Hydrogen retention and outgassing analysis with examples from JET-ILW, including long-pulse discharges

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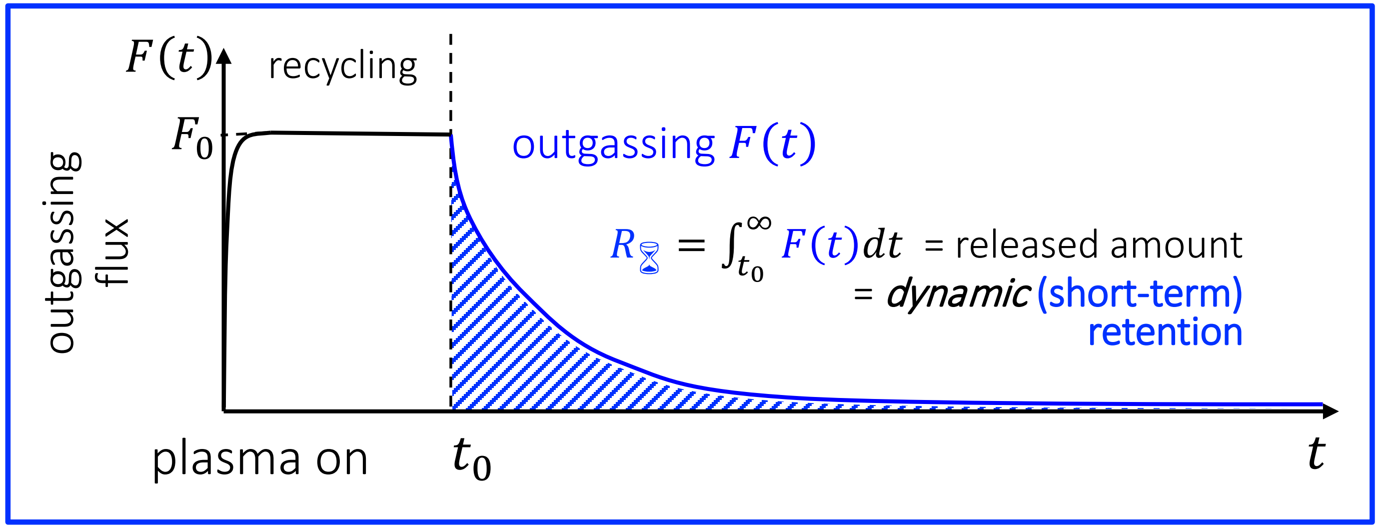
Plasma-wall interaction (PWI)

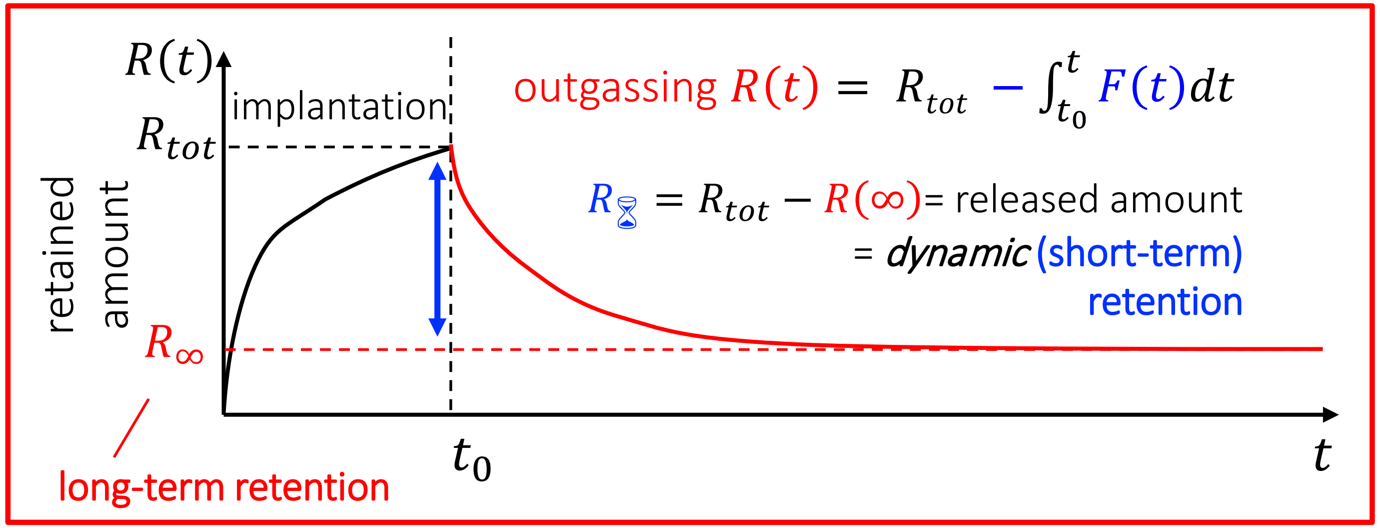
- PWI aspects of wall heat loads:
  - Potential failure of plasma-facing components (PFC)
  - Effect of wall temperature on fuel recycling

- PWI aspects of wall particle loads:
  - Material erosion (wall life time)
  - Plasma contamination (dilution, radiation)
  - Material re-deposition (potential for dust formation, retention via co-deposition)

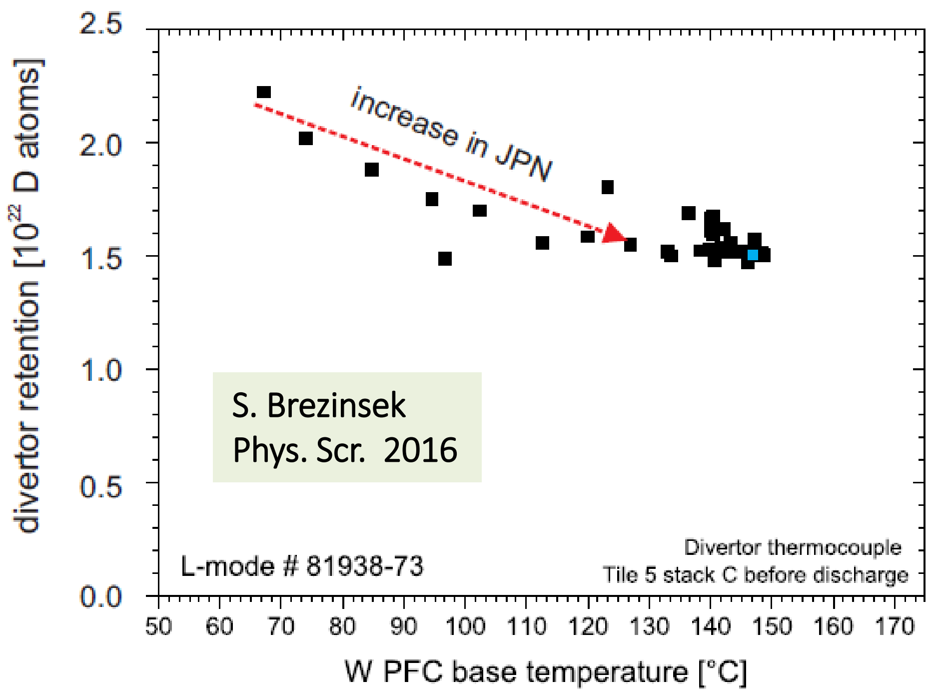
- PWI aspects of hydrogen (H/D/T) fuel:
  - Wall pumping ↔ plasma fueling
  - Fuel retention via implantation (and diffusion), co-deposition
  - Fuel permeation to coolant
  - Fuel release between pulses (base pressure for plasma start-up)

Short-term (transient) and long-term (permanent) retention





Short-term ($R_{⌛}$) and long-term (R_∞) retention can grow or decrease from pulse to pulse depending on the wall temperature and particle flux evolution



Fuel retention measurement

Local measurements

- Lased-based methods
- Inter- or intra-shot
- Short- or long-term

Intra- and inter-shot gas balance

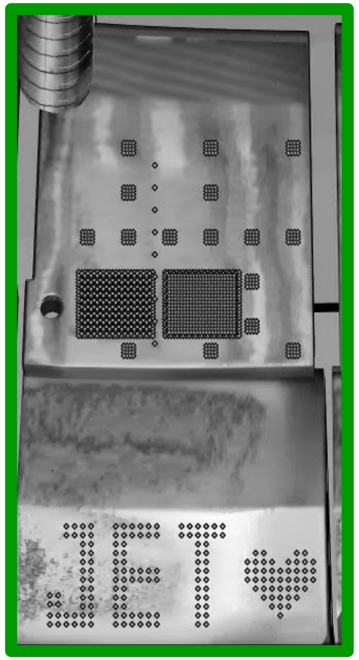
- Single discharge
- Transient effect
- Short-term retention

Global gas balance

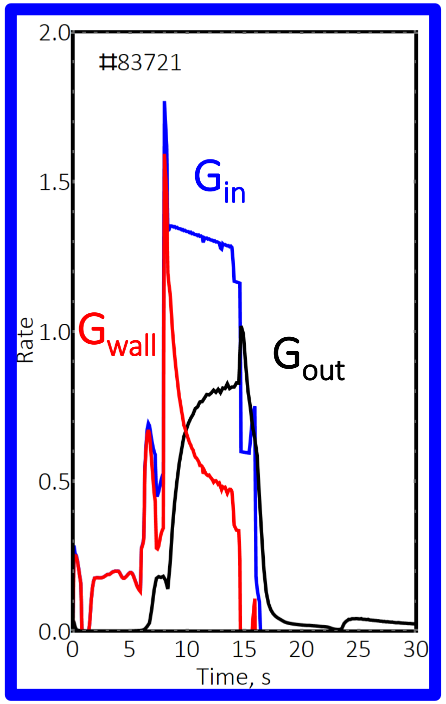
- Multiple discharges
- Includes inter-shot outgassing
- Long-term retention (~1 day)

Post-mortem analysis

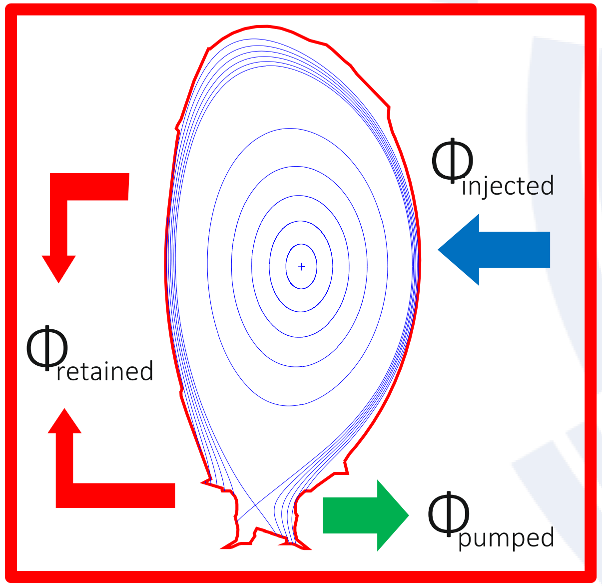
- Entire campaign or longer
- Includes outgassing in long-term
- Long-term retention (~1 year)



