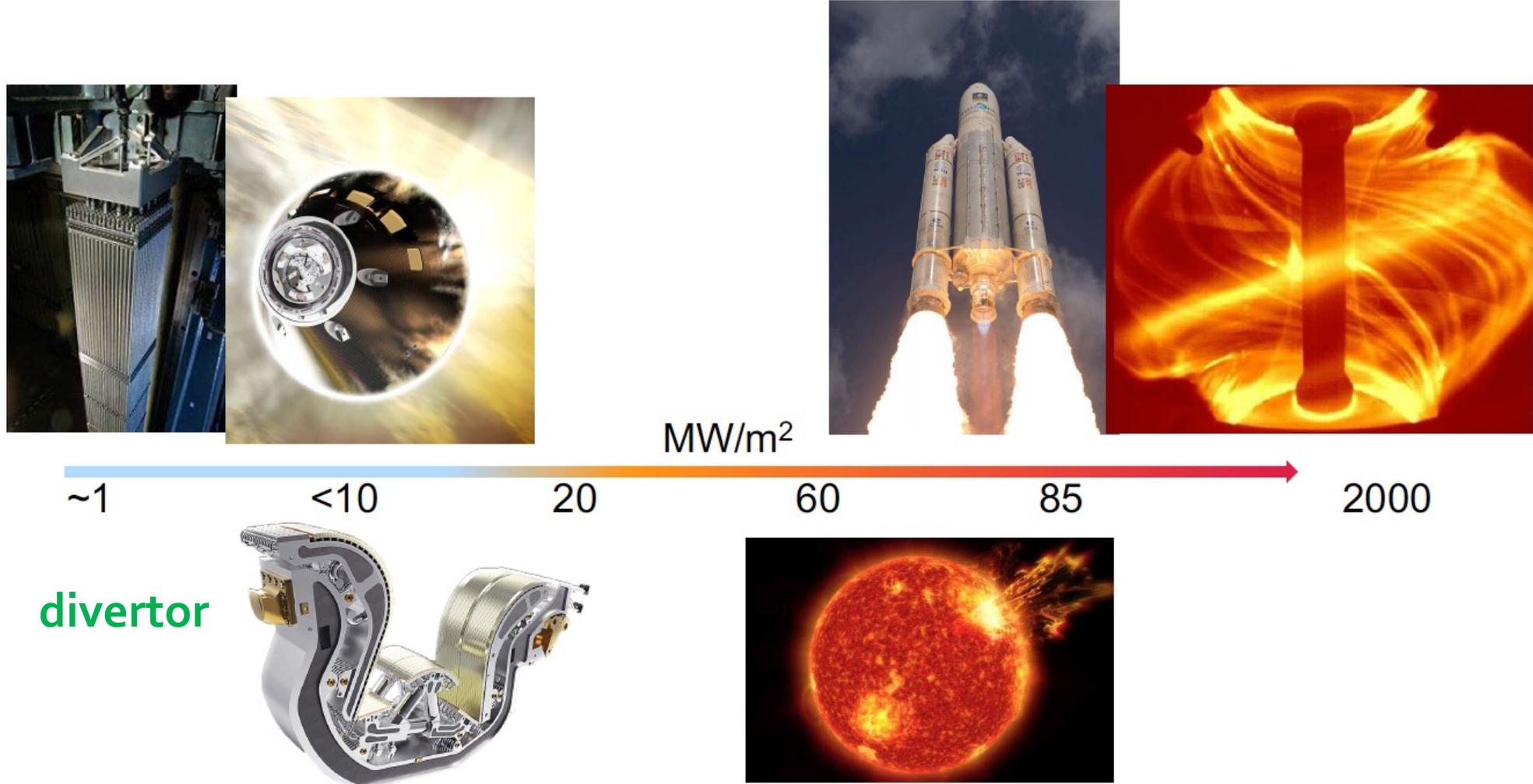


Plasma-facing components in divertor must handle enormous heat and particle fluxes

- ITER baseline scenario: $P_{\text{fus}} = 500\text{MW}$
 - finite core plasma confinement: $P_{\text{core} \rightarrow \text{boundary}} = 100\text{MW}$
- 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 $\sim 10\text{MWm}^{-2}$**
 - **Very high particle flux $\sim 10^{24}\text{m}^{-2}\text{s}^{-1}$**



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: $T_{\text{melting}} > 2000\text{K}$, thermal conductivity $> 50\text{W m}^{-1}\text{K}^{-1}$
 - 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!

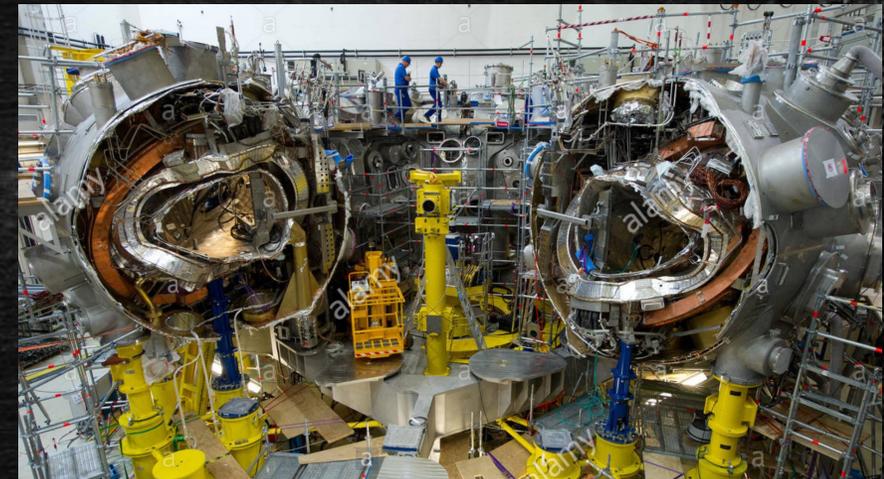
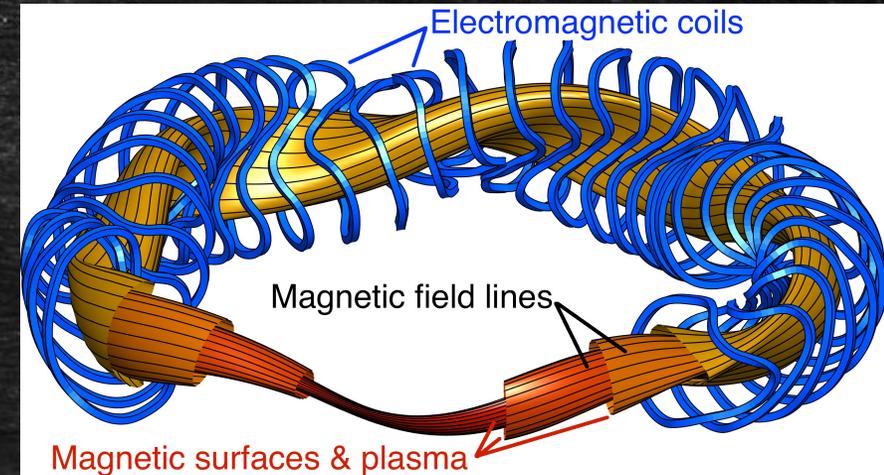
Plasma-material interactions in tokamaks are very similar in other magnetic confinement configurations

