Particle balance and D retention in tokamak discharges

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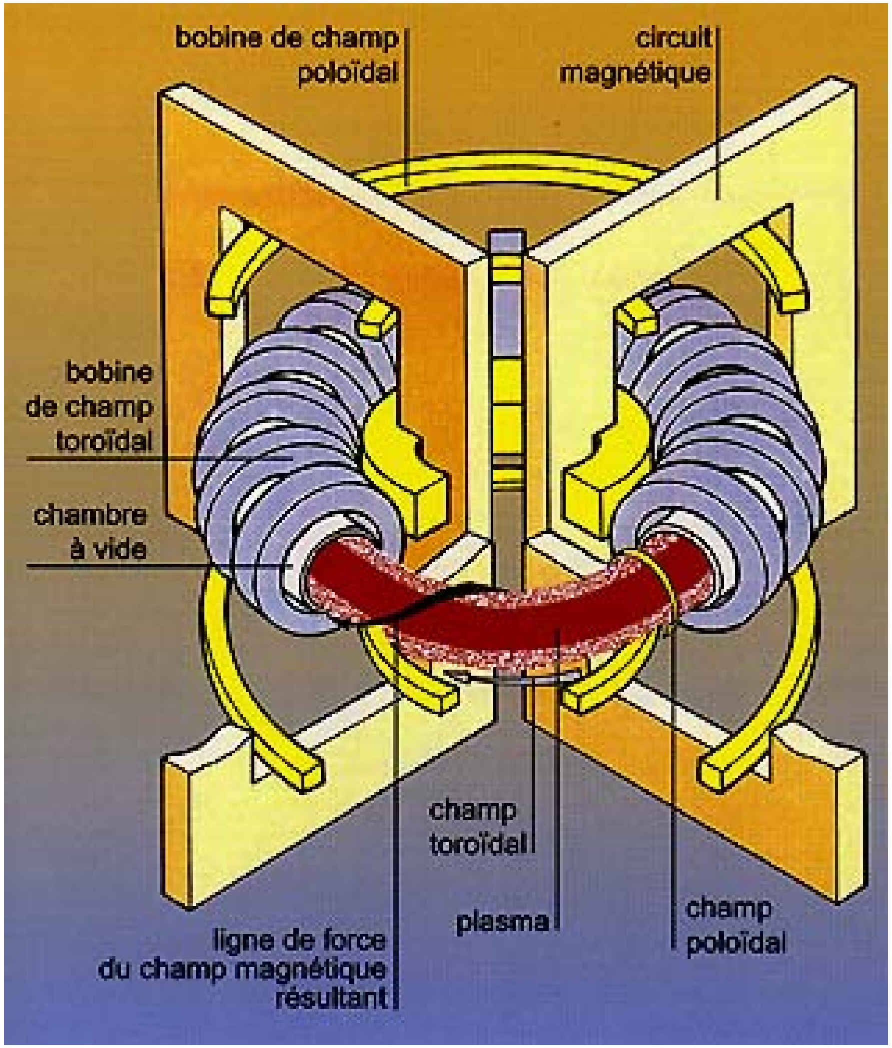
- Tokamak : machine and plasma
- D retention – magnitude / variation / recovery
  – carbon erosion/redeposition
  – global balance
- What about next step (ITER) ? / conclusion

What is a Tokamak ? (TS & ITER)



Tore Supra

R = 2.4 m

a = 0.7 m

V = 25 m^3

B = 3.4 T

I_p = 1.7 MA

P = 10 MW

ITER

R = 6.2 m

a = 2.0 m

V = 840 m^3

B = 5.3 T

I_p = 15 MA

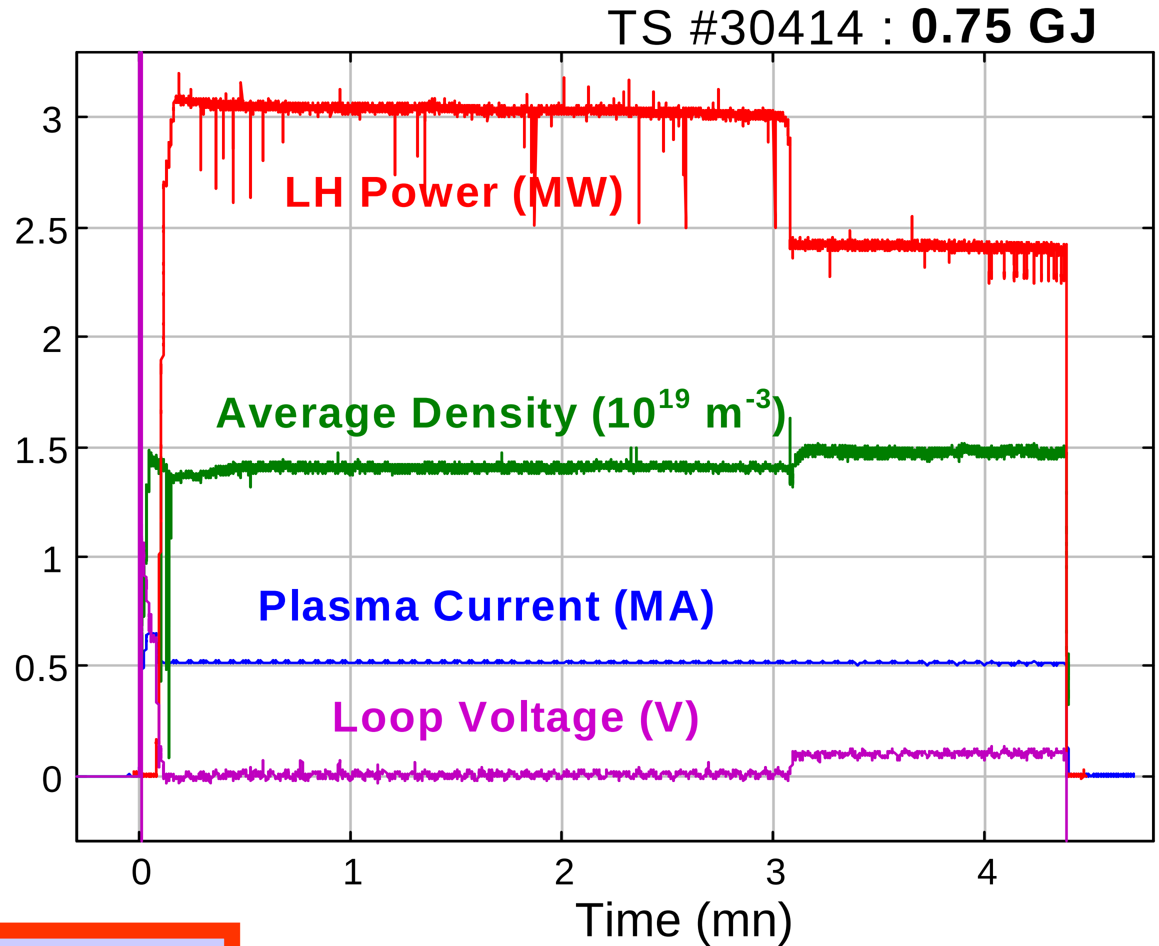
P = 500 MW

Discharge / plasma parameters

4mn 25 & 0.75 GJ

limitation : LH power

- LHCD only (P_{LH} = 3 MW)
- Low current (I_p = 0.5 MA)
- Low density (f_{GW} = 0.6)

