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TORE SUPRA

Plasma wall interactions in ITER and the deuterium tritium inventory problem

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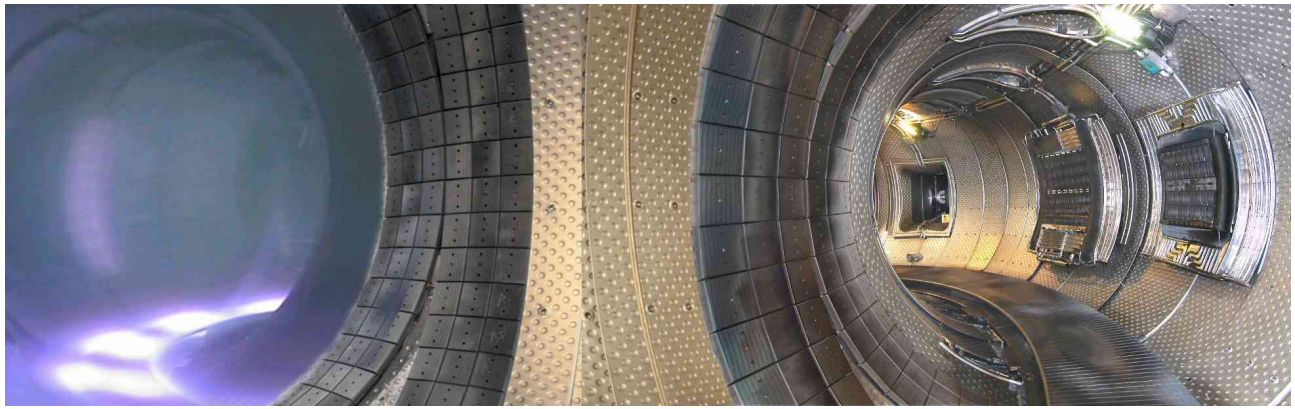
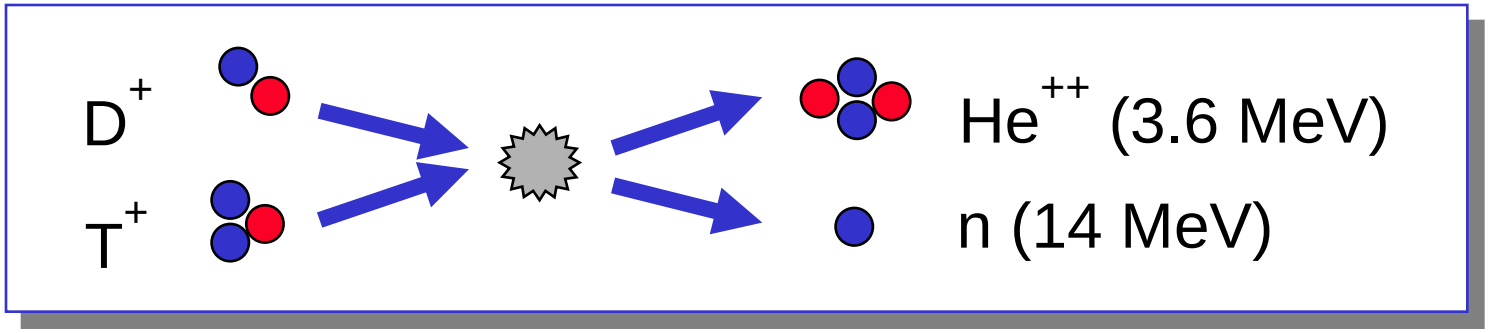
CEA (IRFM, DEN, LPS), University of Provence (PIIM), IPP Garching (EU PWI TF)



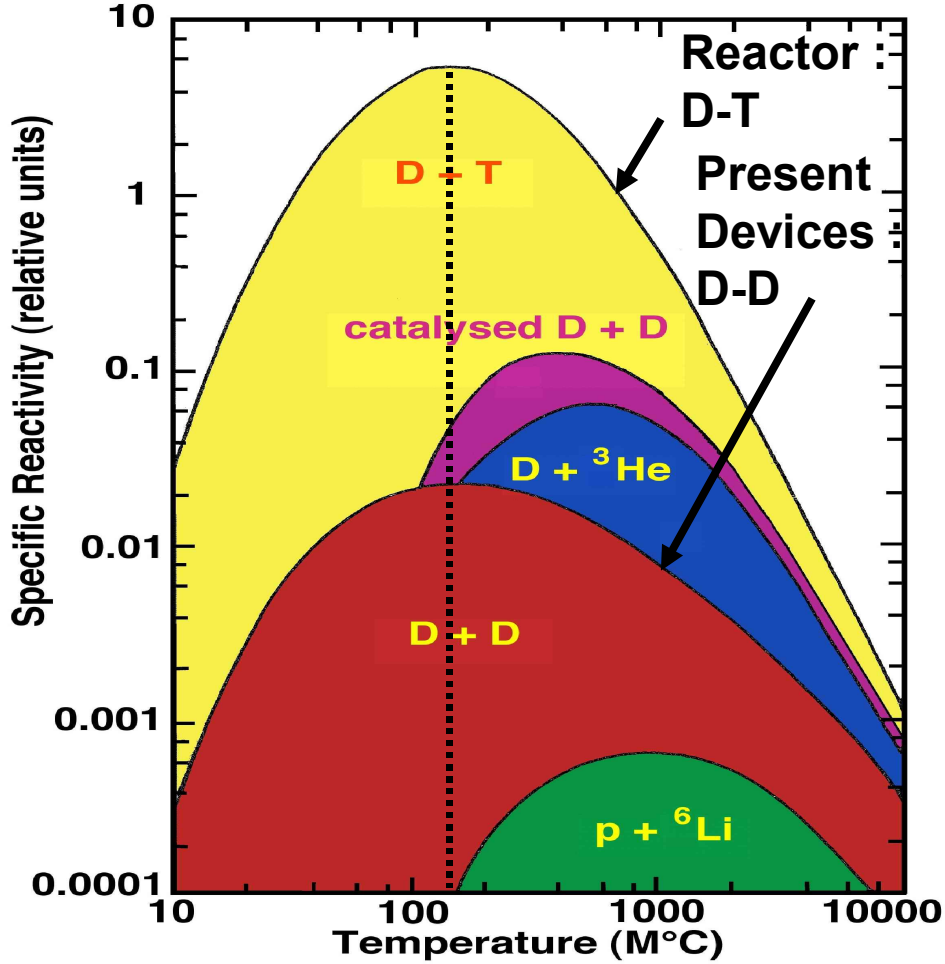
Introduction to fusion and plasma wall interactions in ITER

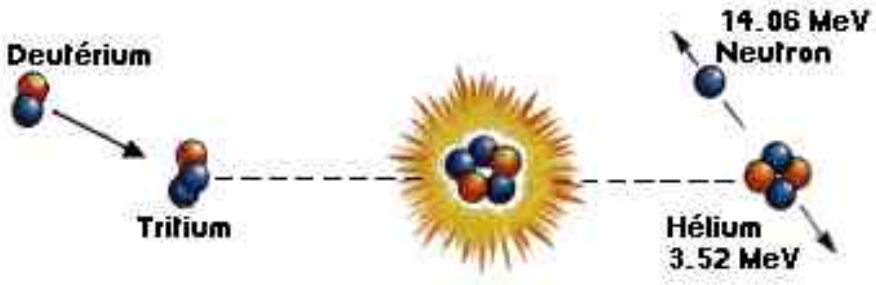
Fusion



Need to control plasma content, He content, fuel recycling

Fusion on earth

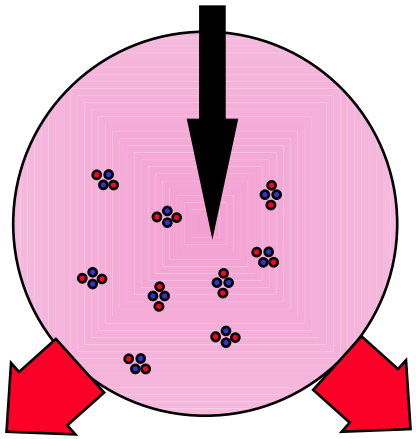




T ~ 20 keV ➔ plasma

Energy balance

- $P_{fus} = P_{neut} + P_{alpha} \approx 5\ P_{alpha}$
- $dW_P/dt = P_{inj} + P_{alpha} - P_{losses} = 0$
- $Q = P_{fus} / P_{inj}$

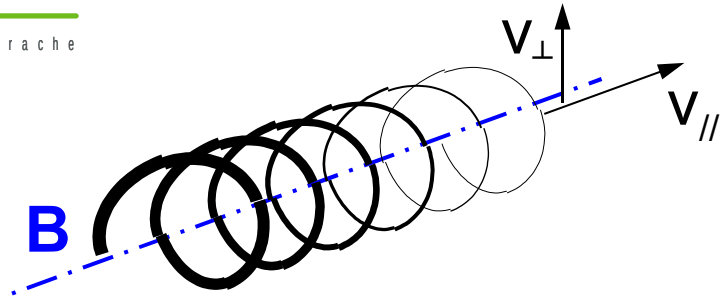


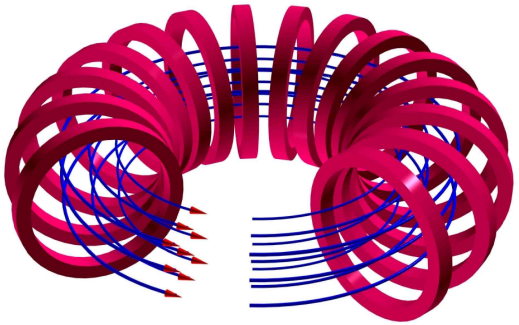
- Break-even: $Q = 1$ $P_{fus} \geq P_{inj}$
- Ignition: $Q = \infty$ $P_{alpha} \geq P_{losses}$

$P_{inj} = 0$

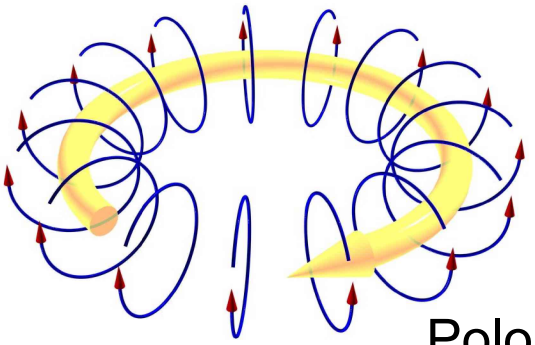
- ITER Goal $Q = 10$ $P_{alpha} \geq P_{inj}$

Fusion on earth : the magnetic trap



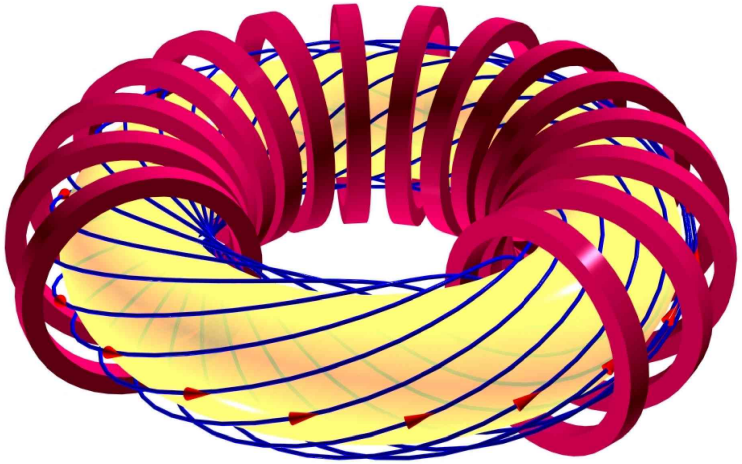


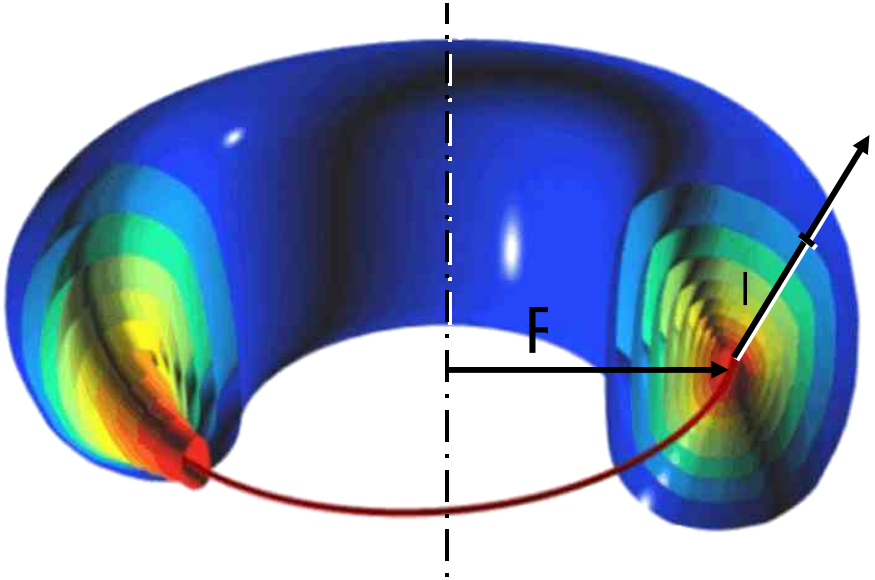
Toroidal field



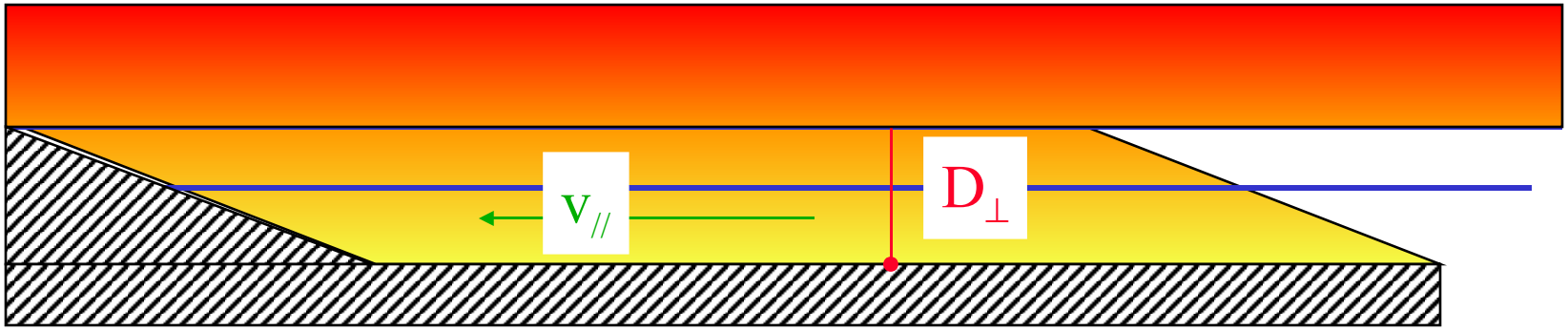
Poloidal field

Total field





Plasma edge : a very thin scrape off layer



- SOL : Scrape off layer

Open field lines : transport ⊥ and transport // at equilibrium

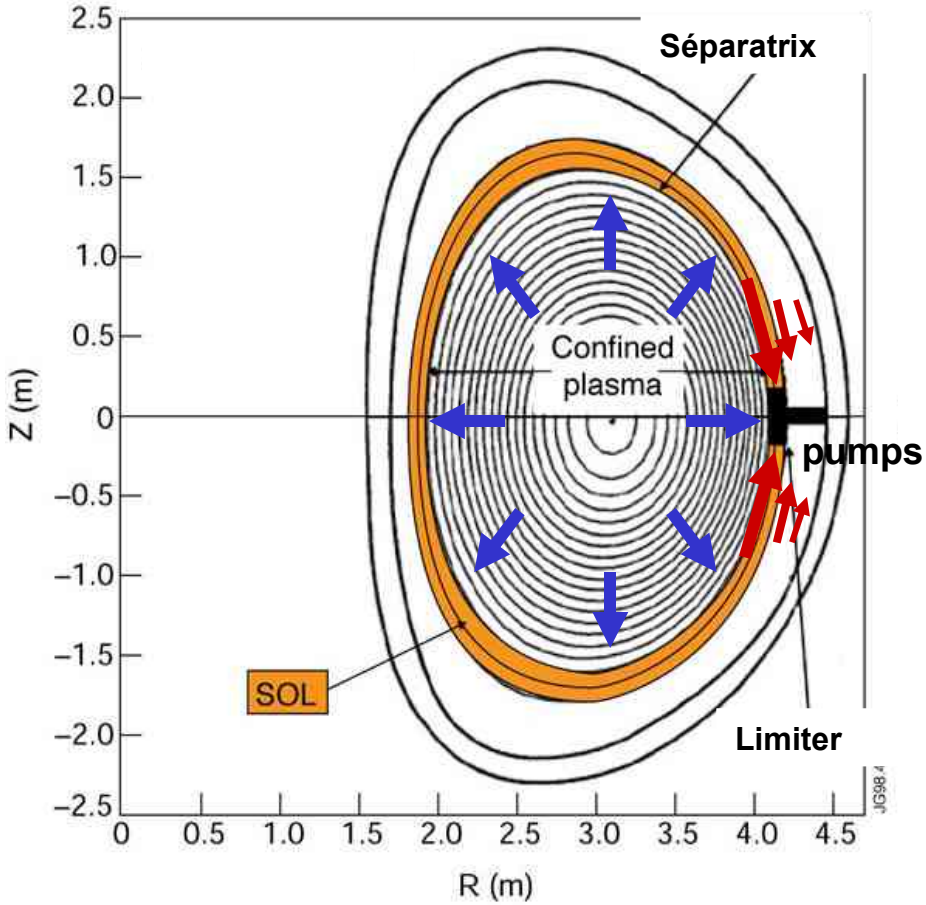
Lifetime // : $\tau_{//} \sim L / v_{th} \sim 1$ ms for ions (100 eV)

Radial diffusion : $\lambda^2 \sim D_\perp \tau_{//}$; $\lambda \sim 30$ mm $\sim 100\ \rho_i$

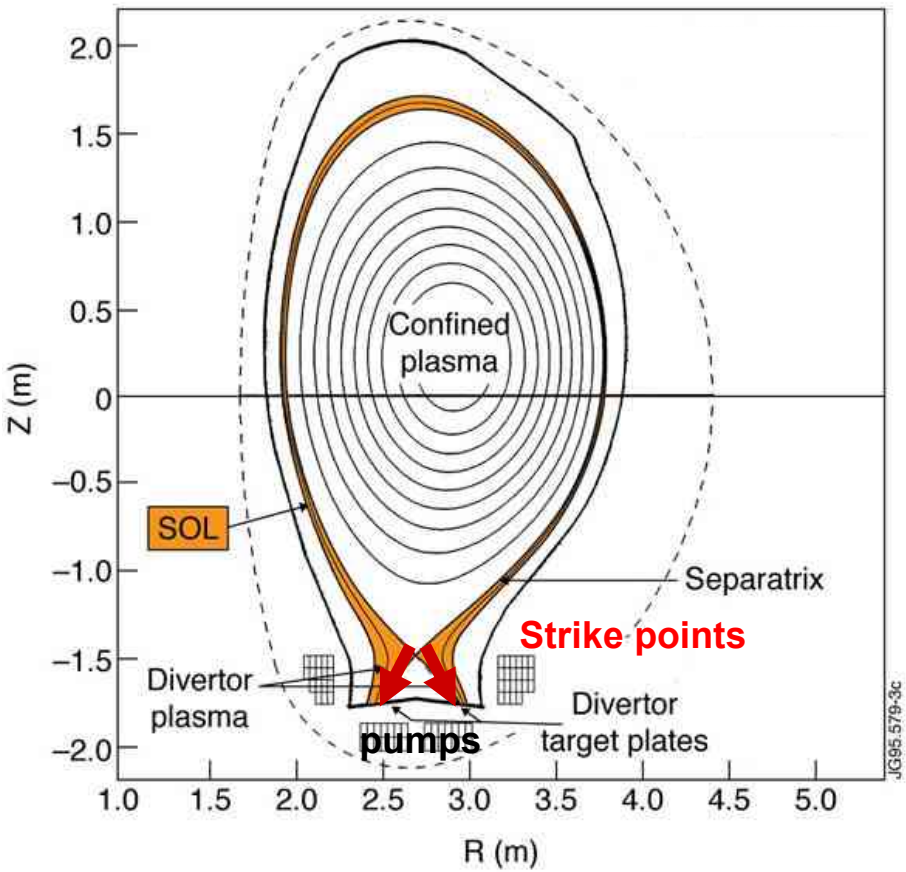
Parallel heat fluxes up to 1GW/m²!!!