- 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 ($\gg 1$ second)
 - Inertial Confinement Fusion high-density plasma and short pulse ($\ll 1$ 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-1¹

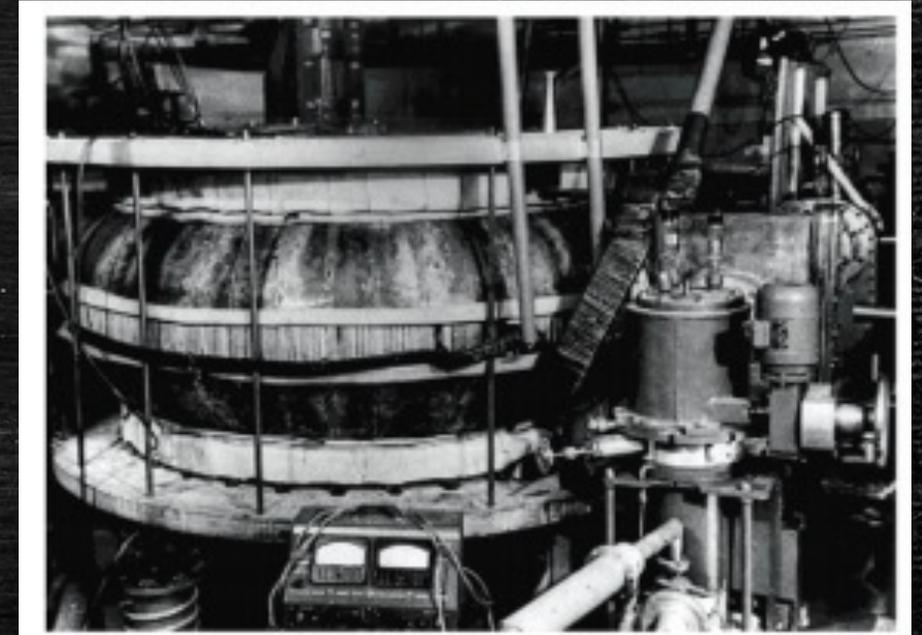
as unity. It is apparent that the radiation from deuterium is only $\frac{1}{15}$ to $\frac{1}{20}$ of the total energy radiated in this region of the spectrum.

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)

