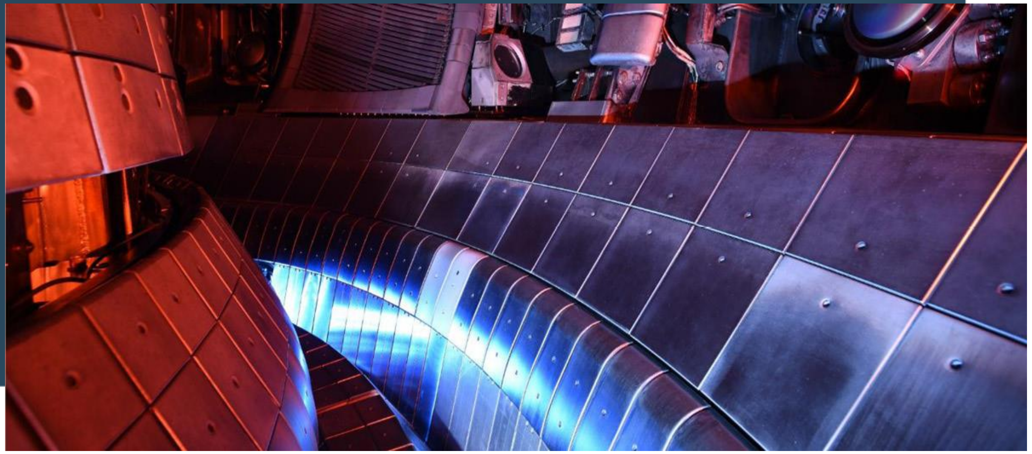
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

IPP

Overview of boronization process at ASDEX Upgrade

Sehoon An, Volker Rohde, Karl Krieger, Tim-Oliver Hohmann, Andreas Redl, Matej Mayer, Jörg Hobirk, ASDEX Upgrade Team, EUROfusion Tokamak Exploitation Team



EUROfusion

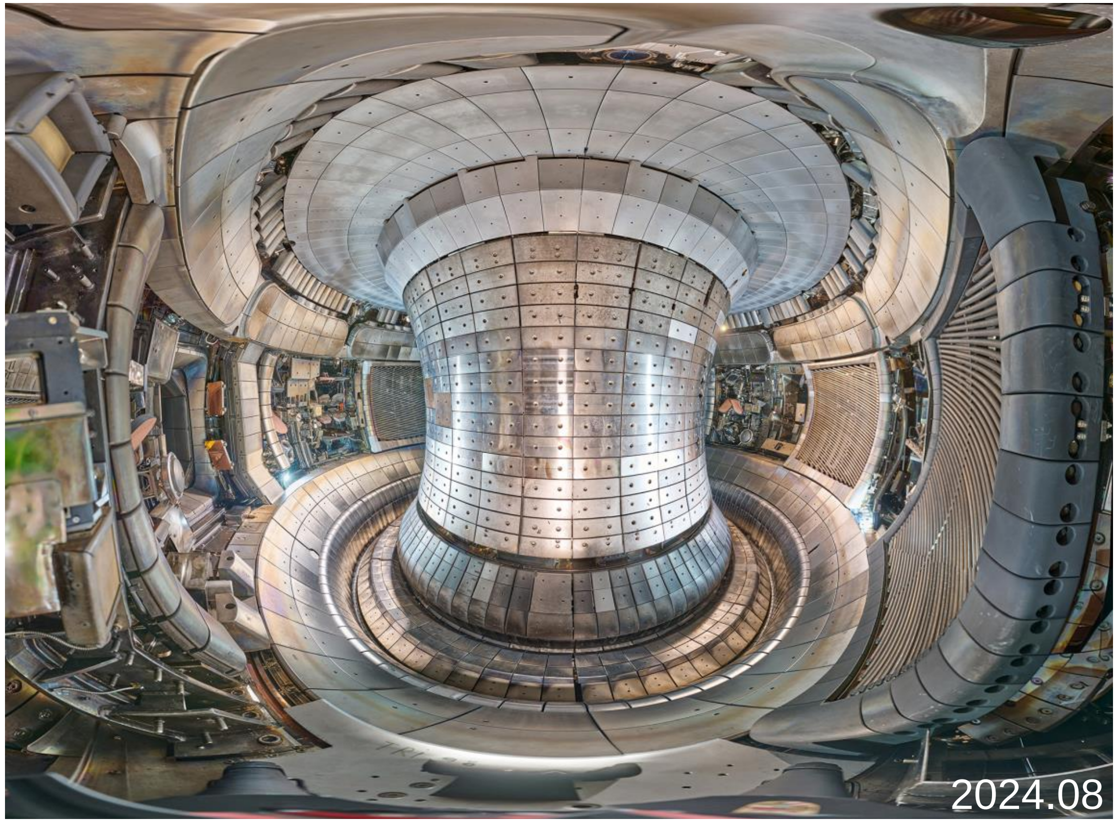
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Contents

- **Introduction**
  - Motivation
  - Boronization process at AUG
- **Experimental detail**
  - Boronization experimental setup
  - In-situ measurement of Boron layer thickness by QMB
- **Results and discussion**
  - Boronization effect on limiter startup phase
  - Evaluation of QMB measurment
  - Comparison of active anode configuration
  - Evaluation of sticking coefficient
  - Layer stability under air exposure
  - Gas tracing by residual gas analyzer (RGA)
- **Summary and Outlook**

Introduction

ASDEX Upgrade (AUG) in Garching

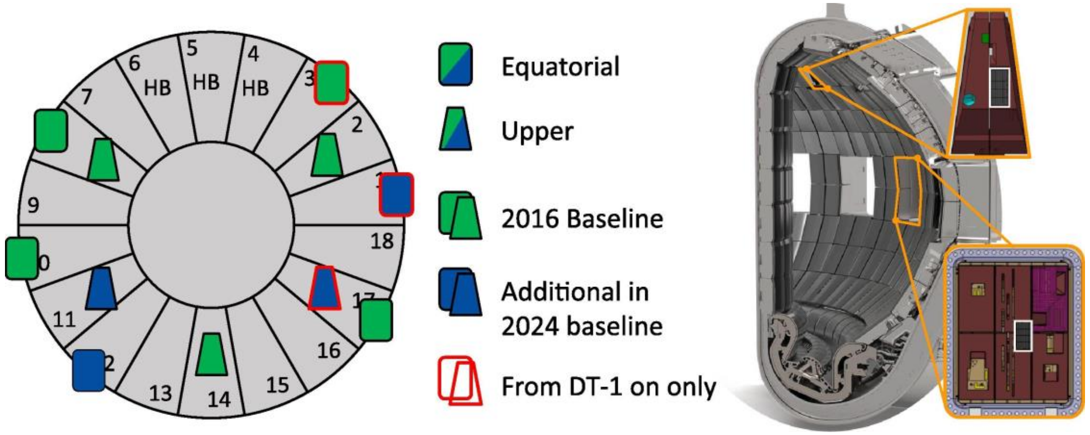


- Mid-sized **tokamak** (major radius ~1.65 m), plasma duration ~10 s, plasma current ~1.2 MA
- Equipped with Full W Plasma Facing Component

Background

- ITER switched first wall material from Be to W.
- W walls increase the risk of O contamination and radiative losses.
- **Boronization** is desirable to control impurities and ensure stable plasma start-up.