Glancing incidences needed : technology

Plasma facing components (PFCs) : Limiter and divertor



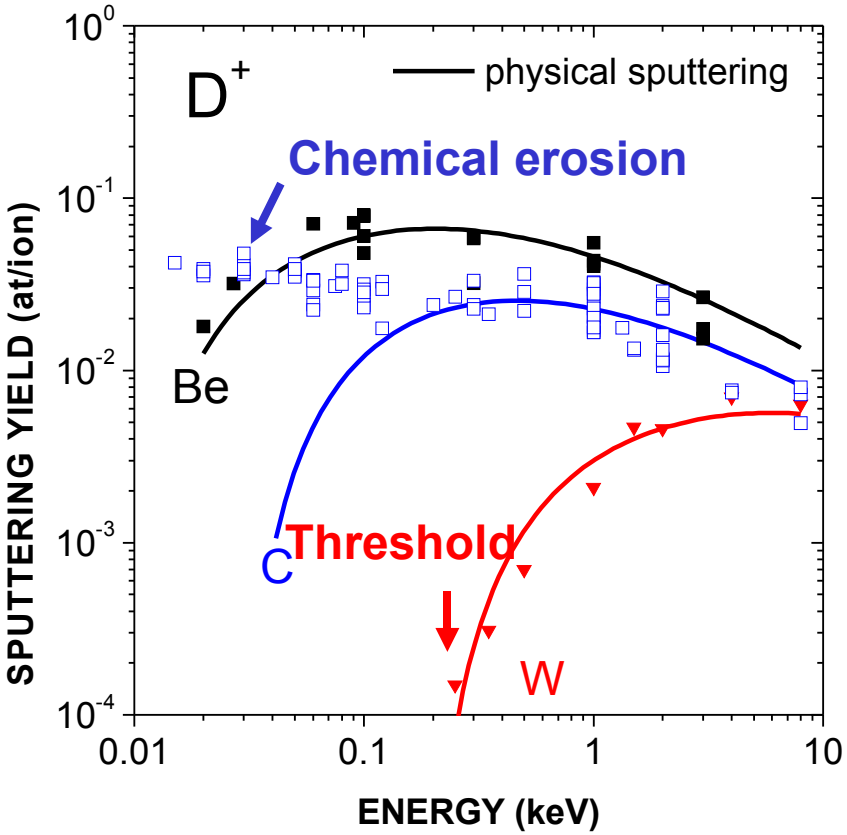
LIMITER



DIVERTOR ➔ H mode (ELMs)

What is the ideal plasma facing material ?

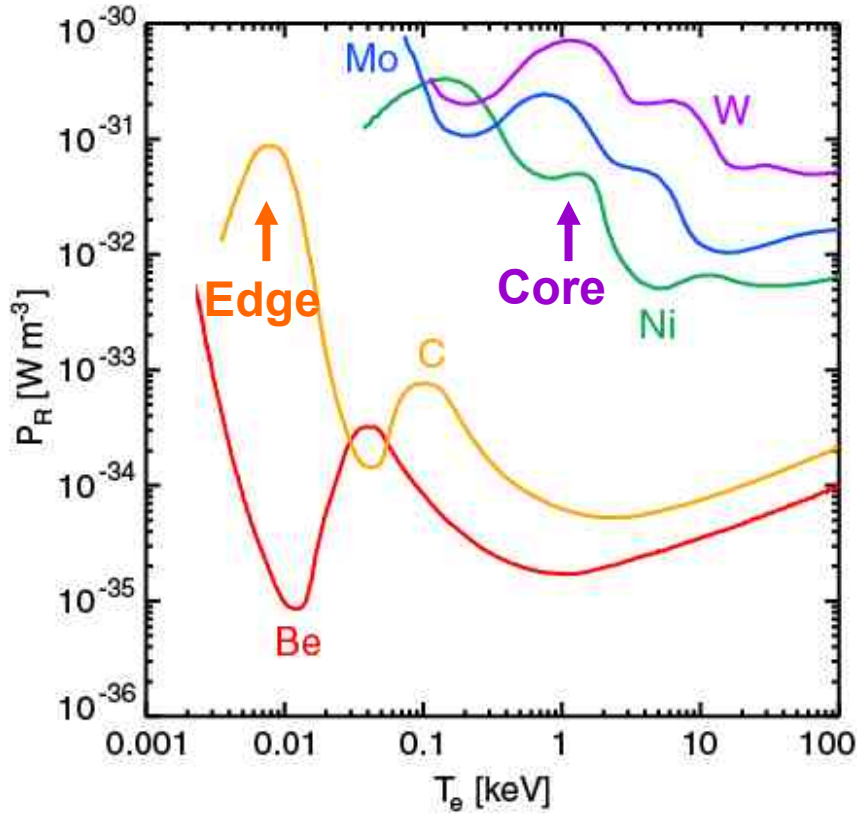
Low Z materials (carbone, beryllium) :
erosion / pollution / fuel retention



Impurity production yield

$n_{imp} = \Phi_{ion}\, Y / \tau_{conf}$

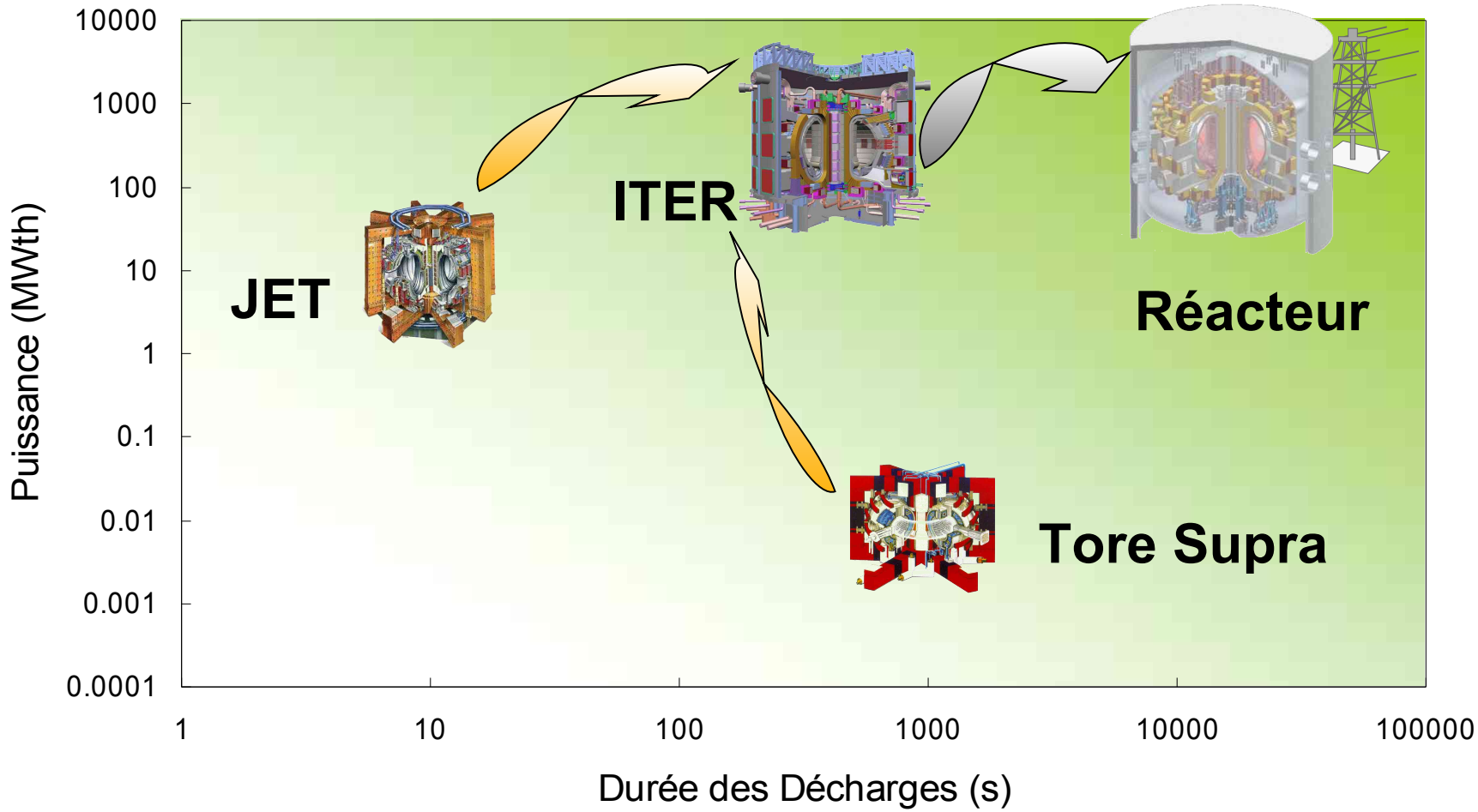
High Z materials (tungsten) :
erosion / pollution / fuel retention



Energy loss by radiation

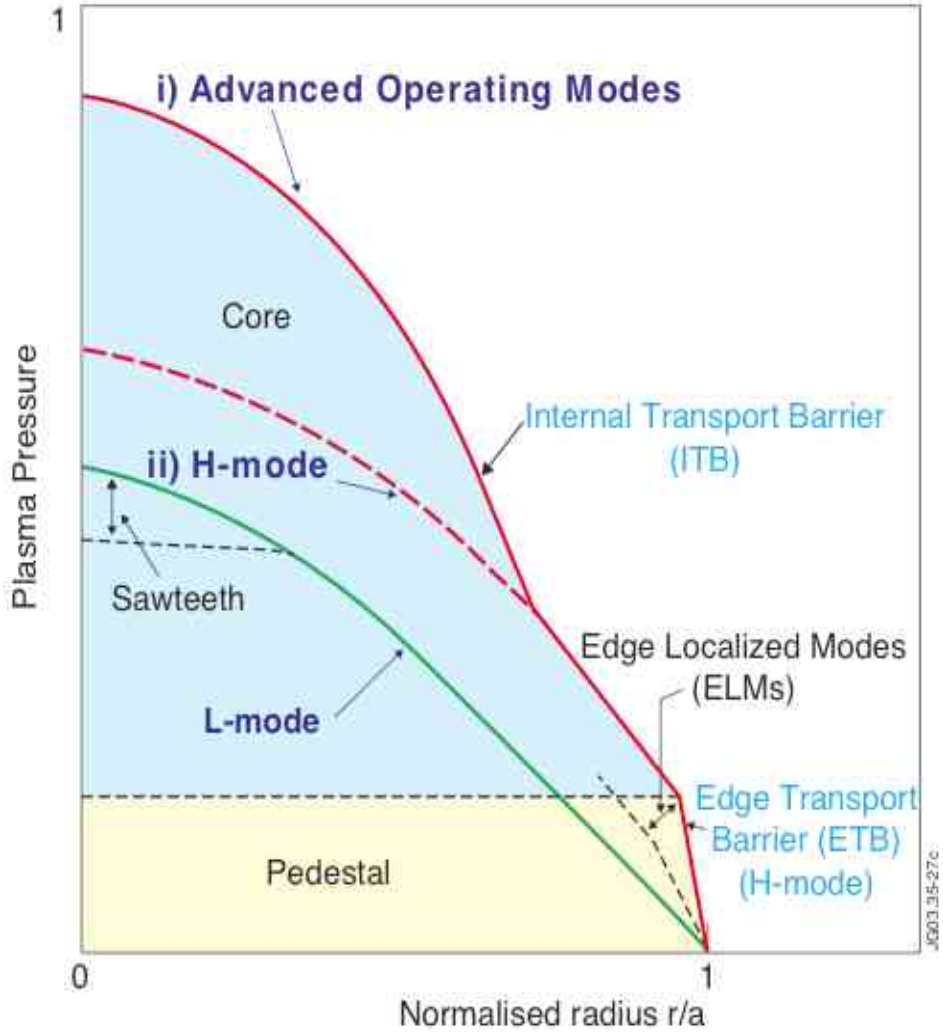
$P_{rad} = n_e\, n_{imp}\, P_R$

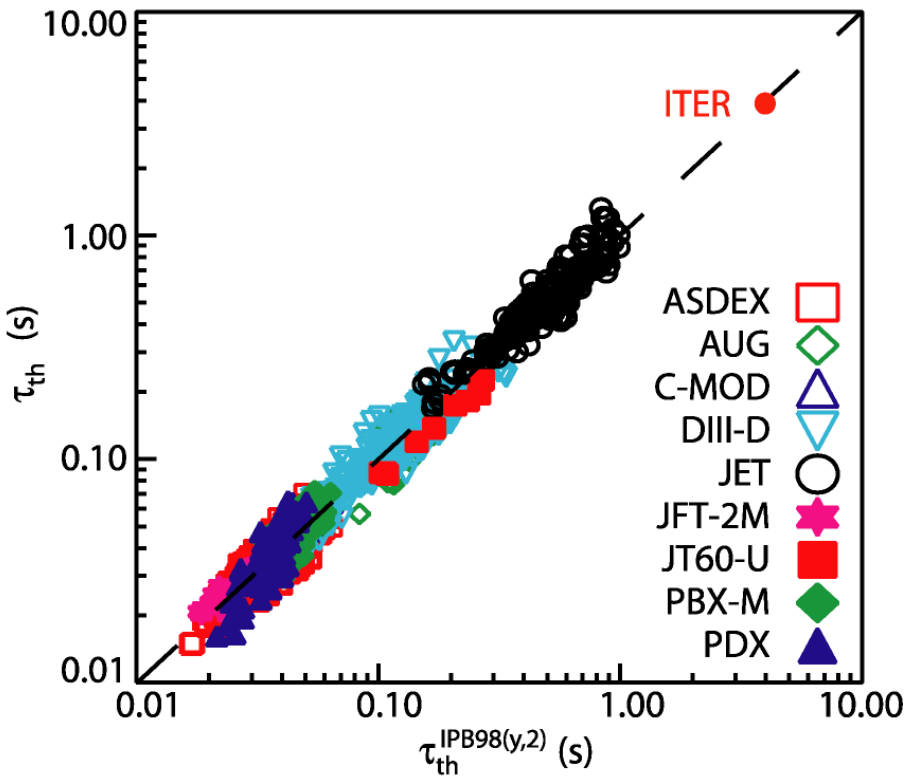
ITER : The WAY towards fusion reactor



Confinement

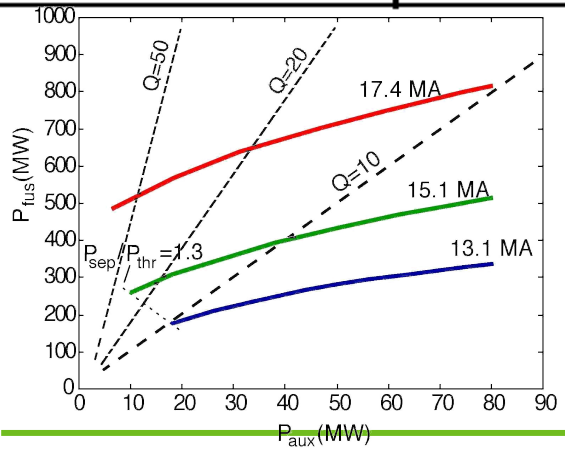
Tokamak transport > collisions ➔ turbulence

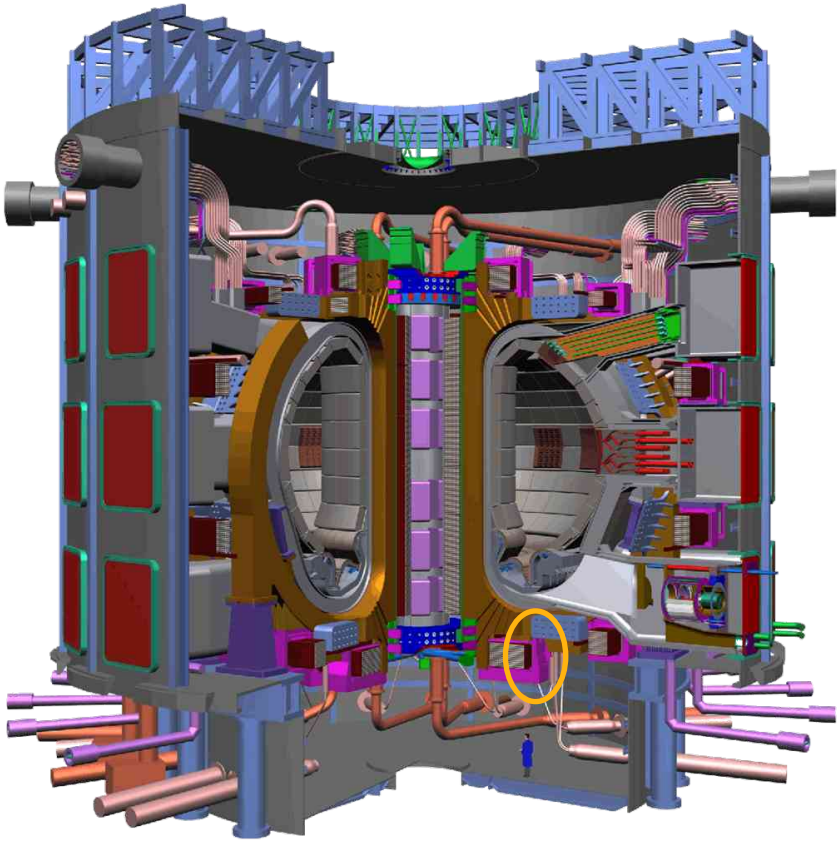




ITER

Paramètre	ITER
Grand rayon (m)	6,2
Petit rayon (m)	2
Élongation verticale	1,7 / 1,85
Volume plasma (m^3)	837
Champ magnétique (T)	5,3
Courant plasma (MA)	15
Puissance fusion (MW)	500
Flux de neutrons (MW/m^2)	0,5
Facteur d'amplification (Q)	10 (ignition possible)

