Plasma Wall Interaction and transport of neutral particles in turbulent plasmas

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Outline

Introduction: magnetic fusion and the ITER project

1 – Basics of edge plasma modelling: why and how ?

2 – Effects of fluctuations on the transport of neutral particles: a stochastic model

3 – Plasma Wall Interactions on turbulent scales

Conclusion and outlook

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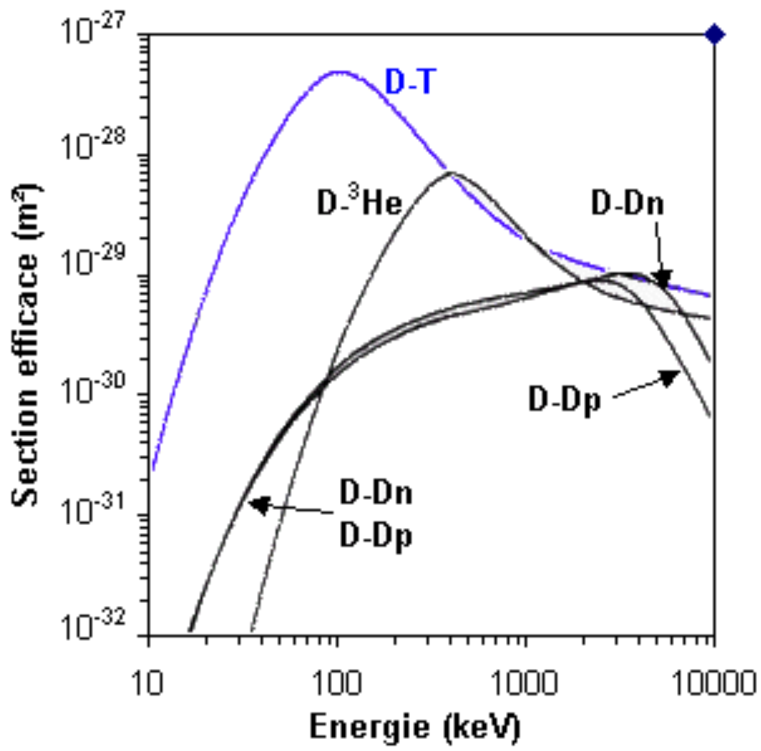
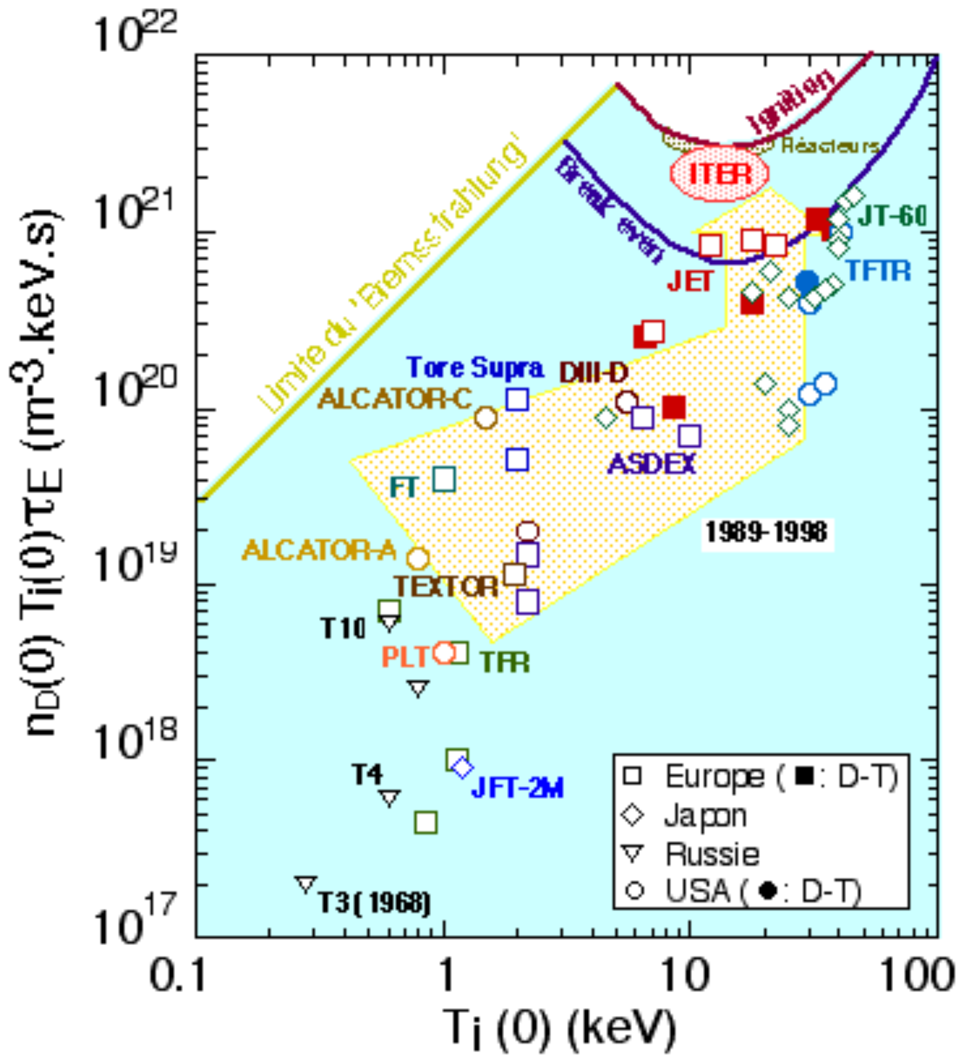
Introduction: thermonuclear fusion



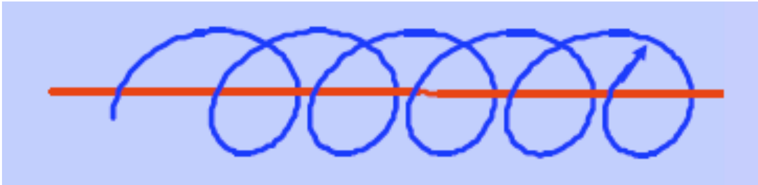


$$D + T \rightarrow^4 \mathrm{He} + n$$

3.5 MeV   14 MeV

How does magnetic confinement work ?

Cyclotron motion



Provides confinement **across** the B field, but not along it …

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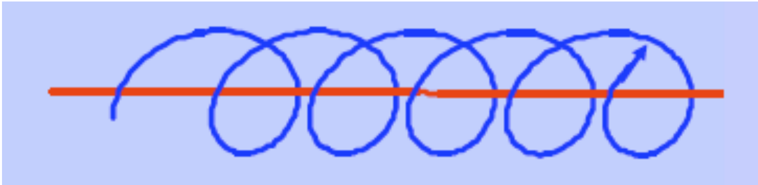

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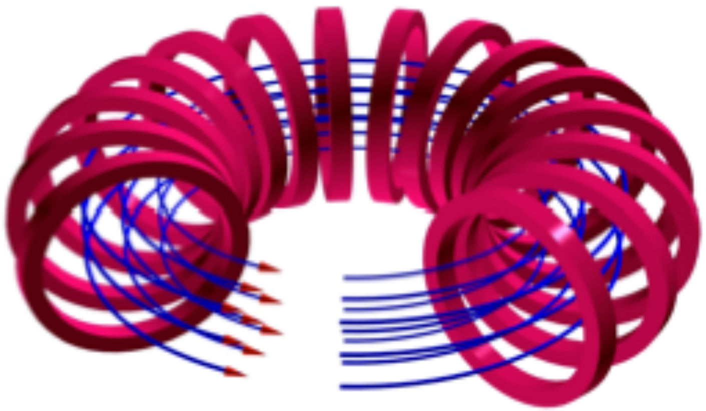
Build a torus … !



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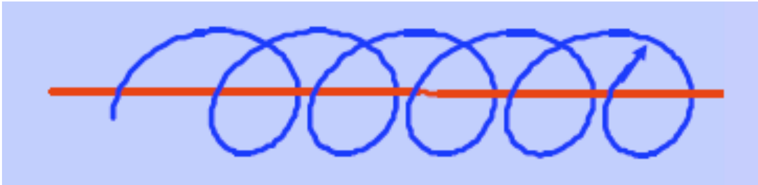

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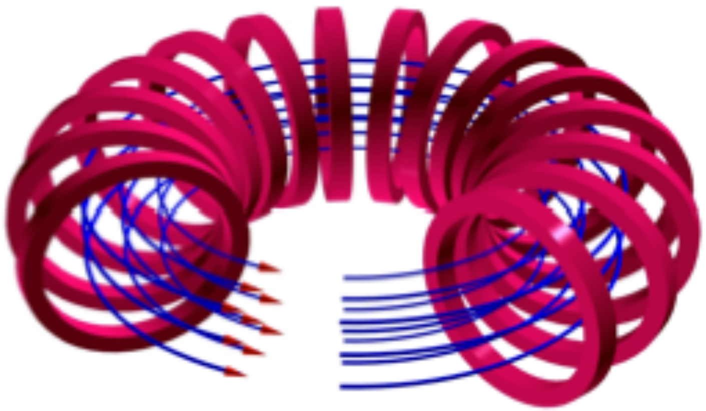
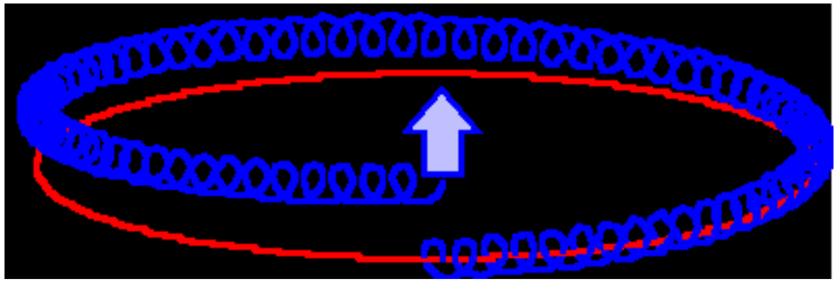