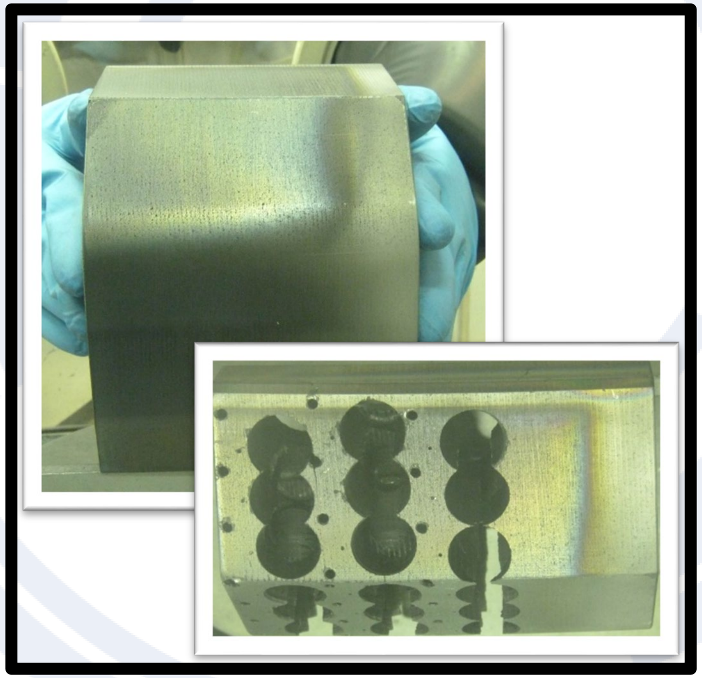
Local retention



Retention per pulse



Upper limit on fuel remaining in the vessel



Permanent in-vessel inventory

Particle balance equation

Particle balance equation [J. Bucalossi, EPS-28 2001]:

$$\int_0^t Q_{gas}dt+\int_0^t Q_{NBI}dt+\int_0^t Q_{pellet}dt=\langle n_e\rangle V_p+\int_0^t P_{ves}S_{ves}dt+\int_0^t P_{div}S_{div}dt+N_{Wall}$$

Q_{gas} , Q_{NBI} , Q_{pellet} – particle injection rates for gas, NBI and pellet fueling

$<n_e>$ – volume average plasma density,

V_p – plasma volume

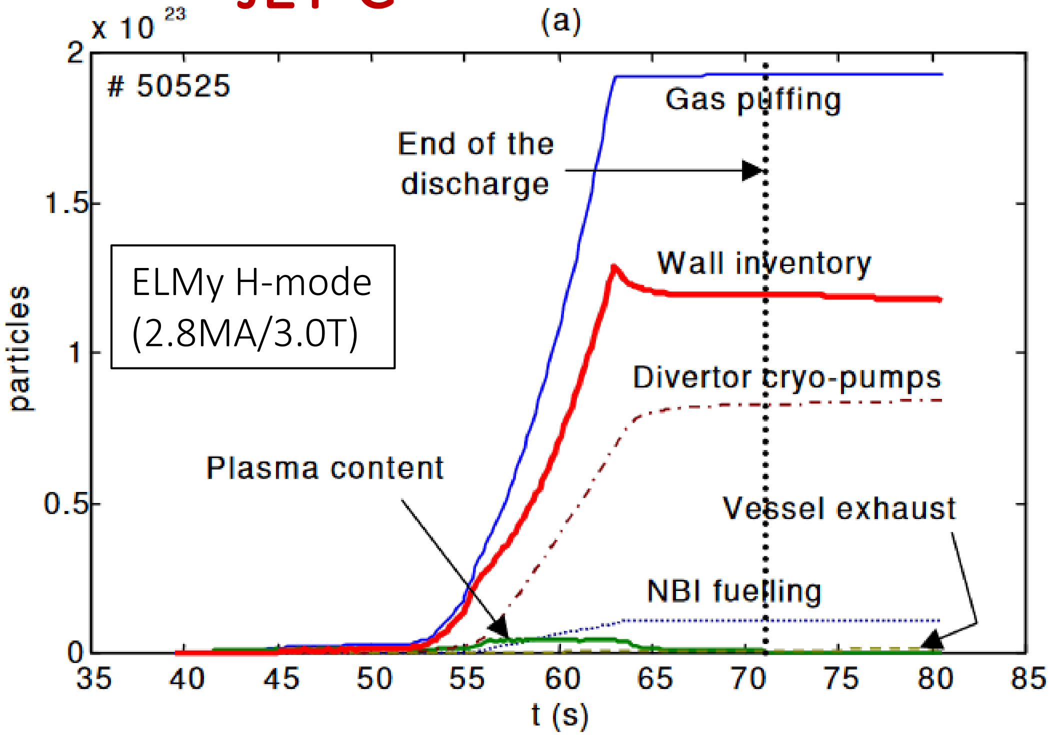
($<n_e>V_p$ = plasma content)

$P_{ves/div}$, $S_{ves/div}$ – vessel/divertor neutral pressure and pumping speed

(PS = pumping rate)

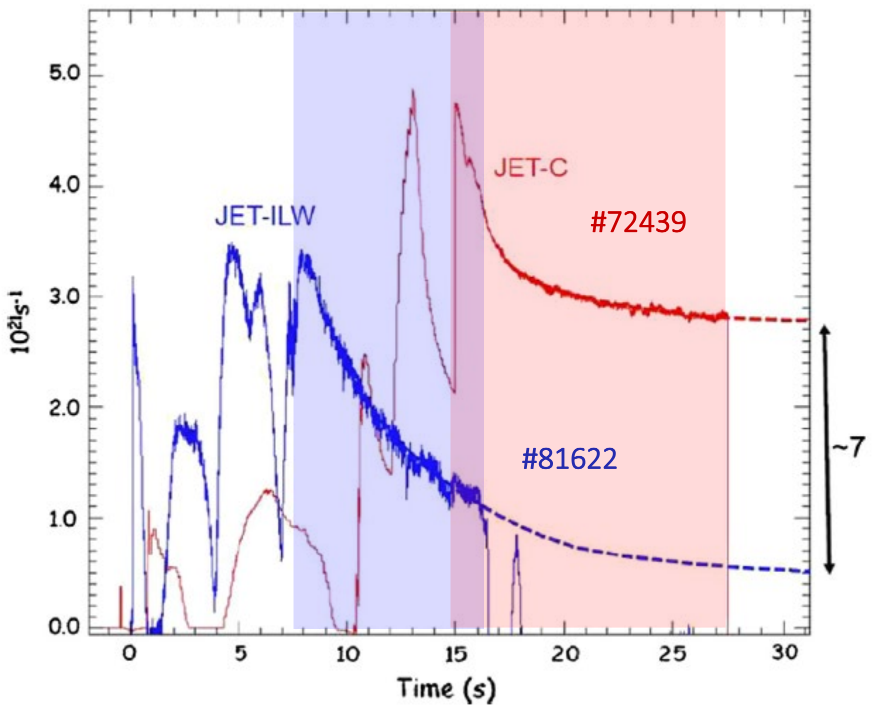
N_{wall} – amount of particles trapped in the wall

JET-C



Gas balance in JET-ILW

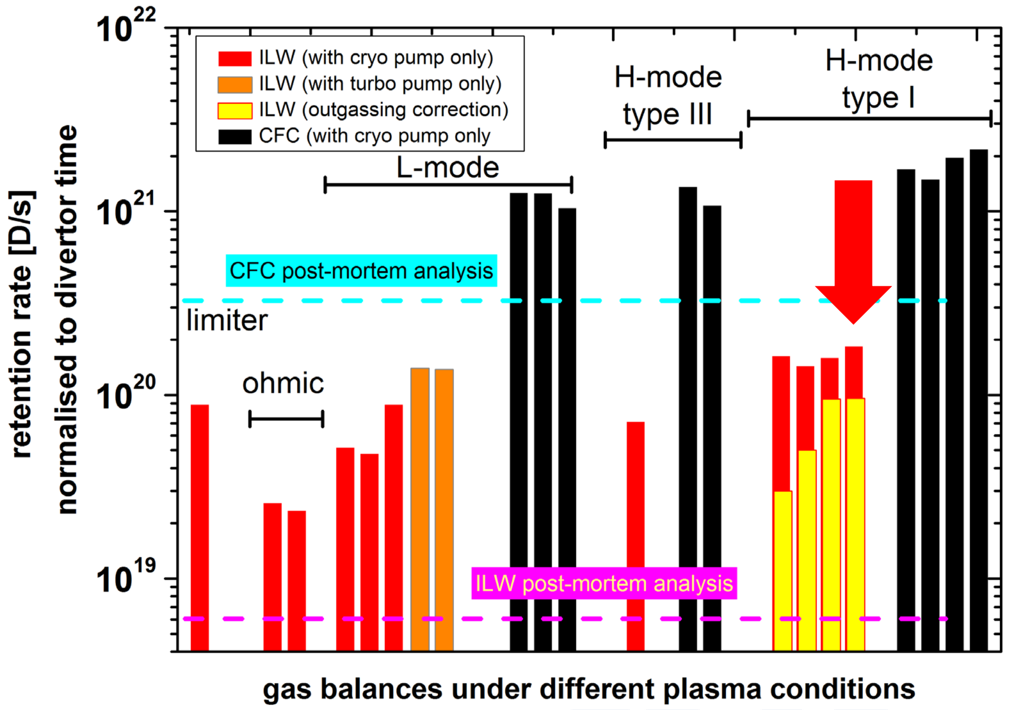
Intra-shot retention rate



T. Loarer et al., JNM 438 (2013) S108

No saturation of wall retention is observed in earlier JET-ILW gas balance experiments (2011-2012)