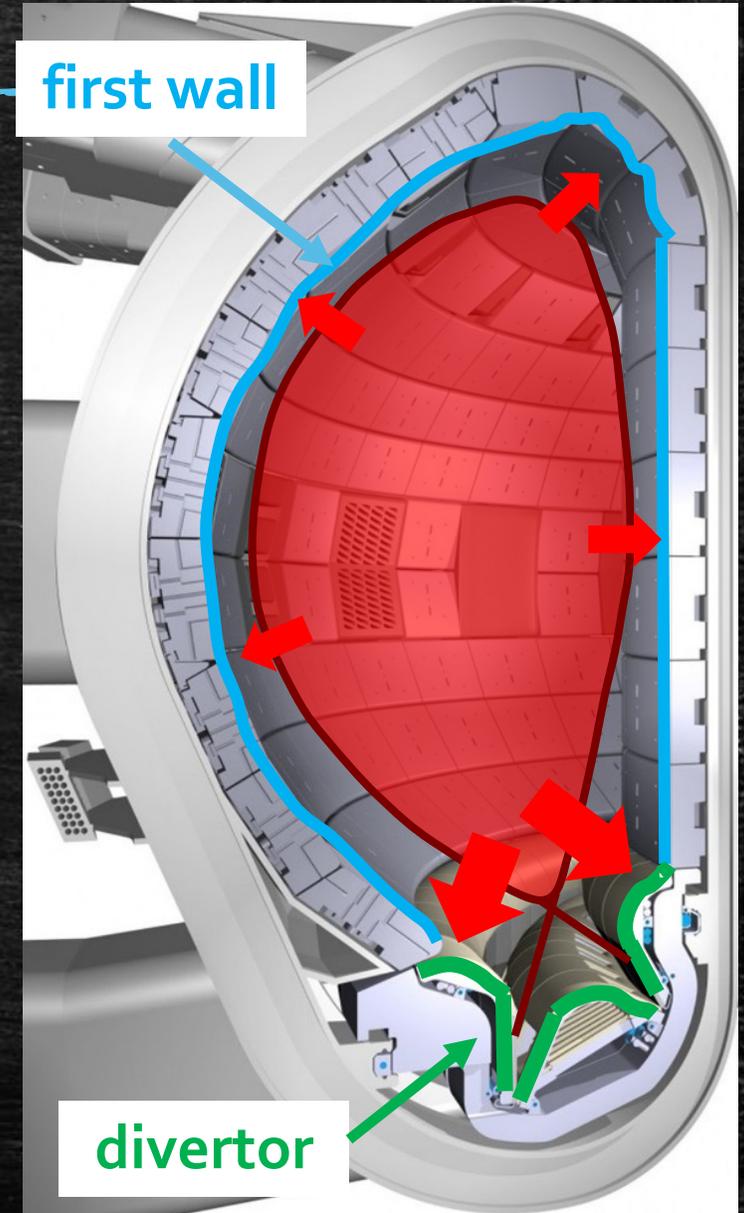
Part III

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: $P_{\text{fus}} = 500\text{MW}$
 - finite core plasma confinement: $P_{\text{core} \rightarrow \text{boundary}} = 100\text{MW}$
- Plasma-facing components in **divertor** will face extreme plasma conditions:
 - Very high heat flux $\sim 10\text{MWm}^{-2}$**
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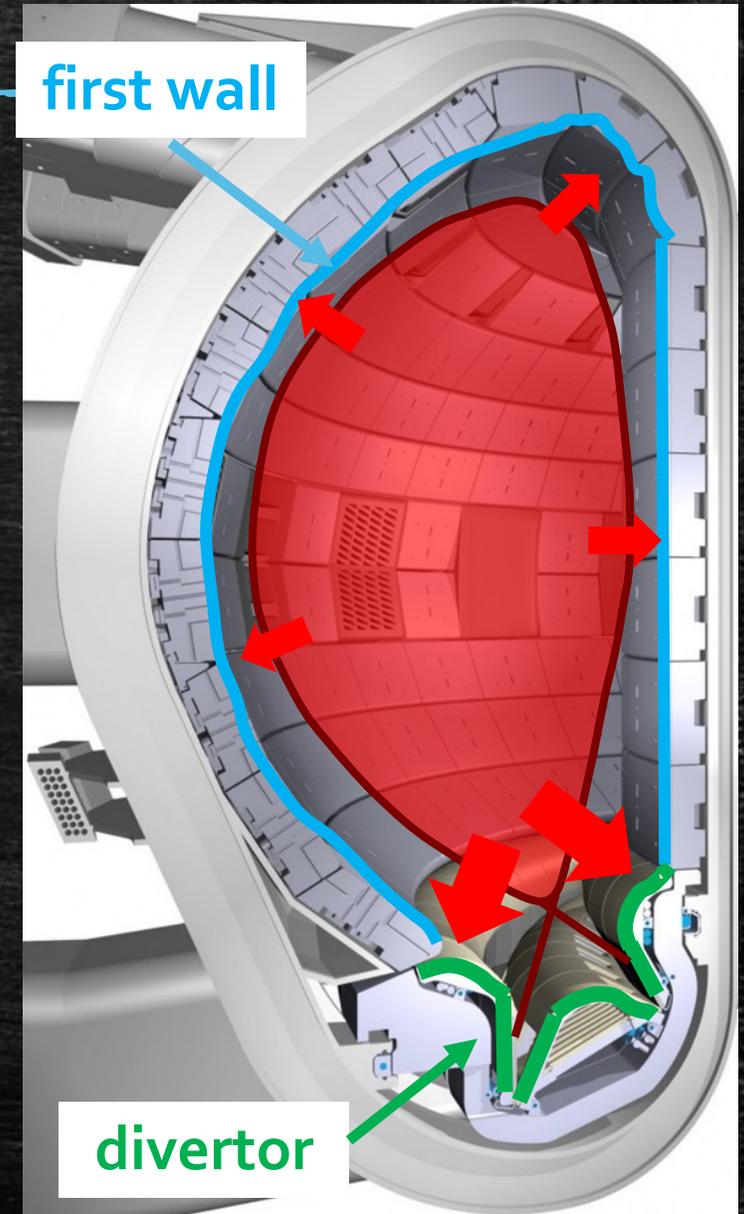


Which materials to build a divertor in a fusion reactor?

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Constraints for divertor material

- Operate at high temperature
 - $T_{\text{melting}} > 2000\text{K}$
 - Thermal conductivity $> 50\text{W m}^{-1}\text{K}^{-1}$
 - High recrystallization temperature
- Widely available and cost-effective
- Low/medium activation by neutrons
- Limit accumulation of fusion fuel (D+T)



Which materials to build a divertor in a fusion reactor?

Constraints for divertor material

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1 IA 1 H Hydrogen 1.008 1	2 IIA 4 Be Beryllium 9.012 4	13 IIIA 5 B Boron 10.81 5	14 IVA 6 C Carbon 12.01 6	15 VA 7 N Nitrogen 14.007 7	16 VIA 8 O Oxygen 15.999 8	17 VIIA 9 F Fluorine 18.998 9	18 VIIIA 2 He Helium 4.0026 2										
3 Li Lithium 6.94 3	10 Ne Neon 20.180 10	11 Na Sodium 22.98976928 11	12 Mg Magnesium 24.305 12	13 Al Aluminum 26.9815386 13	14 Si Silicon 28.0855 14	15 P Phosphorus 30.973762 15	16 S Sulfur 32.06 16	17 Cl Chlorine 35.45 17	18 Ar Argon 39.948 18								
19 K Potassium 39.0983 19	20 Ca Calcium 40.078 20	21 III B 21 Sc Scandium 44.955908 21	22 IV B 22 Ti Titanium 47.867 22	23 V B 23 V Vanadium 50.9415 23	24 VI B 24 Cr Chromium 51.9961 24	25 VII B 25 Mn Manganese 54.938044 25	26 VIII B 26 Fe Iron 55.845 26	27 VIII B 27 Co Cobalt 58.933 27	28 VIII B 28 Ni Nickel 58.693 28	29 IX B 29 Cu Copper 63.546 29	30 X B 30 Zn Zinc 65.38 30	31 IIIB 31 Ga Gallium 69.723 31	32 IVB 32 Ge Germanium 72.630 32	33 VB 33 As Arsenic 74.922 33	34 VIB 34 Se Selenium 78.971 34	35 VIIB 35 Br Bromine 79.904 35	36 VIIIB 36 Kr Krypton 83.798 36
37 Rb Rubidium 85.4678 37	38 Sr Strontium 87.62 38	39 Y Yttrium 88.90584 39	40 Zr Zirconium 91.224 40	41 Nb Niobium 92.90637 41	42 Mo Molybdenum 95.95 42	43 Tc Technetium 98 43	44 Ru Ruthenium 101.07 44	45 Rh Rhodium 102.91 45	46 Pd Palladium 106.42 46	47 Ag Silver 107.87 47	48 Cd Cadmium 112.41 48	49 In Indium 114.82 49	50 Sn Tin 118.71 50	51 Sb Antimony 121.76 51	52 Te Tellurium 127.60 52	53 I Iodine 126.905 53	54 Xe Xenon 131.29 54
55 Cs Cesium 132.90545196 55	56 Ba Barium 137.327 56	57-71 Lanthanides	72 Hf Hafnium 178.49 72	73 Ta Tantalum 180.94788 73	74 W Tungsten 183.84 74	75 Re Rhenium 186.21 75	76 Os Osmium 192.22 76	77 Ir Iridium 192.22 77	78 Pt Platinum 195.08 78	79 Au Gold 196.97 79	80 Hg Mercury 200.59 80	81 Tl Thallium 204.38 81	82 Pb Lead 207.2 82	83 Bi Bismuth 208.98 83	84 Po Polonium 209 84	85 At Astatine 210 85	86 Rn Radon 222 86
87 Fr Francium 223 87	88 Ra Radium 226 88	89-103 Actinides	104 Rf Rutherfordium 261 104	105 Db Dubnium 262 105	106 Sg Seaborgium 263 106	107 Bh Bohrium 264 107	108 Hs Hassium 265 108	109 Mt Meitnerium 266 109	110 Ds Darmstadtium 268 110	111 Rg Roentgenium 268 111	112 Cn Copernicium 269 112	113 Nh Nihonium 269 113	114 Fl Flerovium 269 114	115 Mc Moscovium 270 115	116 Lv Livermorium 270 116	117 Ts Tennessine 271 117	118 Og Oganesson 274 118
57 La Lanthanum 138.91 57	58 Ce Cerium 140.12 58	59 Pr Praseodymium 140.91 59	60 Nd Neodymium 144.24 60	61 Pm Promethium 145 61	62 Sm Samarium 150.36 62	63 Eu Europium 151.96 63	64 Gd Gadolinium 157.25 64	65 Tb Terbium 158.93 65	66 Dy Dysprosium 162.50 66	67 Ho Holmium 164.93 67	68 Er Erbium 167.26 68	69 Tm Thulium 168.93 69	70 Yb Ytterbium 173.05 70	71 Lu Lutetium 174.97 71			
89 Ac Actinium 227 89	90 Th Thorium 232.04 90	91 Pa Protactinium 231.04 91	92 U Uranium 238.03 92	93 Np Neptunium 237 93	94 Pu Plutonium 244 94	95 Am Americium 243 95	96 Cm Curium 247 96	97 Bk Berkelium 247 97	98 Cf Californium 251 98	99 Es Einsteinium 252 99	100 Fm Fermium 257 100	101 Md Mendelevium 258 101	102 No Nobelium 259 102	103 Lr Lawrencium 260 103			

