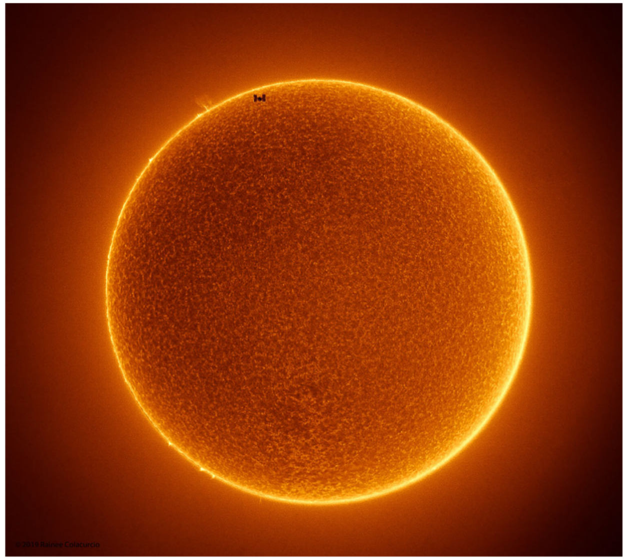
# Physics of heat and particle exhaust in tokamaks

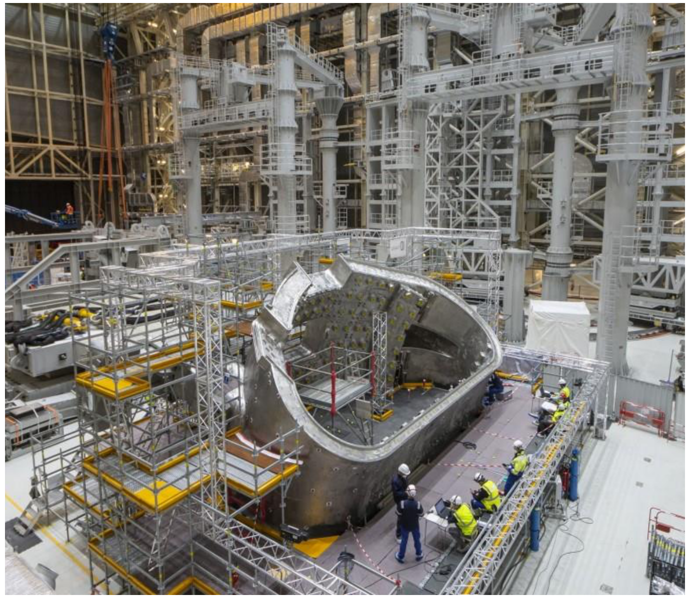
Y. Marandet[1], H. Bufferand[2], G. Ciraolo[2], J. Denis[1], Y. Ferro[1], A. Gallo[2], M. Raghunathan[1], N. Rivals[2], E. Serre[3], P. Tamain[2]

[1] CNRS, Aix Marseille Univ., PIIM

[2] IRFM, CEA Cadarache

[3] CNRS, Aix Marseille Univ., ECM, M2P2

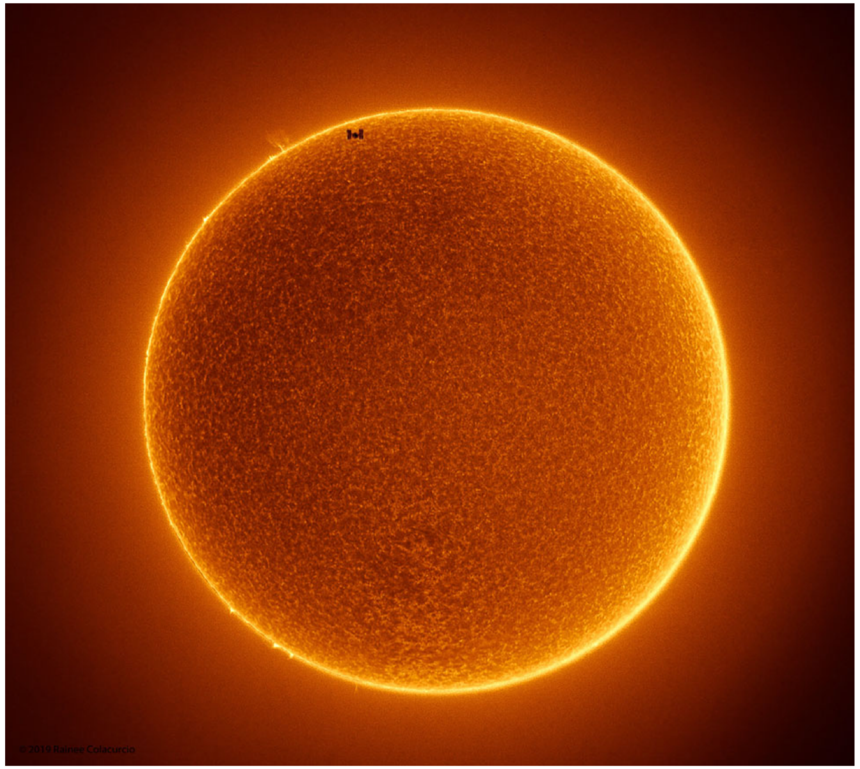




**Réseau Plasmas froids, Dec. 7th 2022**

# Outline

1) The energy of the stars (well, sort of)
2) Building a magnetic bottle
3) Energy exhaust & Numerical modelling
4) Particle control



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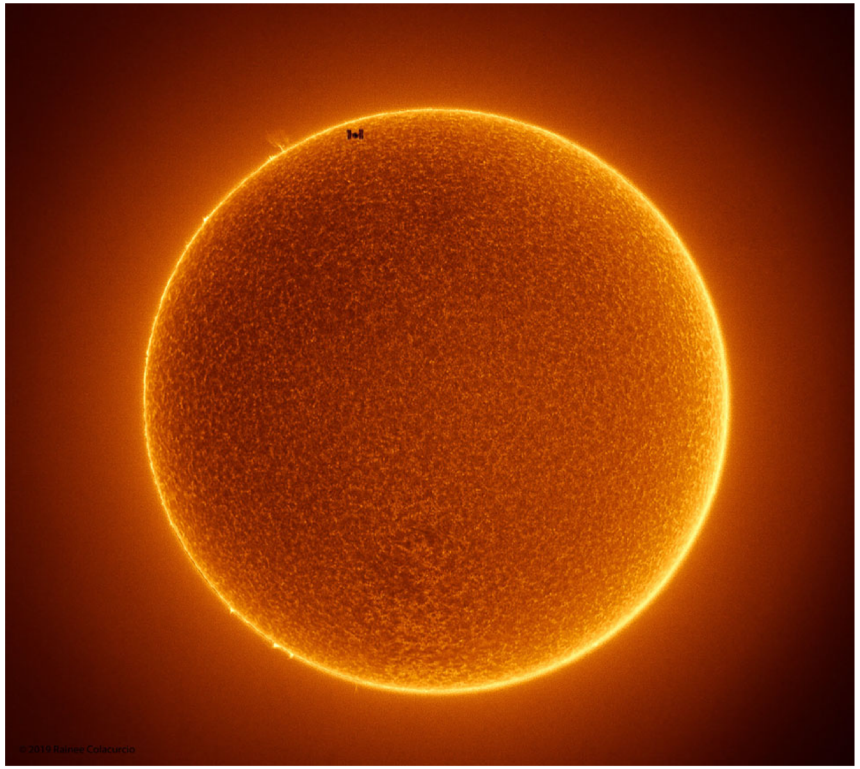

# Fusion reactions powering stars

H. Bethe et al., 1939

$$4\ {}^{1}H^{+} \rightarrow {}^{4}He^{2+} + 2e^{+} + 2\,\nu,\ E = 26.73\ \text{MeV}$$

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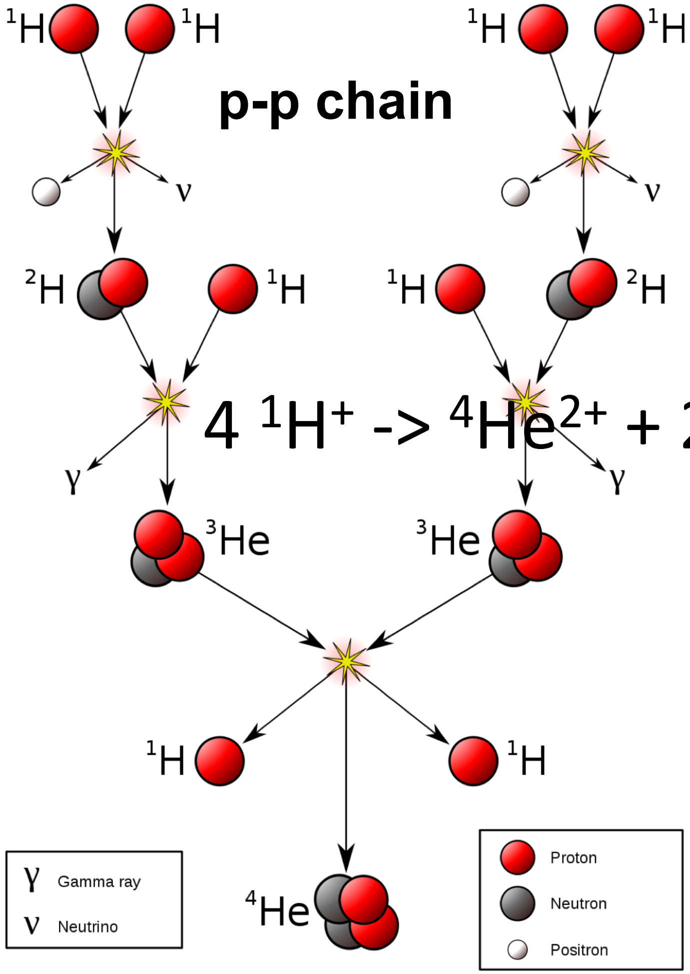
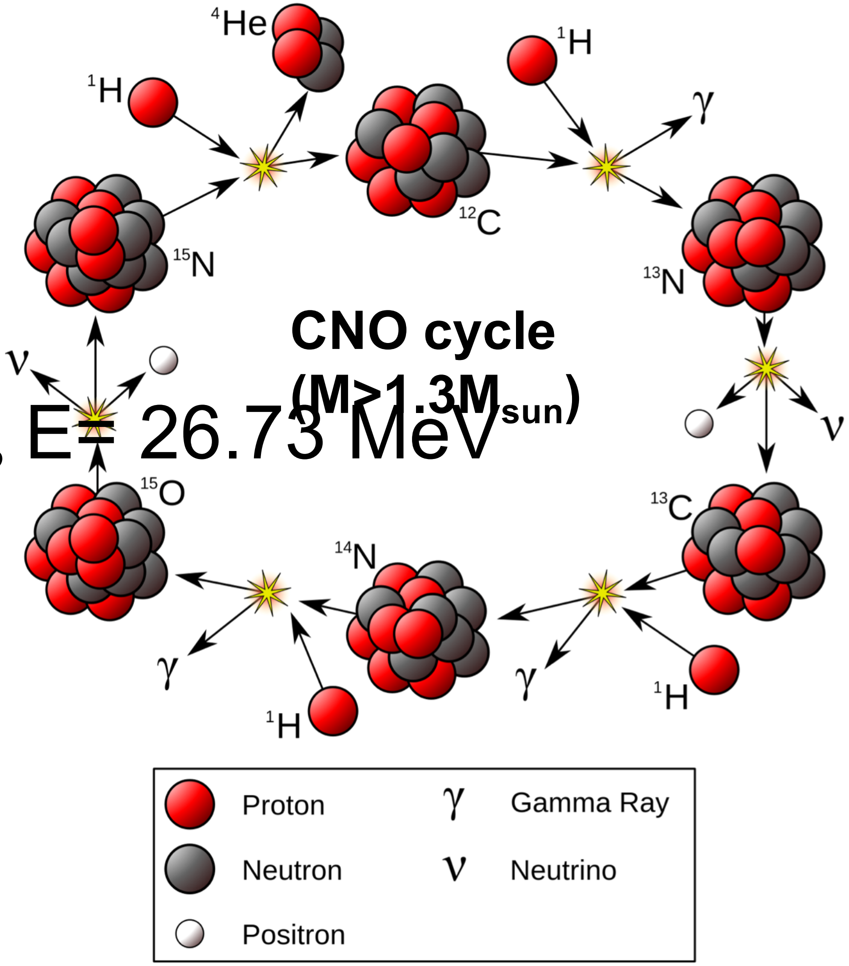



$$4\ {}^1H^+ \rightarrow {}^4He^{2+} + 2e^+ + 2\,\nu,\ E = 26.73\ \text{MeV}$$

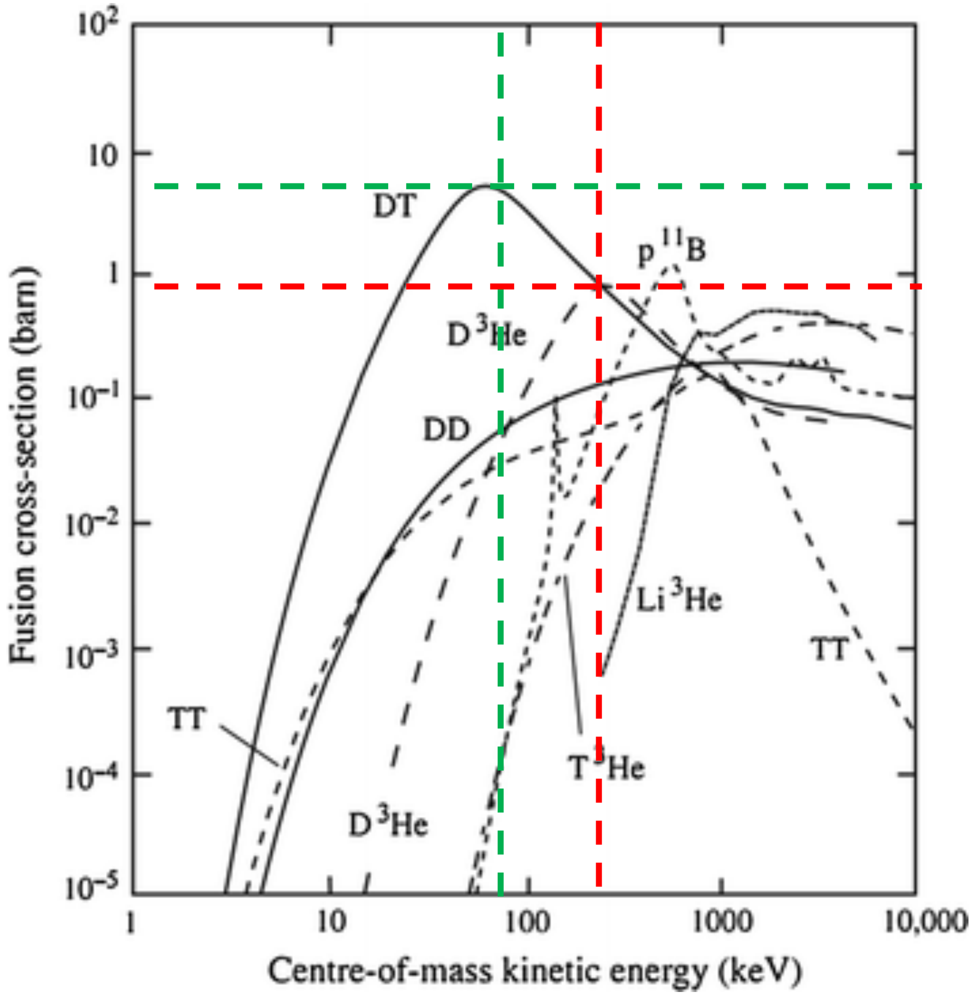



✓ neutrinos ν provide a direct view on these reactions occurring in regions where we have no other access

✓ way too slow to be used for earthly applications : limiting step in the p-p cycle is deuterium formation

# Optimizing fusion rate

➢ Pick the reaction with the highest peak rate at the lowest temperature




(Tanabe)

$$D + T \rightarrow {}^4\,\mathrm{He} + n$$

3.5 MeV 14.1 MeV


➢ **(additional) Pros** :

- vast amount of D available in the oceans (33g/m$^{-3}$ of water)
  Most countries have easy access …

➢ **Cons :**

- **The 14 MeV neutron** : *transmutation of walls, H and He production ...*

- **Tritium** *: radioactive and not produced naturally in large amounts, by-product of fission reactors, cannot be stockpiled on the long run*

# A few illuminating numbers

**For a 1GWth (~ 300MWe) reactor** :

- 17.6 MeV/reaction = 2pJ /reaction, 1GW = $3.6 \times 10^{20}$ reactions/s
- This means a consumption of 1.2mg D/s
- 90% uptime over one year, 33kg D/y and 50kg T/y
- VERY small number for D but LARGE number for T (~ total inventory)
- T must be regenerated using the neutron, 1 Li/reaction ~ 120kg of Li/y (~10-100 car batteries)

  (need a neutron multiplier to compensate for the losses, Be or Pb)

**On the way there : neutron source, heat source**

# Putting the size of the challenge in numbers

- Producing some fusion reactions is not so difficult

- **What is really difficult is producing net power**

A careful study of the power balance leads to the **Lawson criteria** for the triple product

$$n.T.\tau_E > 2.6 \times 10^{21} \mathrm{keV.m^3.s^{-1}}$$

(impressive but not a power generator !)