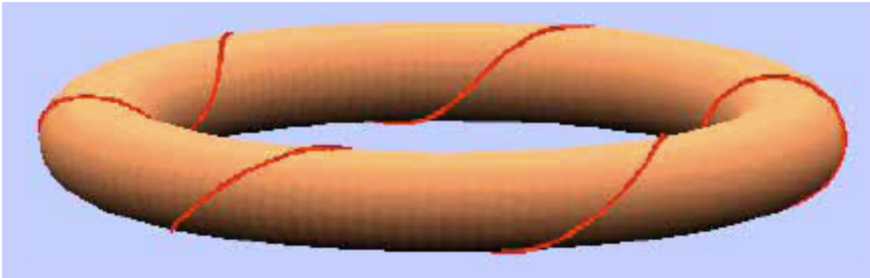
But…



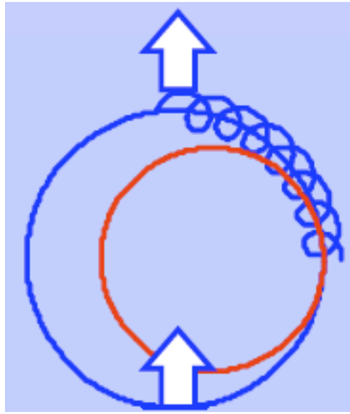
Something a bit more clever needs to be done …

The rotational transform

✓ Same principle as for taking care of the last drops when pouring wine !



Helicoidal field lines



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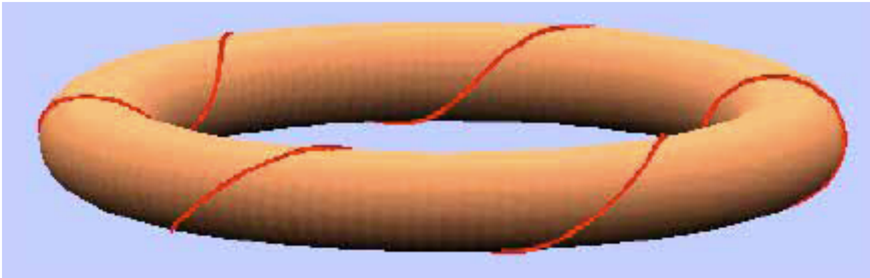

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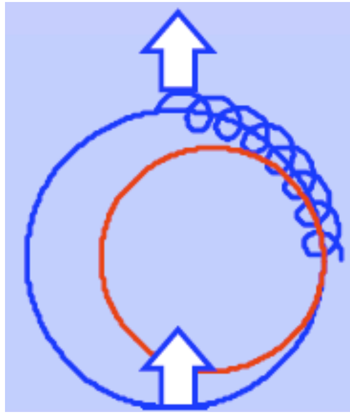
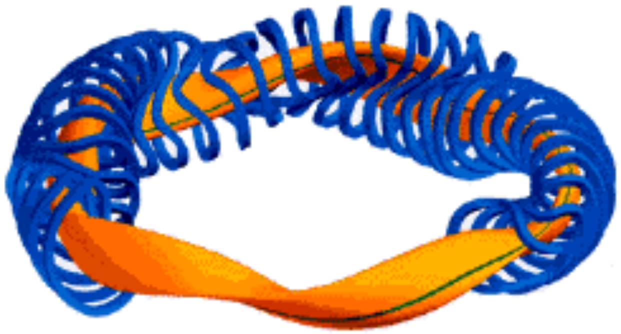
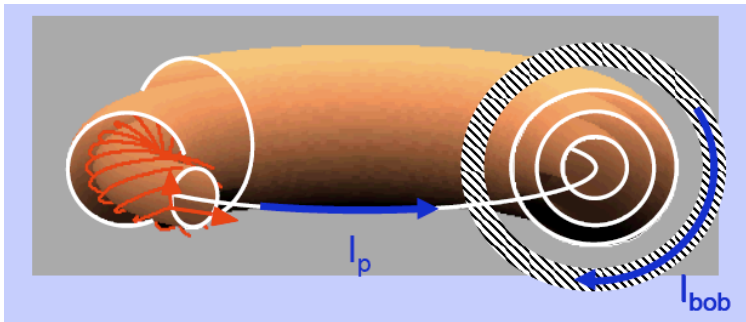


✓ And in practice ?

W7X (2014)

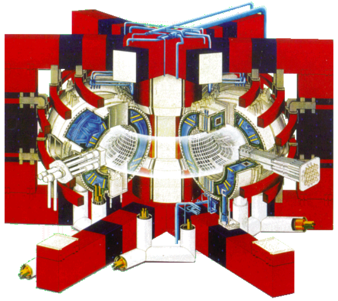


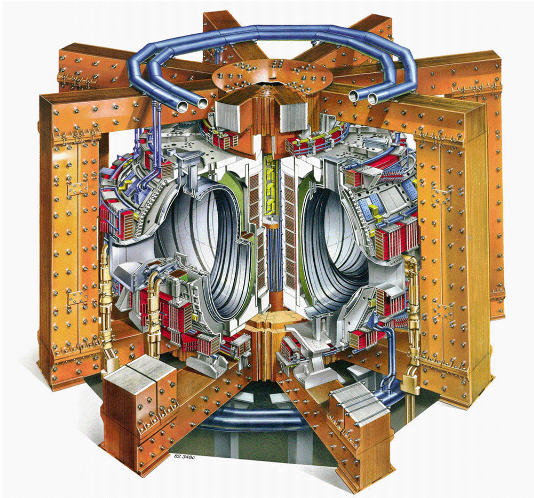
Stellarator

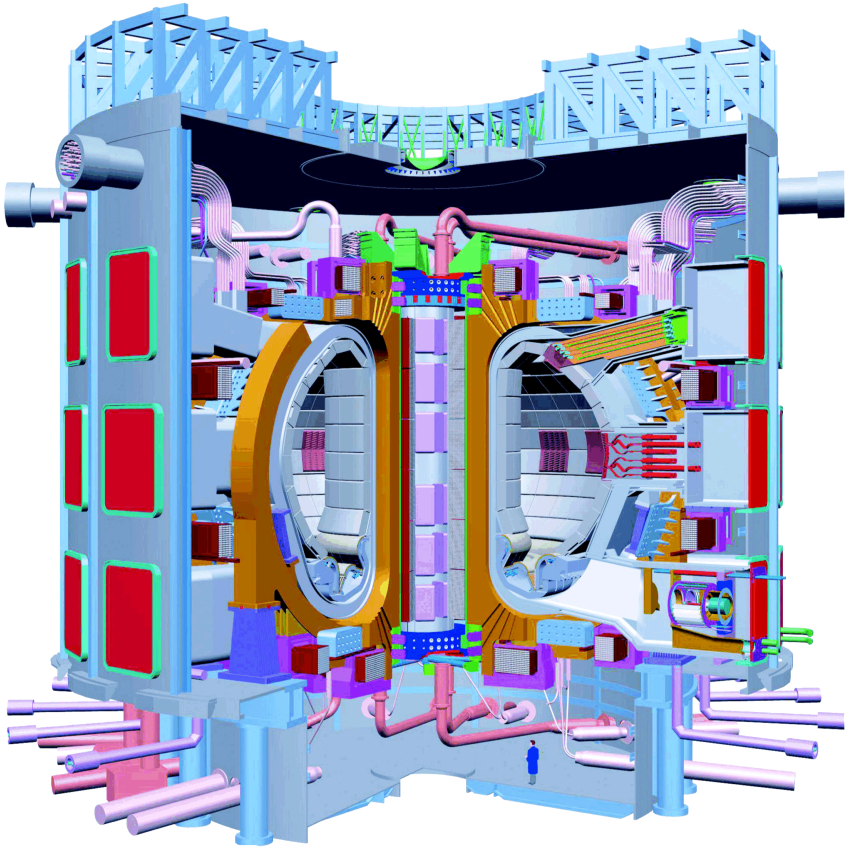


Tokamak

ITER in perspective







Tore Supra	JET	ITER (2019)
CEA Cadarache	Culham, UK	Cadarache (70 km/Marseille)
R=2.4 m	R=3.0 m	R=6.2 m
a=0.8 m	a=1.2 m	a=2 m
		$V=840\ m^3$

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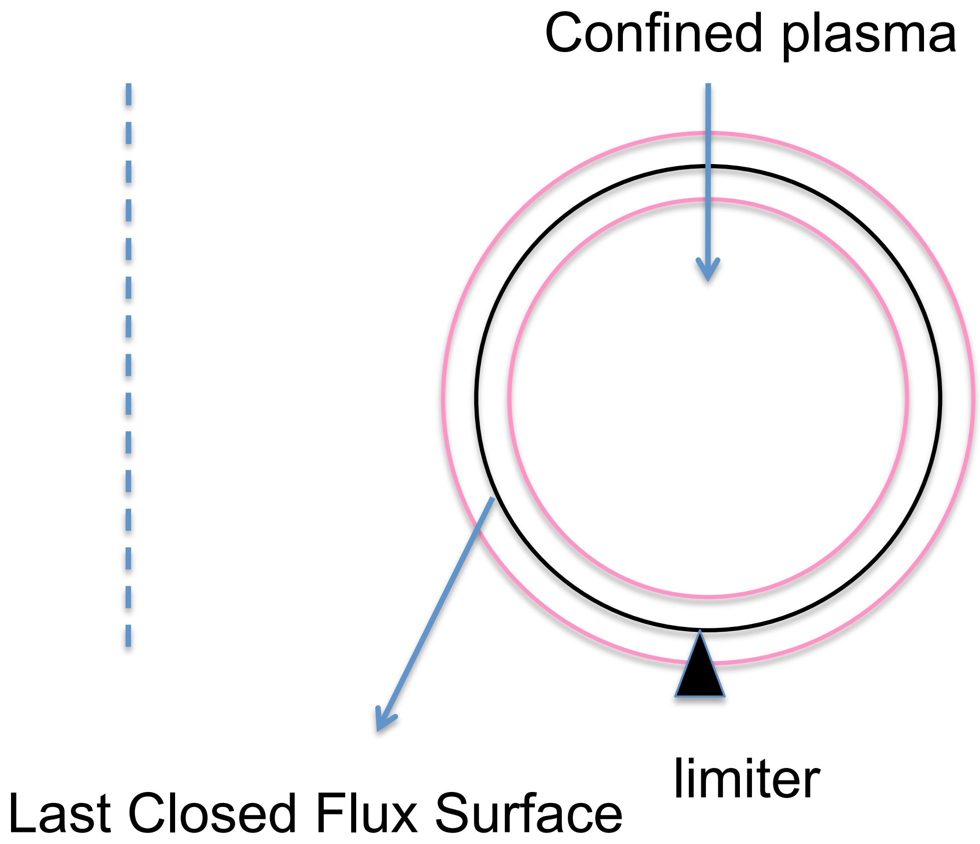
Confined plasma vs Scrape-off layer



