PWIE Meeting November 2025

TOMAS: Status and future plans

Kristel Crombé and the TOMAS team

LPP-ERM/KMS

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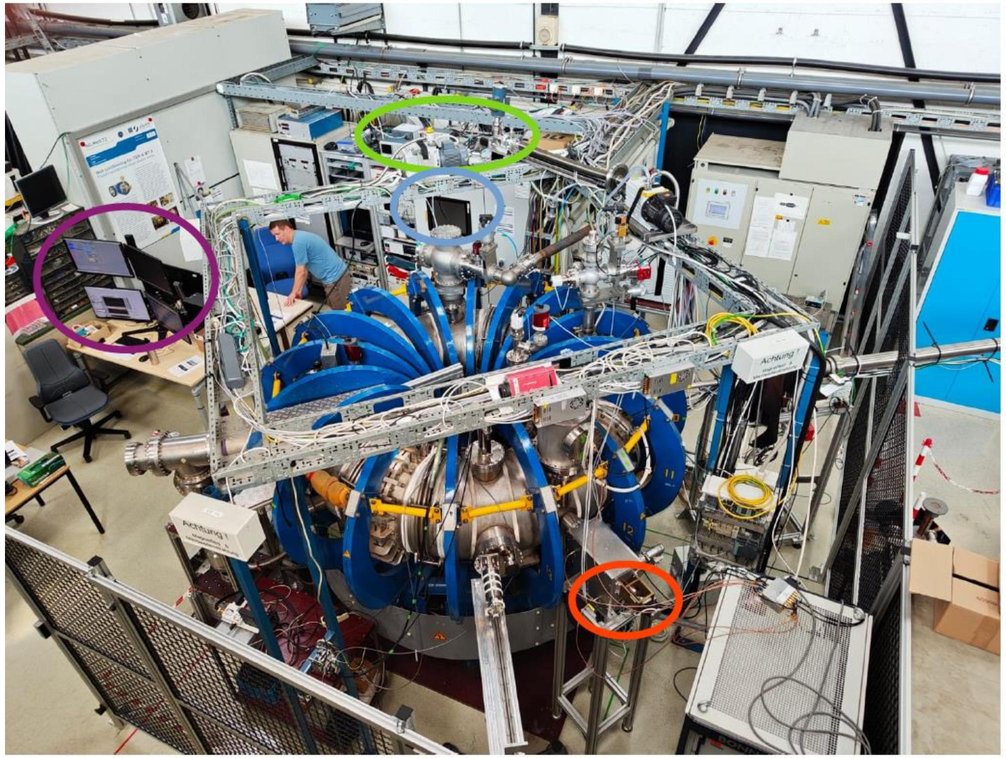
TOMAS device

The TOroidal MAgnetized System (TOMAS) plasma facility aims at complementary research on wall conditioning methods, plasma production and plasma–surface interaction studies.



Parameter*	Value
Volume	1.1 m^3
Major Radius	0.78 m
Field on axis	125 mT
Minor Radius	0.26 m
RF frequency	10–50 MHz
RF power	up to 6.0 kW
EC frequency	2.45 GHz
EC power	0.6–6.0 kW
GD power	9 kW

Diagnostics:

- Horizontal and vertical Langmuir probes
- Microwave Interferometer
- Quadrupole Mass Spectrometer
- Time-of-Flight Neutral Particle Analyzer
- Residual Field Energy Analyzer
- NIR/VIS/UV spectrometer
- Video cameras (incl. fast camera)

Auxiliary systems:

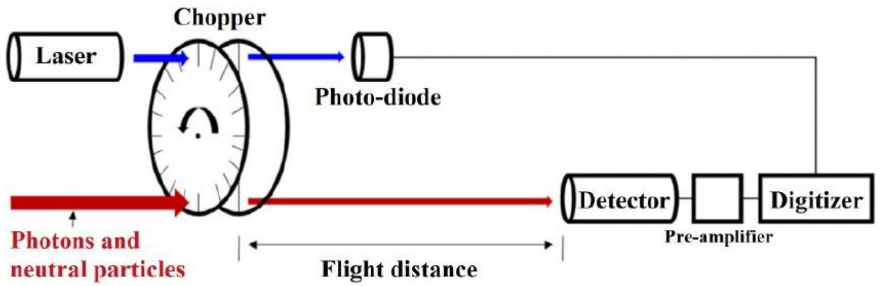
- Control system (Siemens SIMATIC S7-1500 - based)
- Data Acquisition system (NI PXIe-1071 - based)
- Experiment control system (2 x Arduino Mega & 2 x Tektronix AFG 3252)

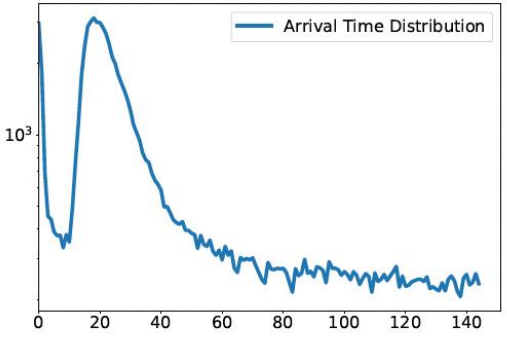
* A. Goriaev et al., Rev. Sci. Instrum. 92 (2021)

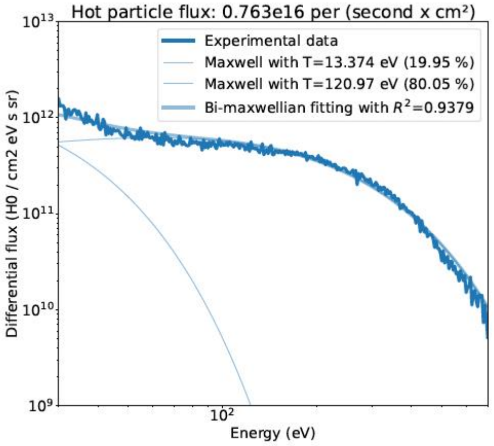
3

Focus on PWIE most relevant diagnostics: ToF NPA and RFEA

Time of Flight Neutral Particle Analyzer → time and energy resolved neutral particle distribution



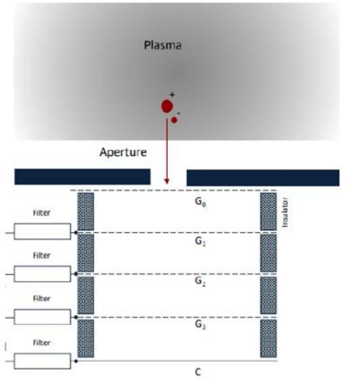


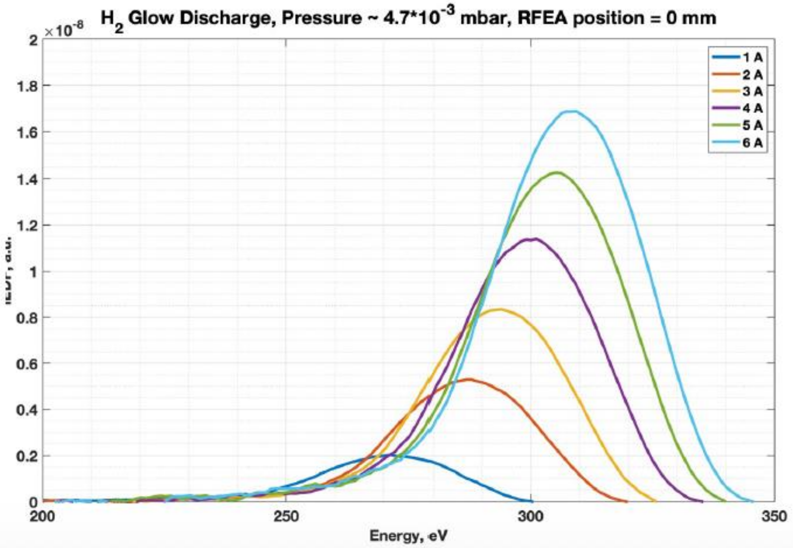


* D. López-Rodríguez et al., Review Scientific Instruments 95, 083542 (2024)

Retarding Field Energy Analyzer → ion fluxes and ion energy distribution

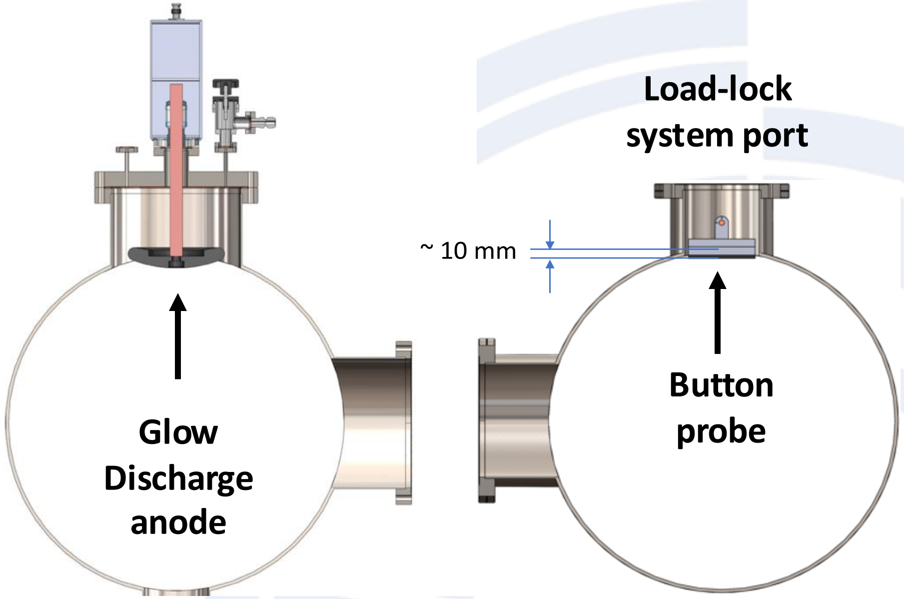
Ion energy range is 0 – 2000 eV and ion flux range is 0.01 – 50 A/m^2

