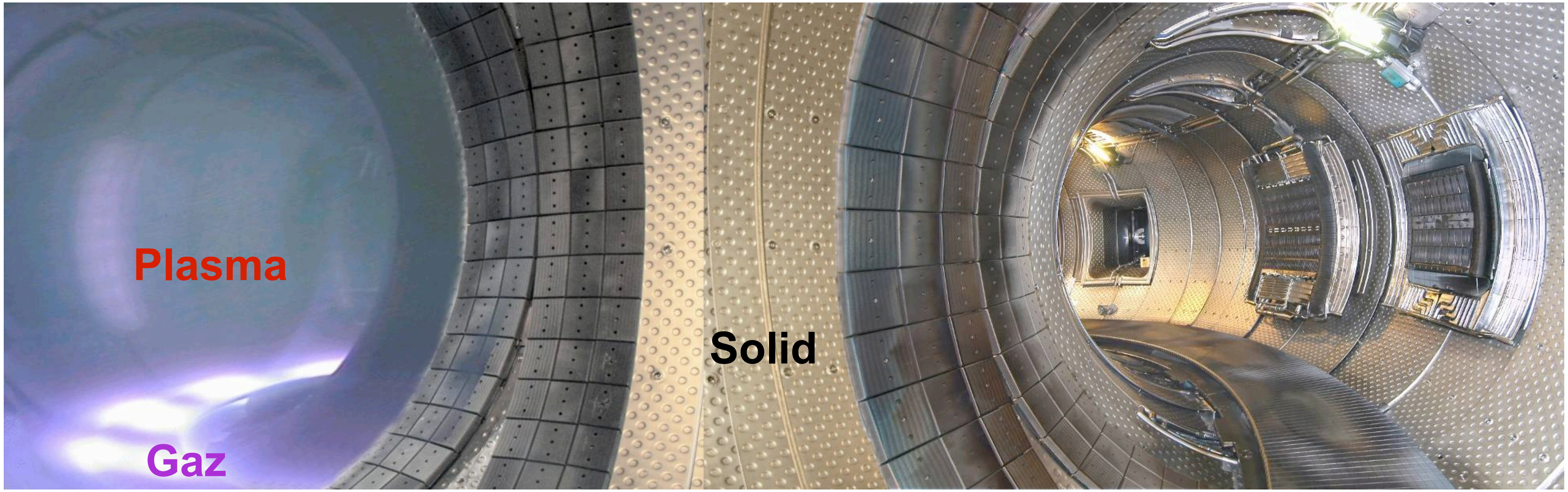
Plasma wall interactions in tokamaks : When the 4th state of matter meets the other 3

Euratom

E. Tsitrone, CEA-IRFM
Task Force leader of the EU Plasma Wall Interaction Task Force

"The boundary edge is where **the stellar world of hot plasmas** meets **the earthly world of cold solids**. Understanding the complex interaction of these two worlds is essential for operating a fusion reactor successfully."
Wojtek Fundamenski, JET TF Leader



Liquid

Outline

- Fusion basics
- On the road to fusion performance : ITER
- Plasma wall interactions : overview
- Challenges for ITER
  - Plasma facing components lifetime
  - Material migration, fuel retention, dust
  - Diagnostics and modelling
- An ambitious worldwide programme
- Summary

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Fusion basics

What is fusion ?

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Fusion on earth : using D-T

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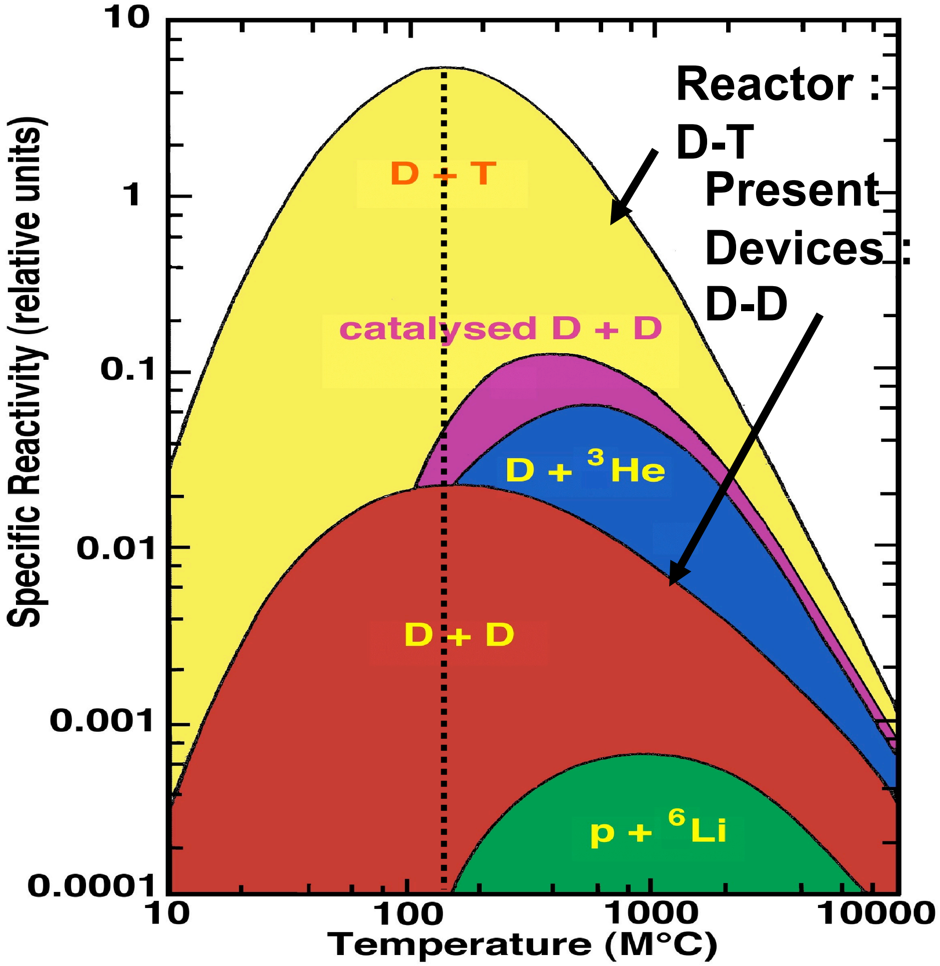

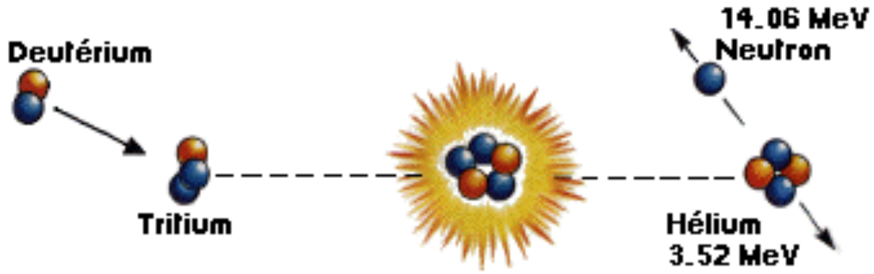

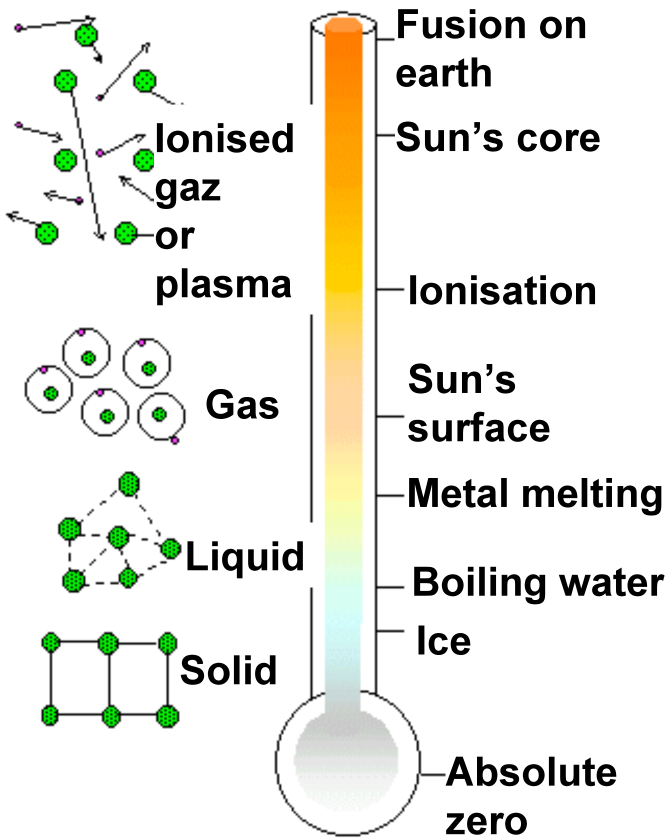

T ~ 20 keV ➔ plasma

Fusion on earth : the magnetic trap

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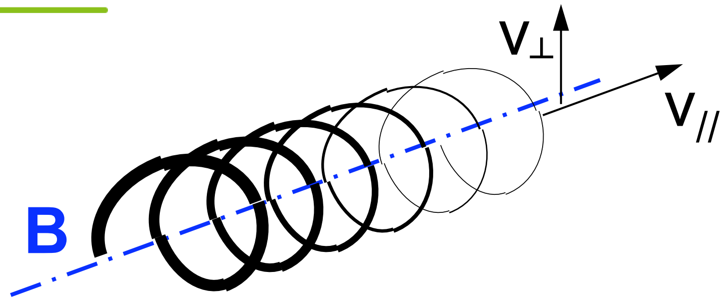
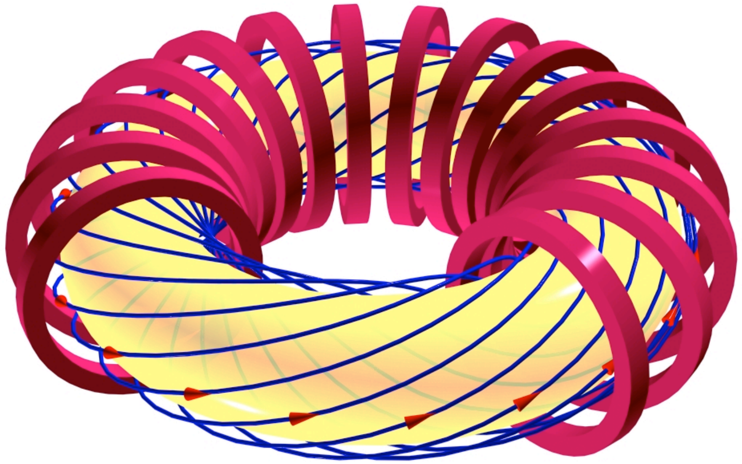
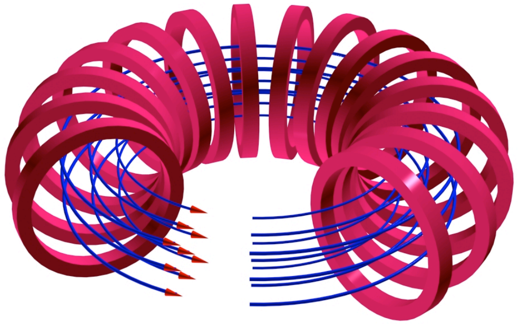
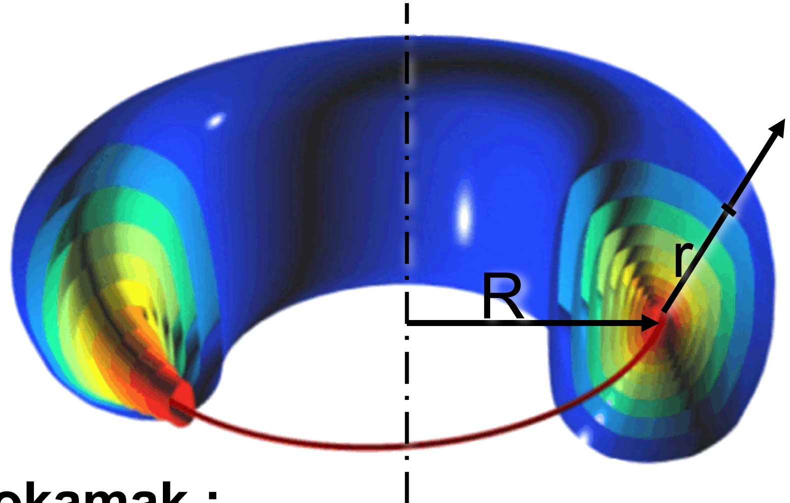


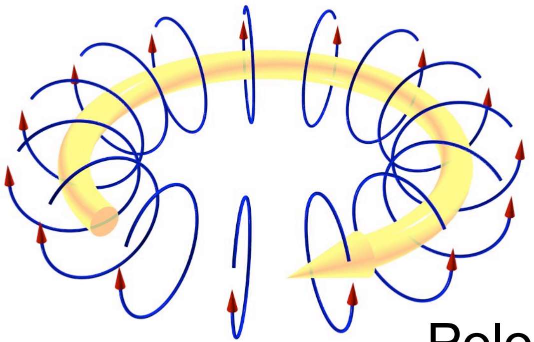
Total field





Toroidal field





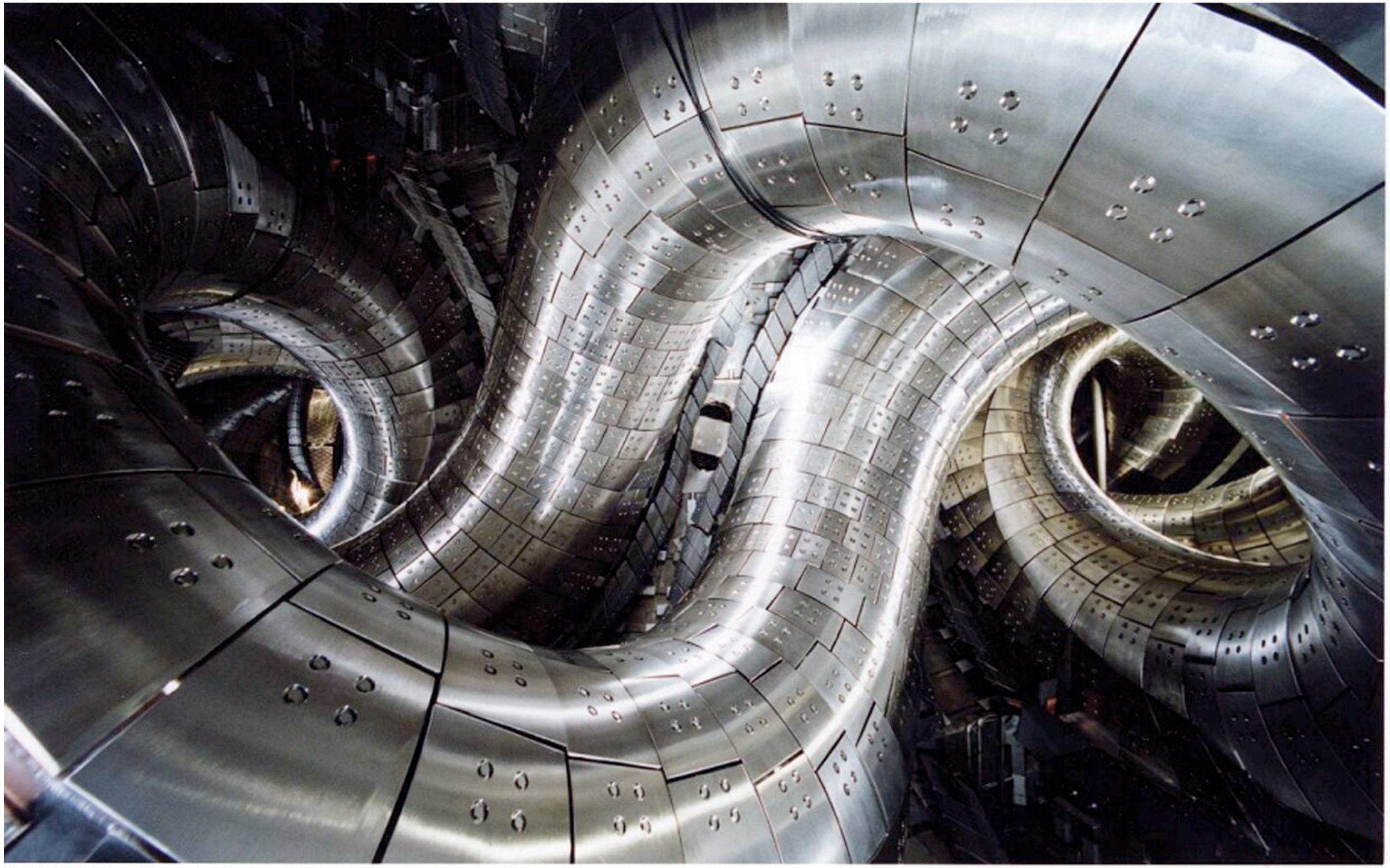
Ip

Poloidal field

- **Tokamak :**
- **external coils ➔ toroidal field**
- **plasma current Ip ➔ poloidal field**

Alternative configuration : the stellarator

• **Toroidal + poloidal field : external magnetic field coils**



Why do we bother ?