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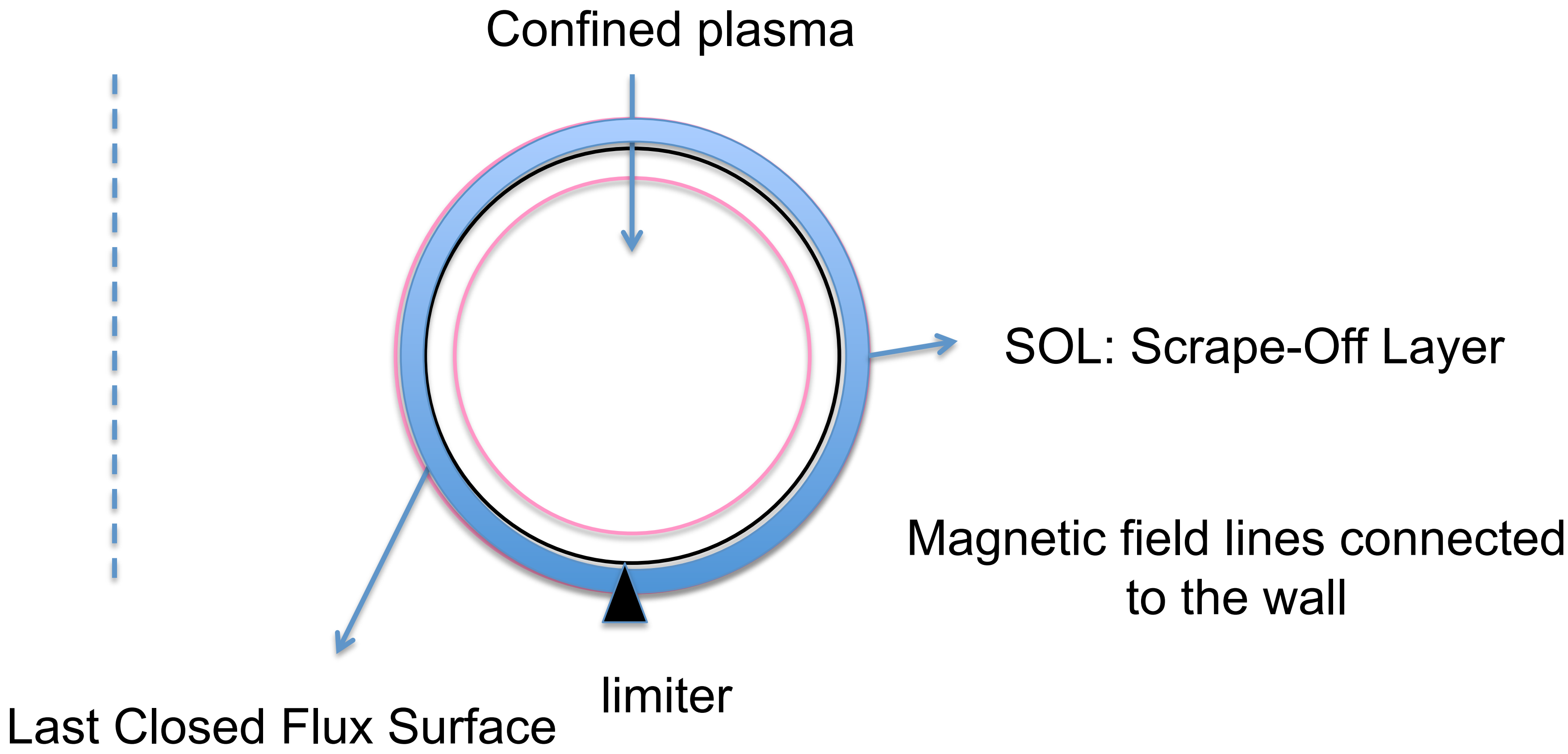

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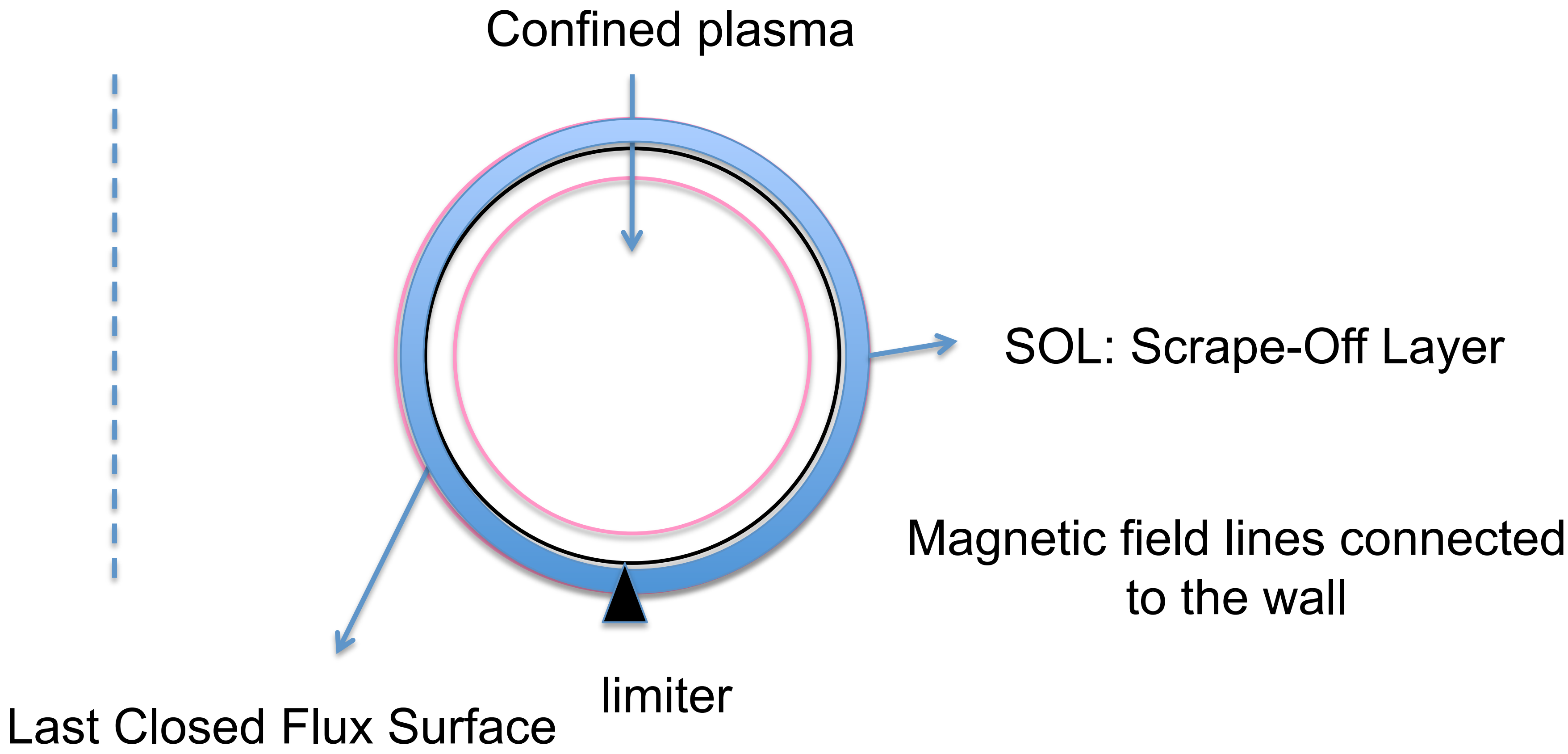
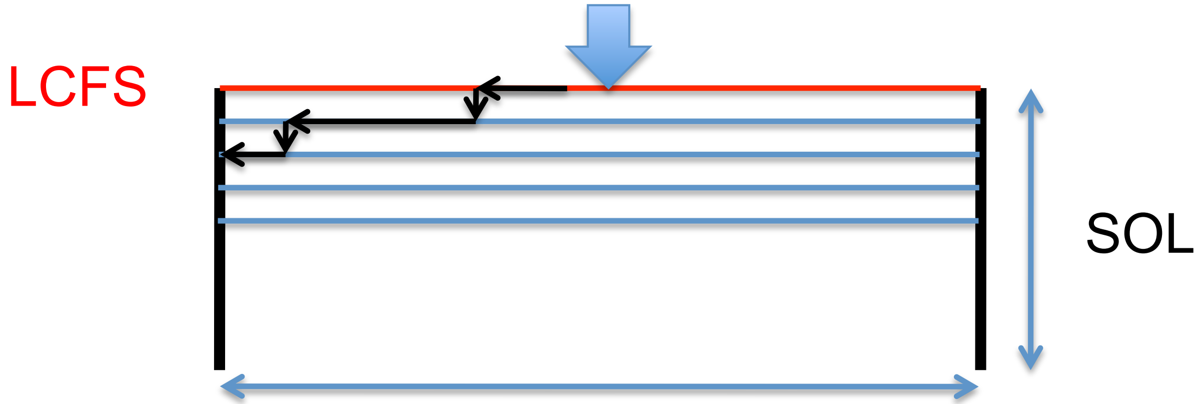


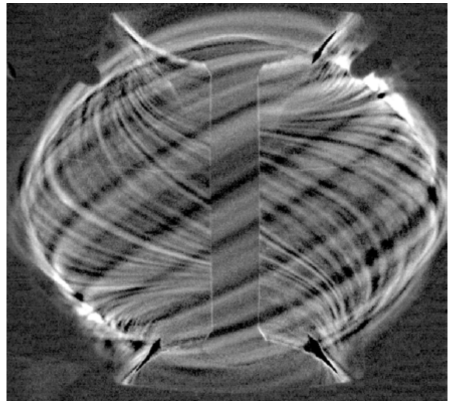
✓ **Core** turbulence controls confinement, **hence fusion power …**

Why is SOL turbulence so important ?