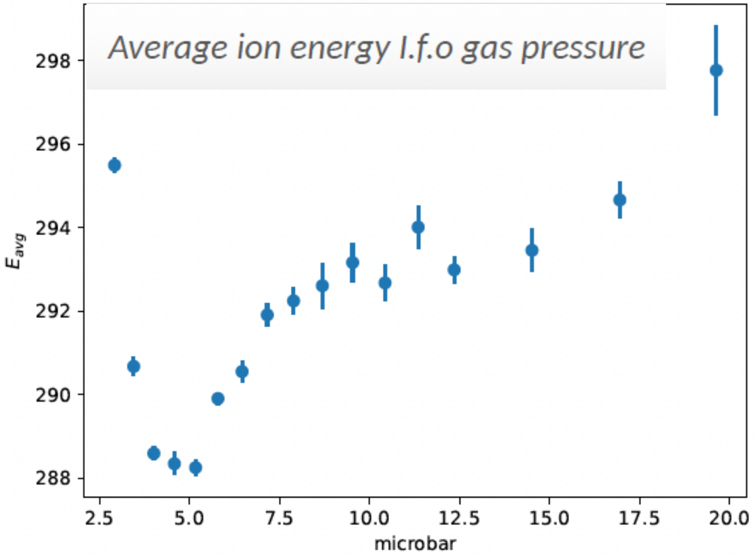


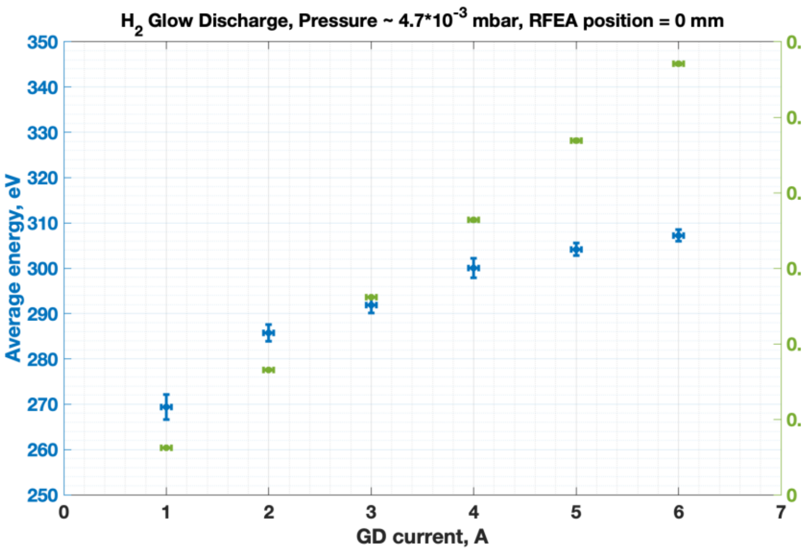


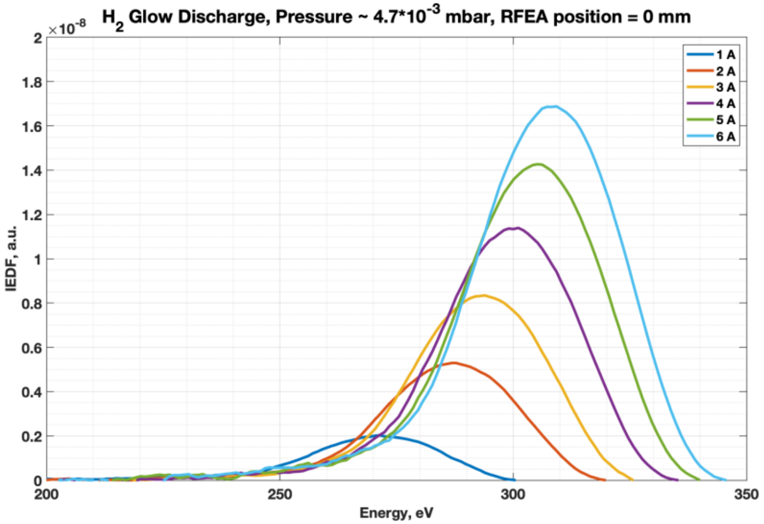
Glow discharge characterization

- Use of RFEA with the **new button probe**
- Local measurements of **average energy** and **ion flux**
- **Pressure**, **current** and **probe** position scans
- Calculation of corresponding boron erosion rates
- Selection of **optimal parameters** for exposure experiment
- ITER relevant pressure, current and sample position

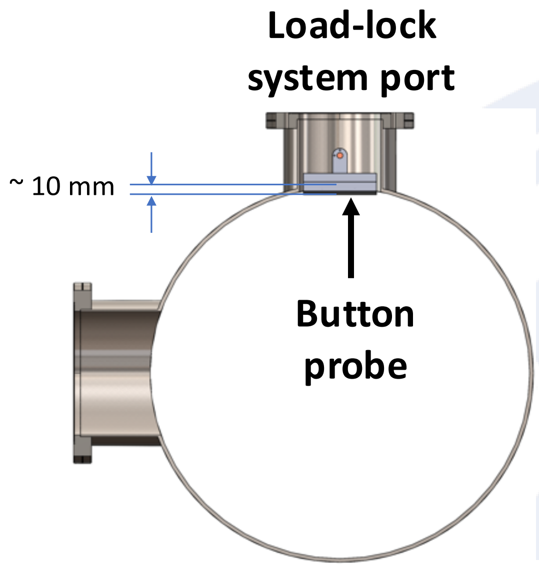




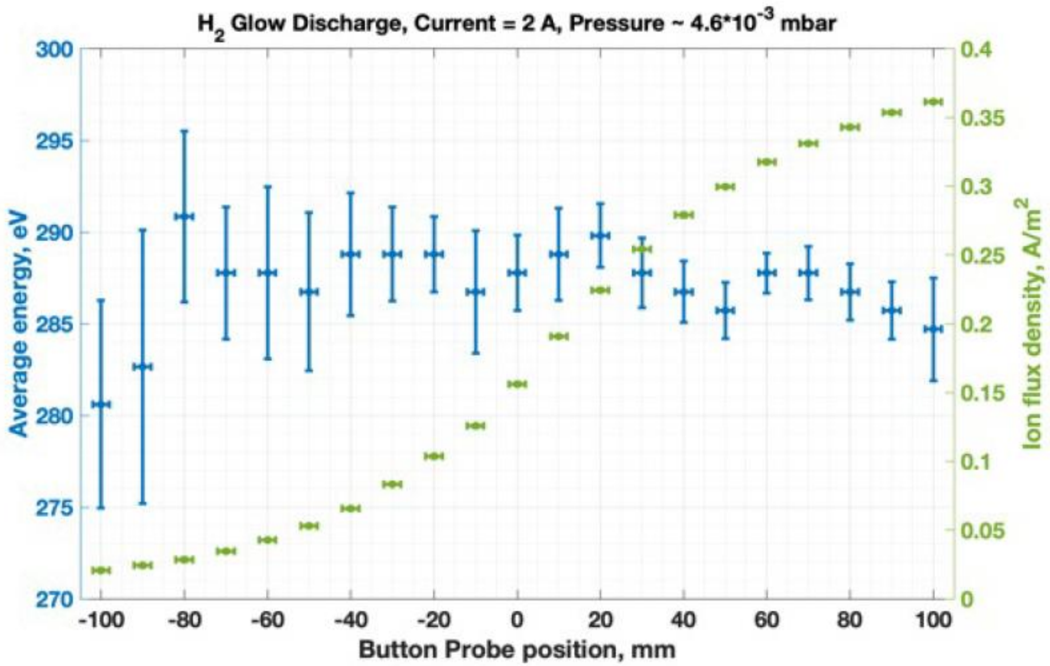


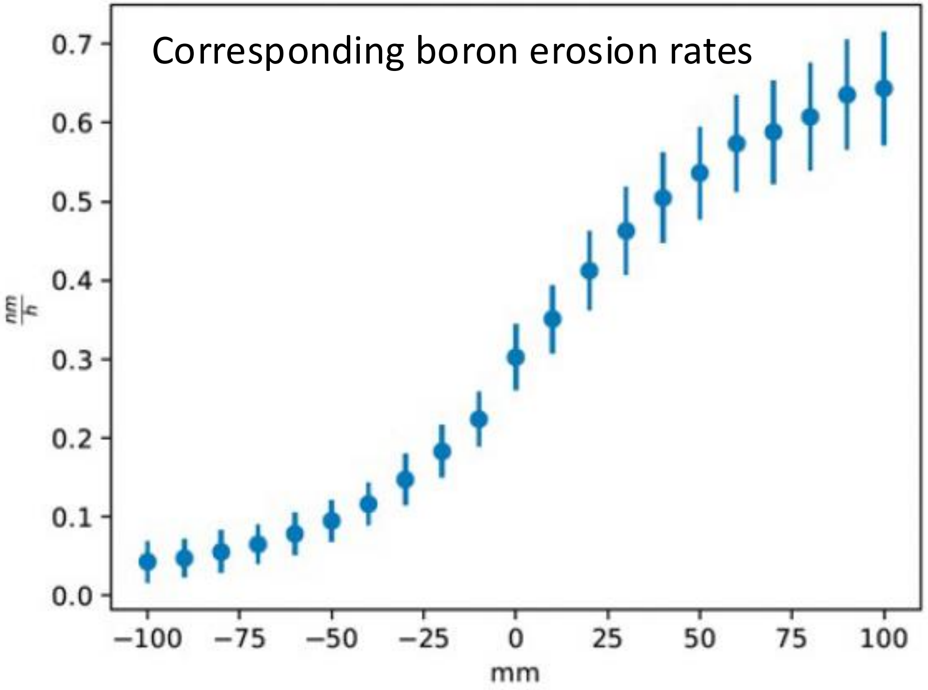


Glow discharge characterization



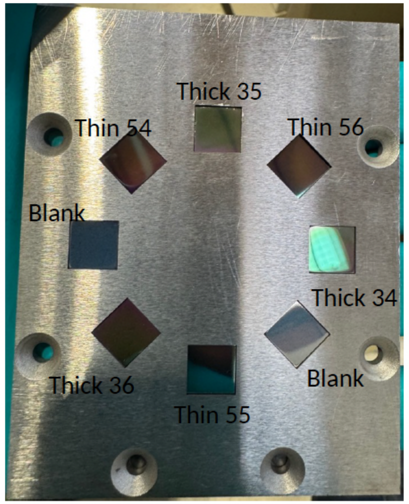
Average ion energy and ion flux density dependence on holder position

