30th IAEA Fusion Energy Conference (IAEA FEC 2025), Chengdu, China

ANALYSIS OF FUEL RETENTION AND RECOVERY IN JET WITH BE-W WALL (JET-ILW)

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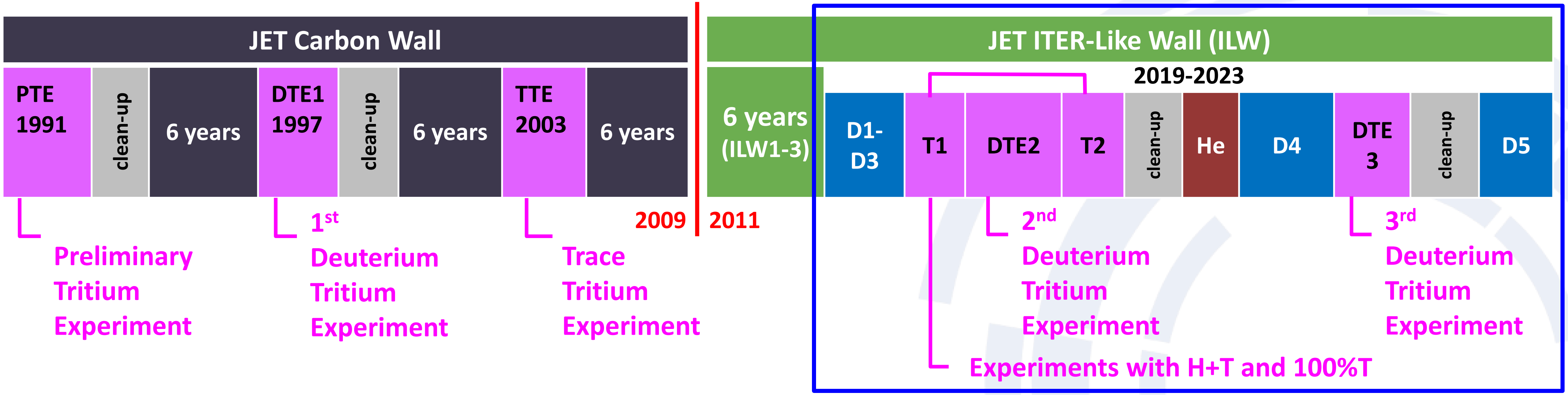
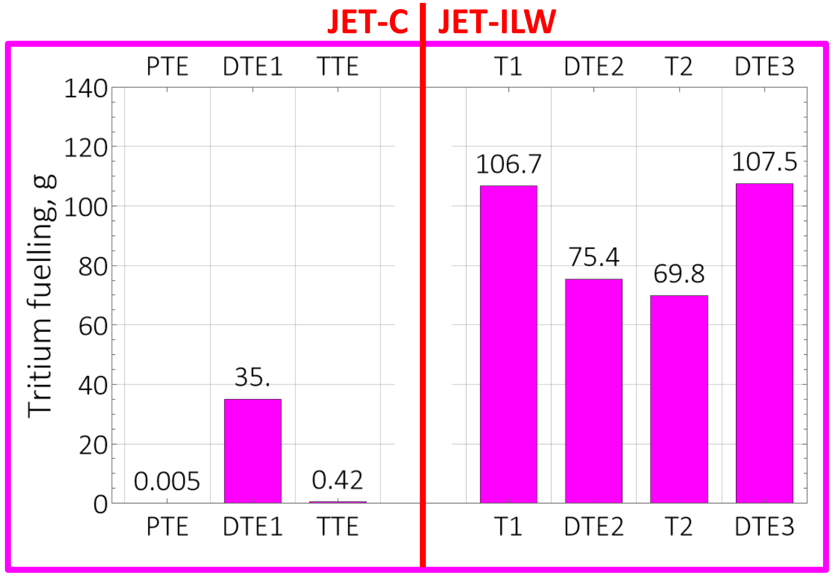
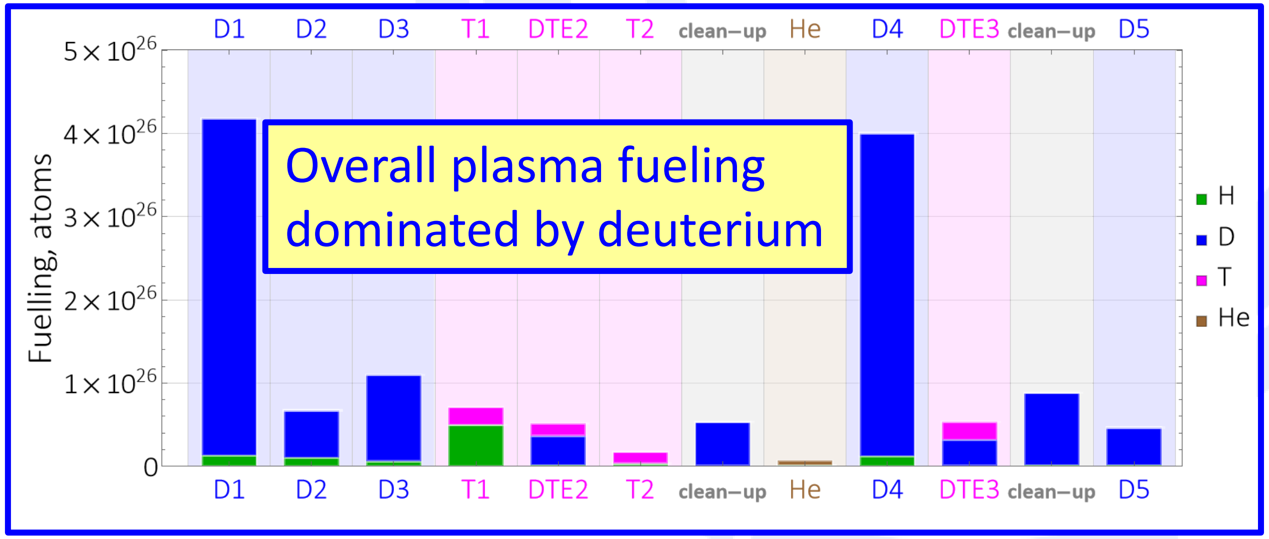
Outline

- A retrospect of JET campaigns in view of fuel inventory
- Overview of fuel retention measurements in JET-ILW
- Assessment of fuel retention for different isotopes
- Results of tritium clean-up campaigns
- Summary and conclusions

A retrospect of JET campaigns in view of fuel inventory







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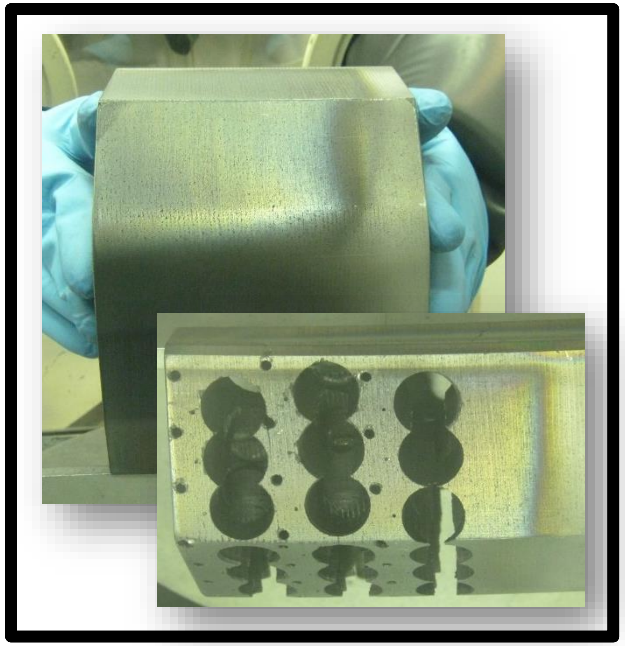
Overview of fuel retention measurements in JET

Post-mortem
material analysis

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

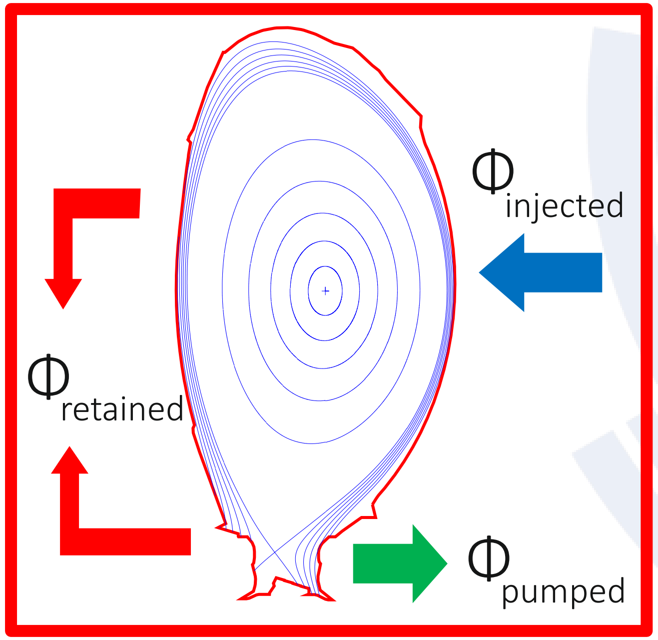
Long waiting times



"Permanent"
in-vessel inventory

Global
gas balance

- Multiple discharges
- After short-term outgassing
- Medium-term retention (hours)