✓ the problem is somewhat different in the SOL (already "de-confined" !)

Particle out-flux from the confined plasma





MAST

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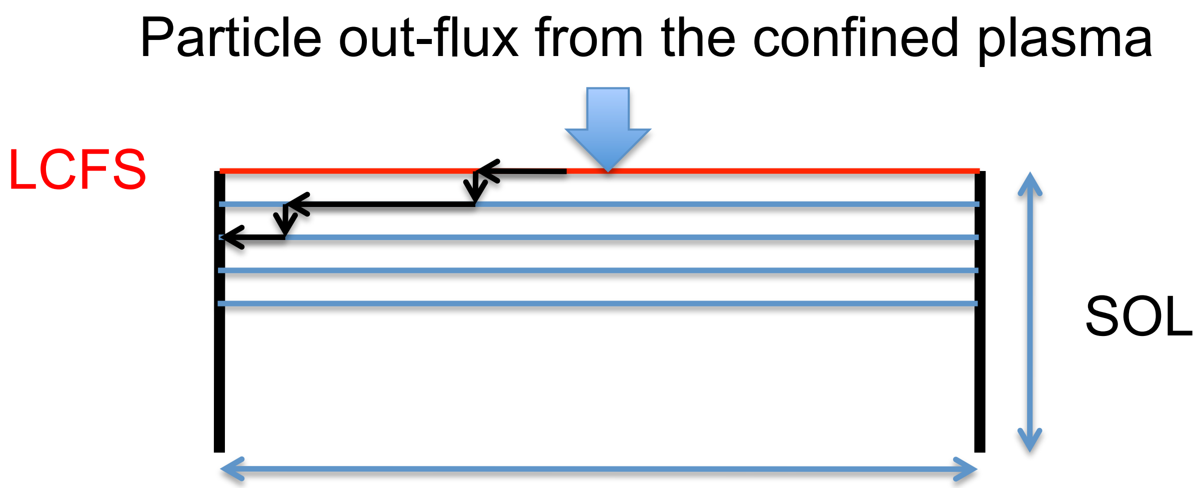

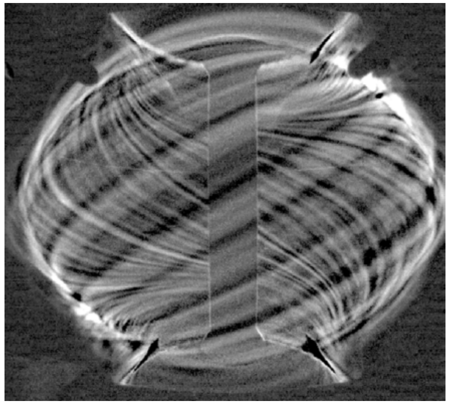

MAST

✓ Turbulent transport controls the SOL e-folding length, i.e. **power density**

✓ bursty nature of particle and heat fluxes on the wall

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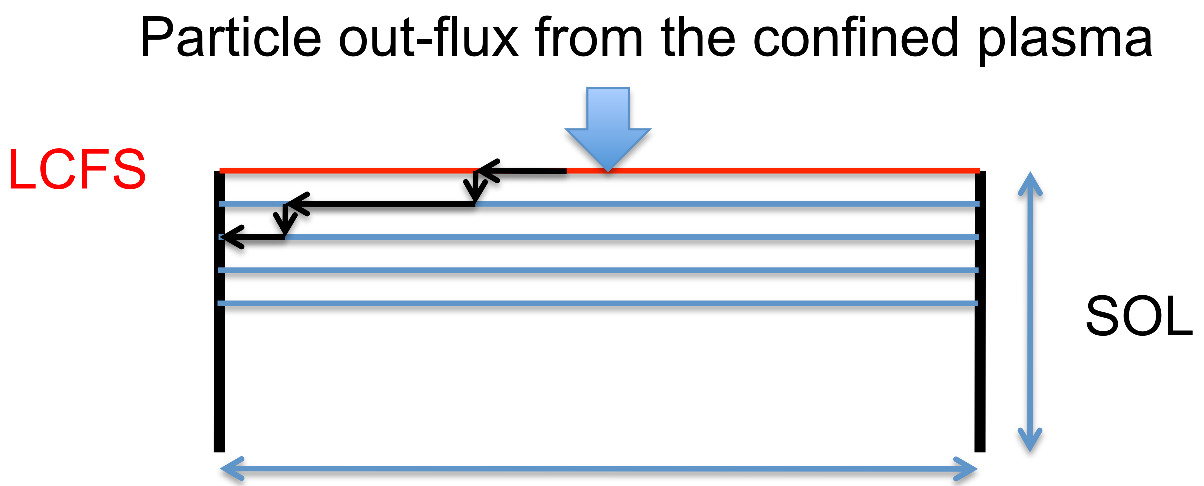

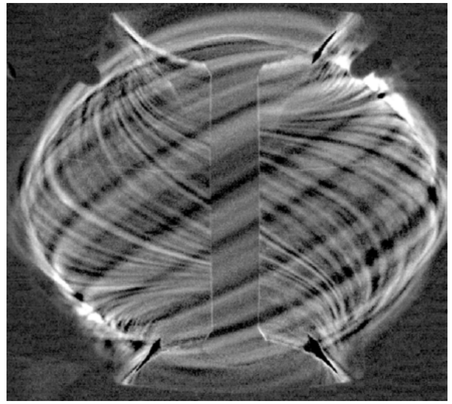

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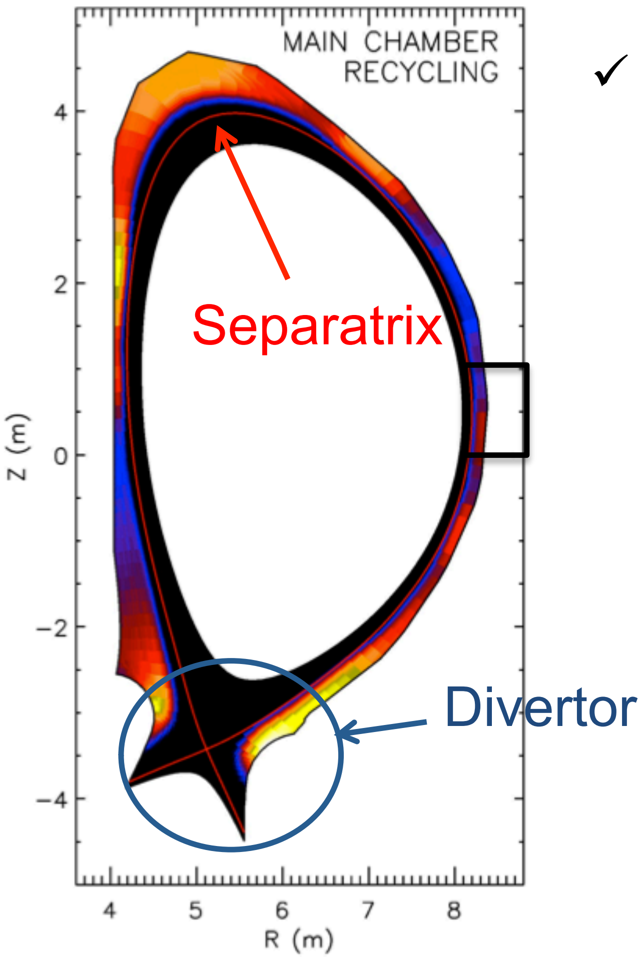
SOL turbulence sets the stage for Plasma Wall Interactions

Long range transport and main chamber recycling



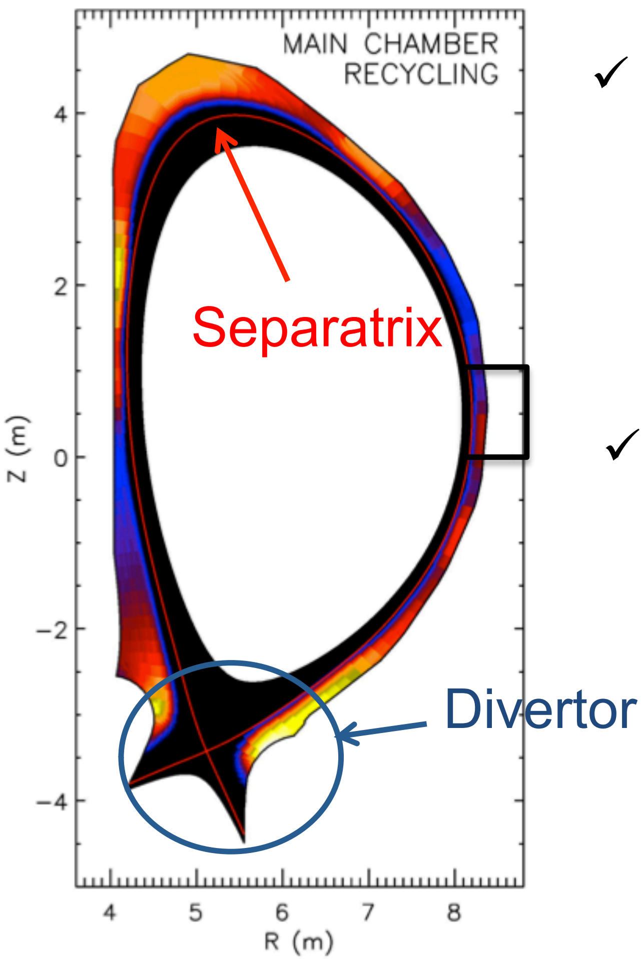
S. Lisgo (IO), D. Reiter (FZJ)