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The image shows a periodic table of elements. The element Carbon (C) is highlighted in green. The table includes element symbols, names, atomic numbers, and atomic weights. The highlighted element is Carbon (C), atomic number 6, atomic weight 12.011, located in group 14, period 2.

1	2											13	14	15	16	17	18
IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA
1 H Hydrogen 1.008												5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3 Li Lithium 6.941	4 Be Beryllium 9.012											11 Al Aluminum 26.982	12 Si Silicon 28.086	13 P Phosphorus 30.974	14 S Sulfur 32.06	15 Cl Chlorine 35.45	16 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57 La Lanthanum (138.905)	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (268)	111 Rg Roentgenium (269)	112 Cn Copernicium (284)	113 Nh Nihonium (285)	114 Fl Flerovium (287)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)
57 La Lanthanum (138.905)	58 Ce Cerium (140.12)	59 Pr Praseodymium (140.908)	60 Nd Neodymium (144.24)	61 Pm Promethium (145)	62 Sm Samarium (150.36)	63 Eu Europium (151.964)	64 Gd Gadolinium (157.25)	65 Tb Terbium (158.925)	66 Dy Dysprosium (162.50)	67 Ho Holmium (164.930)	68 Er Erbium (167.257)	69 Tm Thulium (168.934)	70 Yb Ytterbium (173.054)	71 Lu Lutetium (174.967)			
89 Ac Actinium (227)	90 Th Thorium (232.038)	91 Pa Protactinium (231.036)	92 U Uranium (238.029)	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)			

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The image shows a periodic table of elements. The groups are color-coded: Group 1 (IA) is pink, Group 2 (IIA) is yellow, Groups 3-10 (IIB) are light blue, Group 11 (IB) is purple, Group 12 (IIB) is grey, Group 13 (IIIA) is light green, Group 14 (IVA) is dark green, Group 15 (VA) is light green, Group 16 (VIA) is light green, Group 17 (VIIA) is light green, and Group 18 (VIIIA) is pink. The elements are arranged in rows and columns, with their atomic number, symbol, and name listed. The elements are color-coded according to their groups. The elements are arranged in rows and columns, with their atomic number, symbol, and name listed. The elements are color-coded according to their groups. The elements are arranged in rows and columns, with their atomic number, symbol, and name listed. The elements are color-coded according to their groups.

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The periodic table shows various elements with their symbols, atomic numbers, and names. Elements are color-coded based on constraints:

- Green:** Elements that meet the high melting point and high thermal conductivity constraints: Boron (B), Carbon (C), Nitrogen (N), Oxygen (O), Fluorine (F), Neon (Ne), Silicon (Si), Phosphorus (P), Sulfur (S), Chlorine (Cl), Argon (Ar), Gallium (Ga), Germanium (Ge), Arsenic (As), Selenium (Se), Bromine (Br), Krypton (Kr), Indium (In), Tin (Sn), Antimony (Sb), Tellurium (Te), Iodine (I), Xenon (Xe), Thallium (Tl), Lead (Pb), Bismuth (Bi), Polonium (Po), Astatine (At), Radon (Rn).
- Blue:** Elements that meet the high melting point constraint but have lower thermal conductivity: Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Vanadium (V), Niobium (Nb), Molybdenum (Mo), Technetium (Tc), Ruthenium (Ru), Rhodium (Rh), Palladium (Pd), Silver (Ag), Cadmium (Cd), Tin (Sn), Antimony (Sb), Tellurium (Te), Iodine (I), Xenon (Xe), Tungsten (W), Rhenium (Re), Osmium (Os), Iridium (Ir), Platinum (Pt), Gold (Au), Mercury (Hg), Thallium (Tl), Lead (Pb), Bismuth (Bi), Polonium (Po), Astatine (At), Radon (Rn).
- Yellow:** Elements that meet the high thermal conductivity constraint but have lower melting points: Lithium (Li), Beryllium (Be), Sodium (Na), Magnesium (Mg), Calcium (Ca), Scandium (Sc), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Gallium (Ga), Germanium (Ge), Arsenic (As), Selenium (Se), Bromine (Br), Krypton (Kr), Rubidium (Rb), Strontium (Sr), Yttrium (Y), Zirconium (Zr), Niobium (Nb), Molybdenum (Mo), Technetium (Tc), Ruthenium (Ru), Rhodium (Rh), Palladium (Pd), Silver (Ag), Cadmium (Cd), Indium (In), Tin (Sn), Antimony (Sb), Tellurium (Te), Iodine (I), Xenon (Xe), Barium (Ba), Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu), Francium (Fr), Radium (Ra), Actinides (Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr).