Proposed glow anode configuration (ITER 2024 re-baseline)



T. Wauters, NME (2025)

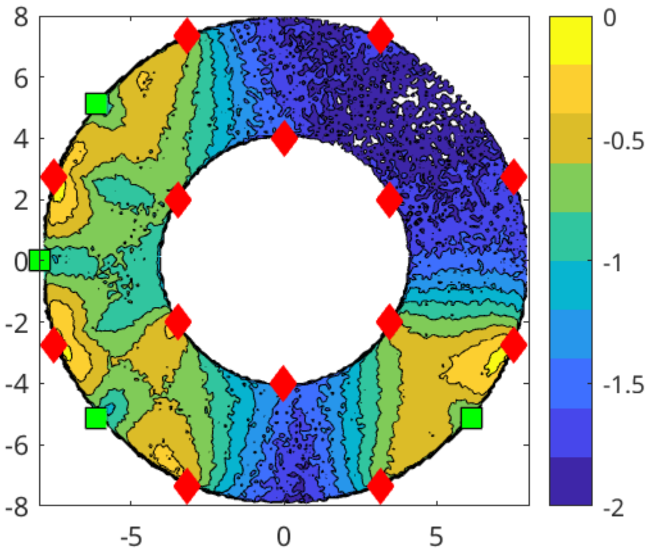
*Optimal arrangement of **gas injection points** and **glow anodes** is essential for homogeneous B coating*

Introduction

Questions from ITER:

- Plasma start-up (with or without GDB)?
- Partial vs. full anodes — homogeneity?
- Boron layer life time
- D/T retention in Boron layers

Reaction density of B_2H_6 (log)

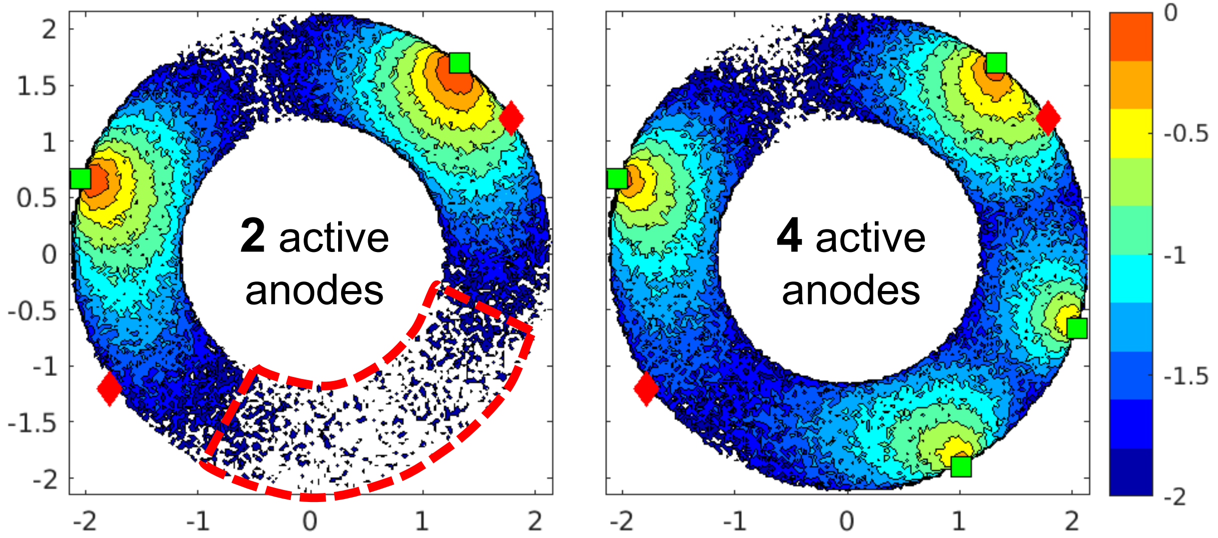


B_2H_6 injected at ◊, Anodes located at ■

T. Wauters, NME (2025)

Observation from modeling for AUG

- Modeling was performed for the **AUG configuration**
- A comparison was made between **2** and **4** active glow anodes
- Simulations predicted up to a **100-fold** reduction in deposition in areas without anodes



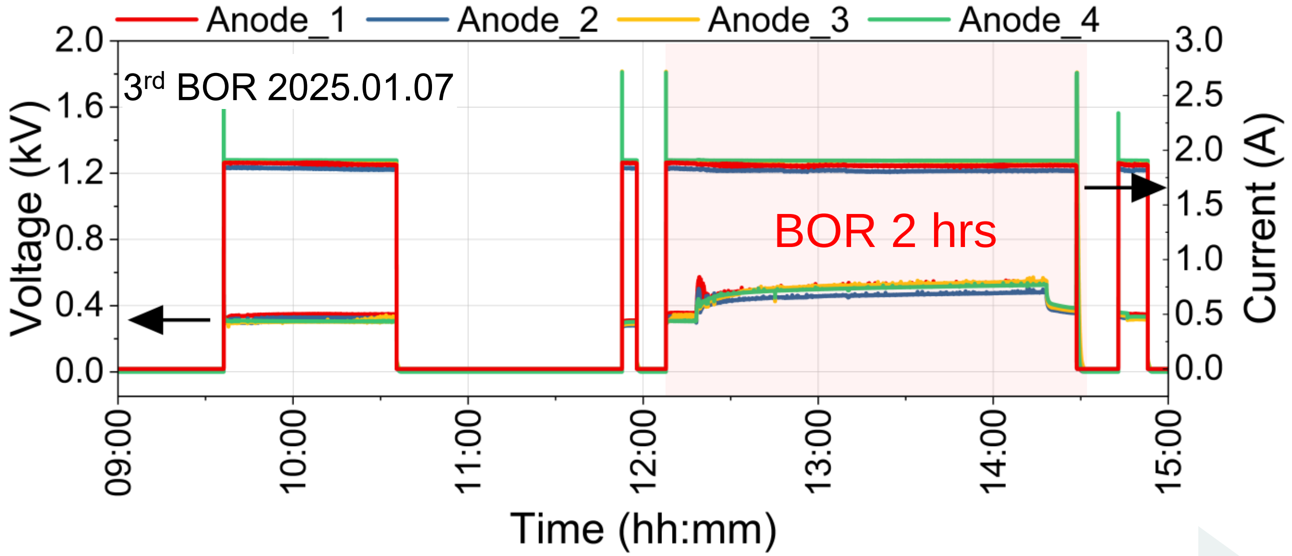
T. Wauters, 35th ITPA DivSOL meeting (2024)

Experimental validation is required!