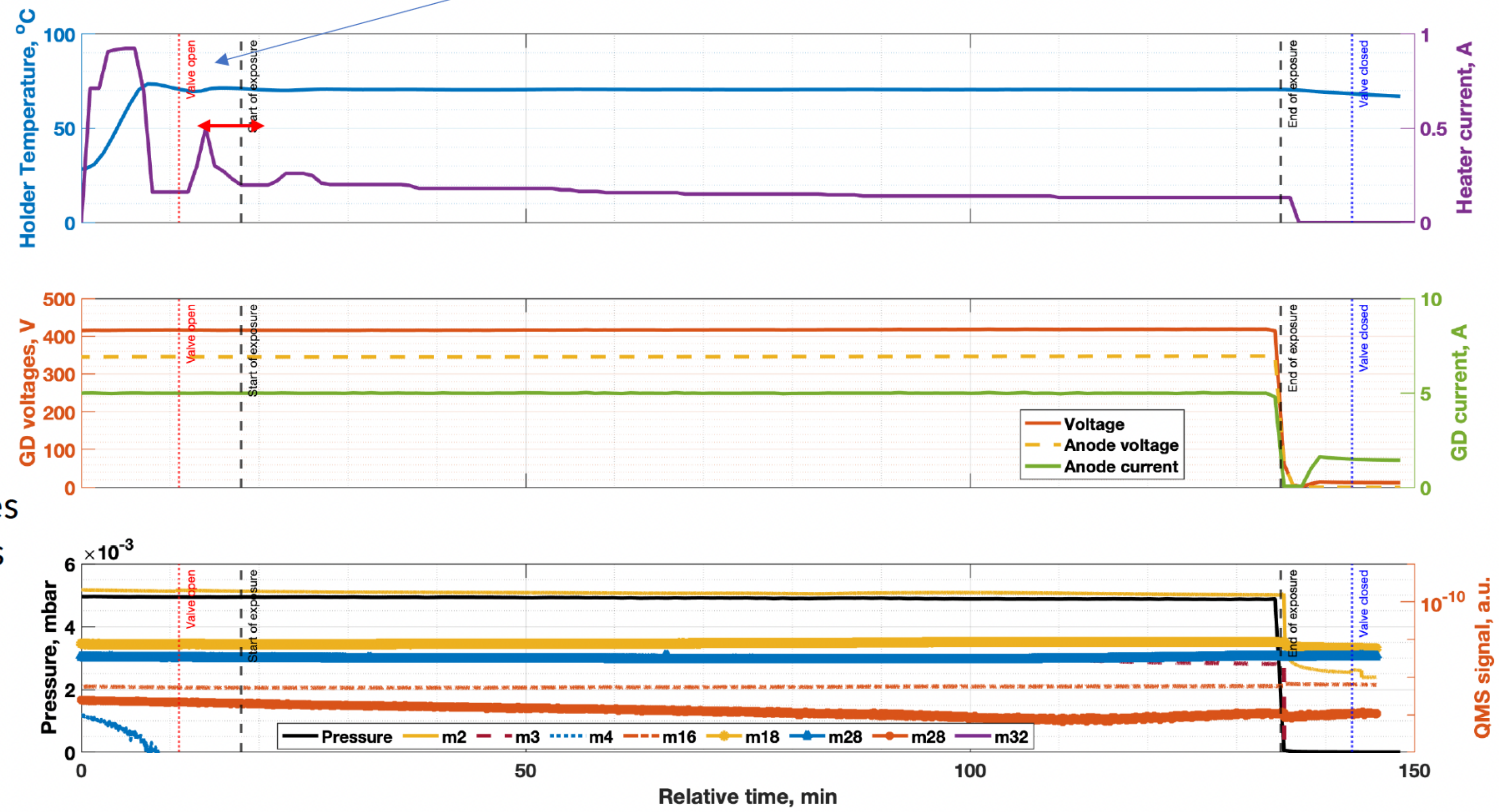




GDC exposure at 70°C

Sample holder movement from idle position to Vessel top





- 3 ”thick” B:D coated samples
- 3 ”thin” B:D coated samples
- 2 dummy clean W samples

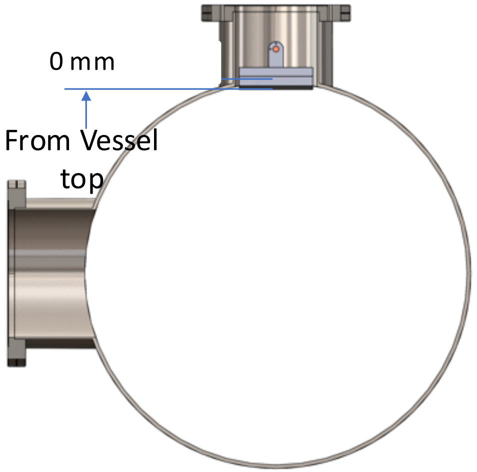
Heating duration at 70 °C: 135 minutes

Temperature ramp up: 6 minutes

Pure GD exposure duration: 117 minutes

Start of sample heating

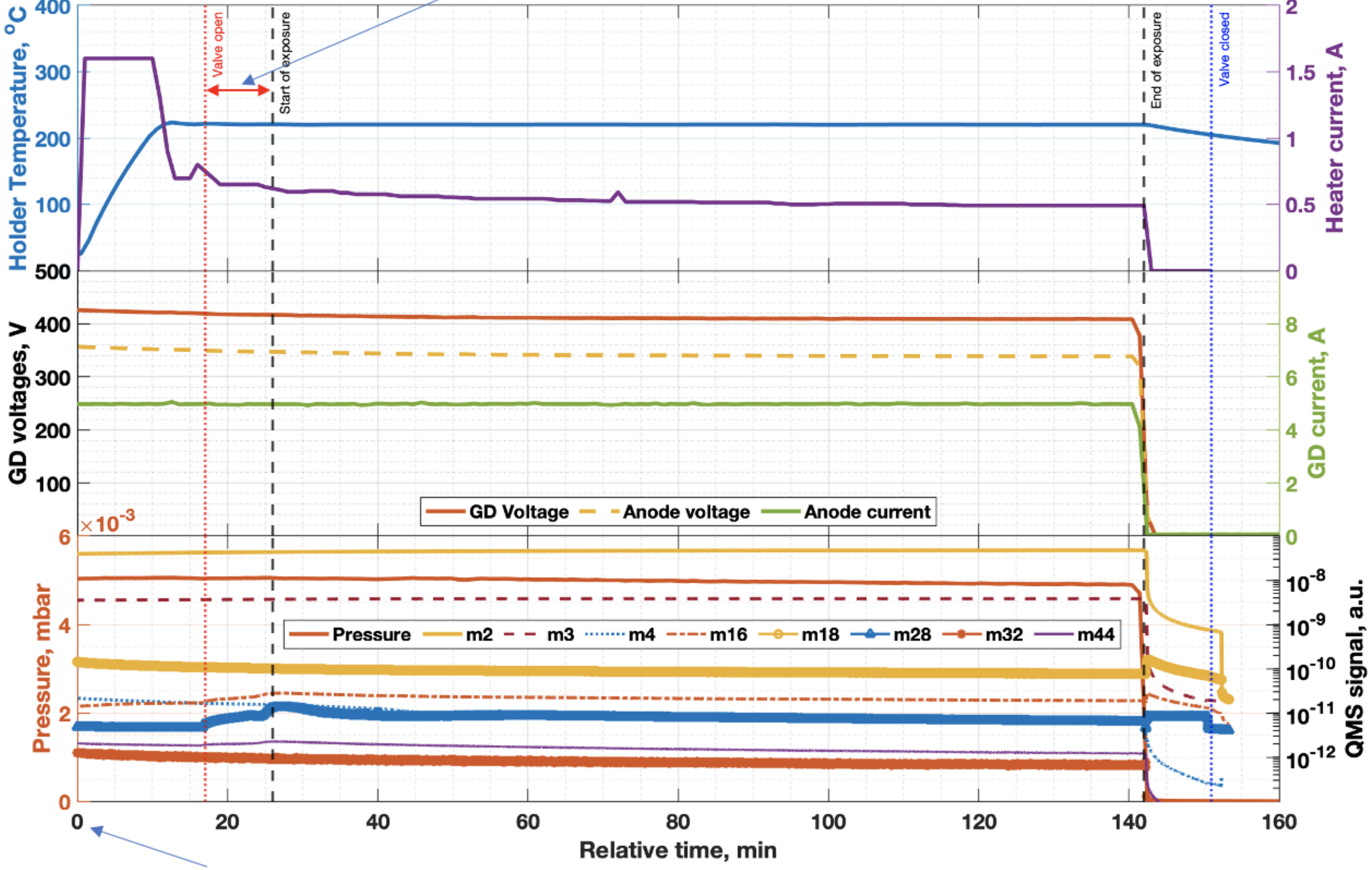
GDC exposure at 220°C



- 4 “thin” B:D coated samples
- 4 dummy clean W samples

Heating duration at 220 °C
-> 131 minutes
Temperature ramp up
-> 12 minutes
Pure GD exposure duration
-> 117 minutes

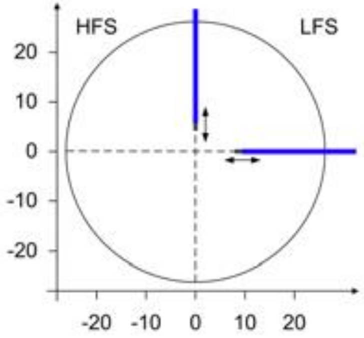
Sample holder movement from idle position to Vessel top