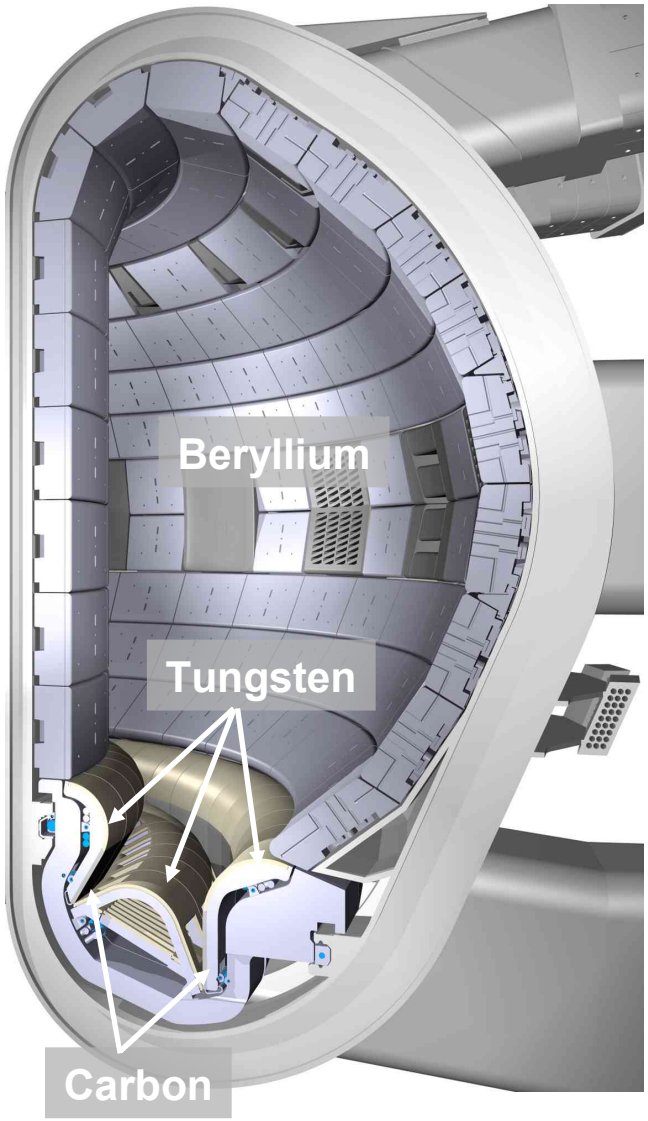




Engineering **Building** **Operation**

1990 2006 2018 2040

Challenges for ITER



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

Main PWI issues for ITER :

- **Plasma Facing Components lifetime :**

steady state ➔ radiation cooling (impurity seeding)

ELMs and disruption ➔ mitigation

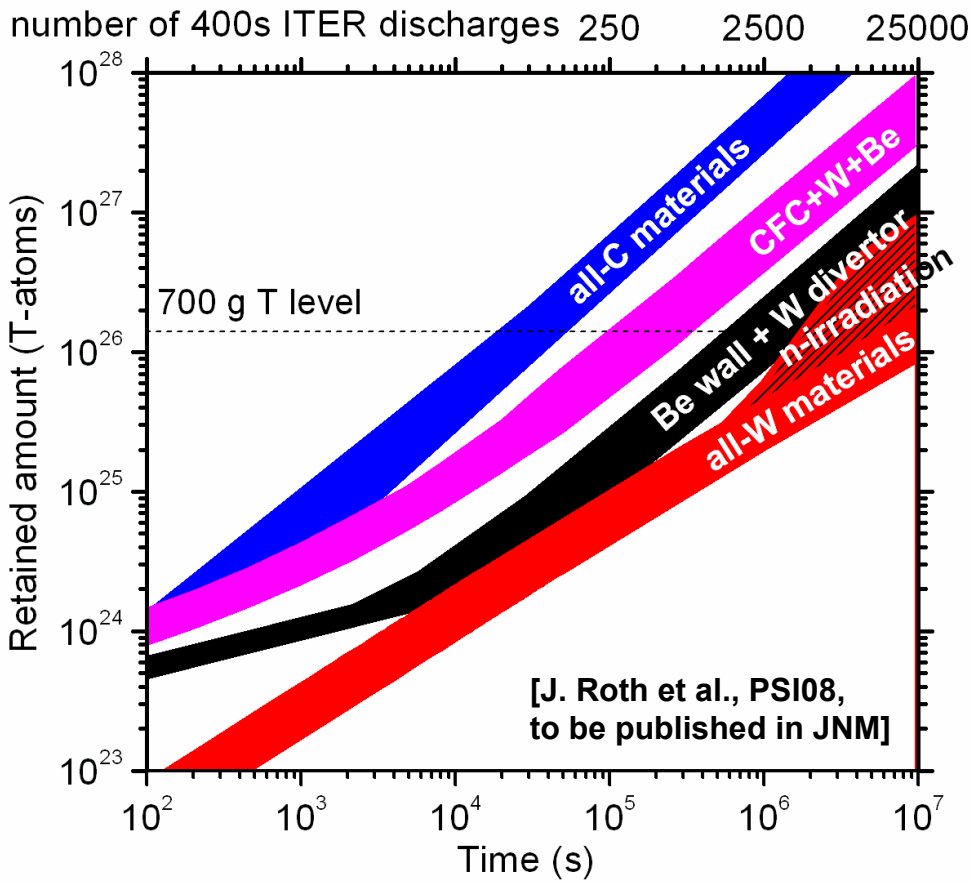
- **Fuel retention (T inventory)**
- **Dust production**

Fuel retention : a major issue for ITER PFCs

- **C/W/Be** : 300-1000 discharges before T limit

Main mechanism :
codeposition of T with eroded carbon

Large uncertainties :
- Wall power and particle fluxes (3D PFCs, gaps)
- Material migration (erosion, transport, redeposition)
- local Tsurf



Tore Supra :

- Actively cooled carbon PFCs with unique long pulse capability :

Fuel retention with relevant pulse duration + steady state PFCs Tsurf

Deuterium inventory in Tore Supra : reconciling particle balance and post mortem analysis

Outline :

- Fuel retention : open questions
  ➔ Deuterium Inventory in Tore Supra (DITS)
- Experimental campaign ➔ particle balance
- Sample extraction
- Post mortem analysis
  ➔ comparison with particle balance
- Summary

Fuel retention

Open questions

Fuel retention : open questions

Retention mechanisms :

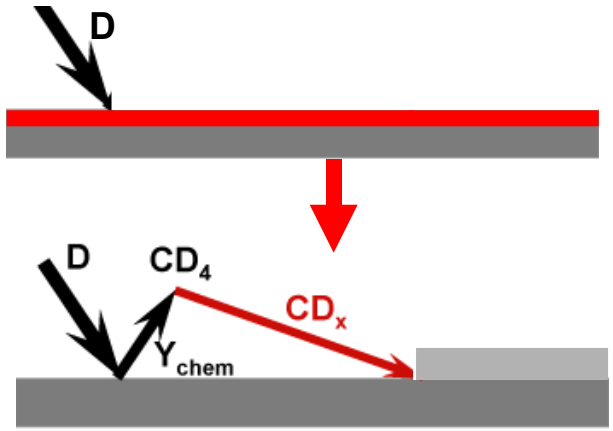
- **Implantation** : until C_{Dmax} reached in d_{imp}

➔ small inventory

- **Codeposition** : C erosion/redeposition

- **Bulk diffusion :** trapping >> d_{imp}

Evidenced in lab experiment for CFC



Codeposition vs bulk diffusion ?

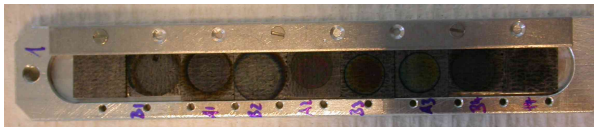
Retention characterisation :

Particle balance (discharge)

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

>>

Post mortem analysis (campaign integrated)



Particle balance vs post mortem ?

Previous studies : factor ~10 [C. Brosset et al., JNM 337-339, 2005]

Deuterium Inventory in Tore Supra (DITS) :

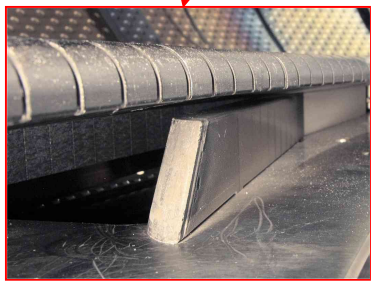
experimental campaign / dismantling of PFCs / analysis phase

The DITS project

Experimental campaign

Inside Tore Supra (2002)

Limiteur pompé



Physics and technology for steady state operation

Everything is actively cooled (same as ITER)

New record: 6 min 18 s, 1.07 GJ

Experimental campaign

Aim ➔ load the vessel walls with D

- Repetitive long pulses (2 minutes) on robust scenario :

Ip = 0.6 MA, ne/n_{GR} ~0.5 , 2 MW LH

- 5 hours of plasma w/o conditionning

(1 year of operation in 2 weeks)

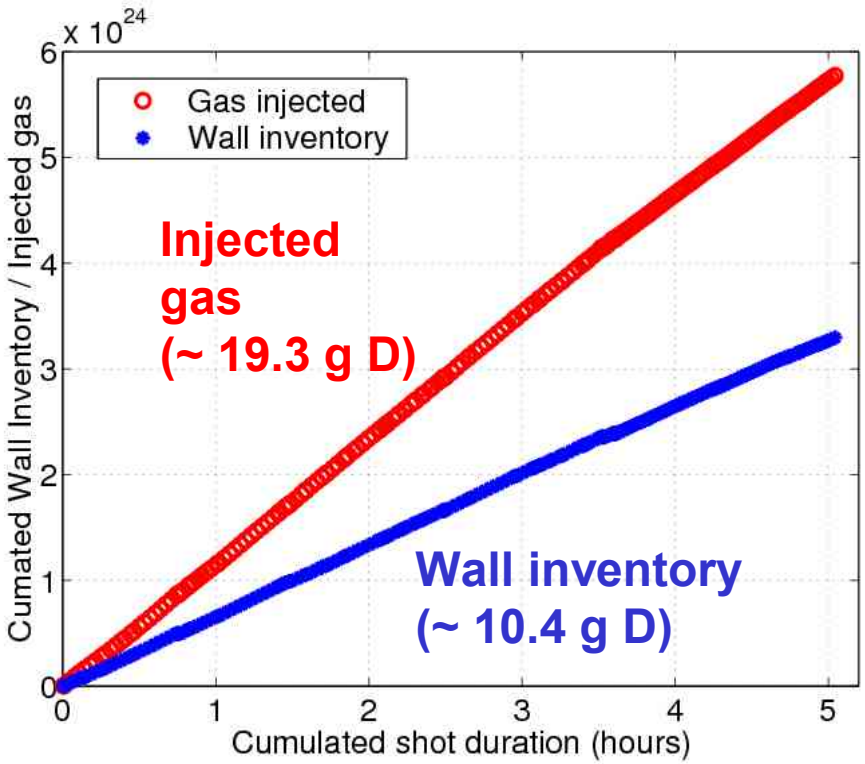
➔ pre-campaign D inventory x 4

[B. Pégourié et al., PSI 2008, to be published in JNM]

Particle balance :

- No wall saturation
- Release after shot ~ 2 minutes
- Long term release ~ 10% of total exhaust

➔ ~ 50 % of injected gas trapped

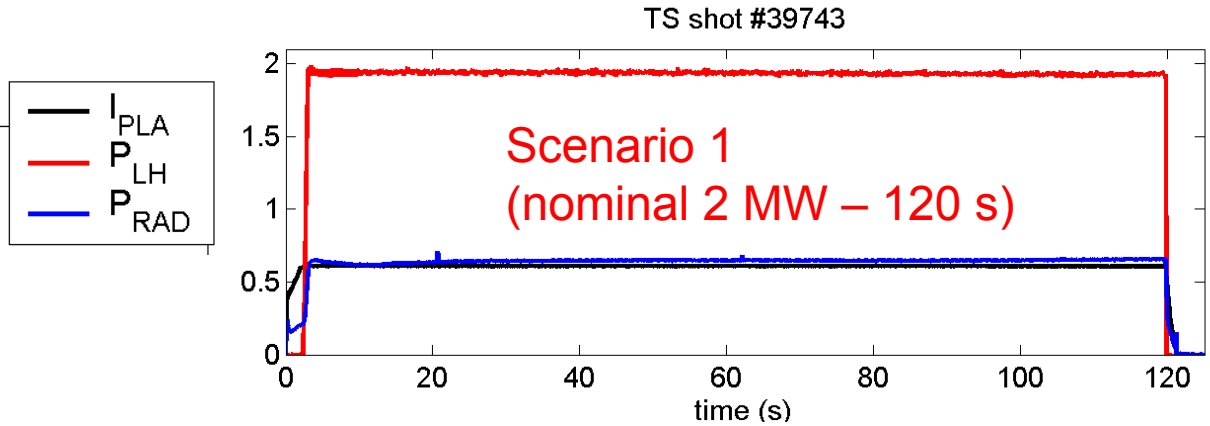


➔Post mortem analysis :

~ 10 g (3 10^{24} D)

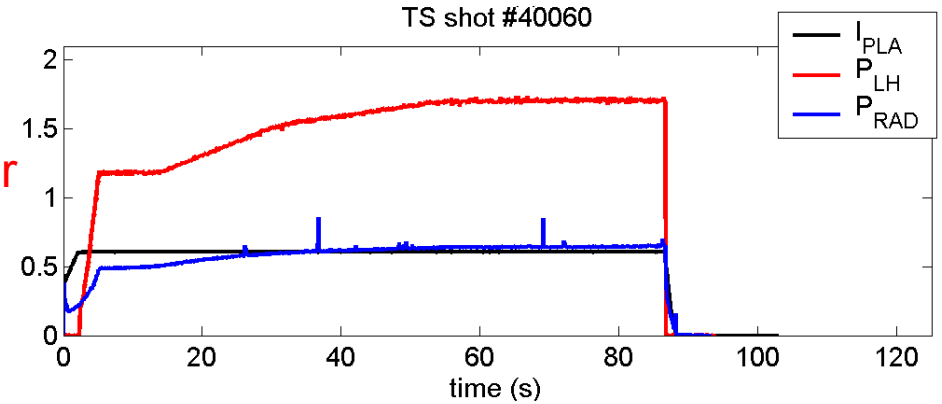
Summary of the DITS campaign

- **Reliable operation** (LH, magnets, cooling loops, PFCs, diags …)
- Repetitive **pulses every 20 mn** (~ 40 mn of plasma each day)
- 5 h of plasma **w/o conditionning**
- **Density control** : ok for plasma breakdown, no density rise



UFOs (C + metals + D ?)
➔ detachment
➔ disruptions

Scenario 2
(lower power
~ 80 s)



➔ scenario at lower LH power (< 1.8 MW) + slow ramp up

Magnetic configuration on the limiter

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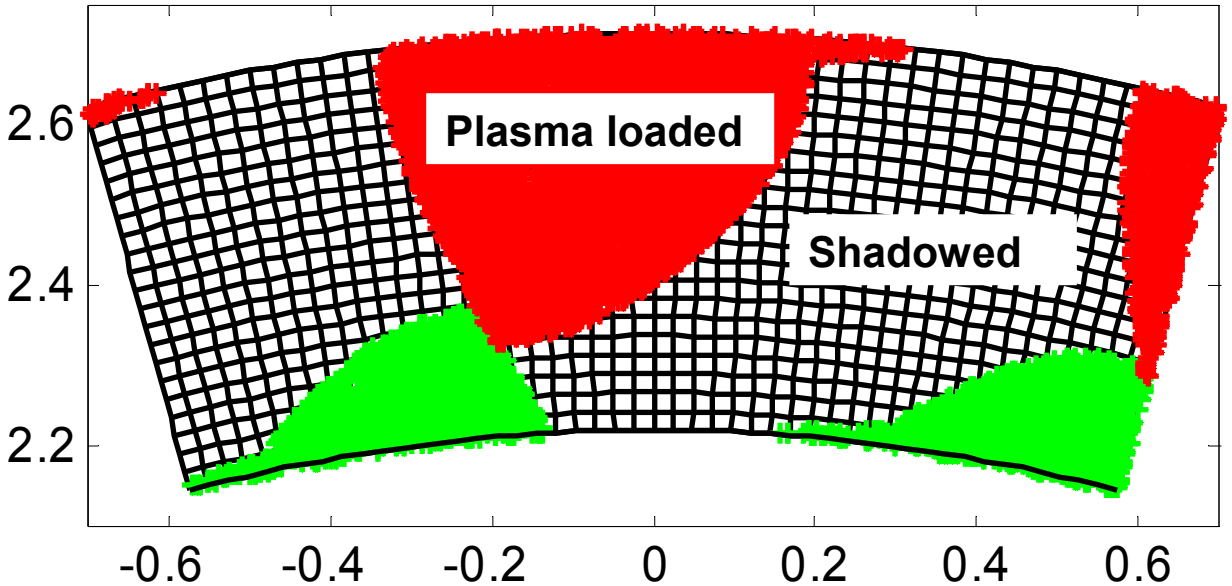
Field line modelling



TPL temperature pattern (IR imaging)

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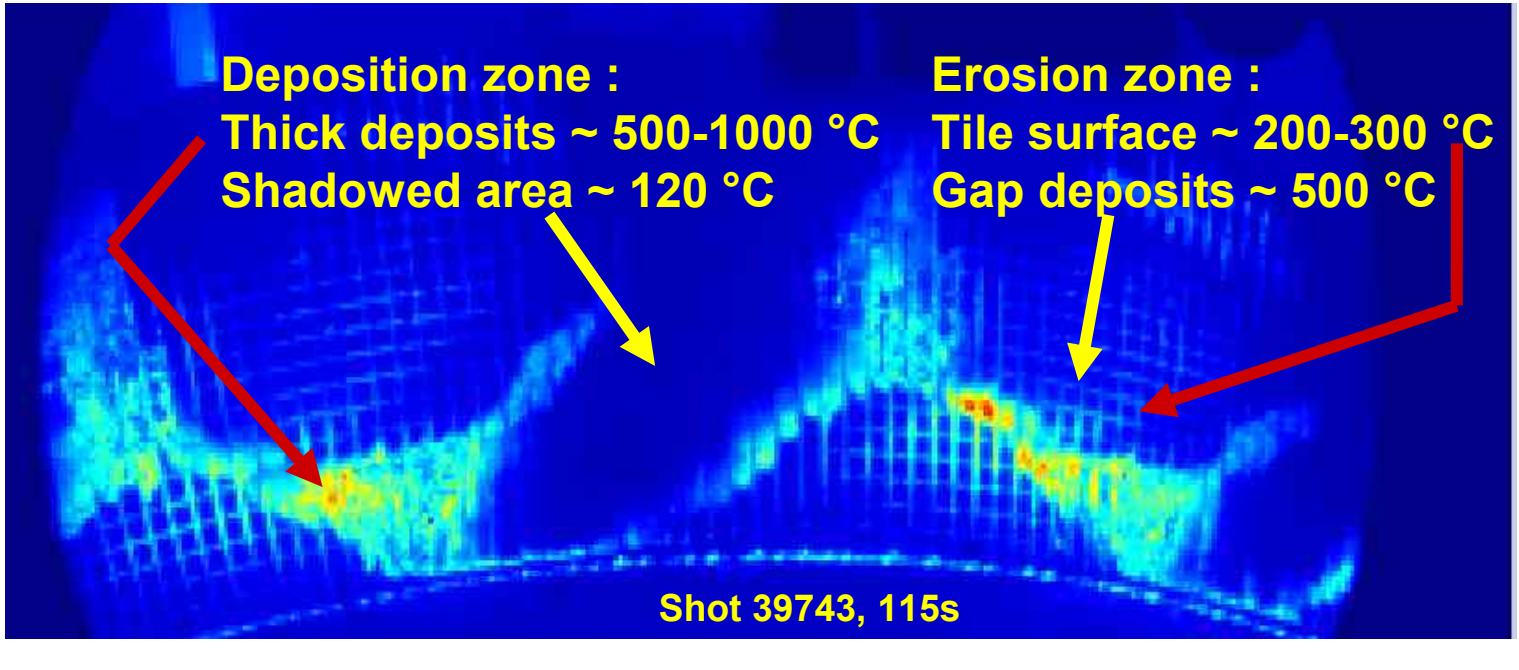
Cooling loop = 120°C
Active cooling :
Tsurf = cte