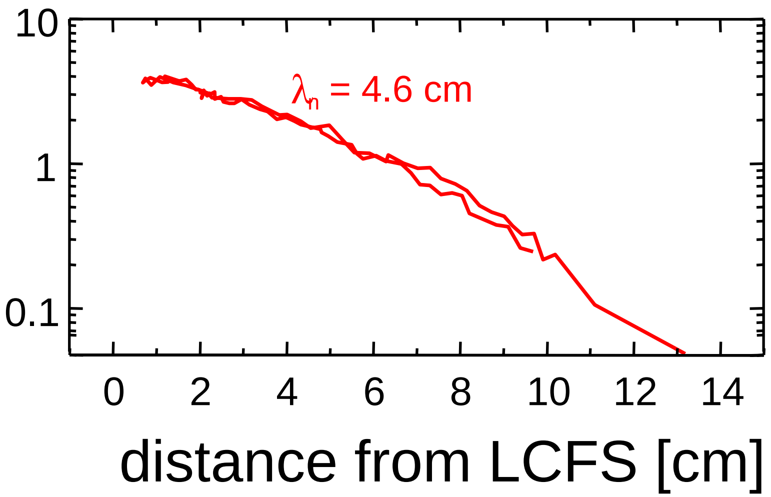


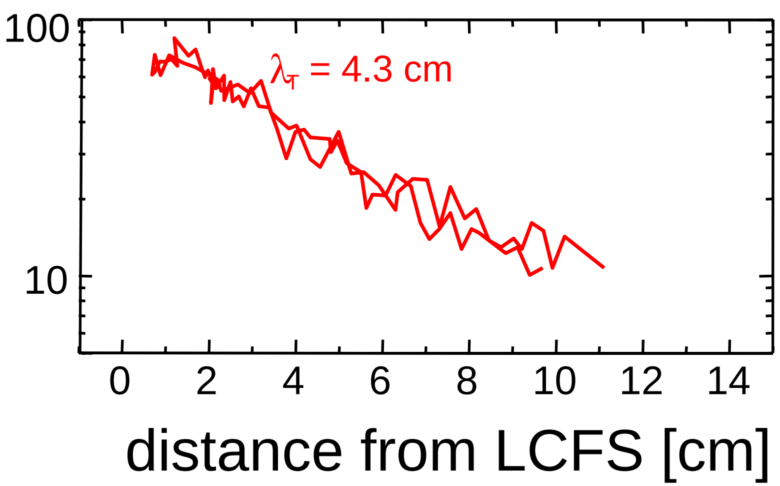
Particle flux = 10^{22} part./m^2
Heat flux = 3 to 5 MW/m^2

reciprocating probe measurements

density:
n(LCFS) ~ 4 10^{18} m^{-3}
λ_n ~ 4.6 cm

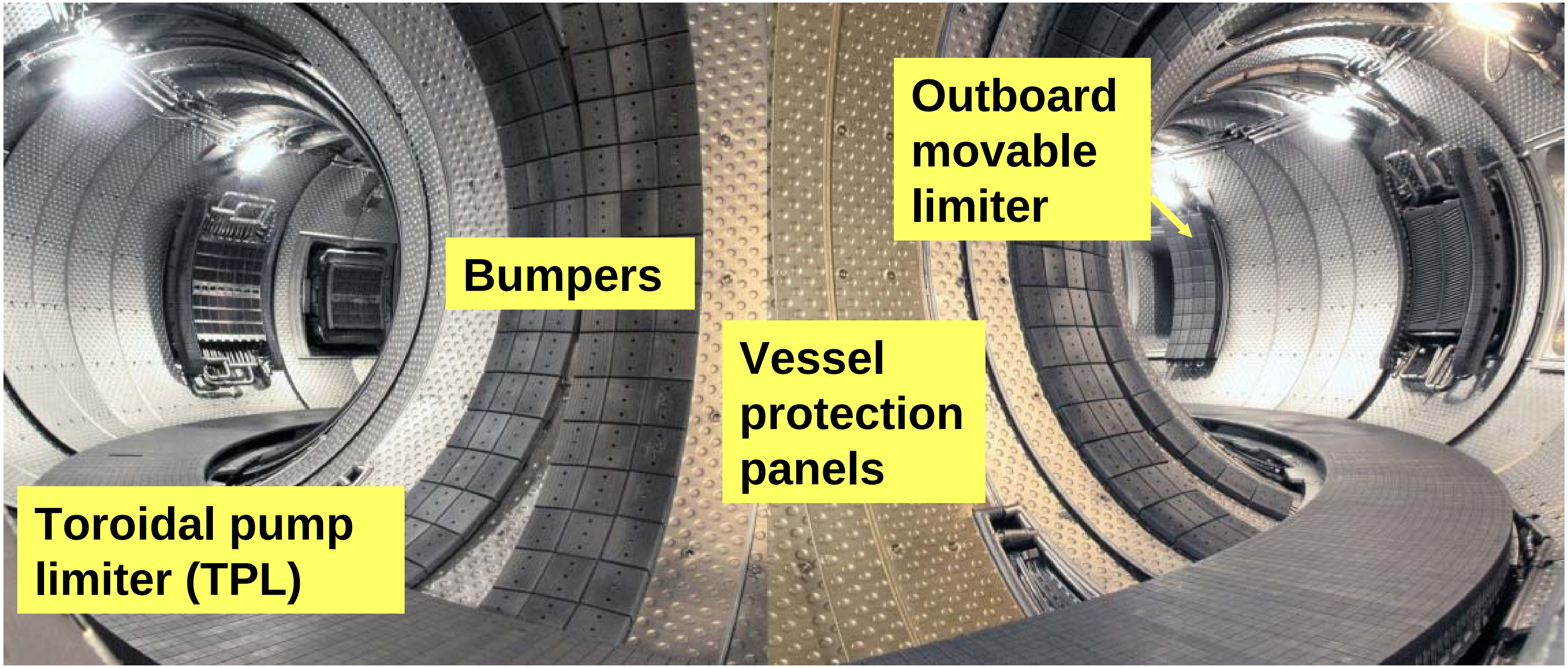
temperature:
T(LCFS) ~ 70 eV
λ_T ~ 4.3 cm