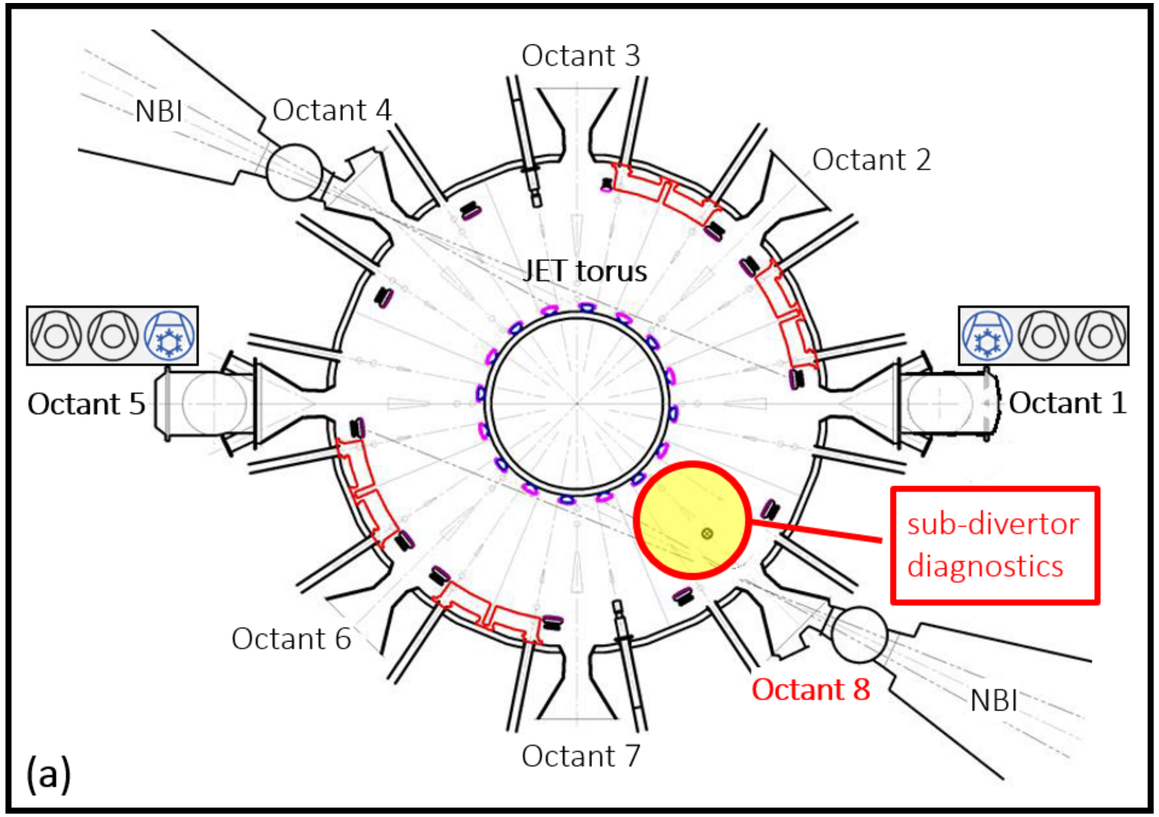
Global retention rate

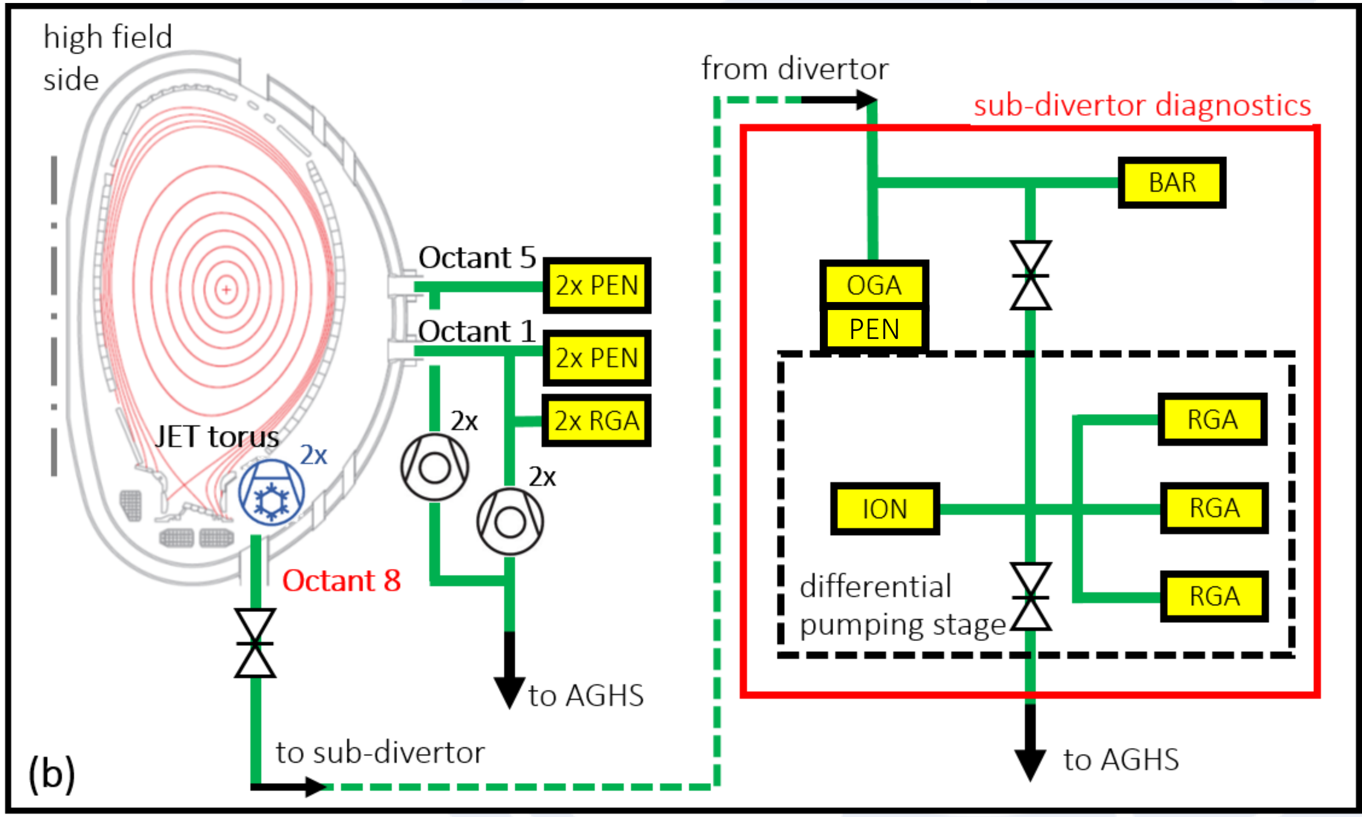


S. Brezinsek et al., NF 53 (2013) 083023

x20 lower retention rates in JET-ILW compared to JET-C
Global retention rates from post-mortem analysis (~0.2%) disagree with gas balance by factor 4 – 20 (strong contribution from outgassing)

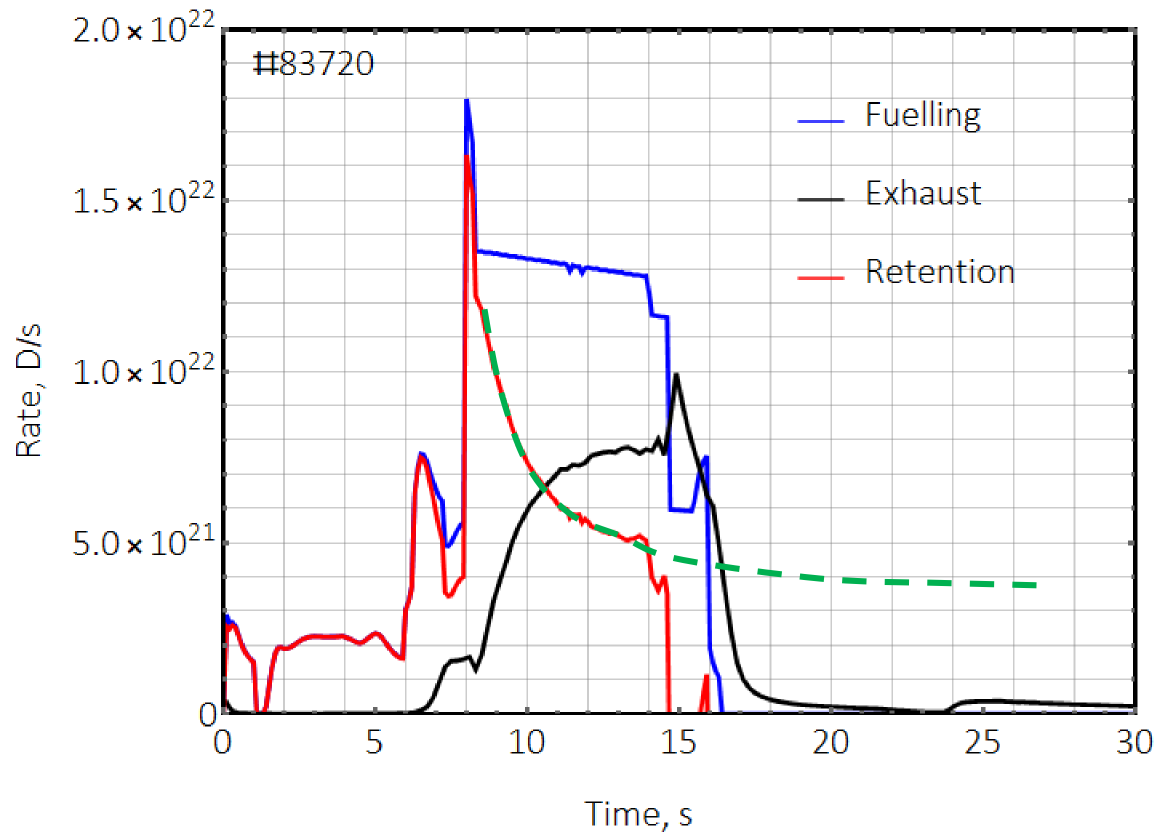
JET neutral gas diagnostics



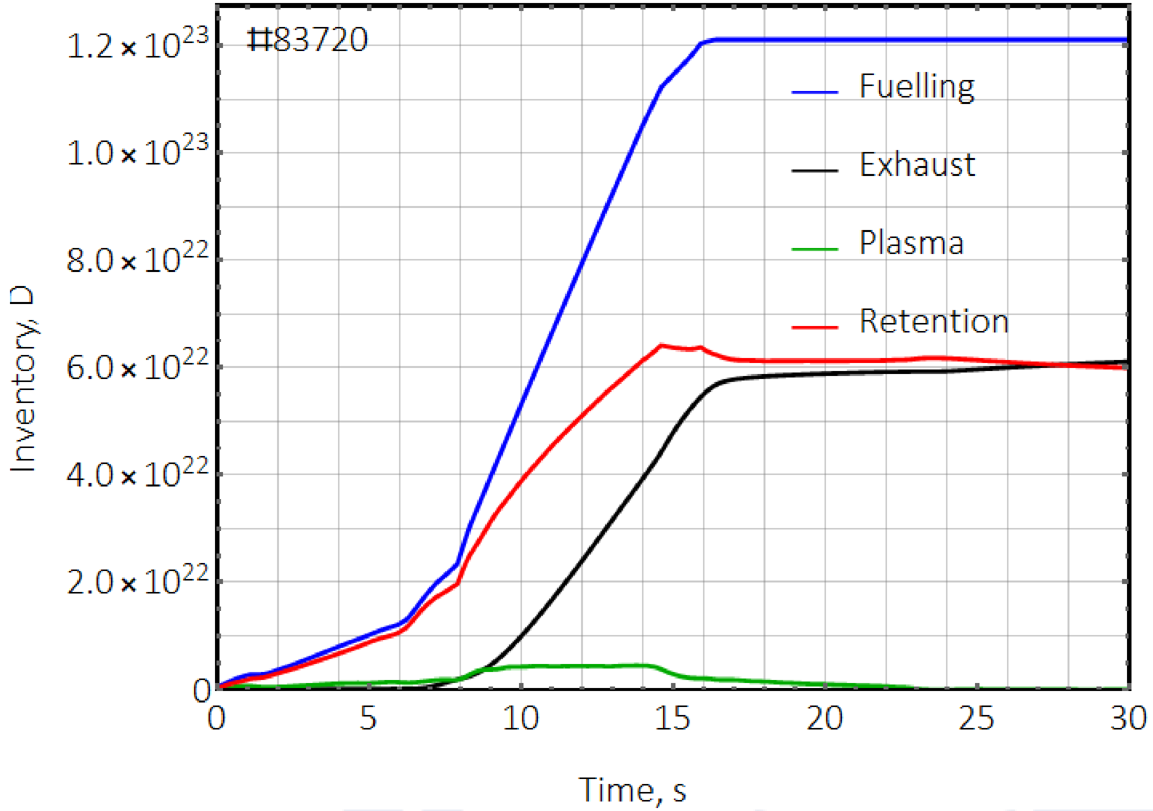


Intra-shot gas balance for earlier JET-ILW pulses (2012)