- n is the **plasma density**
- T the **plasma temperature** ~ 20 keV imposed by reaction rate (20 keV ~ 200 millions degrees)
- $\tau_E$ measures the quality of confinement: decay time for energy if all sources shut down

**If we can make plasmas such that n ~ $10^{20}$ $m^{-3}$ , with T=20 keV this requires $\tau_E$ ~ 1s**

**the triple product is a key metric but not the only one !! (necessary, not sufficient)**

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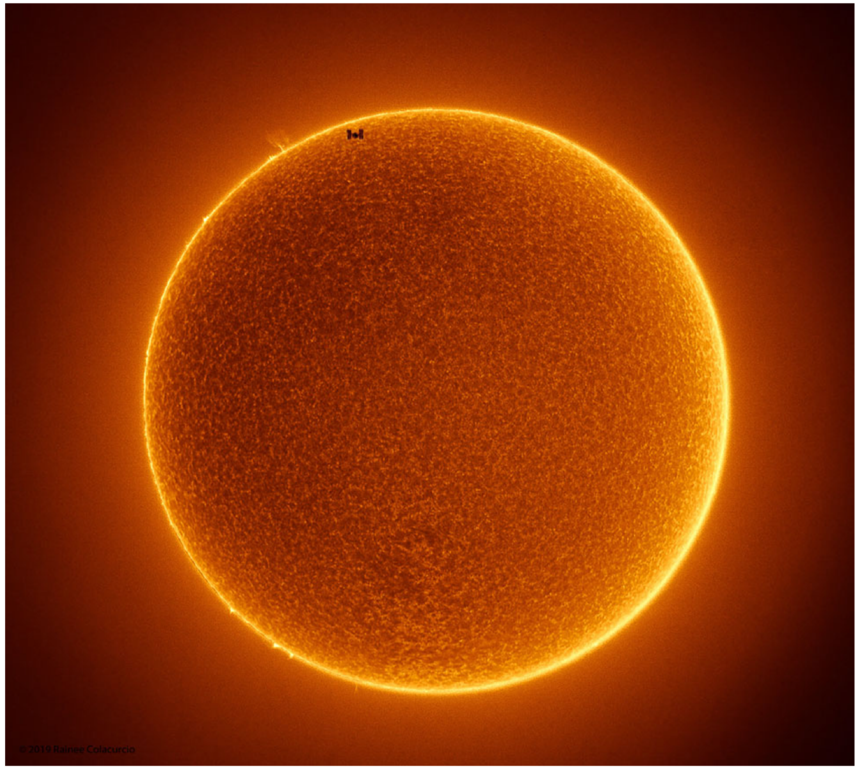
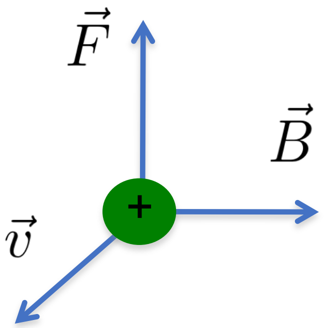
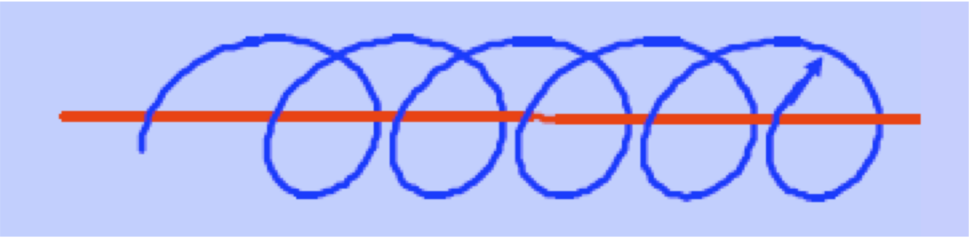


# Charged particles in a B field

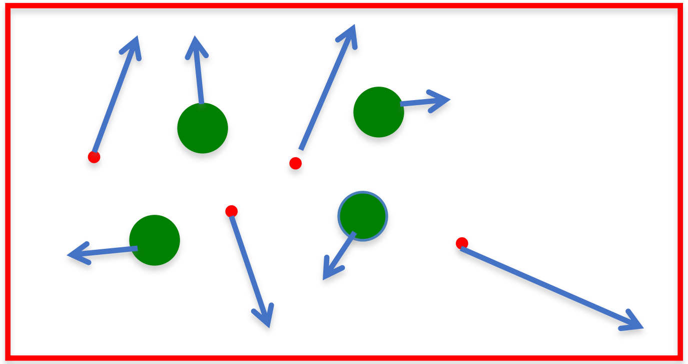
➢ A 20 keV plasma cannot be in contact with a material wall : need to find some kind of ‘insulator’



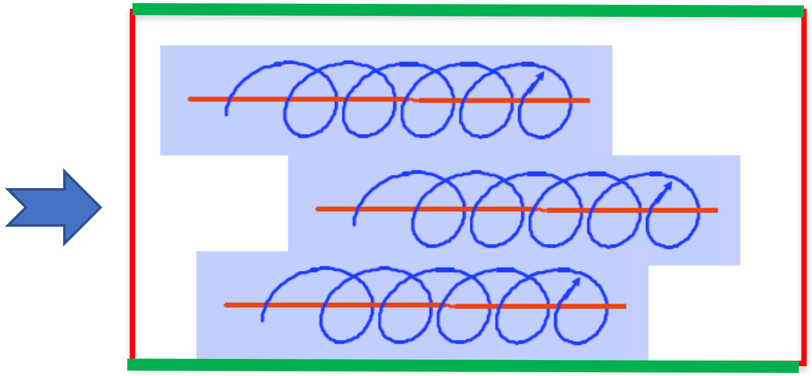



Larmor gyration = confinement in 2 dimensions perpendicular to B*

*Valid if the magnetic field does not vary on the scale of the Larmor radius*



Without $\vec{B}$

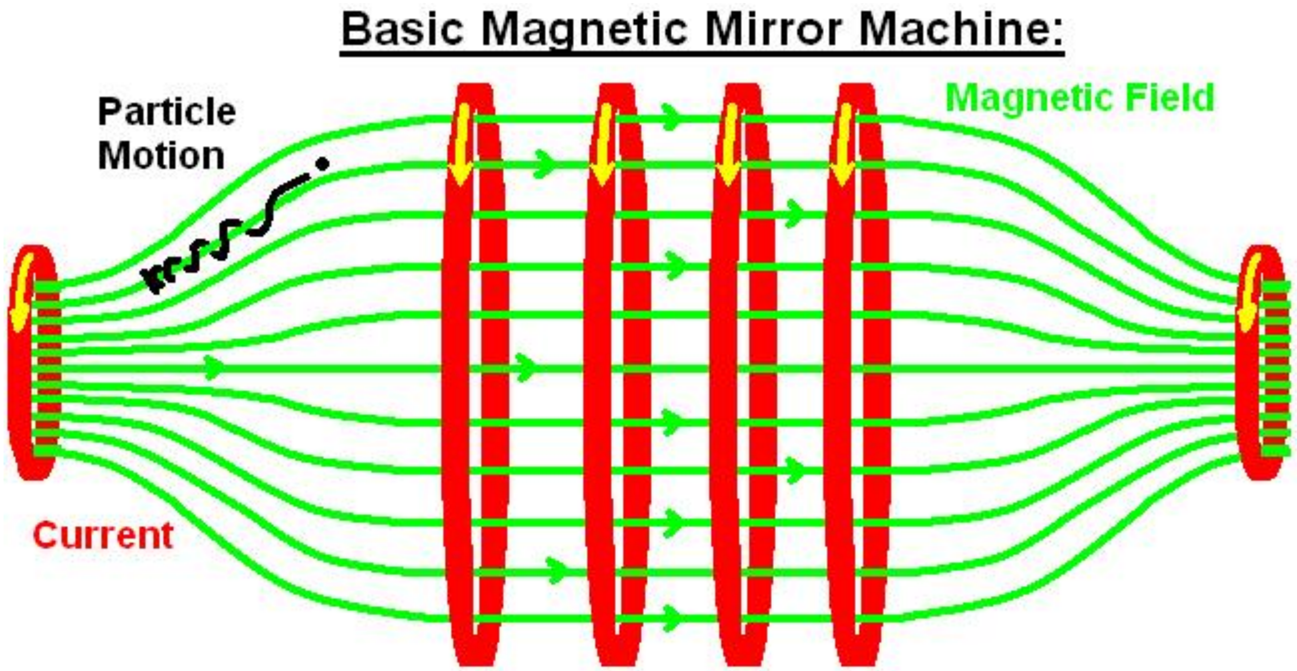


with $\vec{B}$


**Good progress ! But how to plug the bottle ?**

# Magnetic mirrors

Recipe : increase the B field towards the ends of the cylinder, creates a magnetic mirror reflecting particles




Issue : the trap works only for particles such that $\frac{v_\perp}{v} > \frac{1}{\sqrt{r_{\mathrm{mirror}}}}$ $\quad r_{\mathrm{mirror}} = \frac{B_{\mathrm{max}}}{B_{\mathrm{min}}}$

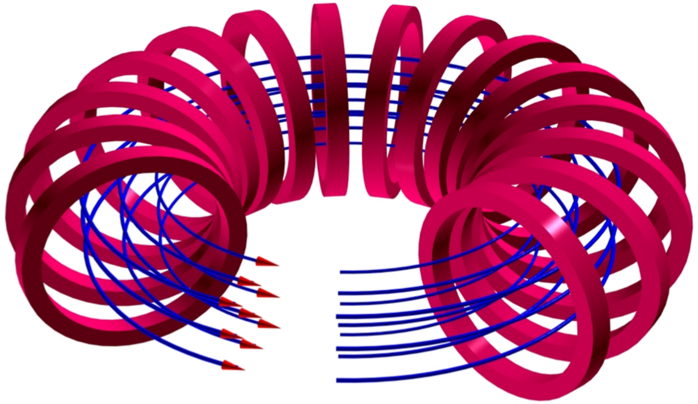
This defines a **loss cone** and collisions repopulates the missing velocity classes

Very active research in the 60’s, more and more complicated « end plugs » designed …

# Getting rid of the need for end plugs

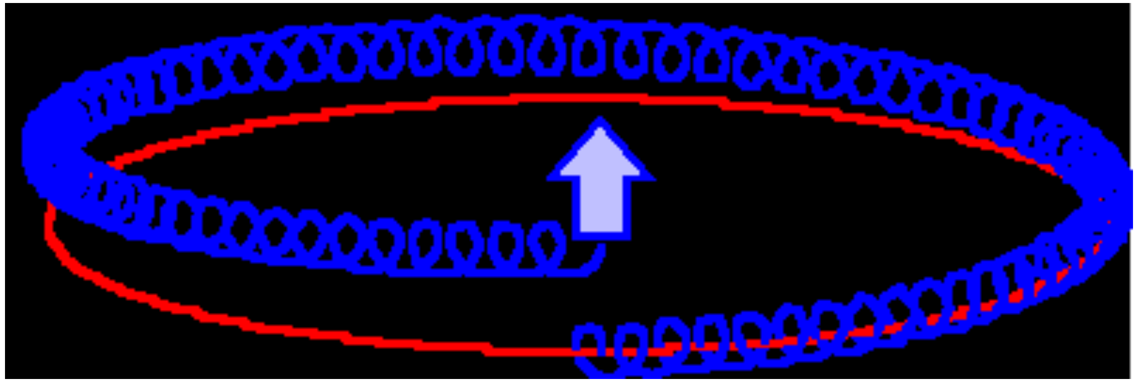
- The ‘hairy ball’ theorem precludes using a spherical geometry (necessarily a null point)
- Instead you can perfectly comb a **hairy torus** ! (very useful - for fusion …)

Toroidal coils



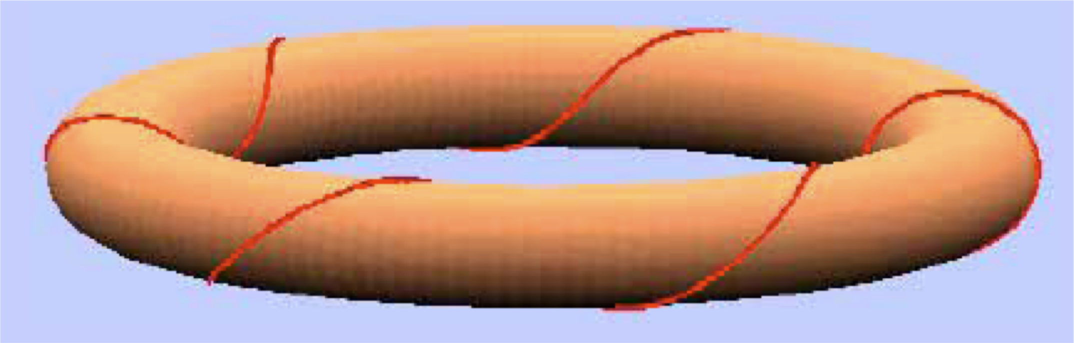
- But the magnetic field is not homogenous in space anymore (read the fine print 2 slides ago !)

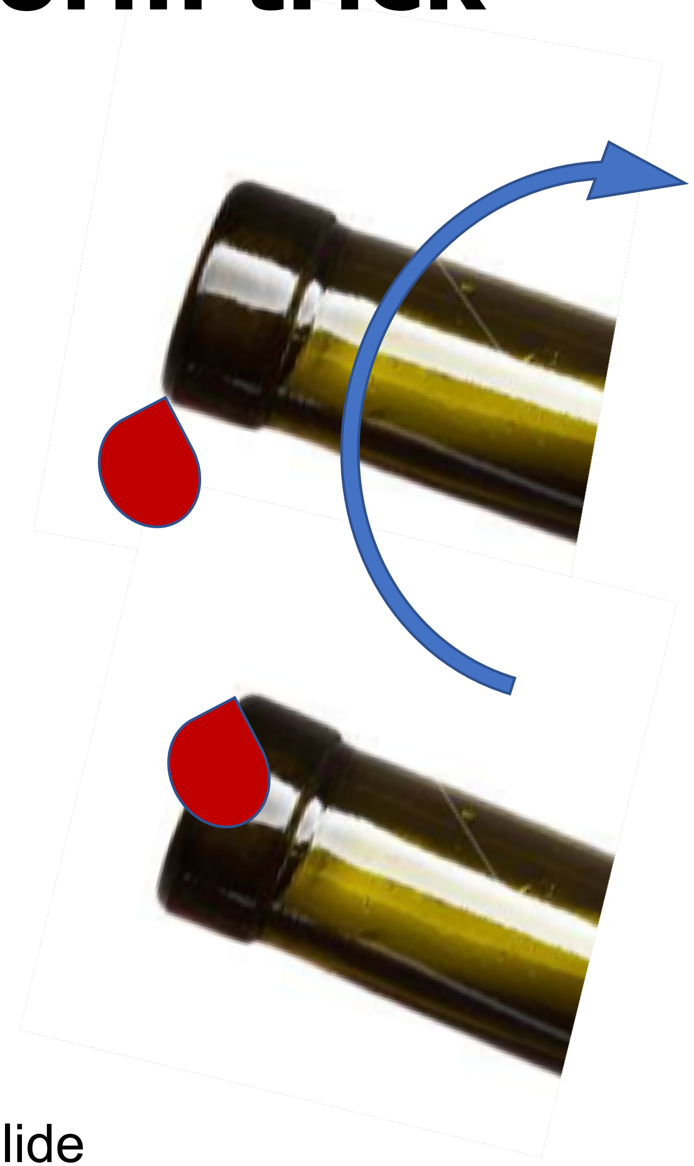
Vertical drift in opposite direction for electrons and ions
(effet of centrifugal force not symmetric on the gyro-orbit)



# The rotationnal transform trick

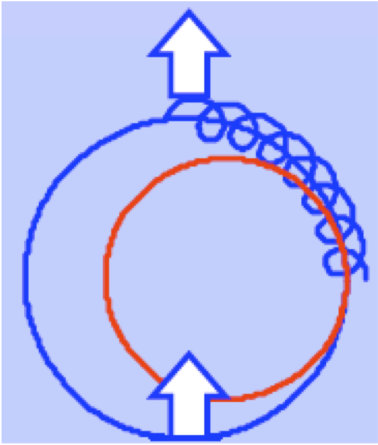
- An elegant solution: twist magnetic field lines around the torus





- The drift cancels **on average**

  (alternatively drifting in and out of the torus)