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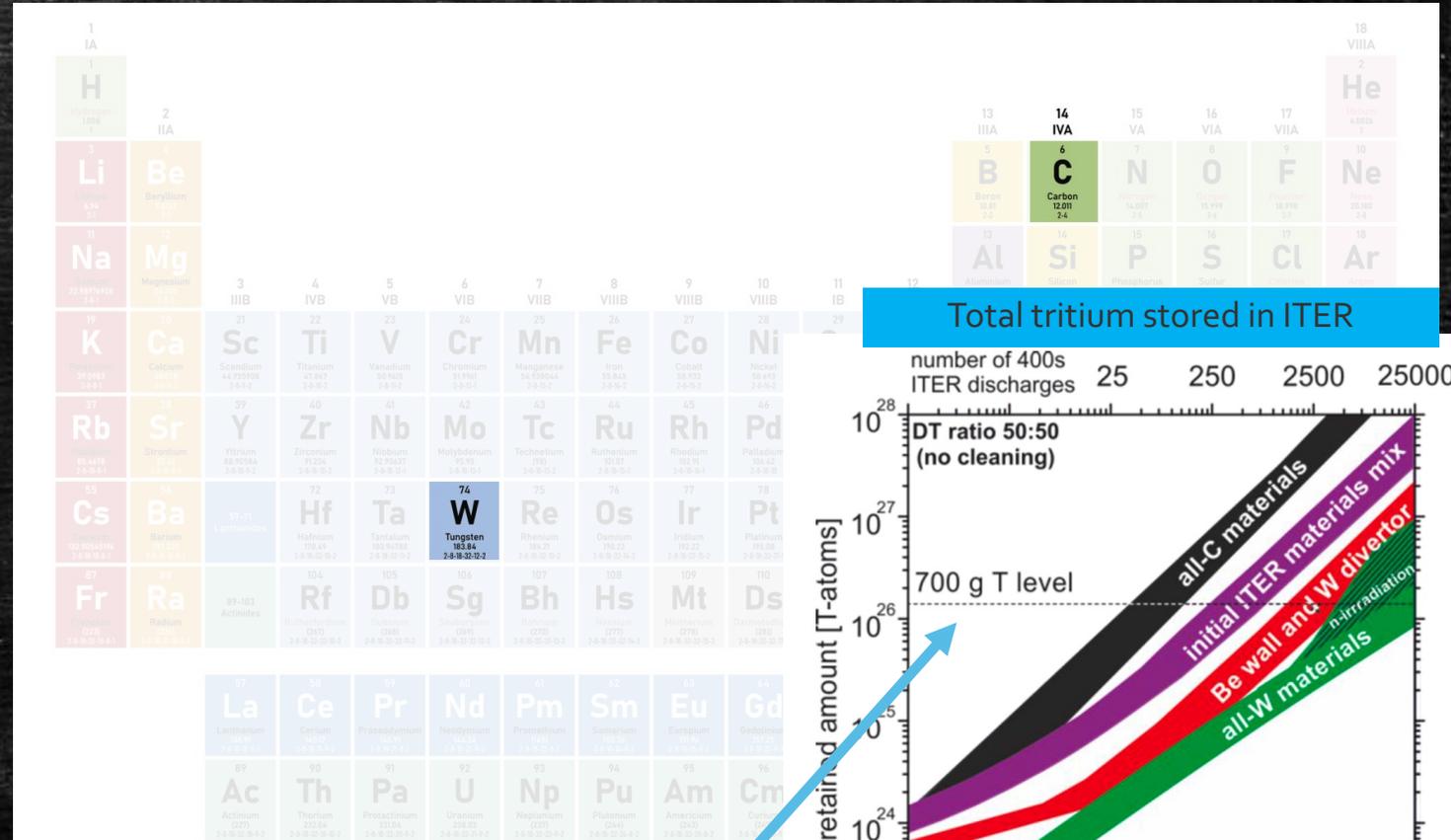
The image shows a periodic table of elements. The element Tungsten (W) is highlighted in blue. It is located in the 6th period, 6th column (Group 6), with atomic number 74 and atomic weight 183.84. The table also shows other elements like Carbon (C) in green, and various other elements in different colors.

1 IA H Hydrogen 1.008	2 IIA He Helium 4.003											13 IIIA B Boron 10.81 10.81	14 IVA C Carbon 12.01 12.01	15 VA N Nitrogen 14.01 14.01	16 VIA O Oxygen 16.00 16.00	17 VIIA F Fluorine 18.99 18.99	18 VIIIA Ne Neon 20.18 20.18
3 Li Lithium 6.94 6.94	4 Be Beryllium 9.01 9.01											5 B Boron 10.81 10.81	6 C Carbon 12.01 12.01	7 N Nitrogen 14.01 14.01	8 O Oxygen 16.00 16.00	9 F Fluorine 18.99 18.99	10 Ne Neon 20.18 20.18
11 Na Sodium 22.99 22.99	12 Mg Magnesium 24.31 24.31	3 IIIB Sc Scandium 44.96 44.96	4 IVB Ti Titanium 47.87 47.87	5 VB V Vanadium 50.94 50.94	6 VIB Cr Chromium 51.99 51.99	7 VIIB Mn Manganese 54.94 54.94	8 VIIIB Fe Iron 55.85 55.85	9 VIIIB Co Cobalt 58.93 58.93	10 VIIIB Ni Nickel 58.69 58.69	11 IB Cu Copper 63.55 63.55	12 IIB Zn Zinc 65.38 65.38	13 IIIA Al Aluminum 26.98 26.98	14 IVA Si Silicon 28.09 28.09	15 VA P Phosphorus 30.97 30.97	16 VIA S Sulfur 32.06 32.06	17 VIIA Cl Chlorine 35.45 35.45	18 VIIIA Ar Argon 39.95 39.95
19 K Potassium 39.10 39.10	20 Ca Calcium 40.08 40.08	21 IIIB Sc Scandium 44.96 44.96	22 IVB Ti Titanium 47.87 47.87	23 VB V Vanadium 50.94 50.94	24 VIB Cr Chromium 51.99 51.99	25 VIIB Mn Manganese 54.94 54.94	26 VIIIB Fe Iron 55.85 55.85	27 VIIIB Co Cobalt 58.93 58.93	28 VIIIB Ni Nickel 58.69 58.69	29 IB Cu Copper 63.55 63.55	30 IIB Zn Zinc 65.38 65.38	31 IIIA Ga Gallium 69.72 69.72	32 IVA Ge Germanium 72.64 72.64	33 VA As Arsenic 74.92 74.92	34 VIA Se Selenium 78.96 78.96	35 VIIA Br Bromine 79.90 79.90	36 VIIIA Kr Krypton 83.80 83.80
37 Rb Rubidium 85.47 85.47	38 Sr Strontium 87.62 87.62	39 IIIB Y Yttrium 88.91 88.91	40 IVB Zr Zirconium 91.22 91.22	41 VB Nb Niobium 92.91 92.91	42 VIB Mo Molybdenum 95.94 95.94	43 VIIB Tc Technetium 98.91 98.91	44 VIIIB Ru Ruthenium 101.07 101.07	45 VIIIB Rh Rhodium 102.91 102.91	46 VIIIB Pd Palladium 106.42 106.42	47 IB Ag Silver 107.87 107.87	48 IIB Cd Cadmium 112.41 112.41	49 IIIA In Indium 114.82 114.82	50 IVA Sn Tin 118.71 118.71	51 VA Sb Antimony 121.76 121.76	52 VIA Te Tellurium 127.60 127.60	53 VIIA I Iodine 126.91 126.91	54 VIIIA Xe Xenon 131.29 131.29
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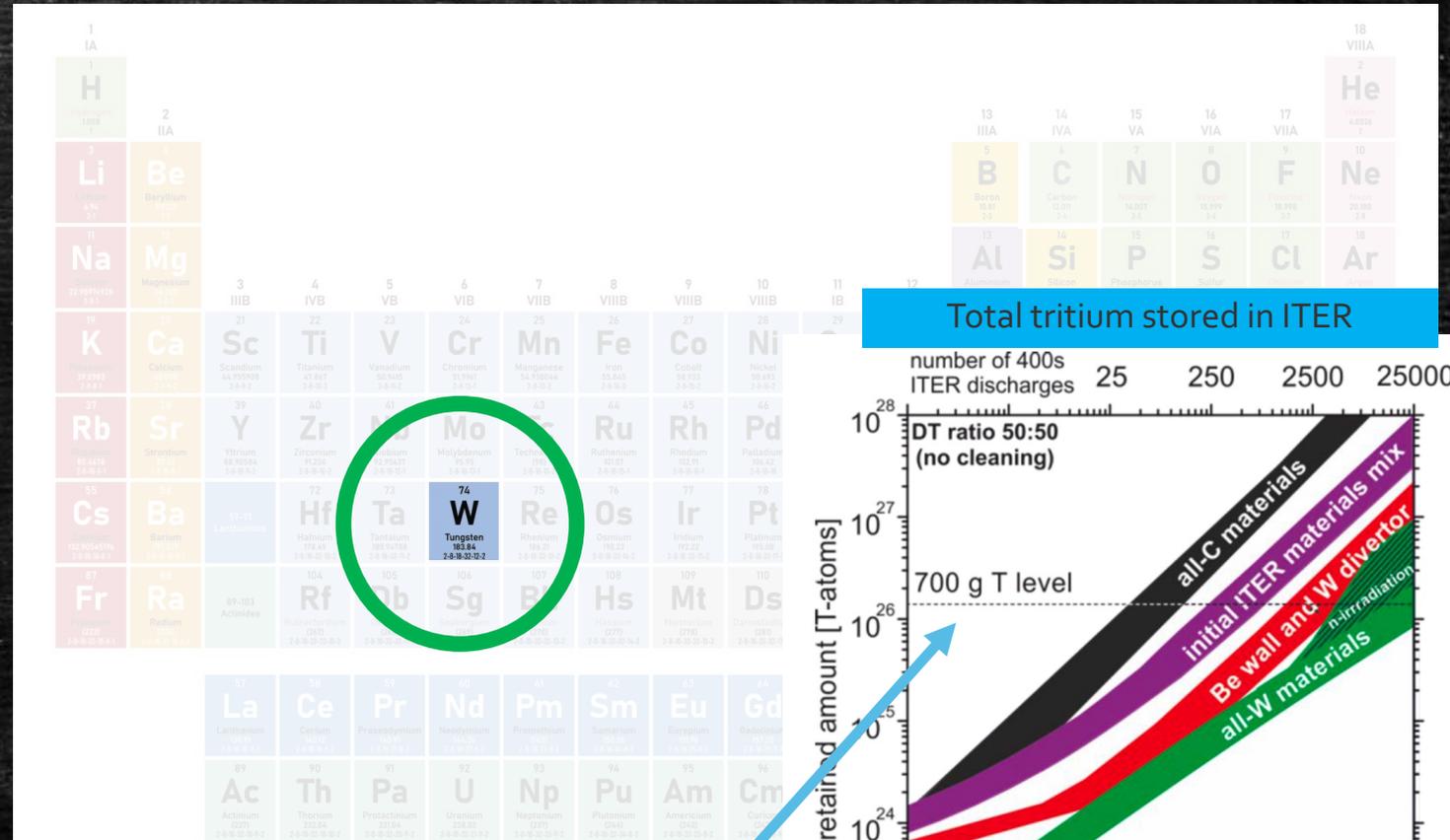