high energy of incident ions on the neutralizers ~ 100 eV

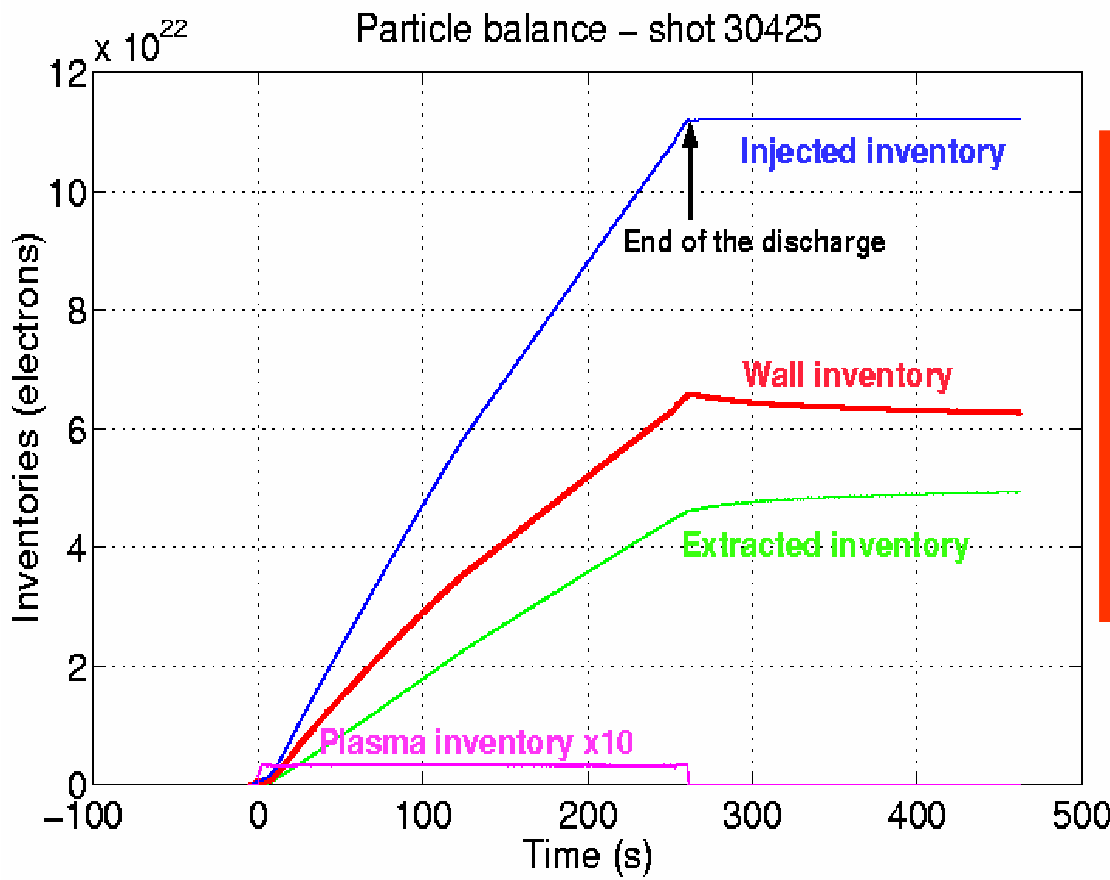
Tore Supra : the CIEL configuration



- Total CFC : 15 m^2 ; TPL : 7 m^2 ; in strong interaction with plasma : 3.5 m^2
- Active cooling (cooling loop at 120-230°C) : steady state PFCs temperature
- Active pumping (10 pumps located below the TPL)
- Fuelling by Gas Puff, Supersonic Pulsed Gas Injection and Pellets

Single discharge particle balance

$$\text{Nwall} = \int \Phi\text{inj}\, dt - \int \Phi\text{pump}\, dt - \text{Np}$$



- Pumped inventory :

40 –50 % of injected particles

- **Wall inventory :**

50-60 % of injected particles

(120 Pam³)

- **Dynamic retention rate :**

•2 10^{20} D/s or 0.8 mg D s^{-1}

- Similar results for JET (16 s) gas puff x 50

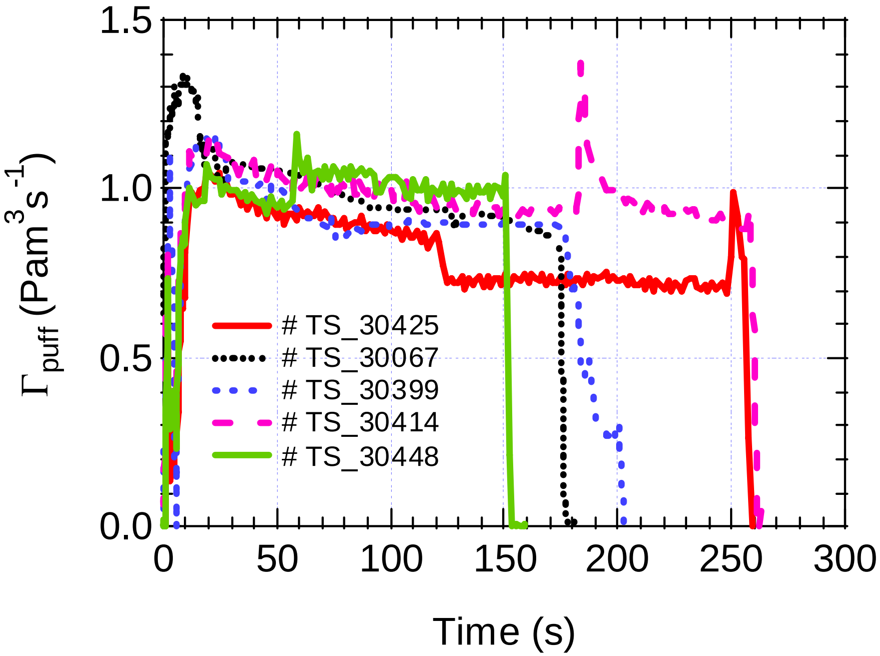
⇒retention rate x 50

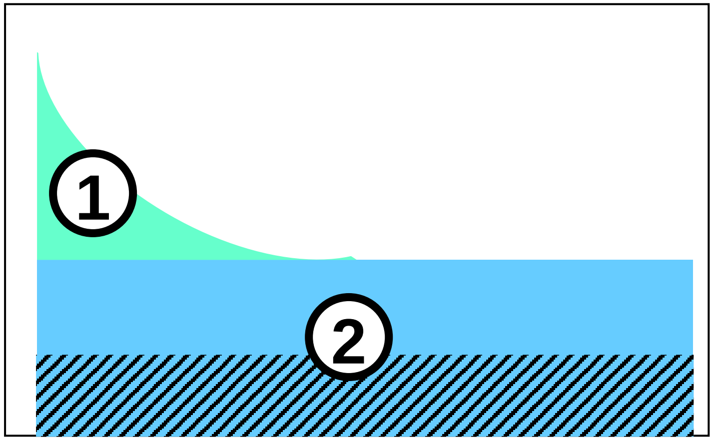
(T.Loarer, 30th EPS)