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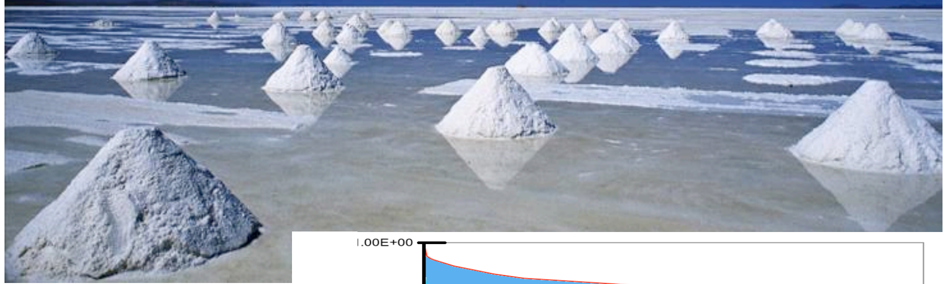
- **Almost limitless fuel supply**

$$D + T \longrightarrow {}^4He + n$$

$${}^6Li + n \longrightarrow {}^4He + T$$

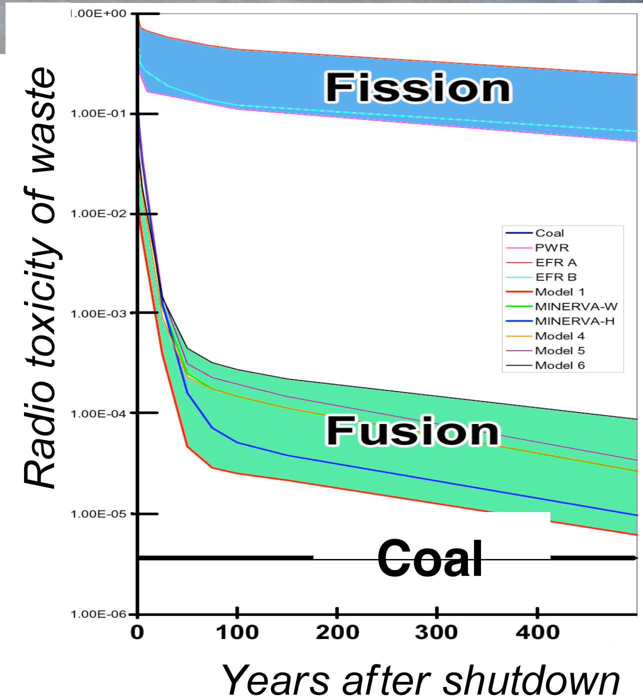
D : 33g/m^3 water ➔ billions of years
Li (for T): 0.17g/m^3 sea water ➔ millions of years



- **No greenhouse gas emission**

- **Intrinsically safe**
- No chain reaction
- Only few g of fuel ➔ enough for a few s burn

- **No long term radioactive waste** :
- not from reaction products (He)
- activation of the vessel (n) : low activity materials



On the way to fusion performance : ITER

How does it produce energy ?

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Fusion power amplification : $Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$

Density (ni): 1×10^{20} m-3 (~10^{-6} of atmospheric particle density)

Temperature (T_i): $1\text{-}2 \times 10^{8}$ °C
(~10 × temperature of sun's core)

Energy confinement time (τ_E): few seconds
(plasma pulse duration ~1000s)

⇒ **Present devices: Q ≤ 1**

⇒ **Next step : ITER: Q ≥ 10**

⇒ **Future Reactors : Q ≥ 30**

Density : fuelling the plasma

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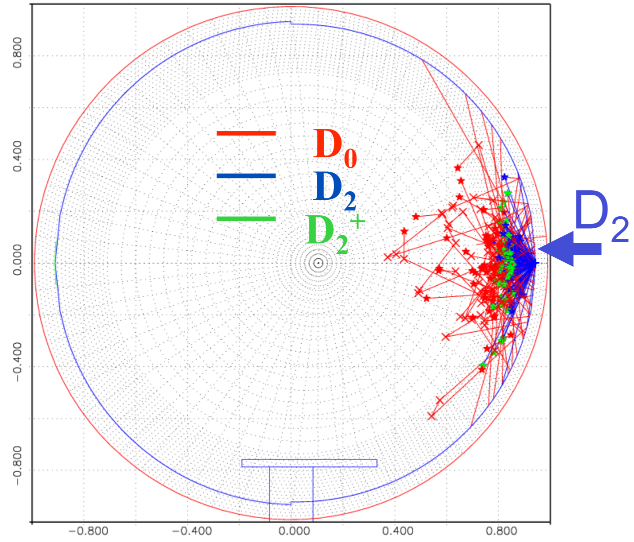
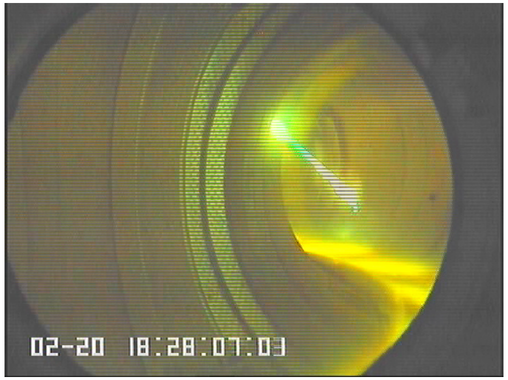
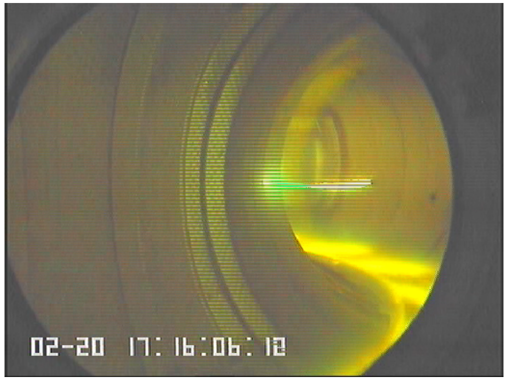
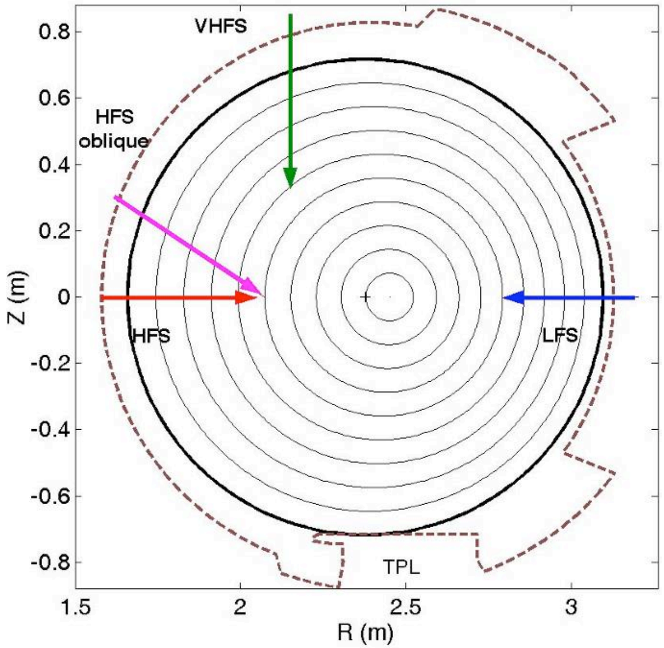
- **Gas injection : easy, poor efficiency**

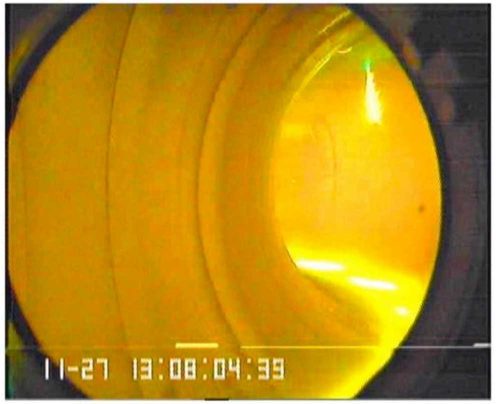


- **Pellet injection : complex, high efficiency**









Temperature : heating the plasma

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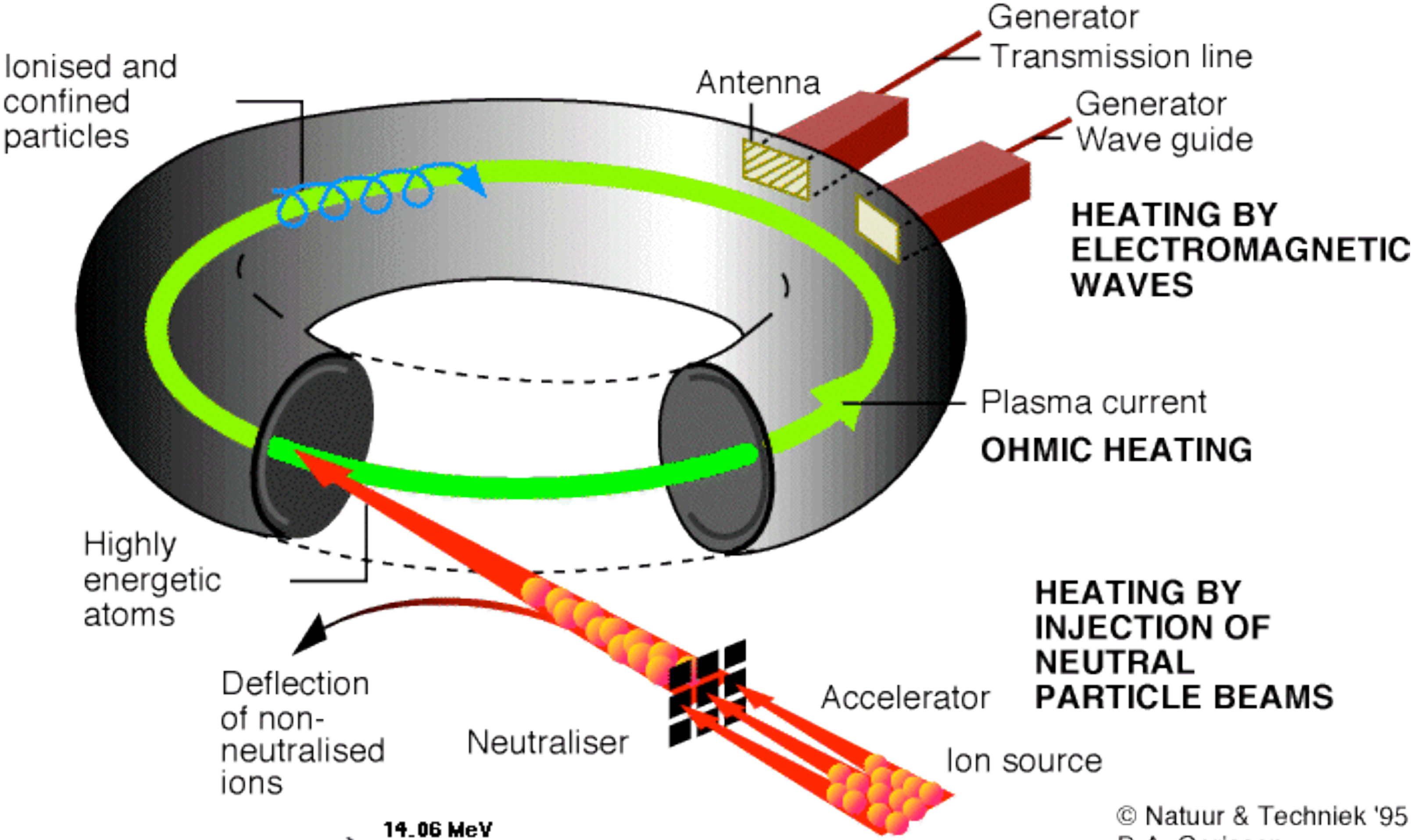
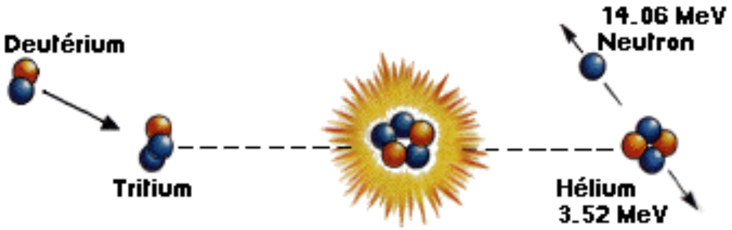
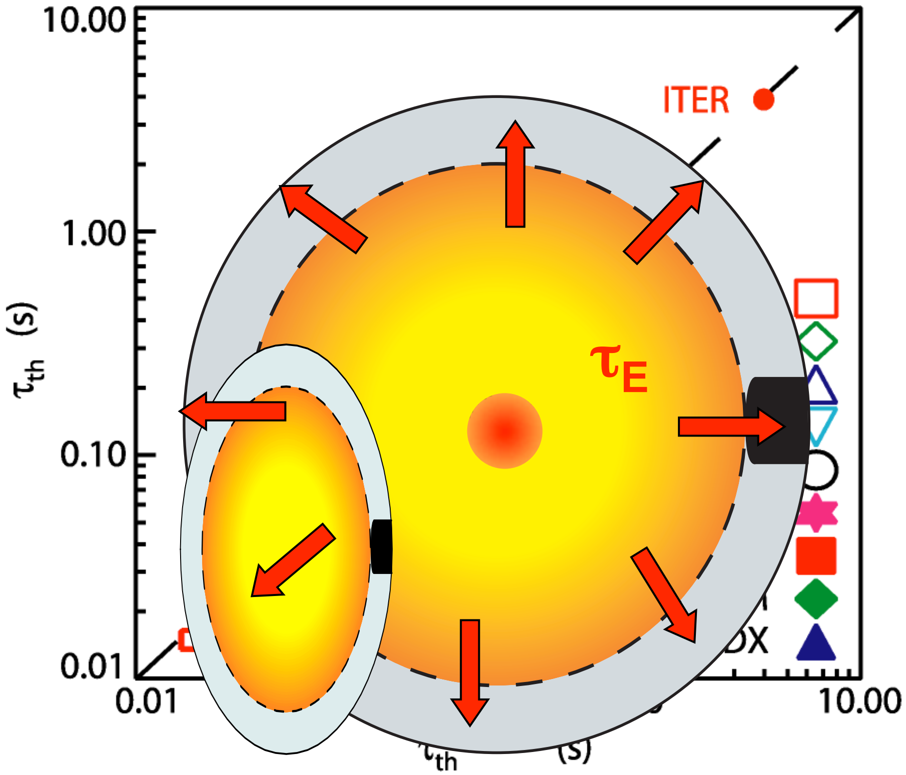