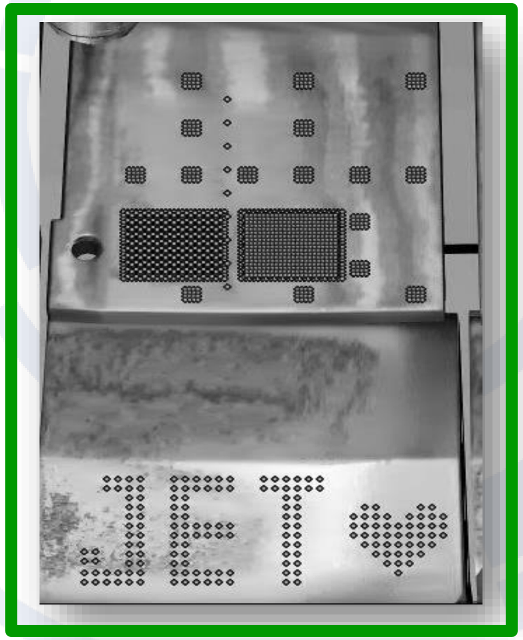


Upper limit on the fuel
remaining in the vessel

Local *in-situ*
measurements

- Lased-based methods
- Retention monitoring
- Short-/long-term retention

LID-QMS & LIBS

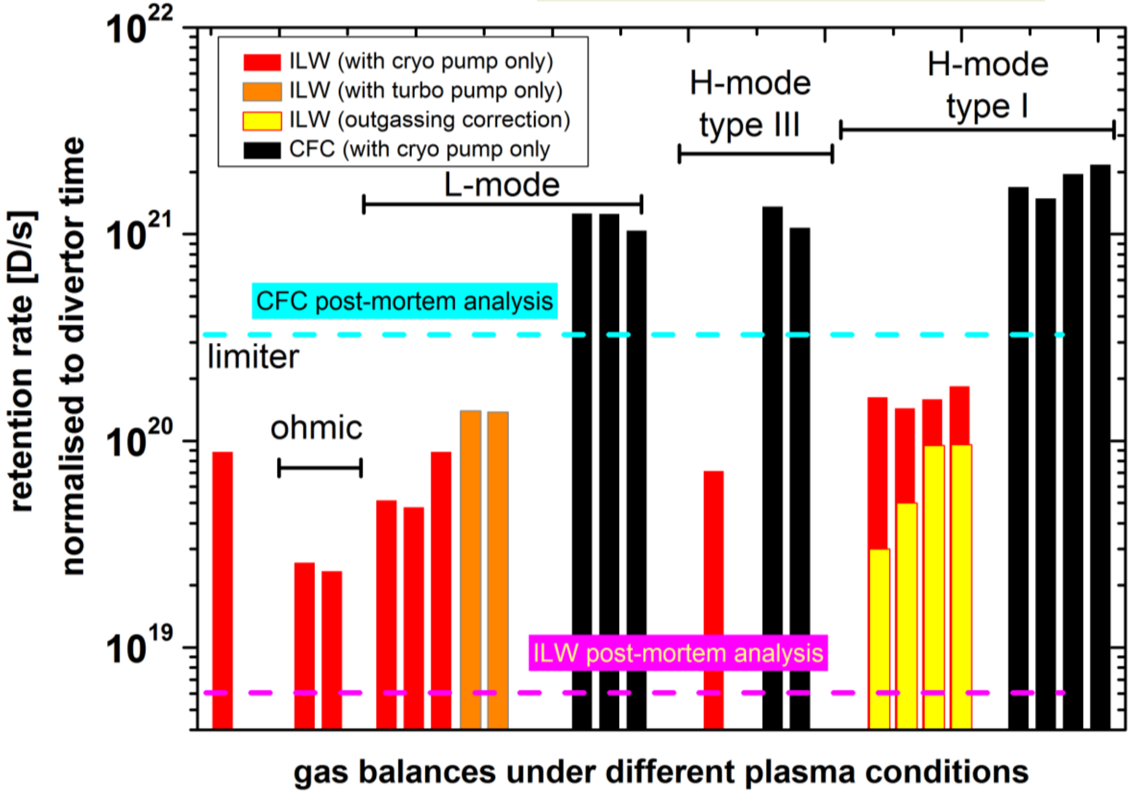


Local retention
(can be depth-resolved)

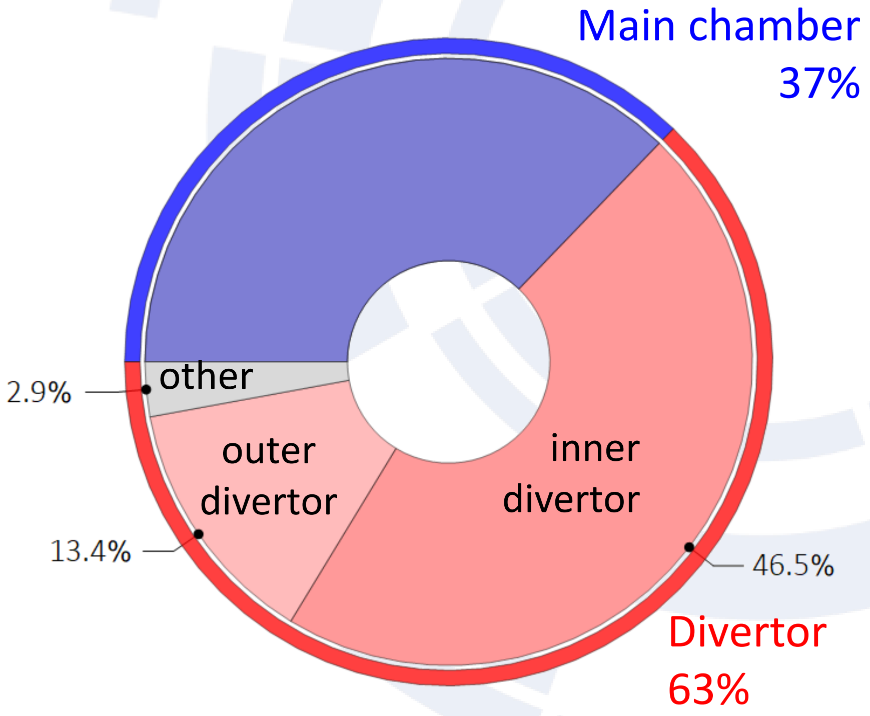
Lessons learned from earlier studies: reference for D retention

In JET-ILW retention is strongly reduced compared to carbon.
Co-deposition is still responsible for 2/3 of long-term retention,
dominated Be layers on the upper tiles of the inner divertor

S. Brezinsek, Nucl. Fusion 2013

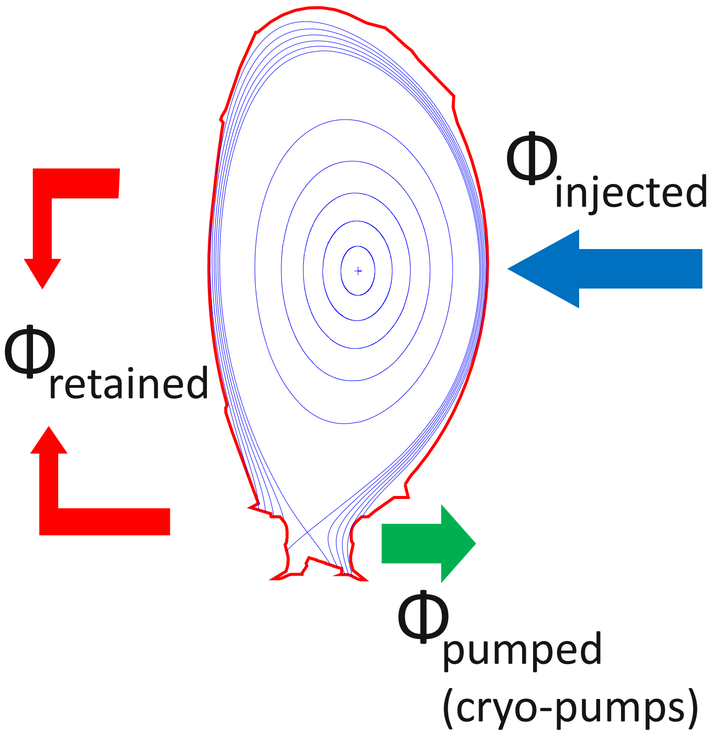


A. Widdowson, Phys. Scr 2021



Global gas balance

Multiple repeated plasmas
(with limited gas throughput)

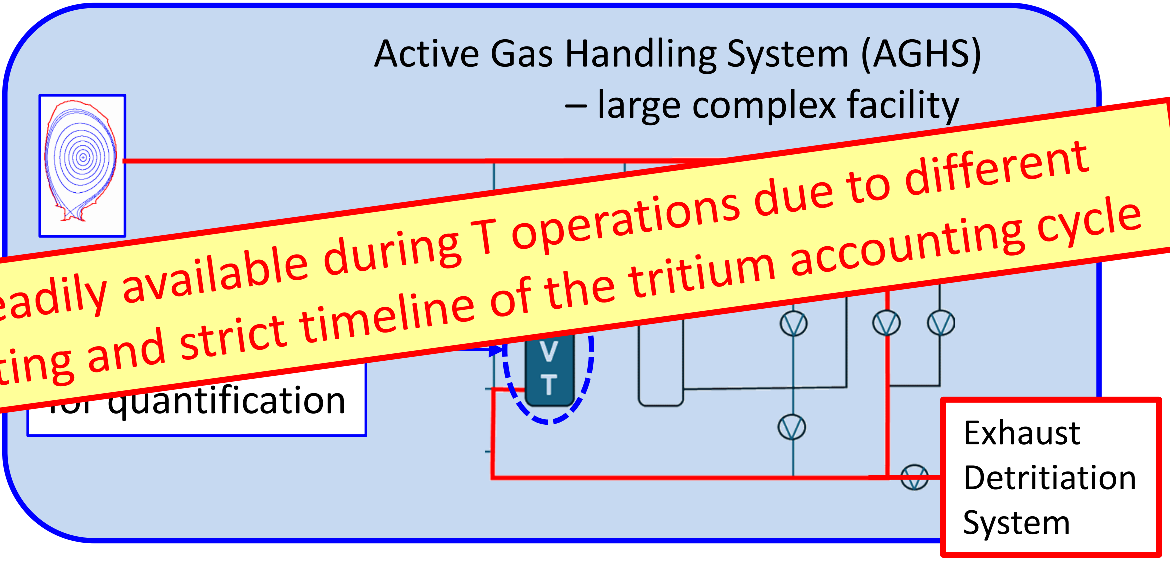


Pumped gas quantification: pVT
(ideal gas equation of state)
Pressure * Volume ∝ Temperature

Composition analysis with gas chromatography

ex-vessel pVT

S. Brezinsek, NF 2013



Not readily available during T operations due to different gas routing and strict timeline of the tritium accounting cycle

Composition analysis with sub-divertor RGA

in-vessel pVT

A. Widdowson,
PSI 2024
NF 2025

More accessible alternative
(requires dedicated calibration)

$$\Phi_{pumped} = \left(\frac{V_{torus}}{T_{gas}}\right)\frac{\Delta p_{pumped}}{R}$$

Sub-divertor Residual Gas Analysers –
Quadrupole Mass Spectrometers (QMS)