Characteristics of gas injection

Depends only on plasma density and injected power

Does not depend on the state of the wall

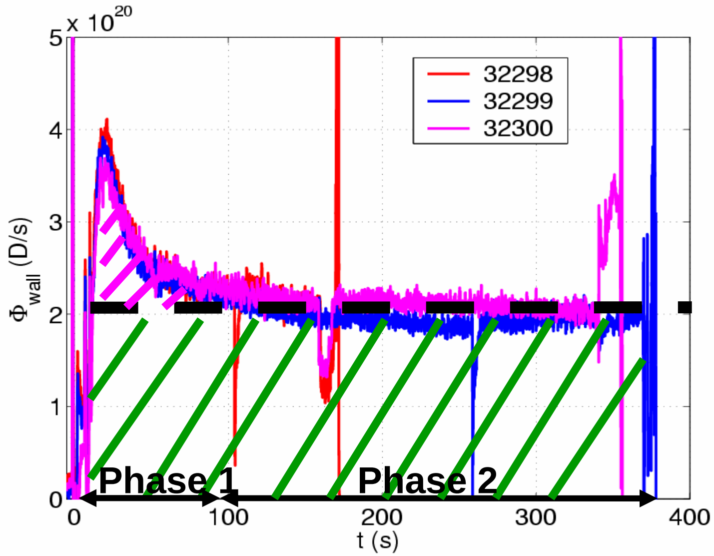


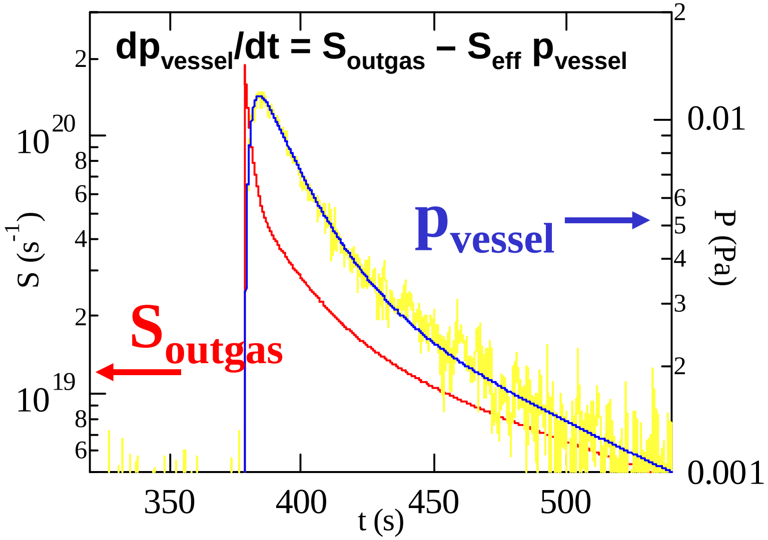


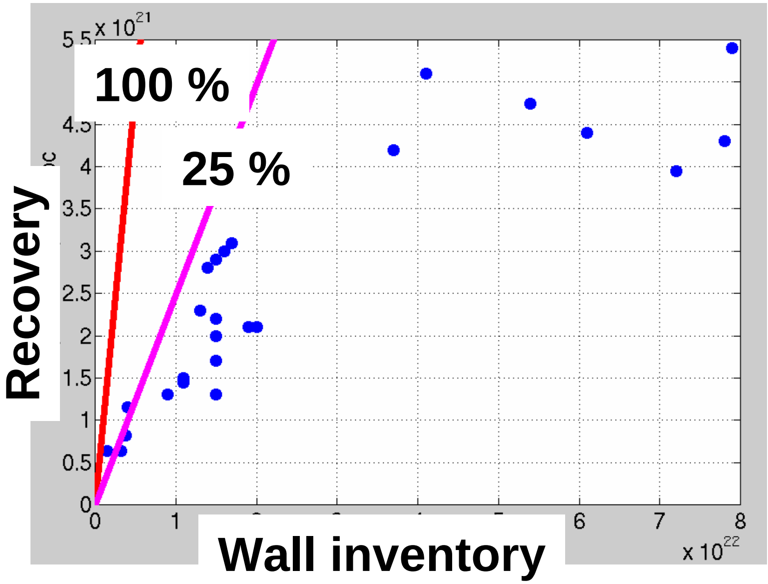
Depends on recycling flux (magnitude, …time-constant)

Does not saturate
Co-deposition (??)

Transcient D retention (1 discharge)