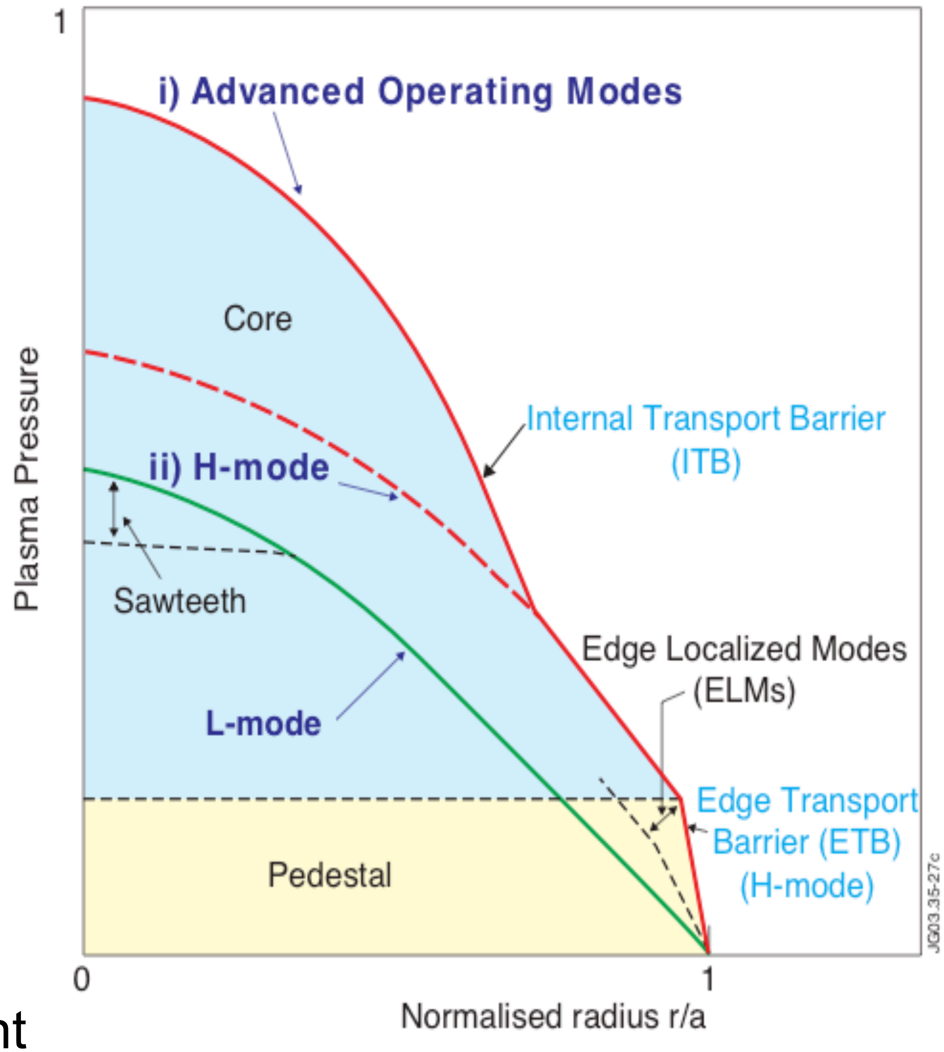


Future reactor : Heating by the alpha's

Confinement

Tokamak transport > collisions ➔ turbulence





L mode : low confinement
H mode : high confinement

The fusion quest

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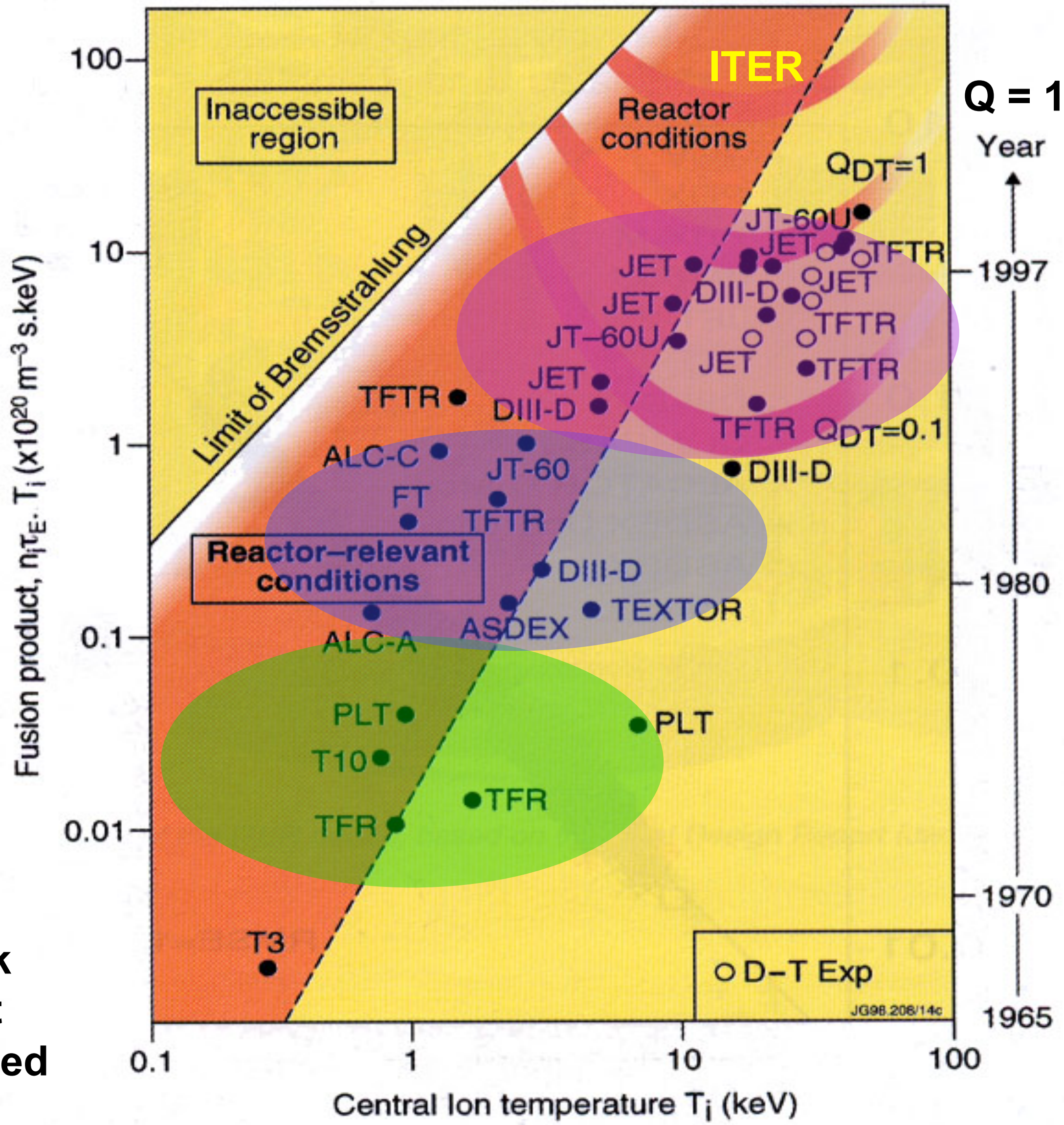


Q = 1, Break-even

- **JET : Joint European Torus, England**
- **ASDEX upgrade, TEXTOR, Germany**
- **Tore Supra, France**
- **MAST, England**
- **TCV, Switzerland**

- **JT60U, Japan**

- **DIIID, USA**
- **Alcator CMod, USA**

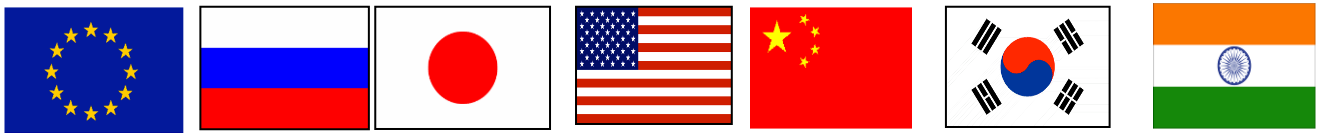
- **EAST, China**
- **KSTAR, South Korea**
- **SST1, India**

+ …

60's : tokamak concept developed

Next step : the ITER project

ITER is a major international collaboration in fusion energy research involving the EU (plus Switzerland, Romania, Bulgaria), China, India, Japan, the Russian Federation, South Korea and the United States



- **Programmatic objective:**
  - to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

- produce a significant fusion power amplification (Q ≥ 10) in long-pulse
- aim to achieve steady-state operation of a tokamak (Q = 5)

⇒ **a burning plasma experiment**

ITER Agreement Signature, Elysee Palace, 21.11. 2006

ITER : an ambitious challenge

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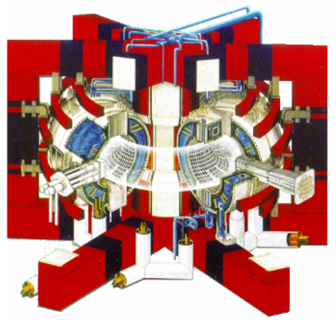
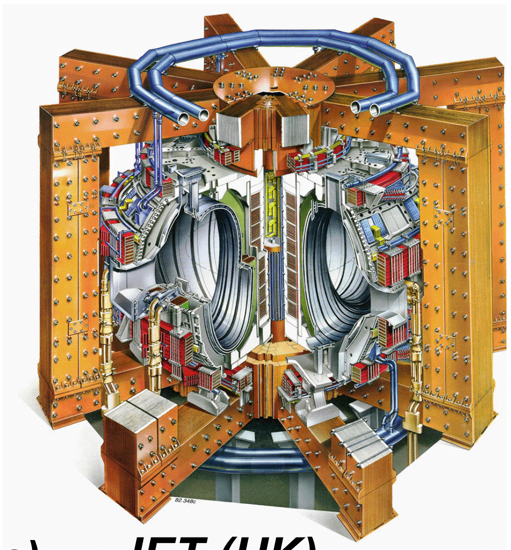
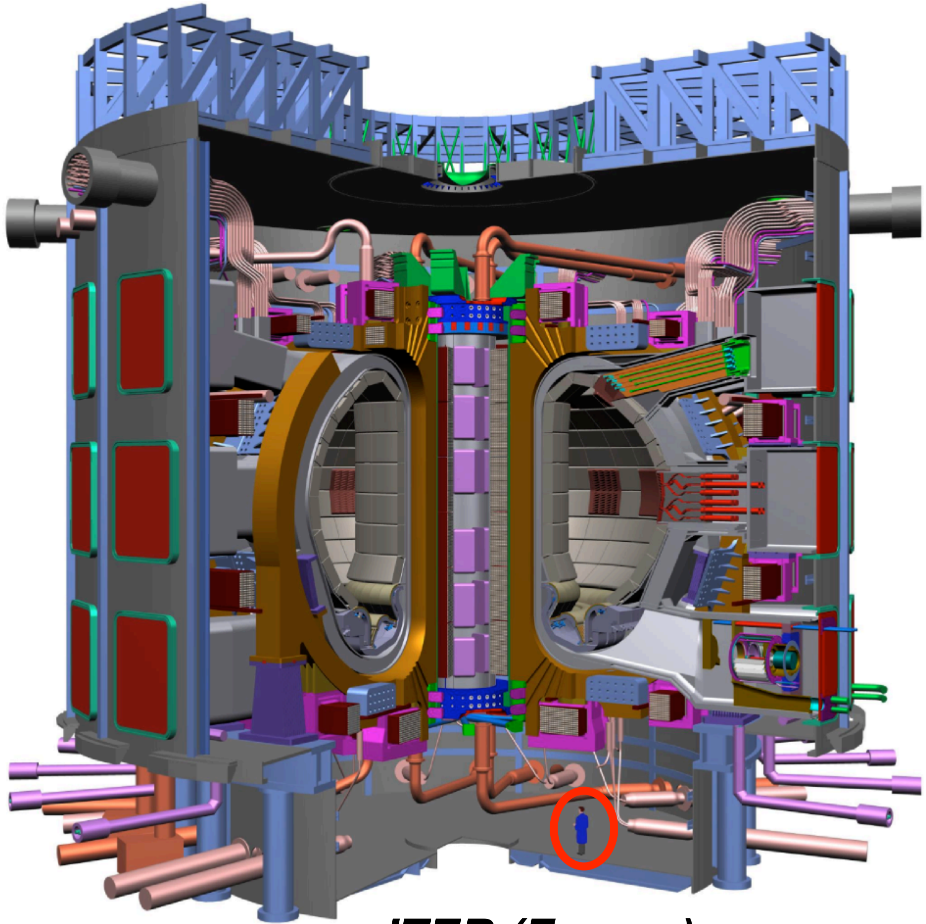
ITER is twice as large as our largest existing experiments







Tore Supra (France)
V_{plasma} ~ 25 m^3
P_{fus} ~ 0 MW
Q<1

JET (UK)
80 m^3
~16 MW
Q=0.5

ITER (France)
Q>10

Design	Construction	Exploitation	
1990	2008	2016	2036

PWI : the step to ITER

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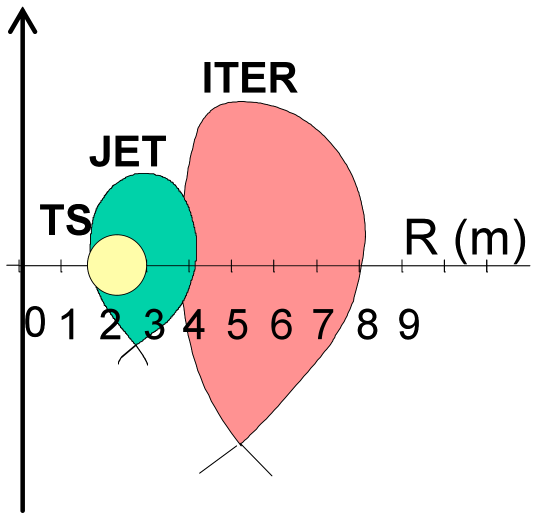