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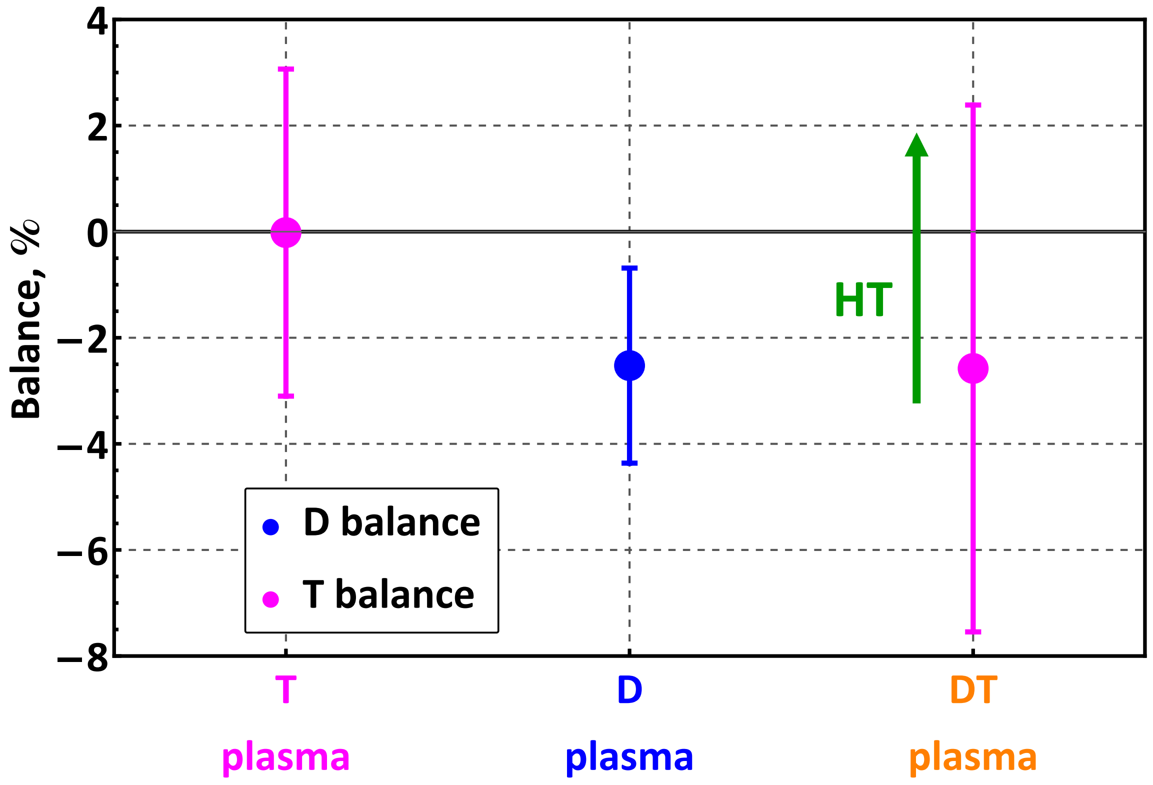
Fuel retention of different isotopes

Assessment by in-vessel pVT – accuracy not sufficient for reliable quantification



Main reasons:

- Low retention – difference of two large numbers (gas quantities) with uncertainties
- Scatter in calibration data for effective T_{gas}
  → not expected from modelling (DIVGAS)
  → ±1.5% absolute gas balance uncertainty
- T balance affected by contribution of **HT** to QMS mass signal 4 (normally D_2)
  → no accurate quantification possible

Nevertheless, no indication of significant differences in retention between D and T, comparable levels with earlier D studies

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Implementation of tritium recovery after DTE2&3

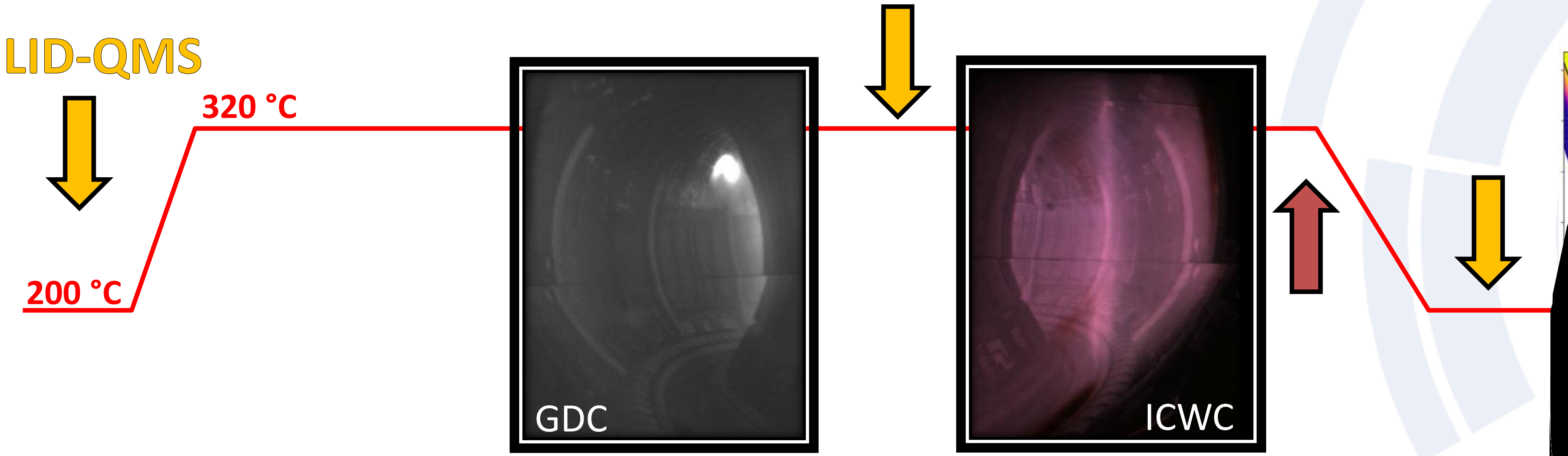
T. Wauters, Phys. Scr. 2022

D. Matveev, NF 2023

A. Widdowson, NF 2025

Motivation of initial clean-up phase: quick transition to low tritium plasma content (<1%) for low neutron rates in subsequent high-power plasma (final goal <0.02% T in exhaust)

Baking → Low temperature D plasma → Low- to high-power D plasma



[redacted]

Baking

Temperature ramp and hold
- Passive outgassing
- T = 200°C→320 °C
- Continuous (days)
- Main chamber mostly

GDC plasma

Glow Discharge Conditioning
- DC discharge (~ kW)
- Without B_T
- Continuous (hours)
- Main chamber recessed

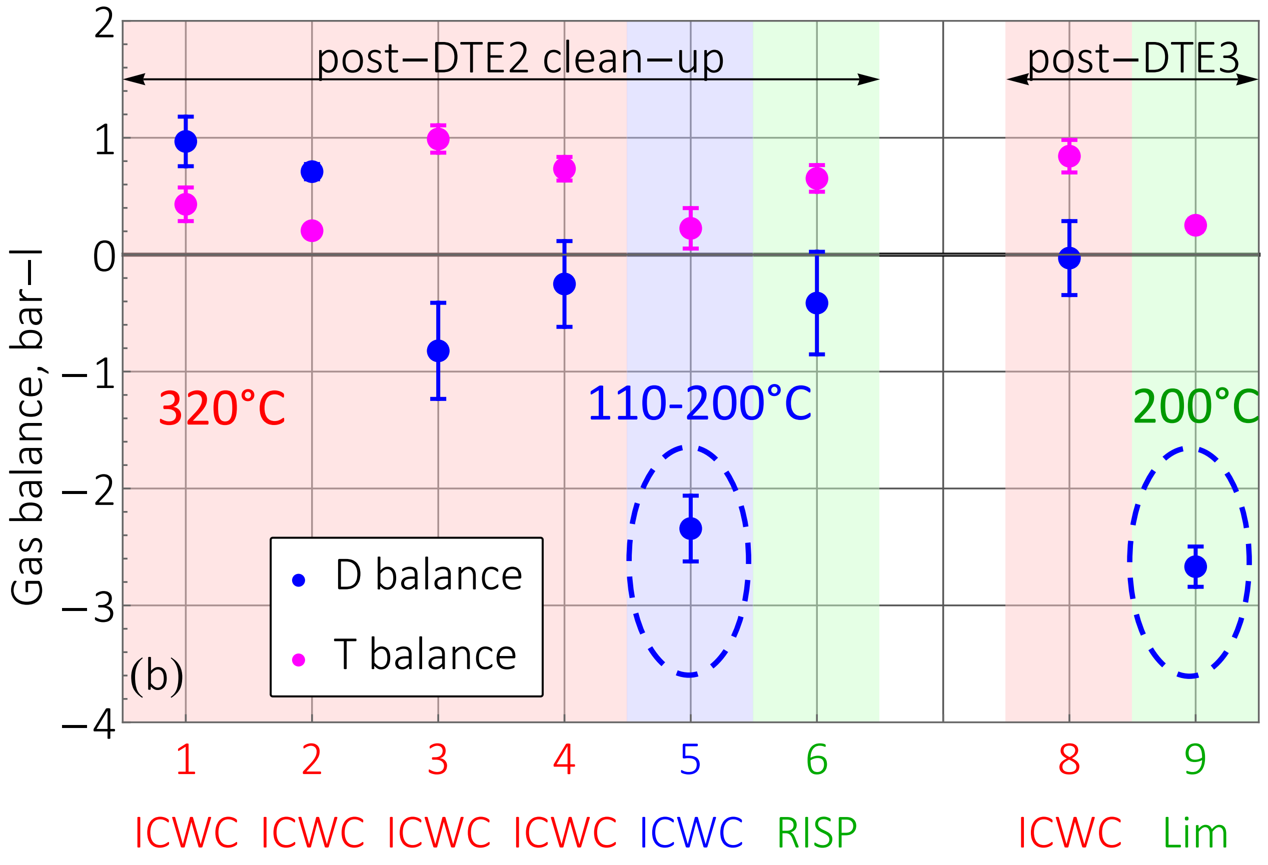
ICWC plasma

Ion Cyclotron Wall Conditioning
- RF discharge (250 kW)
- With B_T
- Pulsed (~10 s)
- Main chamber limiters

[redacted]