Retention rate



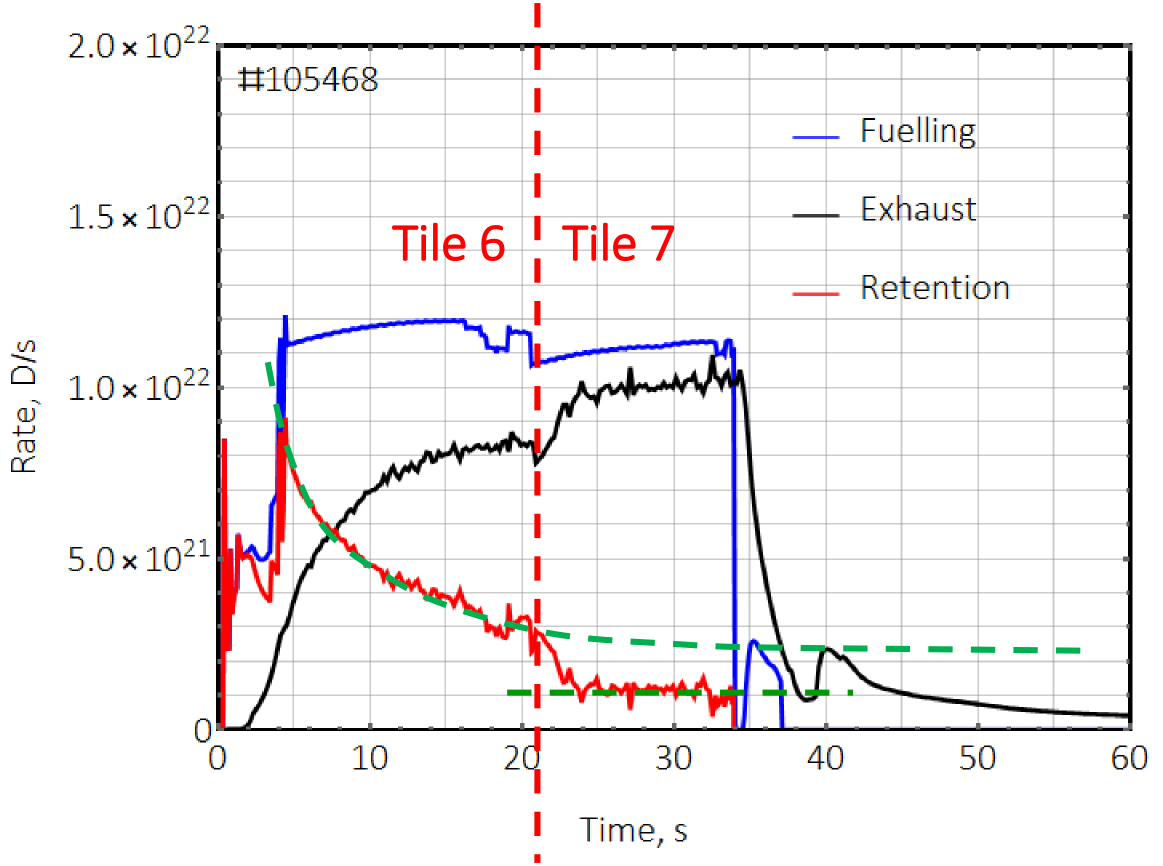
Cumulative inventory



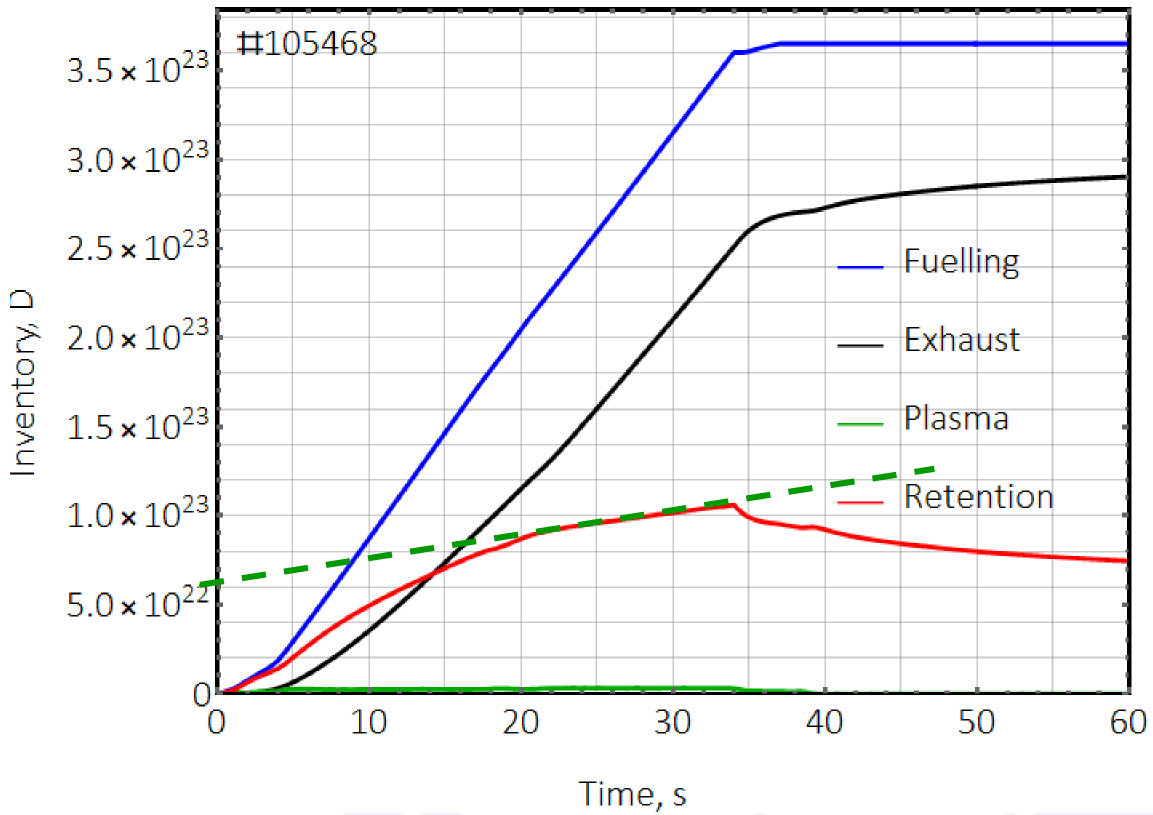
Steady-state retention rate is expected
for pulses with flat-top duration >20s

Intra-shot gas balance for 30s pulses

Retention rate



Cumulative inventory



Steady-state retention rate reached in 30s pulses
15% reduced divertor pumping when on Tile 7 ?

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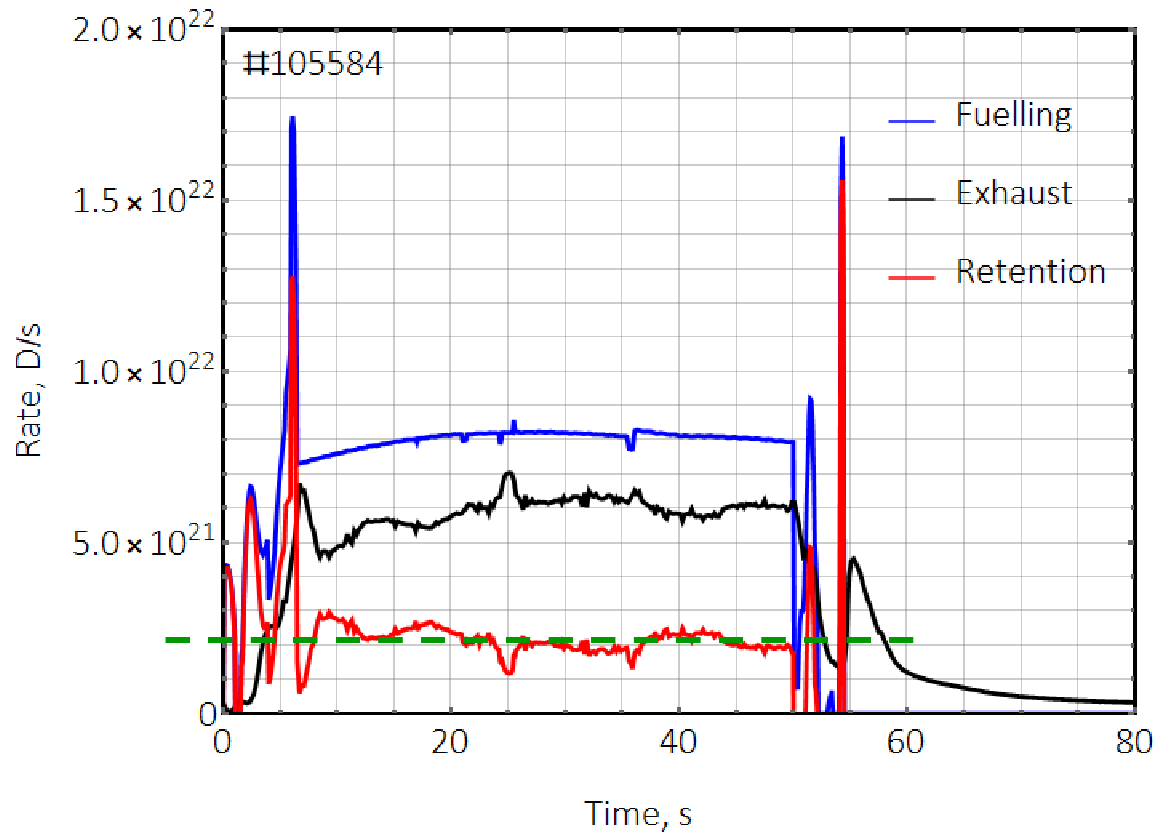
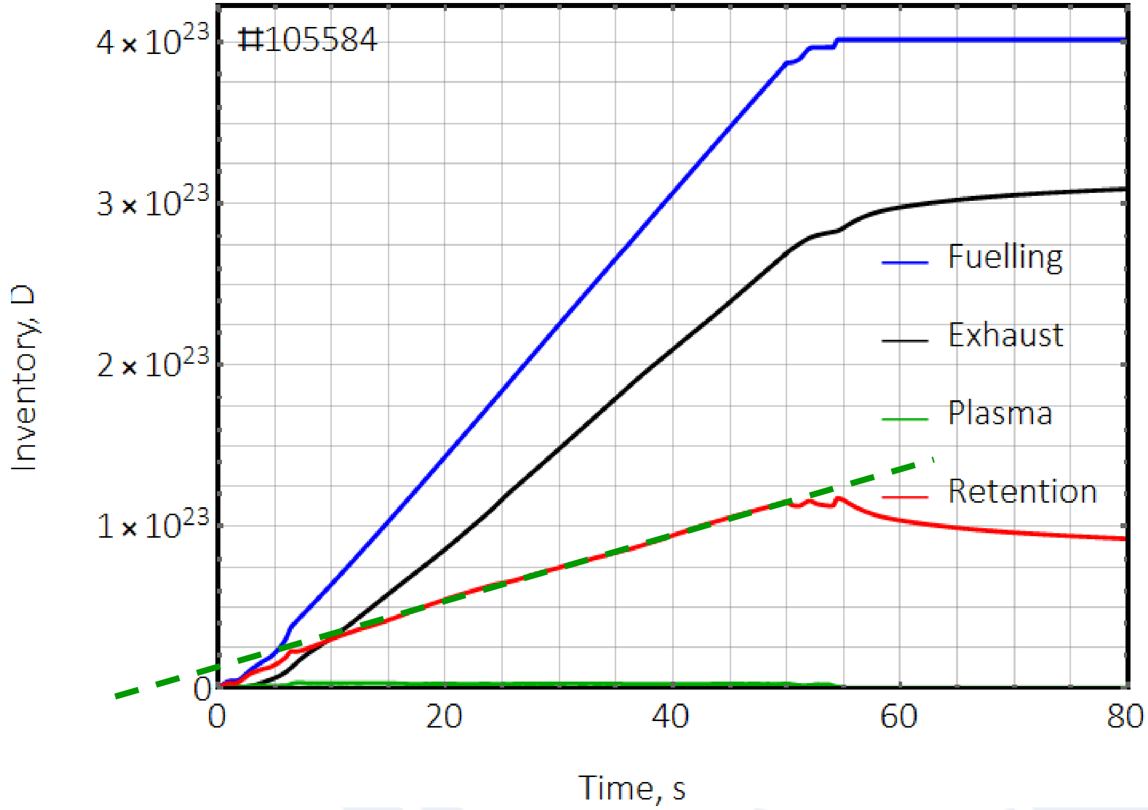
Intra-shot gas balance for 50s pulses