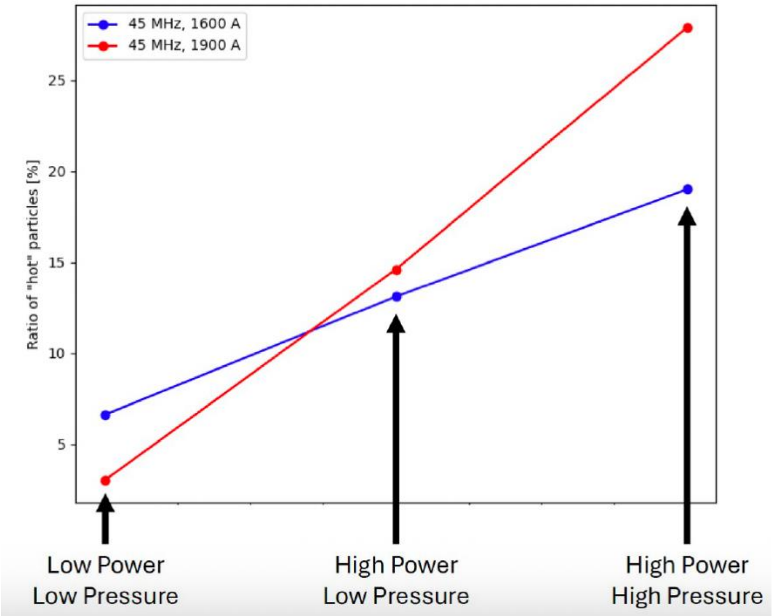


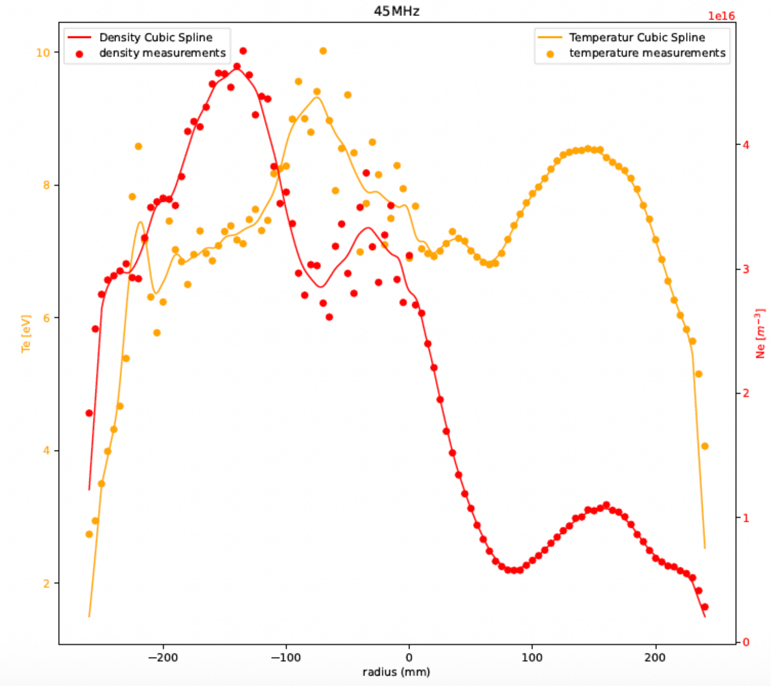
Start of sample heating

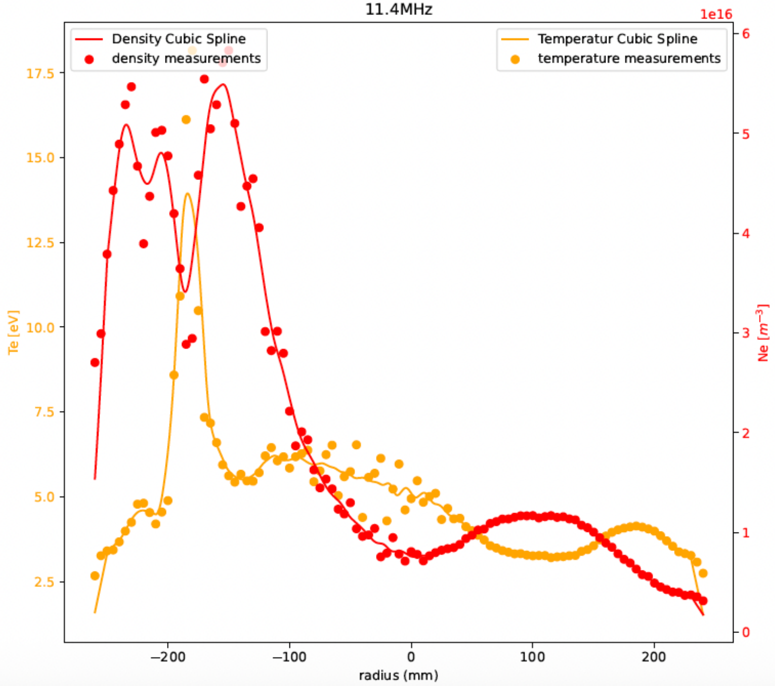
Ion cyclotron wall conditioning characterization

- **Pressure**, **RF frequency** and **magnetic field** scans
- Measurements of **average energy** and **flux** of **CX neutrals**
- Calculation of corresponding boron erosion rates
- Selection of optimal exposure experiment parameters
  - Exposure duration, ICWC duty cycle
  - ITER relevant pressure, RF frequency and magnetic field scans



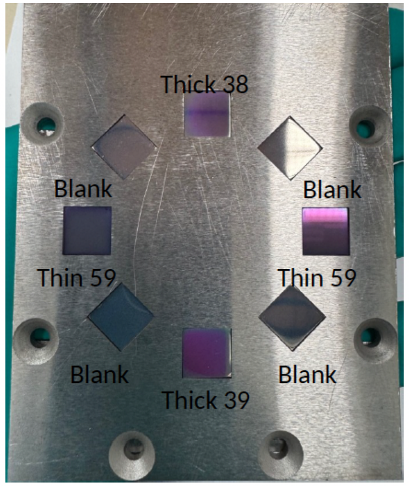




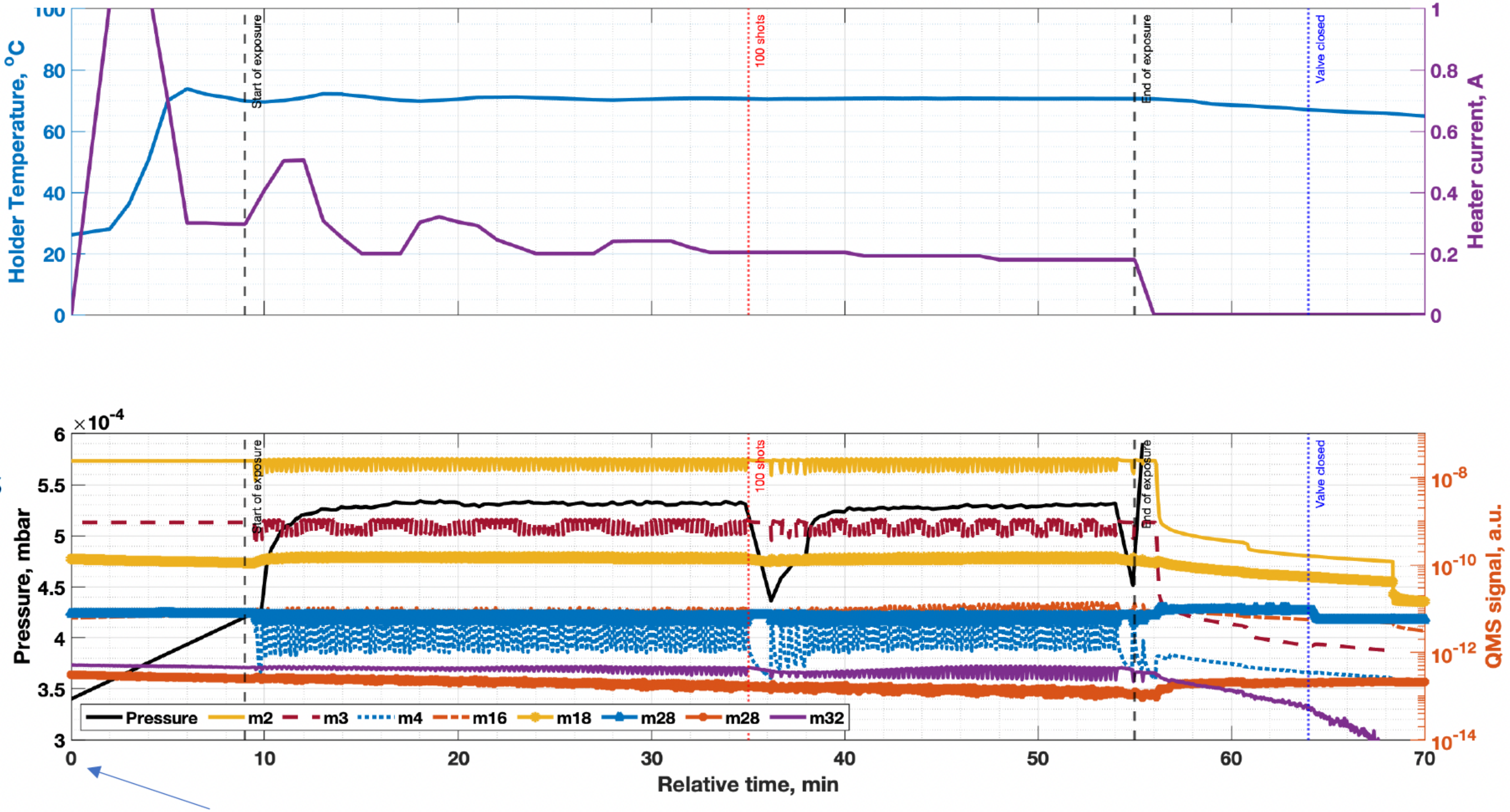


ICWC exposure at 70°C

Parameters:
RF frequency -> 45 MHz, Magnetic field -> 1600 A,
IC pulse length -> 4 s, dwell time -> 10.9 s