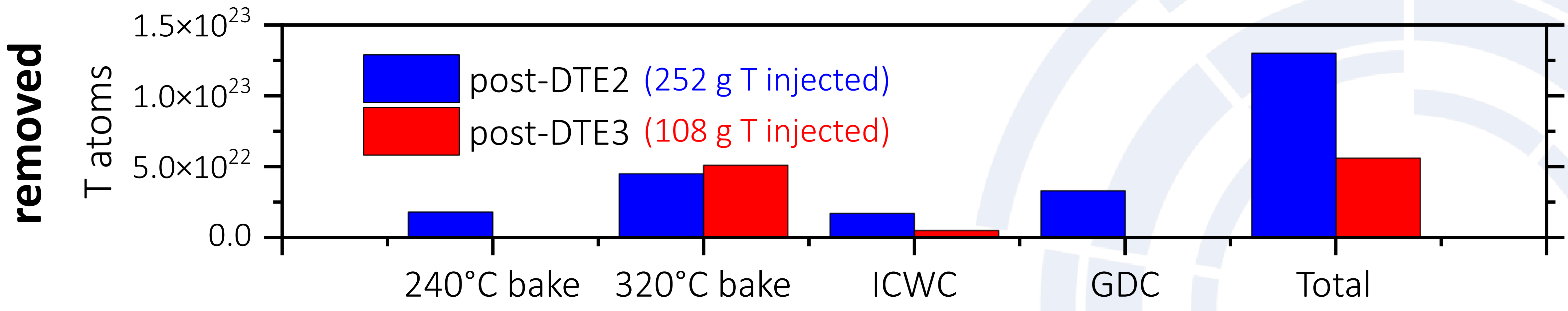
Gas balance with in-vessel pVT

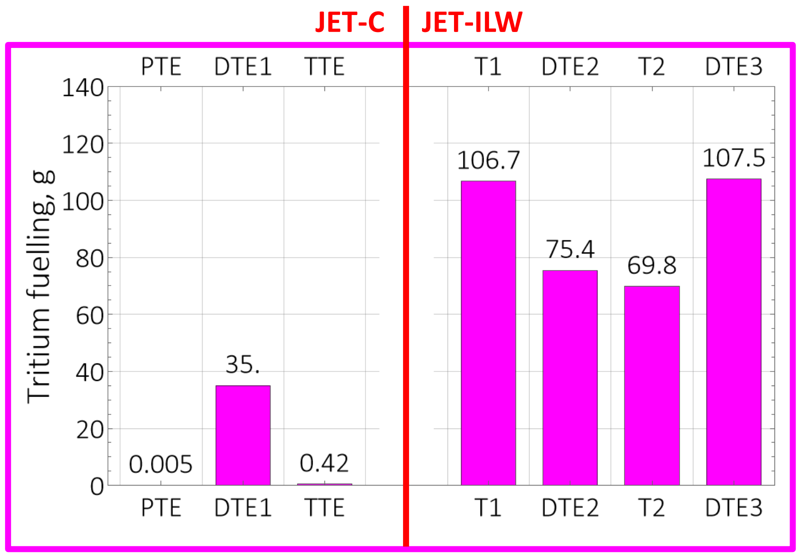
- For quantification of tritium recovery in post-DTE2 and post-DTE3 clean-ups
  → applied for ICWC during baking, limiter and RISP plasma sessions thereafter



- Calibration uncertainties less critical as no T injections are involved
  → all measured T is recovered T
- Role of HT contribution less dramatic
- Clear increase of D retention on the day right after baking
  → wall reservoir depleted by cleaning
  → still measurable T recovery

Results of post-DTE2 and post-DTE3 T clean-up experiments





Consistent results:

post-DTE2 total: 1.3×10^{23} atoms T = 0.65 g T

post-DTE3 total: 5.6×10^{22} atoms T = 0.28 g T

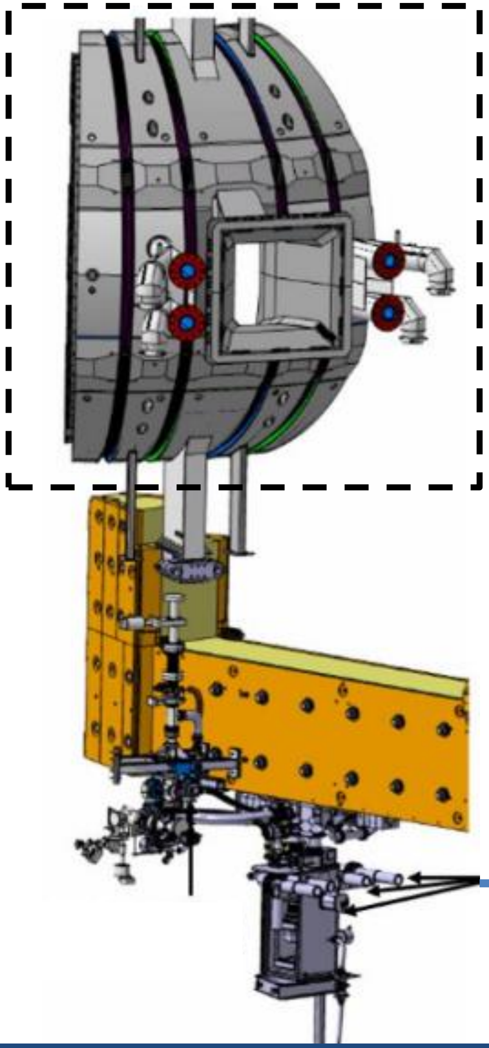
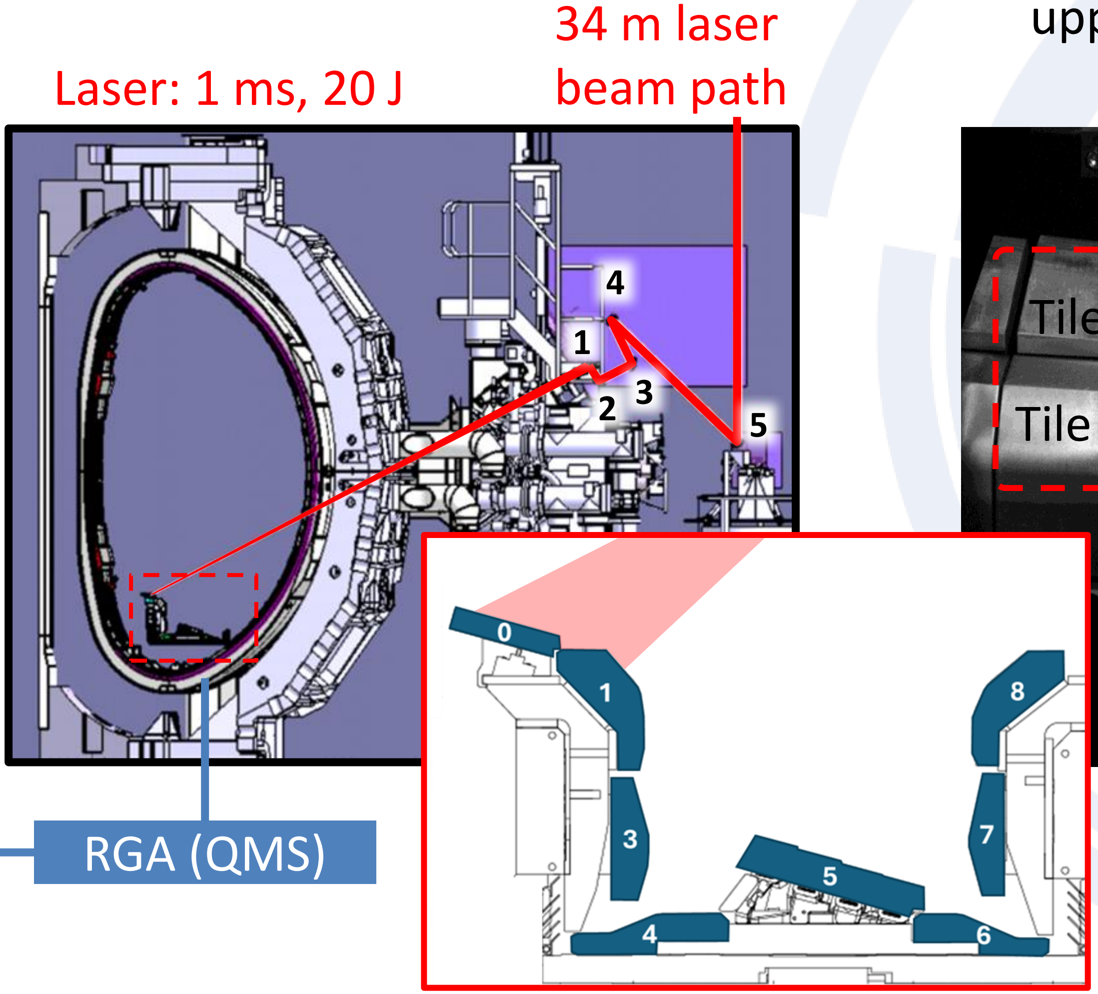
Reasons for ~2 times less T removed after DTE3 compared to DTE2:

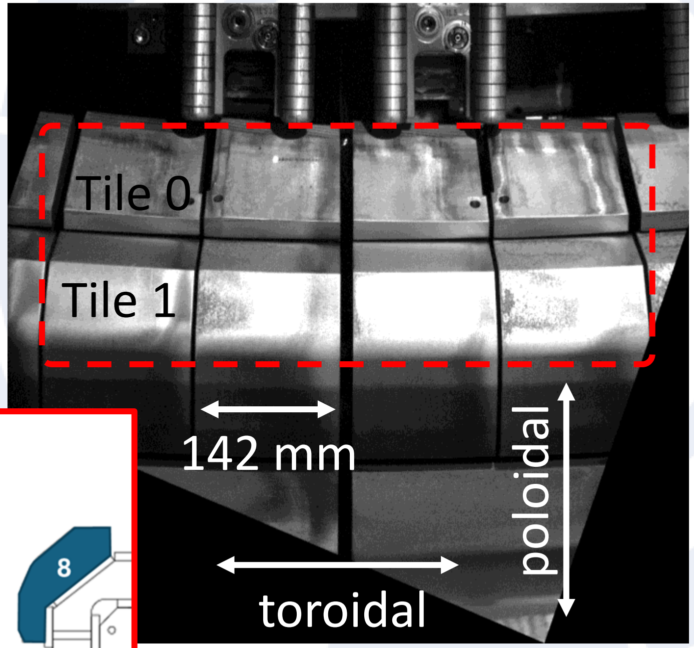
- ~2 times less initial inventory (no ~100%T campaign before DTE3)
- shorter total baking duration (but higher average temperature)
- less number of ICWC pulses, no GDC

Cleaning effectiveness assuming 2% retention: ~13%

Laser-based local *in-situ* measurements: LID-QMS

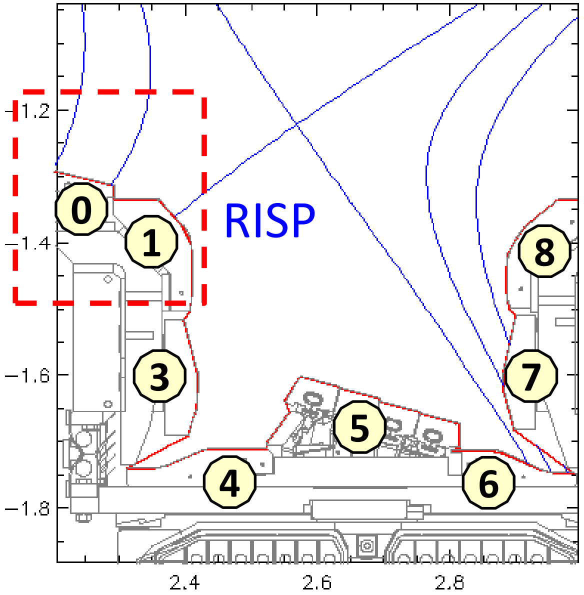
Laser-Induced Desorption (LID) – detection by Quadrupole Mass Spectrometer (QMS)
Commissioned in 2023 prior to DTE3 for divertor areas with major co-deposition