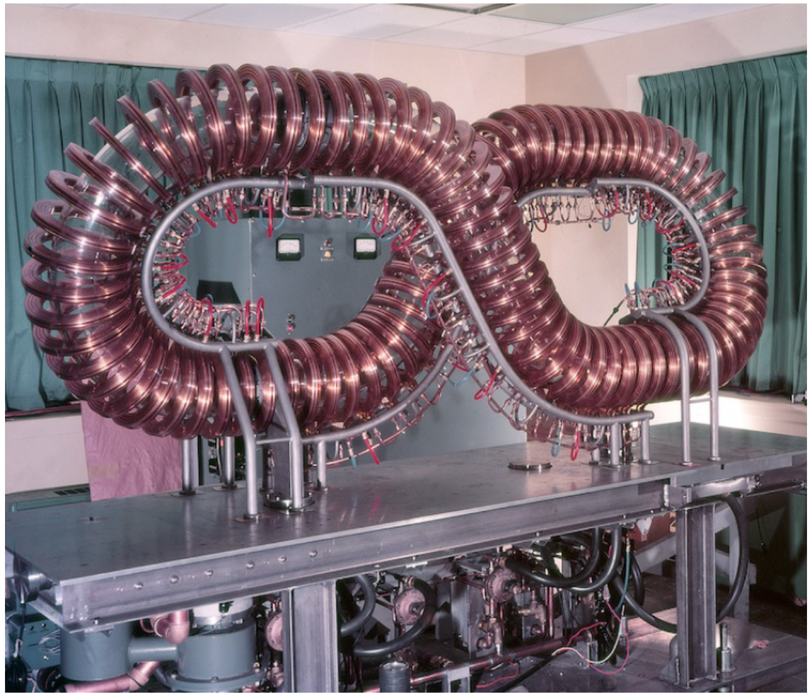


**In this geometry particles are confined** – as long as they do no collide

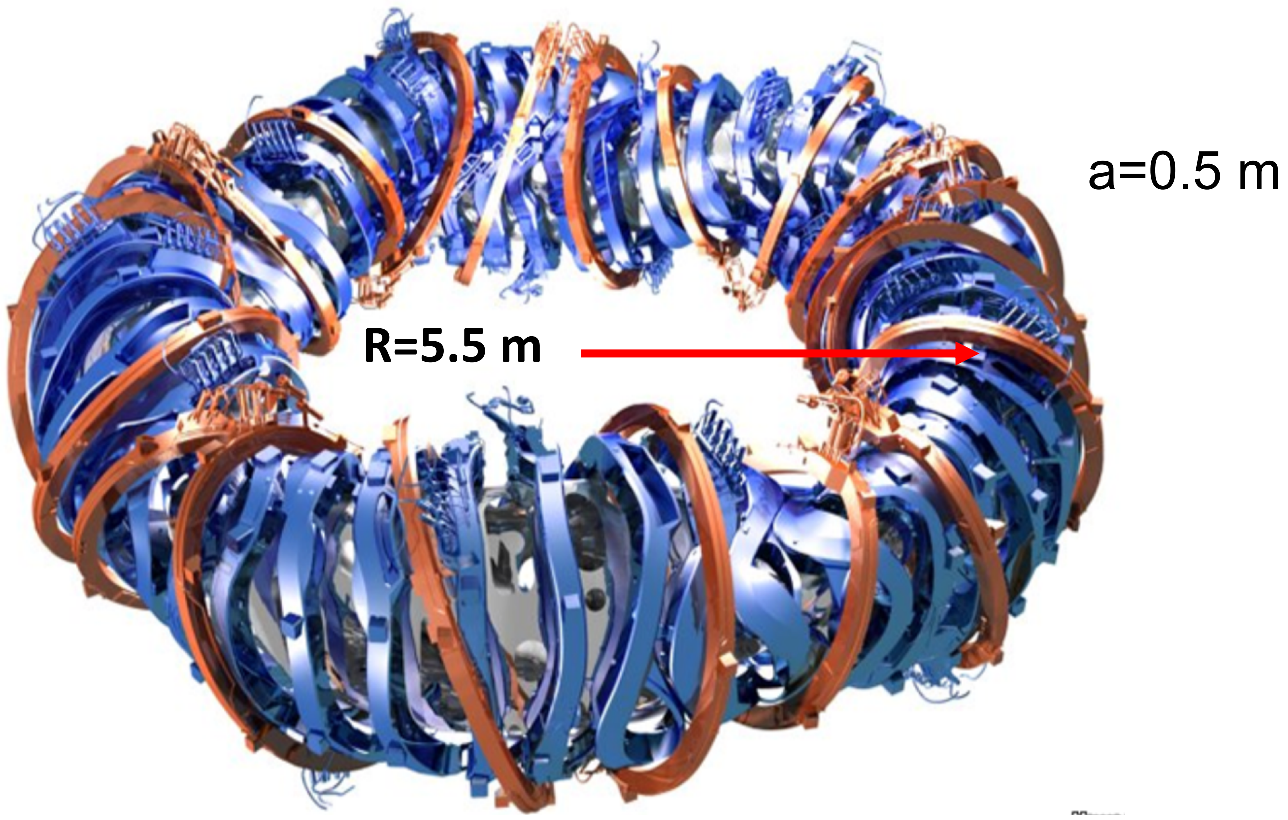
# How to twist the magnetic field lines

- The straightforward way : calculate the arrangement / shape of coils needed .... and build them !

Lyman Spitzer (US) designs the 'stellarator'



IAEA exhibit, 1958
Table-top device



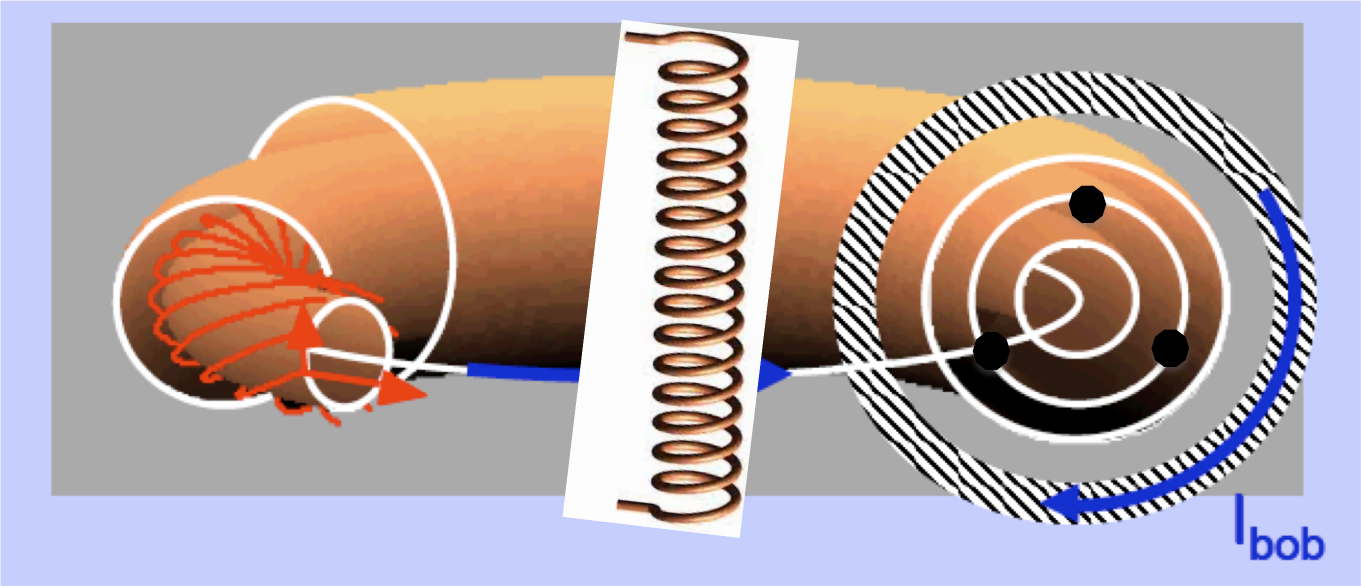

W7X – (Wendelstein 7X)

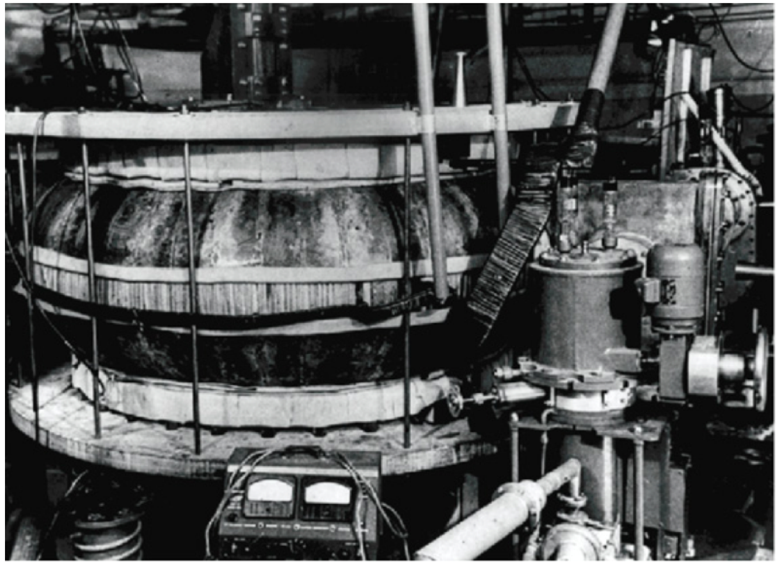
Difficulty: very complex geometry, challenging to manufacture and assemble

# Use the plasma itself as a coil: the Tokamak

*Tamm, Sakharov, Artsimovitch*

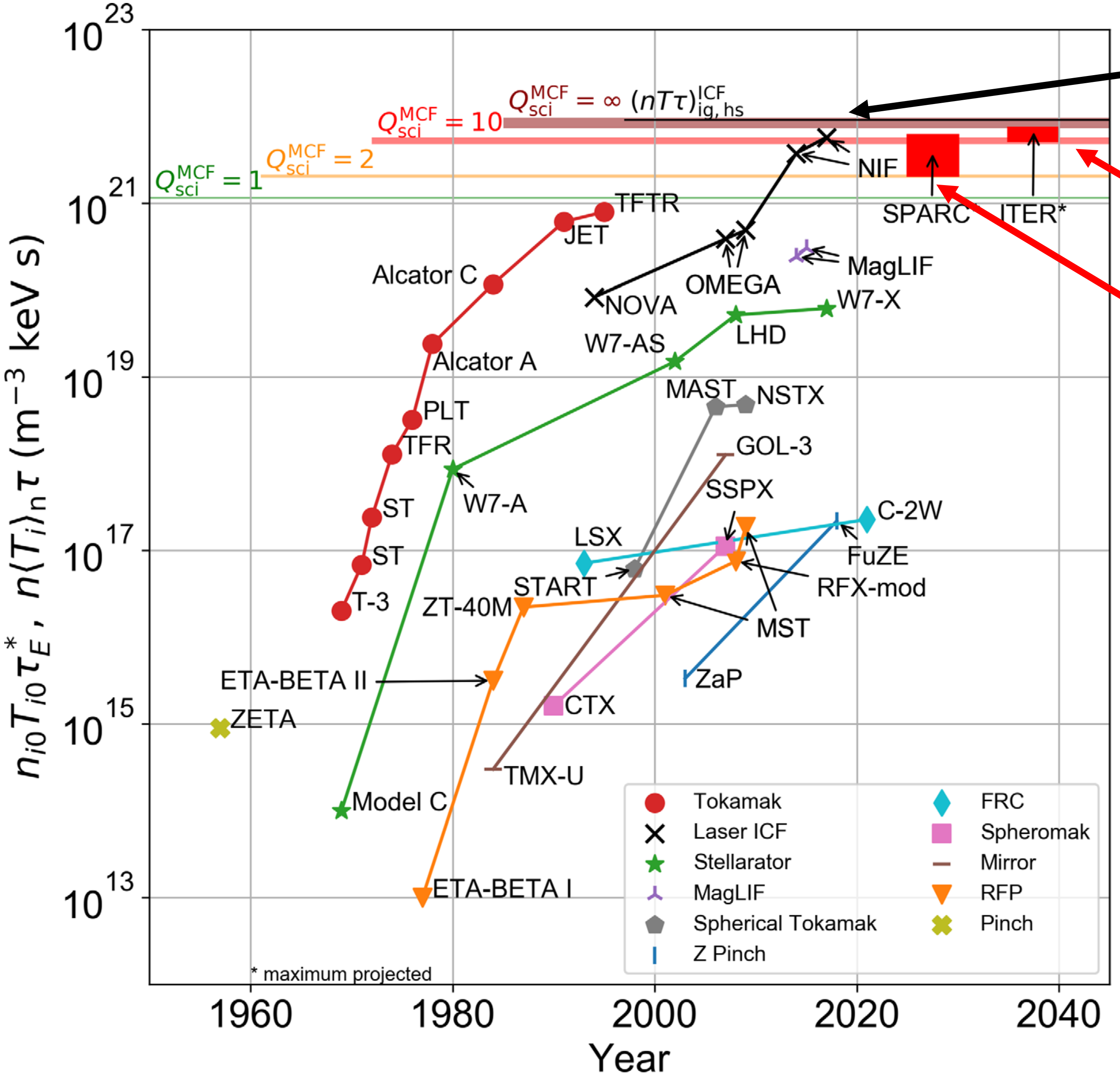
- Induce a current into the plasma with a central solenoid, along the toroidal direction ($I_p$=0.1-10 MA)
- This current creates a poloidal component of B which gives the twist



T1, 1958, Kurchatov institute
R=0.67m, a=0.17 m

# More than 60 years of progress




**First burning Plasmas**

**~1000s discharges**

**PRIVATE**

**~10s discharges**

S. Würtzel et S. Hsu, PoP 2022

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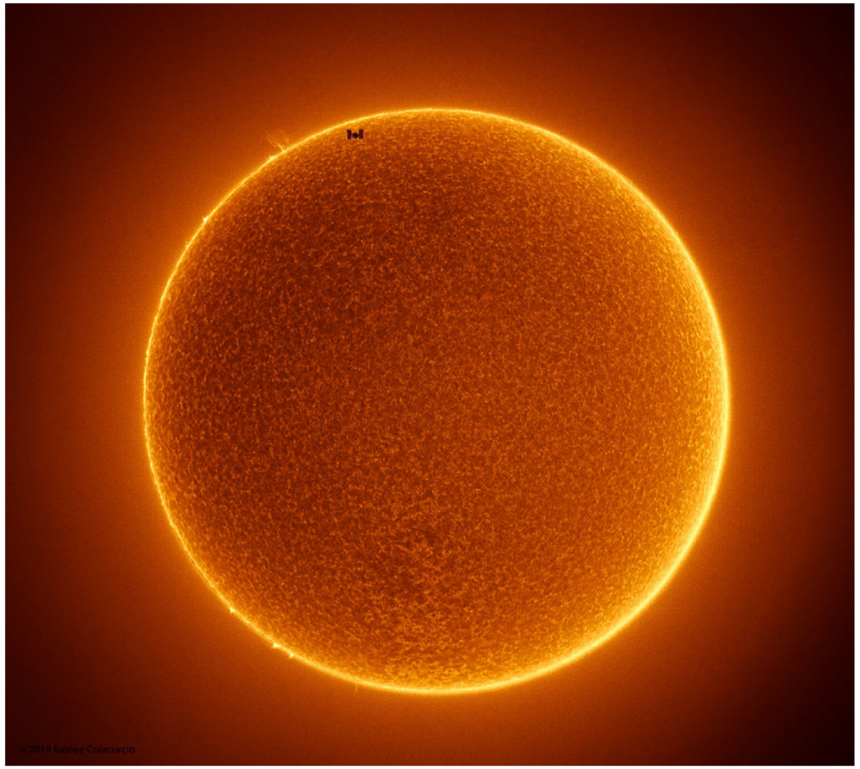
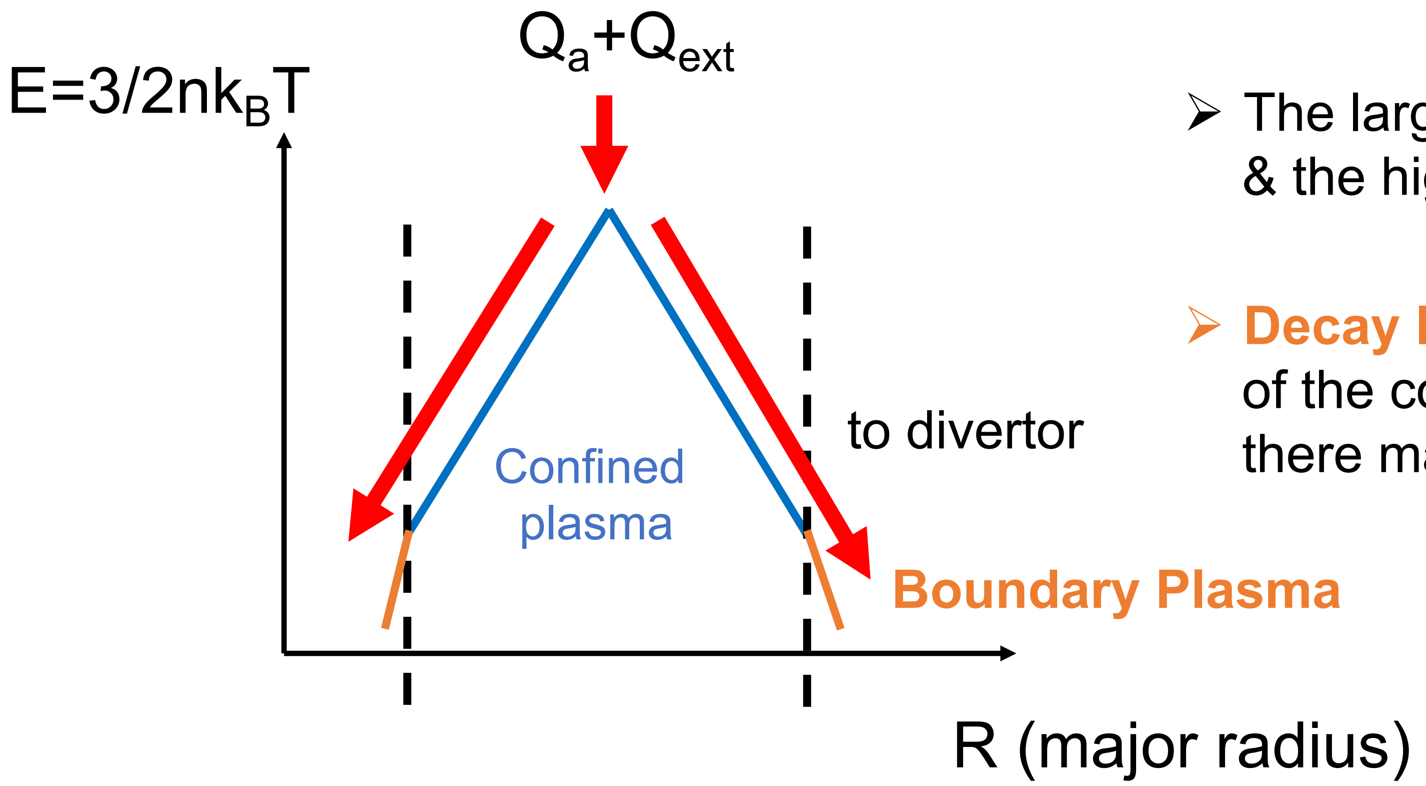