- 2 ”thick” B:D coated samples
- 2 ”thin” B:D coated samples
- 4 dummy clean W samples



Start of sample heating

Heating duration at 70 °C: 50 minutes

Temperature ramp up: 6 minutes

Pure IC exposure duration:11.3 minutes

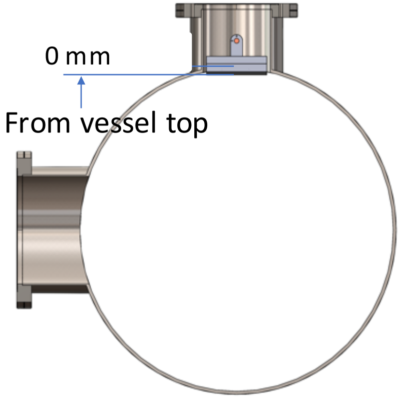
13

ICWC exposure at 70°C

Repeated for longer time

Parameters:

RF frequency -> 45 MHz, Magnetic field -> 1600 A,
IC pulse length -> 4 s, dwell time -> 10.9 s, 510 shots



- 3 ”thin” B:D coated samples
- 5 dummy clean W samples

Heating duration at 70 °C

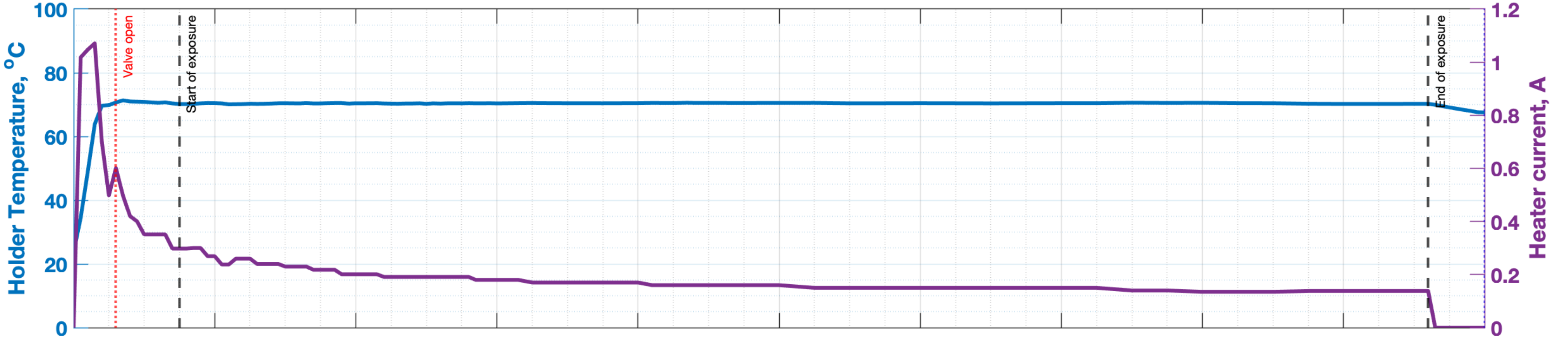
-> 186 minutes

Temperature ramp-up

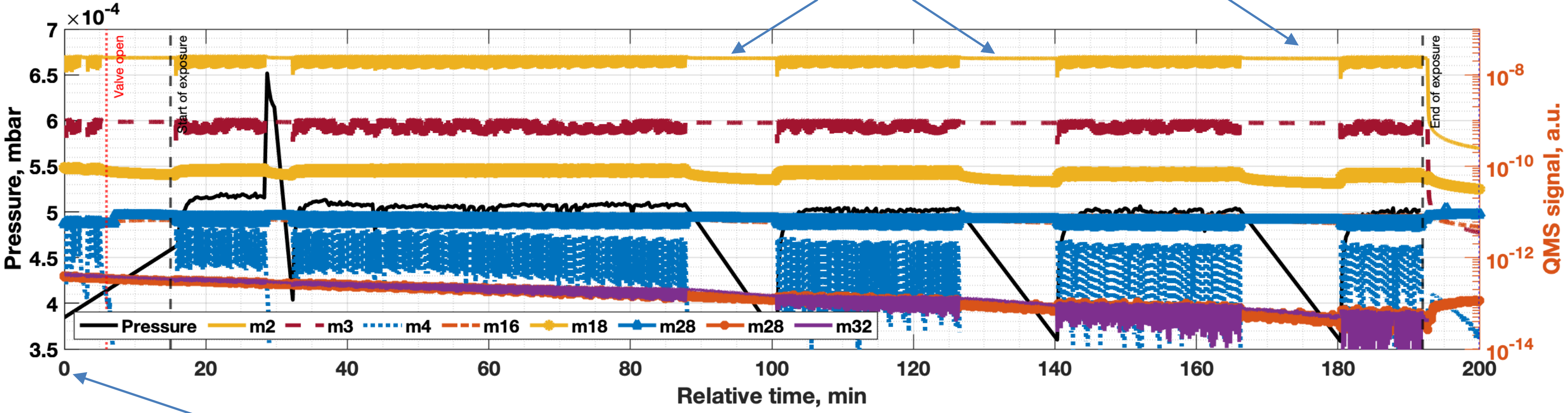
-> 6 minutes

Pure ICWC exposure

-> 34 minutes

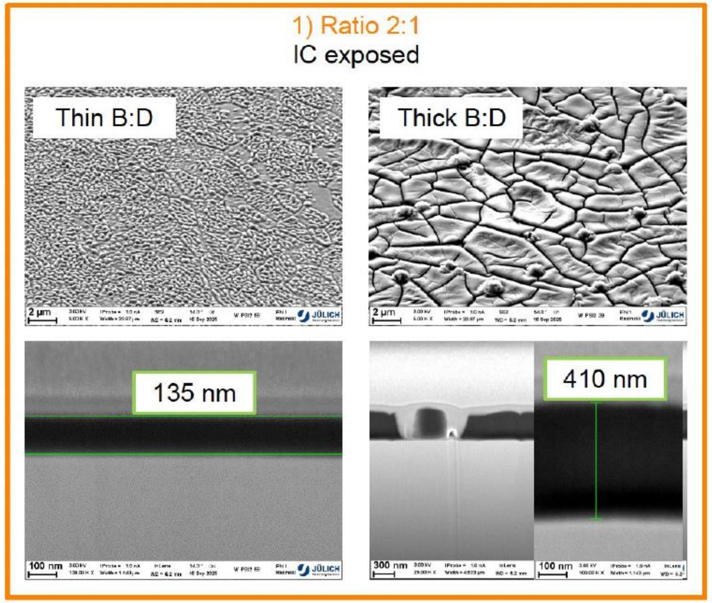


Technical pauses (~ 15 min) to cool down IC system feedthrough

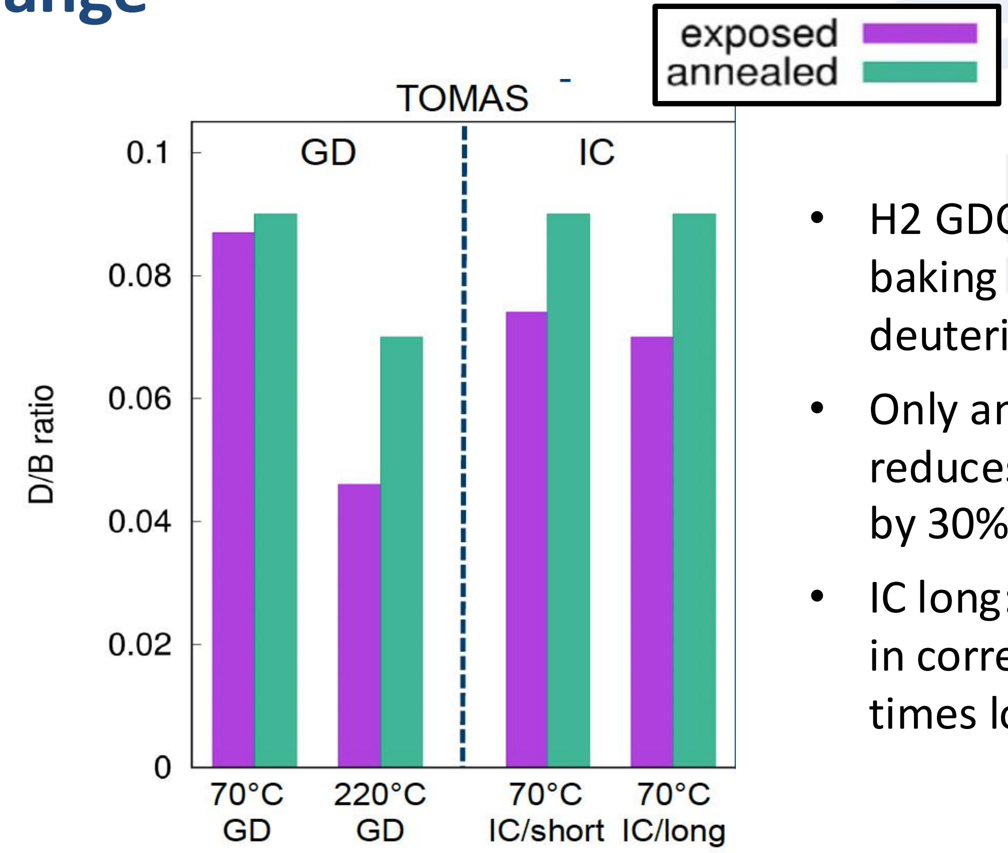


Start of sample heating

B:D ratios and isotope exchange



FIB/SEM measurements



NRA

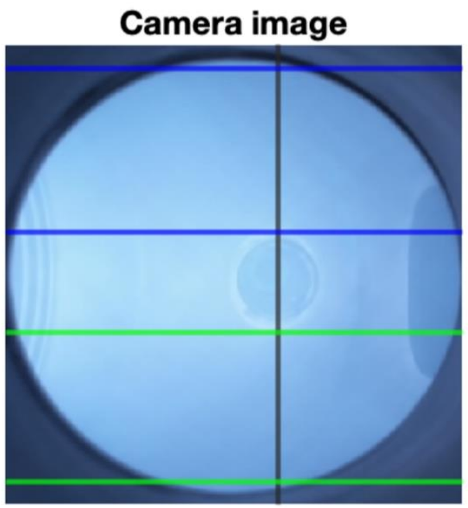
- H2 GDC combined with baking at 220°C reduces deuterium content by 43%
- Only annealing at 220°C reduces deuterium content by 30%
- IC long: D reduction is not in correspondence with 3 times longer exposure