Parameter	JET MkIIGB (1999-2001)	ITER
Integral time in diverted phase	14 hours	0.1 hours
Number of pulses	5748	1
Energy Input	220 GJ	60 GJ
Average power	4.5 MW	150 MW
Divertor Ion fluence	$1.6x10^{27}$	*$6x10^{27}$

*Code calculation

1 ITER pulse ~ 0.5 JET years energy input

1 ITER pulse ~ 6 JET years divertor fluence

Main PWI issues for ITER : [R. Pitts]

- **Plasma Facing Components lifetime :**

steady state ➔ radiation cooling (impurity seeding) [M. Merola]

ELMs and disruption ➔ mitigation [A. Loarte]

- **Fuel retention (T inventory)** [P. Andrew, R. Causey, T. Tanabe]
- **Dust production** [P. Andrew]

Plasma wall interactions : overview

Edge plasma :
extracting heat and particles

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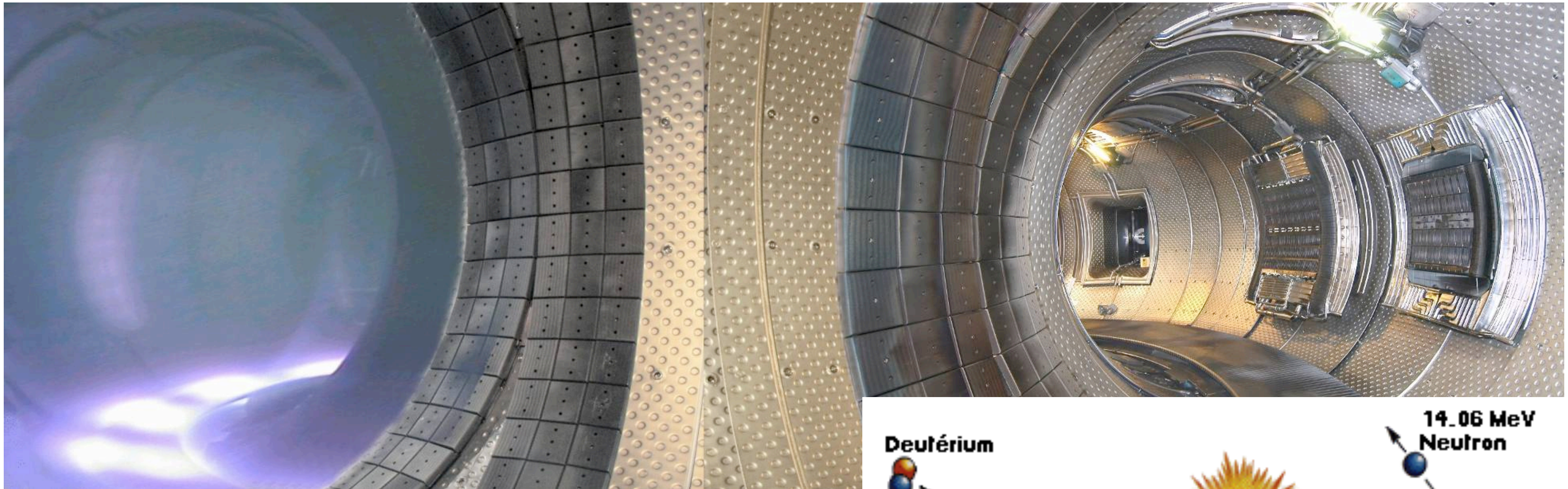

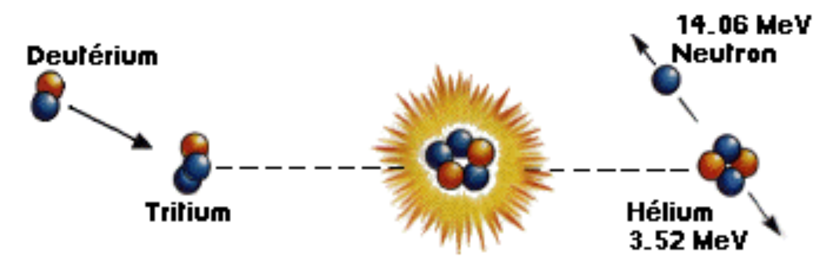

Edge plasma :

- **exhaust heat fluxes (~ 10 MW/m²)**
- **exhaust the reaction ashes (He)**
- **without perturbing core plasma performance (impurities)**

Plasma facing components (PFCs) : Limiter and divertor

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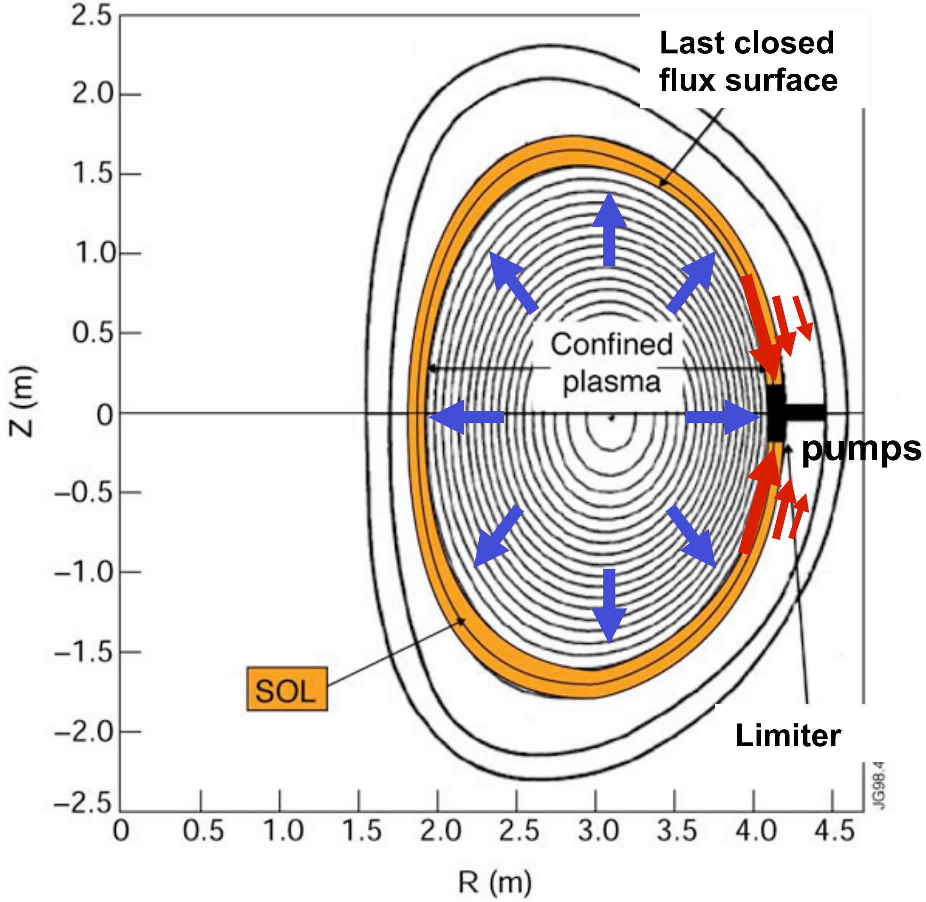
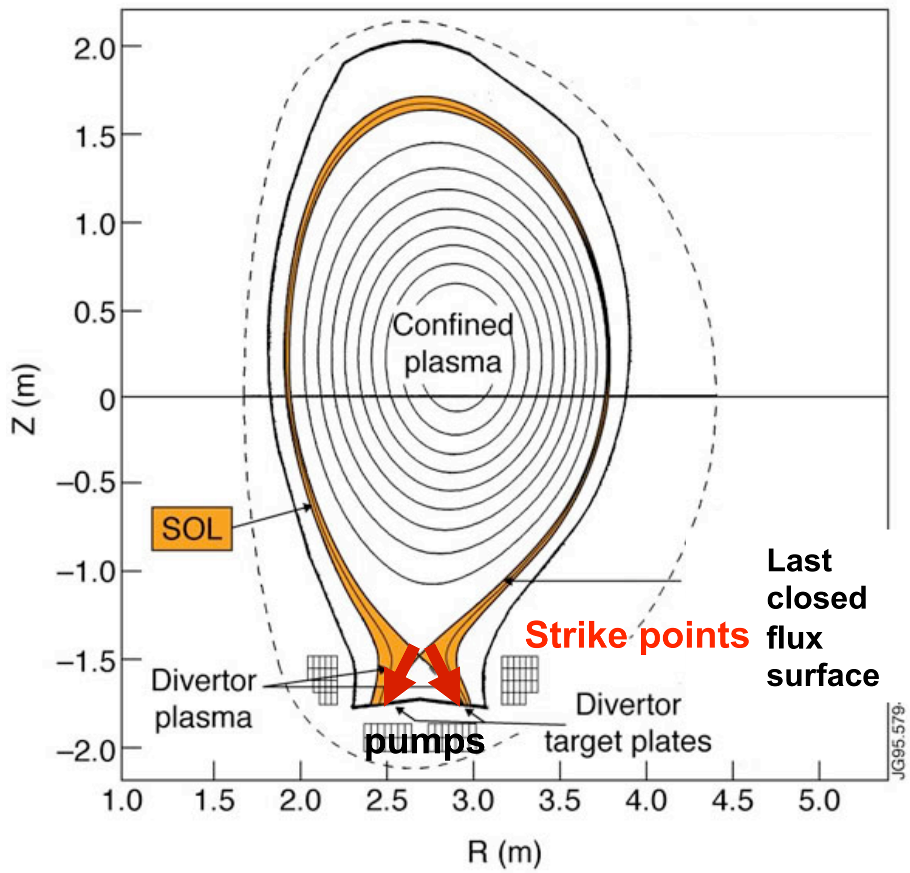


LIMITER



DIVERTOR ➔ H mode (ELMs)

Plasma Wall Interactions

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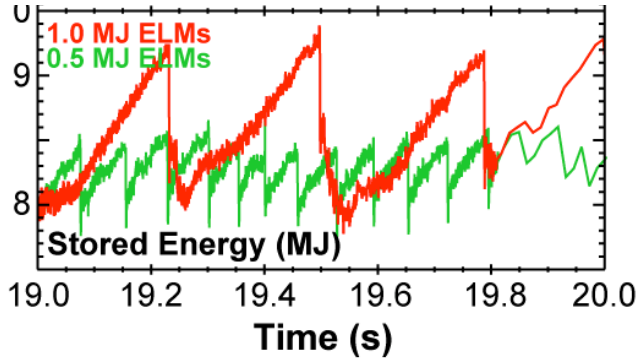
Plasma ➔ wall (heat and particle load ➔erosion, PFCs lifetime)

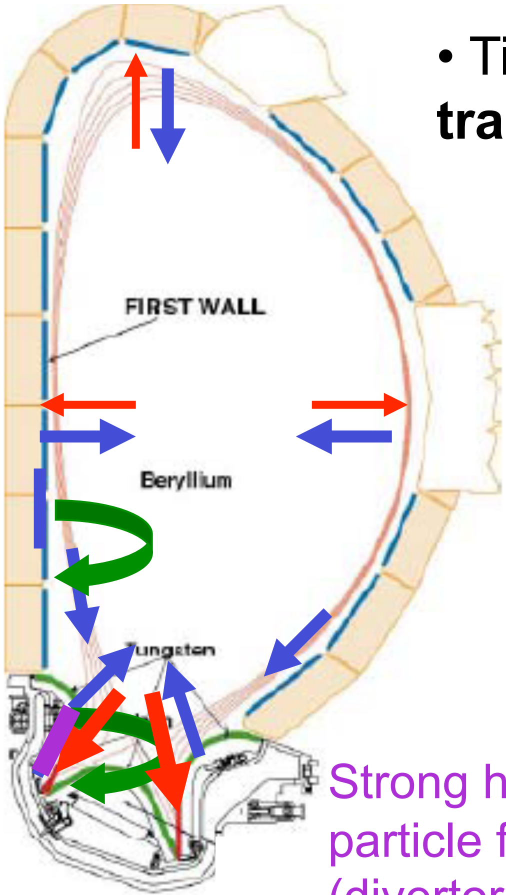
Moderate heat and particle flux (wall)

- Space : Strong **localised** interactions with divertor targets

- Time : **Steady state** loads + **transients** (ELMs, disruptions)

➔ **Radiation cooling**





Strong heat and particle flux (divertor)

Wall ➔ plasma (pollution➔ plasma performance)

Material migration

Erosion ➔ Transport ➔ Deposition ➔ Shadowed area

Deposition ➔ Re-erosion ➔ Transport

[J. Strachan]

Erosion ➔ PFC lifetime

Redeposition

➔ fuel retention and dust : safety issues

What is the ideal material ?

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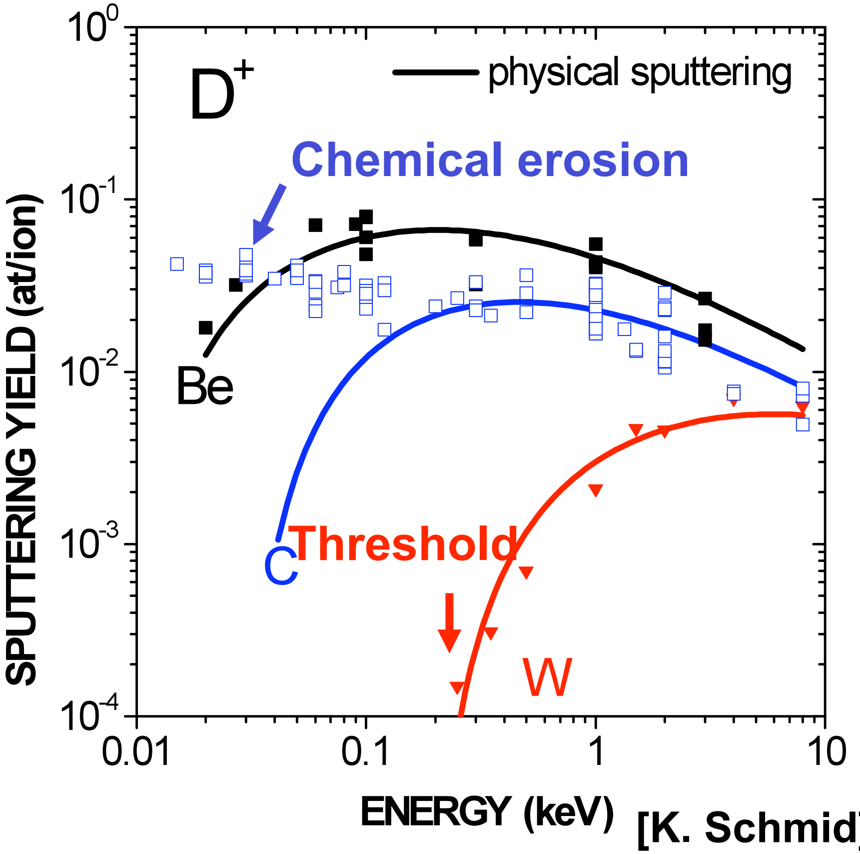
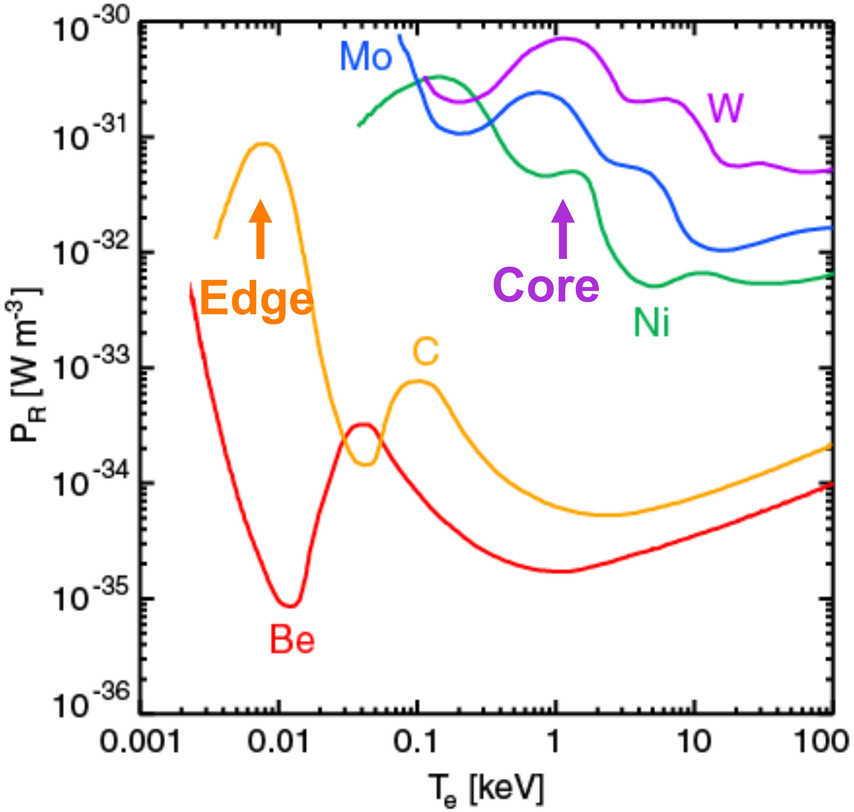
Low Z materials (carbone, beryllium) :
erosion / pollution / fuel retention