Introduction

Description of Boronization process at AUG

Process sequence via V/I time trace



Automated procedure via SIMATIC PLC

HeGD GES	HeGD BOR	B_2D_6 BOR	HeGD BOR	HeGD GES
Wall cleaning	check	coating	clean	Diborane cleaning

F. Stelzer, SOFT (2025)

Boronization conditions

- Working gas: 10% B_2D_6 in He
- Working pressure: 0.005 mbar
- 4-glow anodes at midplane
  Current / Voltage: 1.8 A / 500 V

Process monitoring

- Quartz micro balance (QMB)
- Residual gas analyzer (RGA)
- Temperature sensor

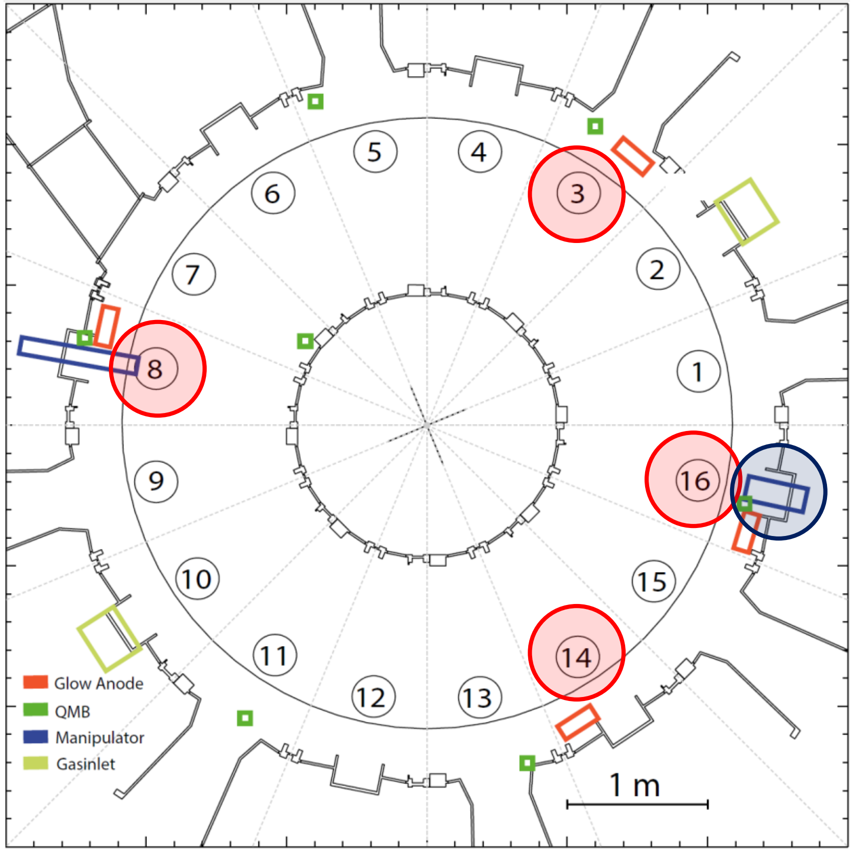
Surface characterization

- Nuclear reaction analysis (NRA)

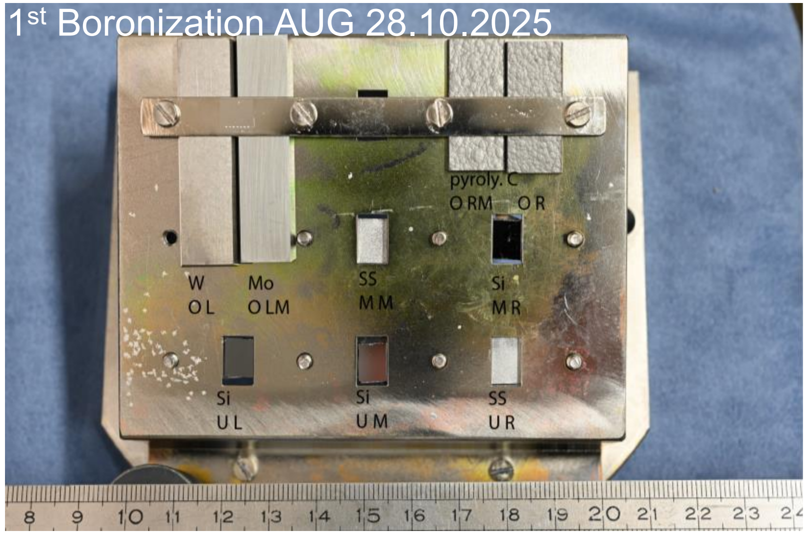
Experimental details

Glow anodes and sample configuration in ASDEX Upgrade

Toroidal position

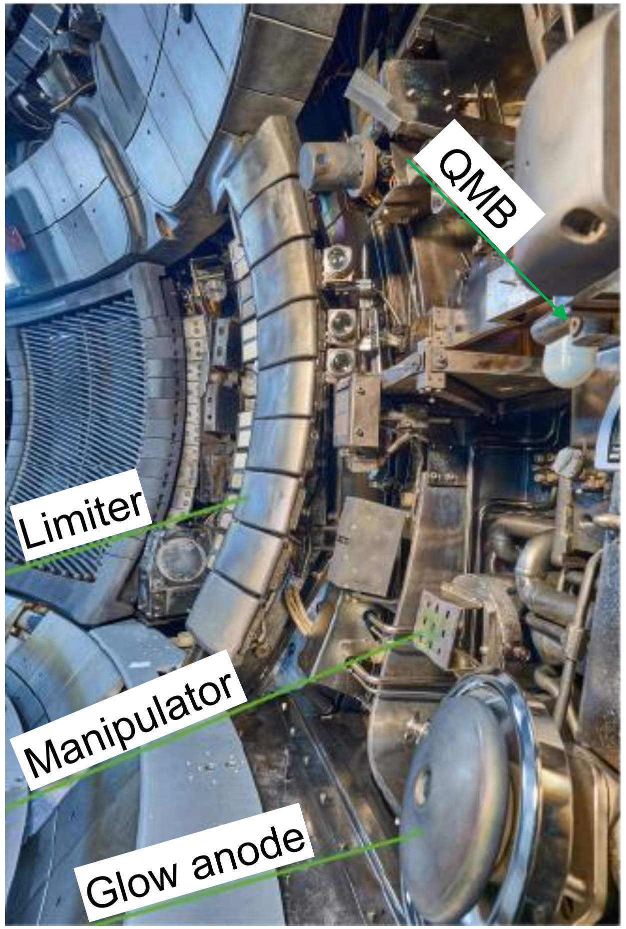


Sample arrangement



- 4 glow anodes are positioned at seg. 3, 8, 14, and 16
- 9 samples were mounted on the LBO manipulator (seg. 16)
- 12 BORs in 2024/25 with varied process time and anodes configuration