Retention rate



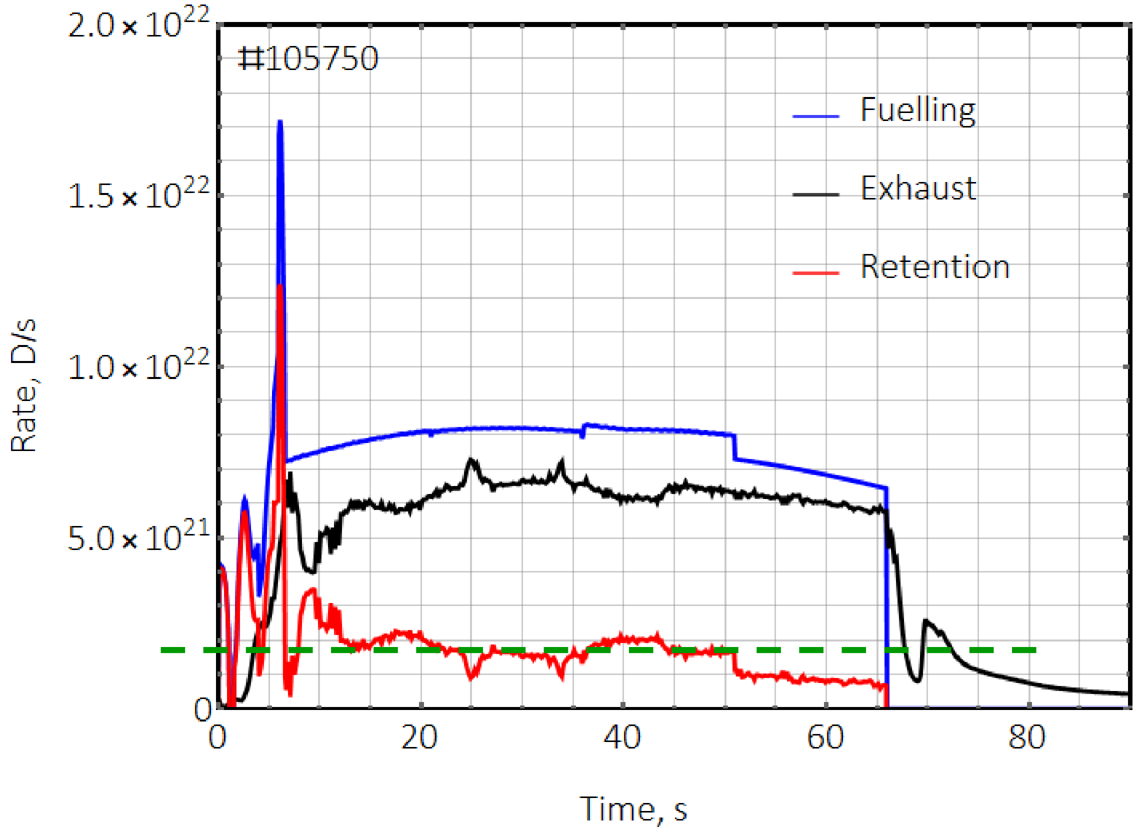
Cumulative inventory



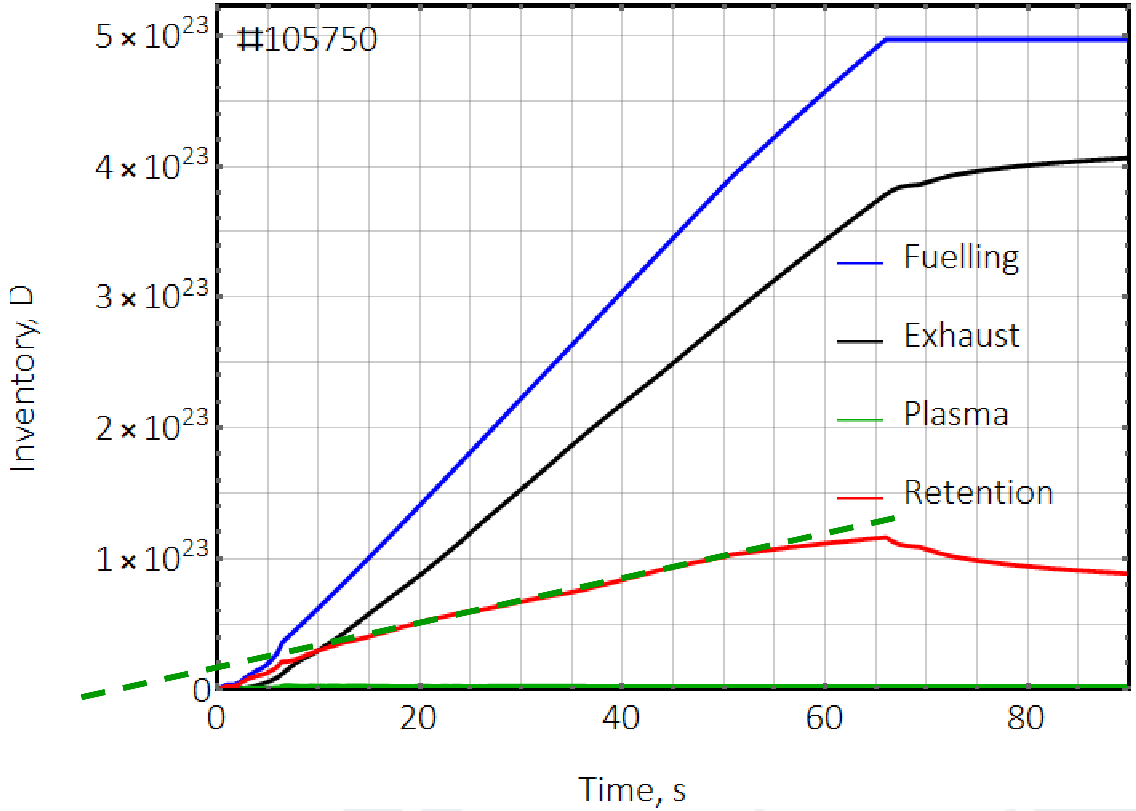
“Dynamic” steady-state retention rate…

Intra-shot gas balance for 60s pulses

Retention rate



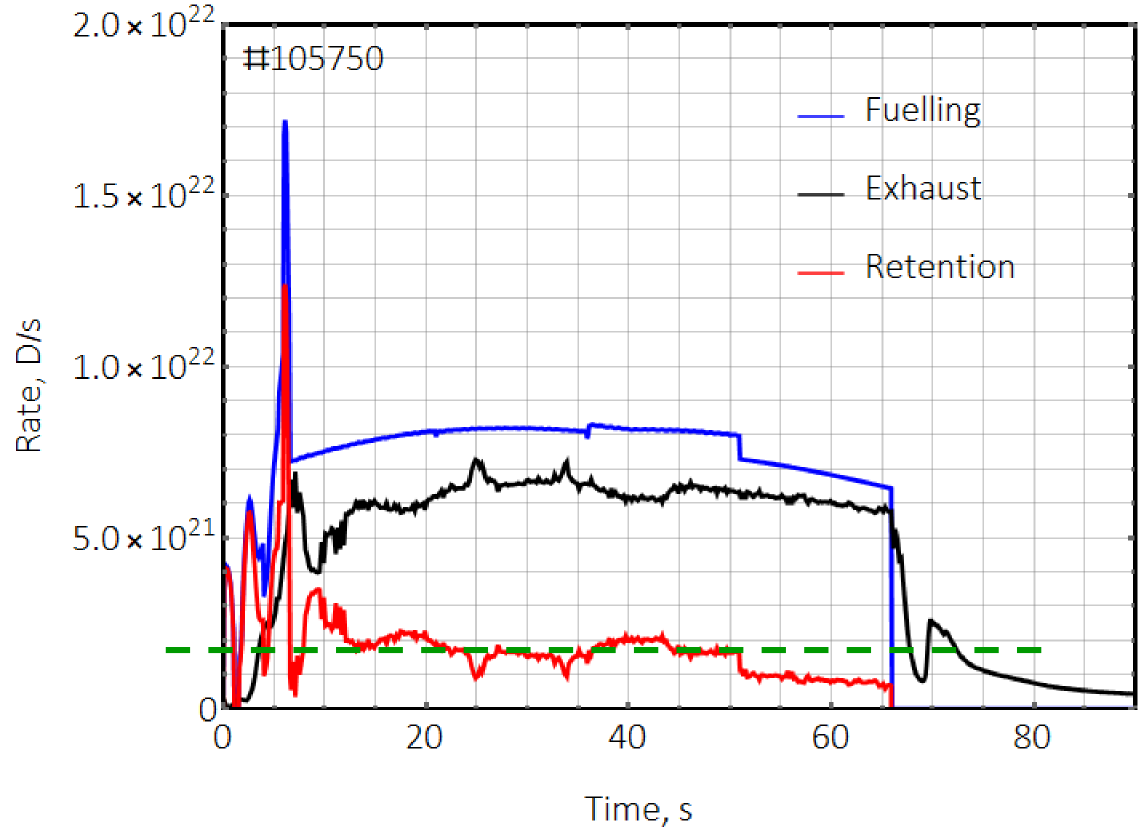
Cumulative inventory



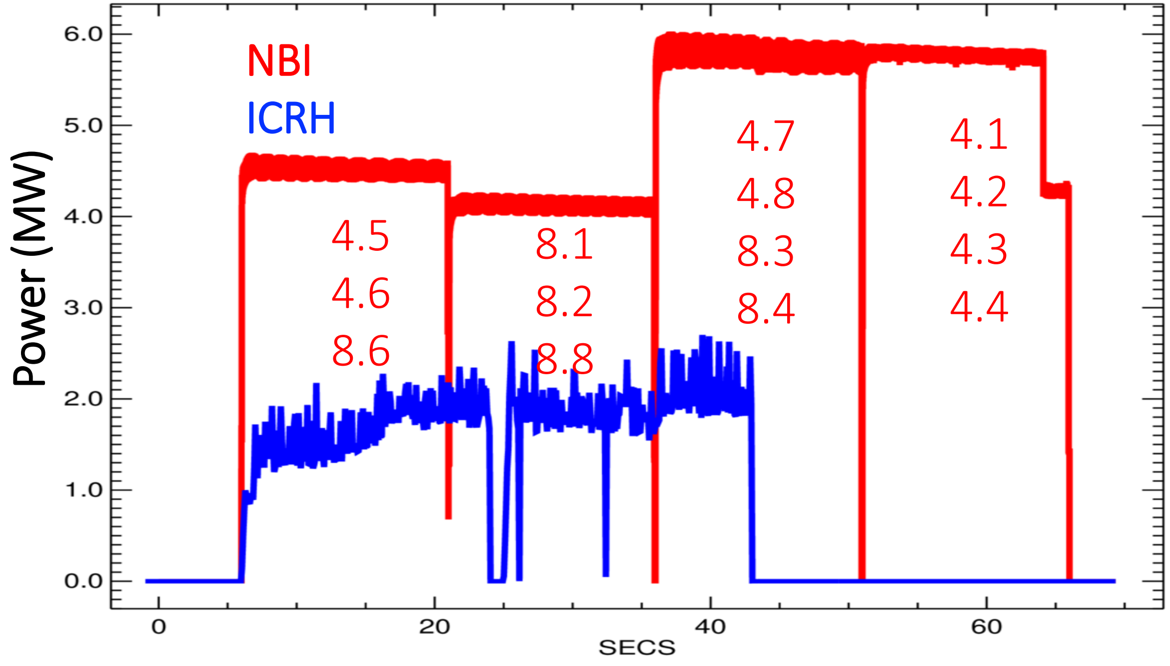
"Dynamic" steady-state retention rate…

Intra-shot gas balance for 60s pulses

Retention rate



Change of the heating arrangement

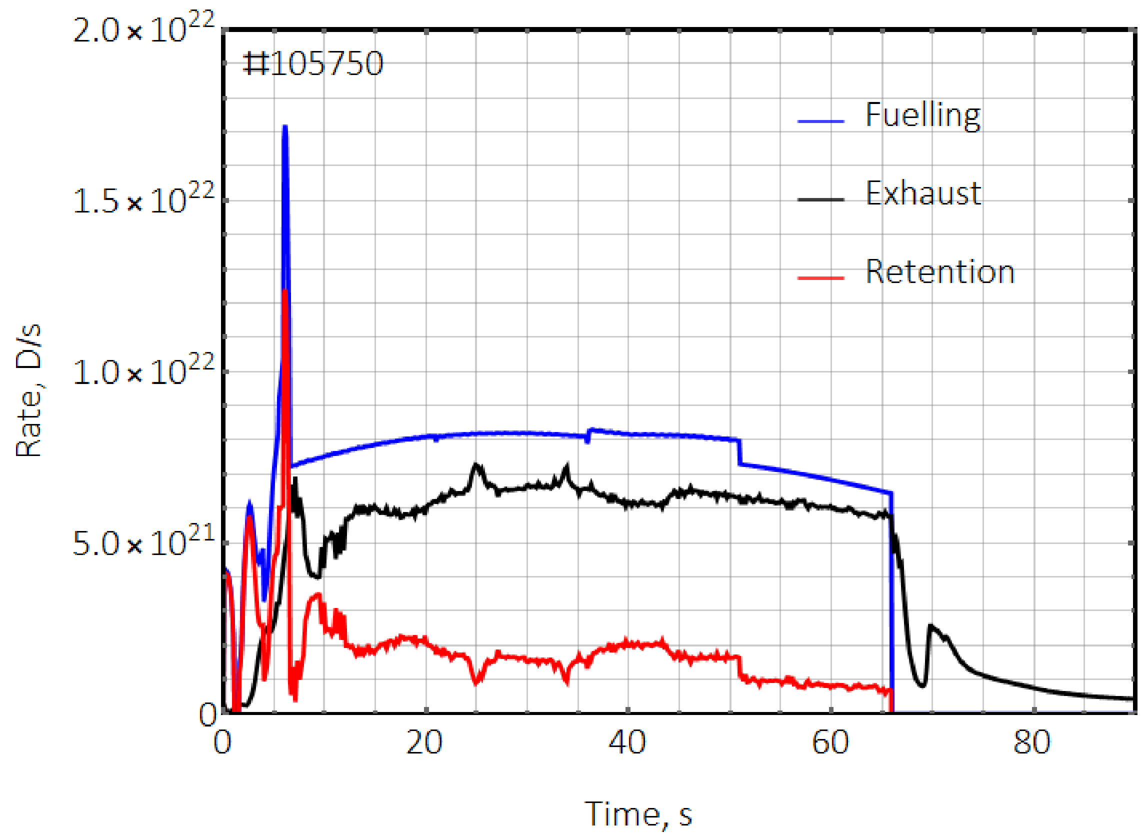