[A. Ekedahl, P. Moreau]



The DITS project

Sample extraction

Extracting a limiter sector

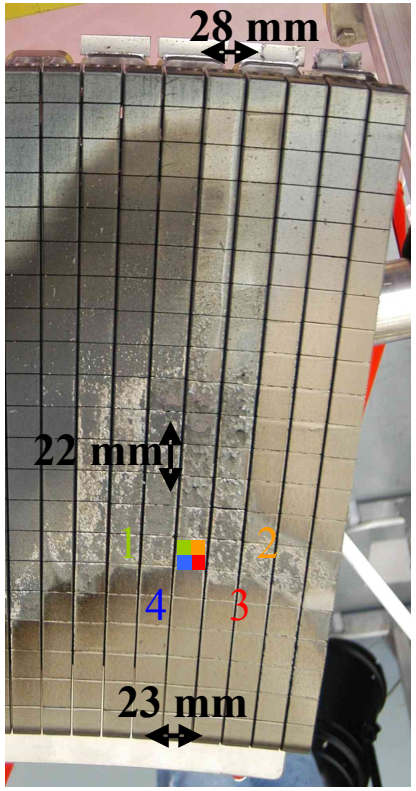
CFC tiles on Cu heat sink
Castellated structure ➔ ITER PFCs

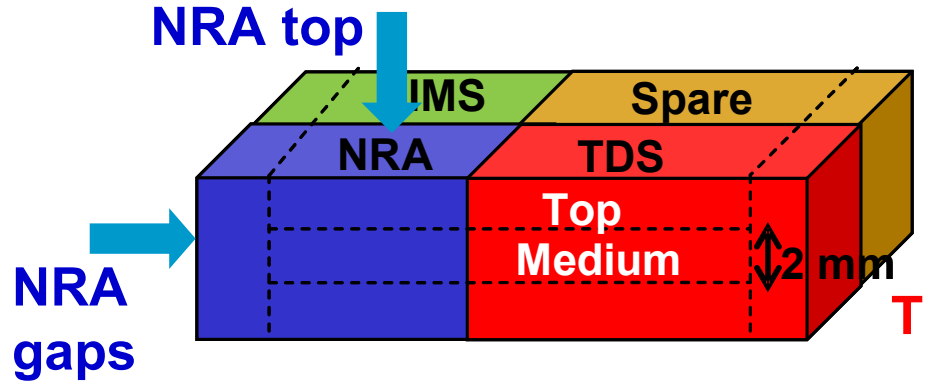
First analysis campaign : 10 tiles (40 extracted)

- **5 in erosion zone**
- **2 in thin deposits (far SOL and shadowed)**
- **3 in thick deposits**

Sample extraction

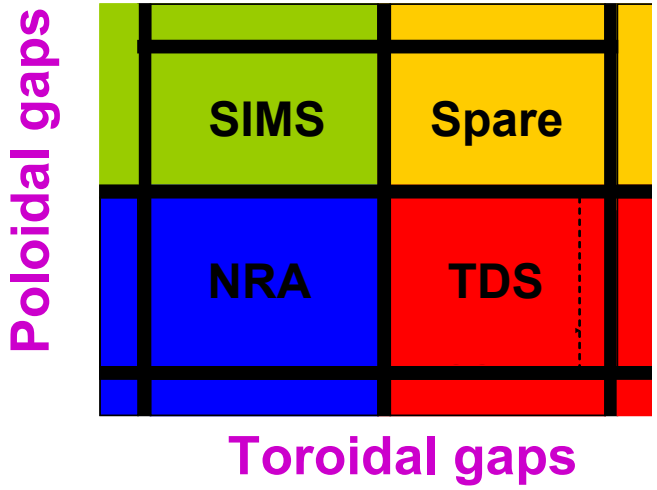
D inventory : Thermodesorption (TDS) ➔ global D content
Nuclear Reaction Analysis (NRA) ➔ local D profile (up to 30 µm)



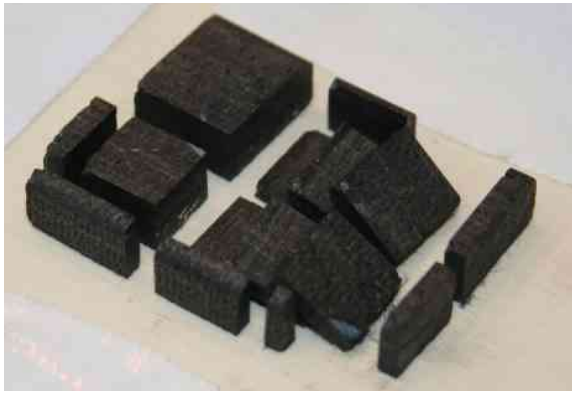


Standard cutting (7 tiles)

TDS : top + medium



Refined cutting (3 tiles ** : ero/thin/ thick)



The DITS project

Post mortem analysis

Consistency NRA/TDS

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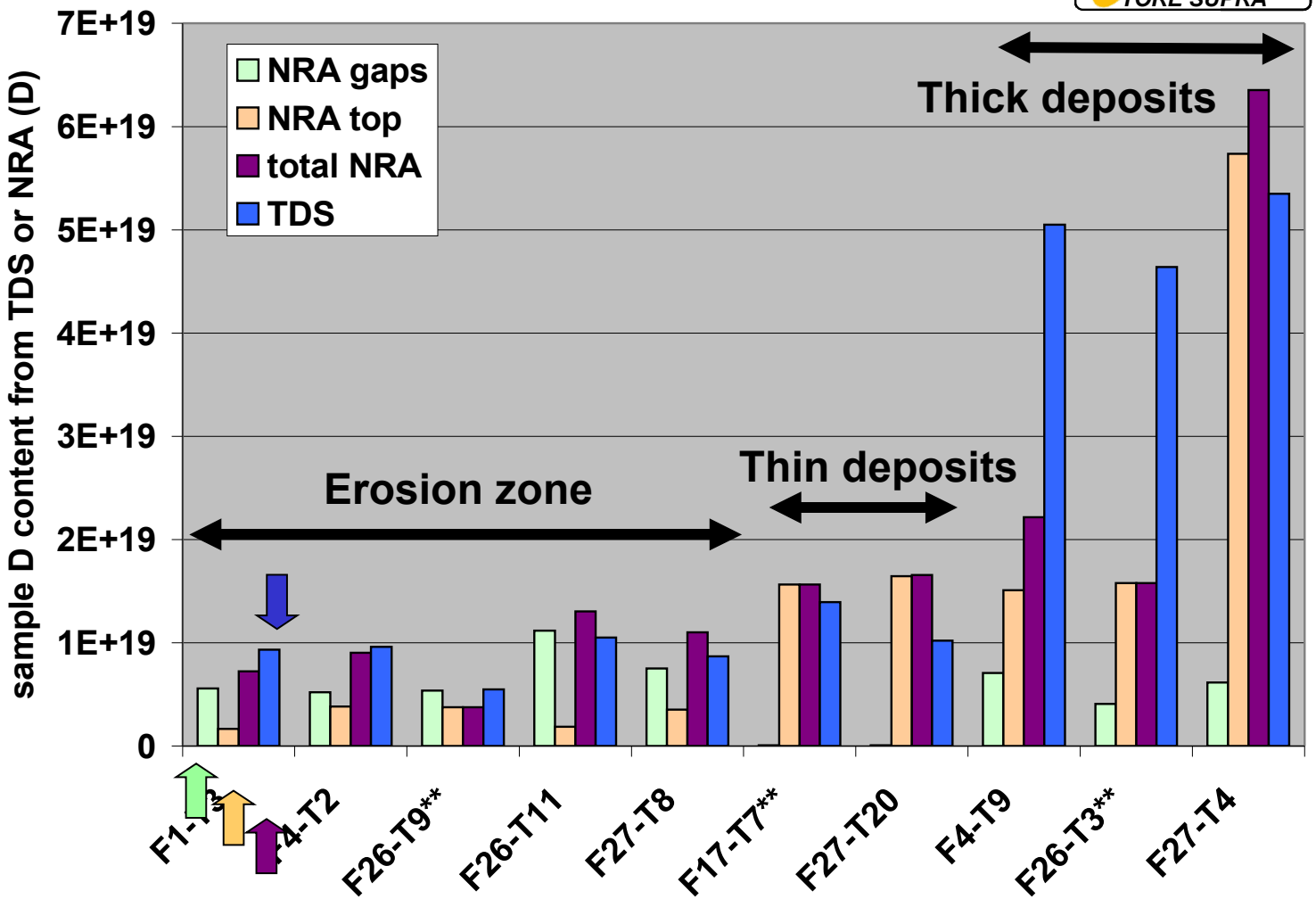
TORE SUPRA

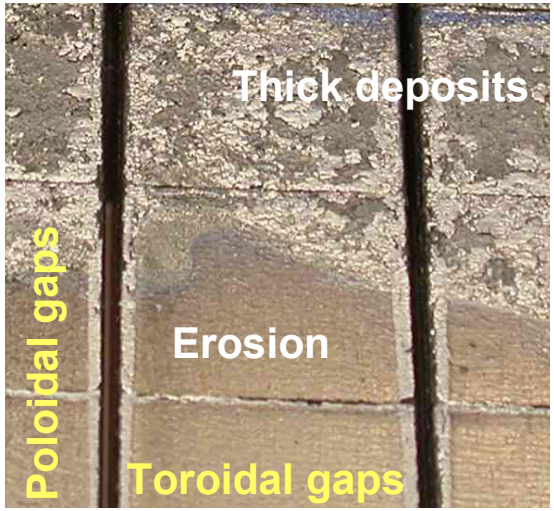
NRA concentration ➔TDS content

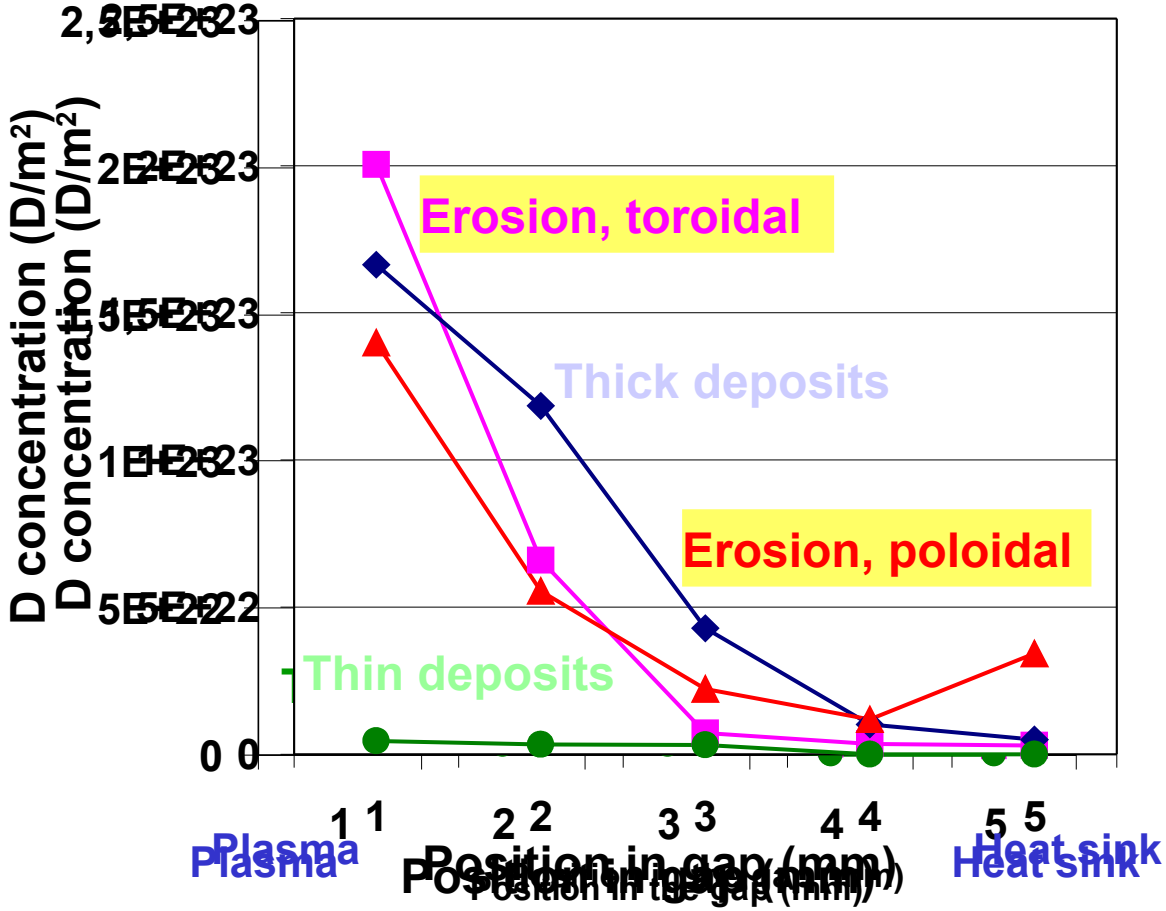


- **Consistency NRA / TDS except for thick deposits : significant D content over NRA range (deposited layers > 30 µm)**

➔ Gaps
➔ Bulk

D inventory in gaps





- D content in gaps : significant for erosion/thick deposits, low for thin deposits
- Erosion zone : no major difference poloidal vs toroidal

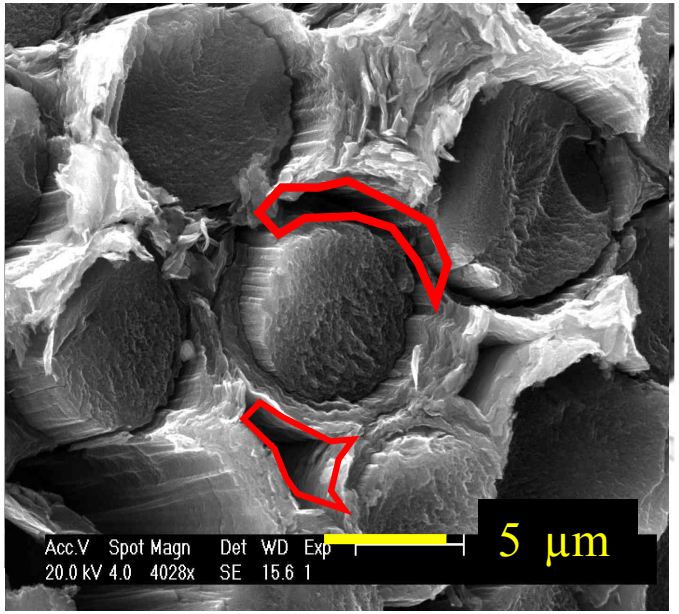
Bulk diffusion

Tile surface in erosion zone : 2-7 10^{22} D/m² ➔ x 10 > implantation

NRA ➔ D down to 10 µm >> d_{imp}

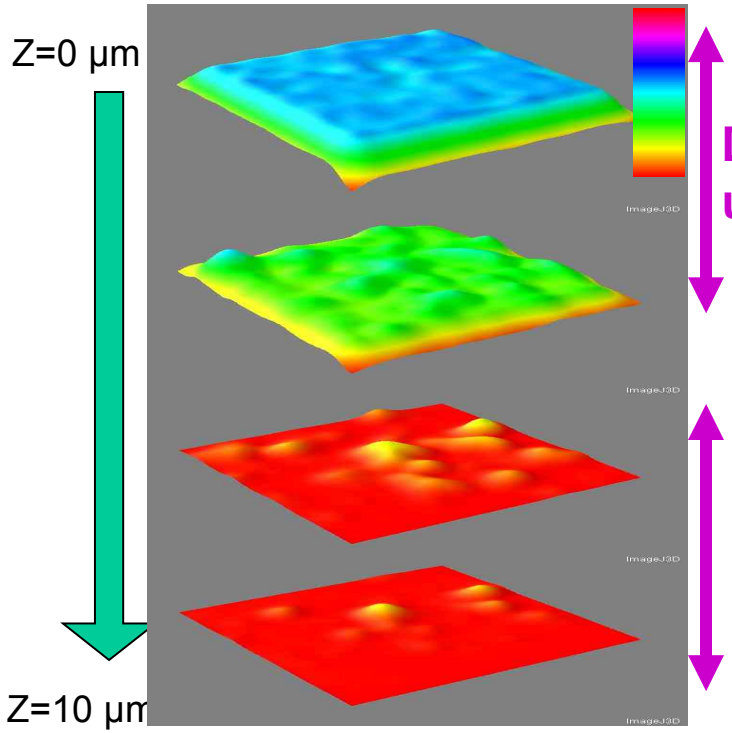
TDS ➔ D detected 2 mm below surface (x 50 lower / top in erosion zone)

Lab exp. : not thermally activated ➔ ~~diffusion~~ [J. Roth et al., JNM 07]



Bulk « diffusion » : codeposition inside porosity network ?