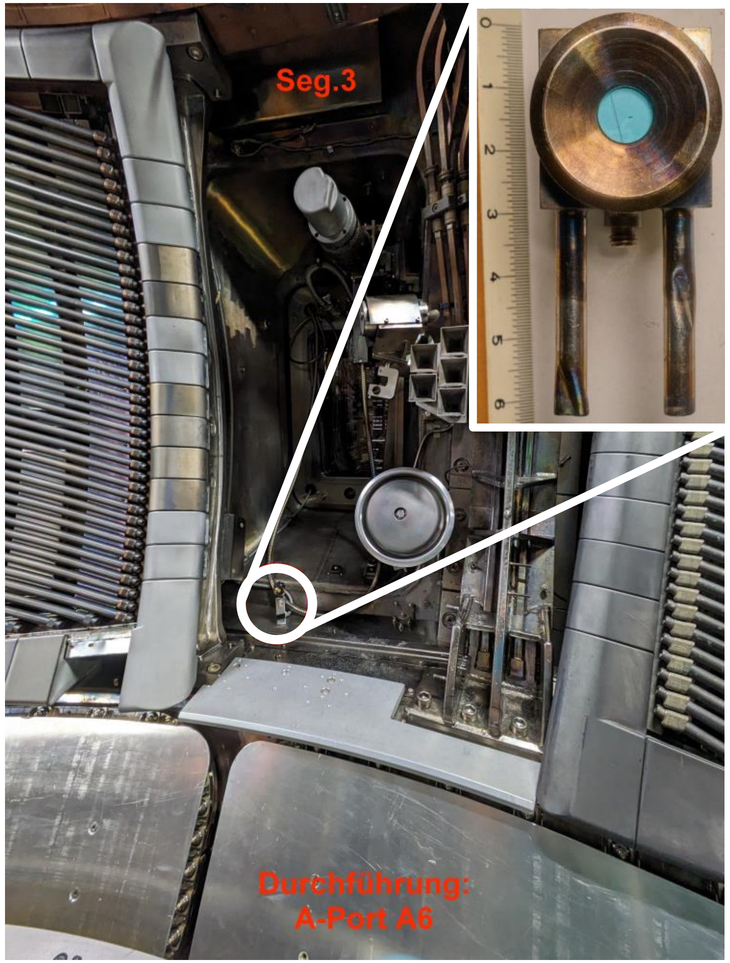
Experimental setup

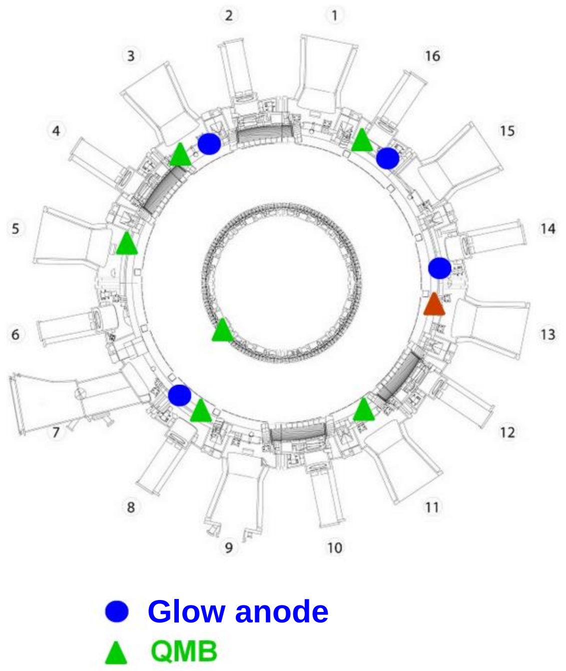


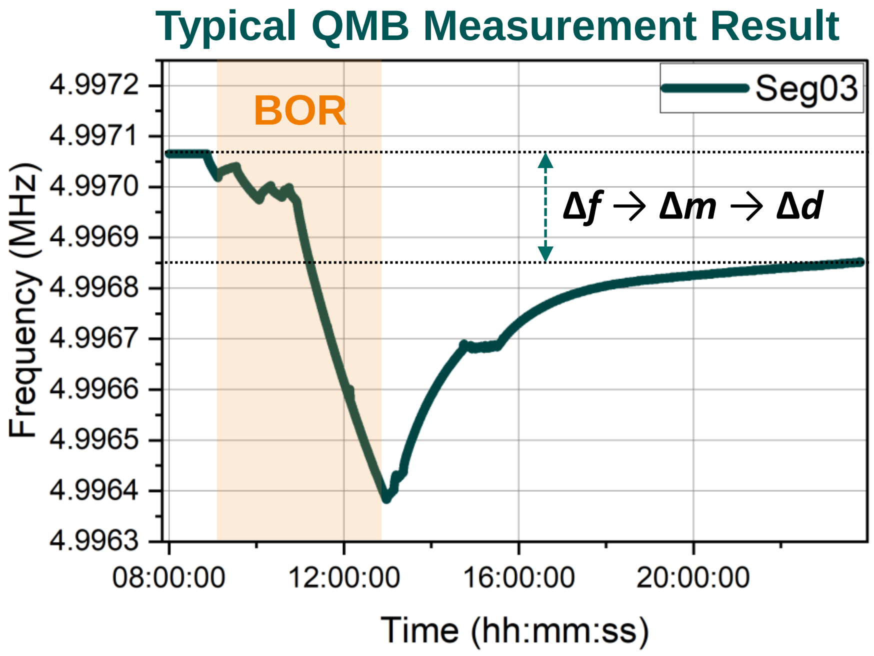
V. Rohde 02.08.2024

Experimental details

Measurement of layer thickness by Quartz Micro Balance (QMB)







- QMBs were installed at 7 different positions (seg. 3, 5, 7, 8, 11, 13, 16)
- By measuring frequency changes (Δf), thickness variation (Δd) can be evaluated as described by the Sauerbrey equation[1].
- The temporal evolution of the a-B:H layer can be monitored during the boronization process.
- Simultaneous probe measurements allow to capture the spatial distribution of the coating.

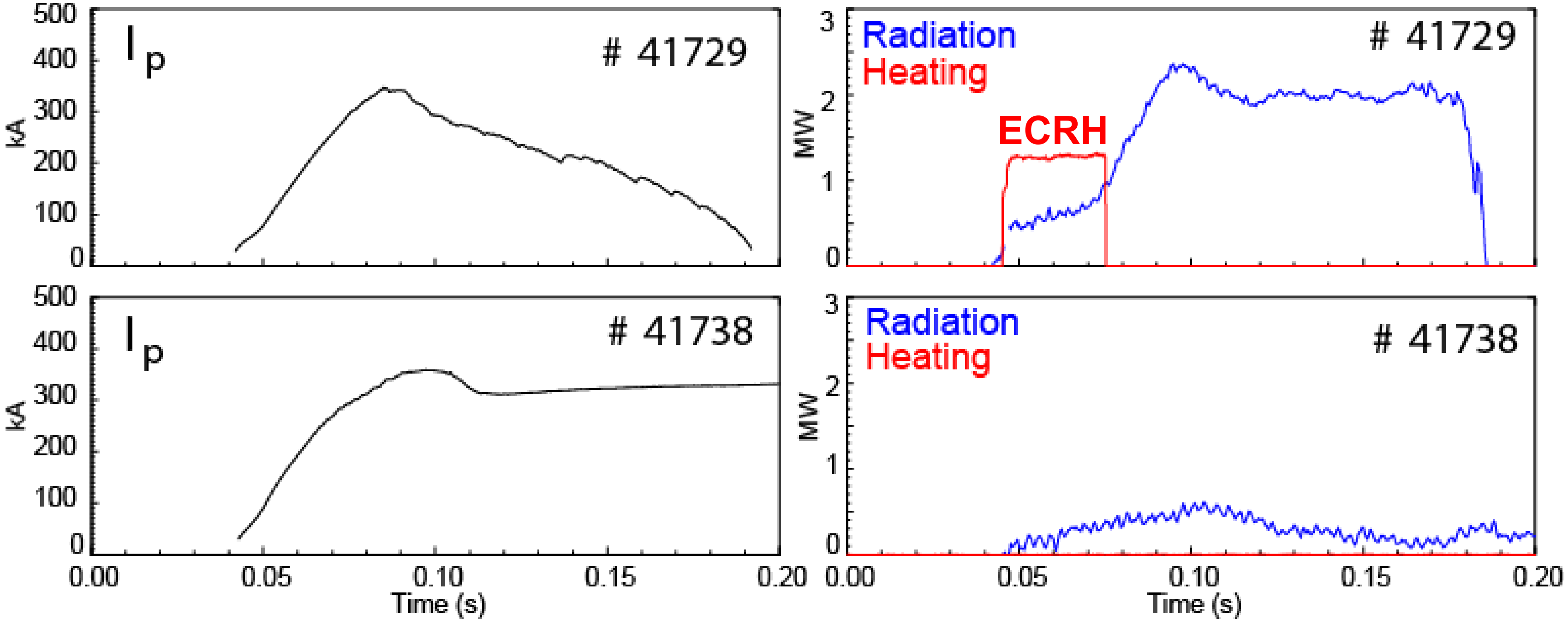
[1] Sauerbrey, G. H. (1959). Zeitschrift für Physik, 155(2), 206–222