[K. Schmid]

Few % of C

High Z materials (tungsten) :
erosion / pollution / fuel retention



Few 10^{-5} of W

[R. Neu]

Materials for ITER

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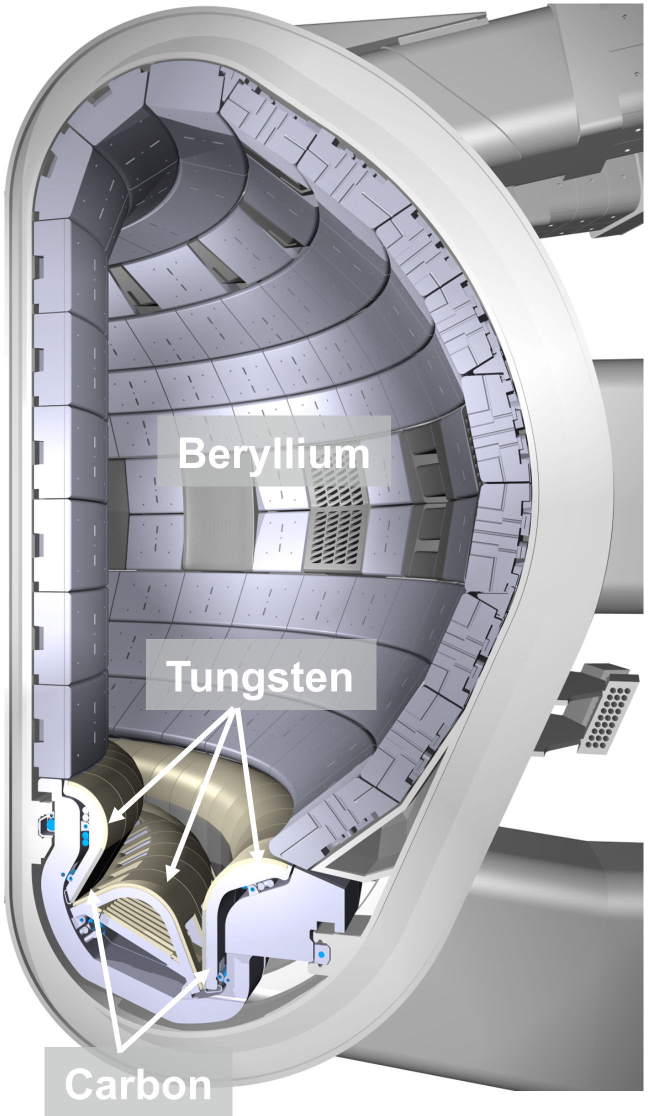

First wall : Be (700 m²)

moderate heat flux

low Z, oxygen getter : control of impurity content

⇒ plasma performance

Divertor baffles + dome : W (100 m²)

medium heat flux

high erosion threshold

⇒ life time + T retention

Divertor targets : Carbon Fiber Composite (50 m²)

high heat flux

Excellent thermo-mechanical properties, low Z

⇒ heat flux handling in divertor

- **ITER second phase of operation :**
W divertor / Be wall

Plasma recycling

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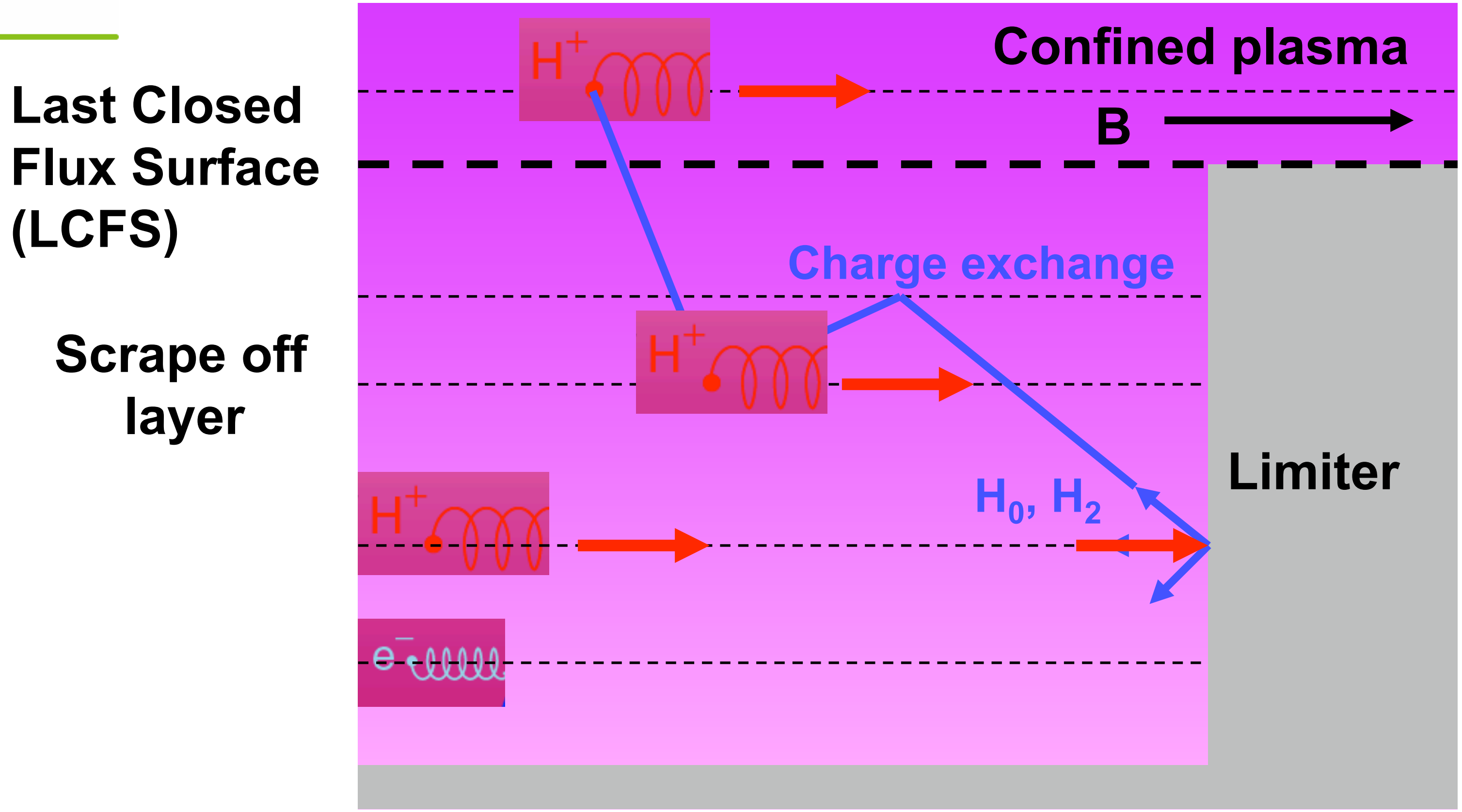
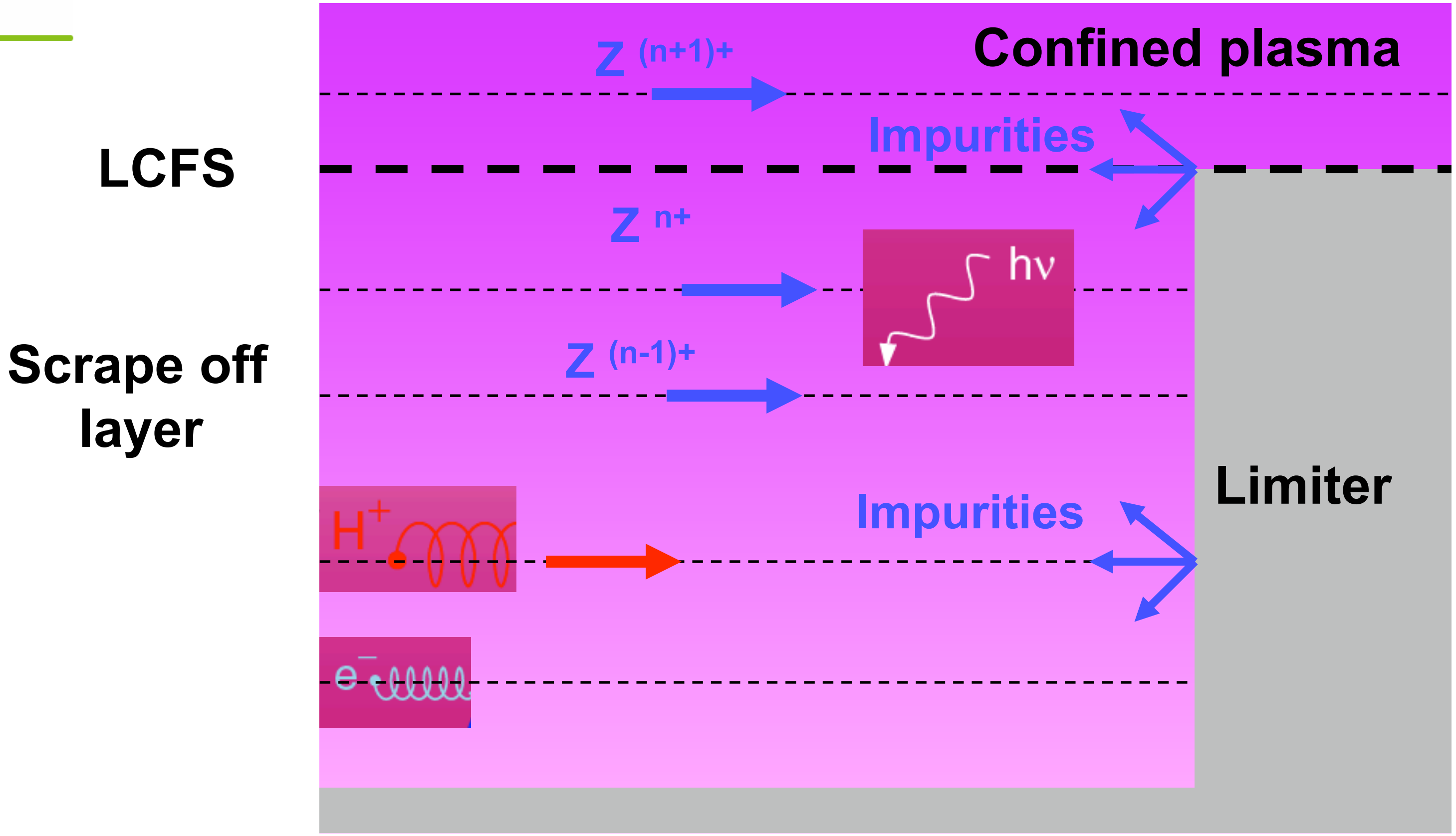


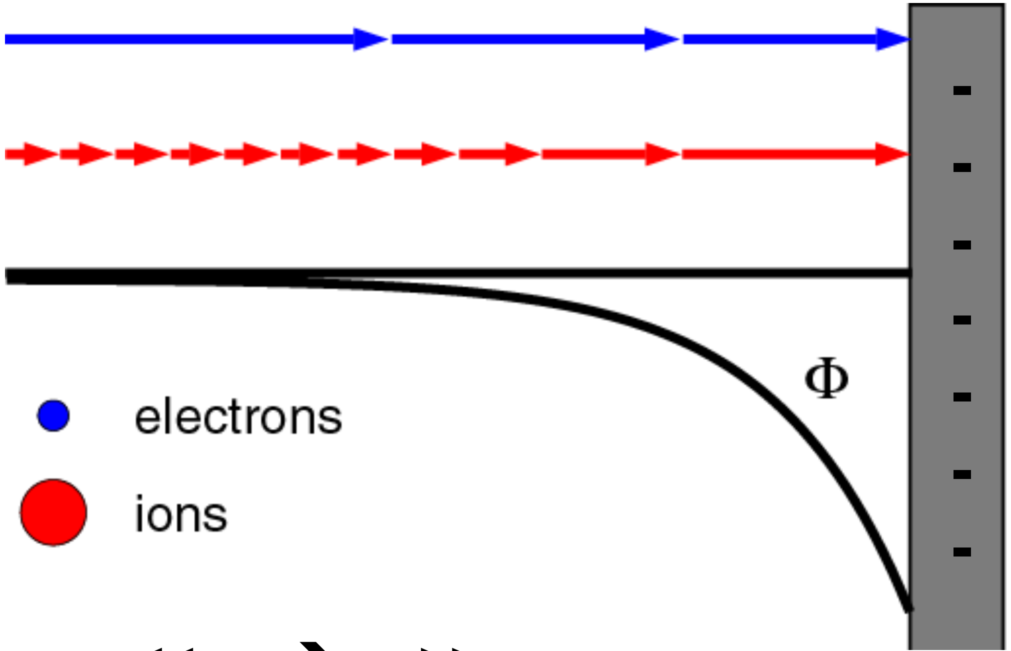
- Plasma hitting a surface recombine ➔ neutrals
- Complex atomic and molecular physics : dissociation, charge exchange, ionisation
- If re-ionisation < LCFS, re-start the process … : recycling

Impurities also …



- Plasma hitting a surface ➔ erosion ➔ impurities
- Atomic and molecular physics processes : photons
  - radiation cooling (edge)
  - Diagnostics (spectroscopy)