MicroNRA : deuterium mapping



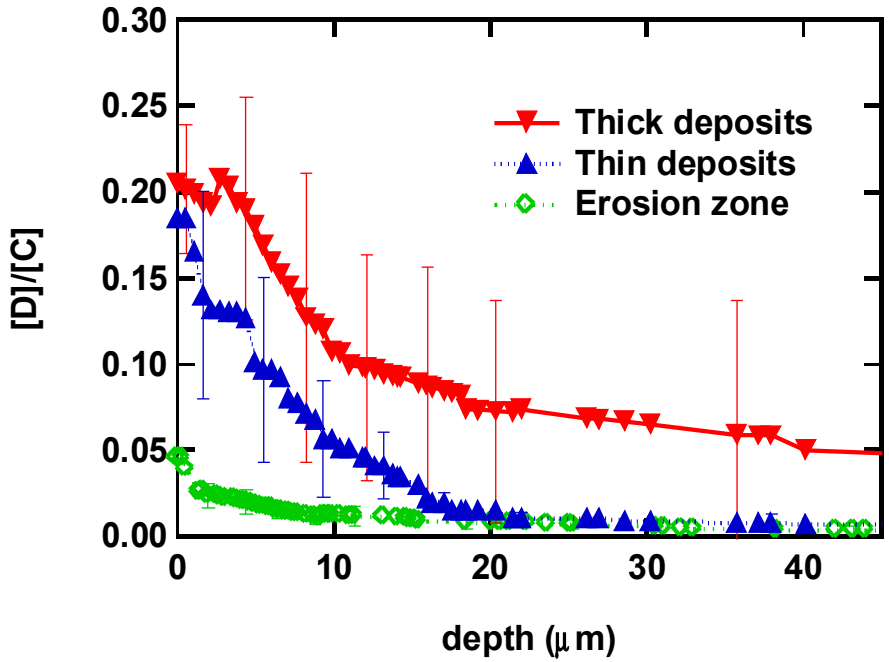
Deposited layers : uniform

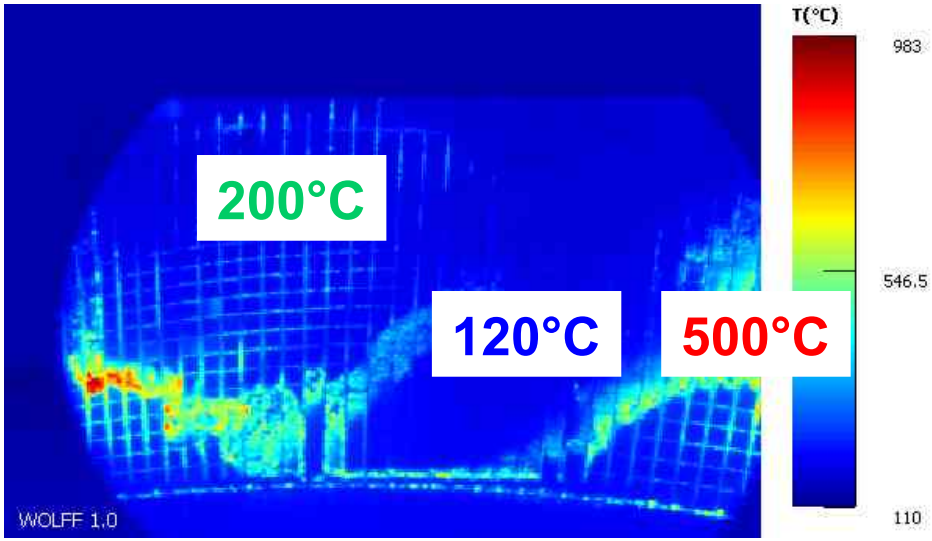
Bulk : localised Trapping sites = porosity along CFC fibers

Tile analysis : NRA - D(^{3}He,p)^{4}He

Local measurement / surface D- concentration

Significant dispersion from sample to sample





~80% of D found in the first 30-40µm

Global inventory from post mortem

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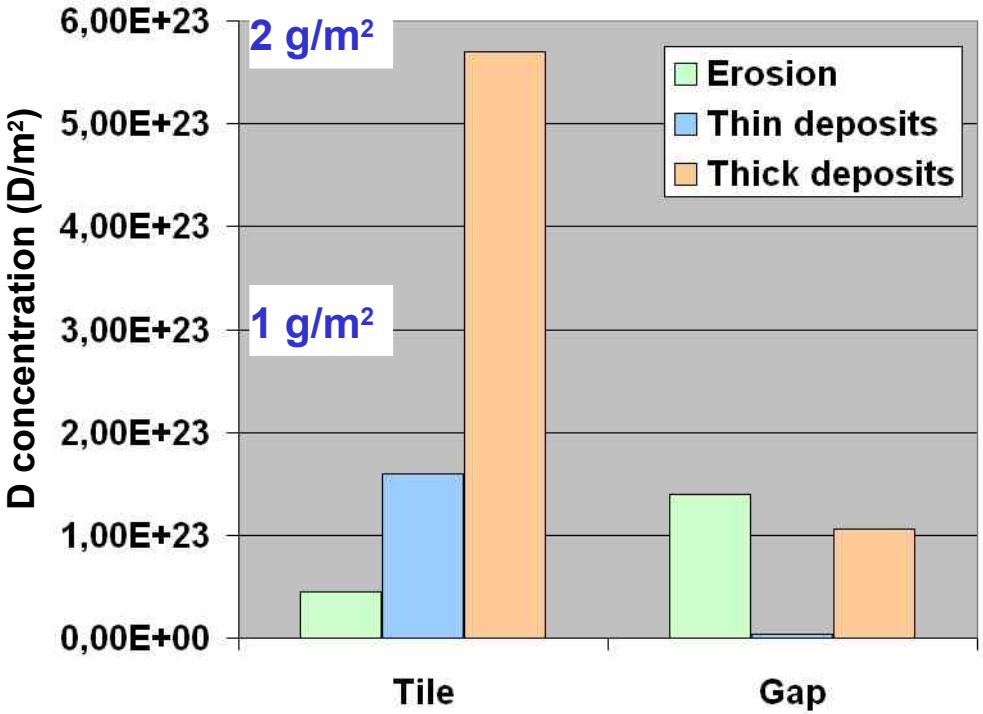
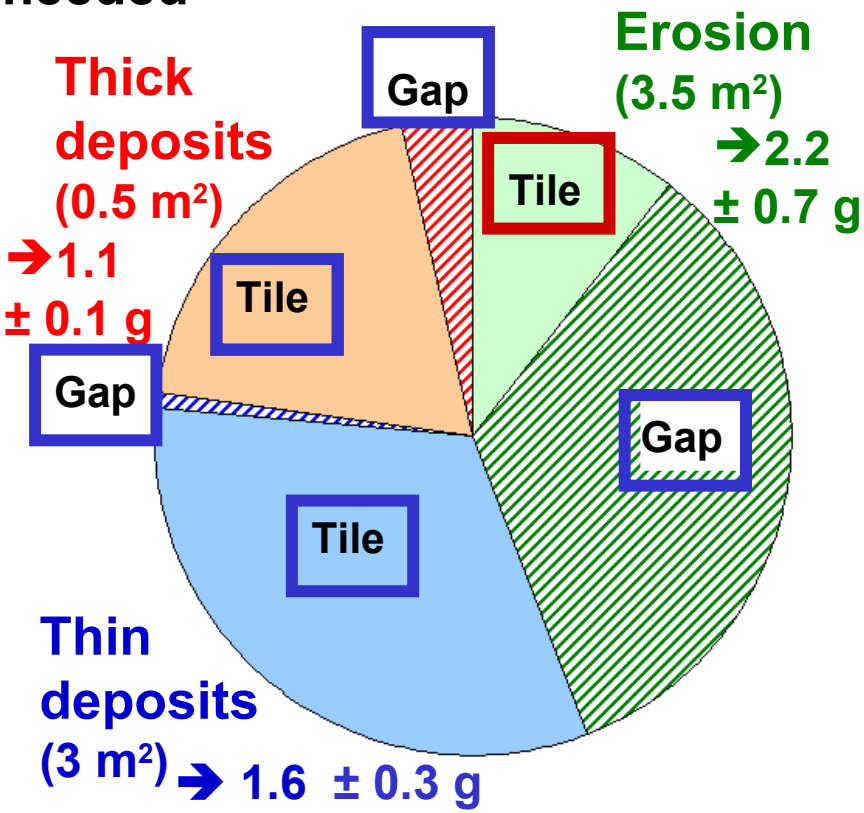
Ongoing work ➔ more statistics needed
(next analysis campaign ~30 tiles)





Retention mechanisms :

- **Codeposition dominant** (shadowed + gaps), 10 % bulk diffusion in erosion zone

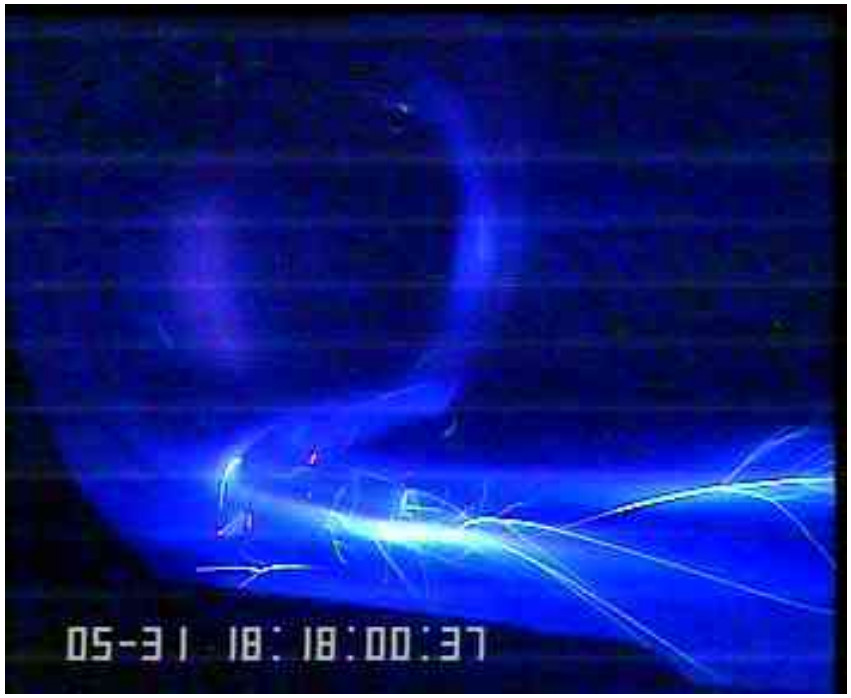
Post mortem D inventory : 4.9 ± 1.1 g D ➔ **~ 50 % of particle balance**

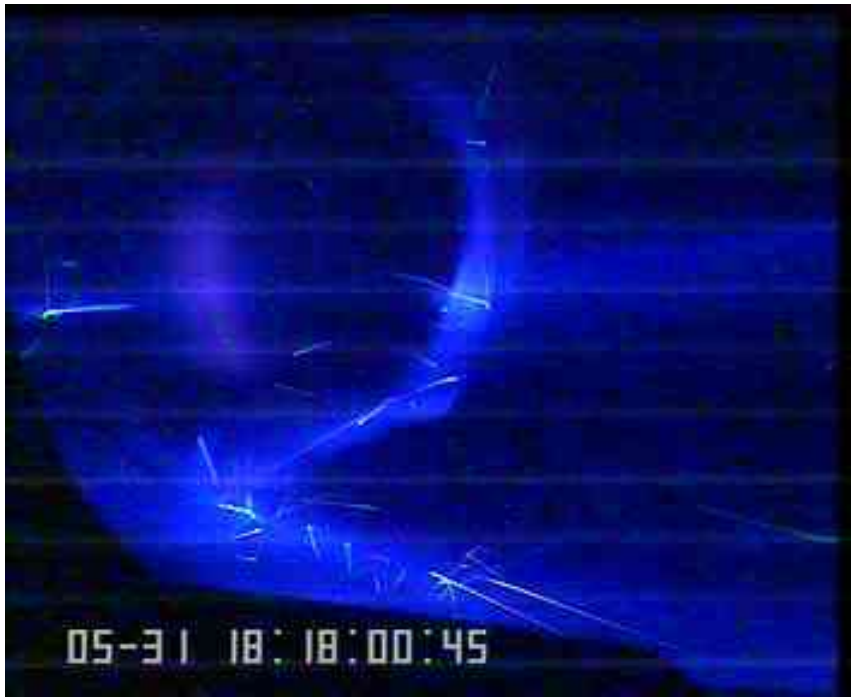
➔ **significant progress** (10% in previous studies (thick deposits))

- **Lower limit** : loss of D with air exposure (~ 6 months), other PFCs (inner bumpers)

UFOs on CCD imaging of the TPL

Critical phases for UFOs



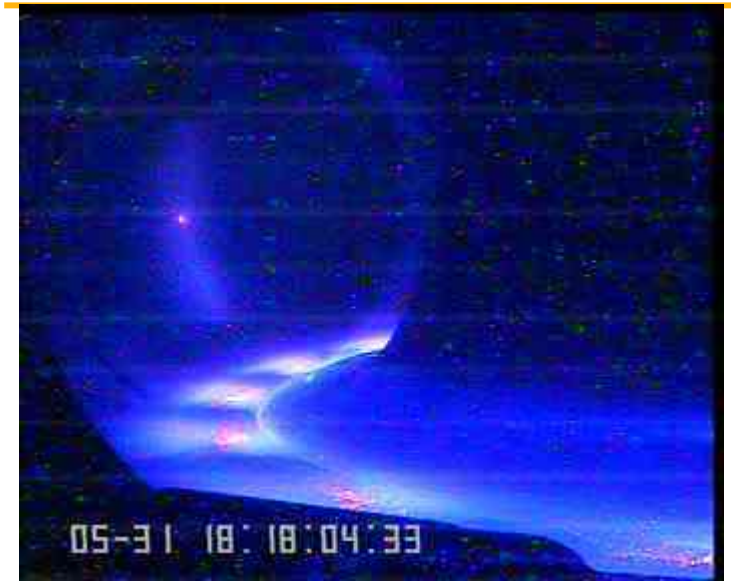


Critical phases :

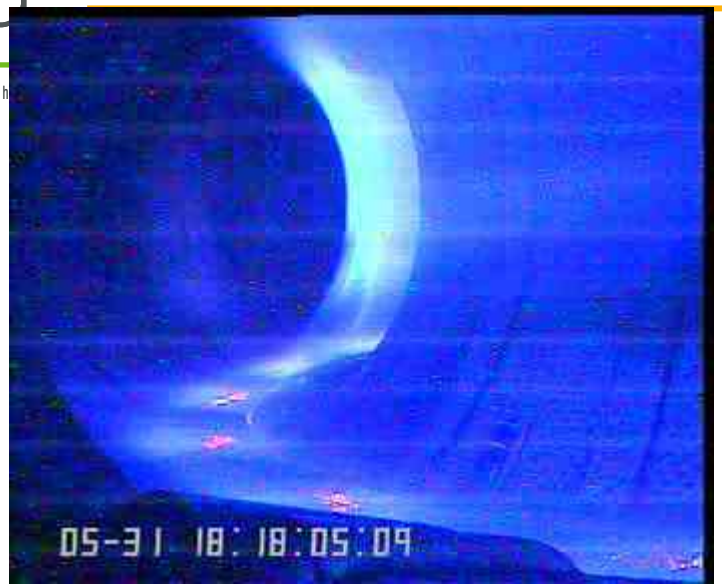
- Plasma start up
- Additional power start

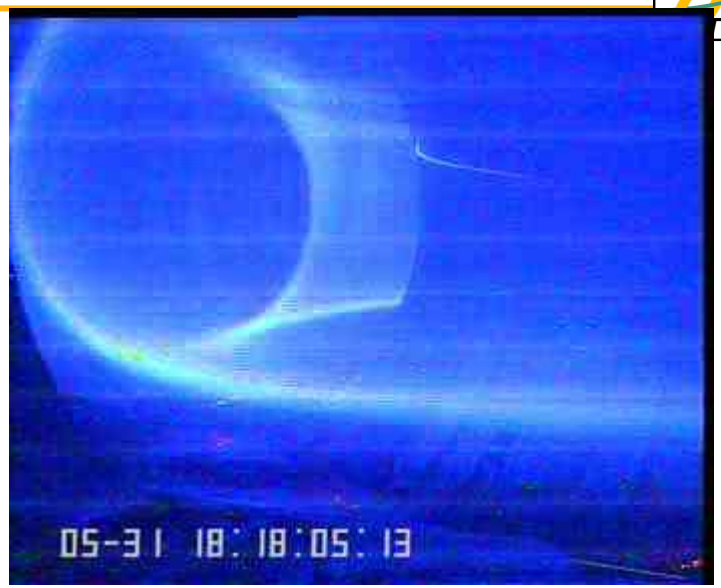
Then sporadic along the shot

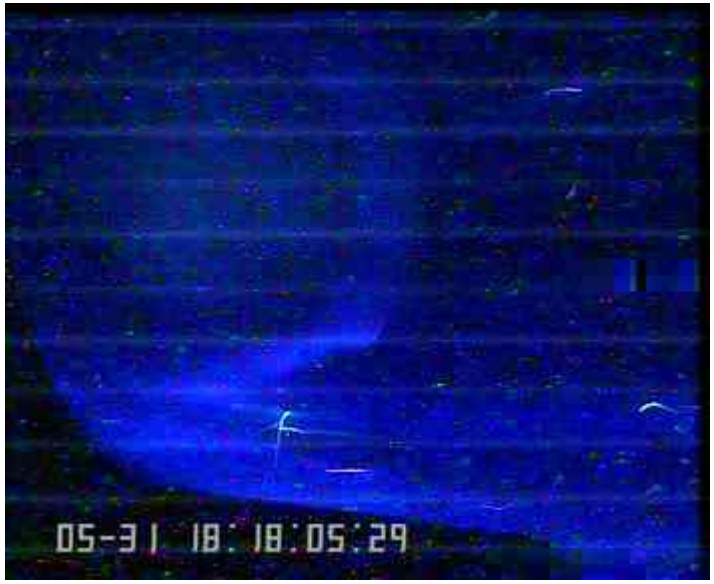
UFOs and MARFE

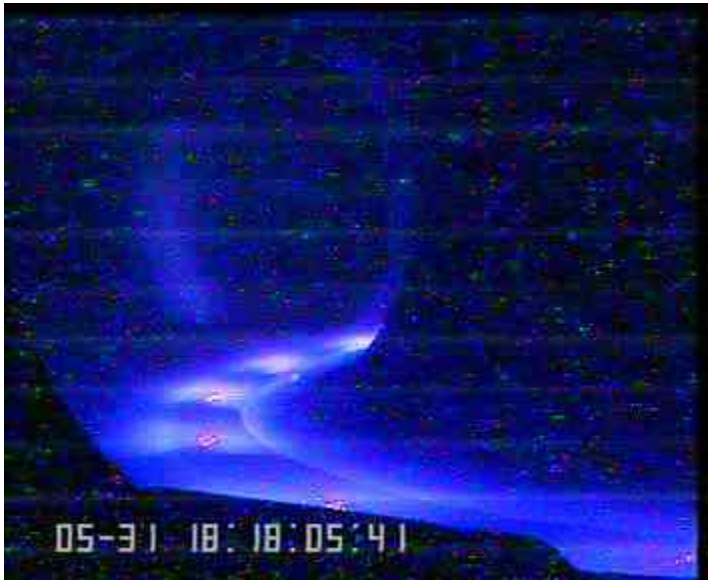


MARFE and detachment

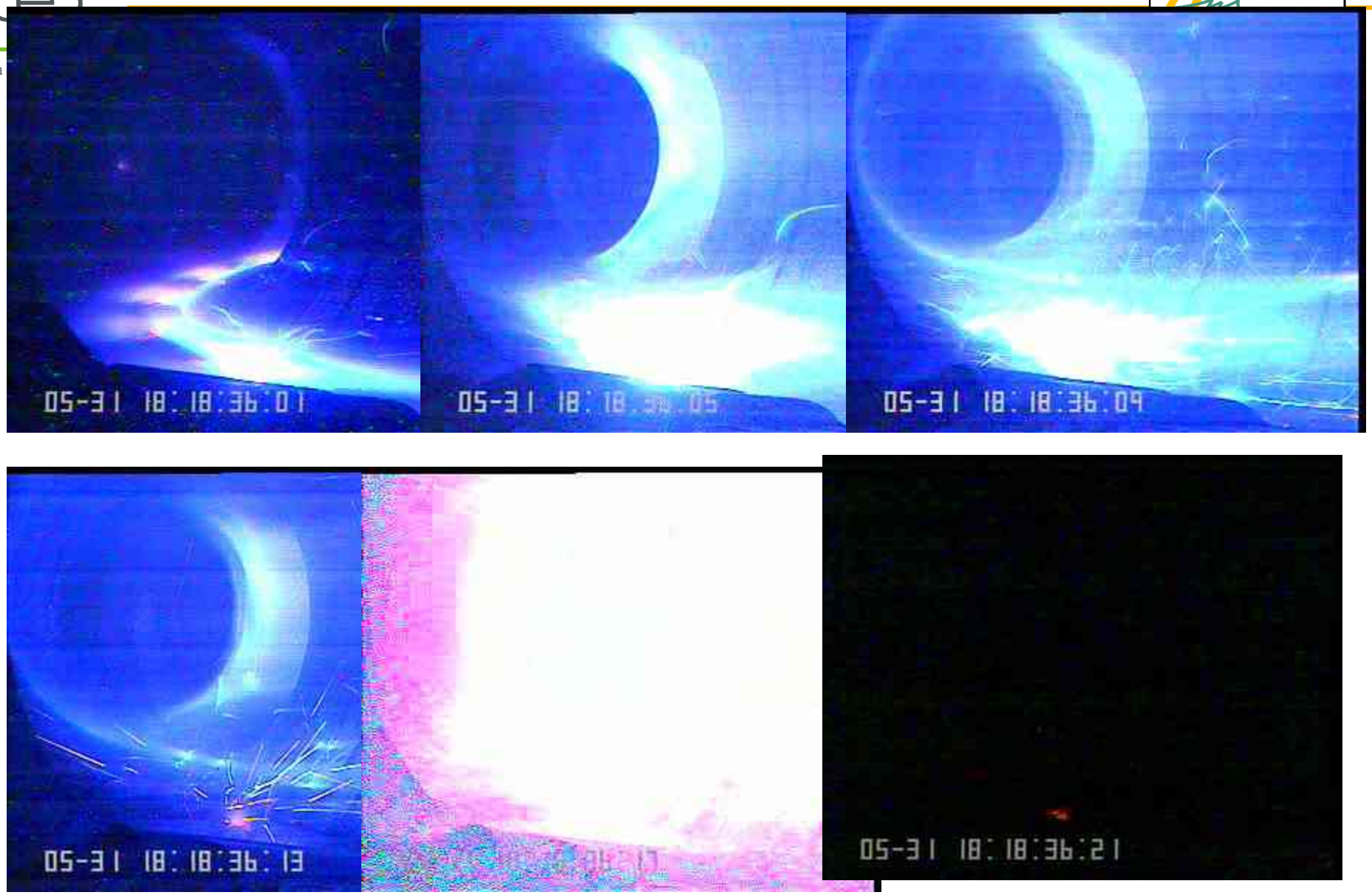








MARFE and disruption …



Summary

Fuel retention major issue for ITER

Studies in Tore Supra :

- codeposition vs bulk diffusion
- particle balance vs post mortem

Dedicated campaign : repetitive long pulses (5 h w/o conditionning)

- max limiter fluence ~ 1 ITER shot at strike point (few 10^{26} D/m^2)
- particle balance ➔ 10 g of D

Retention mechanisms : codeposition dominant

Erosion zone
- Significant gap contribution
- Bulk diffusion (codeposition in porosities ?)