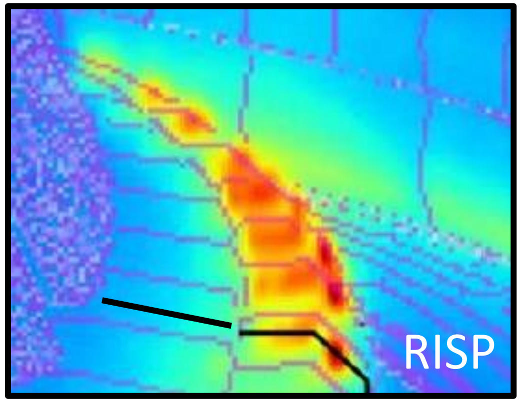



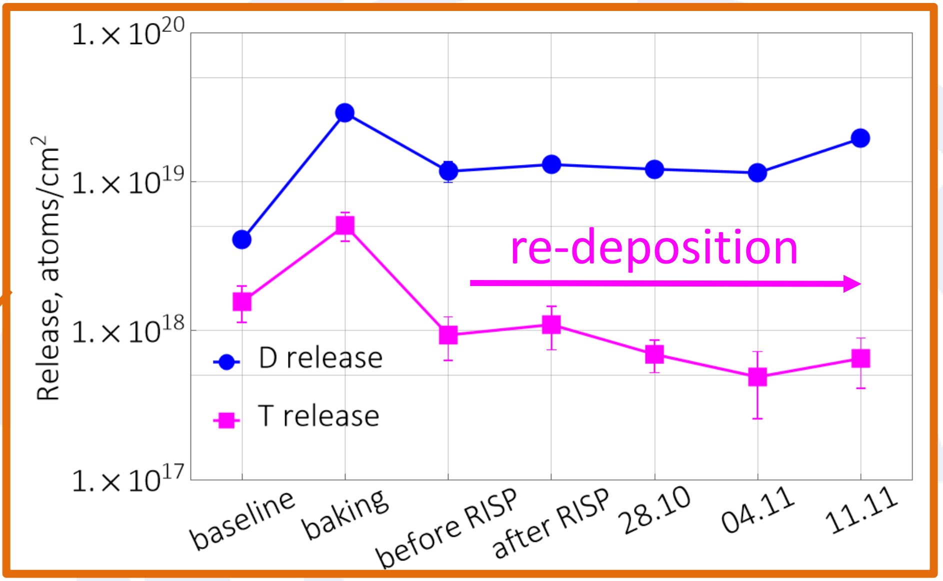


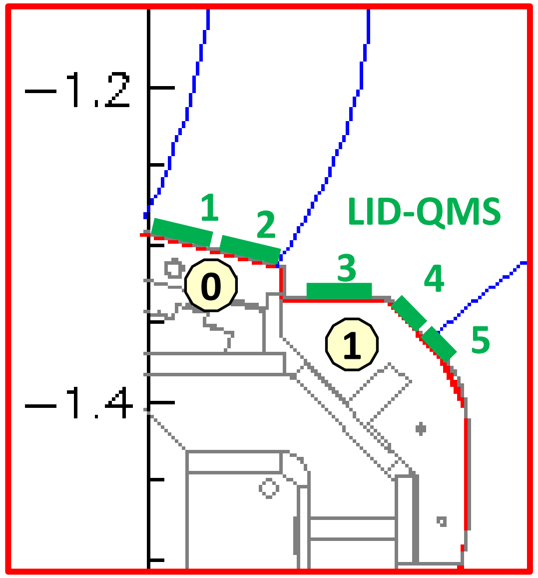
M. Zlobinski, PFMC 2025
A. Widdowson, NF 2025

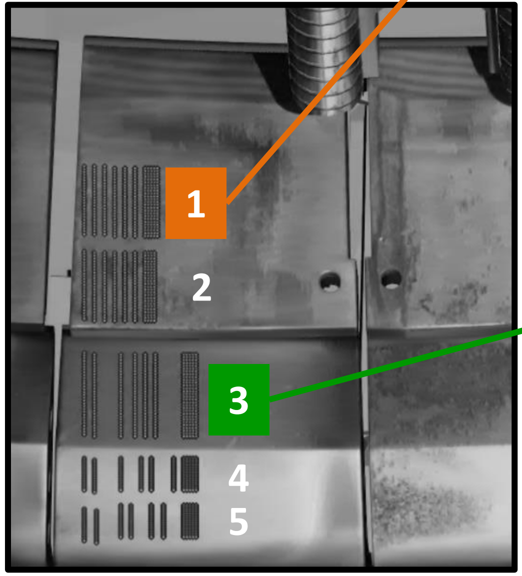
Monitoring of tritium clean-up with LID-QMS

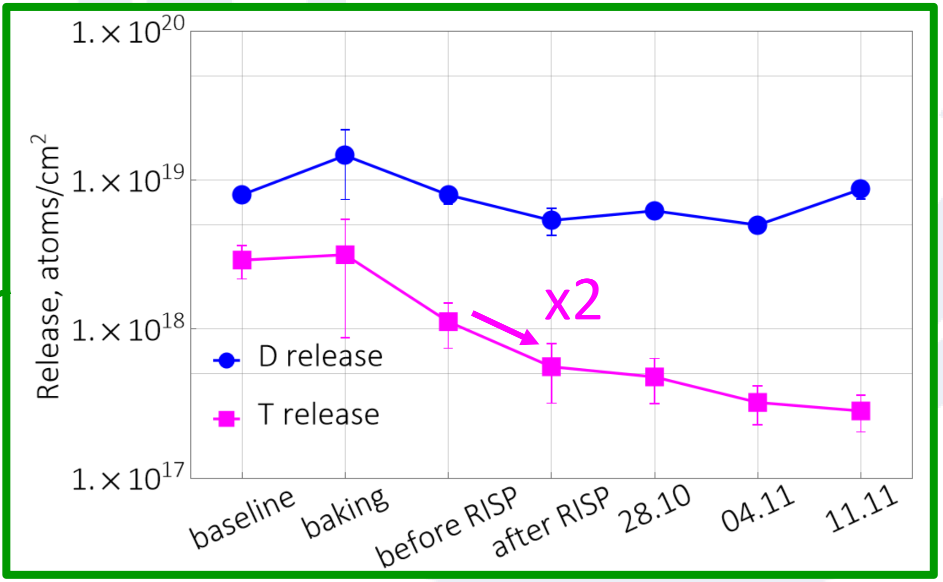






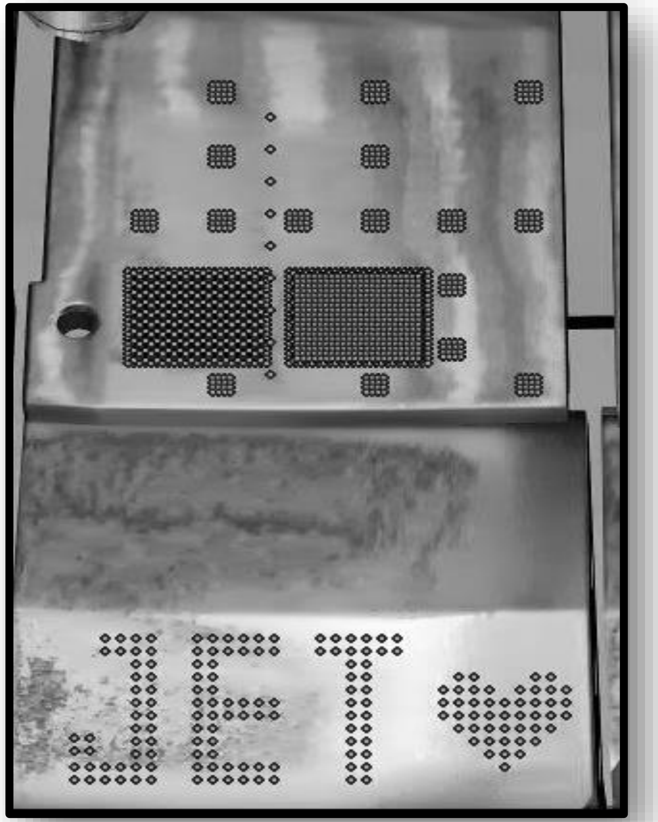






Summary and conclusions

- **JET DTEs offered unique opportunity to compare fuel retention of different isotopes**
  - Accuracy of in-vessel gas balance not sufficient for reliable measurements at low retention levels
  - No indication of significant differences to previous studies, retention comparable for D and T
  - Stronger short-term T retention can be expected due to fueling and wall dominated by D
- **Post-DTE clean-up experiments guide the development of ITER T recovery strategies** *T. Wauters, PFMC 2025*
  - Initial T recovery after DTE2 and DTE3 consistent with total tritium inventory in campaigns
  - Initial cleaning efficient in terms of reduction of tritium plasma content, especially baking and RISP
  - Low T exhaust target achieved by extended clean-up campaigns with high-power pulsing in 6 weeks
  - Global T accountancy still ongoing, completion expected in spring 2026
- **Applicability of laser-based methods for fuel retention monitoring demonstrated** *M. Zlobinski, PFMC 2025*
  - LID-QMS will be applied for *in-situ* fuel retention monitoring in ITER, LIBS under consideration
  - Demonstrated fuel removal by baking and RISP, though indicating re-deposition in far-SOL
  - An extensive body of experimental results has been collected for further evaluation
- **Sample retrieval completed, post-mortem analysis will be done and reported in the coming years**



Thank you for your attention

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See the author list of E. Joffrin et al., Nuclear Fusion 64 (2024) 112019