Results and discussion

Results and discussion

Effect of boronization on limiter plasma start-up scenario

V. Rohde, PFMC (2025)



Without Boronization

- High radiation by low-Z impurities
- No stable plasma

With Boronization (2 anodes)

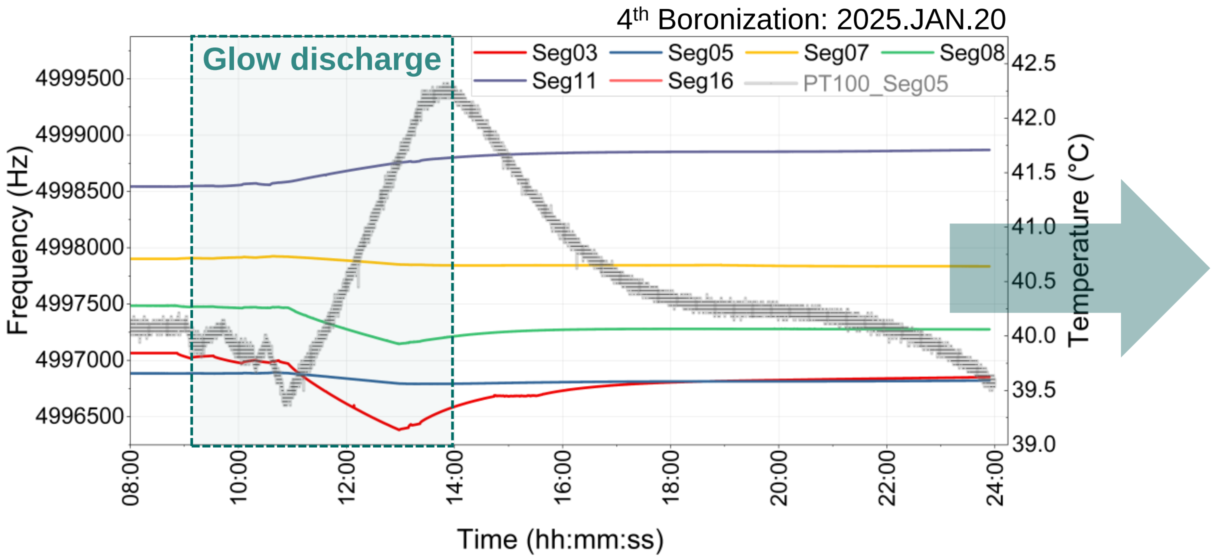
- Successful start-up without ECRH assist after 1st boronization
- Strongly reduced radiation

*Even half number of anodes provides a **clear conditioning effect**, enabling stable plasma formation in limiter startup scenarios.*

Results and discussion

QMB measurement and areal density evaluation

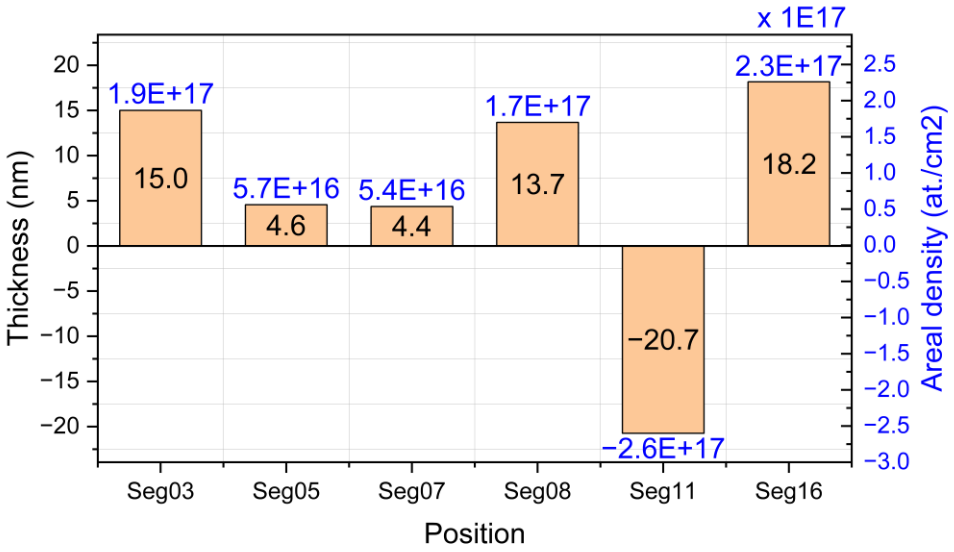
Measurement principle



- Frequencies of 6 channels and the temperature were measured simultaneously.
- Strong dependence of frequency on temperature variations

*Evaluation should be conducted in a **stabilized temperature regime** to ensure accuracy*