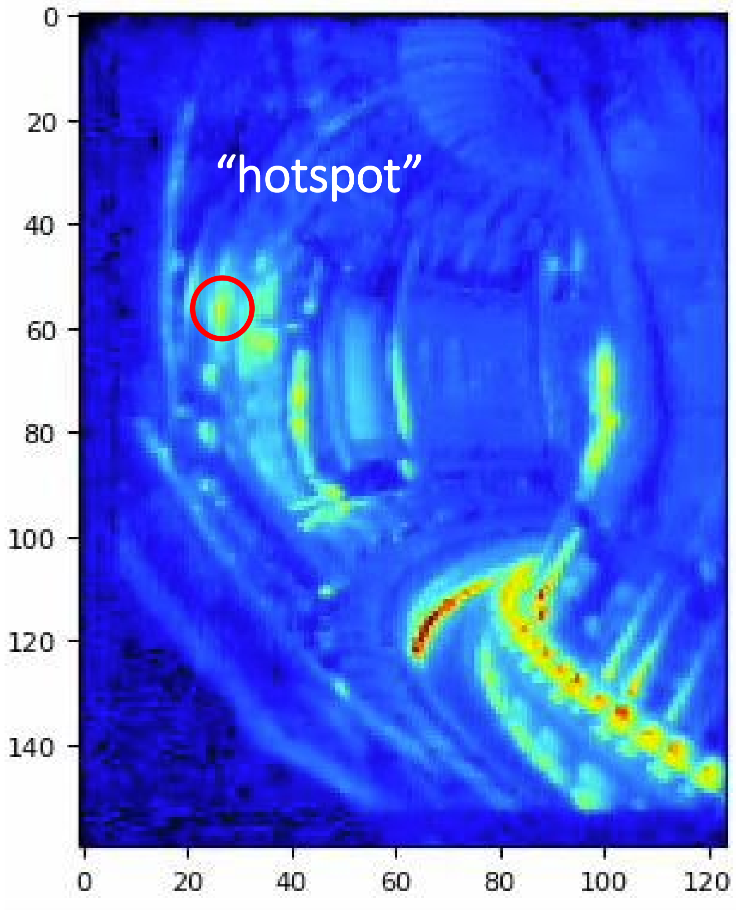
"Dynamic" steady-state retention rate… → Correlation with heating arrangement !

Localized wall heating ?

Retention vs wall and divertor temperatures

Retention rate





Wide angle view (KLDT-E5WC)

"Dynamic" steady-state retention rate… → Correlation with heating arrangement ! Localized wall heating ?

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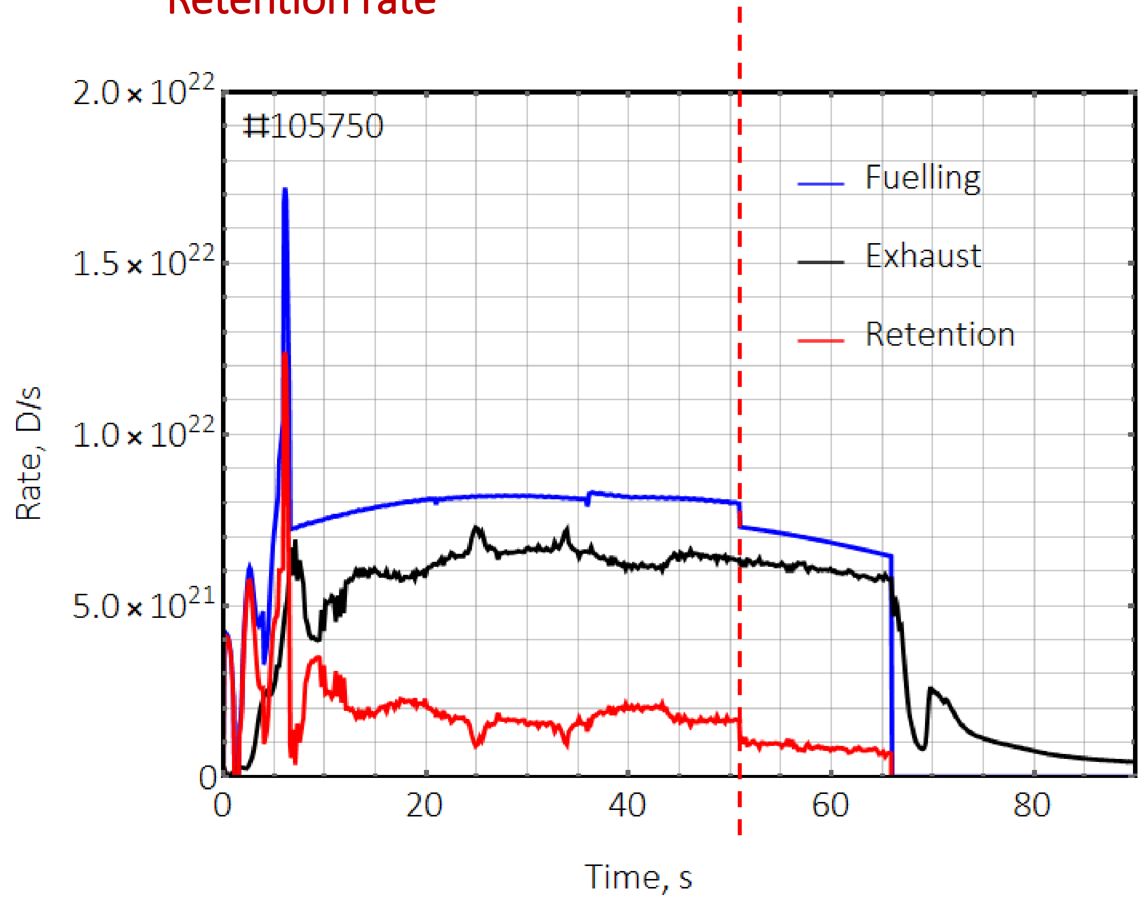
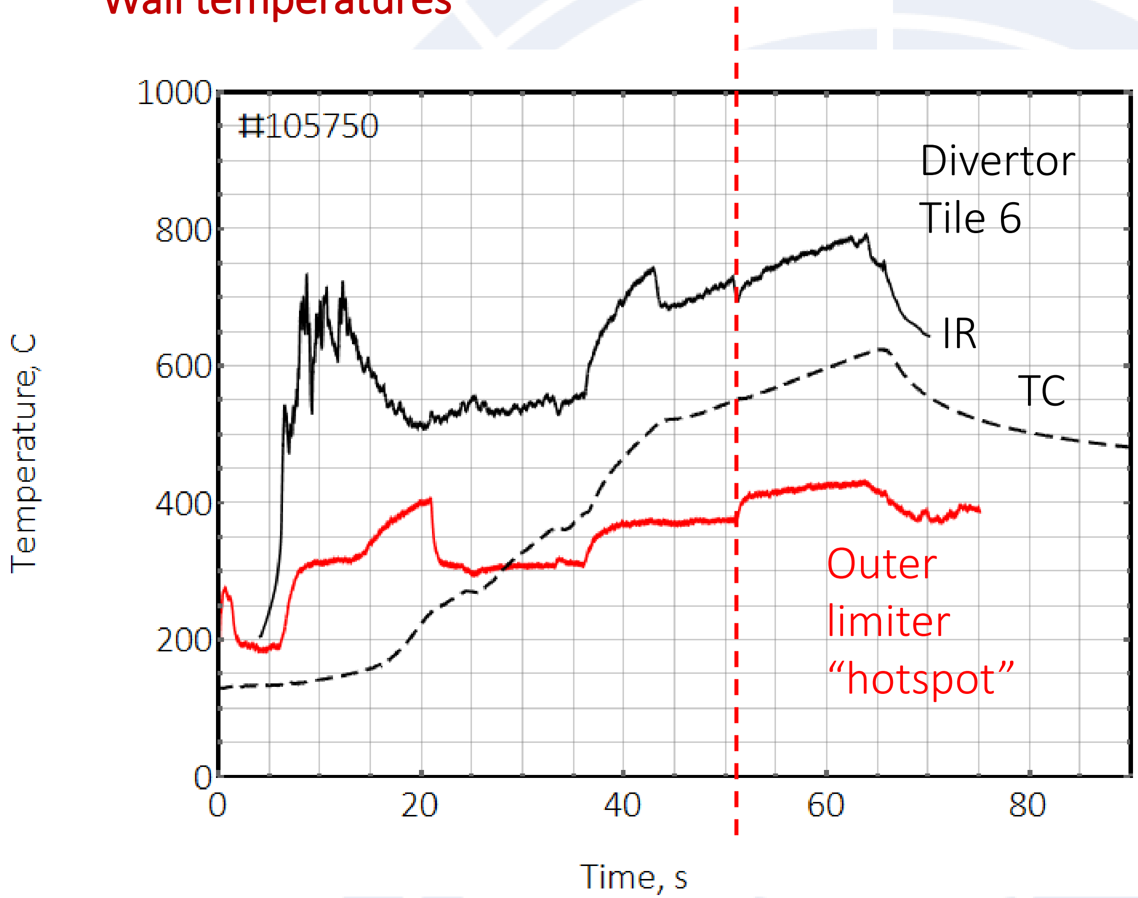
Retention vs wall and divertor temperatures