The sheath potential



$v \propto \sqrt{kT/m}$: $m_e << m_i \rightarrow v_e >> v_i$

Potential : $\Phi = 3\ kTe$

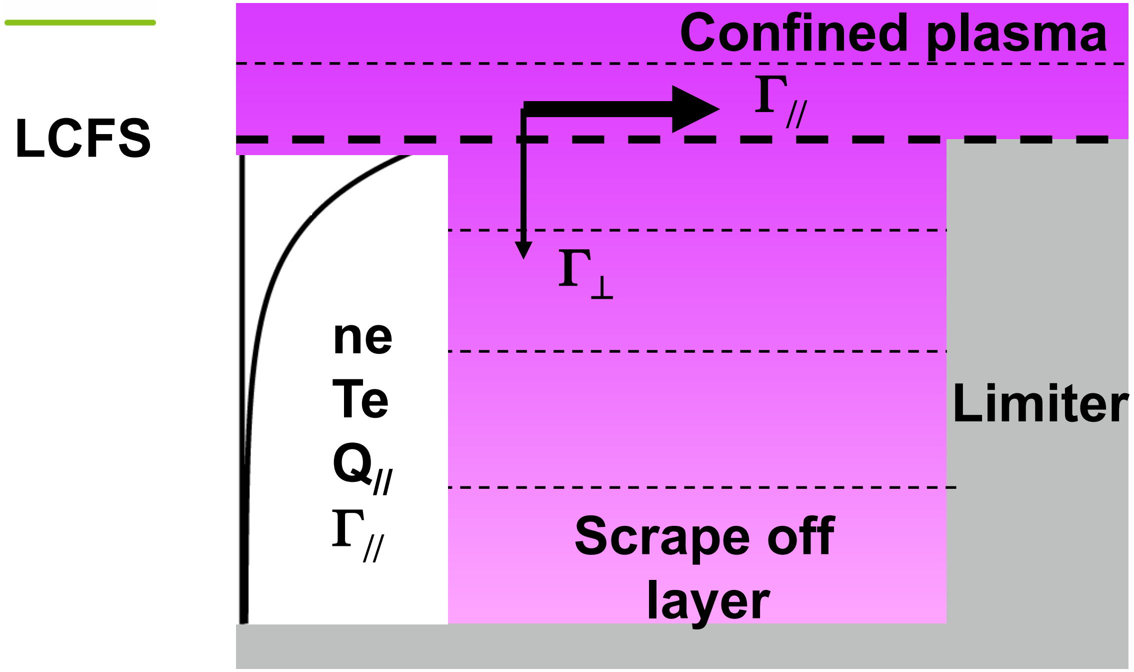
Ion impact energy : 2Ti + 3 Z kTe

- **threshold for erosion**
- **power on surface**

[W. Fundamenski, R. Pitts]

+ Complex poloidal and // flow pattern in SOL

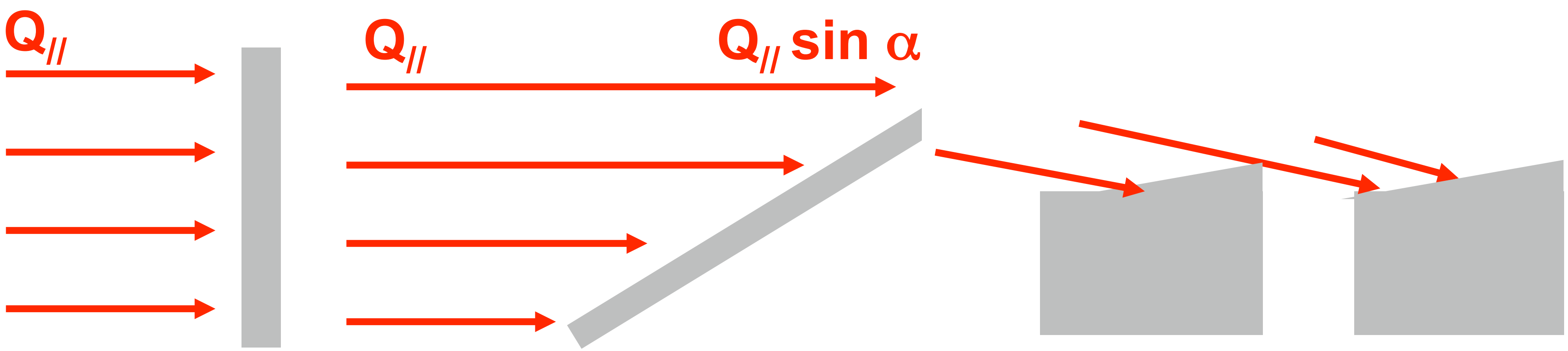
Power handling



ne , Te, $Q_{//}$, $\Gamma_{//}$: ~ exponential decay in the SOL

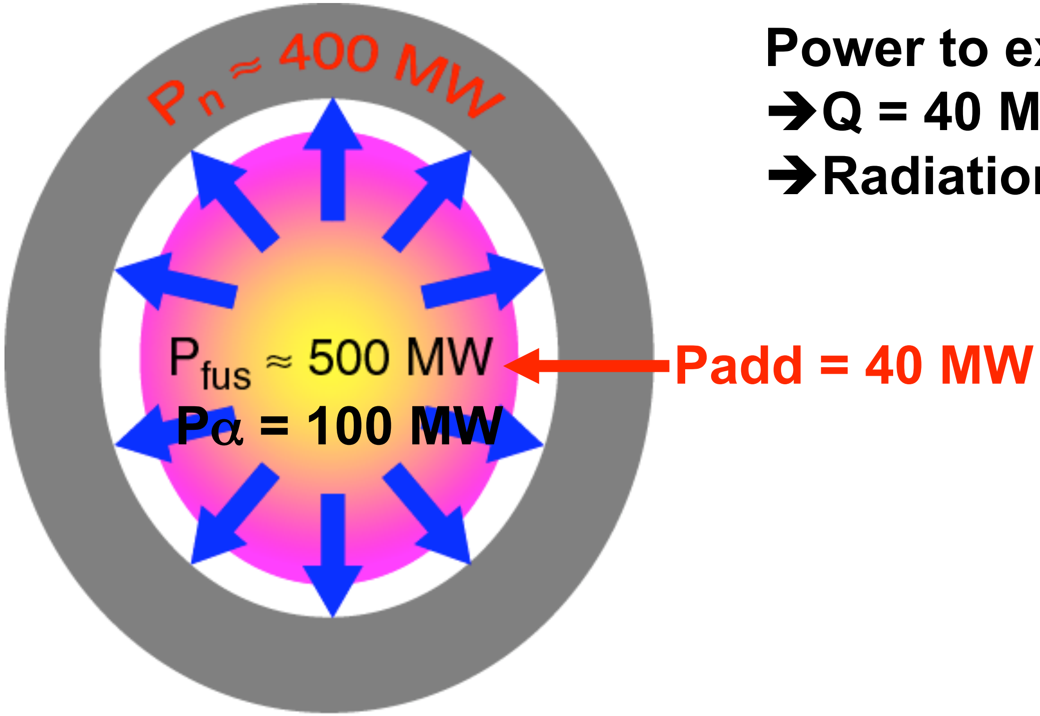
λ_Q ~ 1 cm :
power concentrated in the near SOL

PFC design :
- grazing incidence
- avoid leading edge

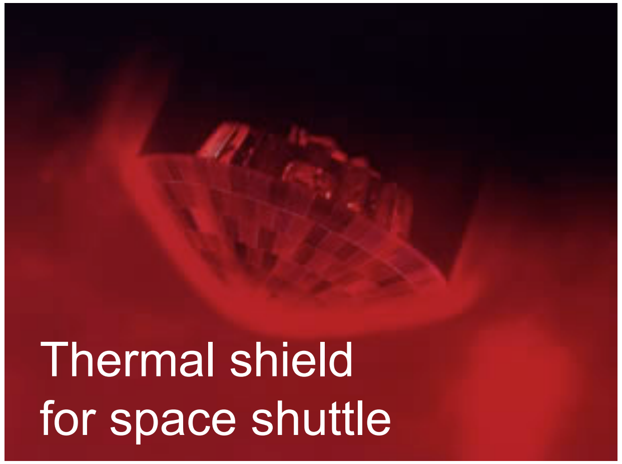


PWI challenges for ITER : Plasma facing components lifetime

Steady state loads



Power to exhaust on PFCs ~100 MW
➔Q = 40 MW / m²
➔Radiation cooling needed



ITER reference scenario :
Partially detached plasma
Extrinsic impurity seeding (Ar, Ne ..)
➔ Q = 10 MW/m²
➔ Active cooling of PFCs

Technology ~ ok
[M. Merola]

Detached plasma in TS

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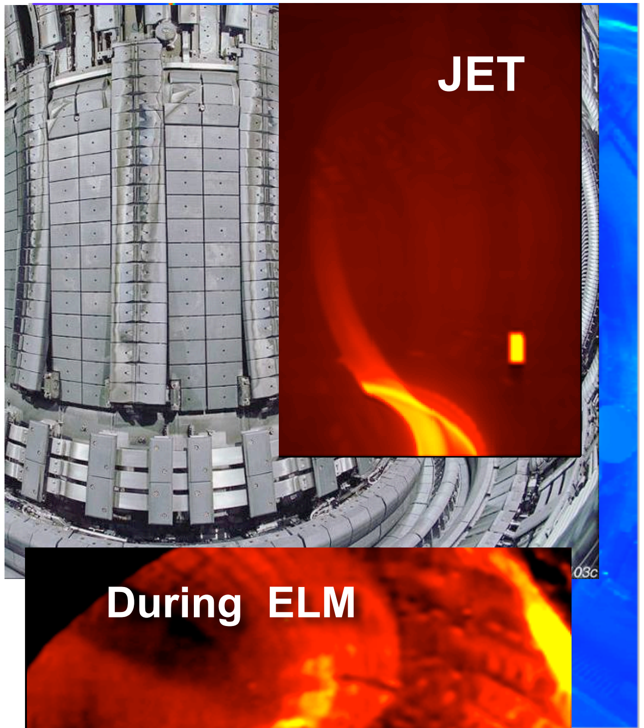
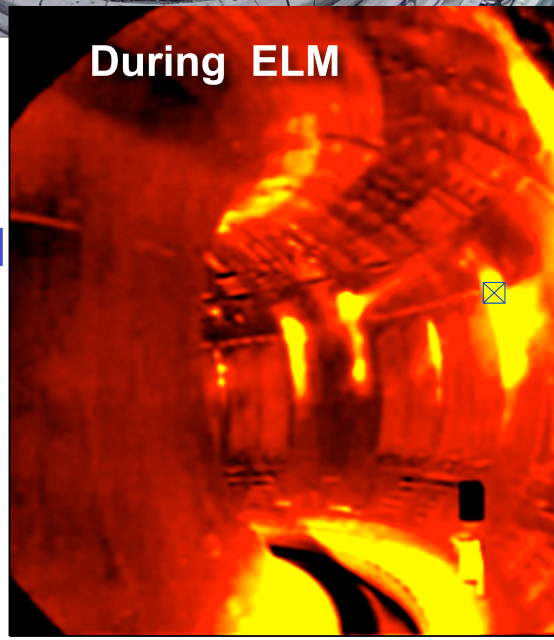
ITER : partial detachment

Transient heat loads

ELMs : 5-10 MJ/m² during 250-500 μs
Disruptions : 5-15 MJ/m² during 1.5-3 ms

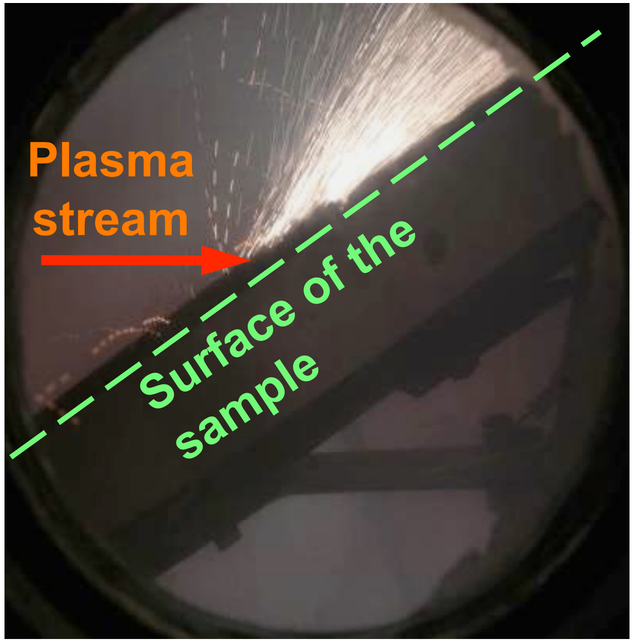
[A. Loarte]