Regulatory limit on the total tritium content in ITER

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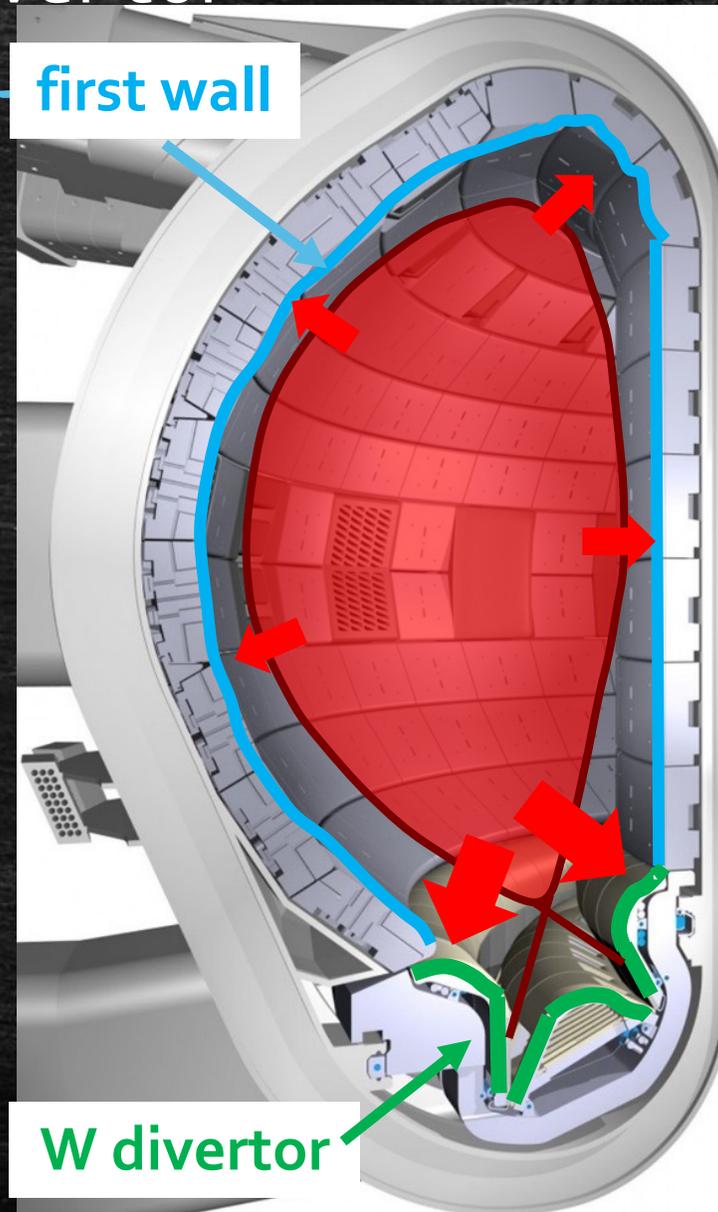
ITER will operate with a tungsten divertor