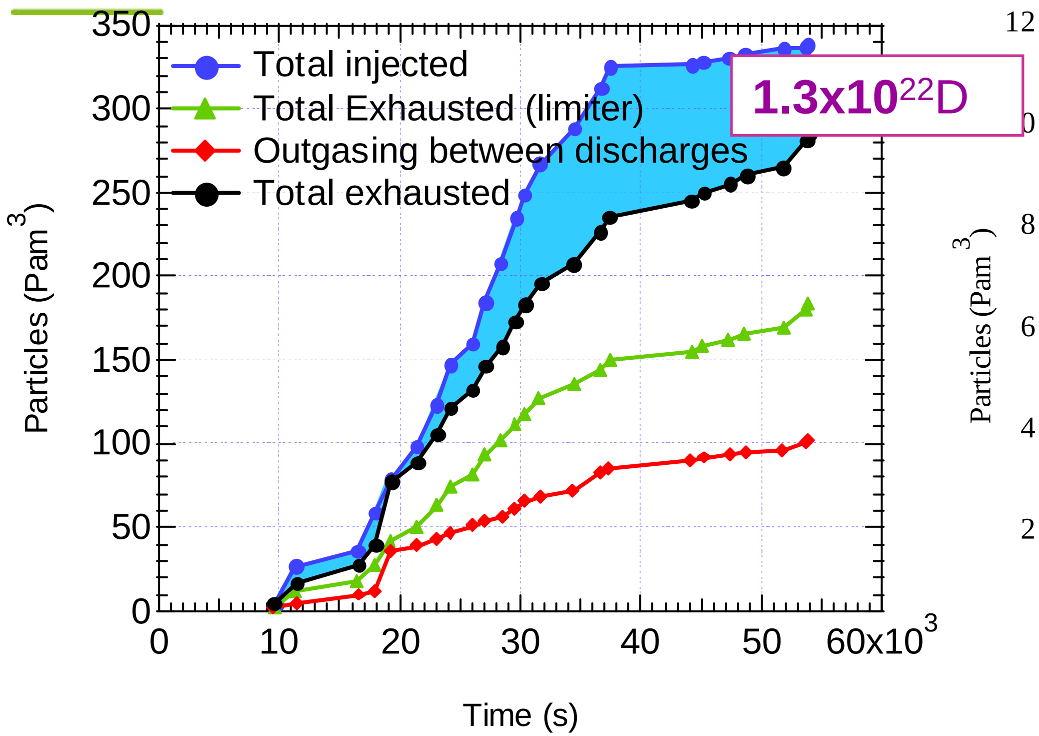


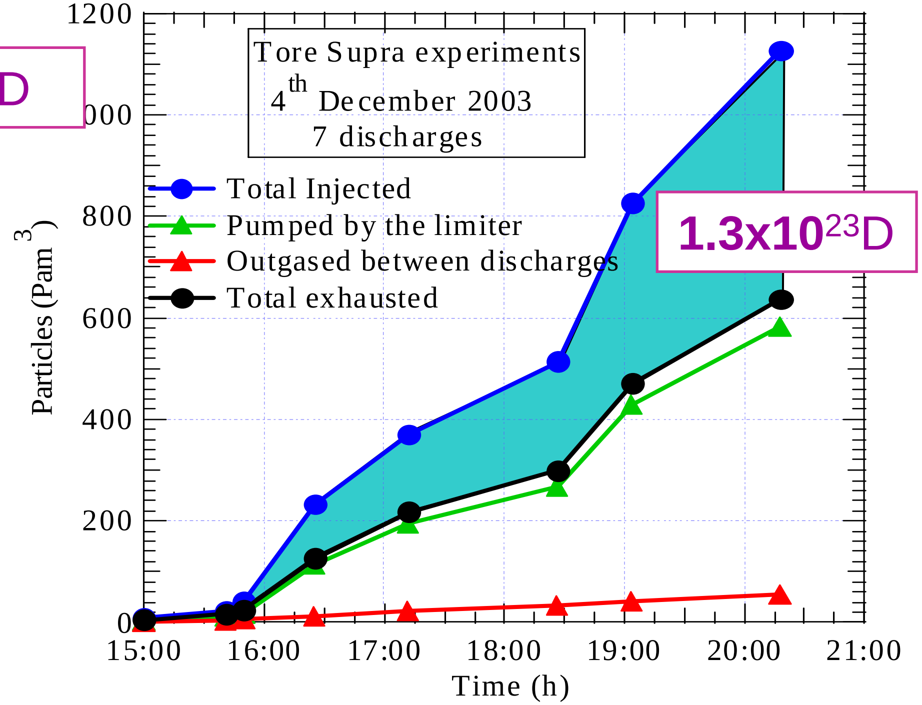




Transient D retention
(post discharge outgassing)
=
overshoot phase 1

D retention during a full day





18 x 20 s ~ 400 s of plasma

7 x 200 s ~ 1400 s of plasma

6h of He glows : 1.5-2x10^{22} D recovered

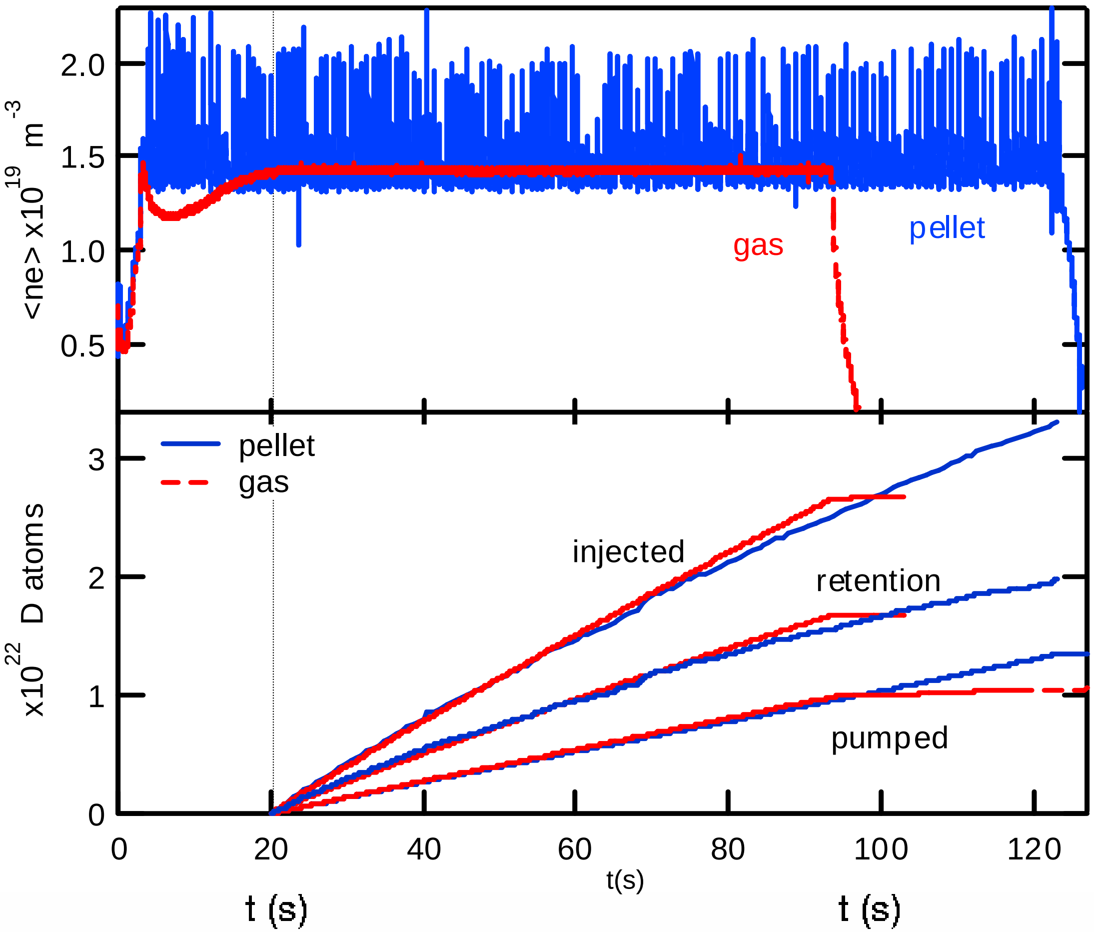
Short pulses:

Particle balance closed with He glows

Long pulses:

Need to find particle recovery means

How to change D retention ?



D retention independent on

- **the recycling flux**
- **the pumping capacity**
- **the fuelling method (or weak)**
- **the edge temperature**
- **the chemistry (scavenger N2)**
- **the temperature of PFCs**