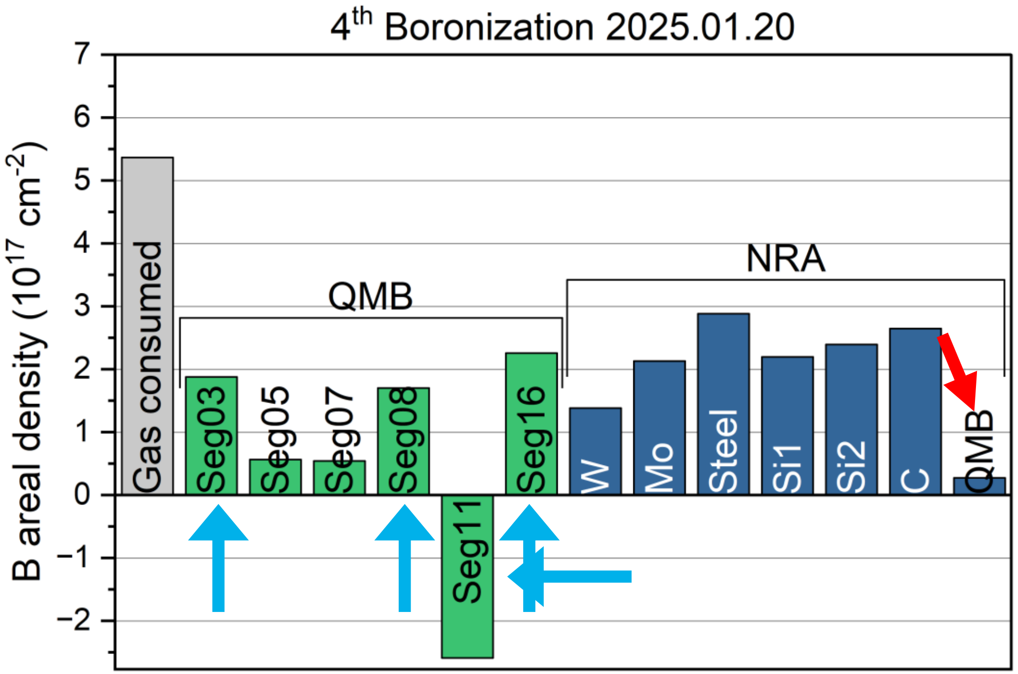
Evaluation of thickness & areal density

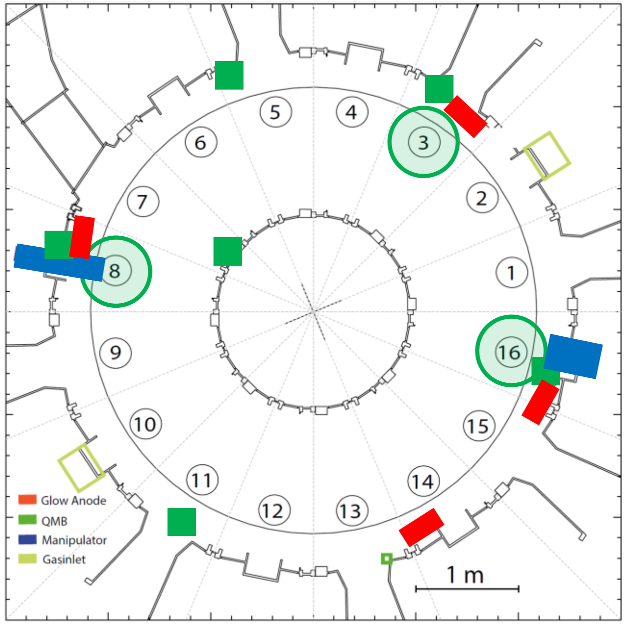


- The QMB measurement can be converted to **film thickness** and **areal density of B**.
- This method enabled **spatially resolved** thickness measurement.
- Due to the temperature increase during the GD process temporal evolution during BOR process is **limited.**

Results and discussion

Comparison of B areal densities





Glow anode

Manipulator

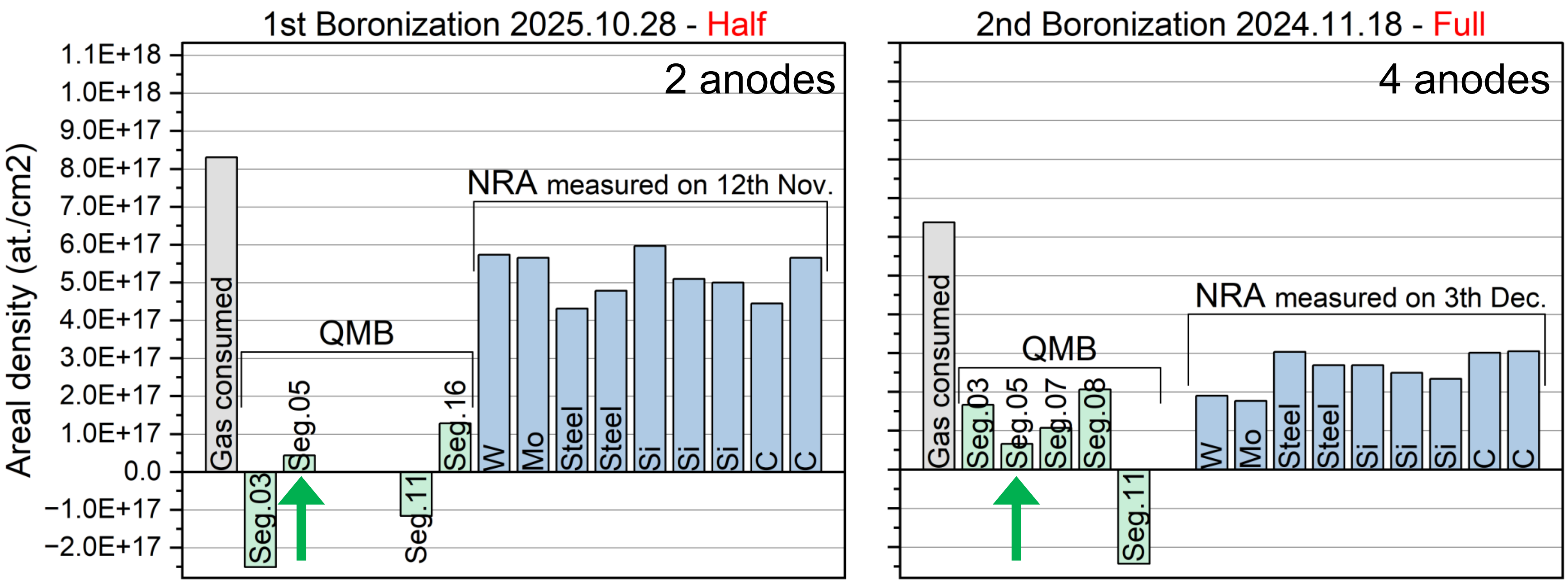
QMB

Various substrates for NRA

- Areal density of B from **QMB** can be directly compared to values obtained from the B_2D_6 **gas cylinder** and **NRA**.
- Values of QMB and NRA are in a similar range but approx. **x2 lower** than those from the gas cylinder. ➔ coating inhomogeneity or the need for a correction factor
- NRA results indicate a much lower B areal density on the QMB substrate. ➔ Floating potential
- At **Seg. 3, 8, 16**, the density is more than **x3 higher** than at **Seg. 5 and 7**, likely due to their proximity to the glow anode region.
- At **Seg. 11**, the areal density shows a negative value. ➔ Possibly, coating erosion or local inhomogeneity

Results and discussion

Dependence of active anodes (Half VS Full)



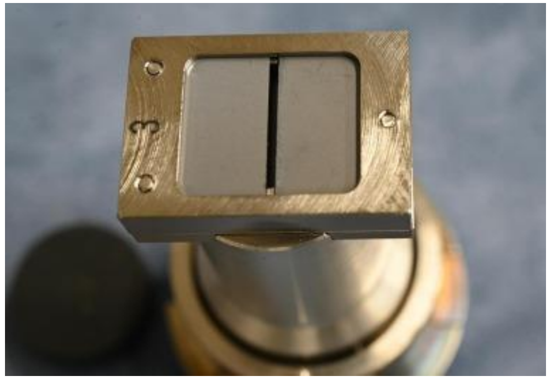
- QMB measurements were unstable in the Half boronization, presumably due to contamination after opening the torus, making areal density evaluation difficult for most segments.
- **Seg. 5** produced more reliable results and can be compared with the Half and Full boronization:
  Half (4.4 ×16 cm^{-2}) vs. **Full** (6.6 ×16 cm^{-2}) → 50% more B density with Full active anodes
- NRA data contradicts QMB, with the Full active anodes (4 anodes) showing a lower areal density.
  → Further investigation is needed via reproducibility test