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

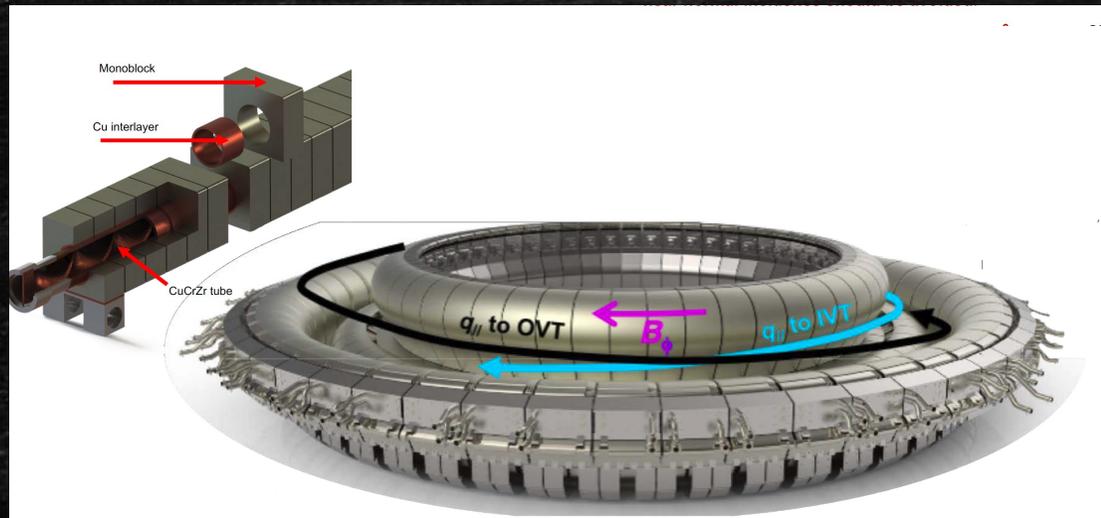


Tungsten is now considered as the material of choice for divertors of future fusion reactors

first wall



W divertor



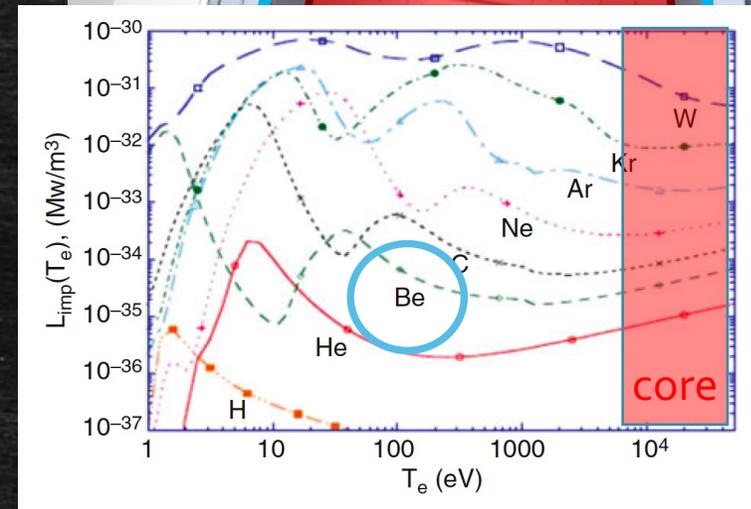
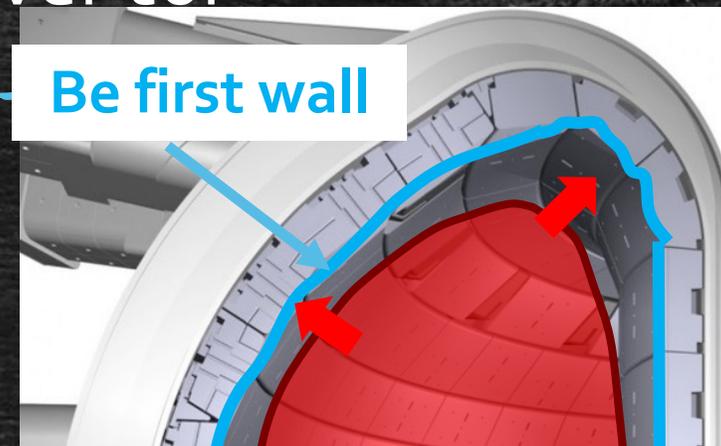
ITER will operate with a tungsten divertor and a beryllium wall!

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



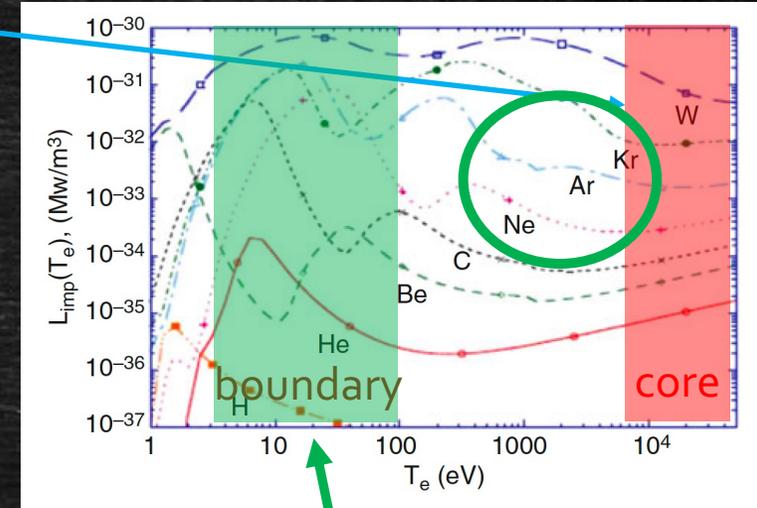
Tungsten is now considered as the material of choice for divertors of future fusion reactors

- ITER 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 10MWm^{-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

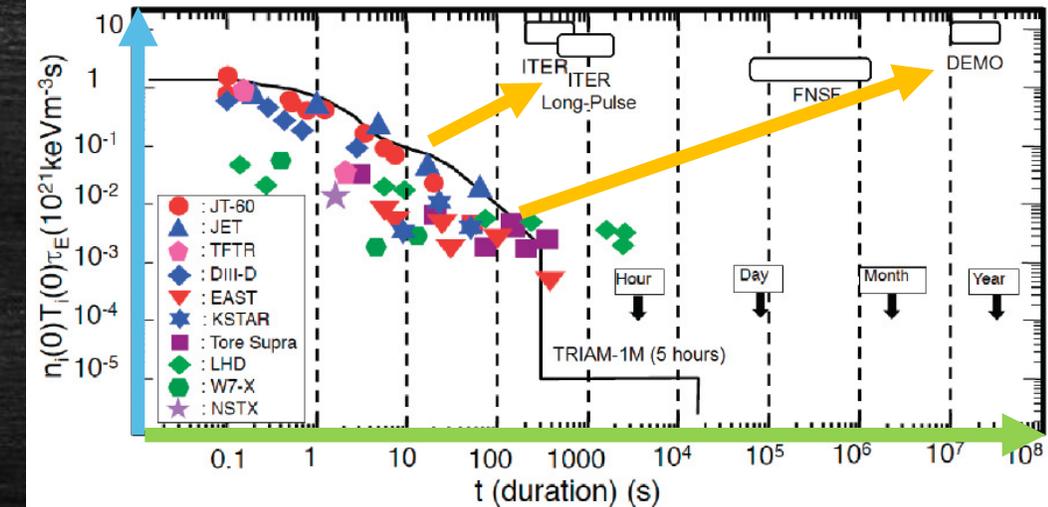
Modeling and simulations of plasma-interactions in tokamaks