It seems to be an intrinsic characteristics of the wall

D retention = $2x10^{20}$ /s ~ independent on plasma conditions

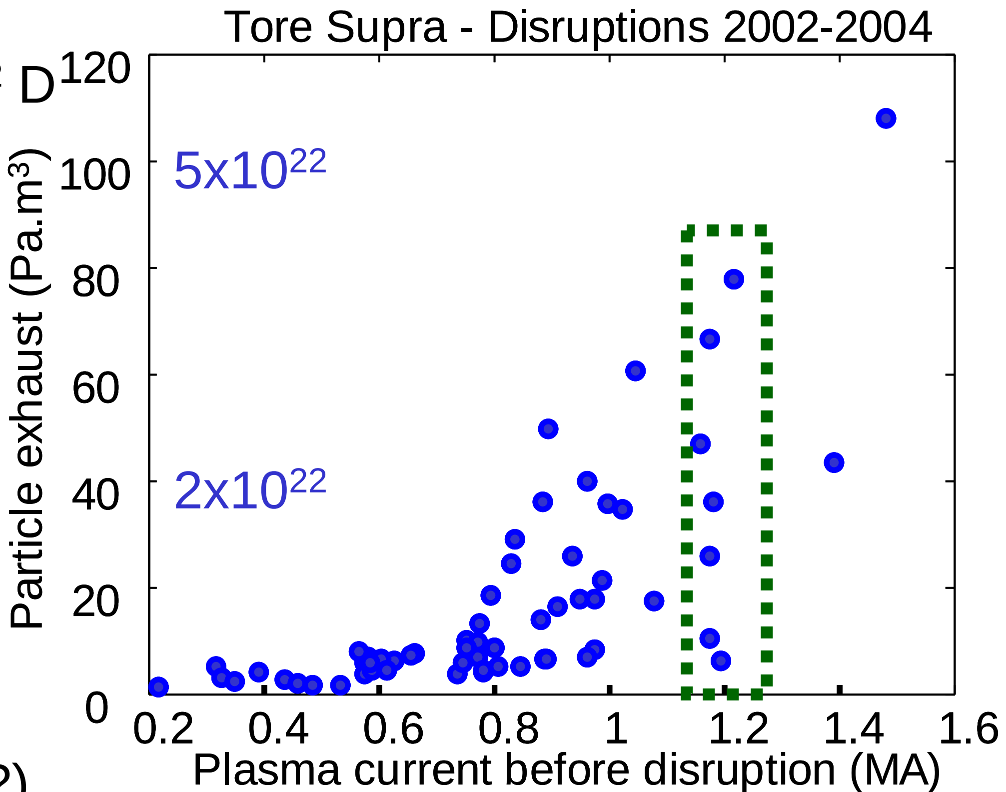
What about recovery means ?

Euratom

6 hours of **He glows** : 1.5 – 2x10^{22} D
~ independent on what was trapped

Taylor discharges : ~ He glows

disruptions : up to 5x10^{22}



but : Ip > 0.8 MA

variable efficiency
(depend on the wall history ?)

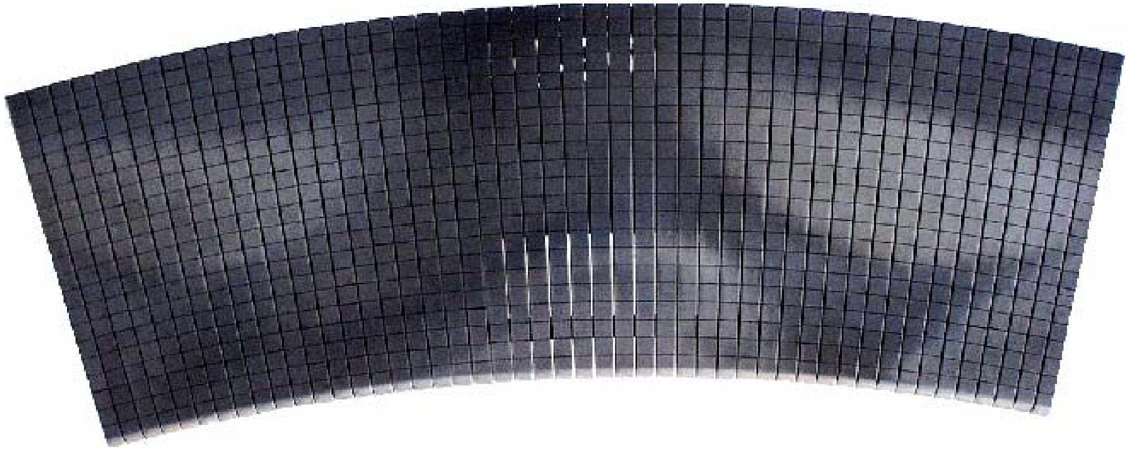
what D content in the gas ?

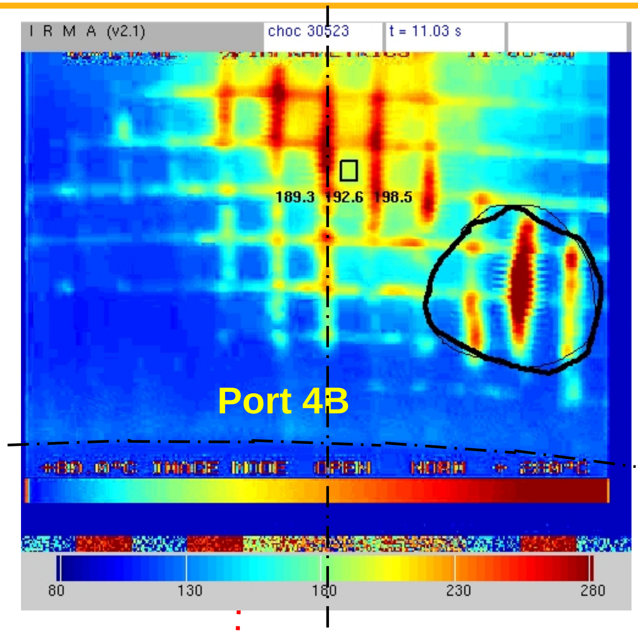
Total permanent retention for a campaign:

2x10^{20} $\times\Sigma_{shots}$ (duration)-$\Sigma_{recovery}$(outgassing, glows, disruptions) = 4x10^{23} D

Carbon deposits (1)