Results and discussion

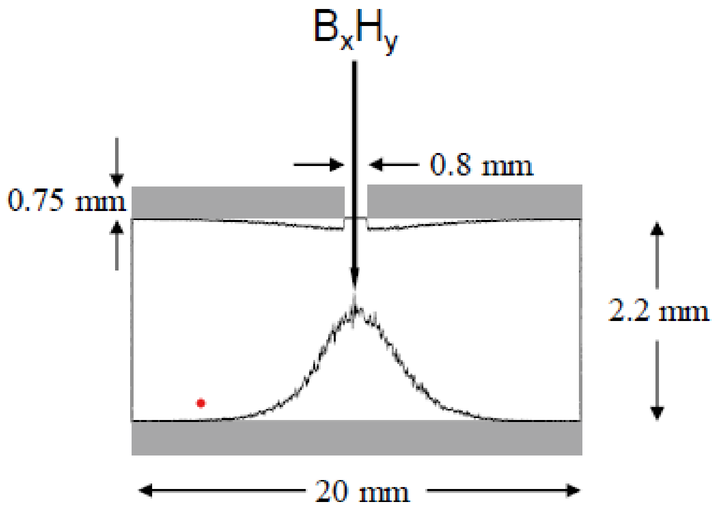
Evaluation of sticking probability

Cavity probe measurement

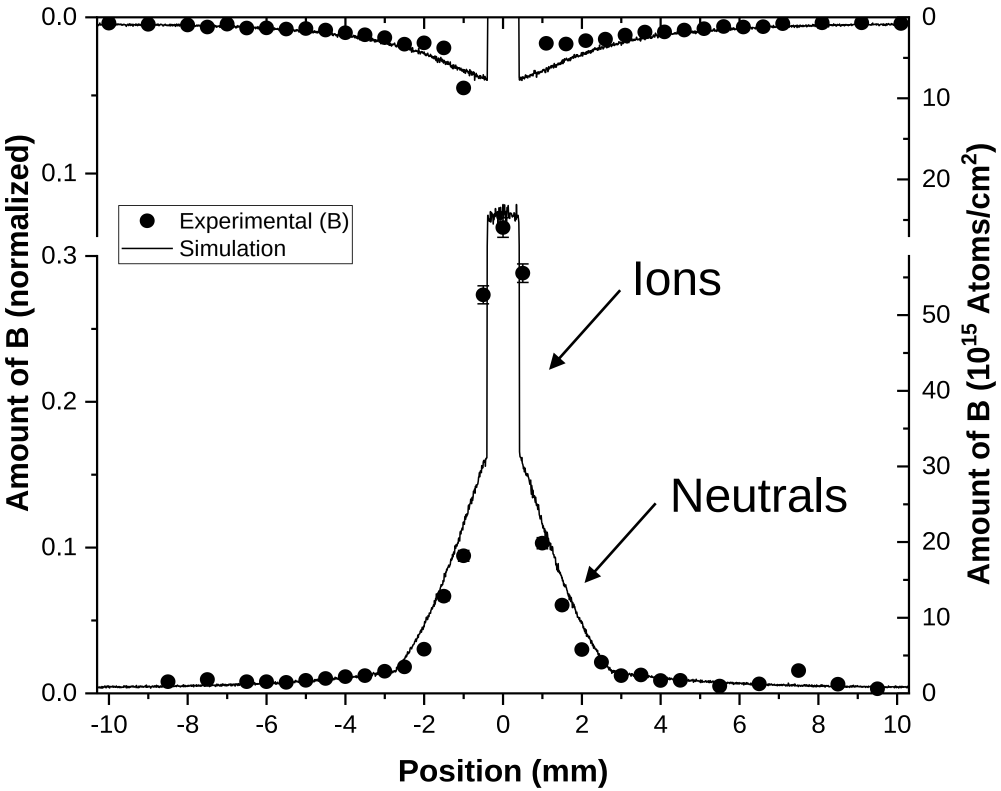
Cavity probe on MEM



M. Mayer, NME (2025)



- Incident flux: 52% Ions + 48% Neutrals
- Best fit: **β = 0.2 (Ions), ~0.7 + ~1.0 (Neutrals)**



- Low **β** → improved layer uniformity
- ITER BOR model does not include the surface deposition (sticking coefficient = 1)

Cavity probe measurements allows to improve the boronization model, incorporating surface deposition

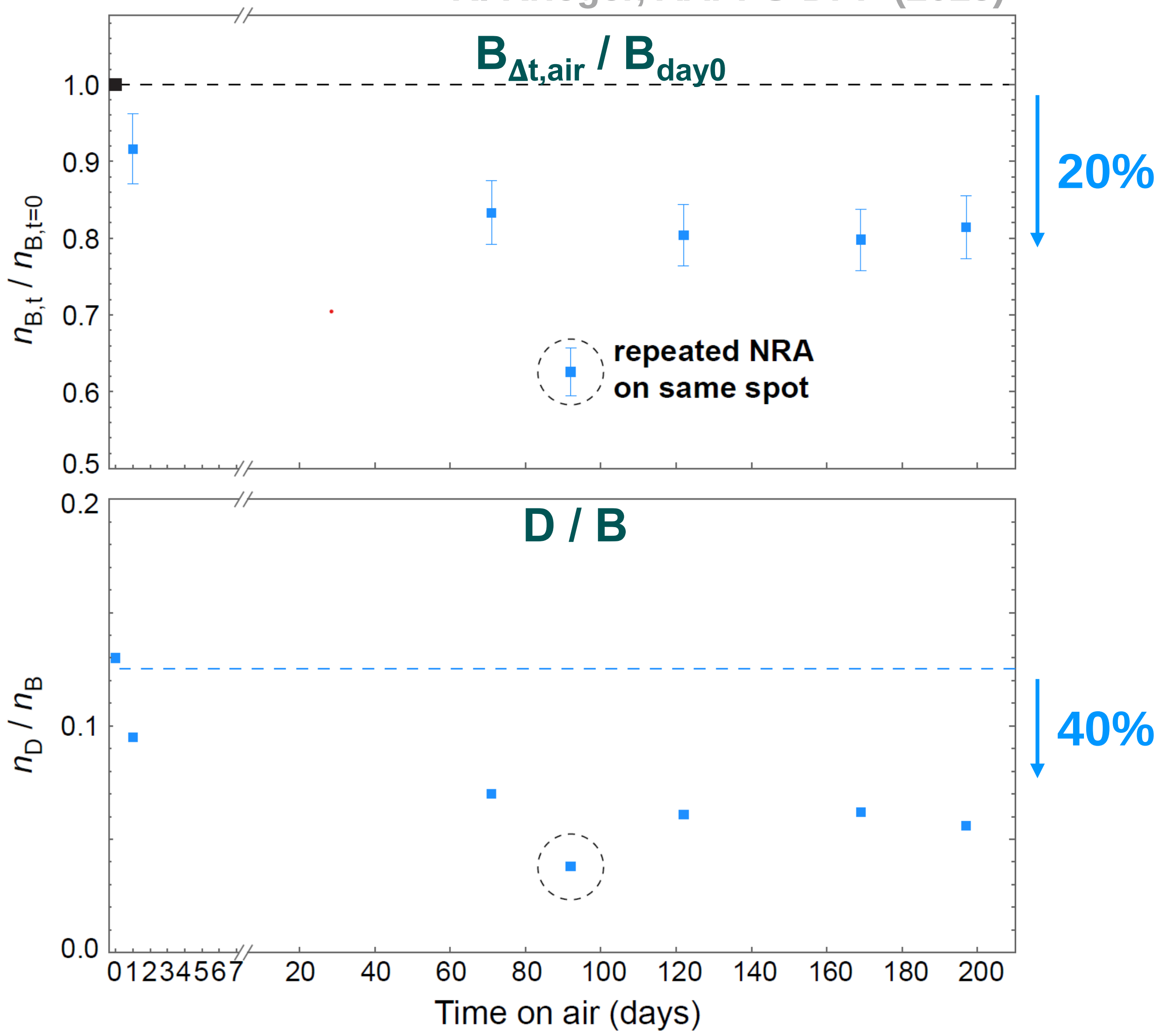
Results and discussion

Stability under air exposure

- Effect of exposure to air tracked by repeated measurements
- B loss mostly in first ~2 months
  ⇒ volatile products with H_2O
- D/B fraction is initially less than 0.2
- Ongoing D depletion (~40%) > rate of B
  ⇒ isotope exchange with H_2O