# Transport Basics

- Both energy and particles flow from the source to the sink
- **Energy** : source at the plasma core (Burn + external heating)

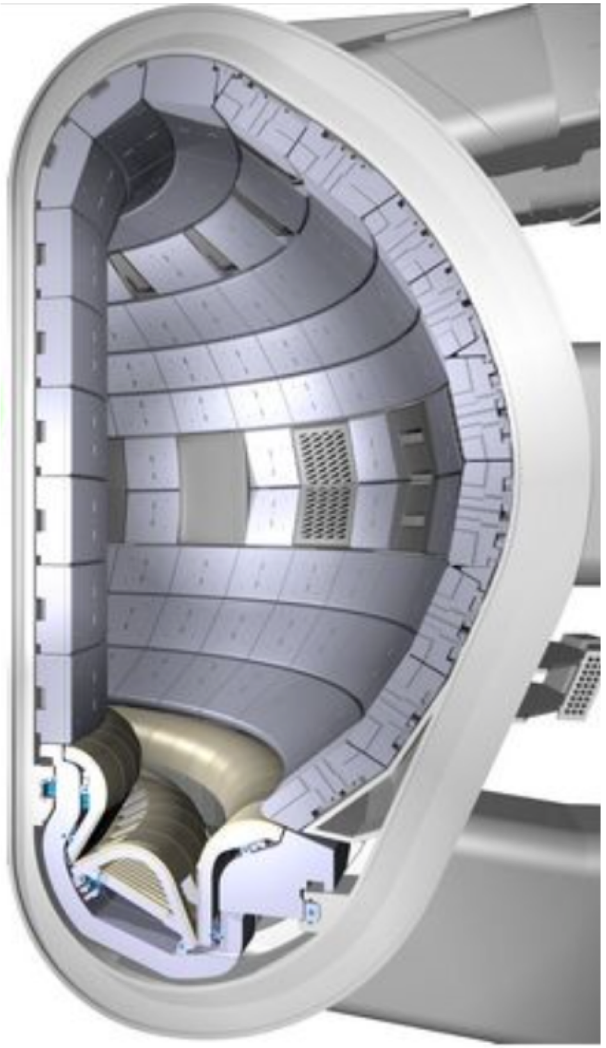



- The larger $\tau_E$, the stronger the gradient & the higher $T_{core}$
- **Decay length beyond the boundary** of the confined plasma is key : there magnetic field lines intercept the wall

- **Particles**: sources are at the boundary, and transported from there to the core (fueling)

# Power exhaust in ITER

➢ In steady state, the fusion energy has to be extracted (even though the plasma is confined !)



ITER :
**$P_{fus}$ = 500MW**

400 MW
Neutrons (**isotropic** !) → ~ 1000 $m^2$

100 MW
$\alpha$ particles → **Plasma heating, sustains the reactions**

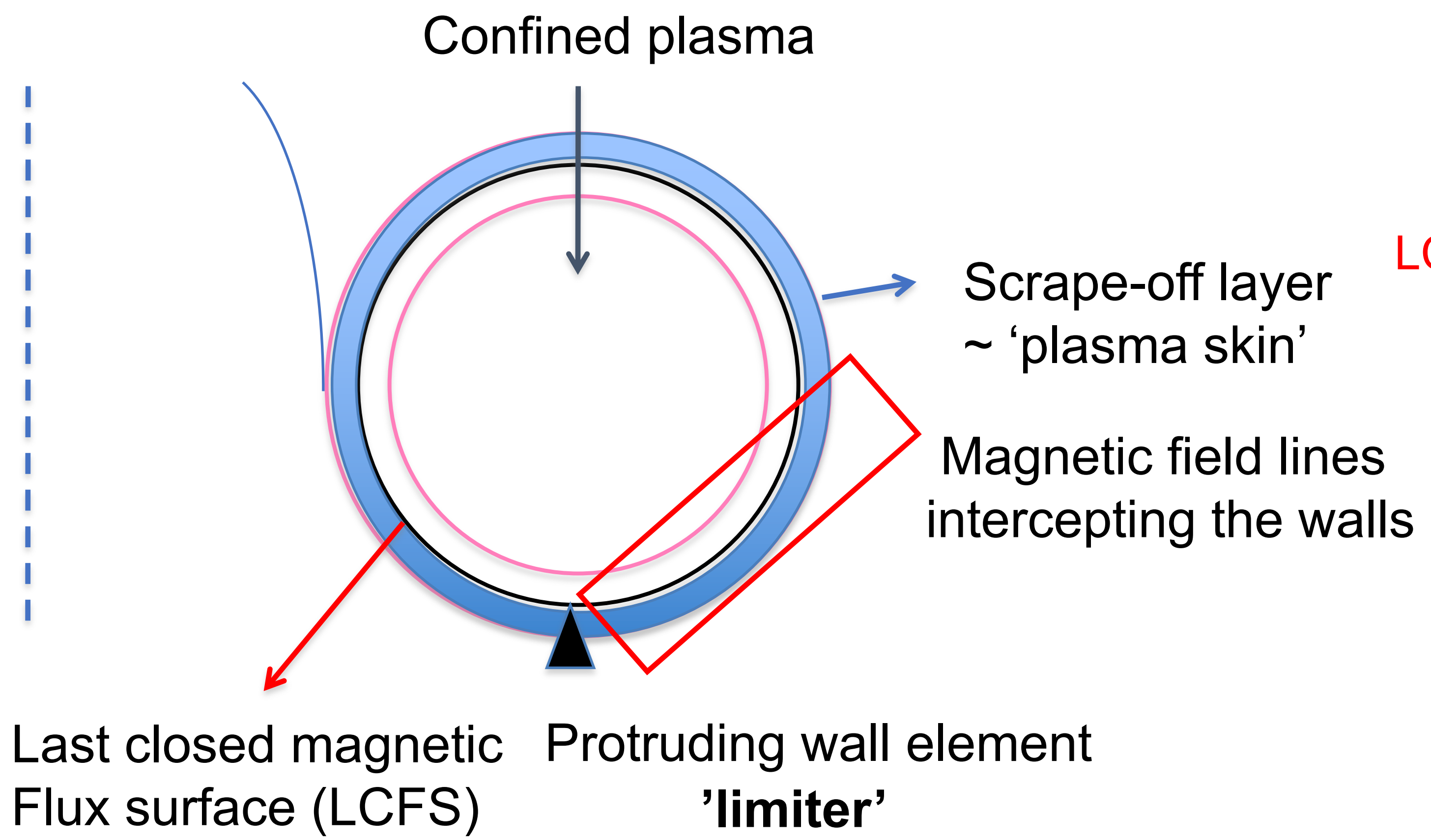
**+ 50 MW heating (Q=10)**

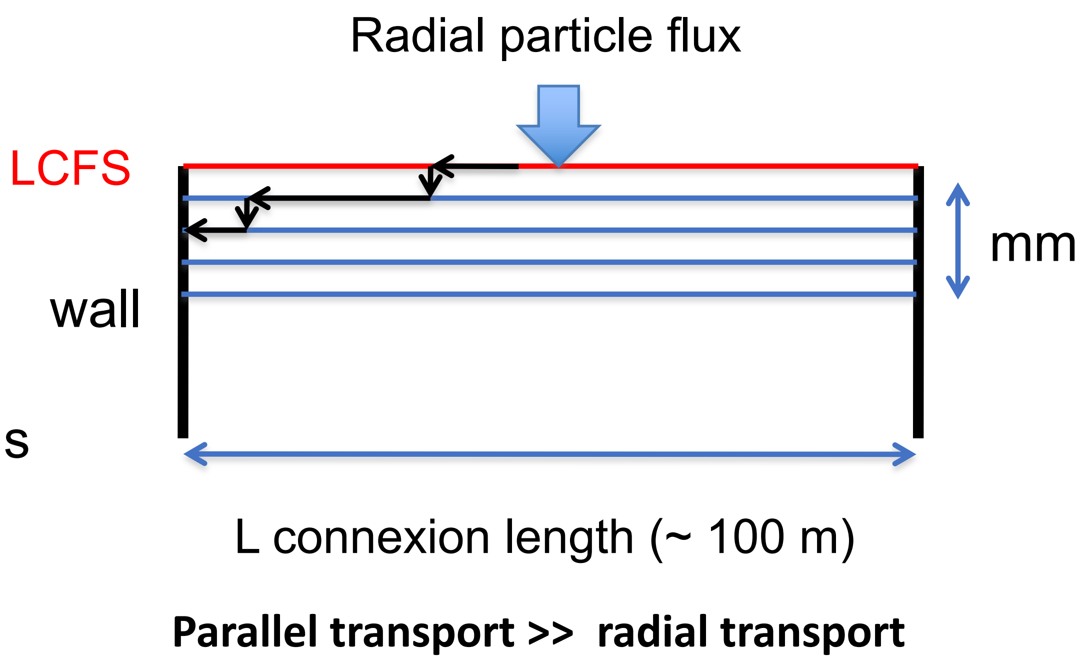
➢ The confined plasma radiates ~ 50MW through line emission (the plasma is transparent in these conditions)

➢ **100MW of 'plasma heat' which has to reach the material wall**

# The scrape off layer

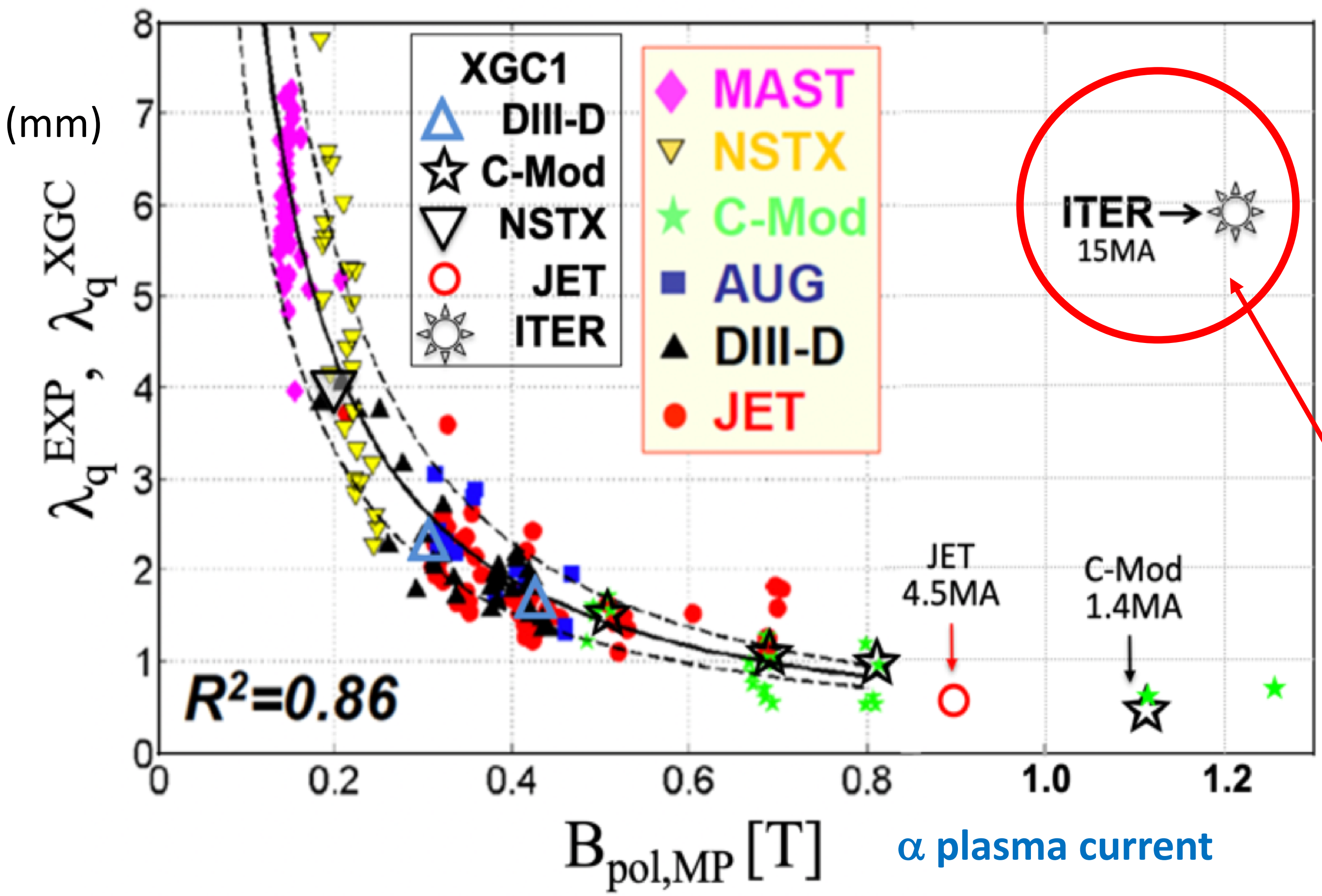
- The irony is that **the confinement works too well at the plasma edge**, where it intersects the wall !