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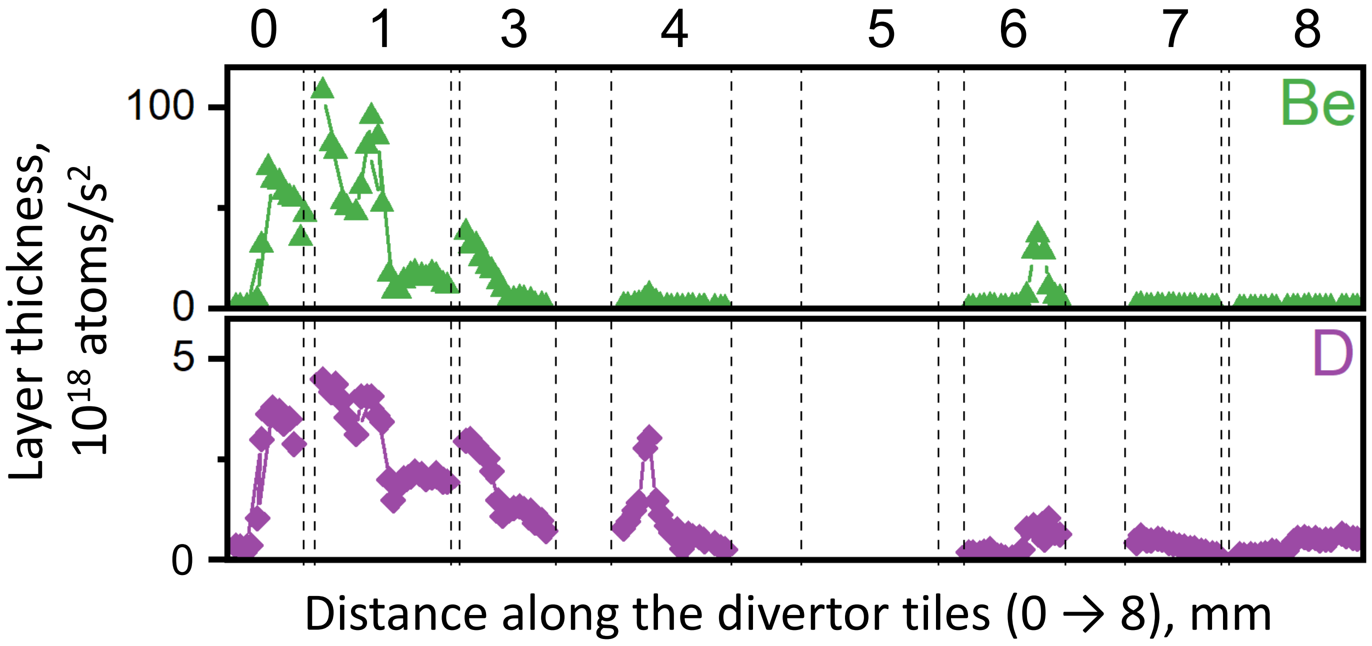
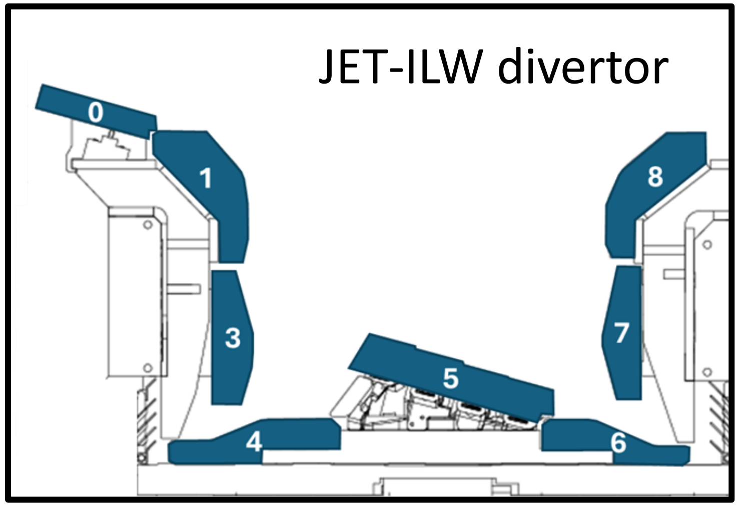
Backup: Lessons learned from post-mortem material analysis

Ion-Beam Analysis (here after ILW2)



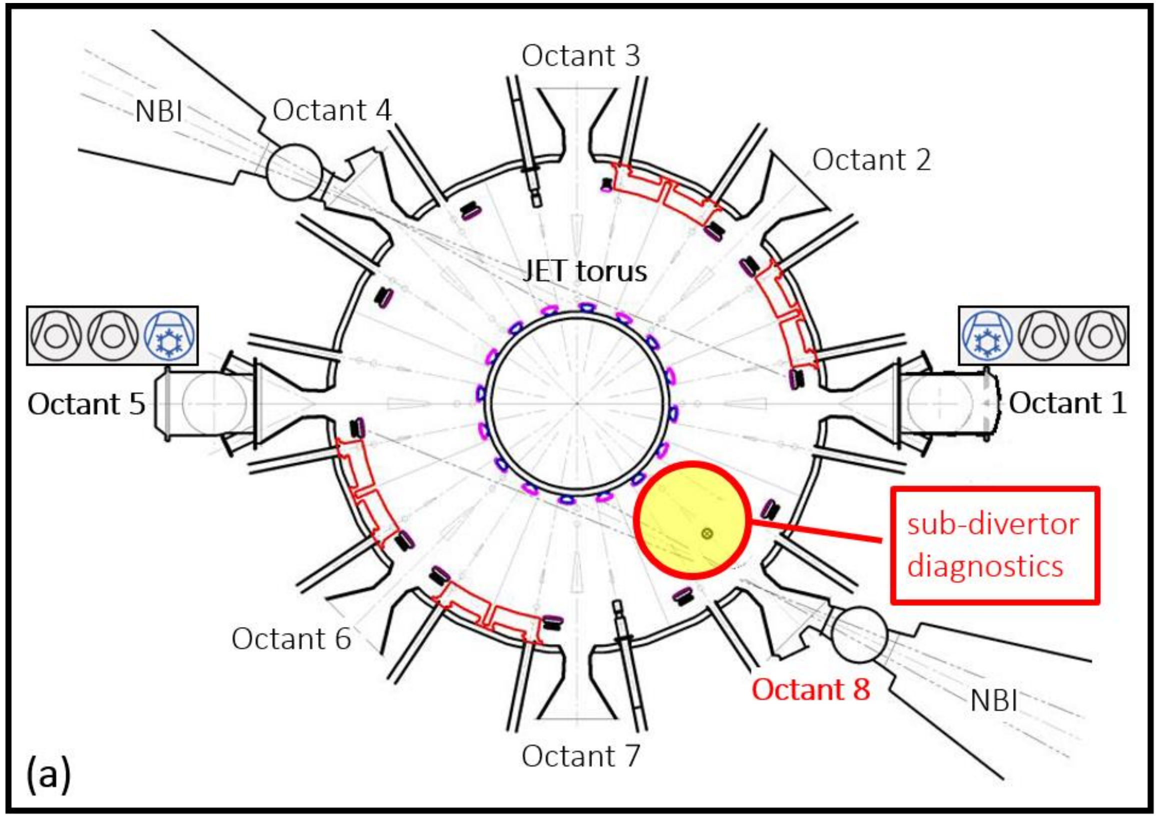


In JET-ILW co-deposition is still responsible for 2/3 of retention, with > 60% in the divertor, concentrated on inner tiles 0 and 1

K. Heinola, JNM 2015
S. Krat, NME 2021
A. Widdowson, Phys.Scr. 2021

Backup: JET geometry, pumping and neutral gas diagnostics

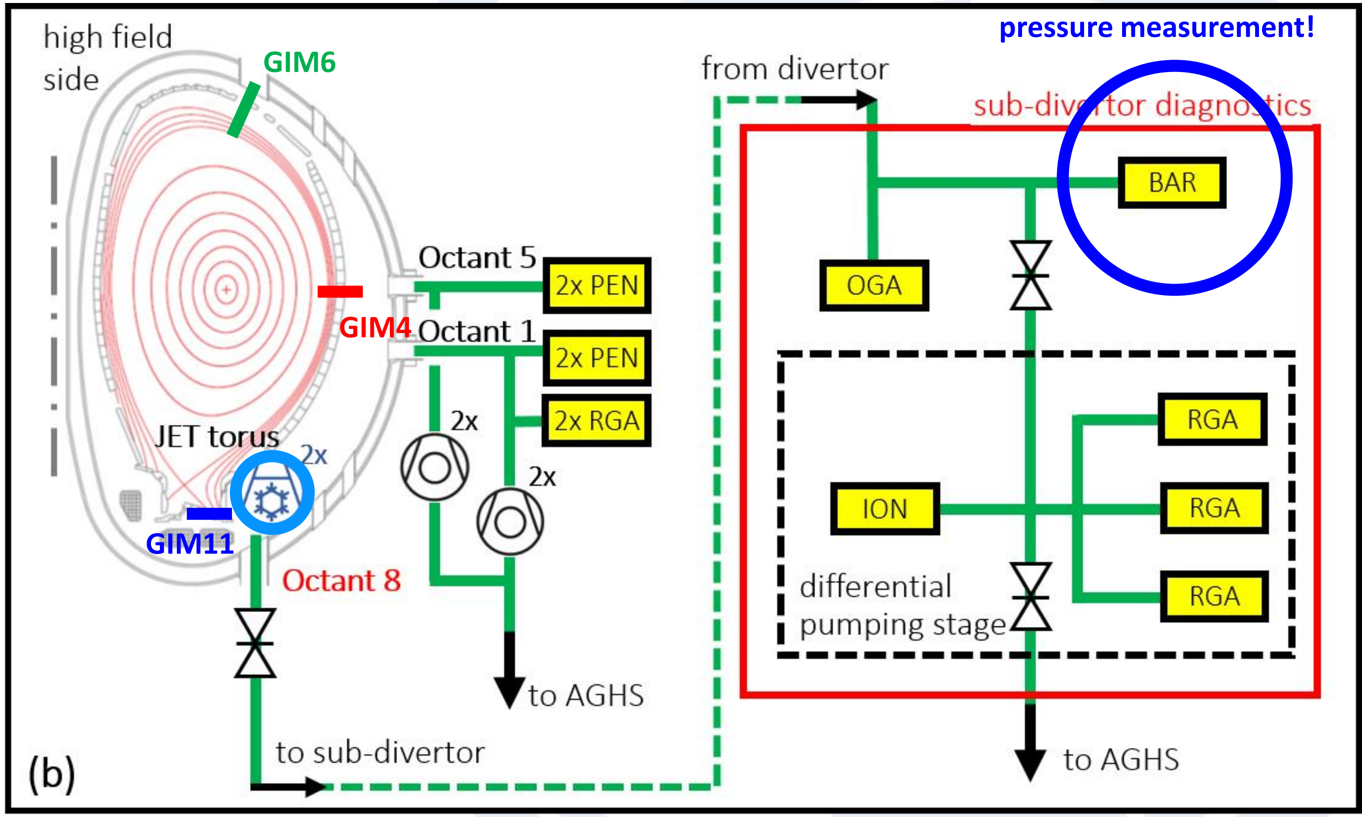
Top view



Poloidal section

Sub-divertor

Absolute torus pressure measurement!