(ITER geometry)

- ✓ The **divertor** is meant to **divert** particle/heat fluxes far from the confined plasma

Impurity screening, density control, …

Long range transport and main chamber recycling



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✓ But « Blobs » can reach the main chamber wall

i) **Impurity production**

main source of W contamination in ASDEX

ii) **Hydrogen isotope recycling**

Increased sputtering by charge exchange neutrals

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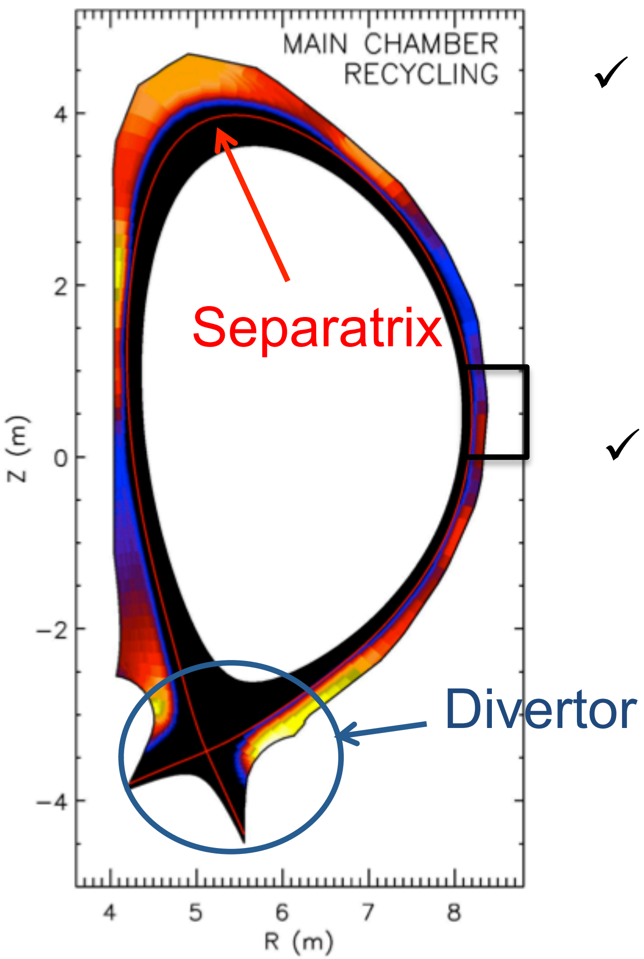
Long range transport and main chamber recycling



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Important to understand this region

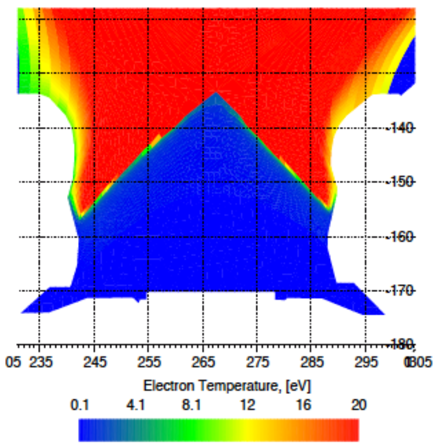
Description of the edge plasma

✓ **Charged particles** :

collisionnal at the edge, fluid equations (Braginskii):

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = S$$

S related to **atoms**, **molecules**



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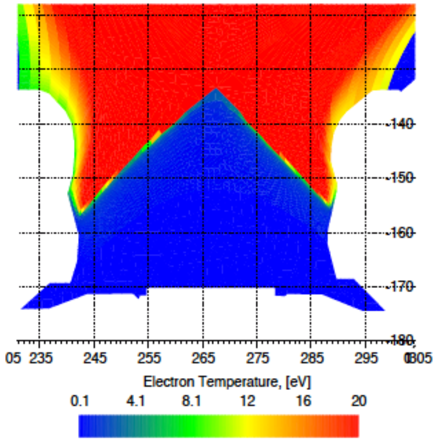

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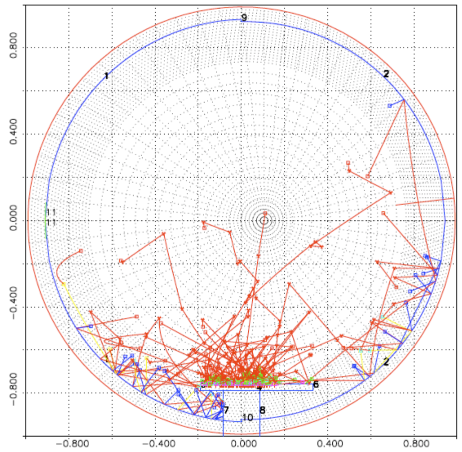
✓ **Neutral particles**:

mean free paths >> gradient lengths

Linear Boltzmann equation (Monte Carlo)



The ITER divertor has been designed using a coupled fluid/MC code

Turbulent transport: time averaged equations

✓ plasma density: $$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = S \qquad \langle \cdot \rangle = \frac{1}{T}\int_0^T \cdot dt$$

$$\mathbf{v} = \langle \mathbf{v} \rangle + \delta \mathbf{v} \quad n = \langle n \rangle + \delta n$$

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$$\frac{\partial \langle n \rangle}{\partial t} + \nabla \cdot [\langle n \rangle \langle \mathbf{v} \rangle + \langle \delta n \; \delta \mathbf{v} \rangle] = \langle S \rangle$$

= turbulent flux (correlation coefficient)

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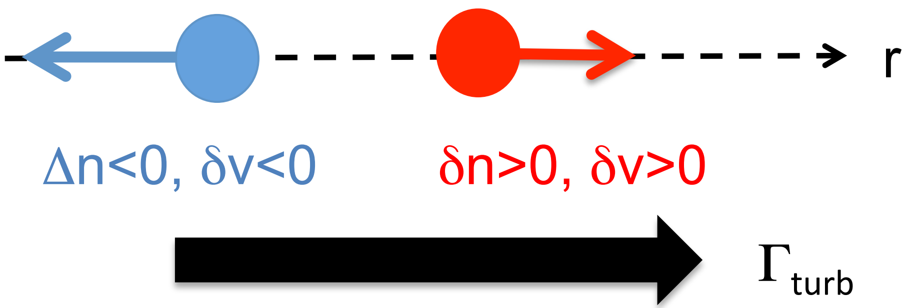
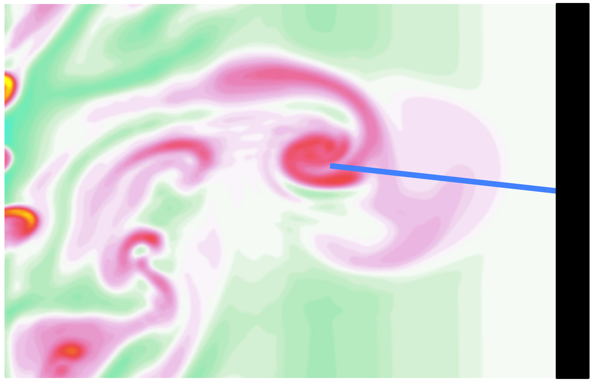


$$\Gamma_{turb} = -D\nabla\langle n \rangle + \mathbf{v}_{pinch}\langle n \rangle$$

Time averaged kinetic equation for neutrals

For consistency, the same averaging procedure should be applied to neutrals

n(**r**,t)



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+ B.C.

$$S(n) = \nu(n) f$$

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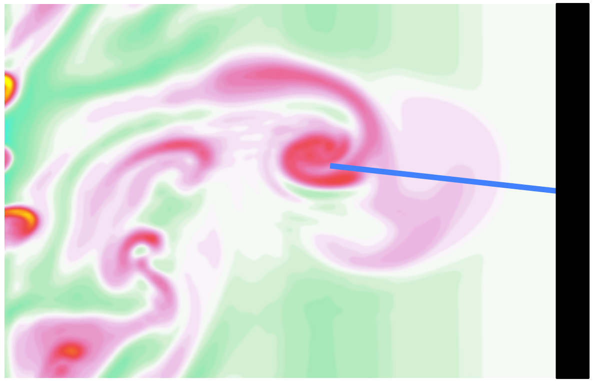

$$\langle \cdot \rangle = \int_0^{+\infty} W(n) \; . \; dn$$

(ergodicity)

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$$\longrightarrow$$

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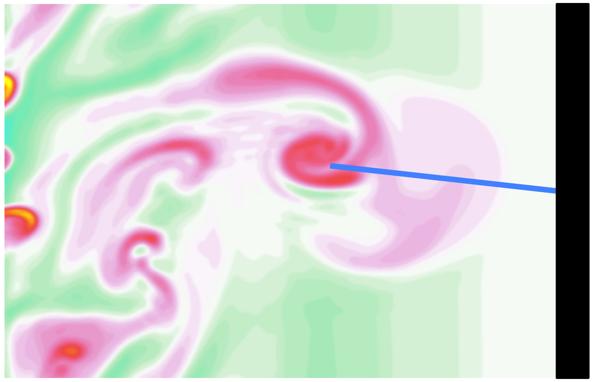

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What is the actual importance of these additional terms ?