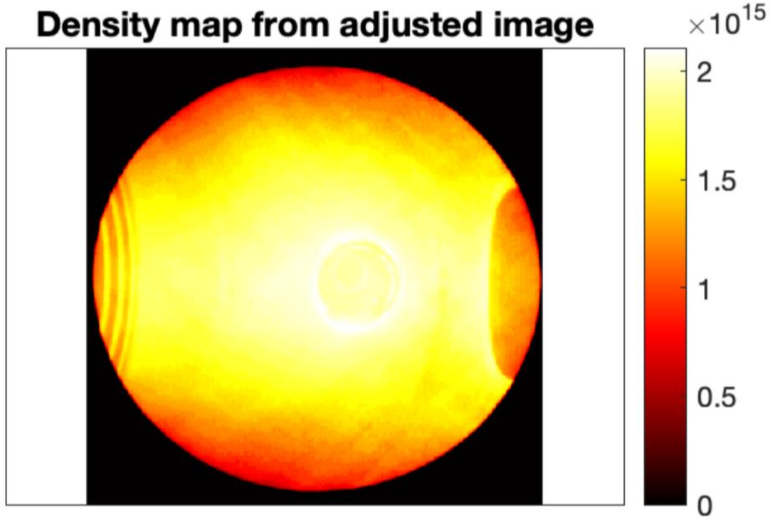
- Clear indication of deuterium reduction in the exposed B:D layers -> further investigation
- Very low erosion of B:D Layer in TOMAS (GDC and IC) -> within FIB/SEM measurement error
- Thick IC/annealed: cracks and delamination due to heat/exposure
- Strong indications of water uptake of B:D layers

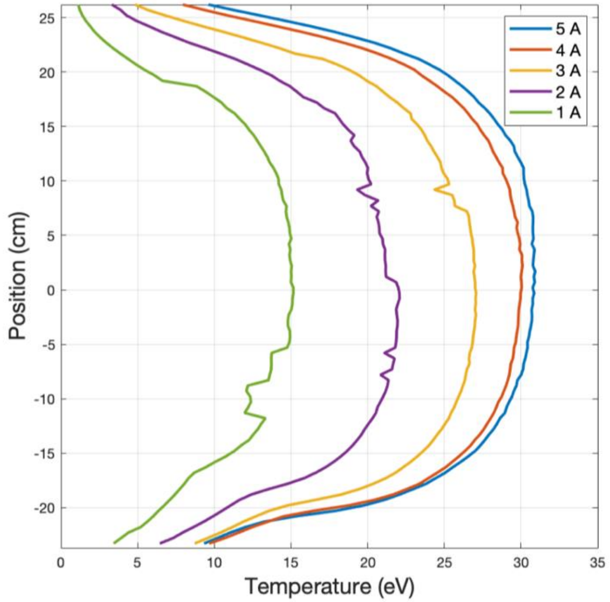
Glow discharge characterization

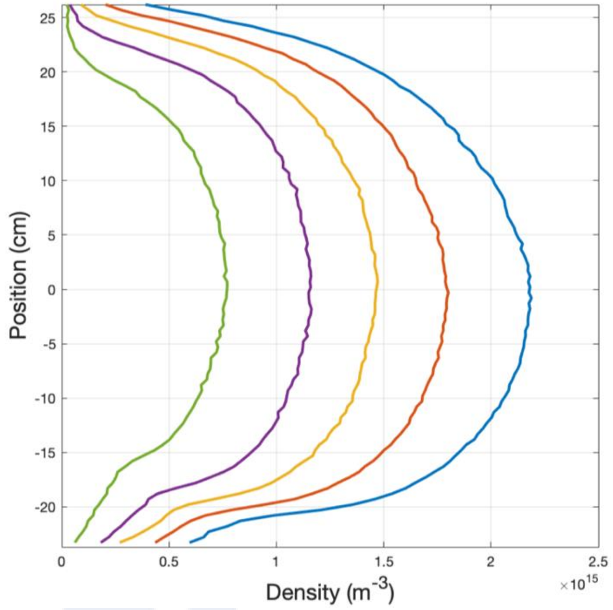
Measurement of electron density and temperature profiles

- Combining camera images and probe measurements for estimating 2D density map
- Ongoing master thesis project by M. Hillen (TU Eindhoven) : autumn 2025 – beginning 2026





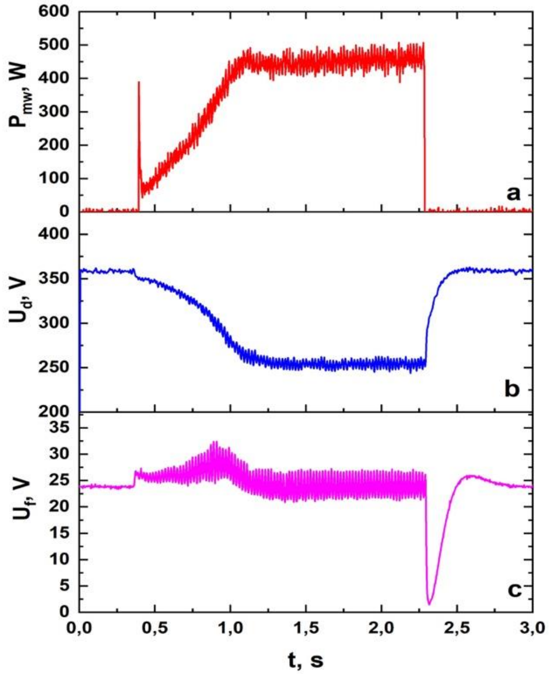




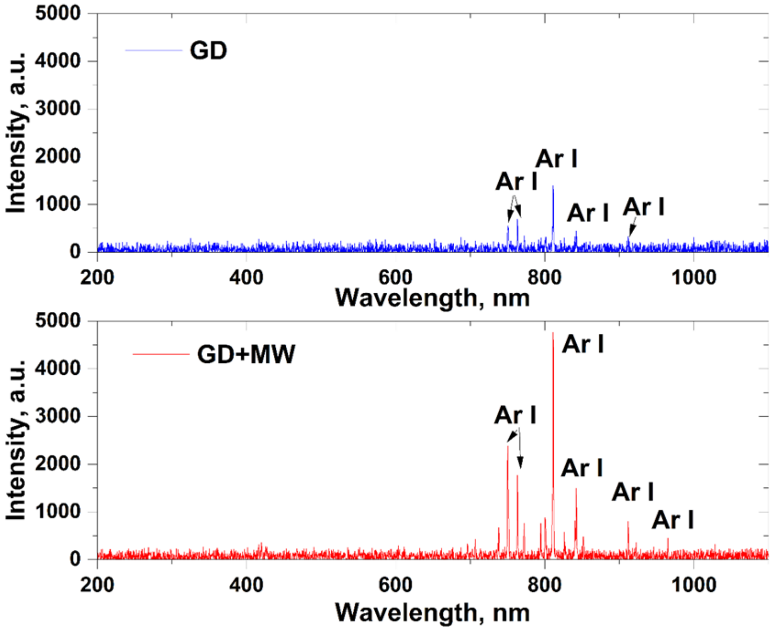
N. Desmet, “Determination of the Vertical Density and Temperature Profiles in an ECRF Plasma in the TOMAS Device“, Master thesis, LPP-ERM/KMS (2023)

Contribution of KIPT (1)

Experiments were conducted on **combined glow and microwave discharge**, in an atmosphere of argon and helium. Data processing ongoing.



(a) Microwave Power P_{mw}, (b) discharge voltage U_d, (c) floating potential U_f. Ar gas, pressure 7 Pa, probe at r = 2 cm.



Optical emission spectra (GD 350 V, P_{MW} = 500 W)

Observations:

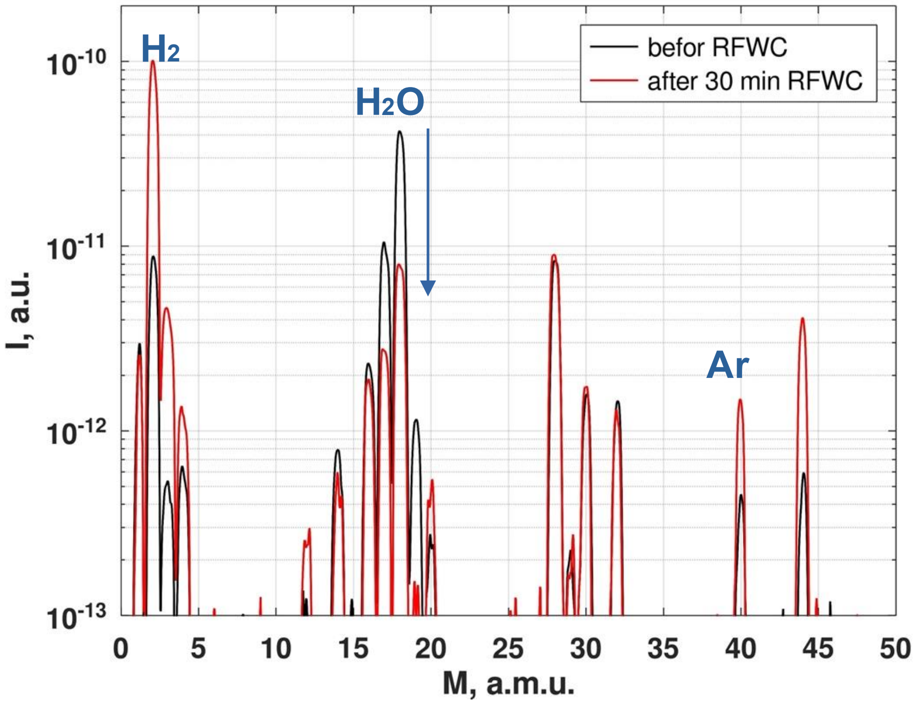
- Injection of **microwave power** allows to **decrease the voltage GD** (decrease ≈ 100 V at microwave power 0.5 kW). Stronger decreased possible with higher microwave power.
- **Intensity of spectral lines** of excited argon atoms in combined glow + microwave discharges also **increases** compared to GD only.
- **Energy of ions decreases as the voltage decreases**

