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**
- $R = 2.4 \text{ m}$
- $a = 0.7 \text{ m}$
- $V = 25 \text{ m}^3$
- $B = 3.4 \text{ T}$
- $I_p = 1.7 \text{ MA}$
- $P = 10 \text{ MW}$

**ITER**
- $R = 6.2 \text{ m}$
- $a = 2.0 \text{ m}$
- $V = 840 \text{ m}^3$
- $B = 5.3 \text{ T}$
- $I_p = 15 \text{ MA}$
- $P = 500 \text{ MW}$
Discharge / plasma parameters

4mn 25 & 0.75 GJ
limitation : LH power

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

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

**Density:**
\[ n(\text{LCFS}) \sim 4 \times 10^{18} \text{ m}^{-3} \]
\[ \lambda_n \sim 4.6 \text{ cm} \]

**Temperature:**
\[ T(\text{LCFS}) \sim 70 \text{ eV} \]
\[ \lambda_T \sim 4.3 \text{ cm} \]

**High energy of incident ions on the neutralizers:** \( \sim 100 \text{ eV} \)
Tore Supra : the CIEL configuration

- Toroidal pump limiter (TPL)
- Outboard movable limiter
- Bumpers
- Vessel protection panels

- Total CFC : 15 m² ; TPL : 7 m² ; in strong interaction with plasma : 3.5 m²
- 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

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

- Pumped inventory:
  40–50% of injected particles

- Wall inventory:
  50–60% of injected particles (120 Pam$^3$)

- Dynamic retention rate:
  \(210^{20} \text{ D/s or } 0.8 \text{ mg D s}^{-1}\)

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

![Graph showing puffing rate over time](image)

- Time (s)
- $\Gamma_{\text{puff}}$ (Pam$^3$/s$^1$)

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Transient D retention (1 discharge)

Transcient 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 : $1.5-2 \times 10^{22}$ D recovered

Short pulses:
Particle balance closed with He glows

Long pulses:
Need to find particle recovery means

B. Pégourié
H2-Surface, Paris, 13-14/06/2005
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 = \(2 \times 10^{20} \text{s}^{-1}\) ~ independent on plasma conditions
6 hours of **He glows**: $1.5 - 2 \times 10^{22}$ D
~ independent on what was trapped

**Taylor discharges**: ~ He glows

**disruptions**: up to $5 \times 10^{22}$

but: $I_p > 0.8$ MA
variable efficiency
(depend on the wall history ?)
what D content in the gas?

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**Total permanent retention for a campaign:**

$$2 \times 10^{20} \times \sum_{\text{shots}} (\text{duration}) - \sum_{\text{recovery}} (\text{outgassing, glows, disruptions}) = 4 \times 10^{23} \text{ D}$$
Complex pattern of deposition: films, flakes, dust
Carbon deposits (2)

neutralizers (after ~8500 s of plasma)

150 μm

200 μm

plasma
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**

- **ToF-SIMS**
  - 4600 s
  - \(~17 \text{ nm/s}\)
  - 1800 s
  - \(~25 \text{ nm/s}\)

- Maximum growth rate \(~20 \text{ nm/s}, \text{ within a factor of 2}\)

- **X-ray EDS**
  - Boron-rich sub-layer

- **B. Pégourié**
  - H2-Surface, Paris, 13-14/06/2005
[D]/[C] ; D content : NRA results

LPT: $1.8 \times 10^{22}$ D
Neutralizers: $2.7 \times 10^{20}$ D
C2: $1 \times 10^{22}$

Total inventory in deposits: $5 \times 10^{22}$ D

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.
Deuterium retention – global balance

Last experimental campaign ~ 20 000 s of plasma

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

**Total D retention**
(retention rate ~ $2 \times 10^{20}$ D/s, i.e. ~ 0.1 % of the recycling flux
....and almost independent on edge conditions)
$2 \times 10^{20} \times \sum_{\text{shots}} \text{(duration)} - \sum_{\text{recovery}} \text{(outgassing, glows, disruptions)}$
~ $4 \times 10^{23}$ D (~ 90 % recovered due to short pulses)

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

$3.5 \times 10^{23}$ 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 ~ $3 \div 14 \times 10^{-6}$)
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 (1.4 \times 10^{26} \text{ 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 / T retention recovery means, deposits removal with W-PFCs, optimized operation**