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✓ we are (**at that time** …) mostly interested in **average values …**

… not in detailed time evolution

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i) Probability Density Function **(PDF)** $W(n) = \frac{1}{\alpha^\beta \Gamma(\beta)} n^{\beta-1} \exp\left(-\frac{n}{\alpha}\right)$

ii) **Correlation function**: typical **size λ ~ cm** of turbulent structures

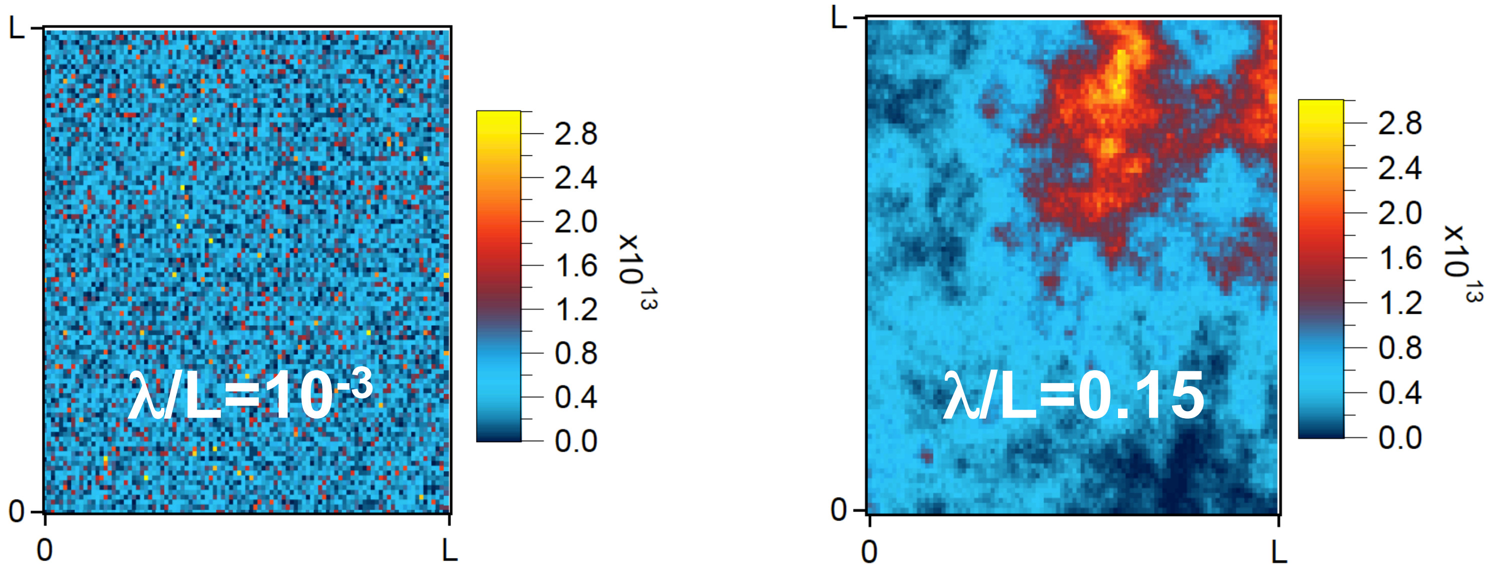
$$\rho(\mathbf{r}-\mathbf{r}') = \exp -\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}$$

Multivariate Gamma distribution

Krishnaiah and Rao *Am. Math. Mon.* ***68 342 (1961)***

✓ Fully specified by its correlation matrix and the amplitude of the fluctuations

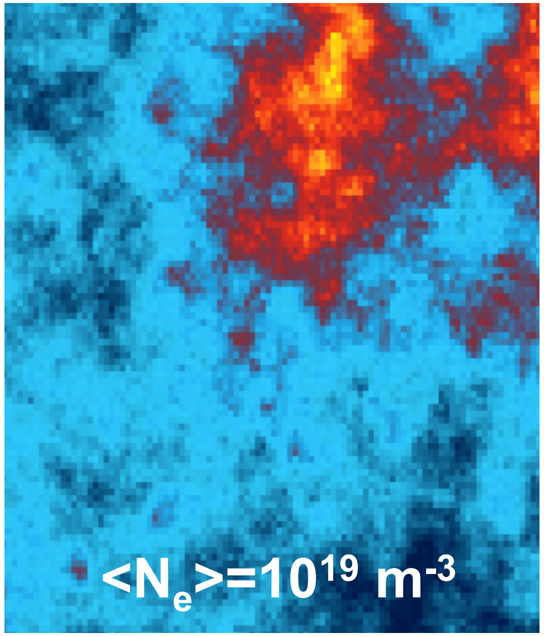
✓ well suited to Monte Carlo (sum of squares of Gaussian numbers)



✓ analytical results can be obtained for <N> and <S>

Plasma stopping power for neutral particles

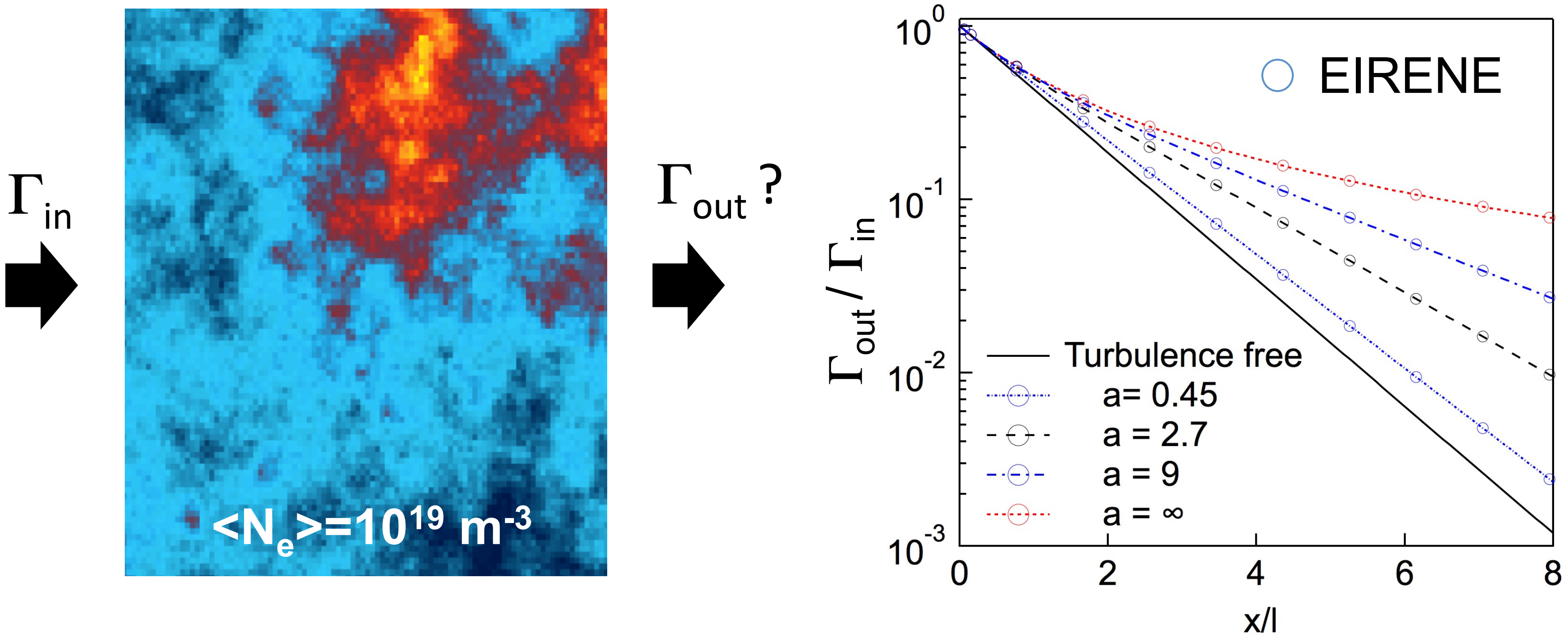
Γ_{in}



Γ_{out} ?

Plasma stopping power for neutral particles

Y. Marandet et al., PPCF 2011



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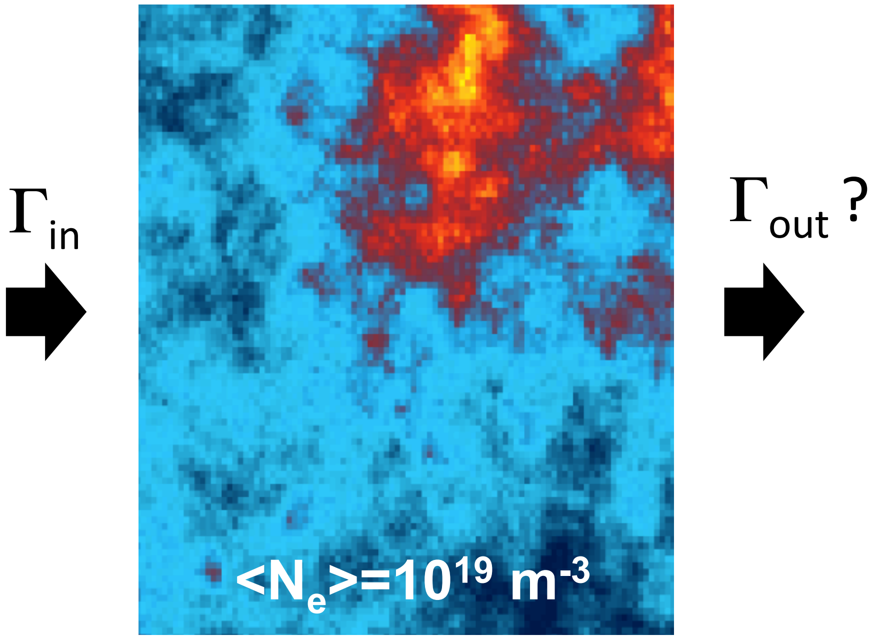

