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


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Tore Supra: Actively cooled PFCs with unique long pulse capability

⇒ Steady state PWI: relevant pulse duration + stationary 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 $C_{\text{Dmax}}$ reached in $d_{\text{imp}}$
  - small inventory

- **Codeposition**: C erosion/redeposition

- **Bulk diffusion**: trapping $>> d_{\text{imp}}$
  - Evidenced in lab experiment for CFC

Retention characterisation:

Particle balance (discharge)

\[ N_{\text{wall}} = \int \Phi_{\text{inj}} \, dt - \int \Phi_{\text{pump}} \, dt - N_p \]

Post mortem analysis (campaign integrated)

Previous studies: factor $\sim 10$ [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
Experimental campaign

Aim ➔ load the vessel walls with D

• Repetitive long pulses (2 minutes) on robust scenario:
  \[ I_p = 0.6 \text{ MA}, \, n_e/n_{GR} \approx 0.5 , \, 2 \text{ MW LH} \]

• 5 hours of plasma w/o conditioning
  (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 \( \sim 2 \text{ minutes} \)
• Long term release \( \sim 10\% \) of total exhaust
  ➔ \( \sim 50\% \) of injected gas trapped

➔ Post mortem analysis:

\(~ 10 \text{ g (3} 10^{24} \text{ D})\)
The DITS project
Sample extraction
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)

**NRA gaps**
- NRA top
- Top
- Medium

**Standard cutting** (7 tiles)
- TDS: top + medium

**Refined cutting** (3 tiles **: ero/thin/thick)
- NRA top
- TDS

**Toroidal gaps**

**Poloidal gaps**

**SIMS**

**Spare**

**NRA**

**TDS**
The DITS project
Post mortem analysis
Consistency NRA/TDS

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

**Gaps**

**Bulk**
D inventory in gaps

- **Erosion zone**: no major difference poloidal vs toroidal

- **D content in gaps**: significant for erosion/thick deposits, low for thin deposits

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**Thick deposits**
- Toroidal gaps
- Poloidal gaps

**Thin deposits**
- (far shadowed)

**No gap deposit visible**

**Erosion**
- Thin deposits
- Thick deposits

**Position in gap (mm)**
- 1
- 2
- 3
- 4
- 5

**D concentration (D/m²)**
- 0
- 5E+22
- 1E+23
- 1.5E+23
- 2E+23
- 2.5E+23
Bulk diffusion

Tile surface in erosion zone: \(2-7 \times 10^{22} \text{ D/m}^2 \Rightarrow x \times 10 > \text{implantation}\)

NRA \(\Rightarrow\) D down to 10 \(\mu\)m \(\gg\) \(d_{imp}\)

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

Lab exp. : not thermally activated \(\Rightarrow\) diffusion \[\text{[J. Roth et al., JNM 07]}\]

MicroNRA: deuterium mapping

Bulk « diffusion »: codeposition inside porosity network ?

Deposited layers: uniform

Bulk: localised Trapping sites = porosity along CFC fibers
Global inventory from post mortem

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: \(4.9 \pm 1.1\) g D ➔ \(-\sim 50\%\) 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)
Summary

Fuel retention 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 $\Rightarrow$ 10 g of D

Retention mechanisms: codeposition dominant
Erosion
  - Significant gap contribution
Erosion zone
  - Bulk diffusion (codeposition in porosities?)

Post mortem D inventory ~ 50 % particle balance
~ 5 g of D in limiter ($\pm$ 20 %) $\Rightarrow$ lower limit (D loss, other PFCs)

$\Rightarrow$ Towards reliable in vessel fuel inventory:
- Particle balance: how much / when? $\Leftarrow$ Scenario optimization
- Post mortem: how much / where? $\Leftarrow$ Detritiation
Annex
D-inventory: effect of time

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

\[ Q_D = 1.97 \times 10^{21} \exp(-t/442.2) + 8.16 \times 10^{21} \exp(-t/22517) \]
where \( Q_D \) is the D amount (0-16 \( \mu \)m) expressed in D/m²,
\( t \) is the storage time expressed in h

- 65%

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)

200 eV D ions, 300 K

V. Alimov, J. Roth,

Incident fluence (ions/m²)

DIT retained (atoms/m²)