Backup: Applicability of gas balance with in-vessel pVT

- For assessment of fuel retention rates in T and DT plasmas in comparison to D
- For quantification of T recovery in post-DTE2 and post-DTE3 clean-up experiments

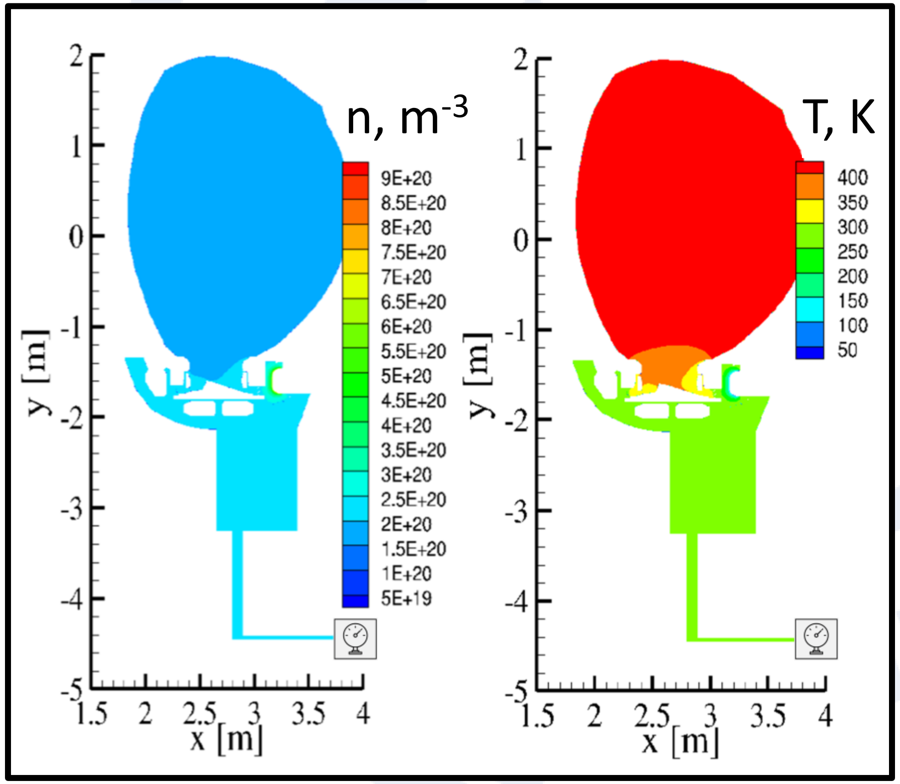
2D DIVGAS code* (Direct Simulation Monte-Carlo) simulations of neutral gas distribution in isolated torus during in-vessel pVT

Addressing ideal gas law applicability in linking gas parameters in sub-divertor to volume average data and total gas amount

Preliminary results support the applicability and physical soundness of the method