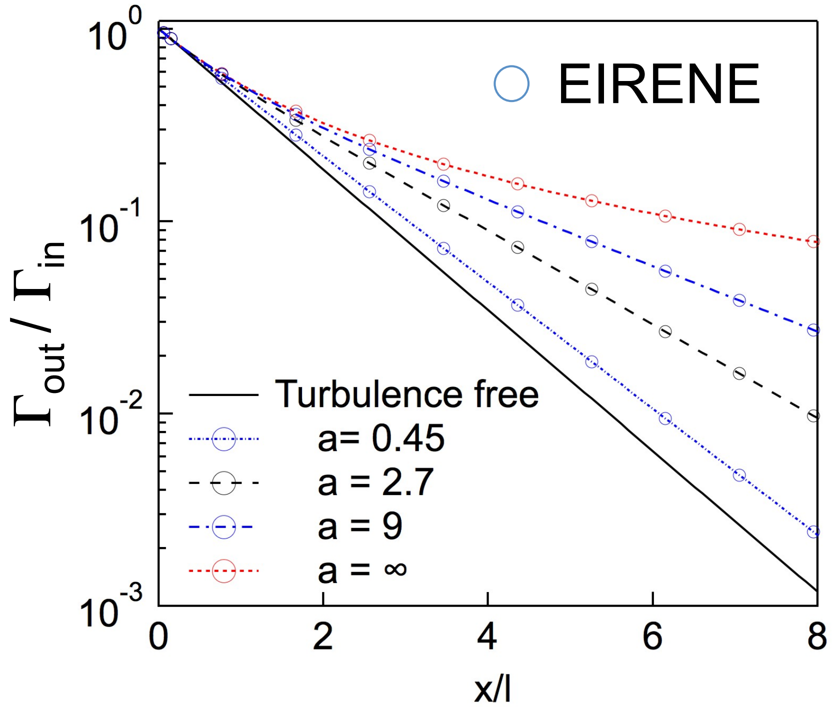

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Molecules and impurity atoms are the most affected

Coarse grained transport model for neutrals

✓ Brute force approach not feasible for **full** plasma edge simulations

✓ For the multivariate Gamma dist. :

$$\langle \delta\nu \ \delta f \rangle + \langle \nu \rangle \langle f \rangle = \varpi(s) \langle f \rangle$$

ϖ : **coarse grained** ionization rate

$$v_0 \frac{\partial \langle f \rangle}{\partial s} = -\varpi(s) \langle f \rangle$$

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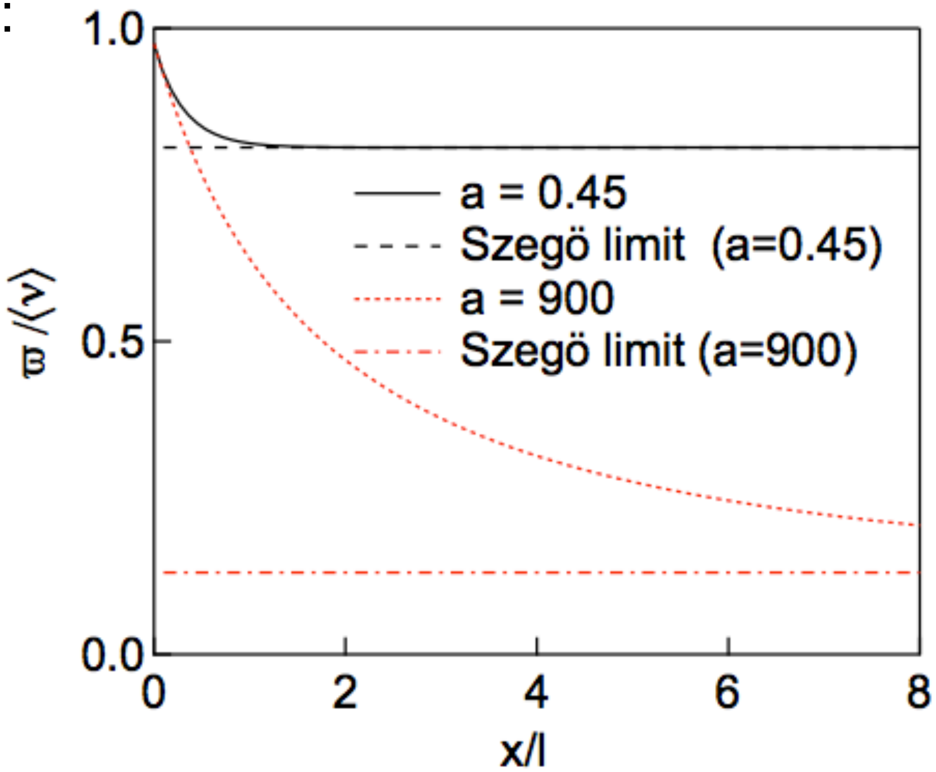

Everything happens as if neutrals where evolving in a quiescent plasma with a decreasing density profile

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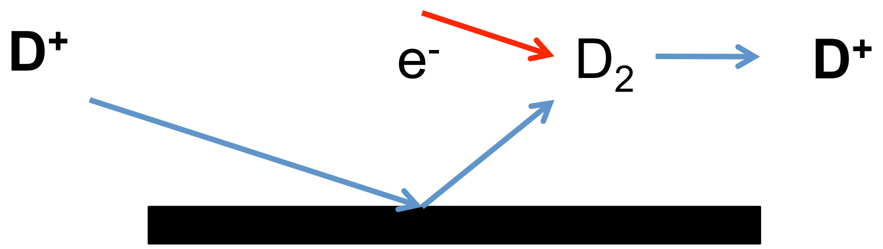
✓ The main source of neutrals for the plasma is **recycling** on the wall



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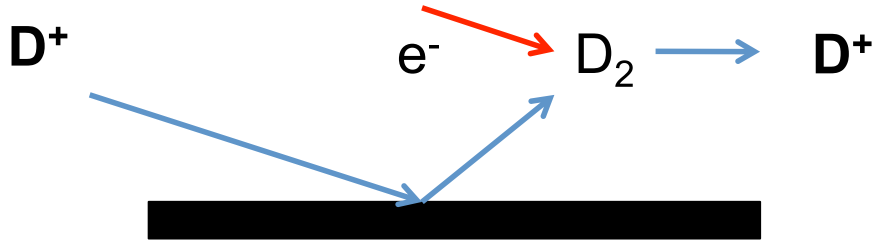

Saturated wall R~1

✓ The neutral in-flux Γ is not necessarilly uniform/constant

We assume a **linear relationship** with the plasma flux:

$$\Gamma(\mathbf{r}_w, t) = \int_{-\infty}^{t} h(t - t')\Gamma_p(\mathbf{r}_w, t')$$

where h(t-t') is the wall **response function** in time

Limiting cases: “slow” and “fast” recycling

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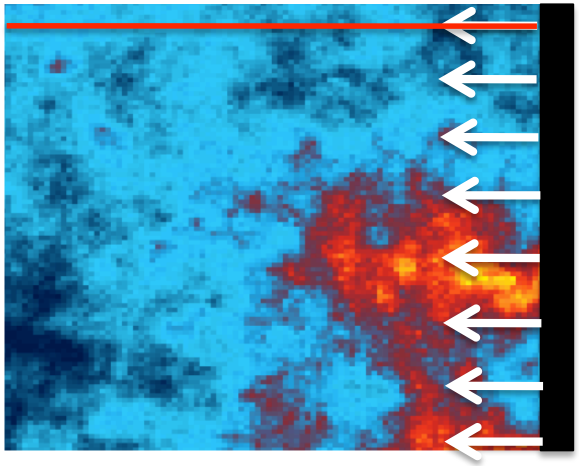
Flux stochastic

$$\Gamma_p = n \ v_{eff}$$

Role of the recycling model: physical picture

✓ Slow recycling, $\tau_R >> \tau_{turb}$



- **Homogeneous** source of neutrals

- Neutrals leave the wall **even in under-dense regions** (where Γ_p is low)

⟶ Stopping power reduction

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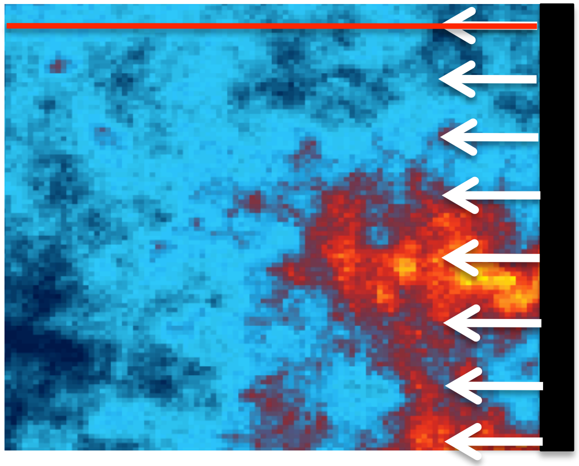

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$\longrightarrow$ Stopping power reduction