Results of previous experiments:

Y. P. Martseniuk et al., Combined glow + microwave discharges in the TOMAS plasma facility, Journal of Fusion Energy, (2025) 44:49

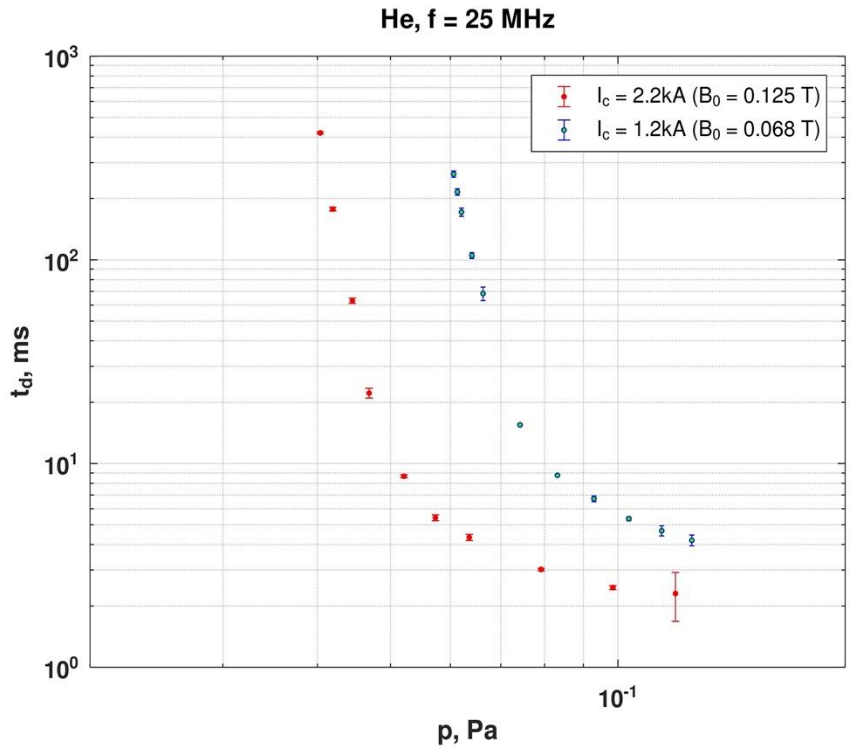
Contribution of KIPT (2)

Radio Frequency RF Wall Conditioning (RFWC) in argon at frequencies significantly higher than resonant ion cyclotron frequencies $\boldsymbol{\omega_{RF} \gg \omega_{ci}}$. **Decrease in partial pressure of water by RFWC**.



Partial pressures of residual gas components.
RF f = 25 MHz, power 2 kW. B(0) = 0.1 T

RF plasma start-up at various frequencies, pressures, and magnetic fields in argon and helium. **Decrease in breakdown time** with an **increase in pressure and magnetic field**.



Dependence of RF breakdown time on pressure.

Diagnostic plans

Use of existing diagnostics

- Employ Langmuir probes, ToF NPA, RFEA, OES, visible cameras, and RGA to study wall-conditioning plasmas and support sample-exposure experiments, delivering data on **erosion**, **deposition**, and **impurities**.

Extension of Diagnostic Capabilities

- PSI-2 Integration: Connect TOMAS to the PSI-2 **LID-QMS** for sensitive, species-selective analysis of desorbed and eroded particles.
- Laser Compatibility: Upgrade TOMAS for laser operation (optical closure, safety) and install a new dedicated **laser system**.
- **Spectrometers**: Adapt and reinstall JET overview and high-resolution spectrometers with new optical interfaces tailored to TOMAS.

Future physics studies

- **PSI on boron layers**: Deuterium-doped boron layers, including impurity-containing mixtures, will be exposed to **ICWC** and **GD** plasmas in TOMAS. A **heated sample holder** will recreate realistic wall conditions to continue the study of fuel retention and impurity behaviour.
- **ITER-relevant GD upgrades**: A second GD anode will be added to replicate ITER's boronization geometry. Gas injection will be reconfigured to test H, He, and H/He mixtures for optimized cleaning and conditioning, supported by modelling from INP Greifswald.
- **In-situ laser diagnostics**: New laser-based analysis will provide direct monitoring of surface modification and fuel retention during and after plasma exposure.
- **Sample testing for W7-X**: Boron-coated CFC samples for W7-X will be assessed for coating stability and erosion. Pre-characterized graphite divertor samples from W7-X (FZJ) will be exposed in TOMAS and subsequently re-analyzed.
- **ECWC plasma studies**: Further experiments and modelling, with emphasis on parametric decay, mode conversion, and tangential injection effects.

Recent publications and achievements

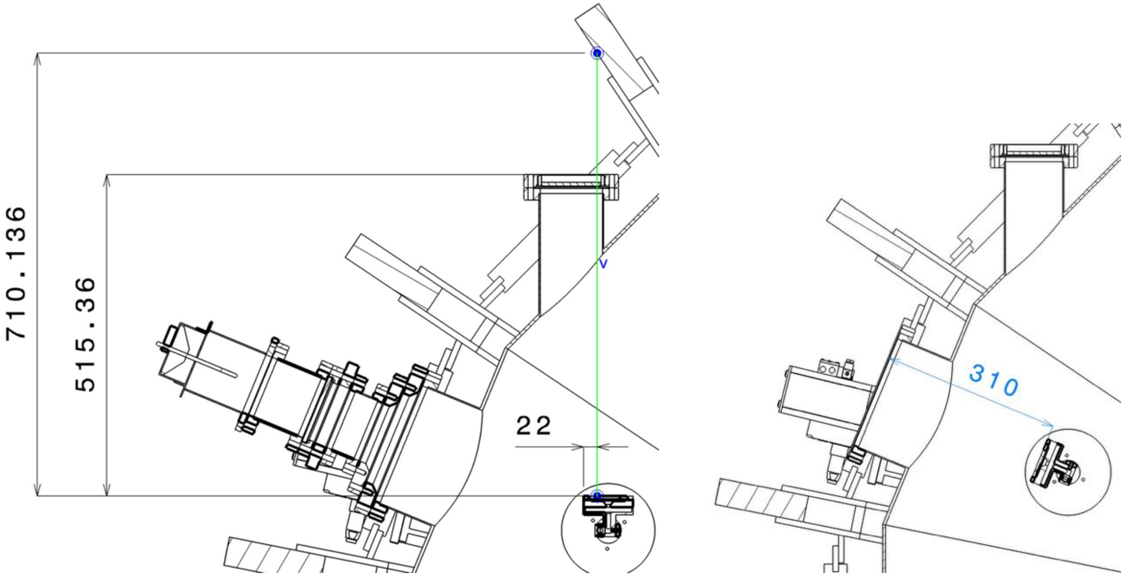
- A. Adriaens et al., “An automatic matching system for the ICRF antenna at TOMAS: Development and experimental proof”, Fusion Engineering and Design 212, 114840 **(2025)**
- Yu. Kovtun et al., "Combined electron-cyclotron resonance and radio-frequency discharges in the TOMAS facility”, Physics of Plasmas 32, 032512 **(2025)**
- Y. P. Martseniuk et al., " Combined Glow + Microwave Discharges in the TOMAS Plasma Facility ", Journal of Fusion Energy **(2025)** 44:49
- J. Buermans et al., " Mode Conversion and Parametric Decay Instabilities in Electron Cyclotron Resonance Heated Helium and Hydrogen Plasmas in TOMAS ", EPS Poster **(2025)**
- A. Adriaens et al., " Wall conditioning on TOMAS with relevance to ITER and W7-X ”, ICRFM Poster **(2025)**
- A. Goriaev, A. Adriaens, et al., " Laboratory Assessment of ITER-Relevant Boron Layer Fuel Removal using Glow Discharge Cleaning and Ion Cyclotron Wall Conditioning in the TOMAS Device ", PMIF, Oral presentation **(2025)**