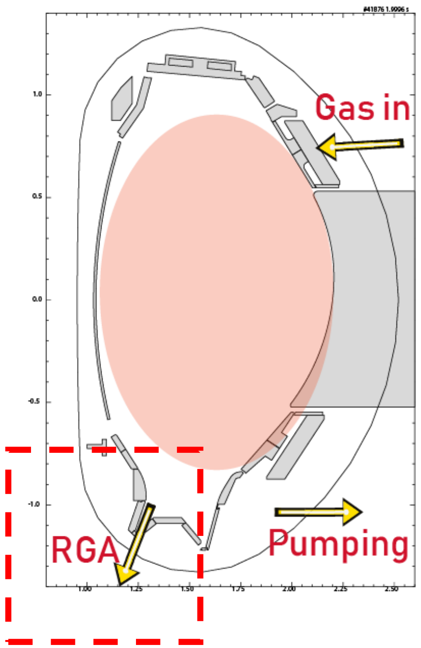
Potential implications for T-retention

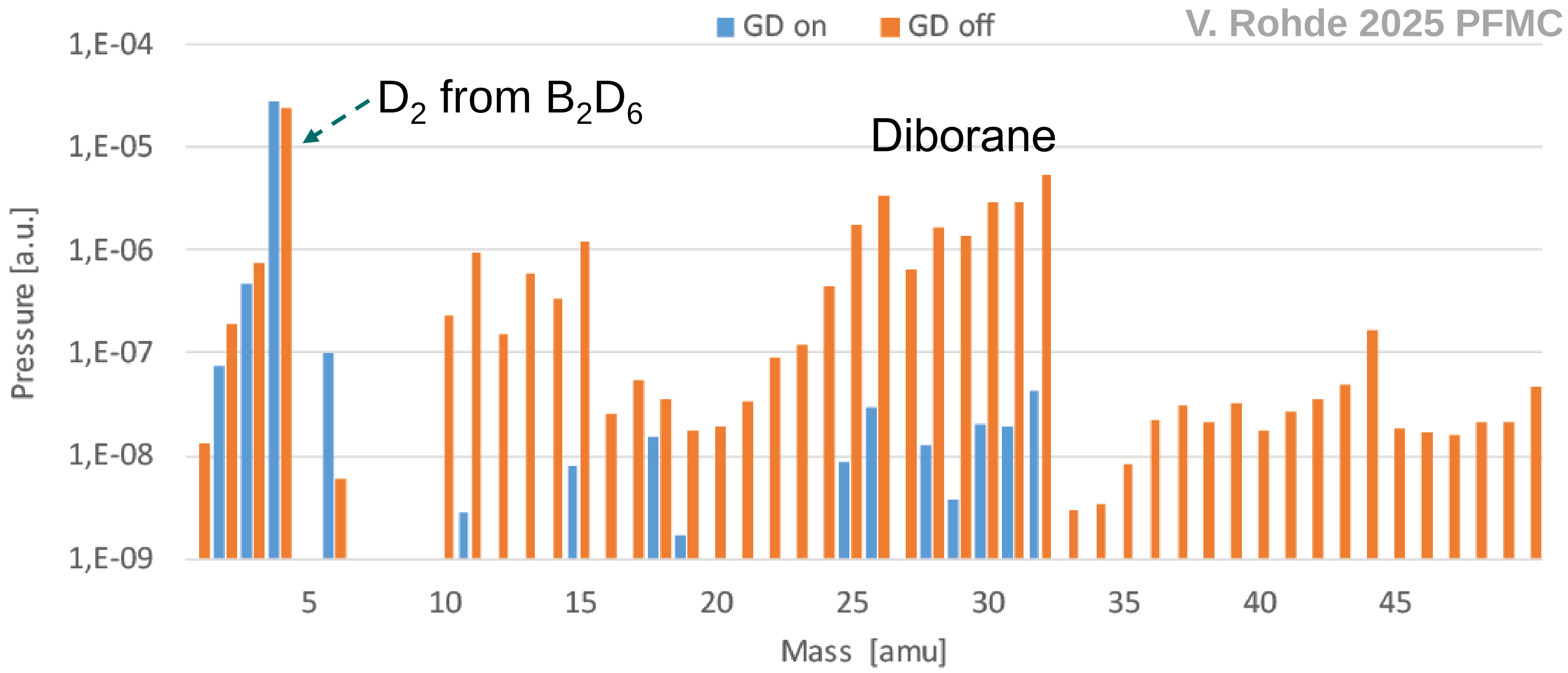
K. Krieger, AAPPS-DPP (2025)



Results and discussion

Gas tracing by residual gas analyzer (RGA)





- The **RGA** was conducted during BOR process, positioned near the **pumping exhaust**.
  → Allows monitoring of outgoing gas species.
- With GD, B_2D_6 relevant signals reduced to **~ 2%** of their values without GD.
- Majority of B_2D_6 gas is dissociated and contributes to wall coating.

Summary and Outlook

Newly automated boronization system at AUG was successfully deployed in the 24/25 campaign

Effect of Boronization and layer characterization

- Plasma start-up was benefited by boronization, even when only half of the anodes were used
- 7 QMBs provided in-situ spatially resolved measurements of B-layer thickness
  → Deposition rates vary with segment position due to geometric/shielding effects

Benchmark to ITER simulation (2 vs 4 anodes):

- 2 anodes: B-layer variation is much smaller than predicted → modeling assumes sticking coefficient = 1
- Sticking coefficient determined using cavity probe investigation → model can be further improved

Deuterium retention & loss

- D/B fraction less than ~0.2 → Tritium inventory not a critical constraint for GDB
- Decrease in D areal density over time, possibly due to isotopic exchange with atmospheric moisture

Residual gas analysis

- Most B_2D_6 molecules are decomposed, effectively contributing to wall coating

Summary and Outlook

Next steps:

Ongoing analysis:

- Post-mortem surface analysis on retrieved samples (e.g. Si wafers, tiles, magnetic shutter, and dust samples)

QMB improvement

- Introduce water cooling to QMB for reducing temperature-driven drift
- Installation of additional PT-100 sensors for improved spatial temperature monitoring

Diagnostics and Modeling for GDB

- Use Langmuir probes to characterize plasma properties and correlate them with the observed spatial thickness variation
- Further development on GDB modeling (currently under discussion)