Post mortem D inventory ~ 50 % particle balance

~ 5 g of D in limiter (± 20 %) ➔ lower limit (D loss, other PFCs)

➔ Towards reliable in vessel fuel inventory :

Particle balance : how much / when ? ← Scenario optimization

Post mortem : how much / where ? ← Detritiation

Prospects

- Now, the « consensus » is on preventing the use of C in nuclear phase of ITER operation

- However, better knowledge may somewhat alleviate the problem

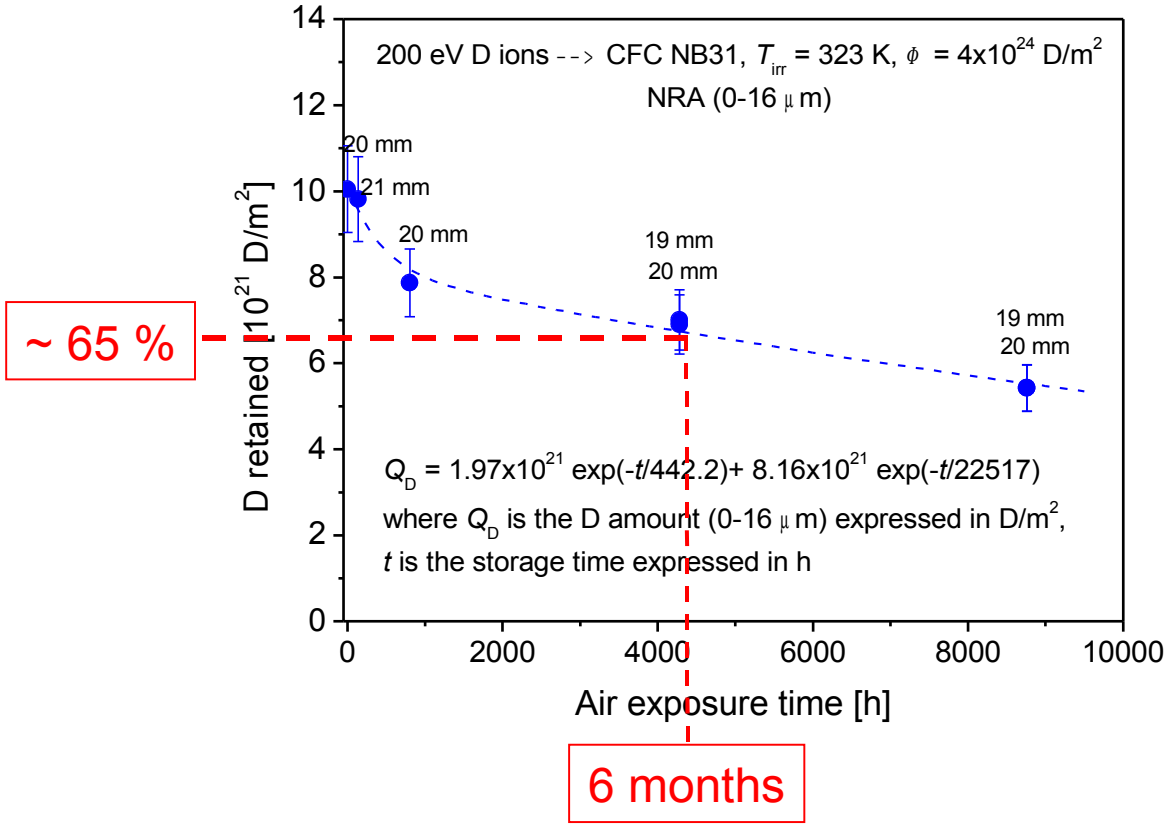
- Questions to the academic (fundamental) community

- Networking through the European Task Force on Plasma Wall Interactions (EFDA) and, in France, the FR-FCM (Fédération de Recherches en Fusion par Confinement Magnétique)

Annex

D-inventory : effect of time

Decrease of the D-content between end of operation and analysis



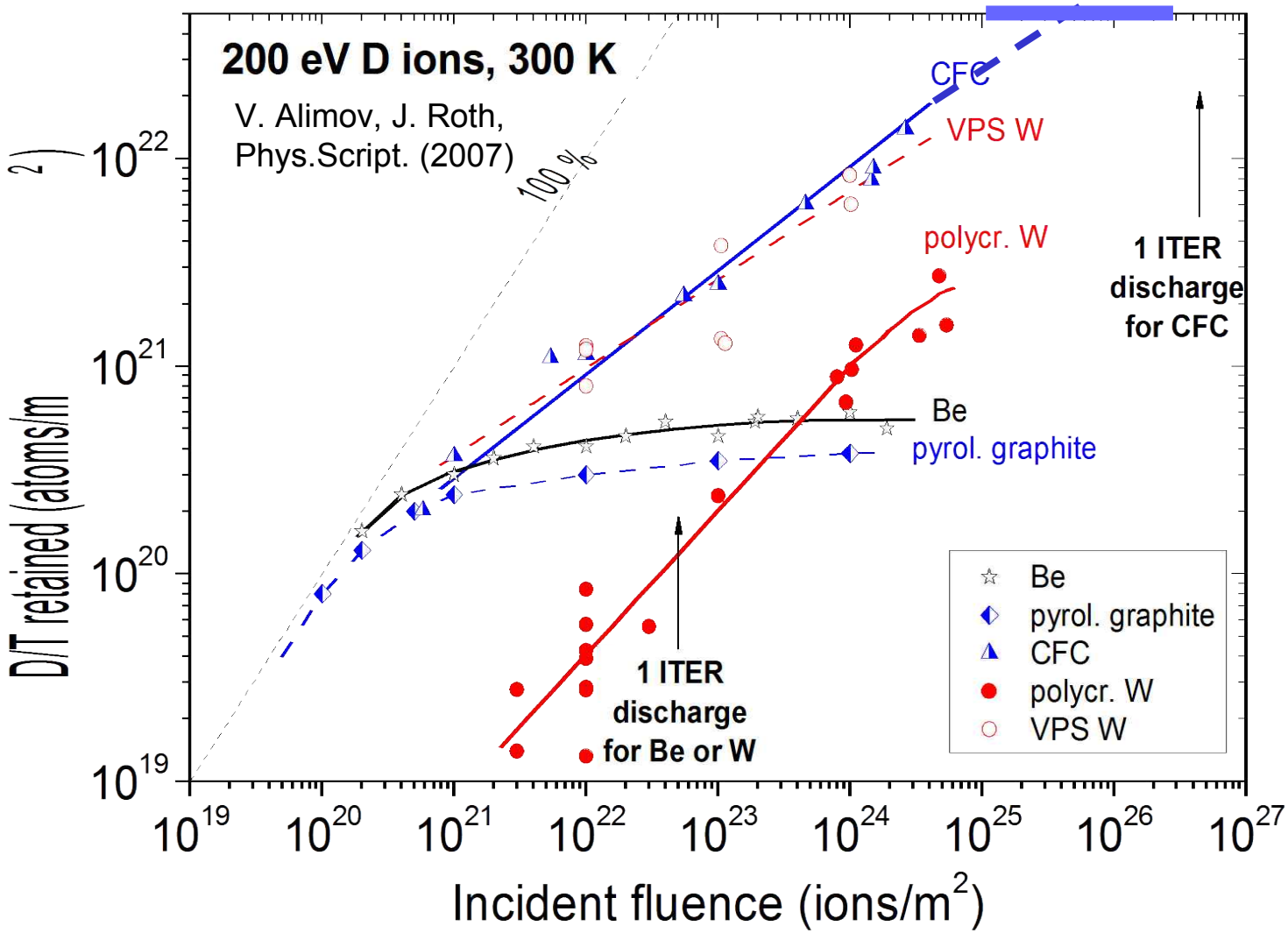
Estimated TPL D-inventory at the end of plasma operation

~7.6 g if CFC and deposits concerned (75 % of total)

~5.1 g if only CFC concerned (50 % of total)

Consistent with lab data on CFC

Preliminary DITS data
(TDS in erosion zone)



Other PFCs cleaning

Scraped deposits

TPL : 145 g of volatile dust (≈50% of TPL surface scraped)

Inner bumpers, outboard limiter,

antennas guard limiters : 645 g of dust

Constant D-retention rate during campaign

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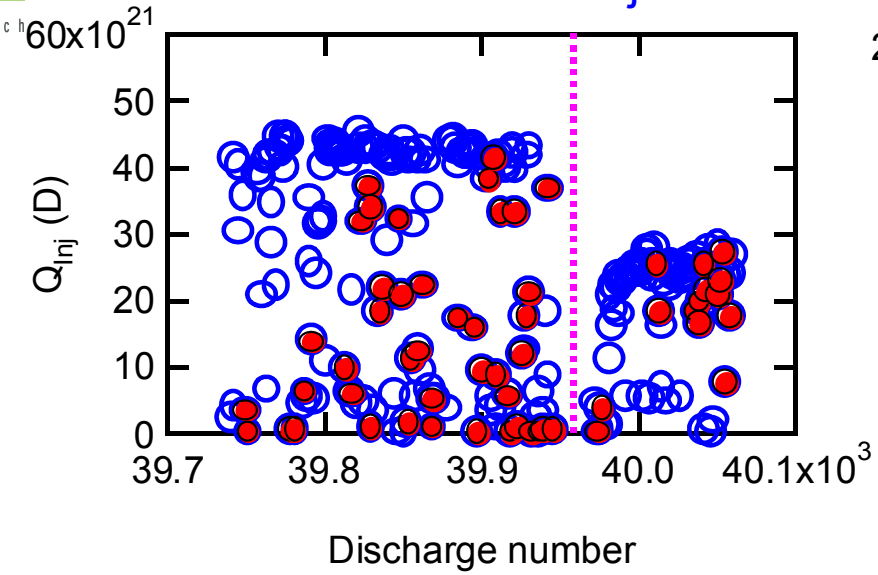
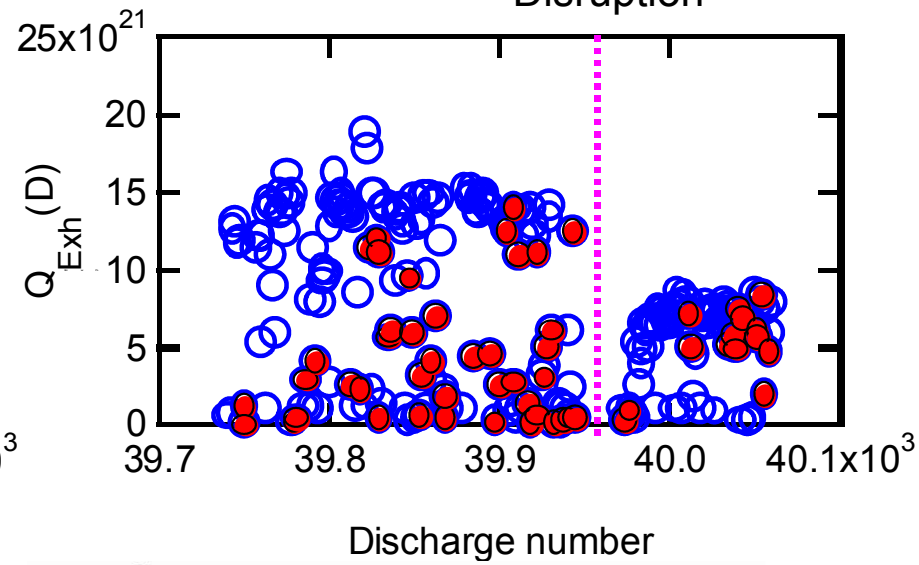
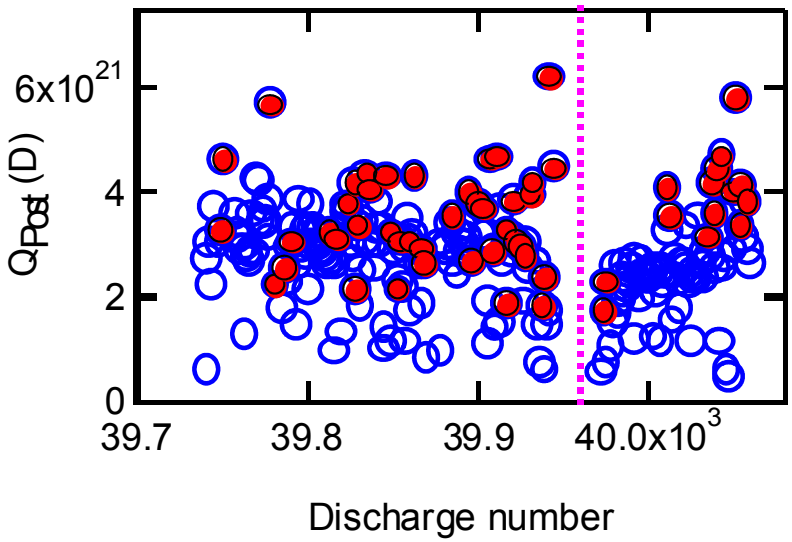
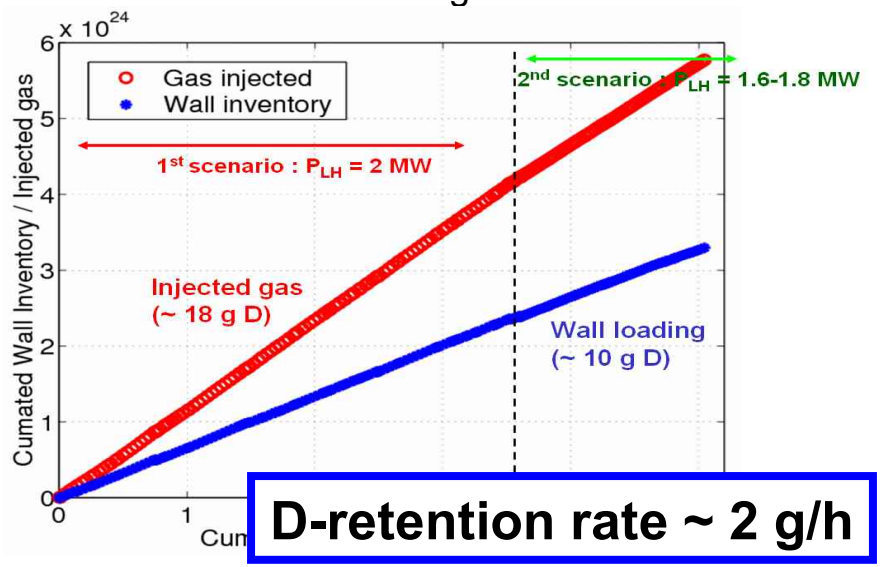
δWI = Inj.Gas – Exh.Gas – Post.Rec