1 ITER discharge
for Be or W

1 ITER discharge
for CFC

Be
pyrol. graphite
crystall. graphite
CFC
VPS W
polycr. W
pyrol. graphite
Be
Other PFCs cleaning

Antenna limiters

Inner bumpers
Scraped deposits

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

Inner bumpers, outboard limiter,
antennas guard limiters : 645 g of dust
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

### Scenario 1
(nominal 2 MW – 120 s)

- Reliably operated
- 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

### Scenario 2
(lower power ~ 80 s)

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

- Scenario at lower LH power (< 1.8 MW) + slow ramp up
Constant D-retention rate during campaign

\[ \delta WI = \text{Inj.Gas} - \text{Exh.Gas} - \text{Post.Rec} \]

D-retention rate ~ 2 g/h
Disruptions at low Ip

not perturbative for particle balance
Global wall inventory

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

Background chamber pressure $\sim 6 \times 10^{-5}$ Pa ($\sim 50\%$ D)

Total exhausted $\sim 0.6$g D

Global $\Delta$WI $\sim 10$g D ($3.0 \times 10^{24}$ atoms)
Magnetic configuration on the limiter

Field line modelling

- Plasma loaded
- Shadowed
- Thin deposits
- Thick deposits
- Erosion

(Shadowed)

(far SOL)

(plasma loaded)
TPL temperature pattern (IR imaging)

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

Deposition zone:
Thick deposits ~ 500-1000 °C
Shadowed area ~ 120 °C

Erosion zone:
Tile surface ~ 200-300 °C
Gap deposits ~ 500 °C

Shot 39743, 115s

[A. Ekedahl, P. Moreau]
Experimental campaign

- Repetitive long pulses (2 minutes) on robust scenario
  \( (I_p = 0.6 \text{ MA}, 2 \text{ MW LH}, ne/n_{GR} \sim 0.5) \rightarrow \text{load the vessel walls with D} \)

- 5 hours of plasma w/o conditionning (1 year of operation in 2 weeks)
  \( \rightarrow \text{pre-campaign D inventory x 4} \)

- Main limitation: UFOs
  \( \rightarrow \text{lower LH power (1.8 MW)} \)

Particle balance:
- No wall saturation
- Release after shot << wall inventory
- Long term \( \sim 10\% \) of total release
- \( \sim 50\% \) of injected gas trapped

\( \rightarrow \text{Post mortem analysis:} \)

\~ 10 g \( (3 \times 10^{-24} \text{ D}) \)
a) TOP SAMPLES

Gap contribution

Desorbed D atoms / sample

- CD3H
- CD4
- HD
- D2

Erosion zone

Thick deposits

Thin deposits

F1-T3  F4-T2  F26-T9**  F26-T11  F27-T8  F27-T20  F4-T9  F26-T3**  F27-T4

• ≠ standard and ** samples : gap contribution
TDS : gap contribution

Deuterium content

b) MIDDLE SAMPLES

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

- Erosion
- Thick deposits
- Toroidal gaps

- Thin deposits (far shadowed)
- No gap deposit visible
NRA : non uniform D concentration

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
Using sophisticated analysis tools

Amorphous layer of 3.5 µm

CFC matrix

MicroNRA: deuterium mapping

D concentration [at.%]

Depth [µm]

Homogeneous in redeposited layer

Localised in the bulk CFC:
Trapping sites = porosity along fibers

In TS: codep into CFC open pores
Tile analysis - NRA: D(He,p) He

Local measurement / surface D- concentration

Significant dispersion from sample to sample

~80% of D found in the first 30-40µm

- Thick deposits
- Thin deposits
- Erosion zone

Thick deposits
Thin deposits
Erosion zone

0.30
0.25
0.20
0.15
0.10
0.05
0.00

[D]/[C]

0 10 20 30 40

depth (µm)

~80% of D found in the first 30-40µm
Preliminary SIMS results

Crater F1/T3 (erosion)

F26T3@1 (fort dépôt) ions - LR

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

![Graph showing fuel retention over time](image)
Tore Supra: equipped for particle balance

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
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 …
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

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

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Post mortem: 4.9 ± 1.1 g D ➔ ~ 50% of particle balance ➔ significant progress (10% in previous studies (thick deposits))

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