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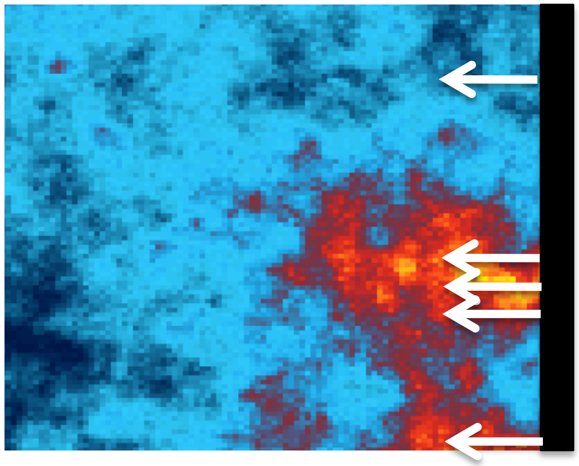
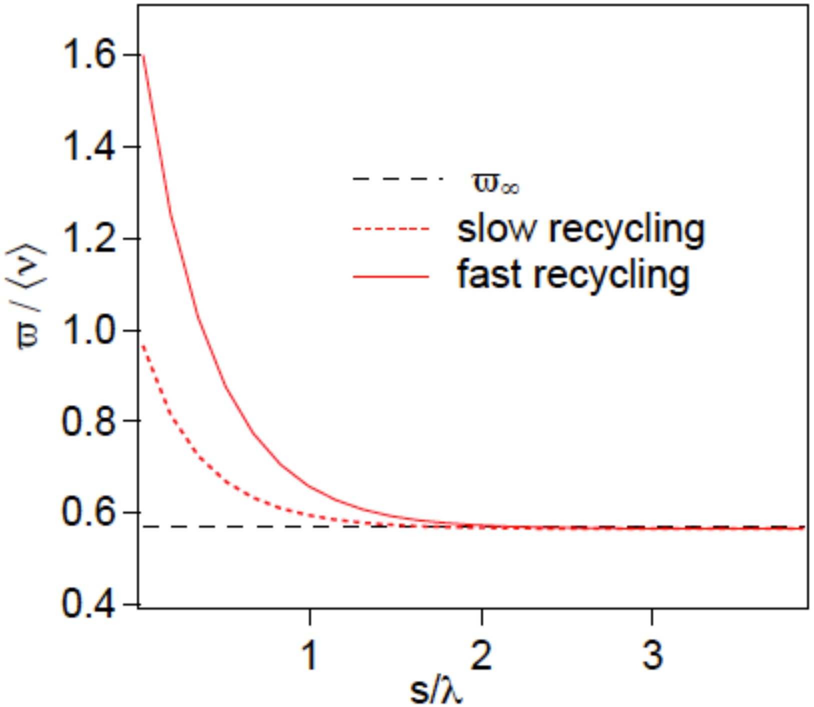


- source of neutrals **concentrated** in high density regions (high Γ_p)

$\longrightarrow$ Strong local re-ionization

Practical importance of the recycling model

i) Coarse grained ionisation rates



Stronger **re-ionization close to the wall**

in the **fast recycling** case

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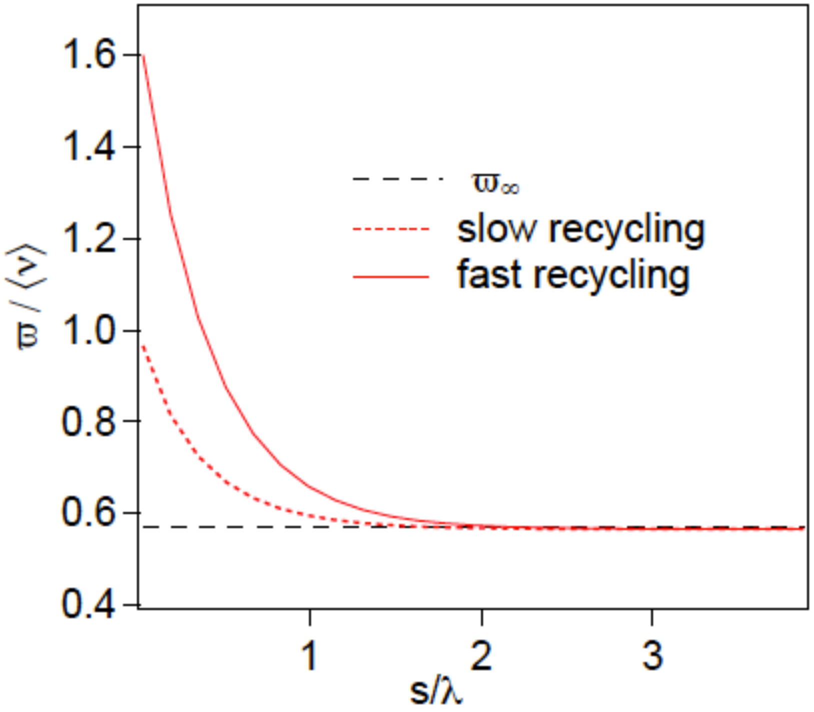

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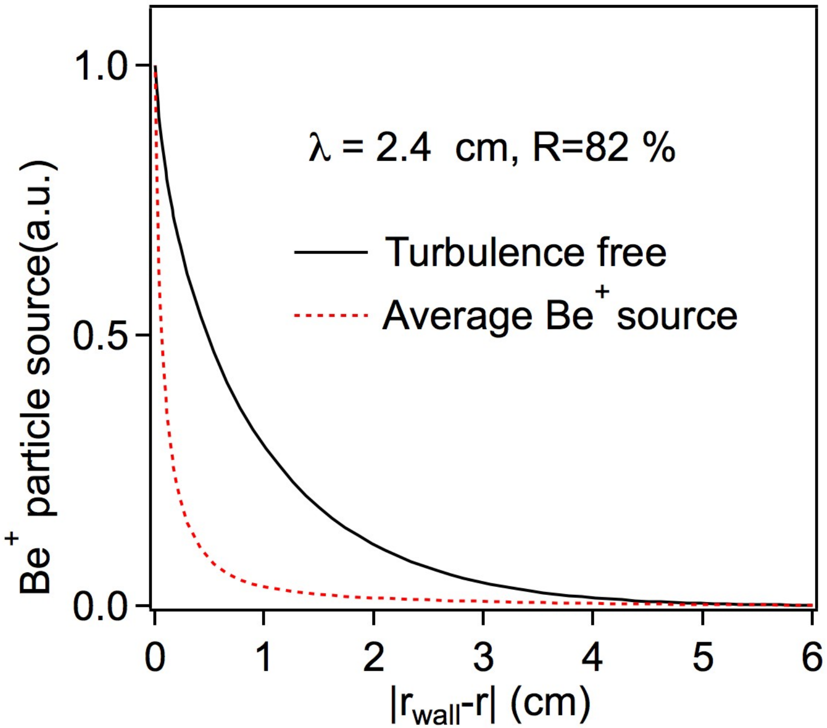
ii) Particle source from Be atoms

(physical sputtering)



Y. Marandet et al., Nucl. Fusion 2011

Most relevant recycling model in a given situation ?

A given situation : wall material, temperature, species involved, flux …

wall status (saturated, …) : history dependent …

In magnetic fusion (ITER): W, Be, C and all possible mixes …

$$\langle \phi_{D+} \rangle = 10^{20} - 10^{24} \; m^{-2}.s^{-1} \qquad T_w \geq 200 \; ^oC$$

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✓ Elementary "release" mechanisms at play must be identified

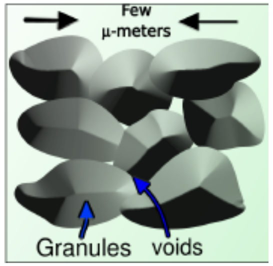
i) backscattering : ~ 10^{-12} s << τ_{turb} **FAST**

ii) « desorption »

Langmuir-Hinshelwood vs Eley-Rideal

✓ **Langmuir-Hinshelwood**: recombination after migration on the surface

the « surface » might be far from the plasma: grain boundaries, pores …



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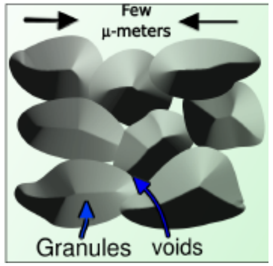

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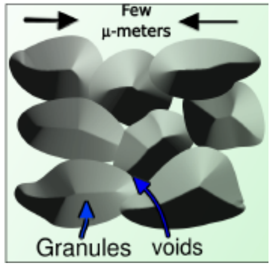

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Linear combination of fast and slow recycling should be reasonable

What proportion of fast and slow recycling ?

✓ ER dominates over LH for T<600 K on carbon (Warrier et al.)

- Quantitative results available in the litterature ?
- What about other materials ?

Multi-scale modelling (Warrier et al.) seems to be able to produce such data

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✓ Effect of **temperature excursions** on desorption ?

- Time scales involved …. ?
- Surface topology is likely to be important

Conclusions and perspectives

✓ interactions between turbulence and neutral particles is a nice topic !

✓ two important control parameters have been identified:

- the ratio between the **size of the turbulent structures** and the **neutral mean free path**

- the ratio of the **time scales** of the **recycling process** to that of **turbulence**

✓ as far as the latter is concerned, much remains to be done

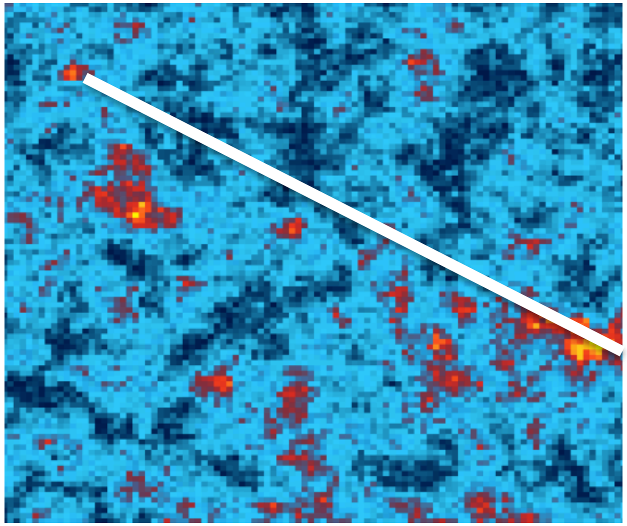
✓ This is especially true in view of the present effort of **coupling turbulence codes** to the EIRENE **neutral particles code** (ANR ESPOIR project, LABEX VENUS)

Physical interpretation of the results

✓Jensen's inequality (convex functions)

$$\langle e^{-\tau} \rangle \geq e^{-\langle \tau \rangle}$$

✓ small structures and/or large mean free paths >> λ



$$\tau(l) = \int_0^l \nu(s)ds \simeq \langle \nu \rangle l$$

ergodic theorem

The effects of fluctuations disappear…