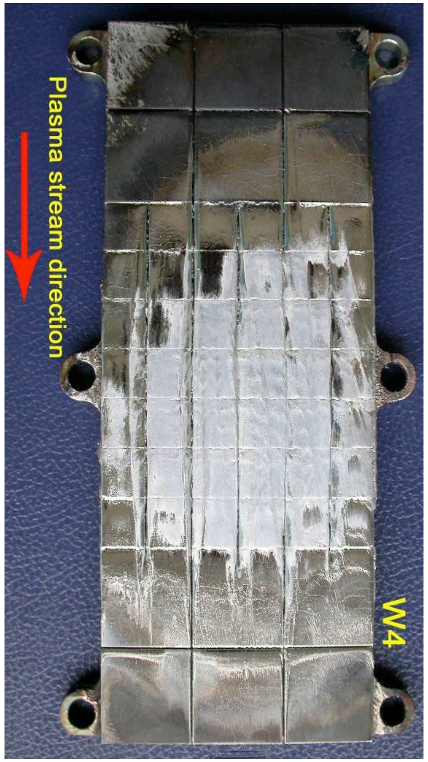




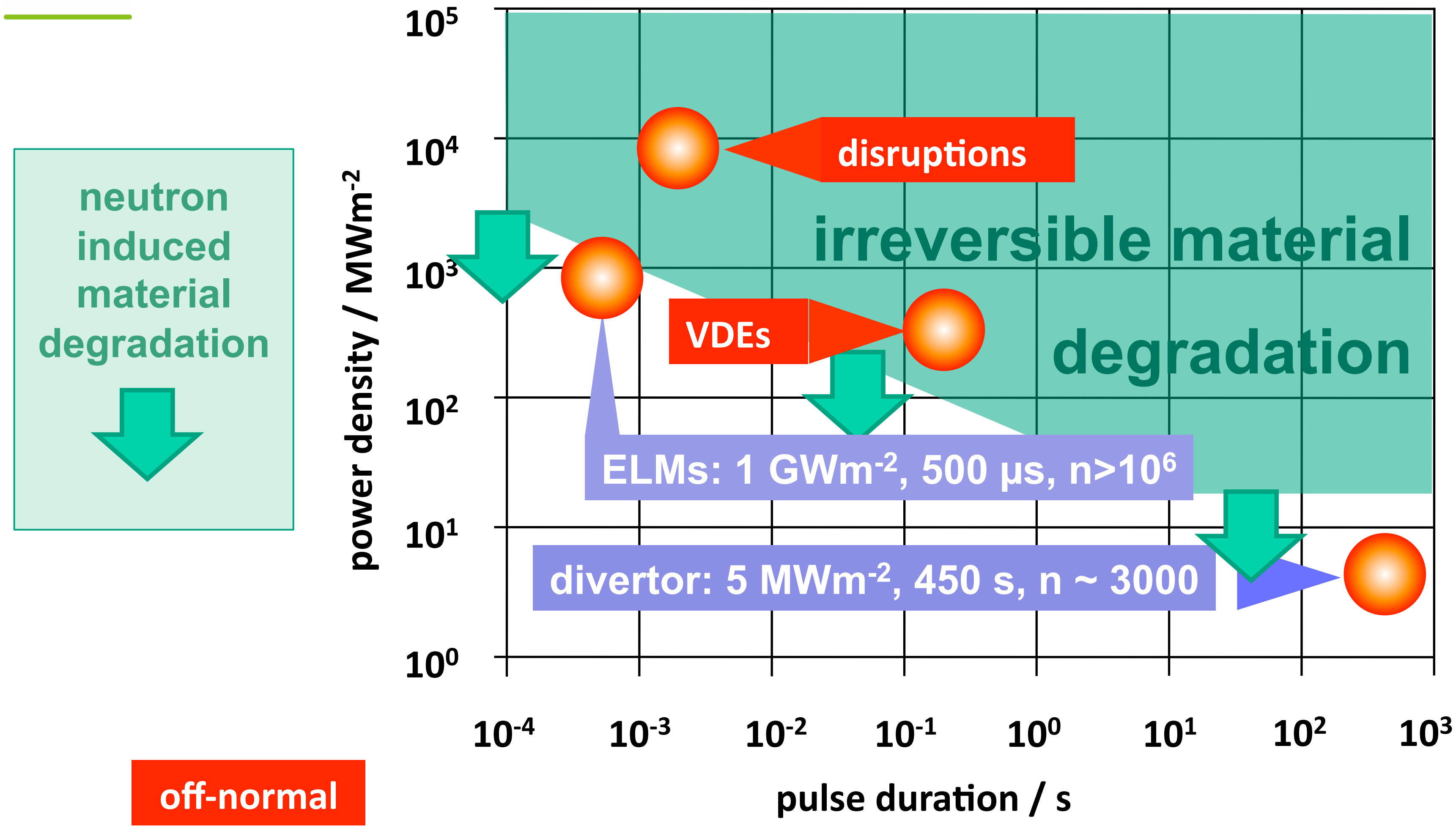
Material damage :

Plasma guns ➔ new limit 0.5 MJ/m²
Hard constraint on scenario (~ELM size / 20)





Neutrons

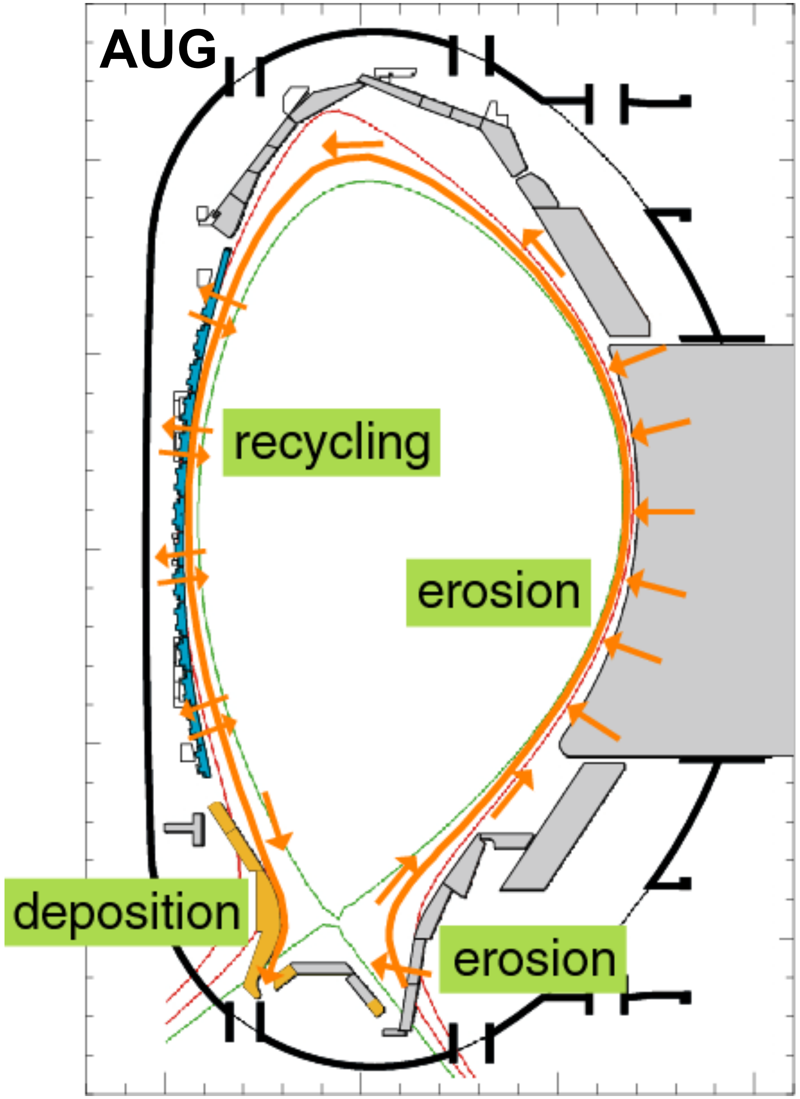


- ITER end of life ~ 1 dpa (neutrons 14 MeV)
- CFC thermal properties degraded, W ok
- Next step (reactor) : IFMIF project

[L. Snead]

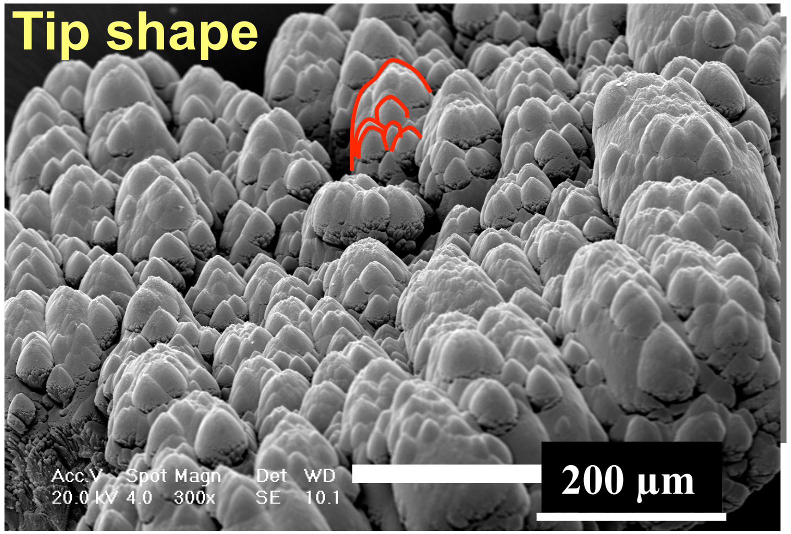
PWI challenges for ITER : material migration, dust and fuel retention

Material migration



- **Divertor :**
  - **Outer divertor : erosion**
  - **Inner divertor : redeposition**

[K. Krieger]



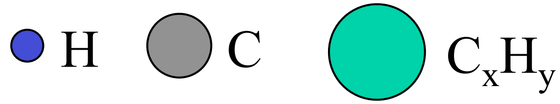
- **Mixed materials :**
  - **Be-W alloy : melting point closer to Be than W**

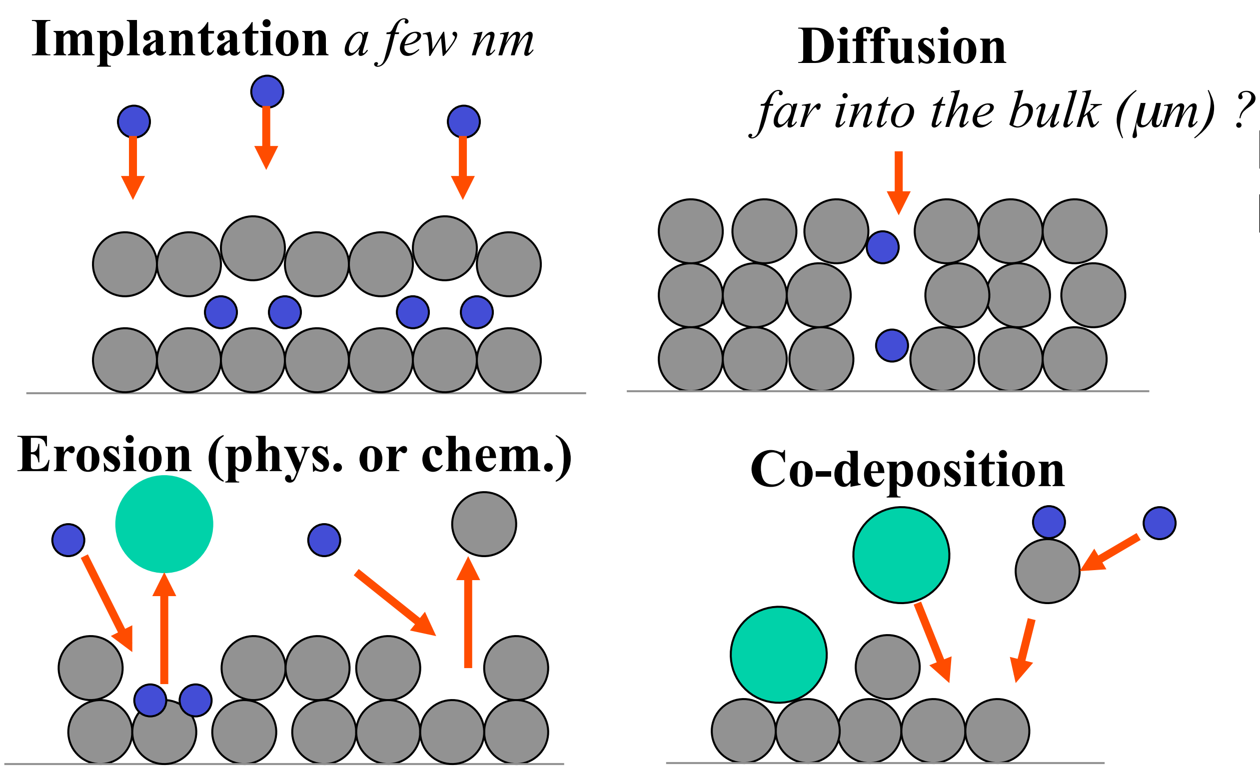
[Y. Ueda, N. Yoshida, G. Tynan]

Fuel retention

Safety limits for T inventory :

- **1 kg (risk = release in environment)**





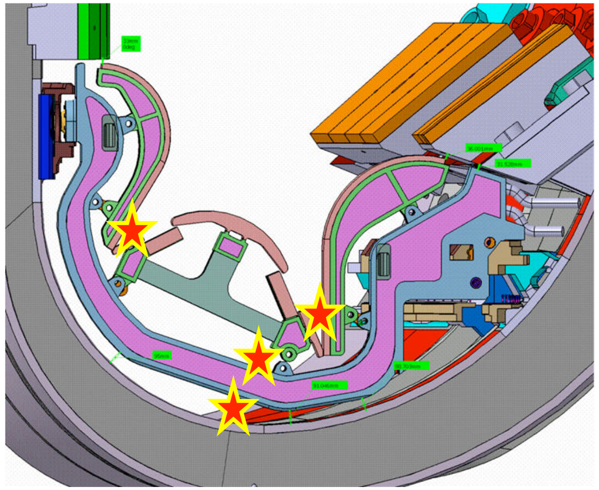
Bulk diffusion :
Main mechanism for W

Codeposition :
Main mechanism for CFC, Be

Retention :
W << Be < CFC

Fuel removal :
Photonic methods (laser)
Chemical methods (cleaning discharges)

Dust



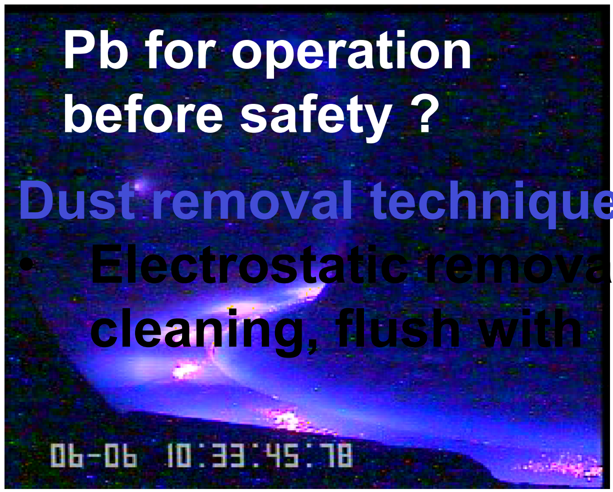
★ *Expected dust location in ITER*

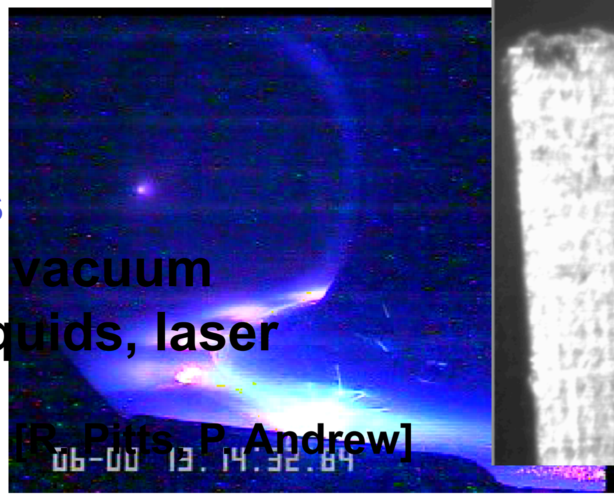
Safety limits for dust :

- **1000 kg (risk = release in environment)**
- **18 kg on hot surfaces (risk = H production)**

Dust production :

- **Thick layers flaking**
- **Transients**
- **Maintenance, cleaning …**





Pb for operation before safety ?