Retention rate



Wall temperatures

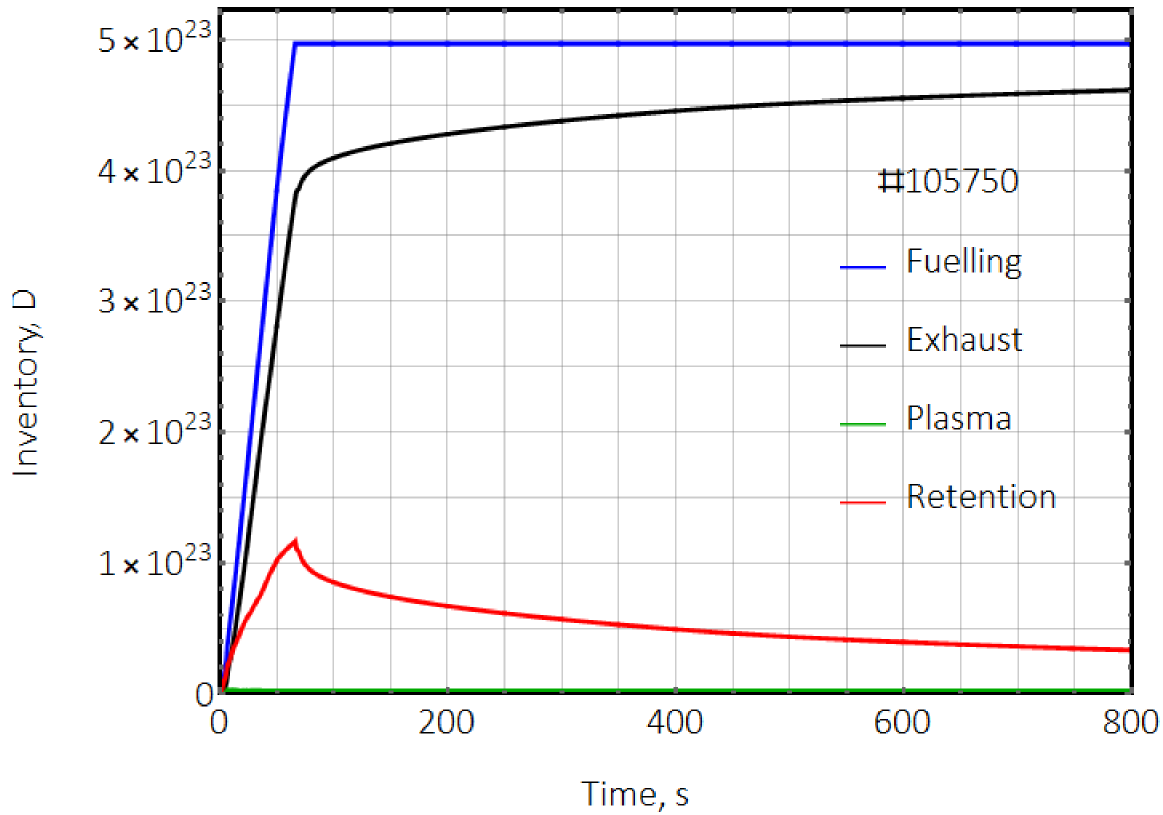


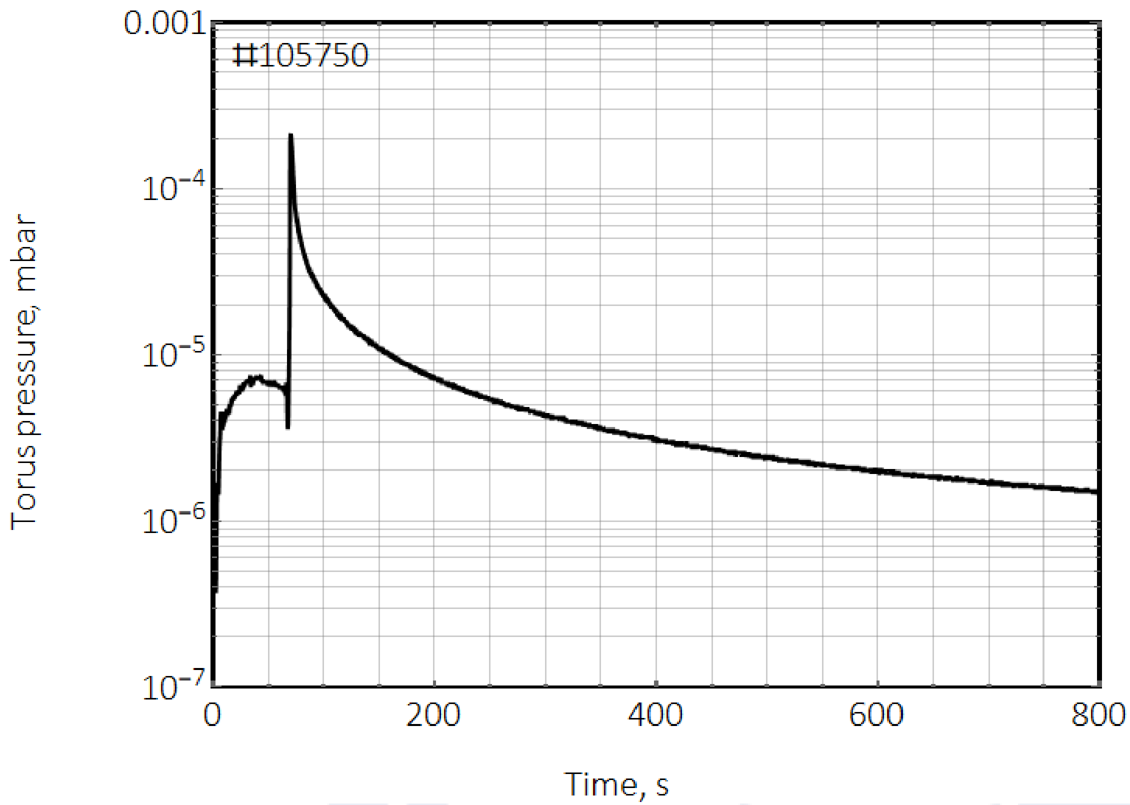
“Dynamic” steady-state retention rate… → Correlation with heating arrangement !

Localized wall heating ?

Inter-shot outgassing (transient retention)

Cumulative inventory



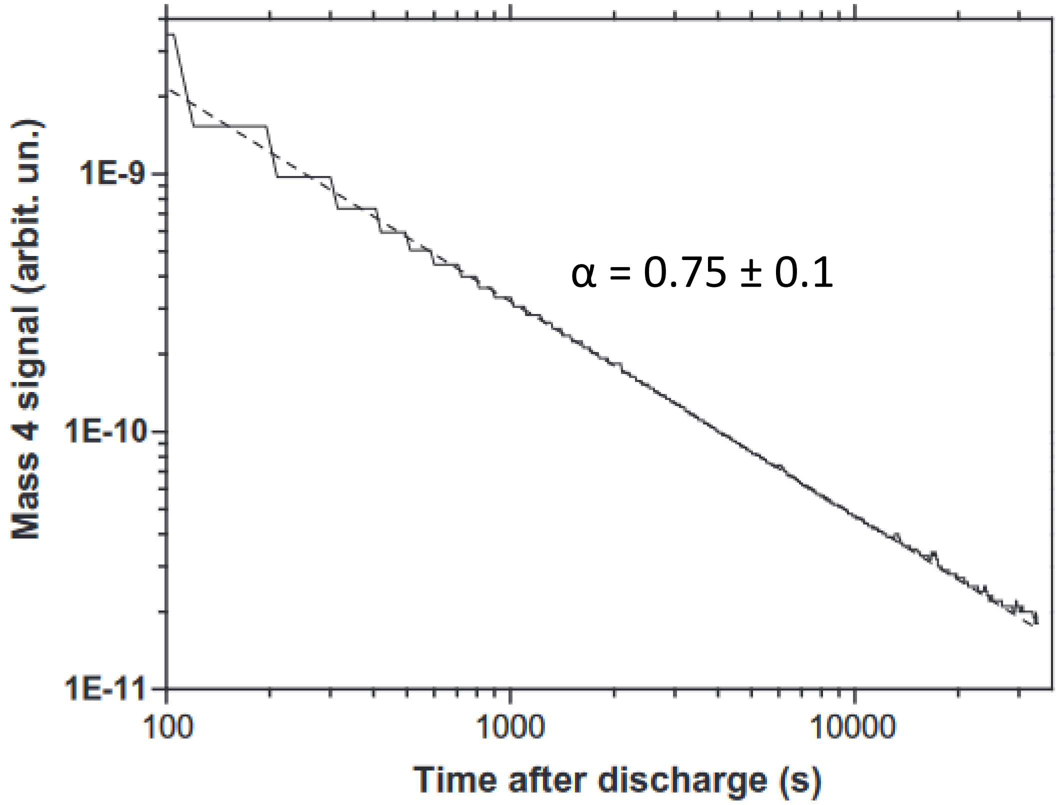


Outgassing continues long time after pulse, significantly reducing the wall inventory