LPT surface

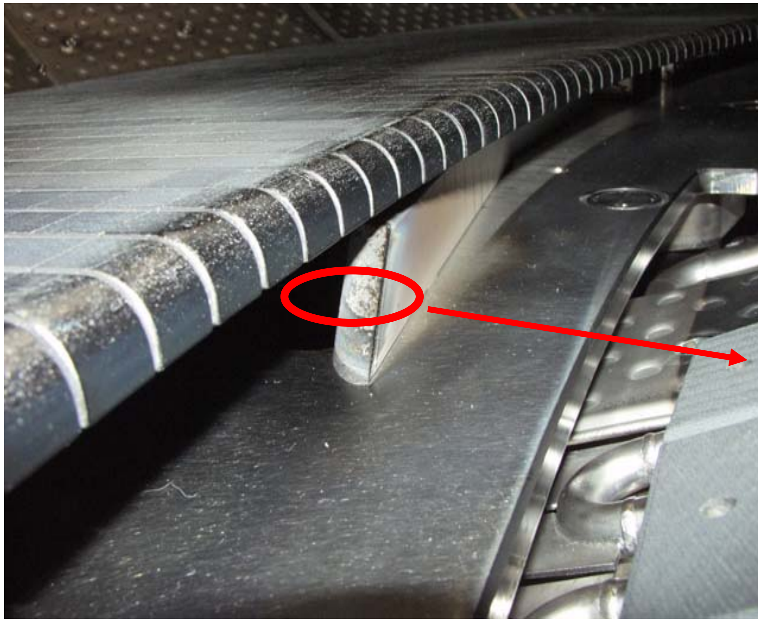


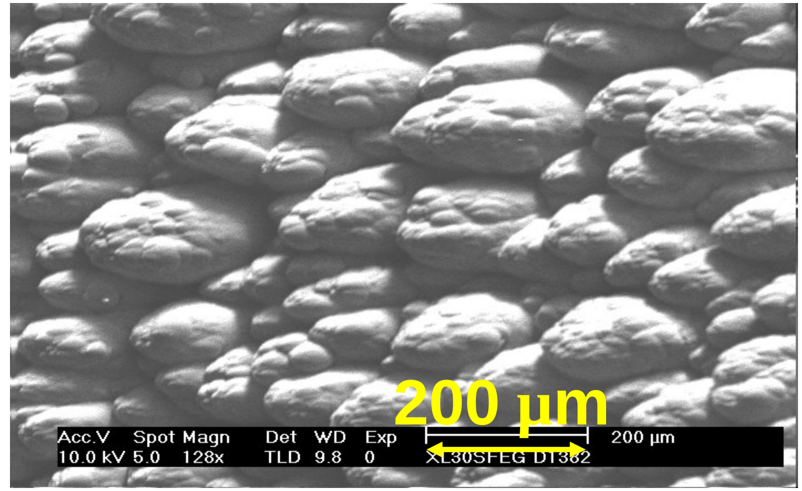


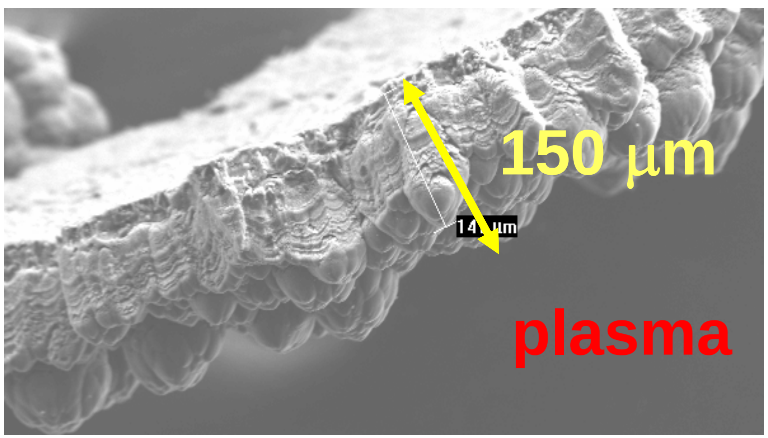
Complex pattern of deposition : films, flakes, dust

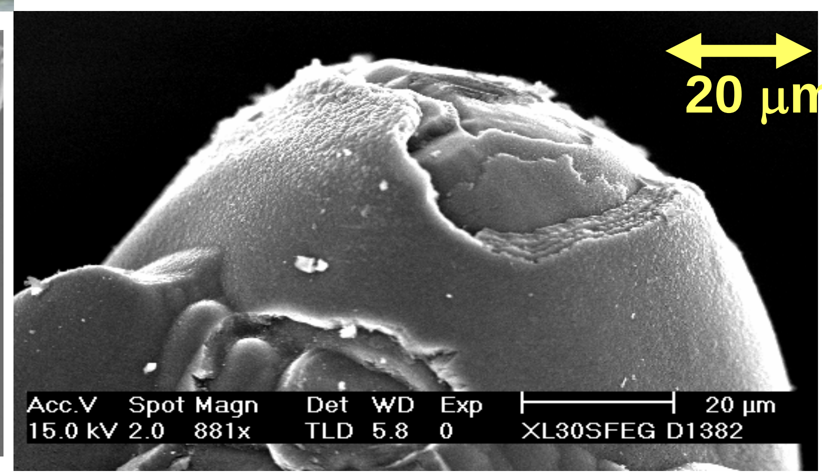
Carbon deposits (2)

neutralizers (after ~8500 s of plasma)



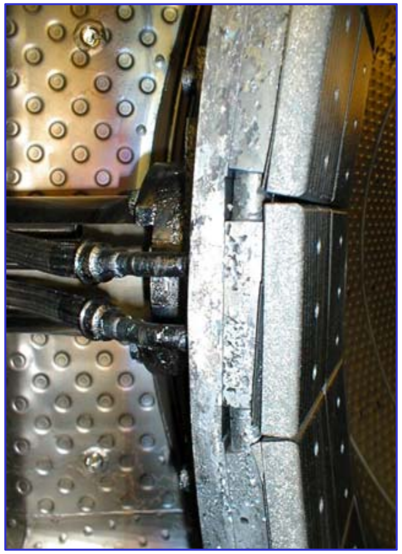


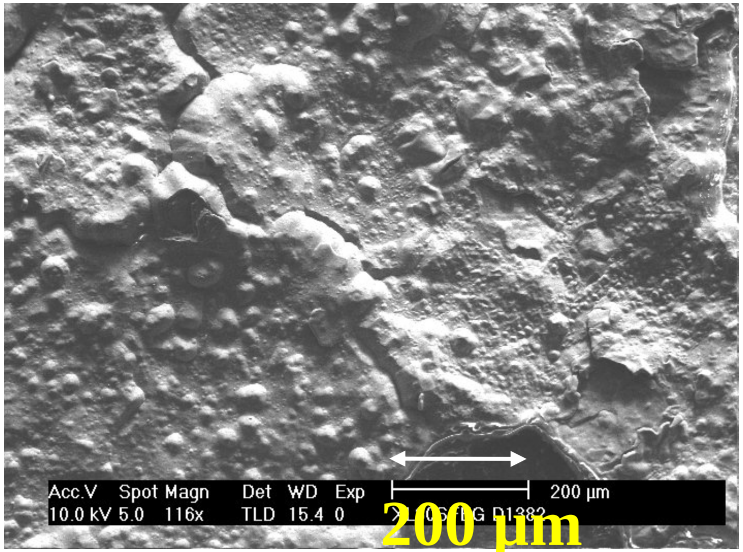




Carbon deposits (3)

Outboard limiter





films and flakes, mainly on the ion side (~100µm thick)

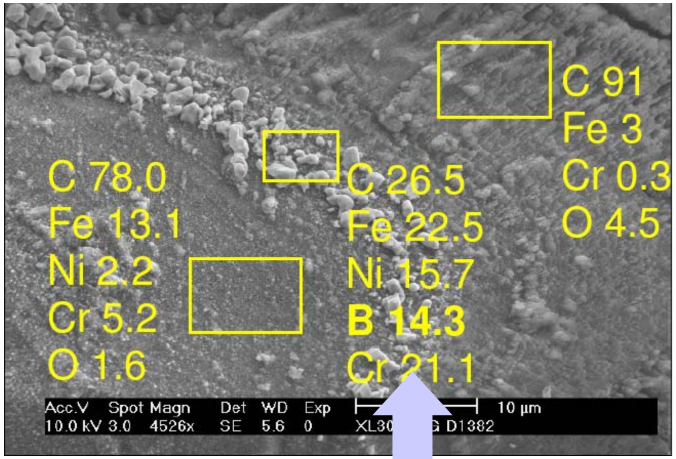
RF antennae : some films and flakes on a LH launcher