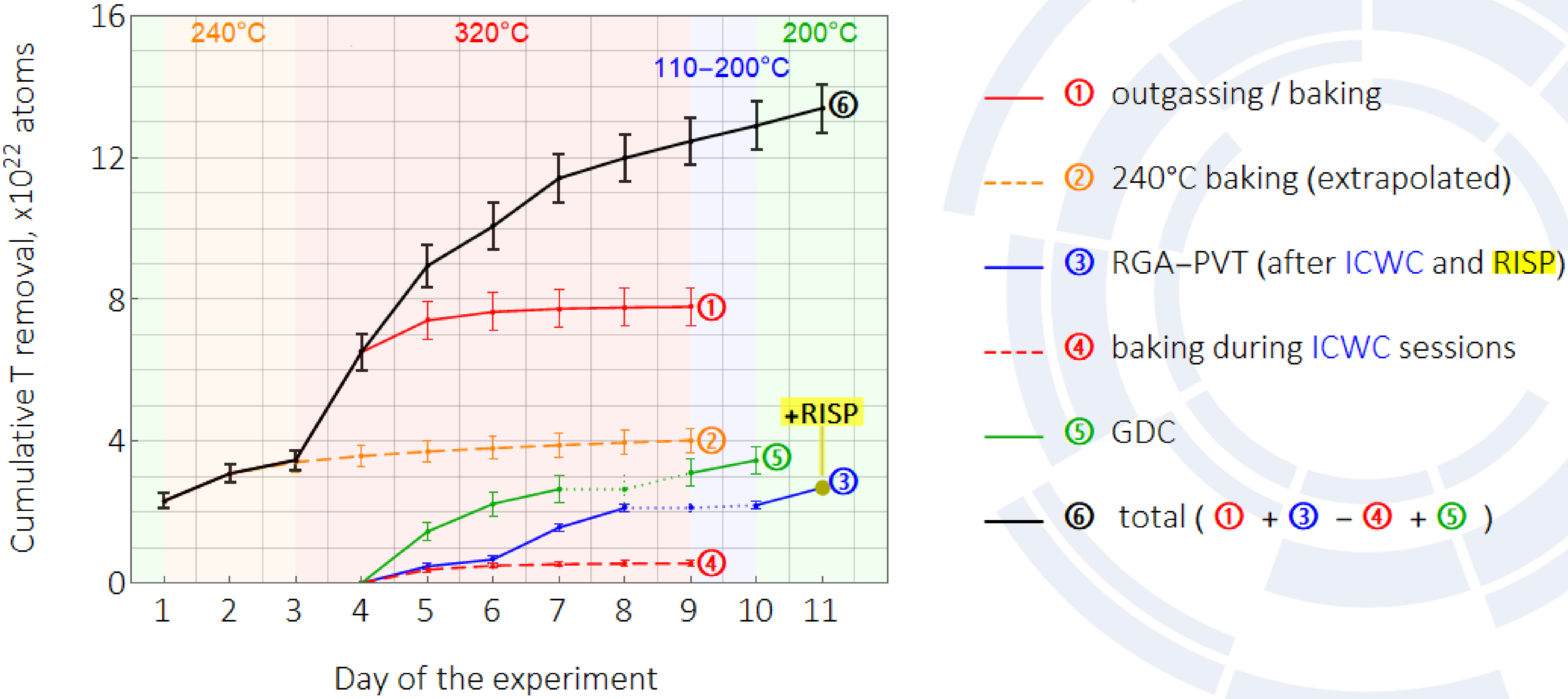
** C. Tantos, NF 2022*

Example for p = 1 Pa



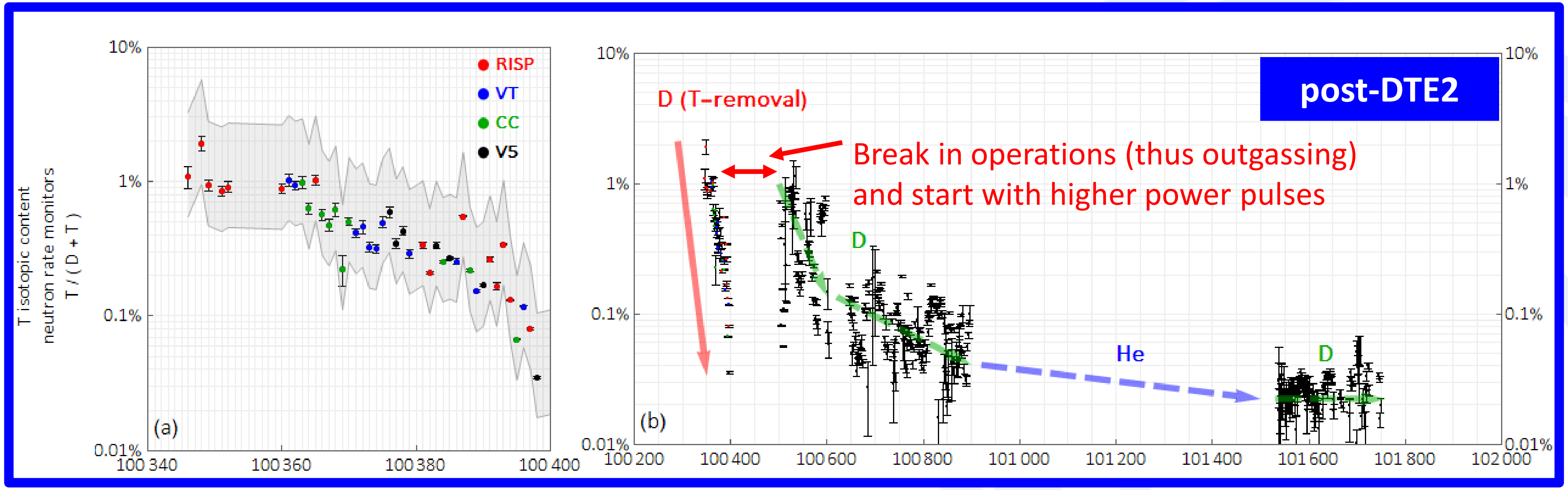
Backup: Tritium recovery after DTE2

D. Matveev, NF 2023

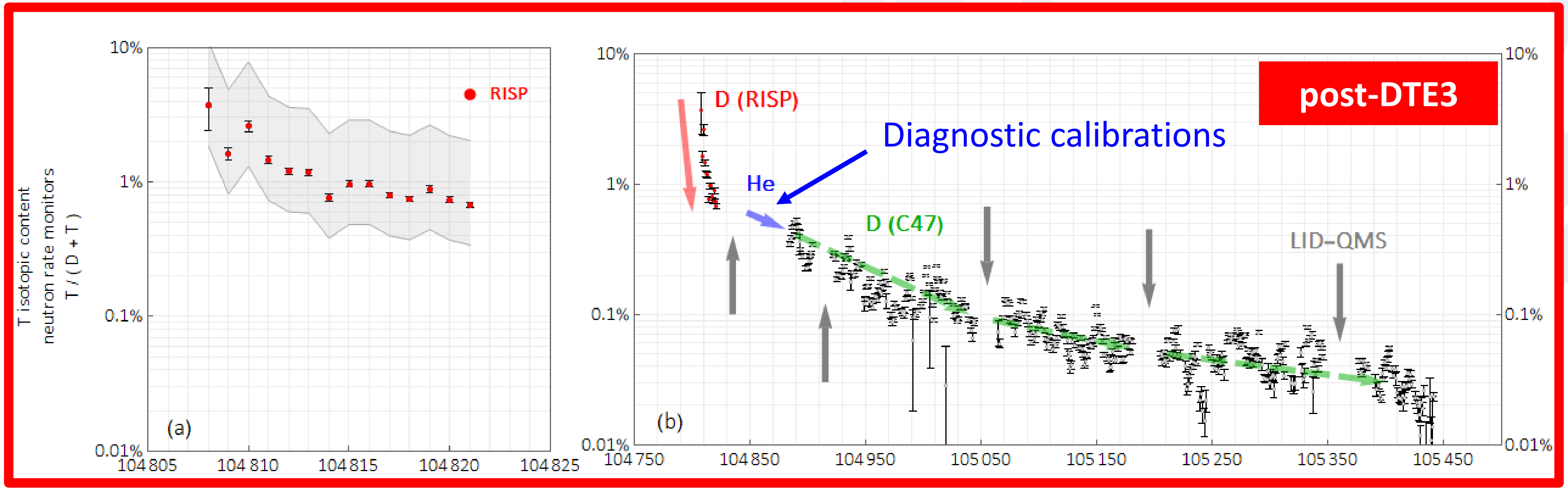


Backup: Tritium plasma content during clean-up

T content in plasma inferred from neutron rates



0.02% tritium in exhaust achieved in 6 weeks

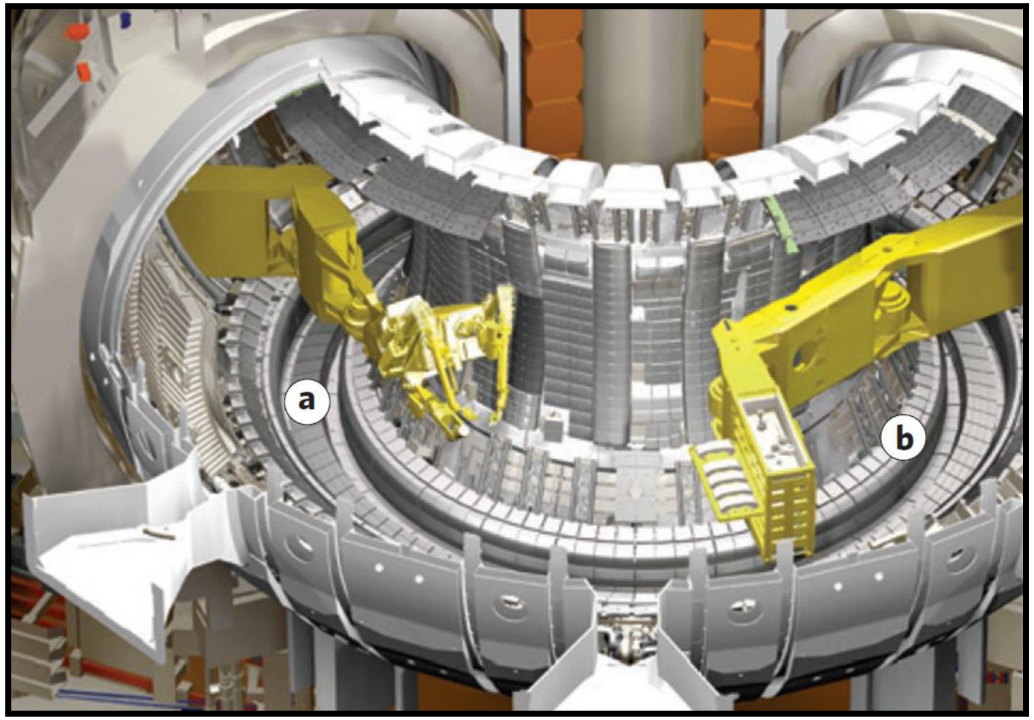


Backup: Laser-based local *in-situ* measurements: LIBS

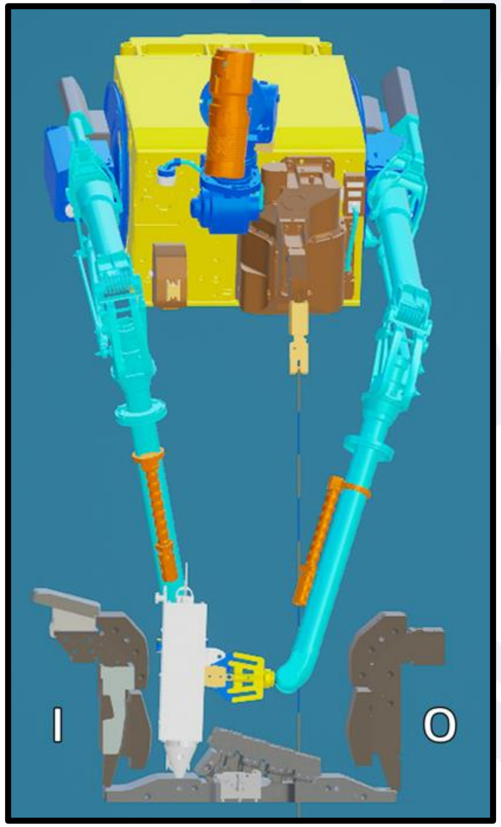
Laser-Induced Breakdown Spectroscopy (LIBS)
– spectroscopical analysis of local laser-induced plasma of ablated material
Measurements on remote handling arm after end of operations and venting (2024)

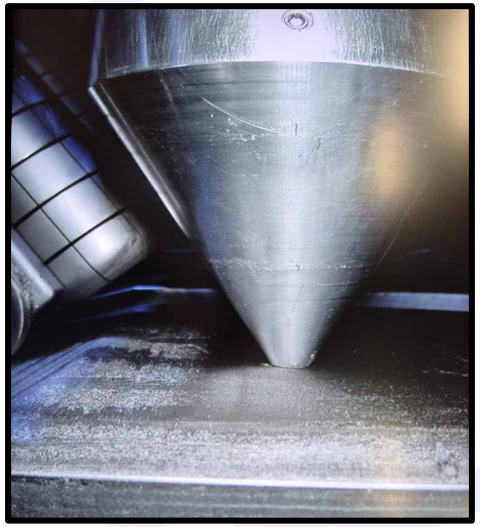
J. Likonen, PFMC 2025
R. Yi, PFMC 2025

Laser: 1 ns, 10 mJ



>800 locations, up to several 100 pulses each

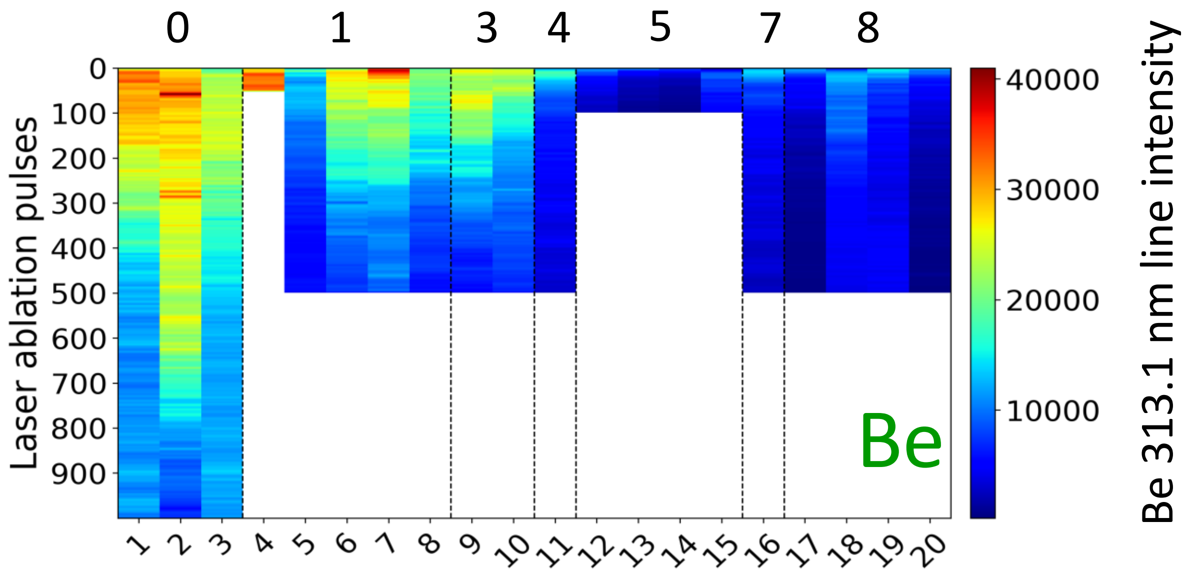


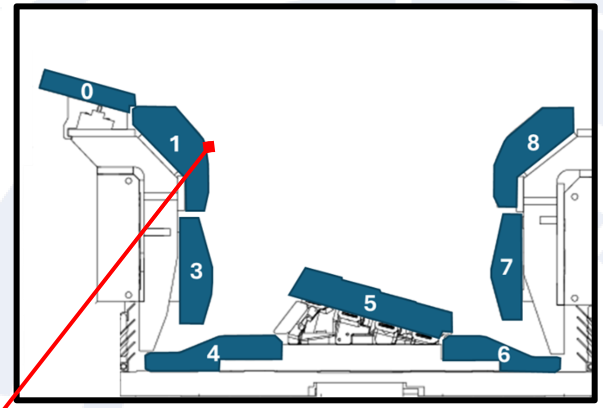


Multiple spectrometers including high resolution Littrow spectrometer to resolve Hα, Dα, Tα

Backup: Local depth-resolved measurements with LIBS

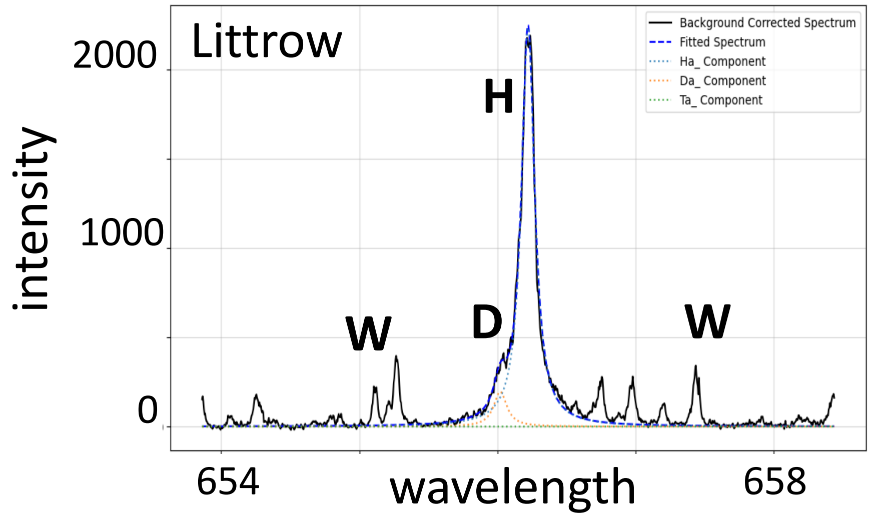
Deposition

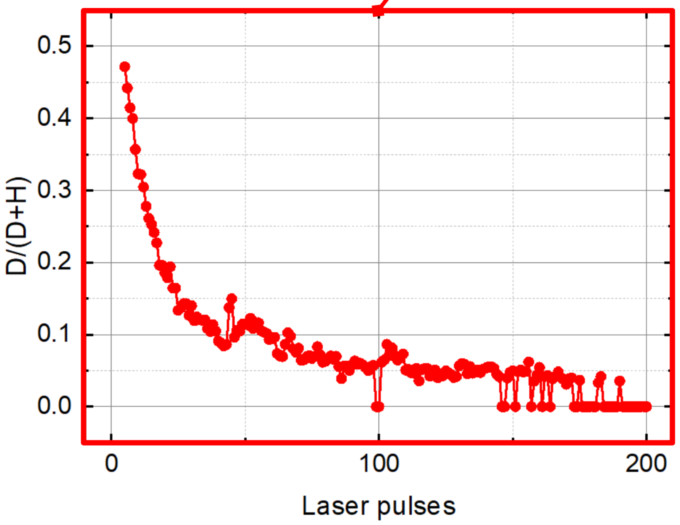




Confirms Be deposited mainly on Tile 0 and 1

Retention





Tritium not detectable for D/T well below 10% due to Stark broadening