- **Concentrates plasma heat flux on a narrow surface area (SOL width in ITER ~ a few mm !)**
- Geometry illustrated here with a limiter bad for impurity contamination (erosion from the limiter)

# The scrape off layer width for energy flow



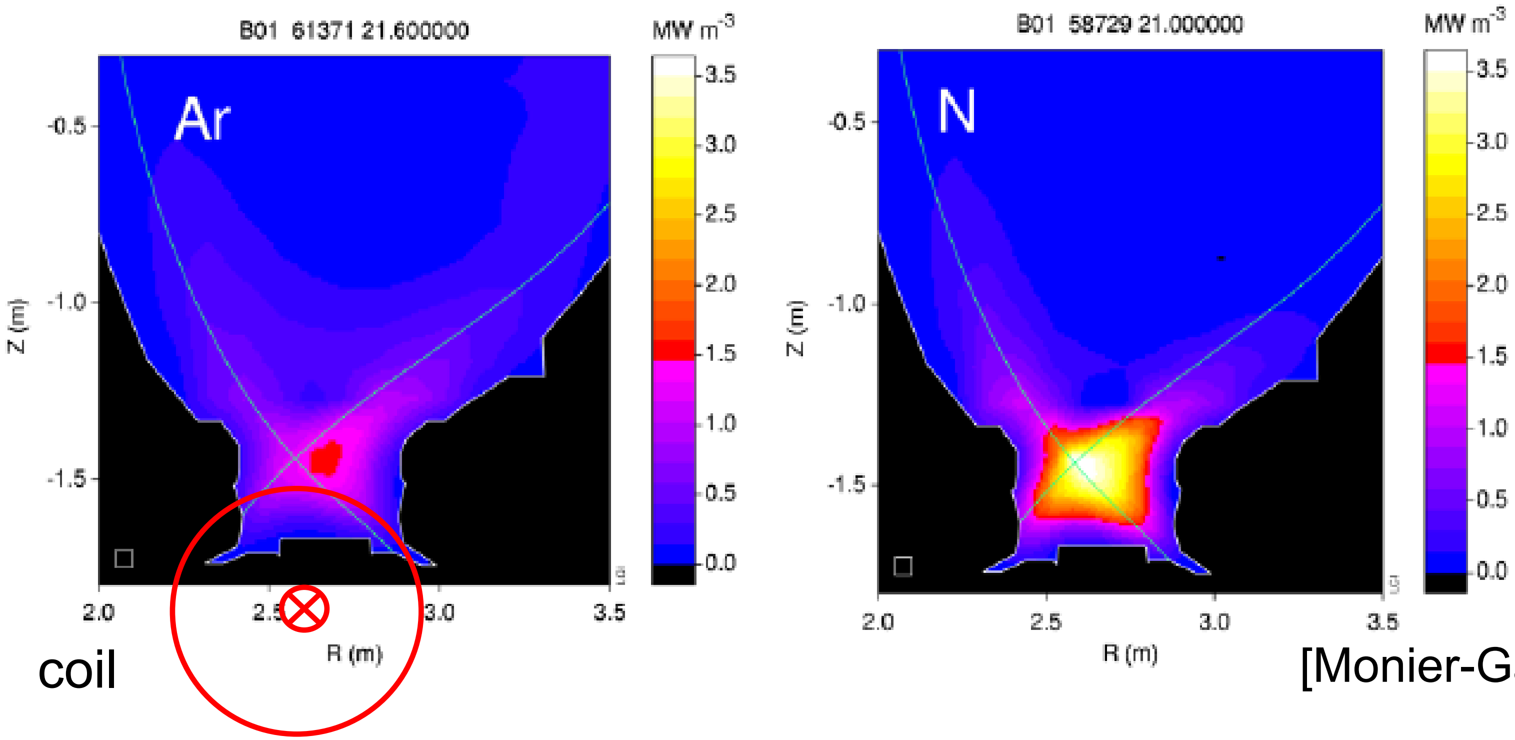

(Taken from C. S Chang et al.)

- ITER is **projected** to operate with **~ 1mm** fall-off length for energy
- **caveat** : scaling not obtained in fully relevant conditions, difficult to measure the heat flux otherwise
- Here largest HPC simulations from US group, suggesting **new physics** comes into play in ITER conditions (??)

# The divertor configuration

- Push regions where the plasma interacts with the wall **farther from the confined plasma**, by diverting the plasma towards a specific plasma facing component : the divertor

Modification of the magnetic Configuration




[Monier-Garbet]

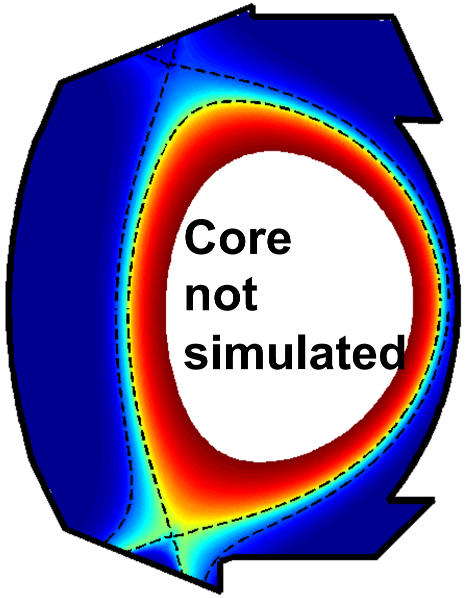
- Need to **transfer plasma heat to non charged species** to spread the power more isotropically : atoms, molecules, photons … very active research areas
- Still challenging situation w.r.t. **plasma wall interactions**

# Numerical modelling of exhaust
# Soledge3x-EIRENE

**Plasma ($e^-$, $D^+$, …)**

Multifluid (Zhdanov)

**3D or 2D**




**Fluid quantities**
**Particle and energy fluxes on the wall**
**Recycling coefficients**

**Soledge3X**
IRFM/M2P2

**STYX**

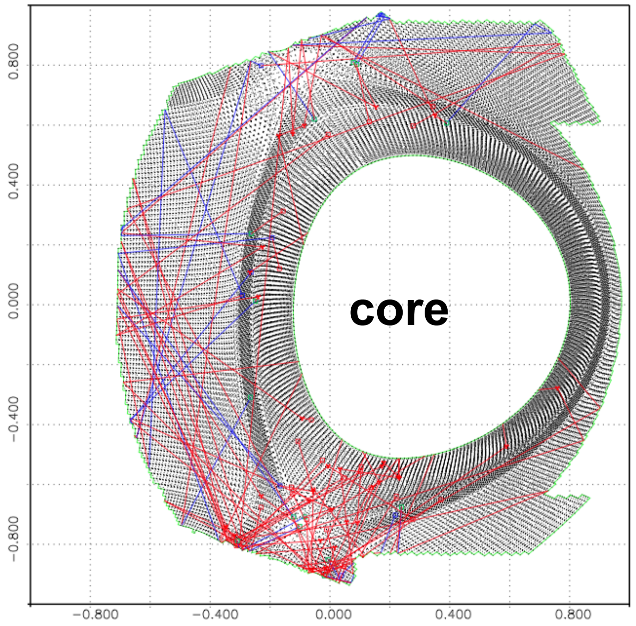
**DWE**

**EIRENE**
FZJ/KUL/
PIIM

**Particle, momentum and energy sources**

**Gaz neutre (D, $D_2$)**

Cinétique (Boltzmann)



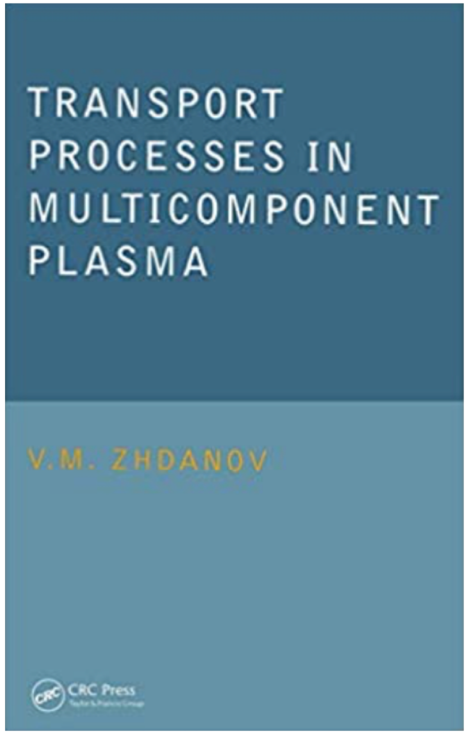

**$D + e^- \rightarrow D^+ + e^- + e^-$**

H. Bufferand et al. PPCF 54 055001 (2022), Nuclear Fusion 61 116052 (2021)

# Non trace multifluid closure

- Work initiated to improve impurity treatment SOLEDGE3X, trace approximation wrong for D-T mix !
- Closure available in a book by V. M. Zhdanov, but no straightforward way to check correctness and assumptions
- **Complete rederivation and extension**

$$\frac{d\rho_\alpha}{dt} + \rho_\alpha \nabla.\mathbf{u} + \nabla.\rho_\alpha \mathbf{w}_\alpha = 0.$$




$$\frac{d}{dt}\rho_\alpha \mathbf{w}_\alpha + \rho_\alpha \mathbf{w}_\alpha.\nabla\mathbf{u} + \rho_\alpha \mathbf{w}_\alpha \nabla.\mathbf{u} + \nabla p_\alpha + \nabla.\pi_\alpha - n_\alpha \langle \mathbf{F}^*_\alpha \rangle = \mathbf{R}^{10}_\alpha.$$

$$\frac{3}{2}\frac{d}{dt}(n_\alpha k T_\alpha) + \frac{5}{2} n_\alpha k T_\alpha \nabla.\mathbf{u} + \nabla.\mathbf{q}_\alpha + \pi_\alpha : \nabla\mathbf{u} - n_\alpha \mathbf{w}_\alpha.\langle \mathbf{F}^*_\alpha \rangle = R^{01}_\alpha.$$

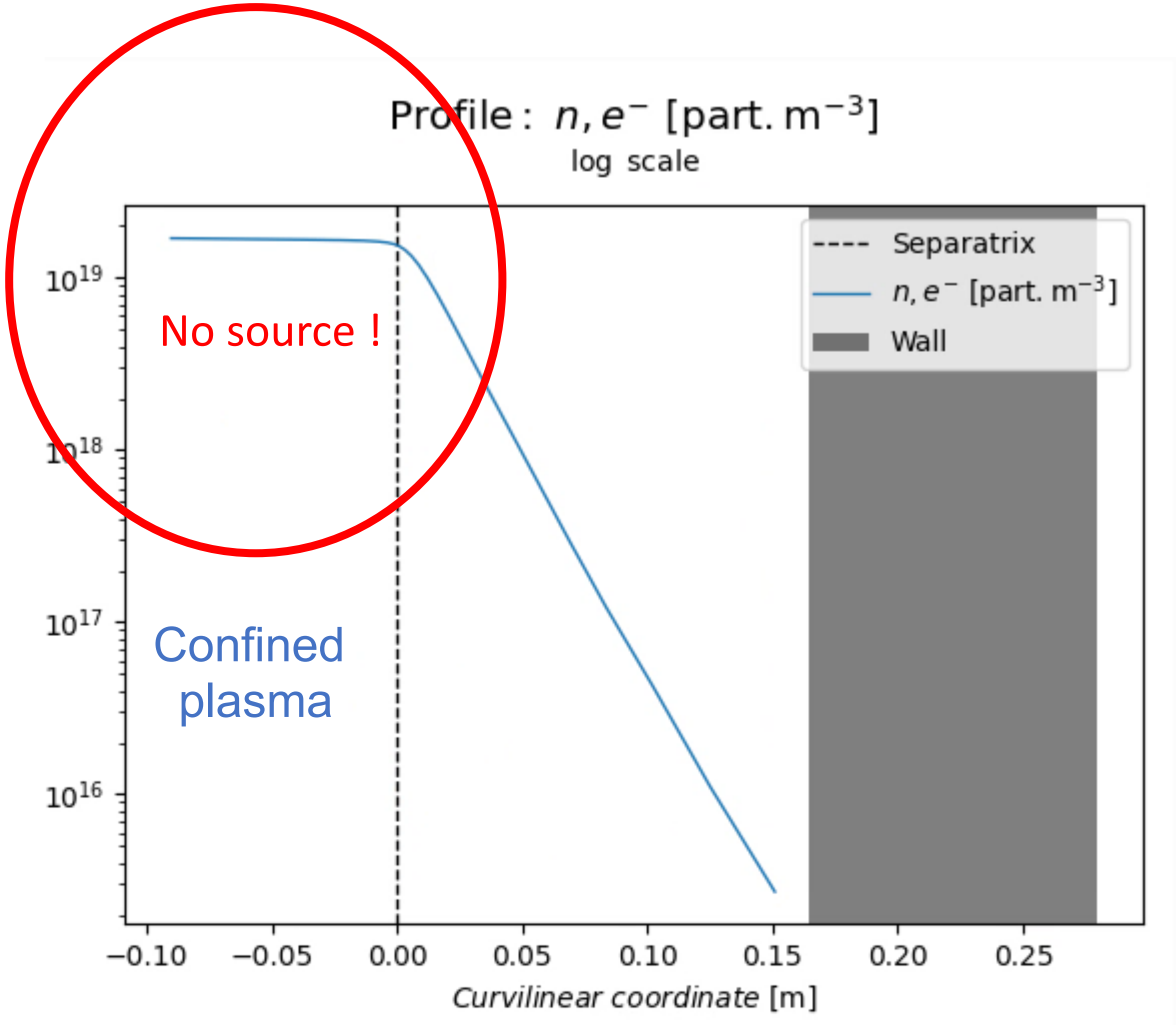
$$\mathbf{R}^{10}_\alpha = \sum_\beta G^{(1)}_{\alpha\beta}(\mathbf{w}_\alpha - \mathbf{w}_\beta) + \sum_\beta \gamma_{\alpha\beta} G^{(2)}_{\alpha\beta}\left(\frac{\mathbf{h}_\alpha}{\gamma_\alpha p_\alpha} - \frac{\mathbf{h}_\beta}{\gamma_\beta p_\beta}\right) + \ldots$$