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

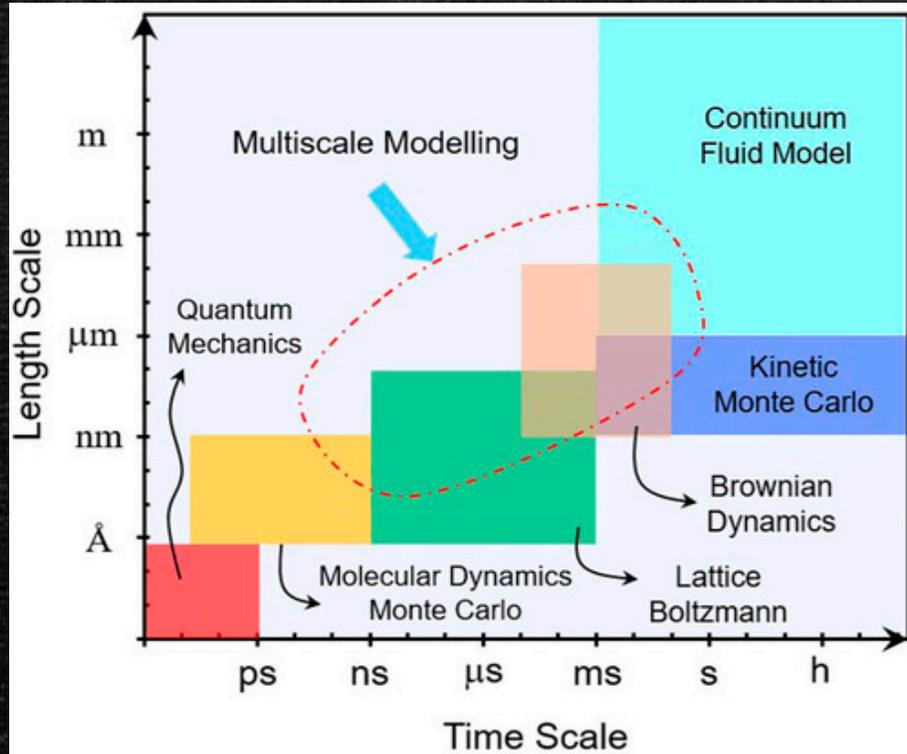
Modeling and simulating of plasma-material interactions are critical to design future fusion reactors

- 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**

(b) Fusion Triple Product vs. Plasma Duration



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

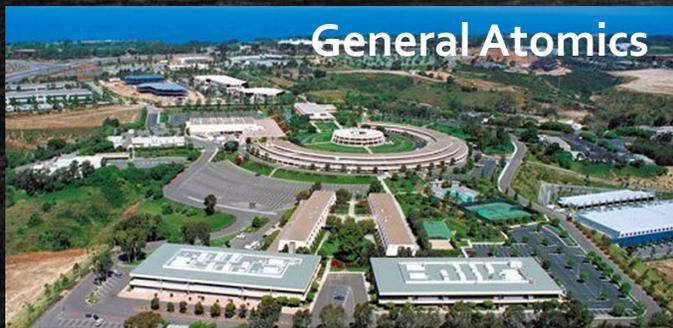
- **Plasma-material interactions are governed by various complex and multi-faceted atomic and plasma processes**
- **PMI impact the plasma through:**
 - the recycling of plasma particles as neutrals from the material surface into the plasma
 - the sputtering of material atoms into the plasma, resulting 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 ($t \sim$ 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 constraints 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!**
- ⇒ **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



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

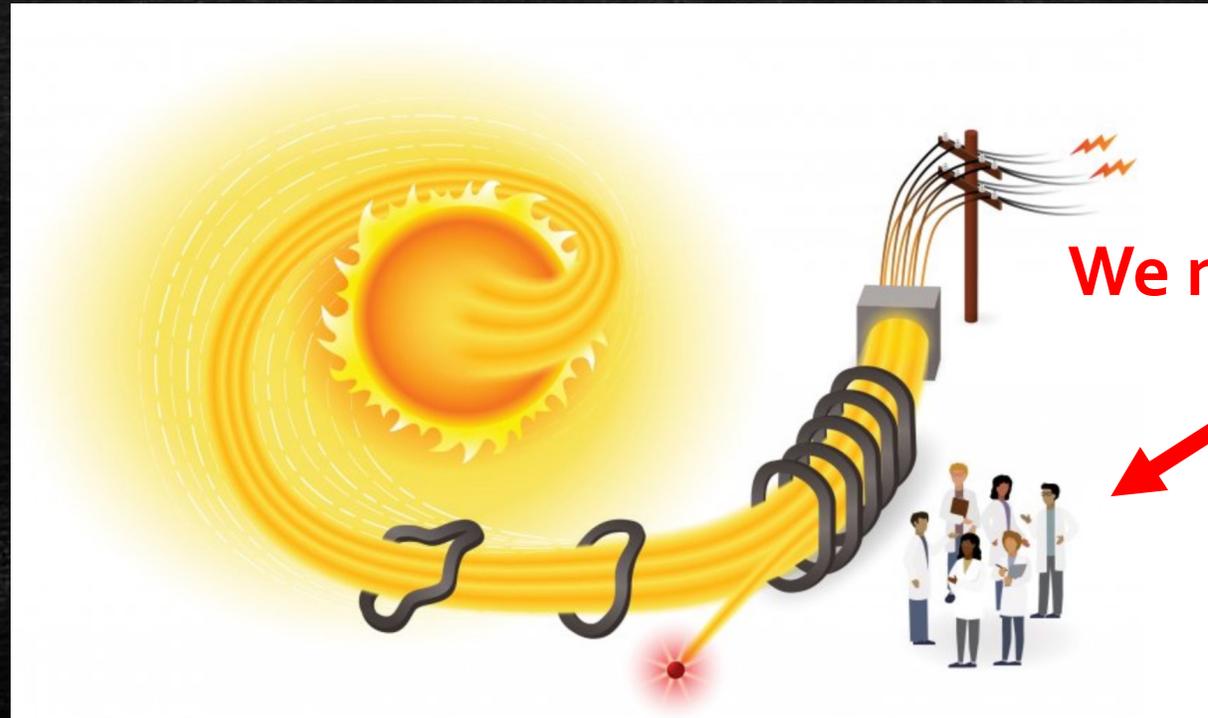


Some references to go further

- F. Chen, *An indispensable truth: how fusion power can save the planet*. Springer Science & Business Media, 2011.
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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!