Normal discharge
Disruption



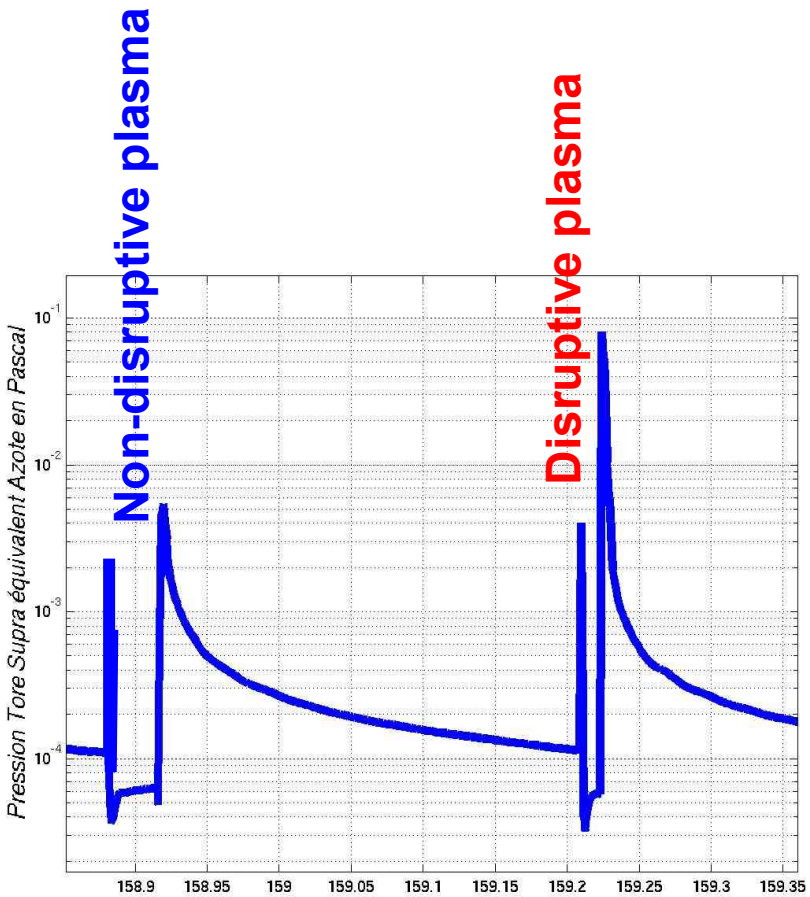


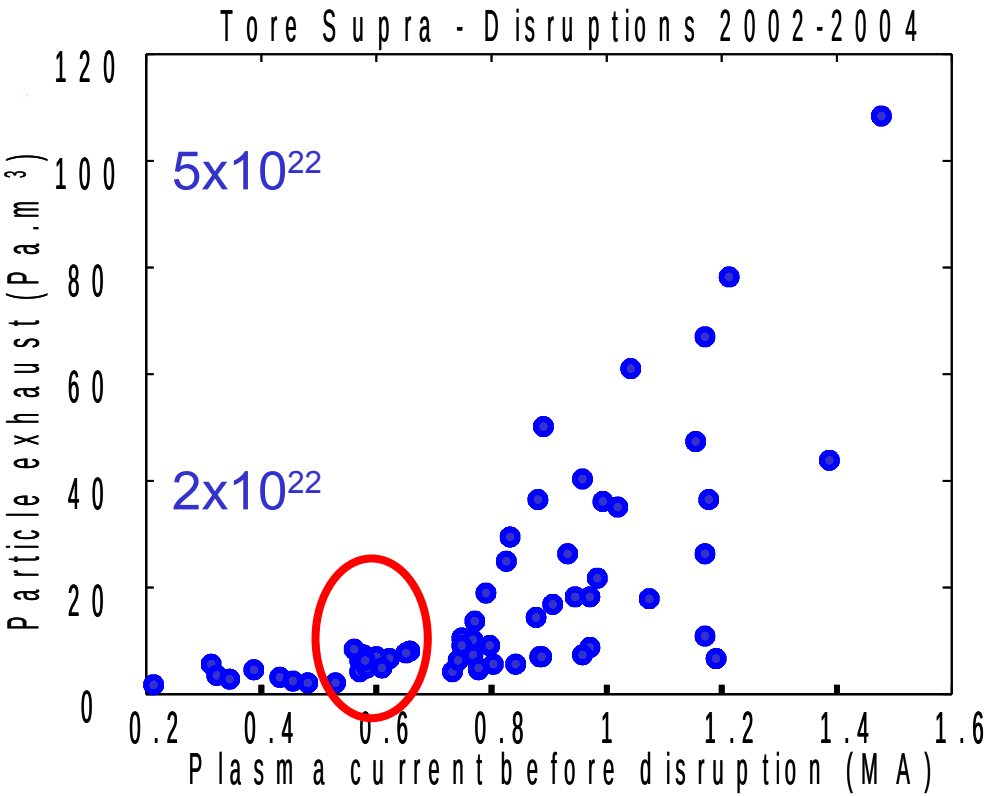




D-retention rate ~ 2 g/h

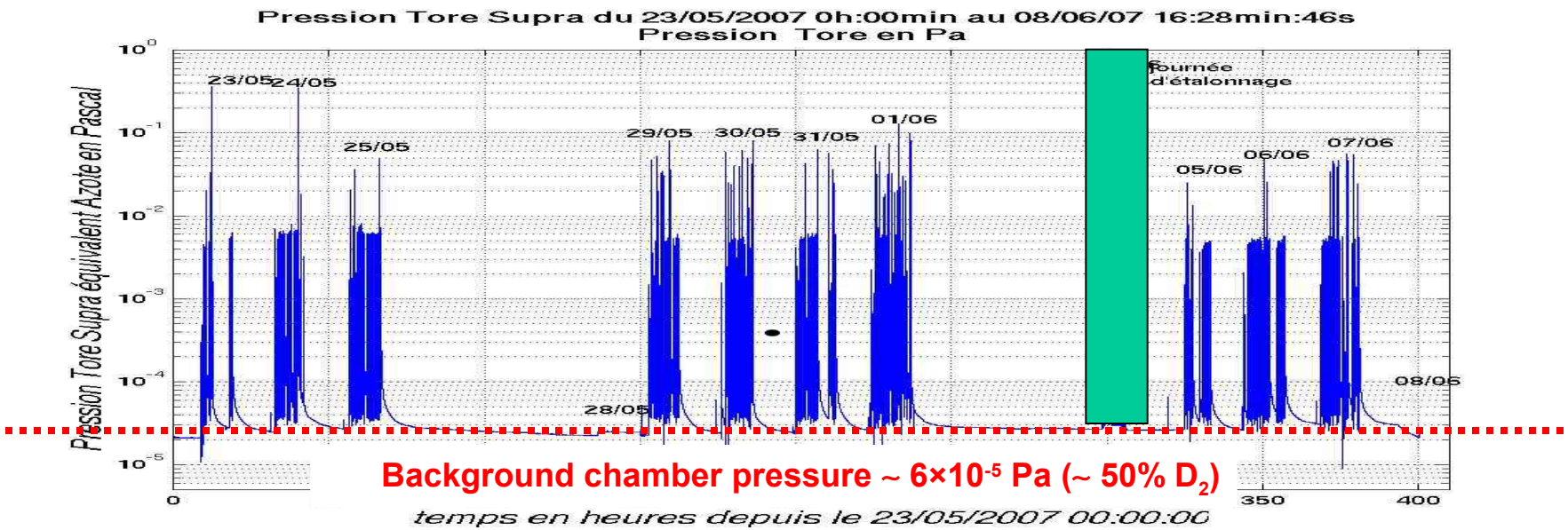
Disruptions at low Ip
not perturbative for particle balance





Global wall inventory

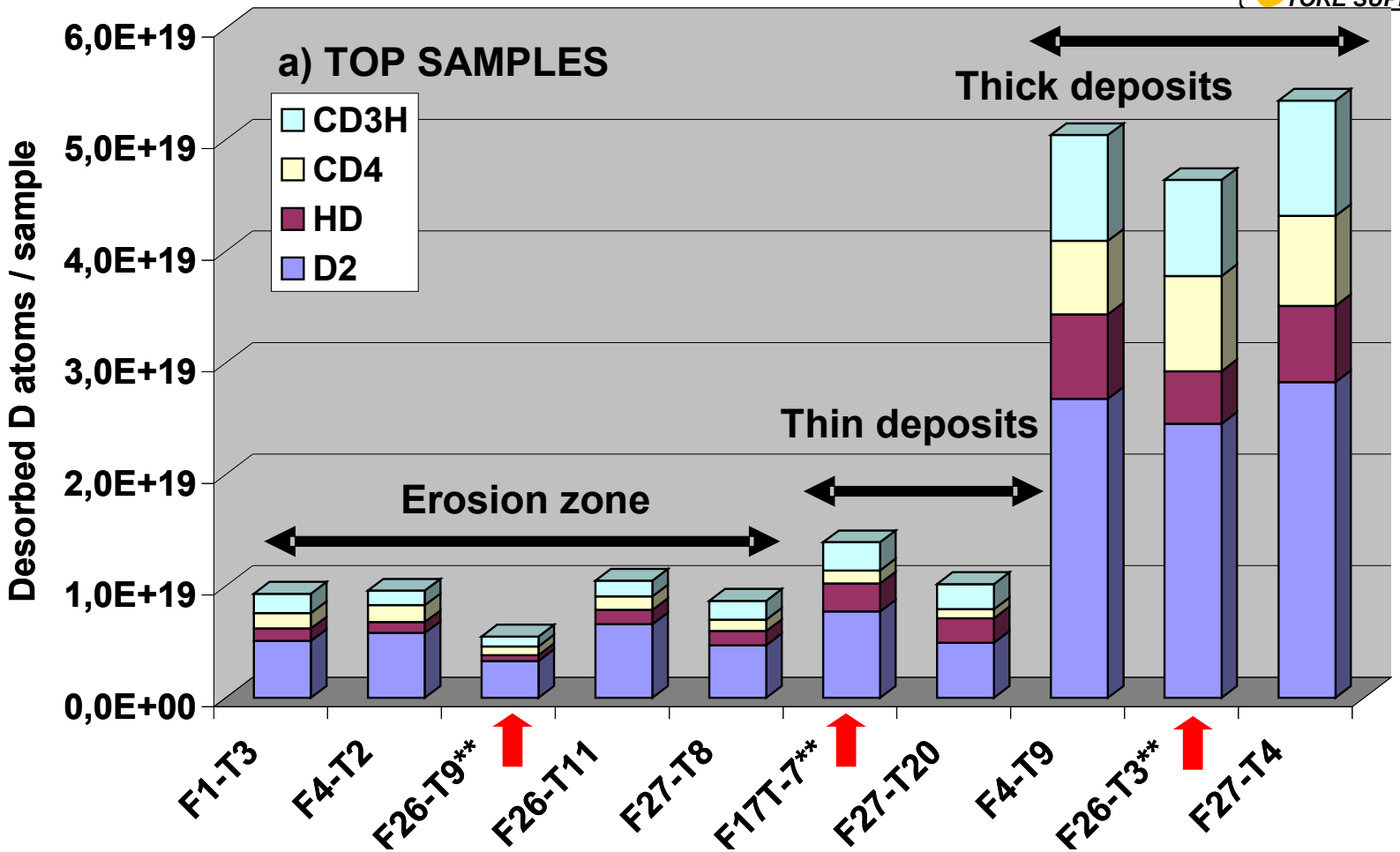
Global WI = $\Sigma\delta$WI during plasmas – exhaust during nights & week-ends



Total exhausted ~ 0.6g D

Global ΔWI ~ 10g D (3.0×10^{24} atoms)

Gap contribution



- ≠ standard and ** samples : gap contribution

TDS : gap contribution

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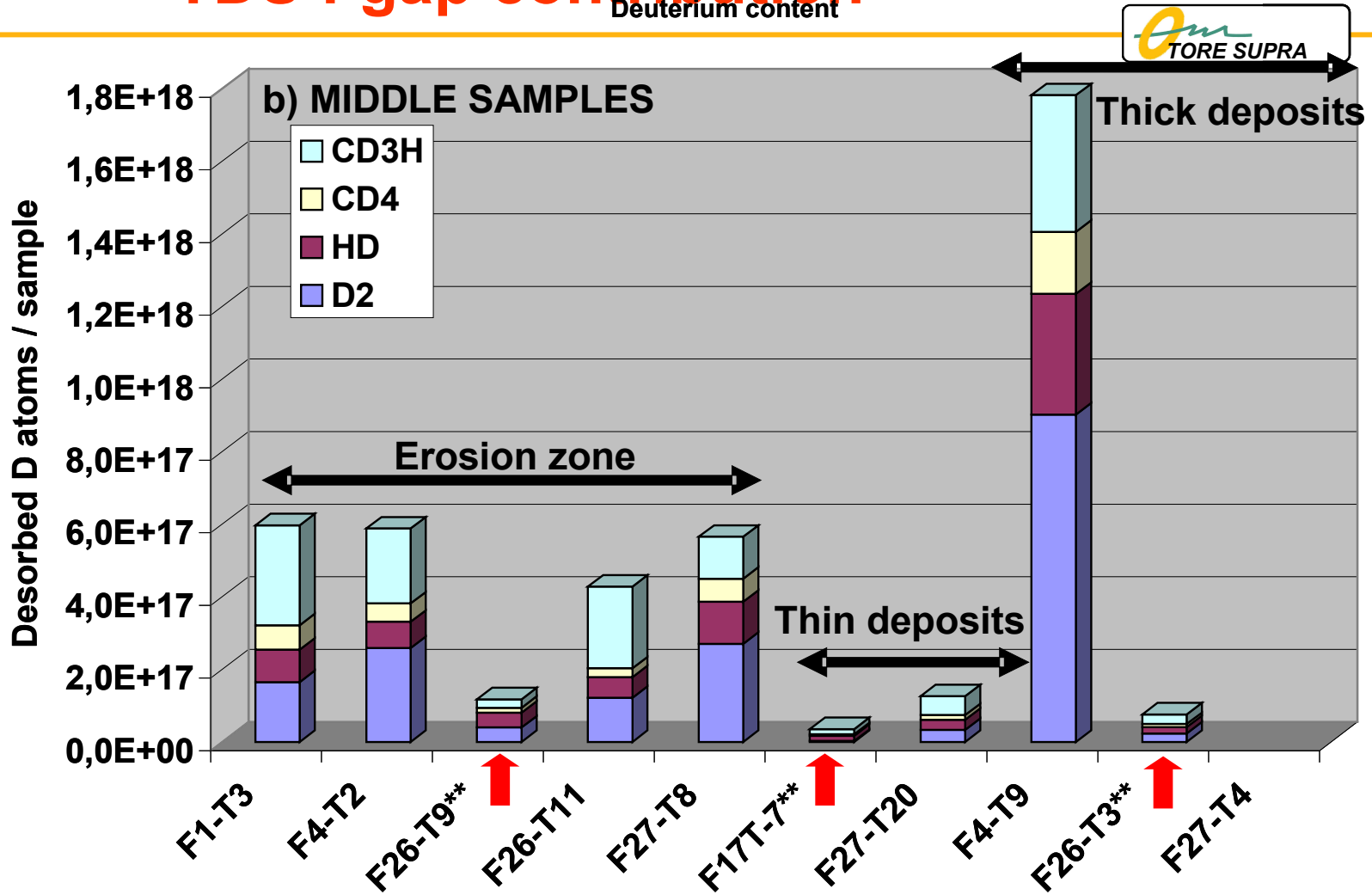
D still detectable 2 mm below surface



- Gaps significantly contribute (≠ standard and ** samples)
- From ** samples : x 50 lower for erosion, 500 lower for thin-thick deposits / top

➔ bulk tile < 1 % of inventory in top samples from ** samples

Gap deposits on the TPL

NRA : non uniform D concentration

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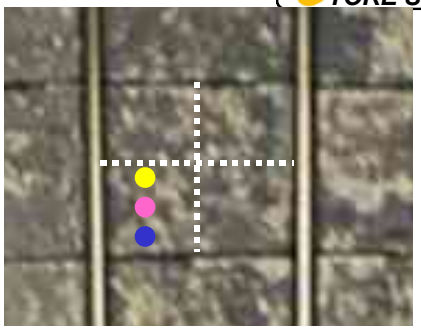


On 1 sample :

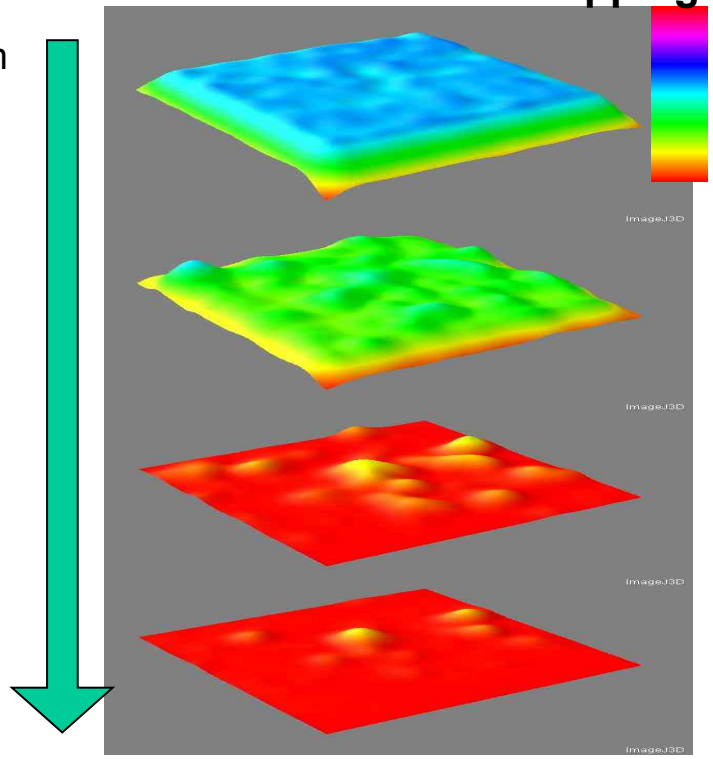
- low energy (800 keV) : std deviation 10-20 % for all zones (erosion, thin, thick deposits)
- higher energy (4-6 MeV) : std deviation 30-50 % (but on lower D concentration)

On samples from the same zone :

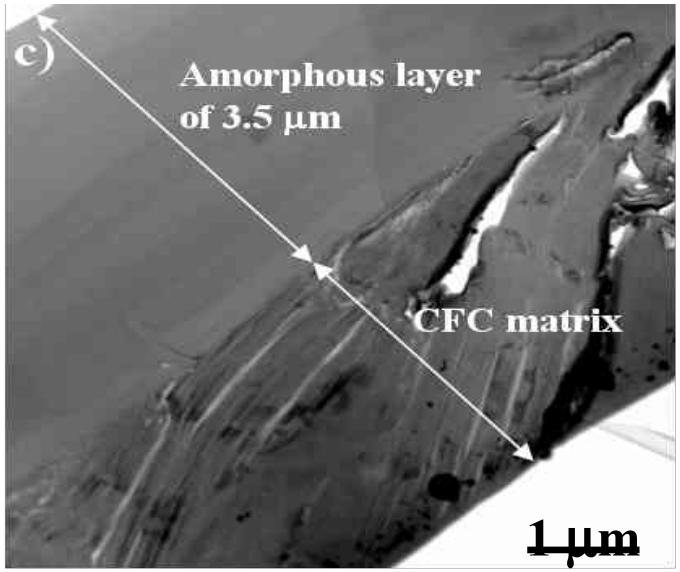
- factor 2 (erosion) to 4 (thick deposits) on top samples

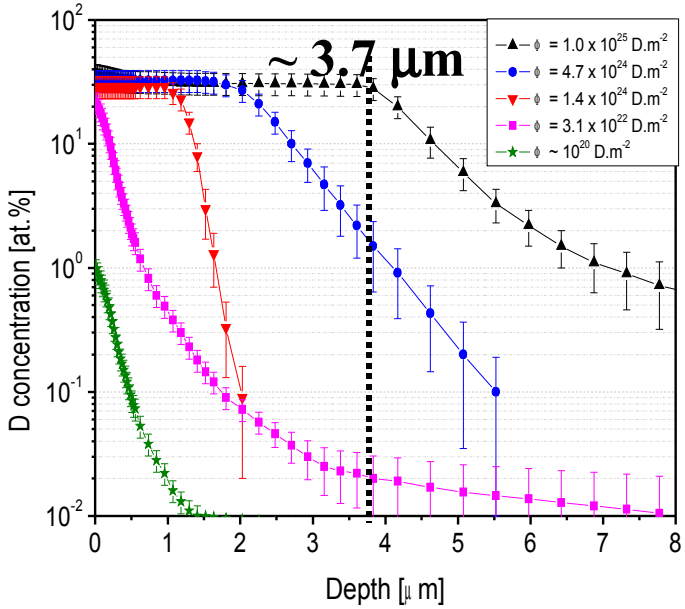
➔ **Non uniform D concentration**, specially deep in the material
Could be linked to the porosity network in CFC
➔ Statistics needed to assess integrated inventory from NRA