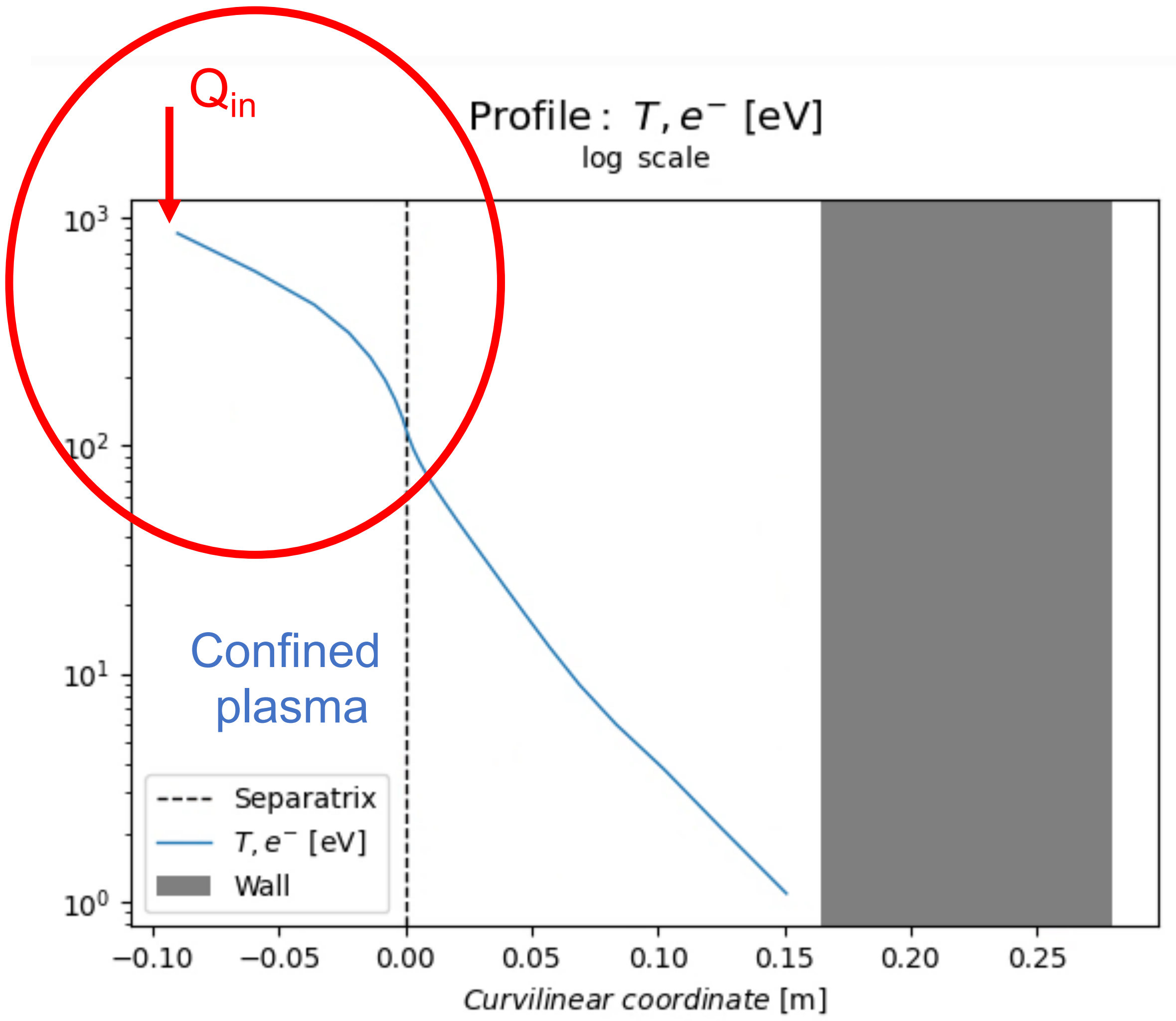
Force de friction

$h_\alpha$ = flux de chaleur

M. Raghunathan et al., PPCF 2021 & PPCF 2022;

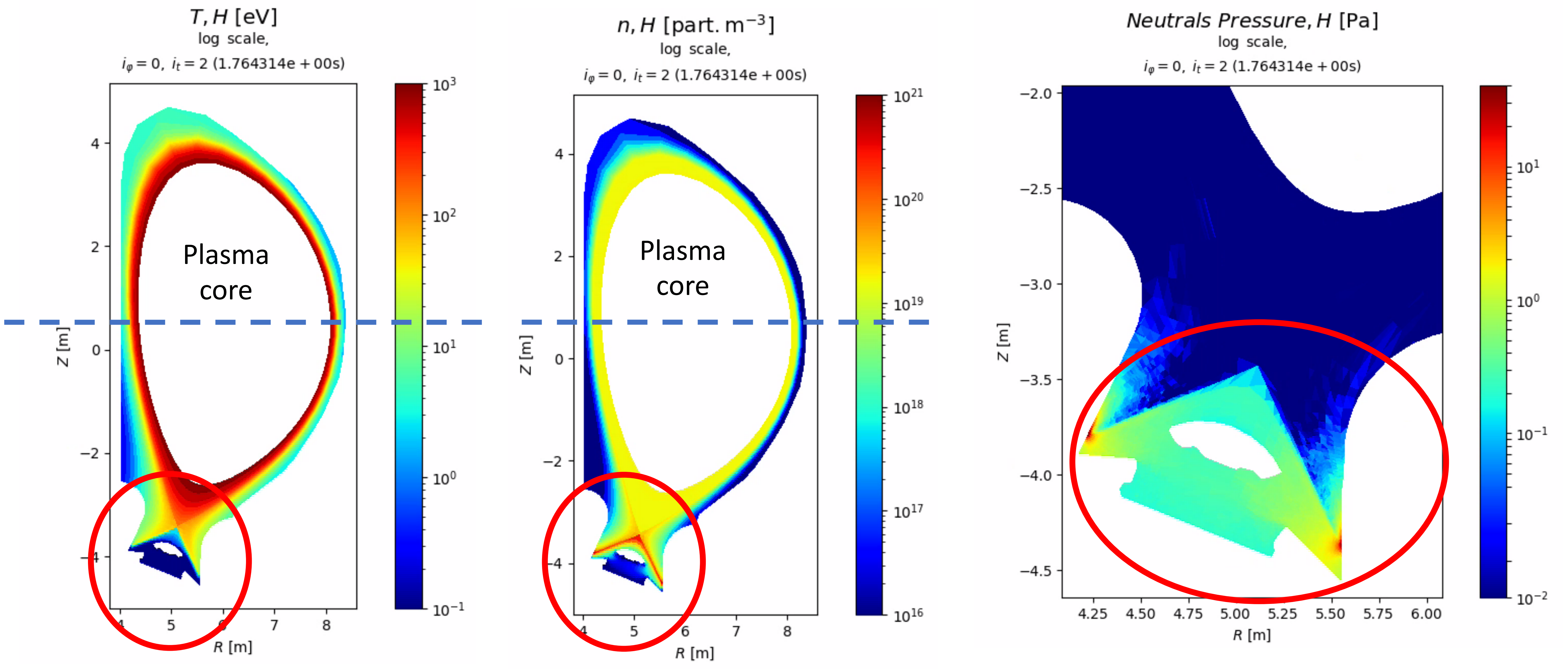
# Transport Basics in ITER simulations




N. Rivals et al., Nuclear Materials and Energy, 101293 (2022).

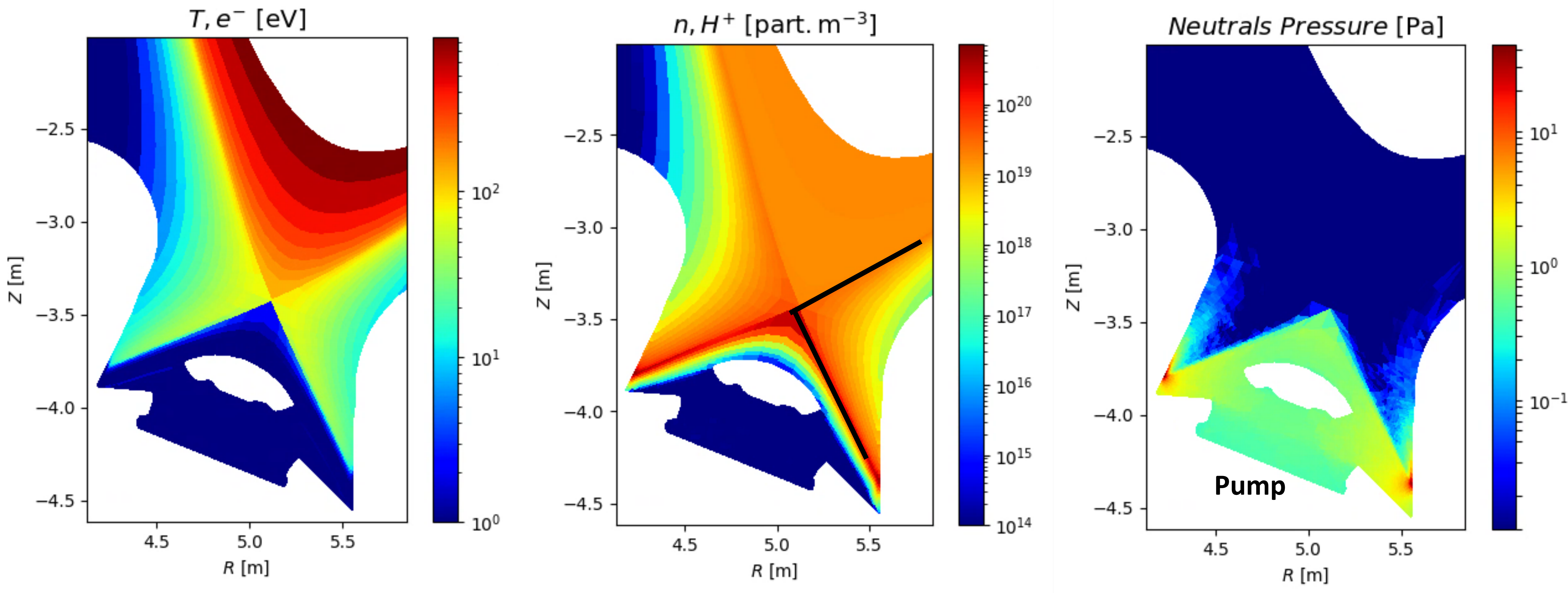
# Thinking 1D is not enough at the boundary !




- ➢ Aim of these simulations : calculate particle fluxes on the wall outside of the divertor
- ➢ Benchmark our code vs SOLPS-ITER (S. Wiesen et al.)

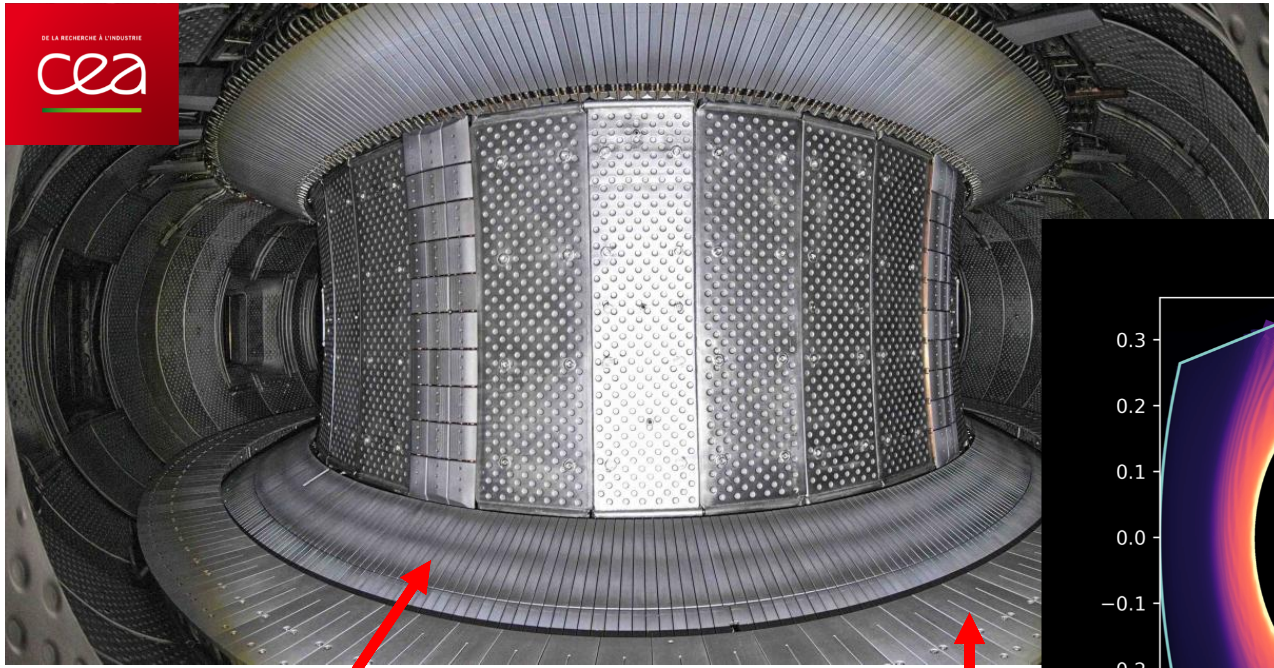
(N. Rivals et al.)

# Focus on divertor conditions

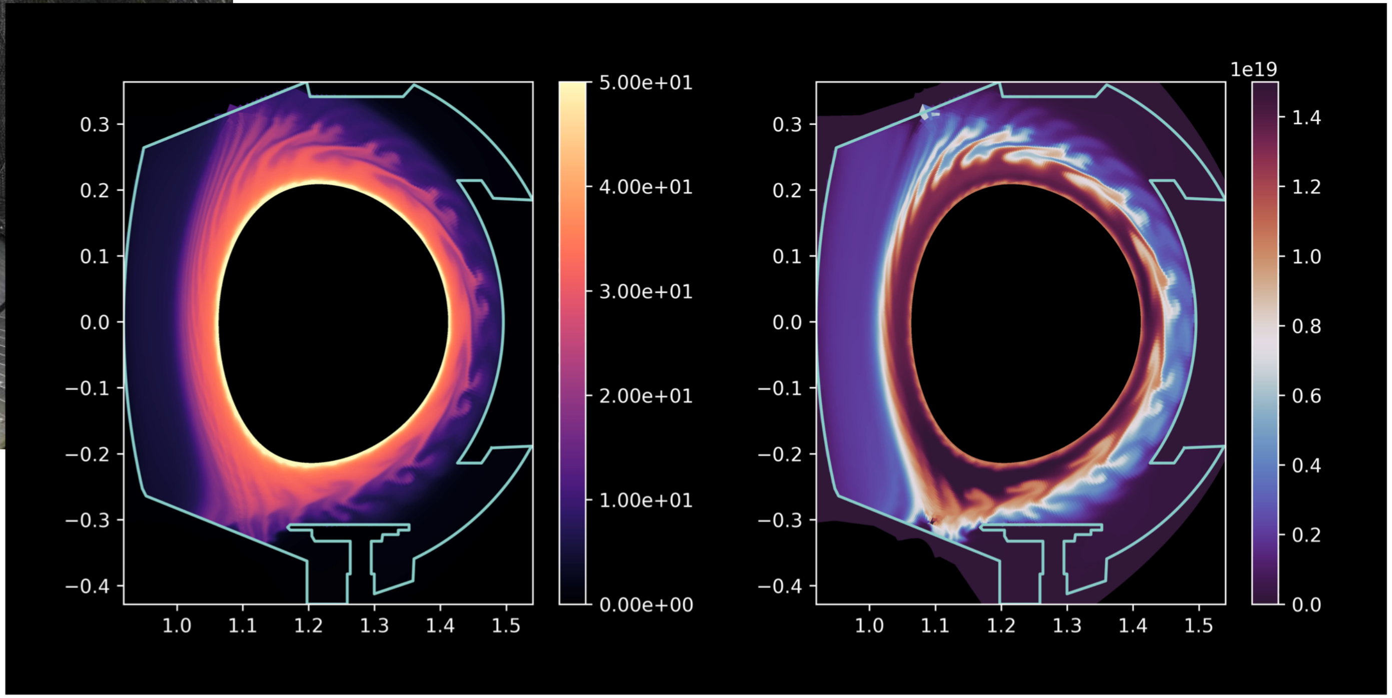



- ➢ Strong gradients along the magnetic field lines (projection), $n_e^{div} >> n_e^{up}$ & $T_e^{div} << T_e^{up}$
- ➢ Puff rate = pump rate = $1.1 \times 10^{22}$ part.s$^{-1}$ **<<** Wall flux = $1.7 \times 10^{24}$ part.s$^{-1}$

# WEST: a tokamak focused on heat exhaust



Accompanied by a strong numerical effort



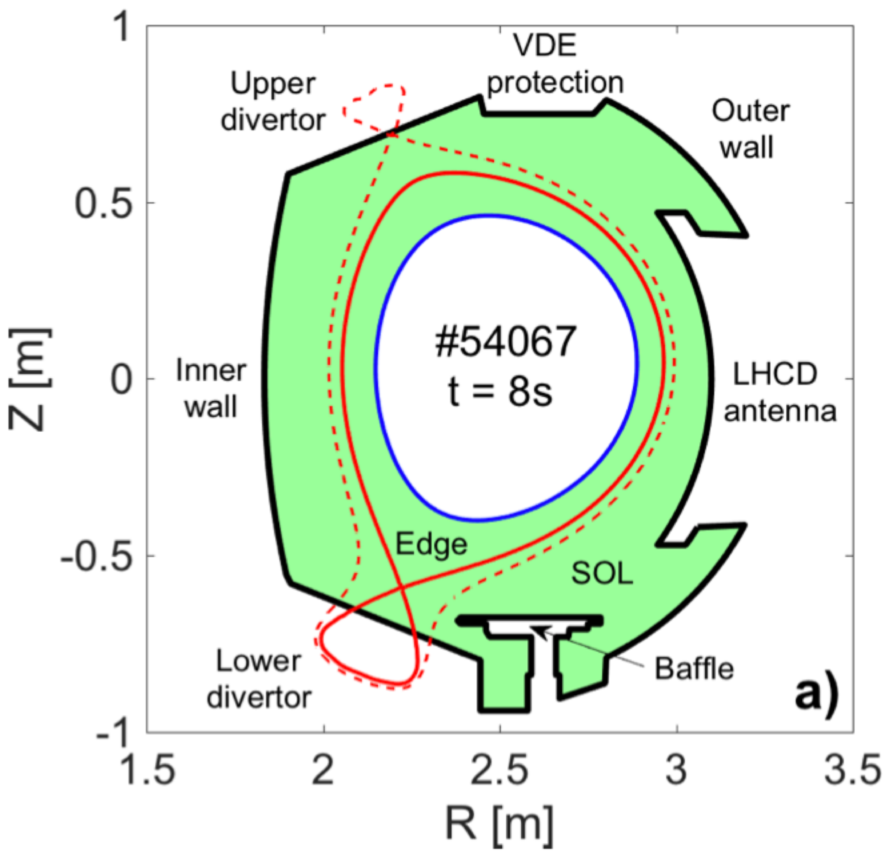

ITER-like divertor components
Actively cooled W monoblocks

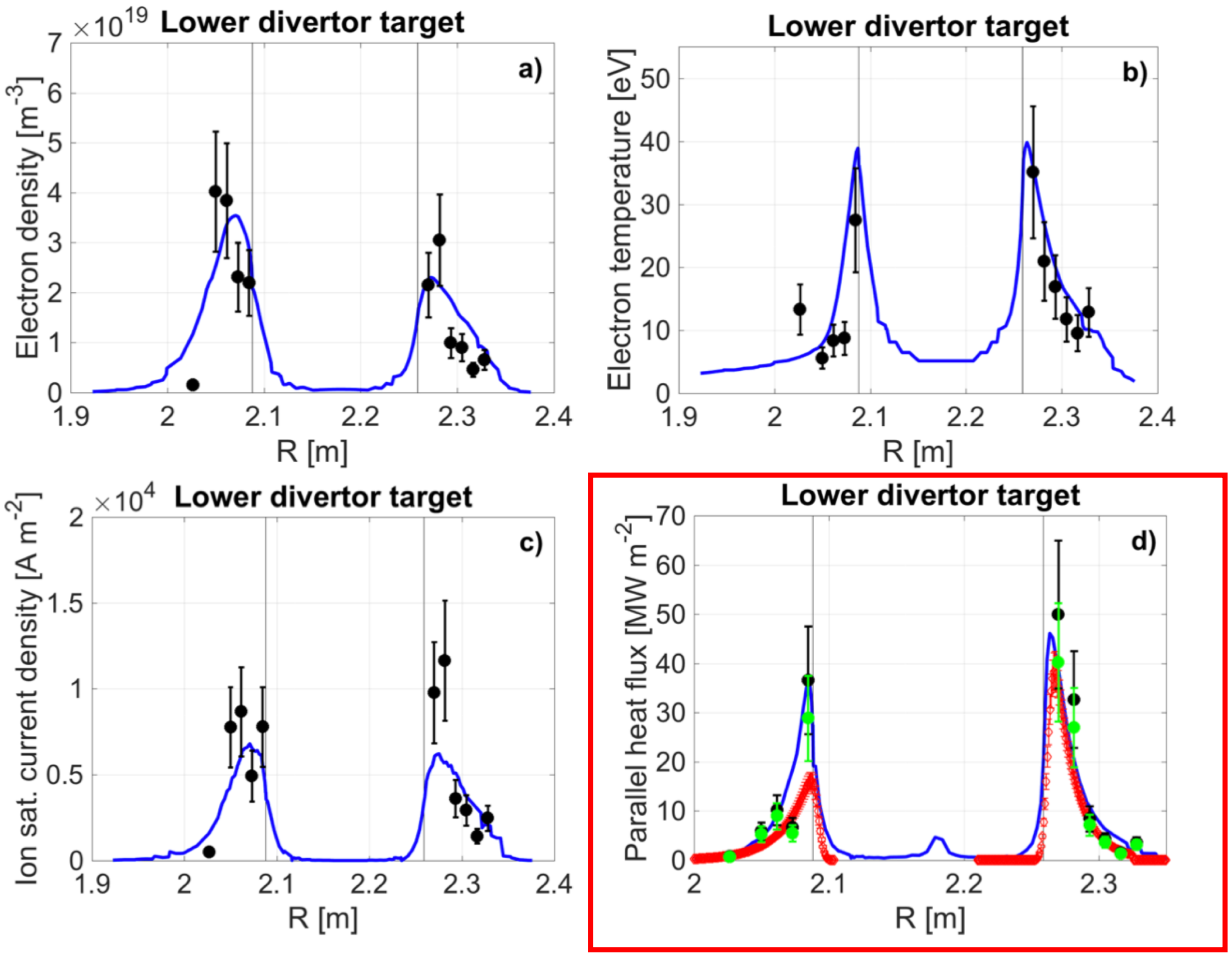
Pumping baffle

SOLEDGE3X, H. Bufferand, P. Tamain et al.