Short-term and long term outgassing

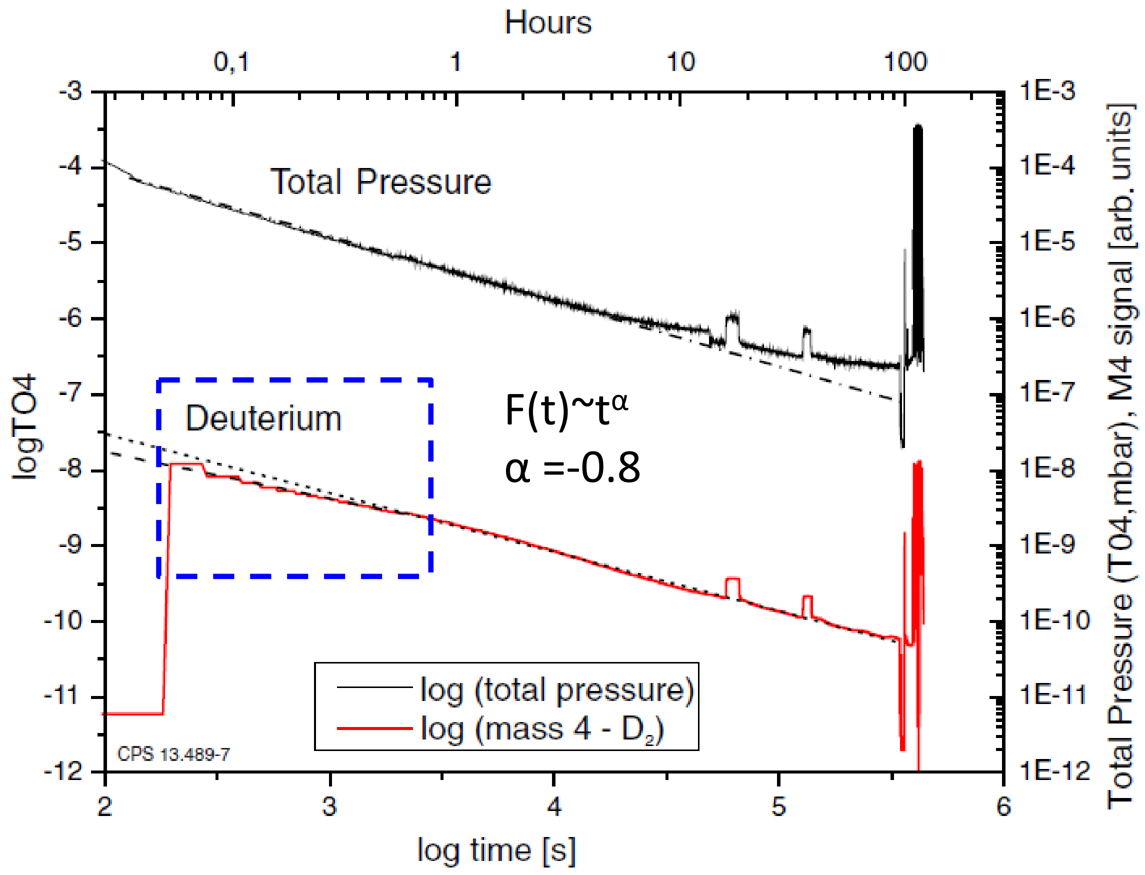
Mid-term outgassing

V. Philipps JNM 2013



Long-term outgassing

S. Brezinsek NF 2013



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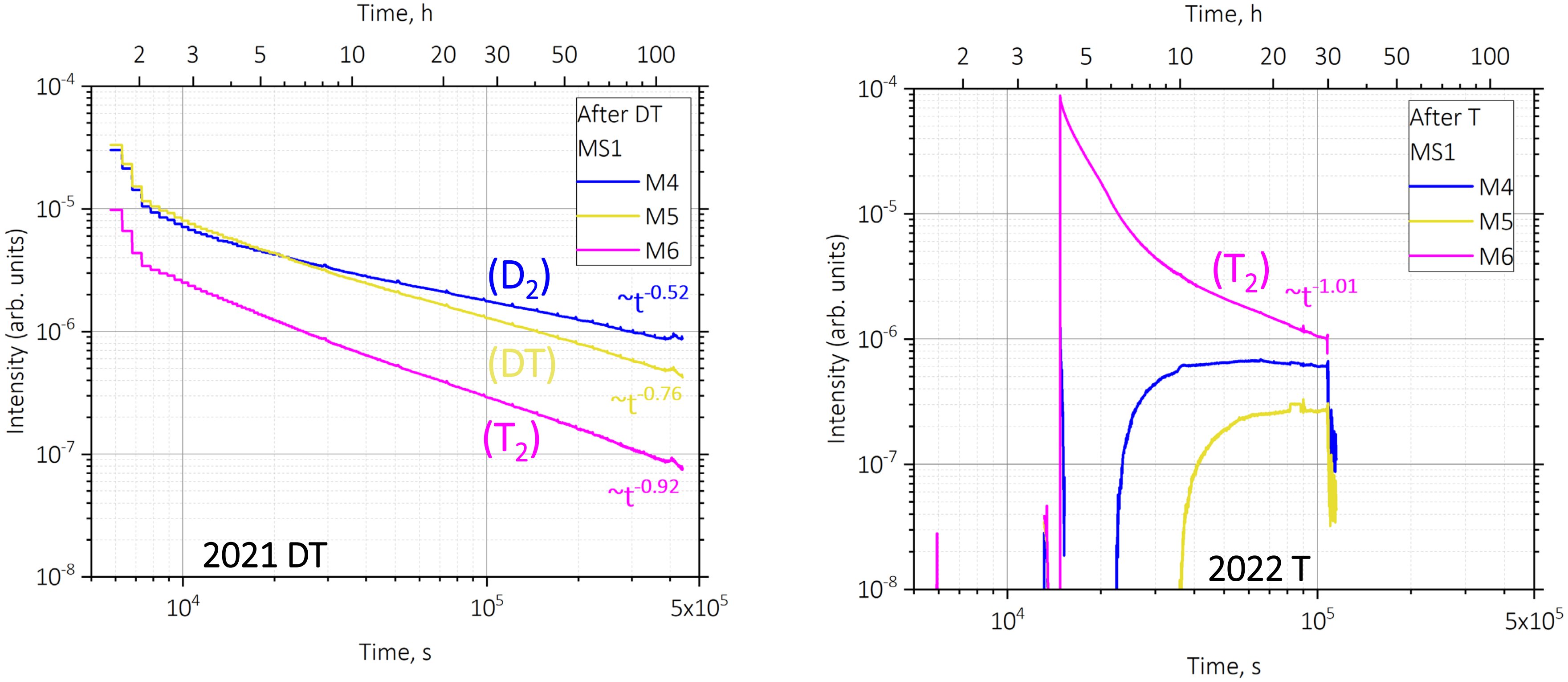
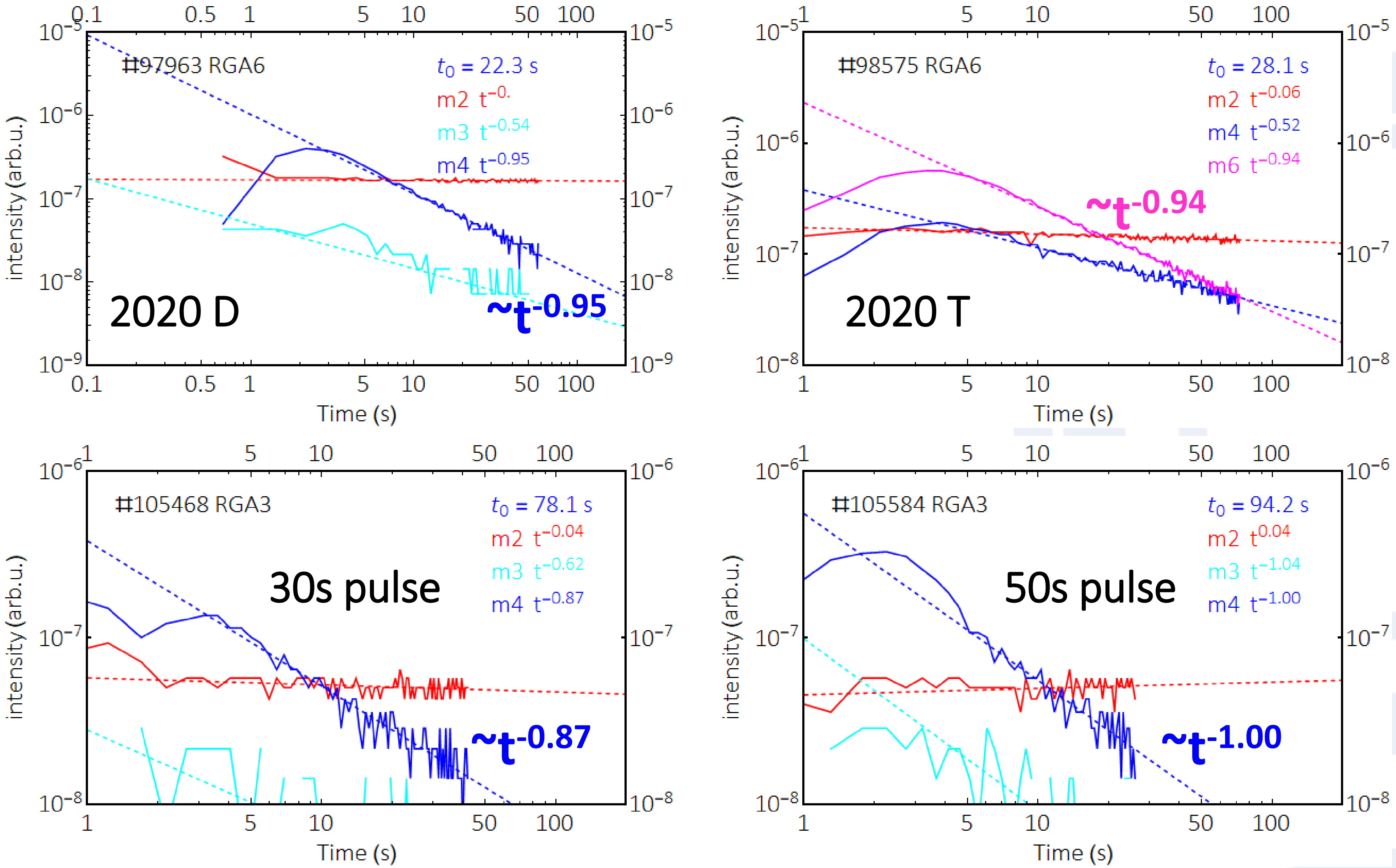
Long-term outgassing (fuel release e.g. over weekend)



RGA signal	08/2022 (D)	10/2021 (DT)	03/2022 (T)	Main species
M2	0.5	-	-	H_2^+, D^+
M3	0.5	-	-	HD^+, T^+, H_3^+
M4	0.7	0.5	-	D_2^+, HT^+, H_2D^+
M5	-	0.8	-	DT^+, D_2H^+, H_2T^+
M6	-	0.9	1.0	T_2^+, D_3^+

Short-term outgassing (fuel release between pulses)



Summary

- Plasma-wall interaction aspects in JET-ILW long-pulse operation experience
  - PFC (over-)heating → no overheating of divertor or limiter tiles, divertor not yet in equilibrium
  - PFC erosion (core impurities) → no accumulation in the core (divertor screening, SOL flows)

- Observations in view of fuel retention from JET-ILW long pulses:
  - Retention dominated by co-deposition with Be in the divertor (mainly inner divertor)
  - Standard pulses (<20s) only marginally reach steady state retention rates
  - Long pulses (>30s) reach steady state retention rates, fluctuations correlated to plasma heating
  - Quantitative particle balance analysis not possible (no gas collection, no calibrations)
  - Short-term outgassing behavior right after plasma exposure qualitatively the same as for shorter pulses

- Differences in long-term outgassing of D and T probably due to D legacy (D deep, T shallow)

Thank you for your attention!