Dust removal techniques

- **Electrostatic removal, vacuum cleaning, flush with liquids, laser**

[R. Pitts, P. Andrew]

Dust removal with laser

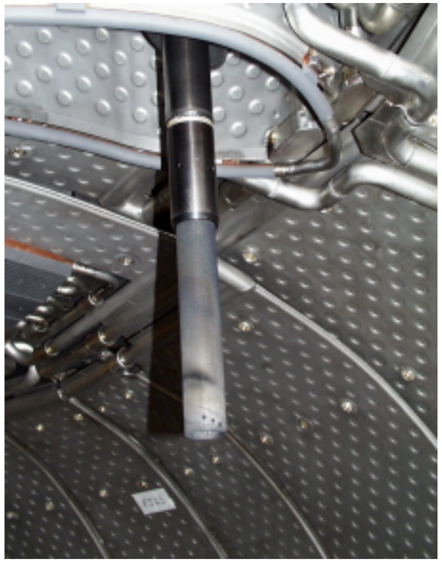
PWI challenges for ITER : Diagnostics and modelling

Diagnostics and modelling

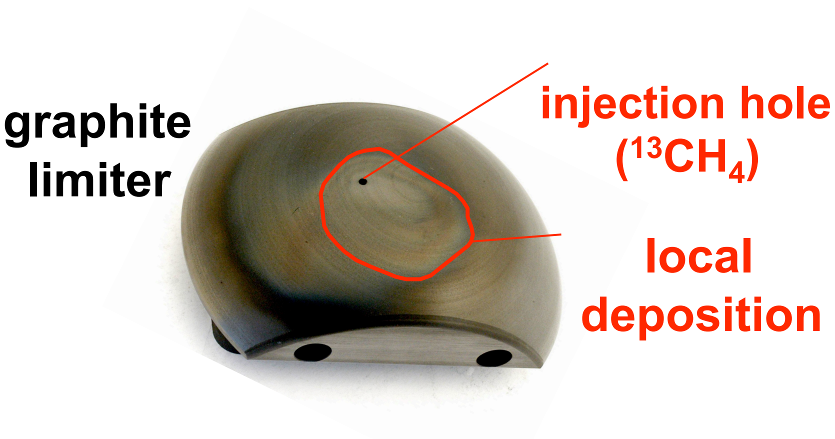
Diagnostics : measure and control :

- Plasma properties (ne, Te, impurities …)
- Heat fluxes on PFCs
- Dust and fuel inventory (safety)

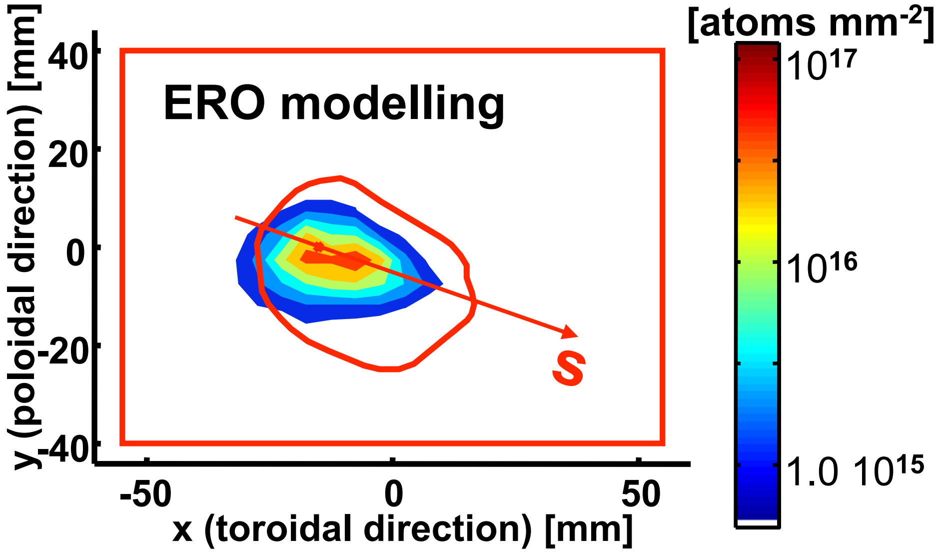
[S. Pitcher]



- **Modelling : understand and extrapolate**
- Plasma transport
- Heat fluxes on PFCs
- Erosion, material migration, fuel retention …



[T. Tazikuka, M. Kobayashi, K. Ohya]



Plasma wall interactions :
An ambitious programme worldwide

ITPA DivSOL and EU-PWI TF : targeted at ITER

Euratom

International Tokamak Physics Activities
on Divertor and Scrape off layer

Experts from the 7 ITER partners

European Task force
on Plasma Wall Interactions

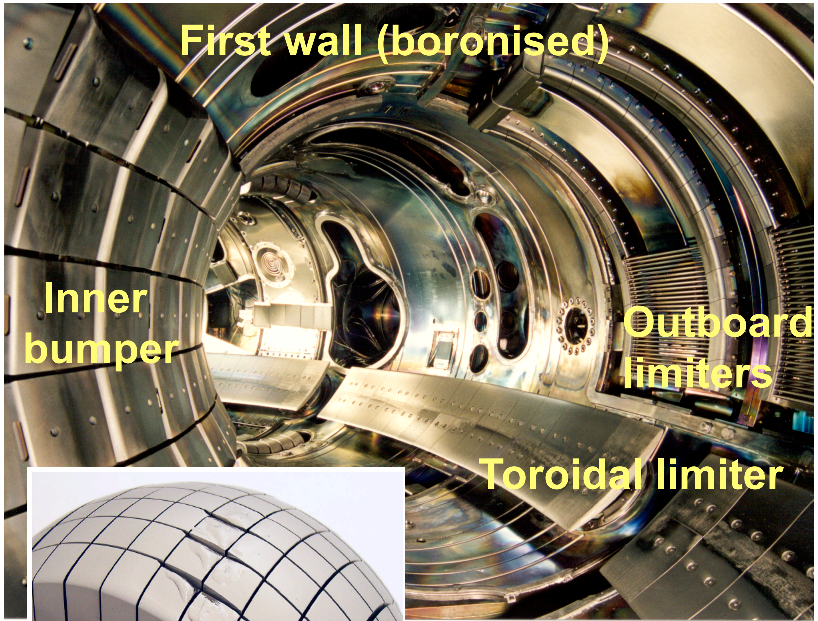
24 associations (~ 80 ppy)

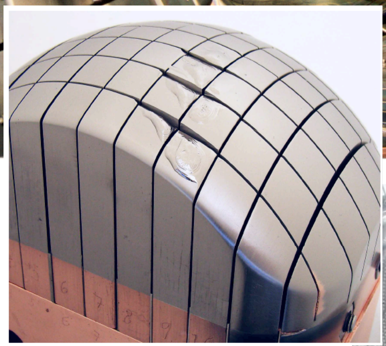
http://www.efda-taskforce-pwi.org/

Complementary PWI programmes

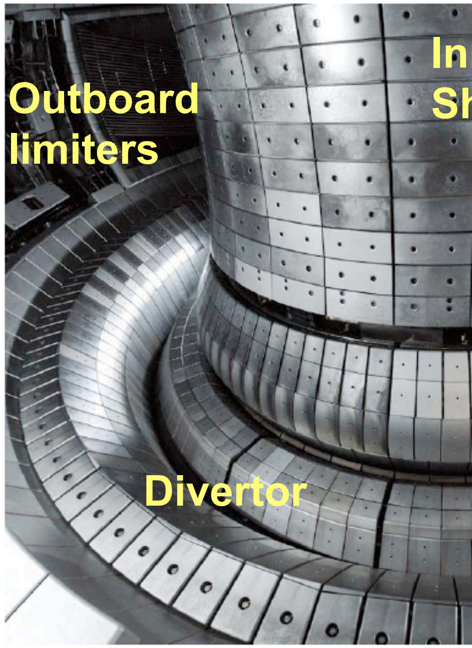
Euratom

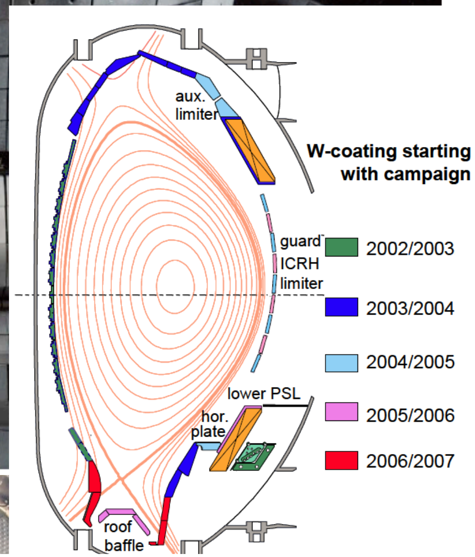
TEXTOR : Flexible PWI tools



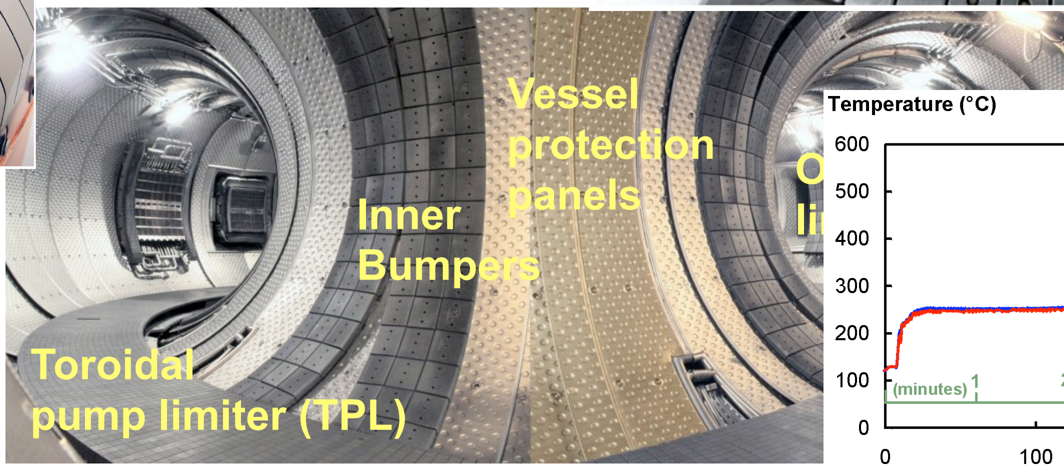


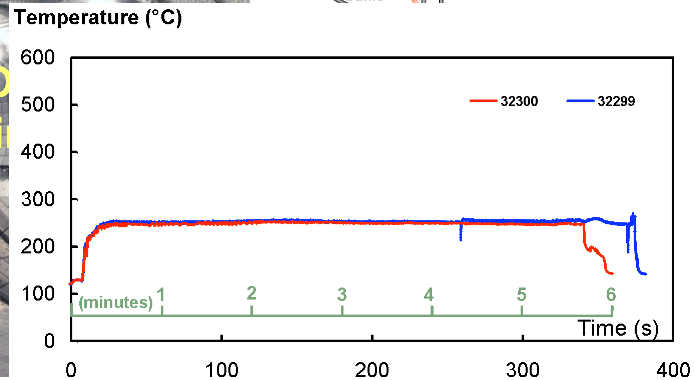
AUG : Pioneering W operation





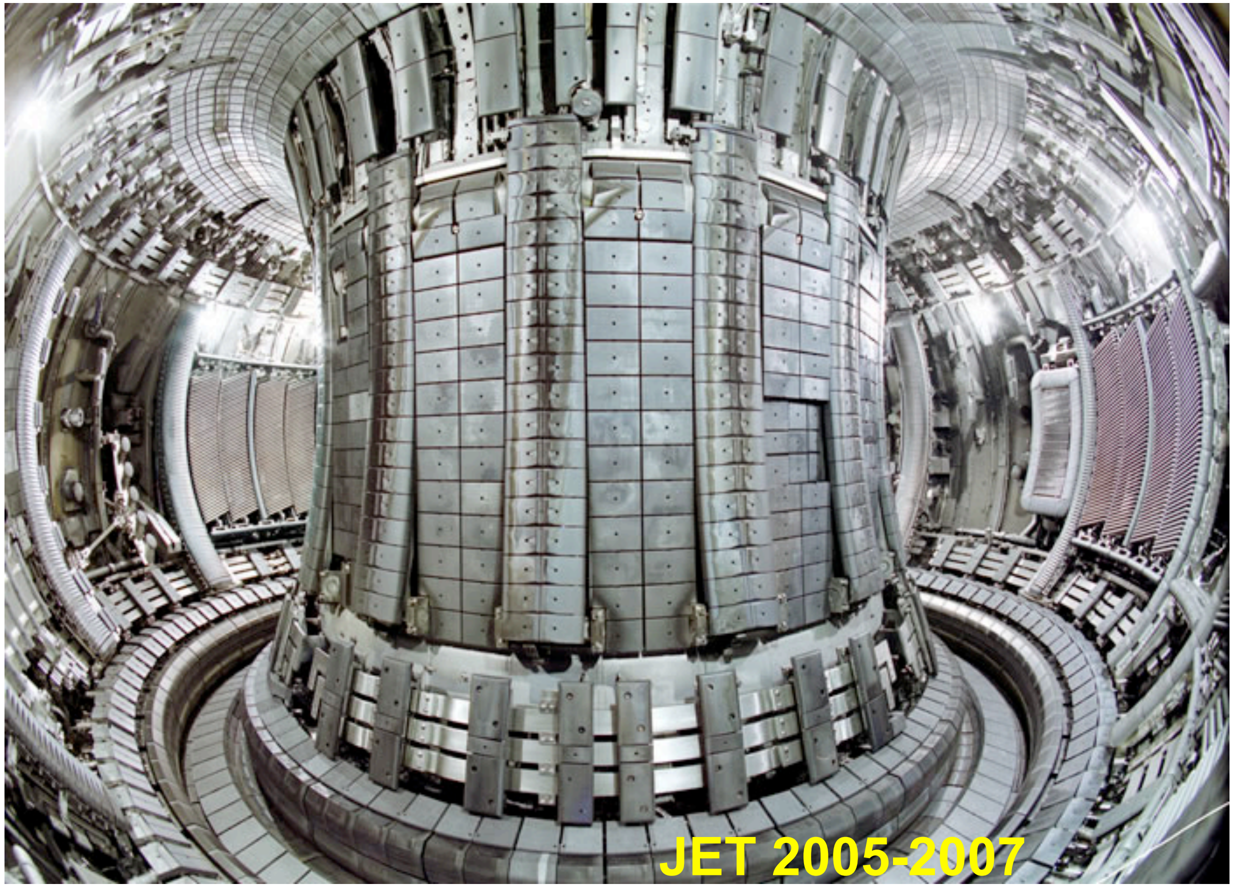
Tore Supra : Steady state PWI (Tsurf)





JET ITER like wall

JET ITER like wall : W divertor (coatings + bulk W)
Be first wall



Shutdown for installation of JET ITER like wall starting end 2009

Summary

Plasma wall interactions : interdisciplinary field

- Plasma physics (edge : sheath, 3D !)
- Atomic and molecular physics
- Plasma-wall interactions (erosion …)
- Solid state physics (wall : fuel retention, mixed material)

Edge plasma : a central question for fusion devices

- Exhaust the **heat**
- Exhaust the **ashes** (He)
- without perturbing the core plasma **(impurities)**

PWI issues for ITER

- Plasma Facing **components lifetime**
  - Minimize thermal loads (PFC design, radiation cooling)
  - Mitigate **transients** (ELMs, disruptions)
- **Tritium** retention / **Dust** production
  - Develop diagnostics (safety), implement fuel/dust removal techniques

A coordinated program at the international and European level : welcome !

(Selected) useful references

Euratom

Book :

"The plasma boundary of magnetic fusion devices", P. C. Stangeby, IoP Publishing Ltd, Bristol, 2000

Overview papers :

"Experimental divertor physics", C. S. Pitcher and P. C. Stangeby, Plasma Phys. Control. Fusion 39 (1997) 779

"Plasma-material interactions in current tokamaks and their implications for next step fusion reactors", G. Federici et al., Nucl. Fusion 41 (2001) 196

"ITER Physics basis: Chapter 4, power and particle control", Nucl. Fusion 39 (1999) 2391

"Plasma-surface interaction, scrape-off layer and divertor physics: implications for ITER", B. Lipschultz et al., Nucl. Fusion 47 (2007) 1189

"Recent analysis of key plasma wall interactions issues for ITER", J. Roth et al., J. Nucl. Mater. 390-391 (2009) 1

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