# Benchmarking numerical simulations on WEST

SolEdge3X-EIRENE




A. Gallo et al., Nuclear Fusion 2020

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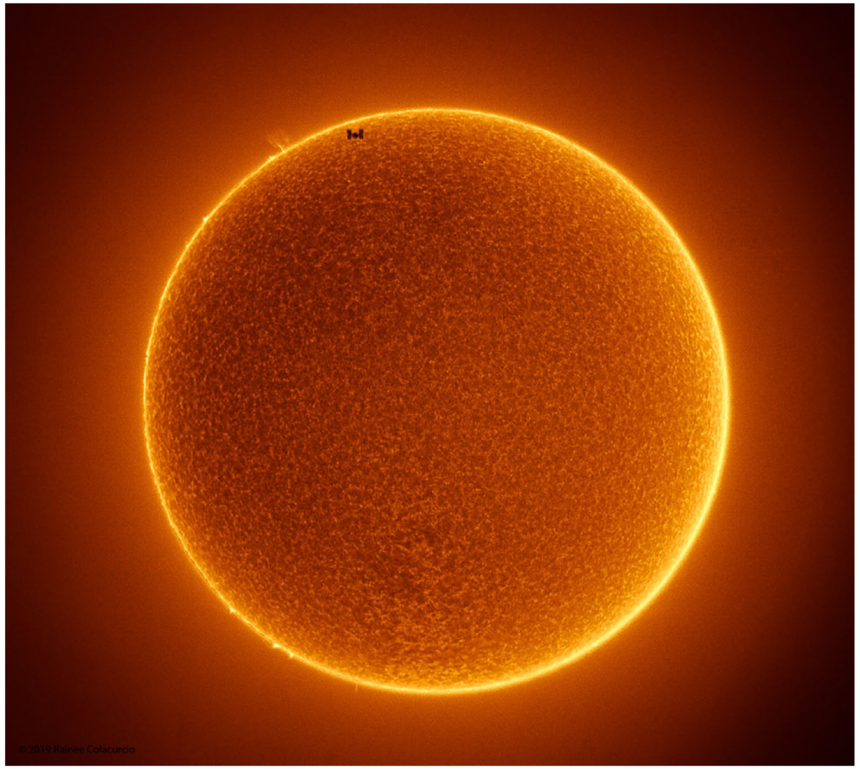
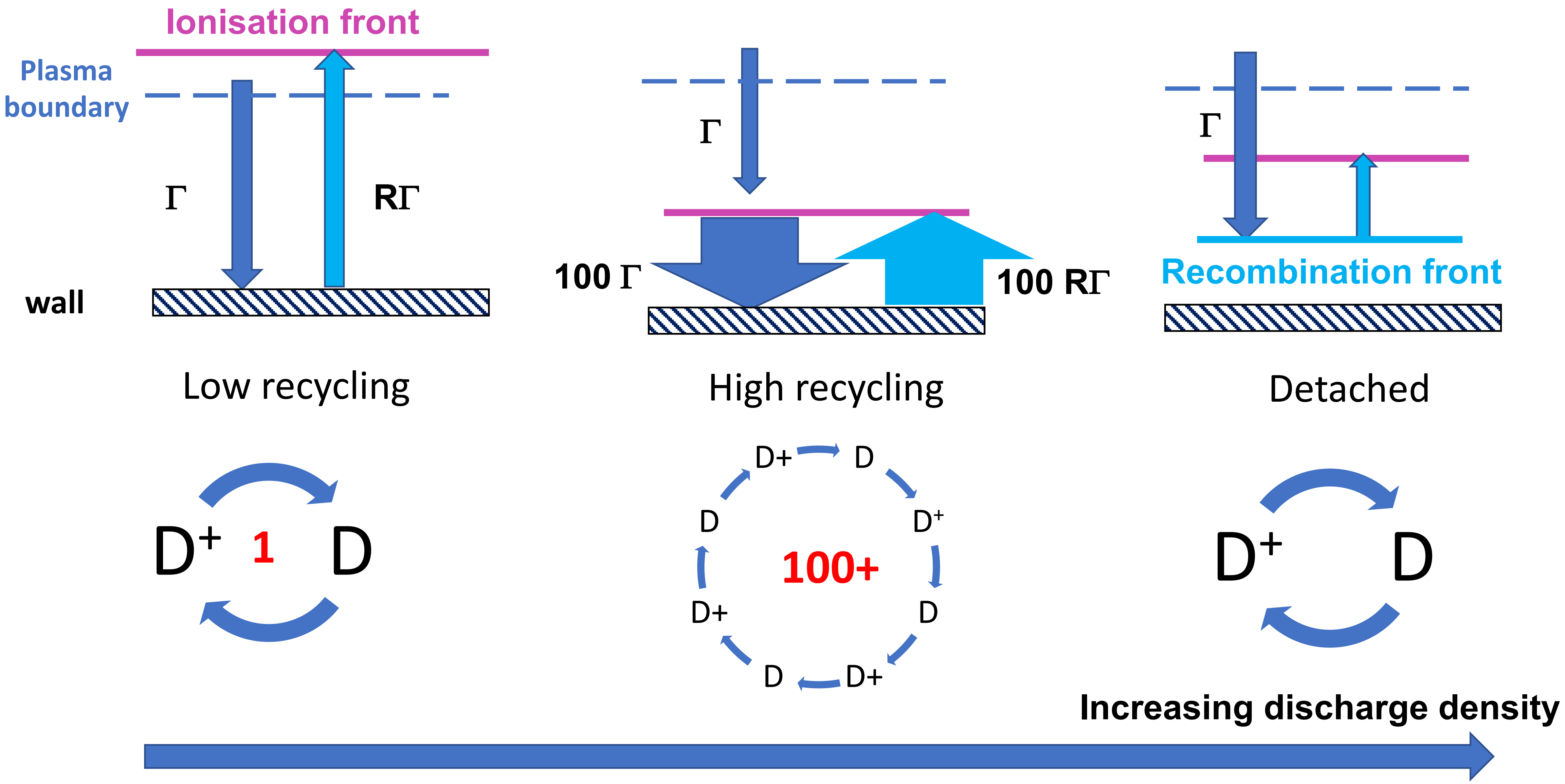
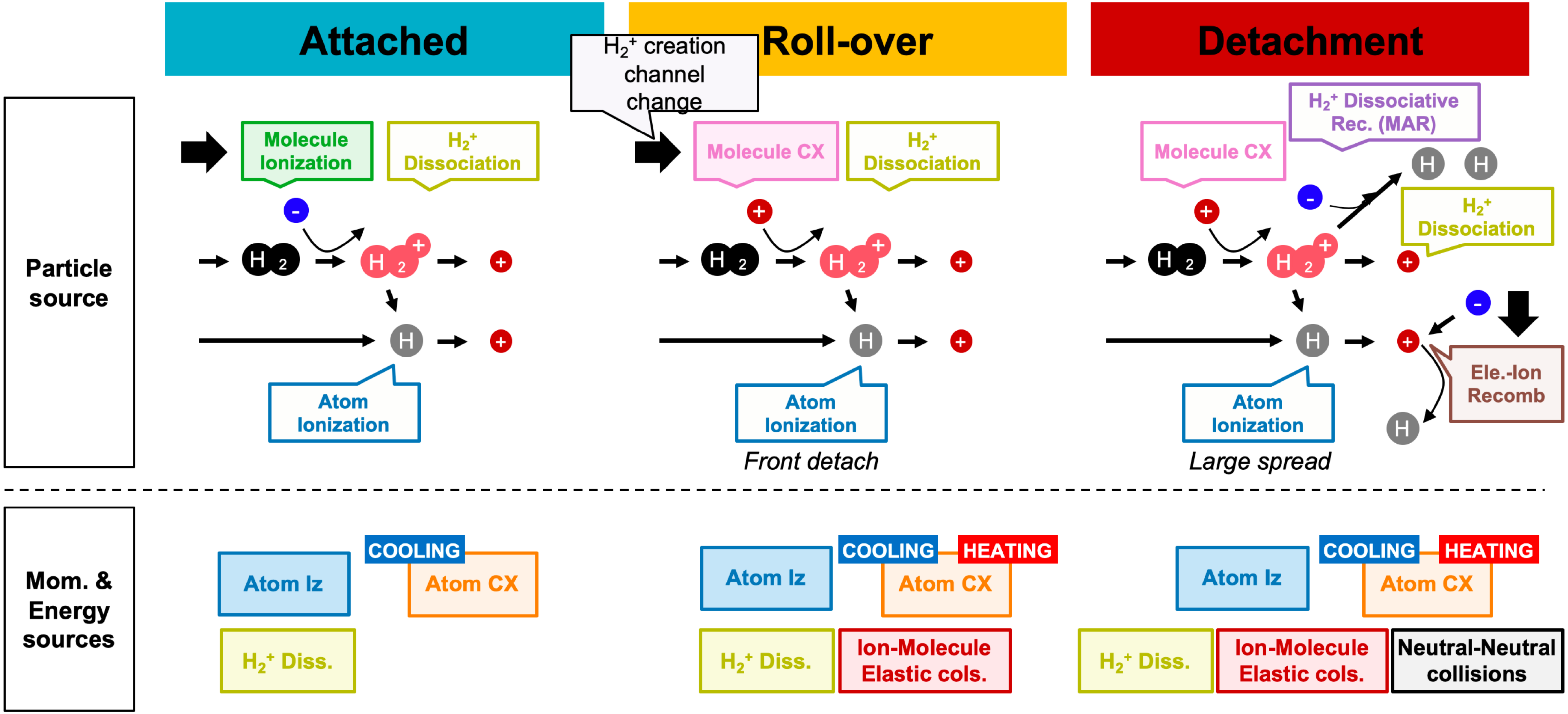


# Particle recycling and divertor regimes



# Getting colder : more complex A&M physics

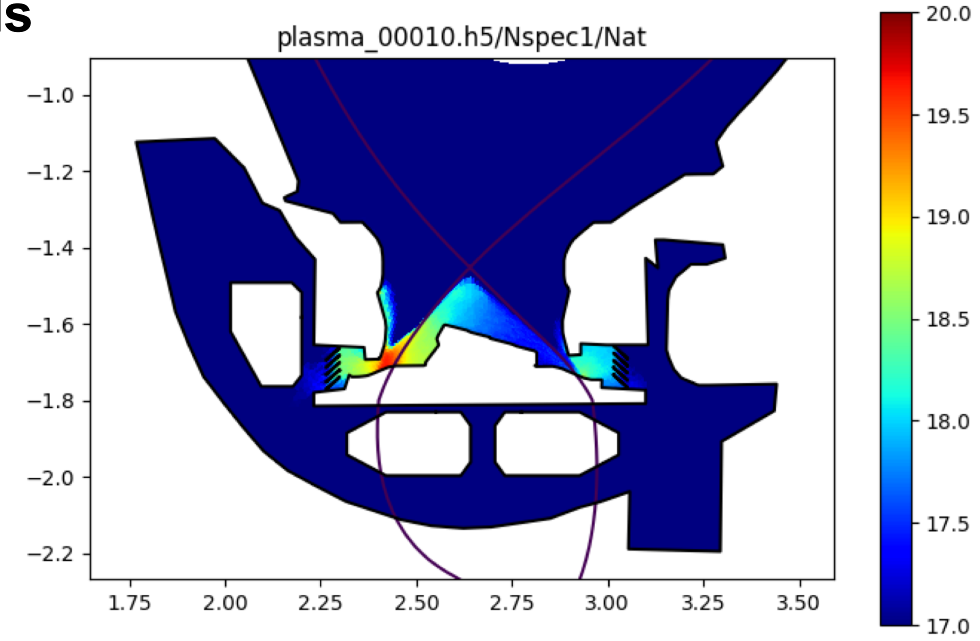



N. Rivals et al., 4th IAEA divertor concept meeting, Vienna, 2022

# Recycling: take away points

- High recycling implies **that the flux at the wall is much larger** (x 100) **than fueling/pumping**
- **LARGEST plasma source is ionization of recycled neutrals**
- **Favorable for pumping** through increased neutral density
- The same energy flows on the wall but the **energy per particle is strongly reduced**, favorable for **sputtering**
- **Energy recycling** can be substantial on W (large mass ratio and grazing ion incidence) – H. Bufferand JNM 2014

  Incident plasma heat flux > flux absorbed by the wall




JET Subdivertor (D density)

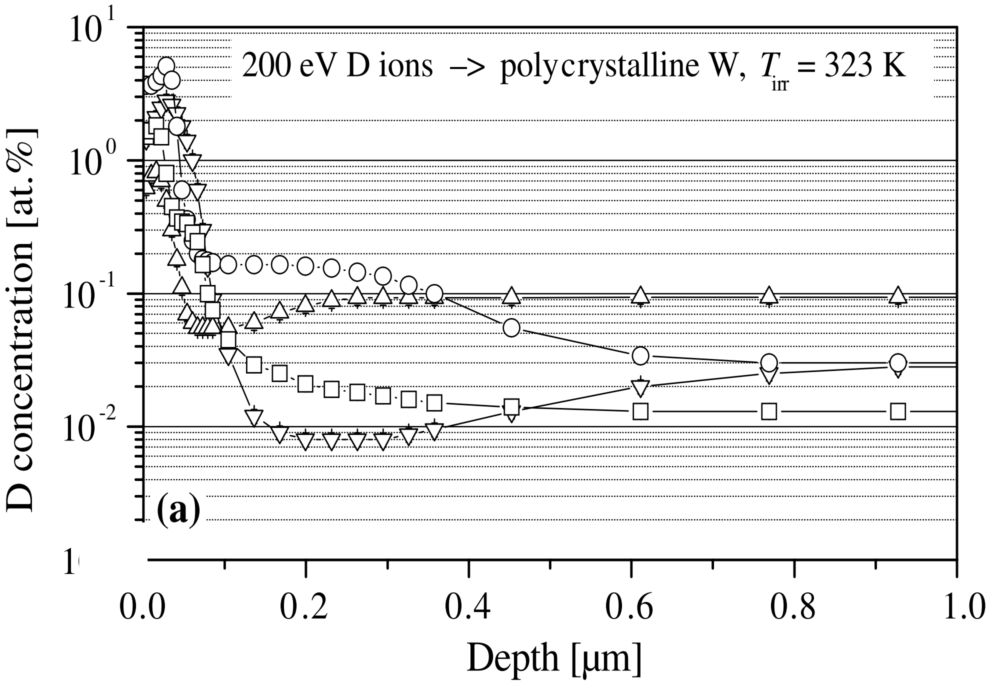
- The plasma coexists with a potentially large fuel reservoir trapped in the wall