Bumpers and Vessel protection panels: .....under the tiles

Growth rate of the deposits

Euratom

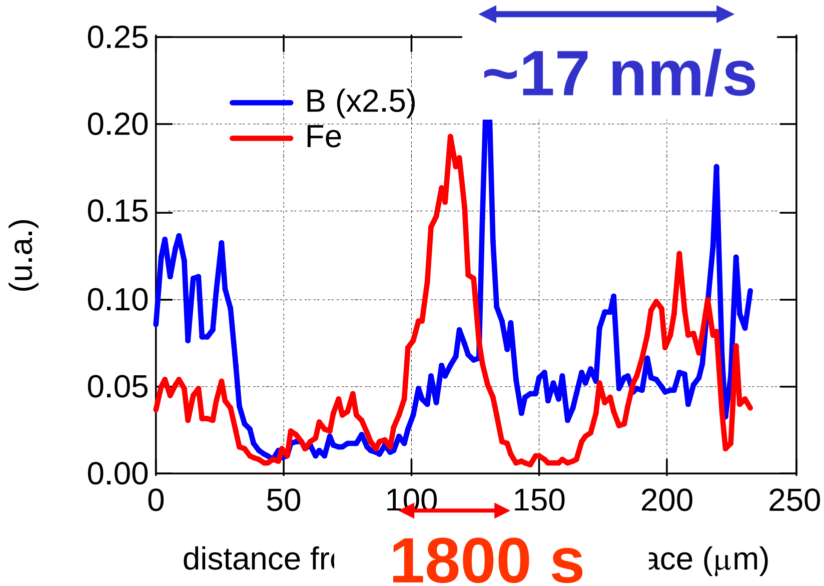
X-ray EDS



Boron-rich sub-layer

ToF-SIMS

4600 s



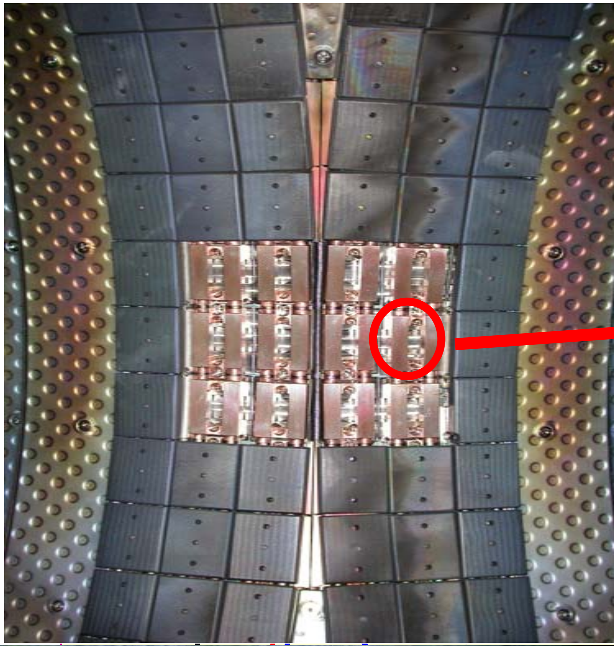
1800 s

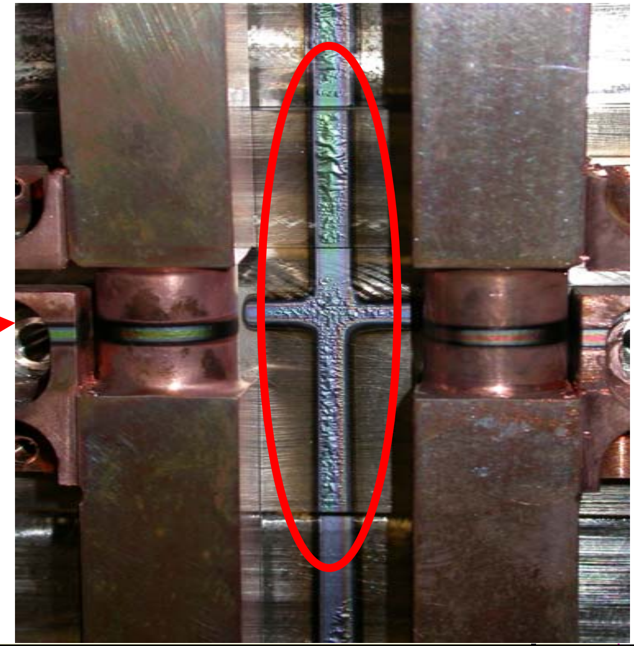
~25 nm/s

Maximum growth rate ~ 20 nm/s, within a factor of 2

[D]/[C] ; D content : NRA results

Euratom





Deposits and flakes also found under the tiles of the bumpers and in the volumes under the TPL.
Not yet collected nor analysed.
Work underway.

LPT:

0^{22} D

Deuterium retention – global balance

Last experimental campaign ~ 20 000 s of plasma

Total C source (from C/D lines ratio and probe measurements)
~ 8×10^{24} atoms (i.e. 160 g), Y ~ 1.7 %

Total D retention
(retention rate ~ 2x10^{20} D/s, i.e. ~ 0.1 % of the recycling flux
….and almost independent on edge conditions)
2x10^{20}×Σ_{shots} (duration)-$\Sigma_{recovery}$(outgassing, glows, disruptions)
~ 4x10^{23} D (~ 90 % recovered due to short pulses)

Deposits ~ 20 g (D/C ~ 1÷10 %) and debris ~ 20 g (D/C not yet analysed)
C close redeposition ~ 75 % ; D content ~ 5×10^{22}

3.5x10^{23} D are yet missing (but huge error bars !)
Two possible mechanisms: deposits / flakes under TPL (but D/C=0.35 !)
diffusion in porous CFC ?? (D/C ~ 3÷14x10^{-6})

What about other devices ? ITER ?

Other devices (JET, AUG, TEXTOR, JT60, DIII-D)
less retention (3-10 %)
but short pulses (about 30-50 s, and non actively cooled PFCs)
(T PFC increases up about 1000 C during plasmas)

ITER or future reactor
pulse length = few 1000 s, actively cooled PFCs
for safety, T-inventory < 350g ($1.4X10^{26}$ atoms for D/T retention)
depending on extrapolation,

T-retention exceeds limit after few 10^3 to 10^4 s !!!

(of the order of an experimental campaign…)

If retention due to co-deposition (dust & flakes)
possible use of carbon, but developments for T recovery
deposits removal

If retention due to deep diffusion in CFC
probably requires to change PFC material (tungsten)
development required in plasma operation (better edge control)

Summary / Conclusion

Short pulses, high PFC temperature:
closed particle balance, no significant retention

Long pulses, low (constant) PFC temperature:
the wall appears as an infinite reservoir

In Tore Supra, the particle balance is not closed by a factor 20 to 30 (in 2 years , almost 1 mole of D in the vessel)
…. but difficult to be accurate, huge error bars…

Carbon erosion / re-deposition (line emission / observed deposits) in global agreement with present knowledge

Need of another retention mechanism ? Deep diffusion in CFC ?

Simple extrapolation yields unacceptable limitation of ITER operation developments are required: better understanding of D / Tretention
recovery means, deposits removal
with W-PFCs, optimized operation