MicroNRA : deuterium mapping



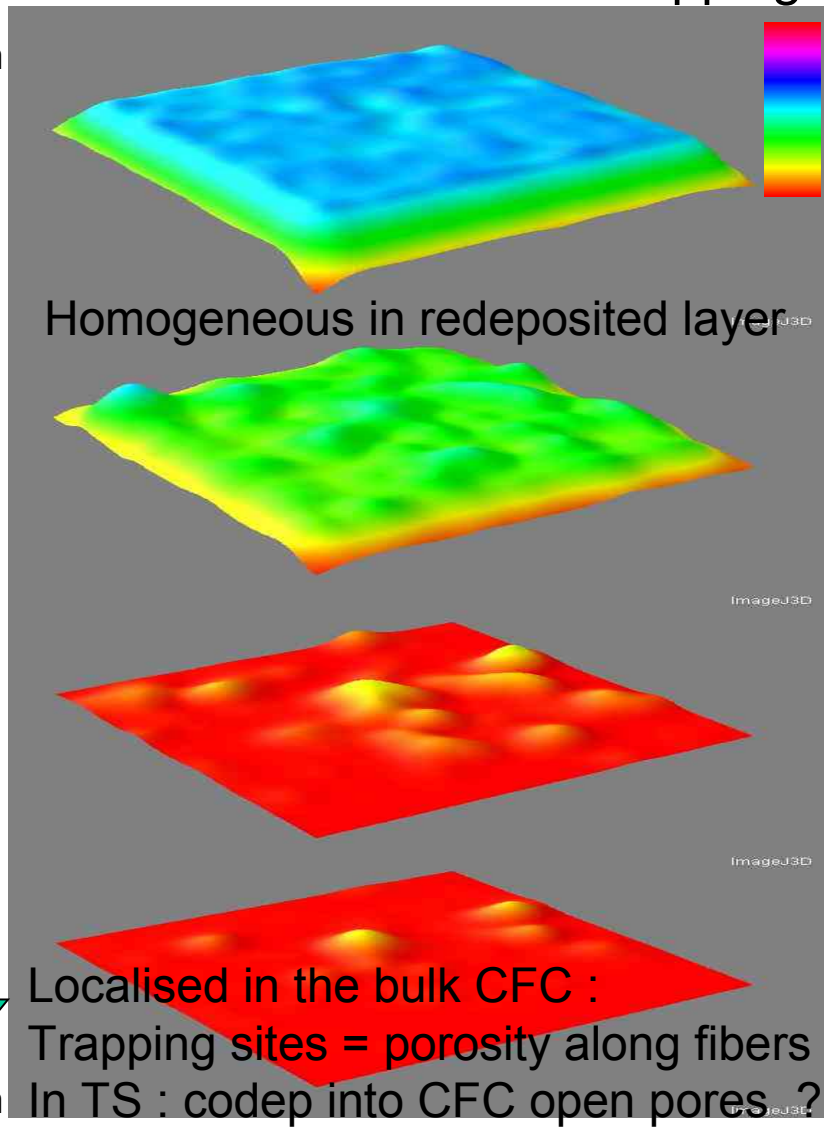
Using sophisticated analysis tools





MicroNRA : deuterium mapping

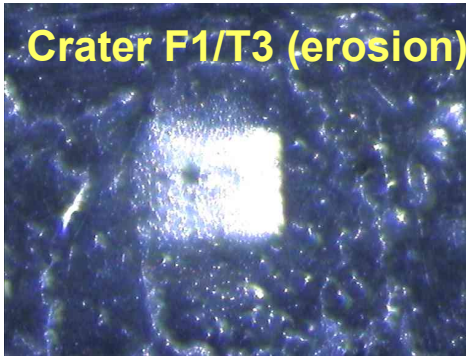
Z=0 µm

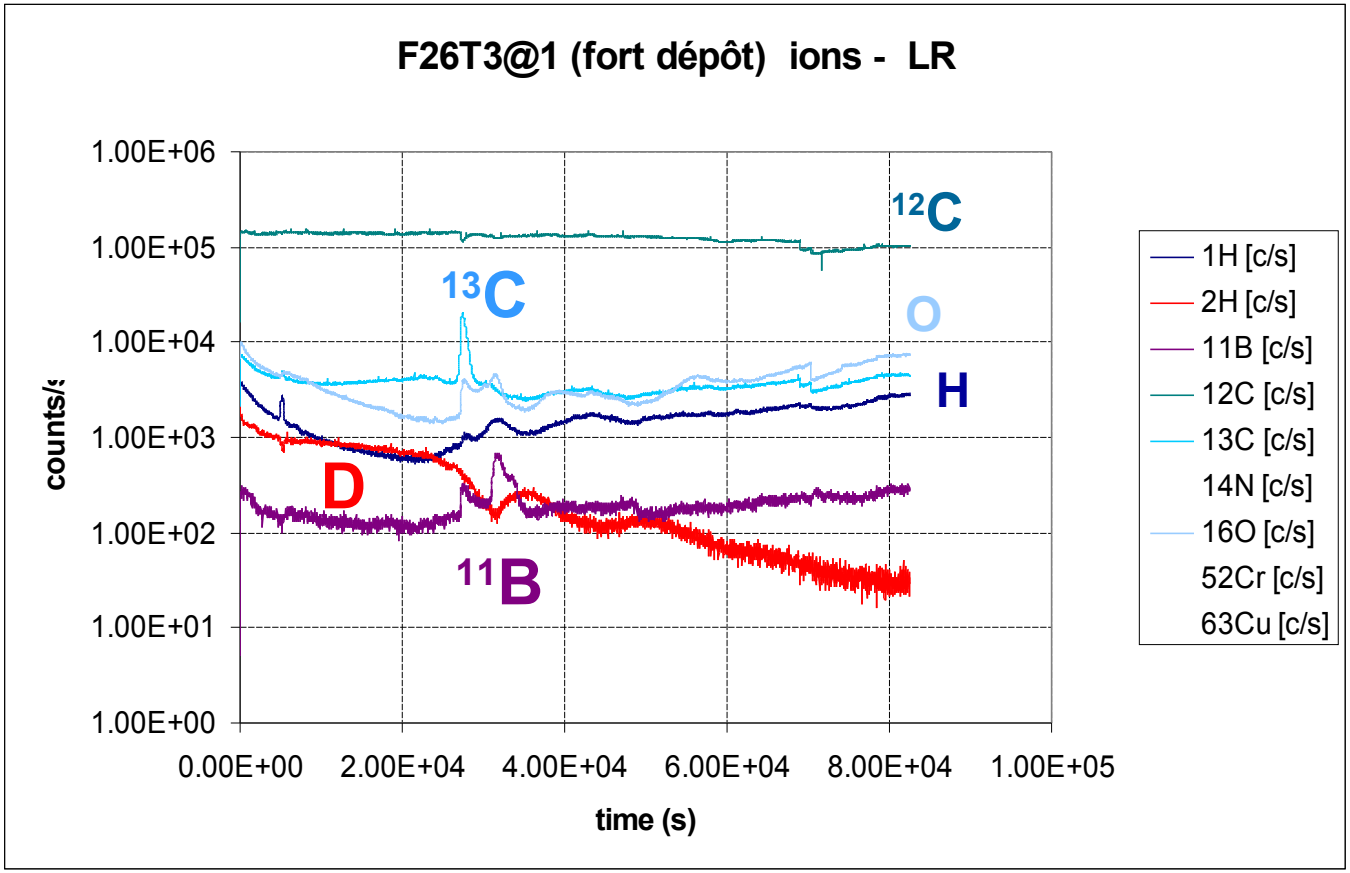


Z=10 µm

Localised in the bulk CFC :
Trapping sites = porosity along fibers
In TS : codep into CFC open pores...?

Preliminary SIMS results





^{13}C + ^{11}B markers visible (start of DITS campaign)
Quantitative analysis difficult (erosion speed)

Tore Supra : equipped for particle balance

Association Euratom-CEA

Exhaust system : TMP

- **TPL pumping** : **20 gauges**
- **Vessel Pumping** : **2 gauges**
- **LH pumping** : small conductance

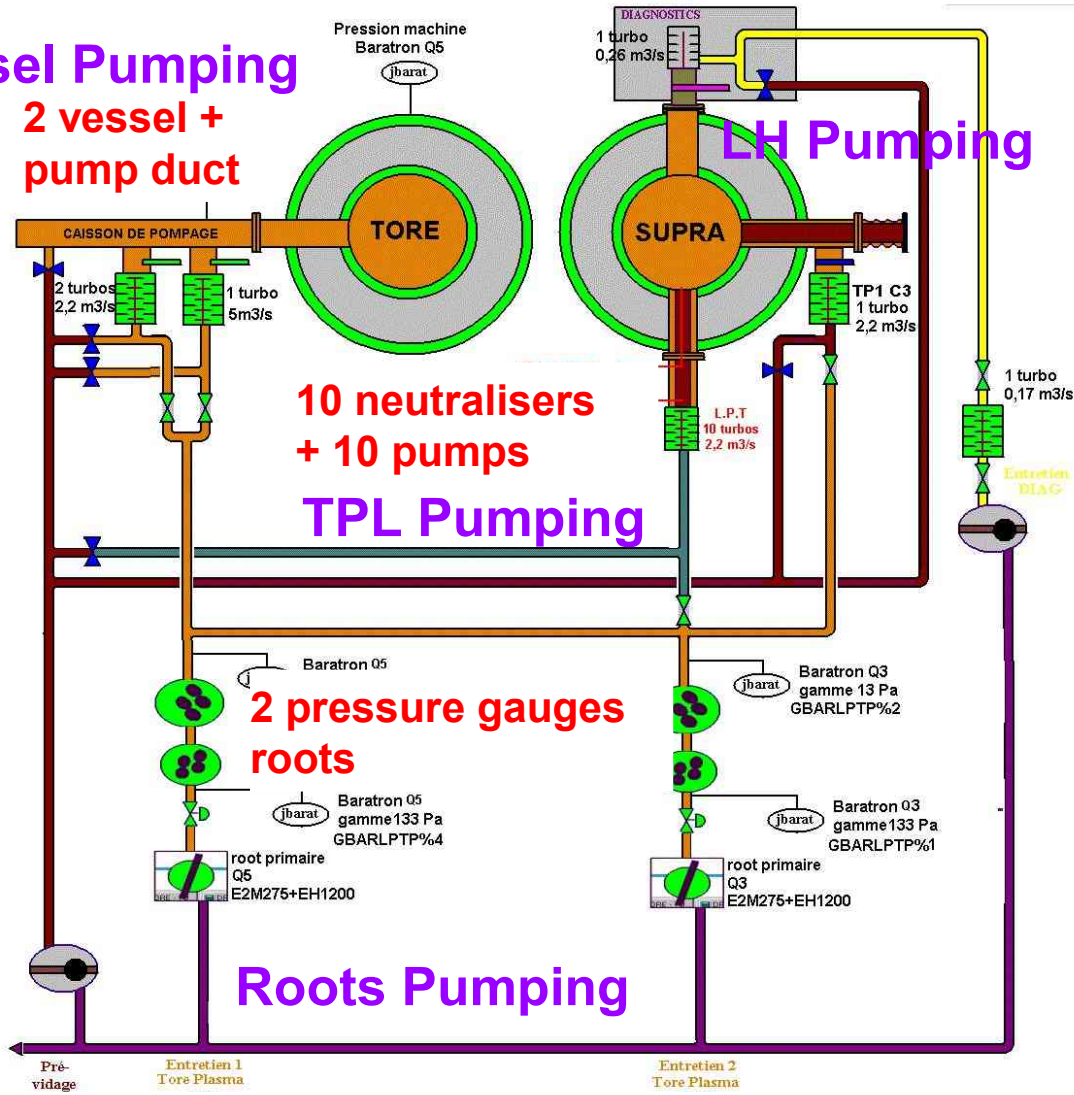
- TMP backed by 2 **roots pumps, 2 gauges**

Consistency checks :

- Calibration on gas injection
- TPL and roots : consistency check
- Pulse w and w/o active pumping

Adapted plasma operation

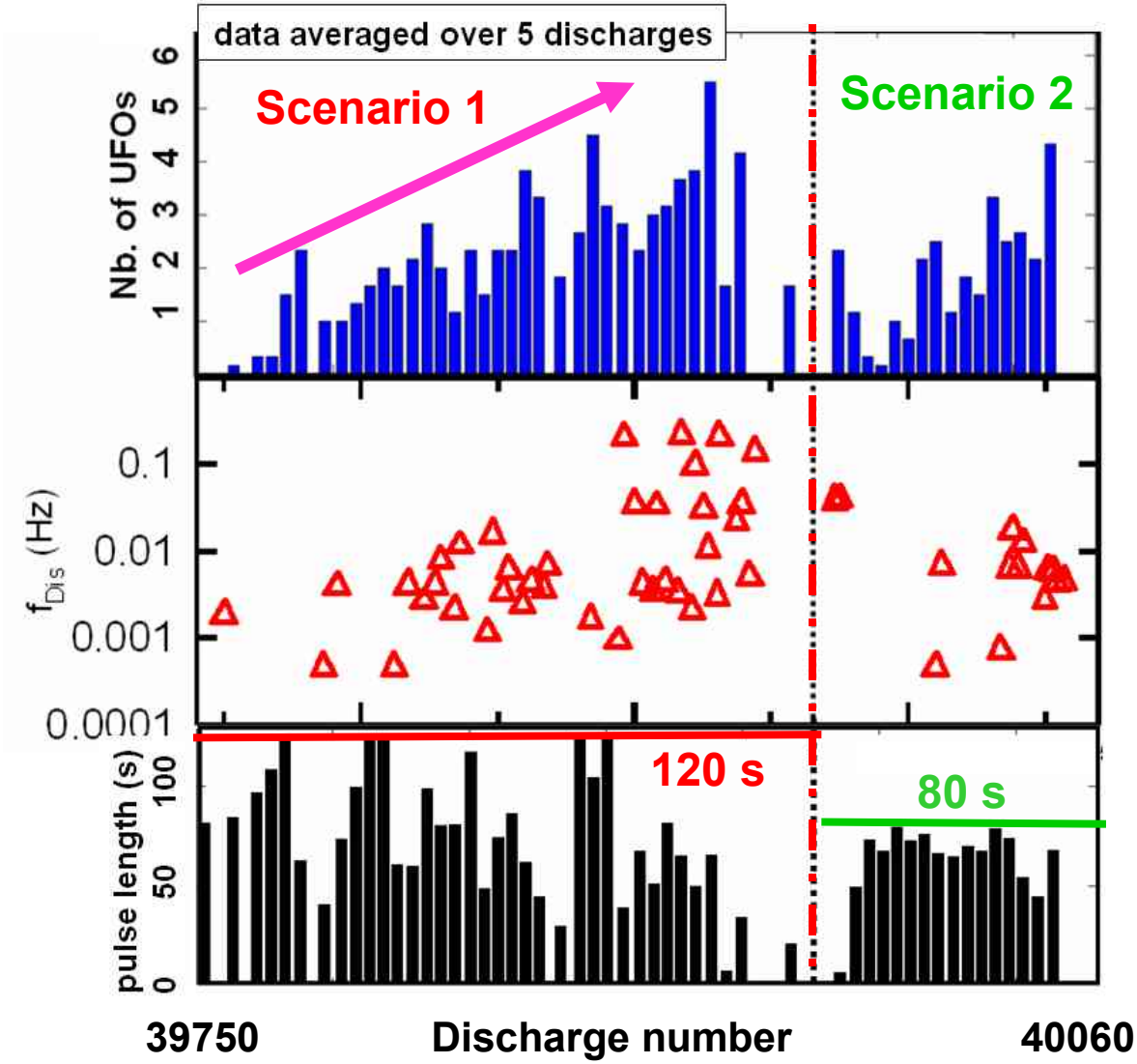
- Long pulse steady state for PWI (cst outgassing)



➔ Particle balance : robust tool on TS

DITS : UFOs limit plasma duration

UFO : Increase in Prad > 20%



Scenario 1 :
2 MW LH, 120 s

Scenario 2 :
1.6 – 1.8 MW LH, 80 s
Slower power ramp up

B. Pégourié et al., PSI2008

Global inventory from post mortem

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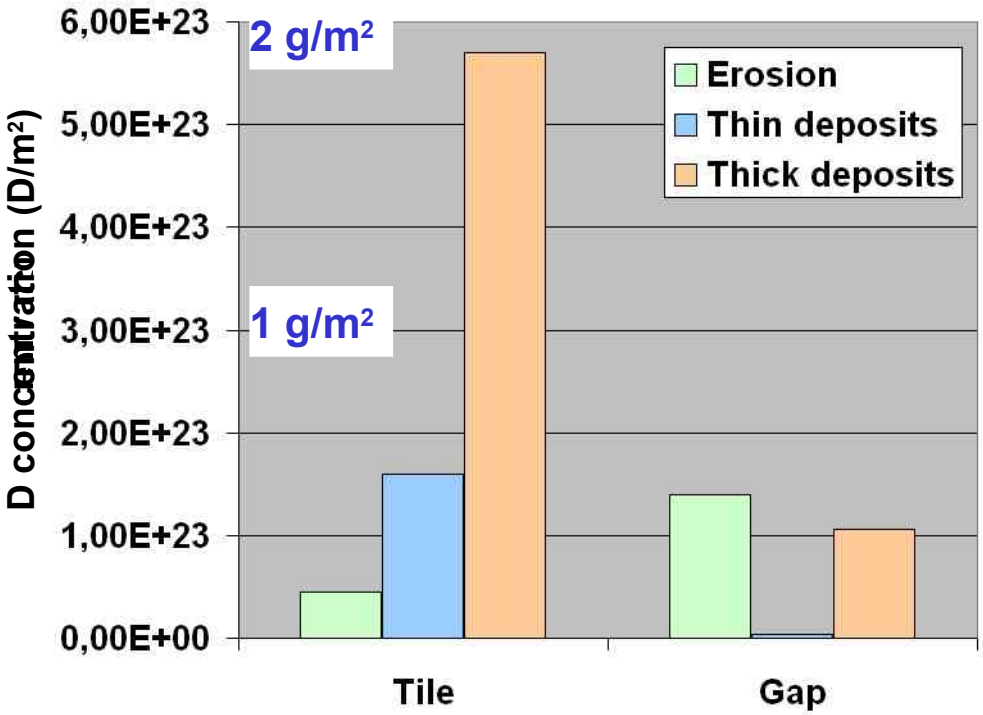
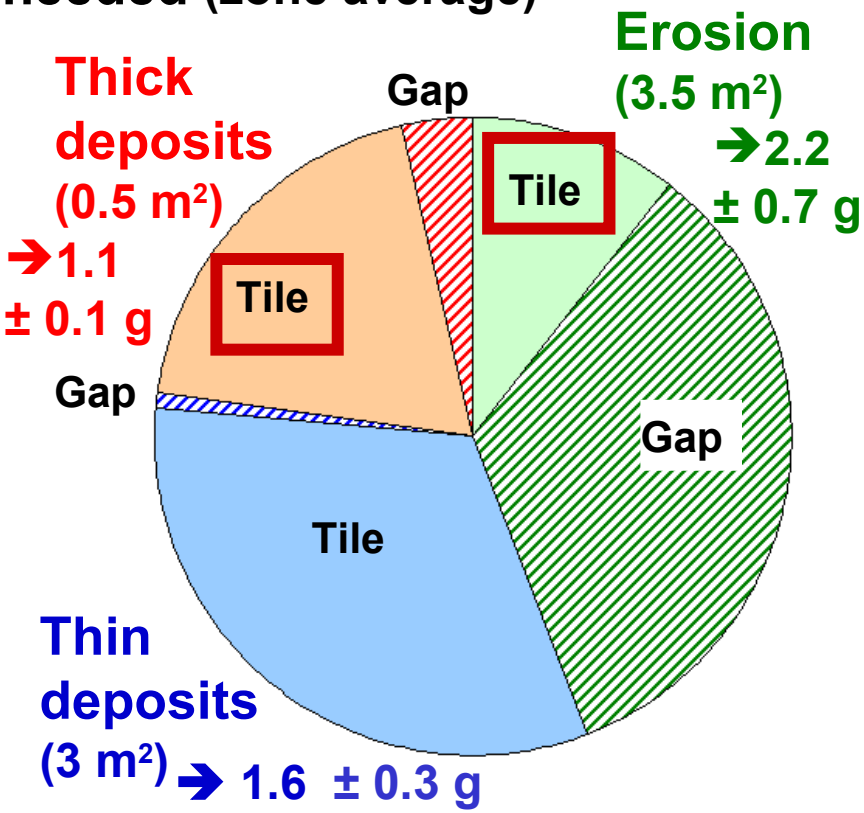
TORE SUPRA

Ongoing work ➔ more statistics needed (zone average)
(next analysis campaign ~30 tiles)





Retention mechanisms :

- **Codeposition dominant** (shadowed + gaps), 10 % bulk diffusion in erosion zone

Post mortem : 4.9 ± 1.1 g D ➔ **~ 50 % of particle balance**

➔ **significant progress** (10% in previous studies (thick deposits))

- **Lower limit** : loss of D with air exposure (6 months), other PFCs (inner bumpers)