# The wall as a (big) particle reservoir

- Energy of incident ions and atoms > 10 eV

⇒ Implantation + defect formation ➔ **Hydrogen retention**

*Deuterium profile in tungsten*

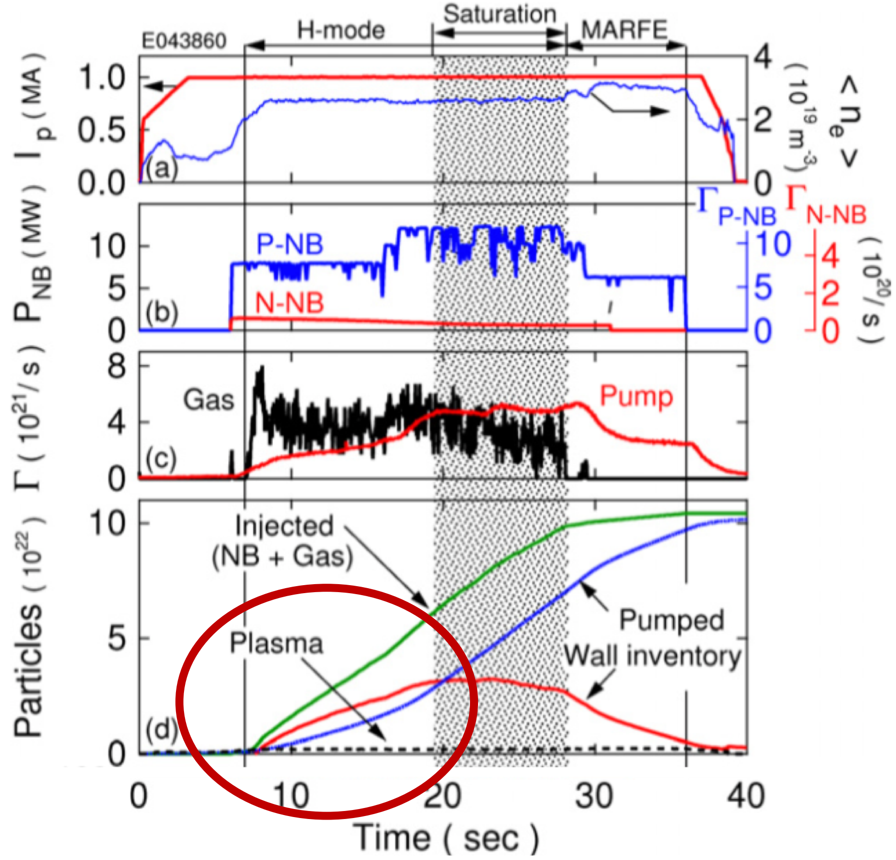



*Alimov et al., JNM 337-339 (2005)*

**Max concentration in implantation zone (< 50nm)**

Be: 30 %
C: 10 %
W: 10 %

JT-60U long high-power discharges




*Nakano et al., Nucl. Fusion 46 (2006)*

**Retention = pumping by wall**

Beginning of discharge: **wall pumping >** external pumping

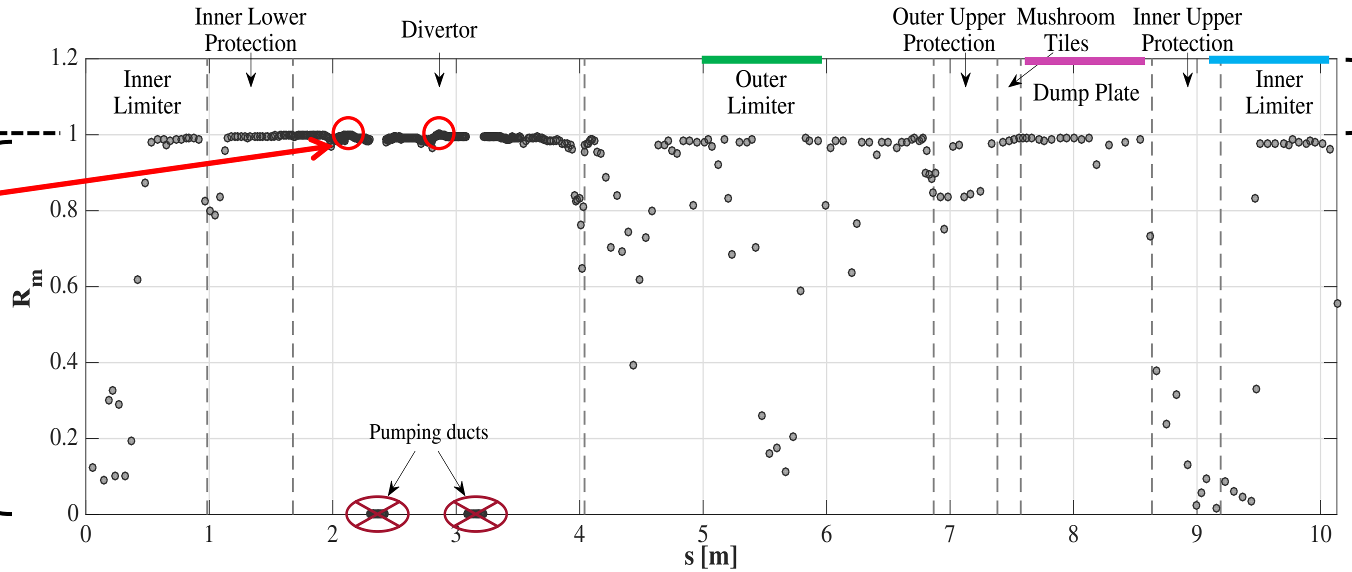
# Modelling outgazing in between JET discharges

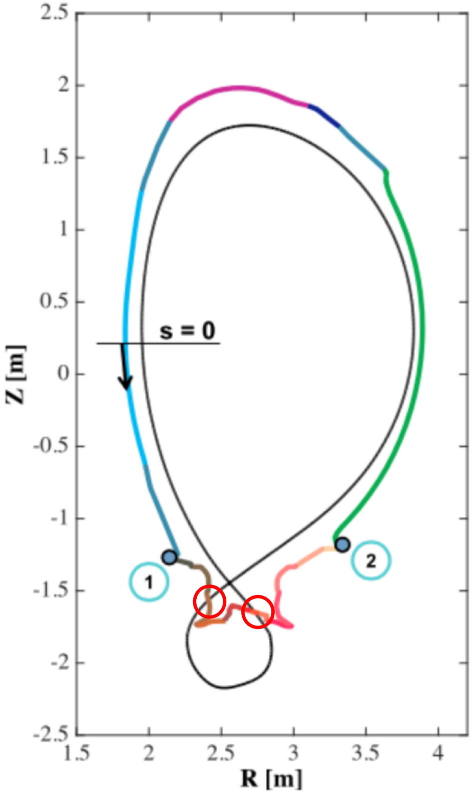
- DWE code calculating wall component temperature and hydrogen trapping/detrapping
- Calculation of retention and outgassing during discharge, example: JET after 2 s of H

Mur source nette

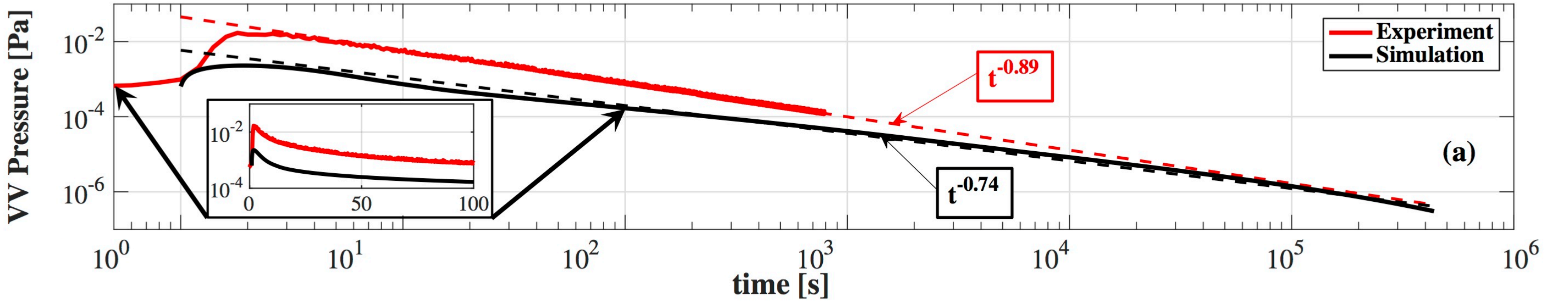
Points d'impact : $R_m > 1$

Mur pompant



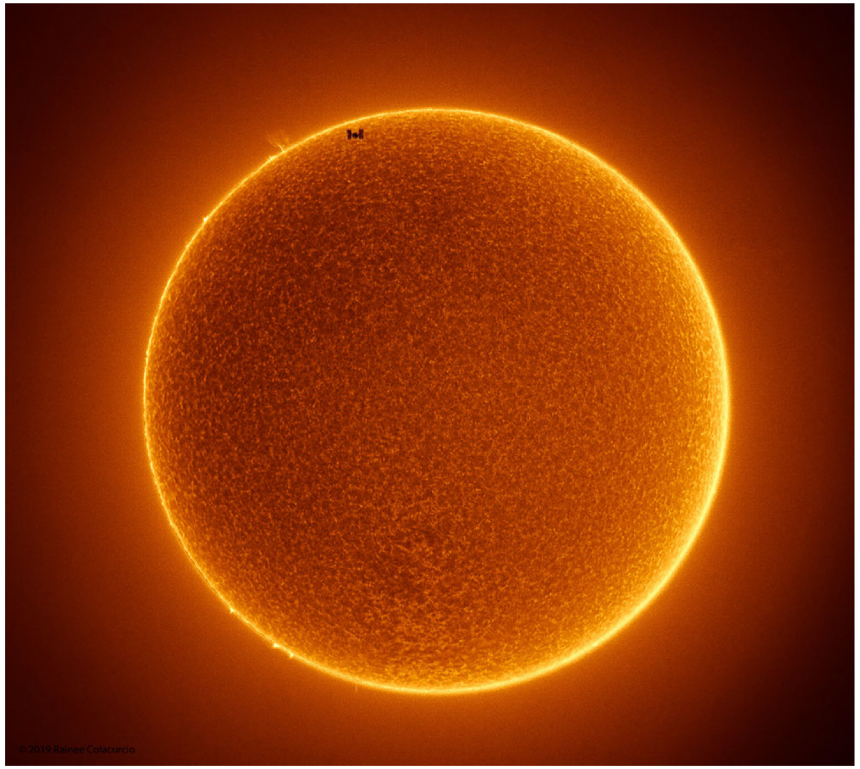




- Calculation of outgassing between discharges on JET and impact on start-up




J. Denis, ERG Grant

# Conclusions



# Key take away points

- **Power exhaust is a challenge in ITER sized tokamaks** because magnetic confinement works so well !

- Particle control and energy exhaust are **strongly intertwined**

- **Strong recycling (ultimately plasma detachement) is key** to address these challenges and make divertor conditions sustainable for plasma facing components

- The **'pumping power' is limited compared** to recycling fluxes and uncontrolled wall outgassing (active cooling mandatory)

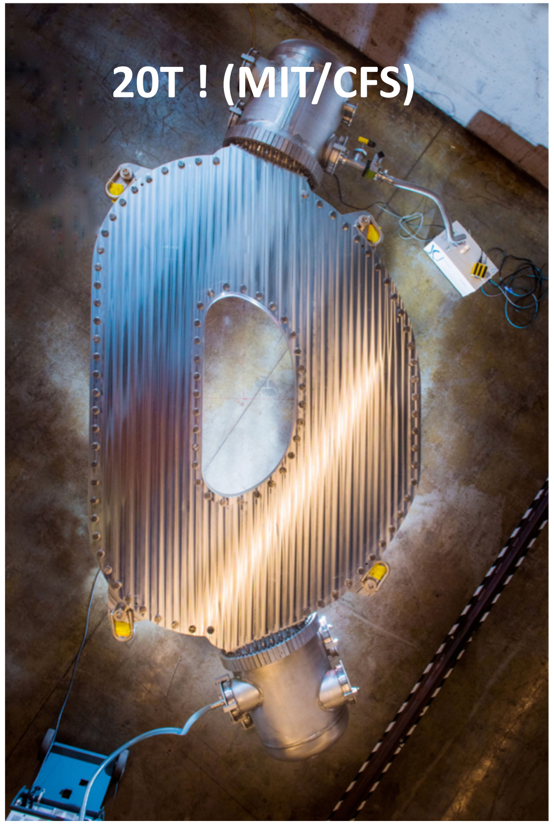
- Current experiments such as WEST key to **validate numerical simulations** tool which will play an essential role in ITER operation : preparation and analysis of experiments

# Backup slides

# Private Tokamak initiatives

- ➢ Promise to leverage technology breakthroughs to make reactors **more compact & cheaper**
- ➢ Rely on the same physics basis as ITER but with new magnets:

**higher fields** (x2), remove the He cooling constrains (**HTS**),
even possibly allow to "open" coils to remove the vacuum chamber for maintenance




- ➢ e.g. SPARC (MIT/Commonwealth Fusion Systems), 50-100MW, Q=2

Make use of new REBCO magnets,
(~ 12T vs 5T for ITER) – much smaller machine (R=1.85, a=0.5 ~ AUG)

- ➢ Very encouraging results on magnets, to be further consolidated

- ➢ But even more challenging to spread the power, increased forces on the structure so mechanical engineering challenge

- ➢ Other compact projects : STEP @ UK, Tokamak Energy (100+ people)

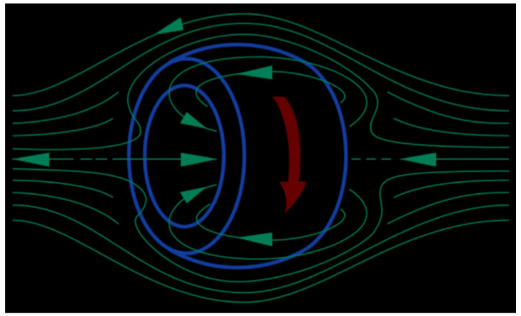
**Very positive : Combined with ITER may accelerate the arrival of fusion electricity on the grid**

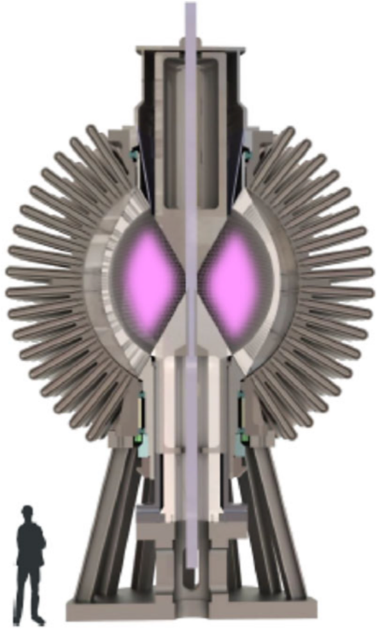
# Private initiatives based on other concepts

- **Stellarator** : Renaissance Fusion (France)

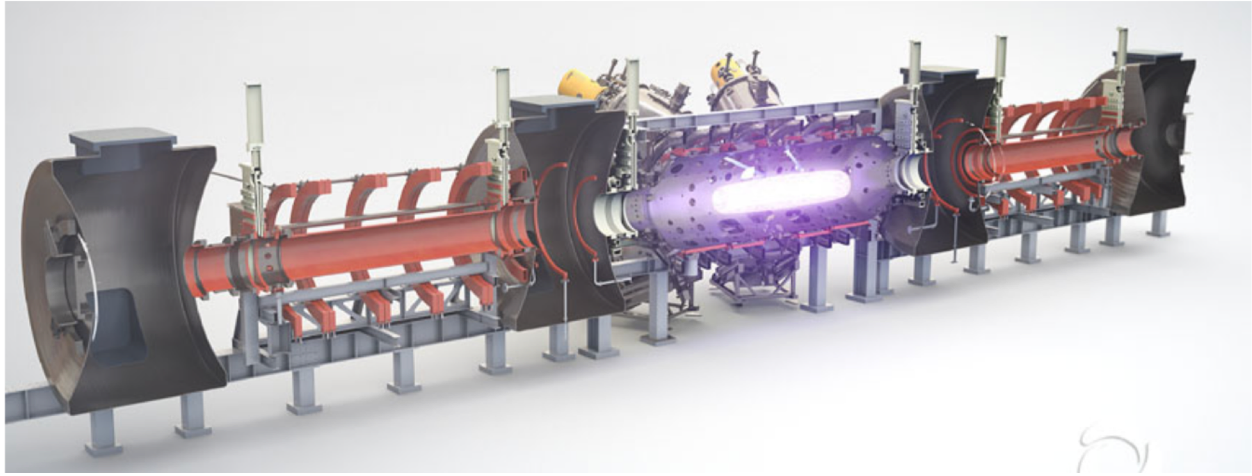
RENAISSANCE FUSION

- **Field Reversed Configurations** : General Fusion (+ compression), TAE technologies (formerly Tri-alpha, $p+^{11}B \rightarrow 3\alpha$) …





~400M$ @ CCFE, Culham



Norman device (TAE)