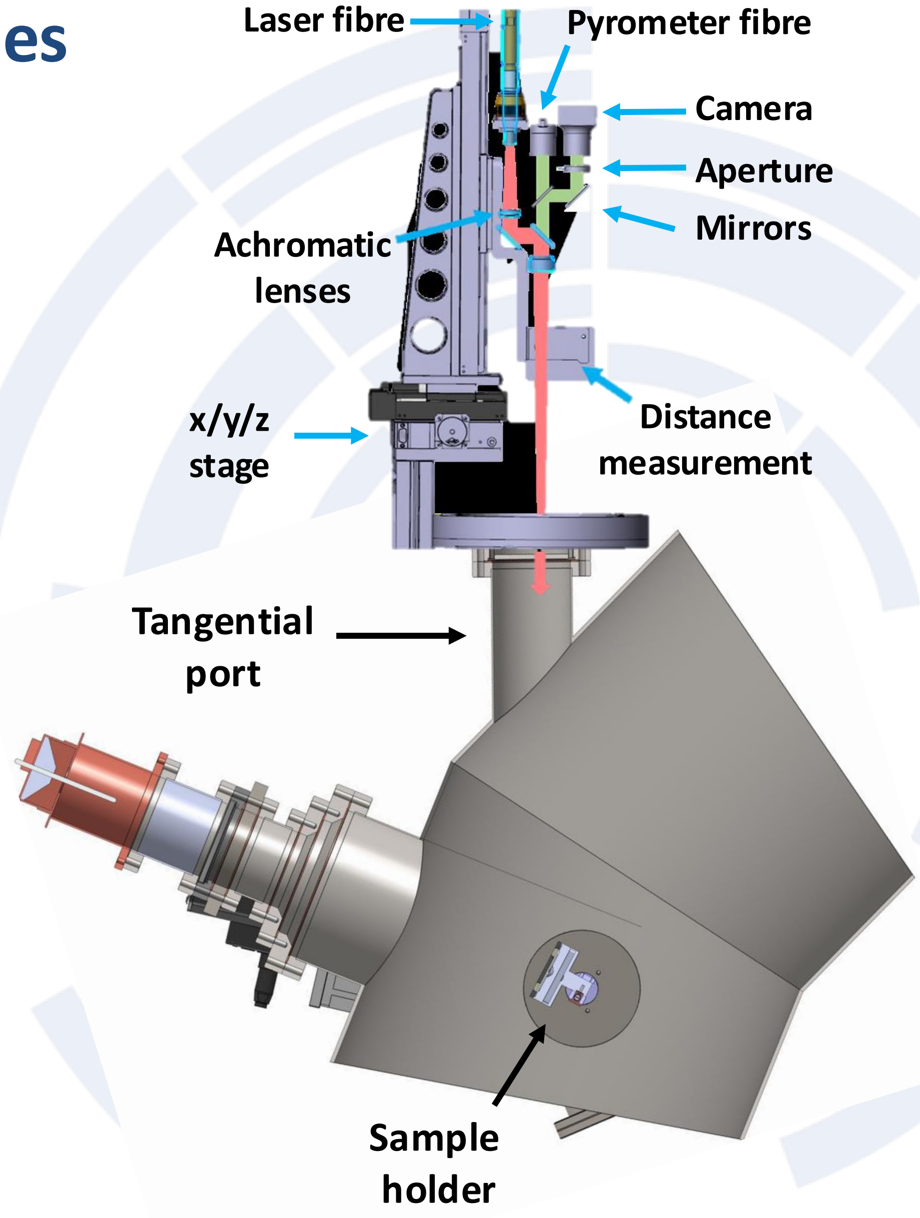
- B. Bozonnet, Sorbonne University, France, internship on simulation of neutral particle fluxes in TOMAS NPA diagnostic **(2025)**
- M. Hillen, TU/Eindhoven, master thesis on camera system as a new diagnostic tool for plasma density measurements, ongoing (**autumn2025 – beginning2026)**

Additional Material

Implementation of in-situ boronization studies

- Preparation for the installation of laser-induced desorption - quadrupole mass spectrometry (LID-QMS)
  - Adaptation of laser-detector geometry
  - Design and assembly of support structures for fiber optics
  - Selection of optical elements



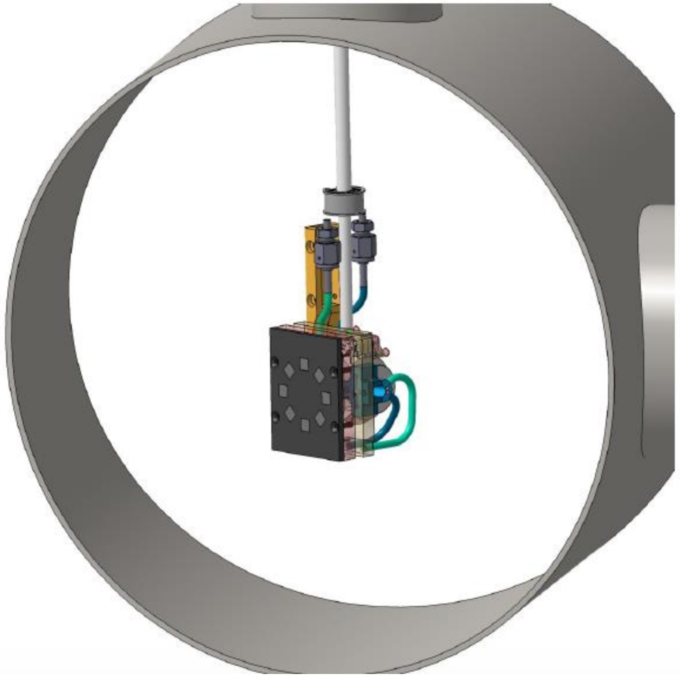


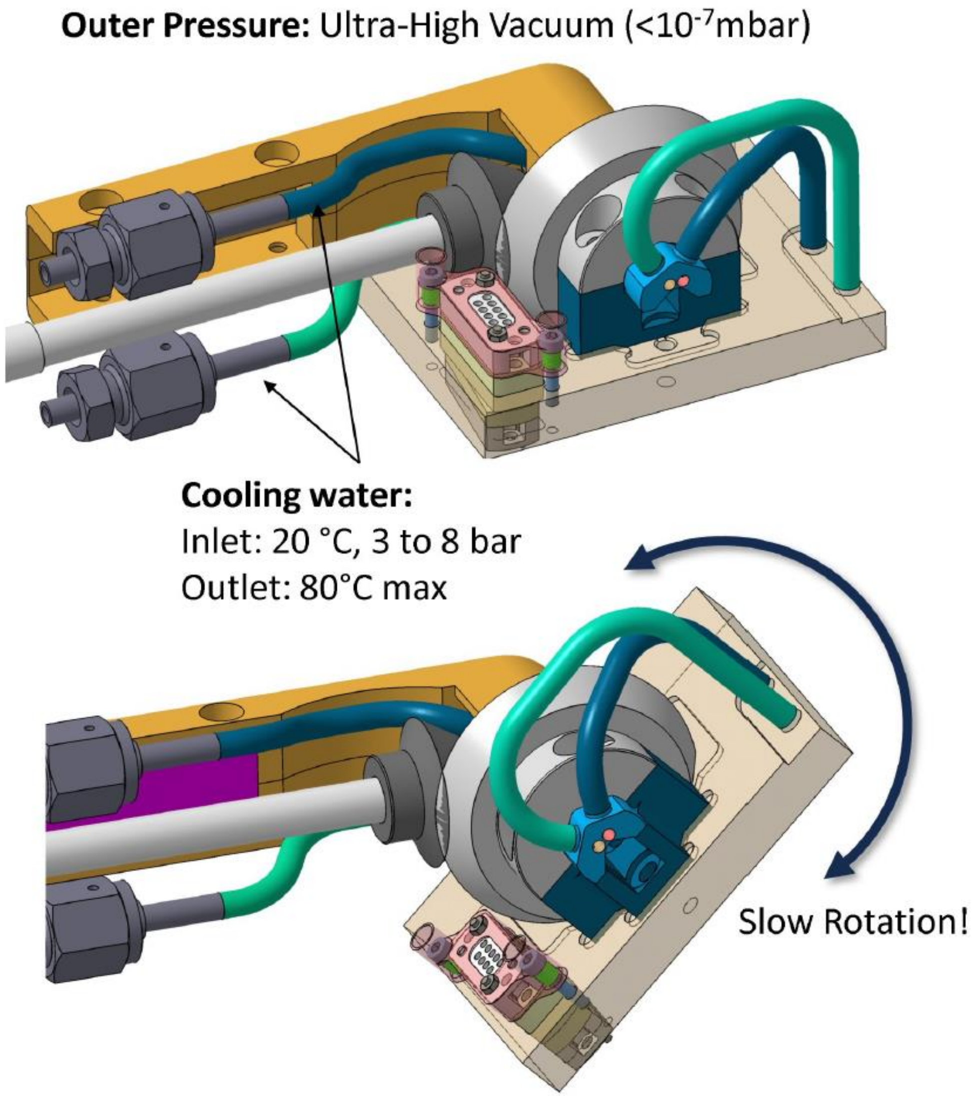
M. Zlobinski et al., Nuclear Fusion 64, 086031 (2024)

Upgrade of sample load lock

The new design of the material sample manipulator

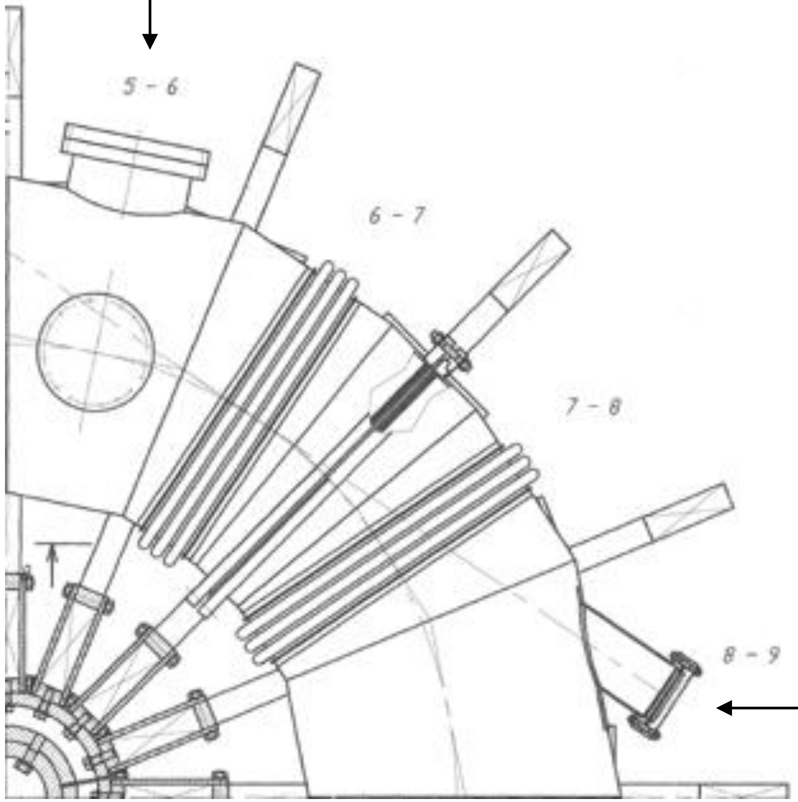
- Actively cooled sample holder
- Fully automated 3d manipulator movement
- Fast and easy exchange of the manipulator holder
- Extended manipulation range
- Upgraded differential pumping





Upgrades to the heating systems

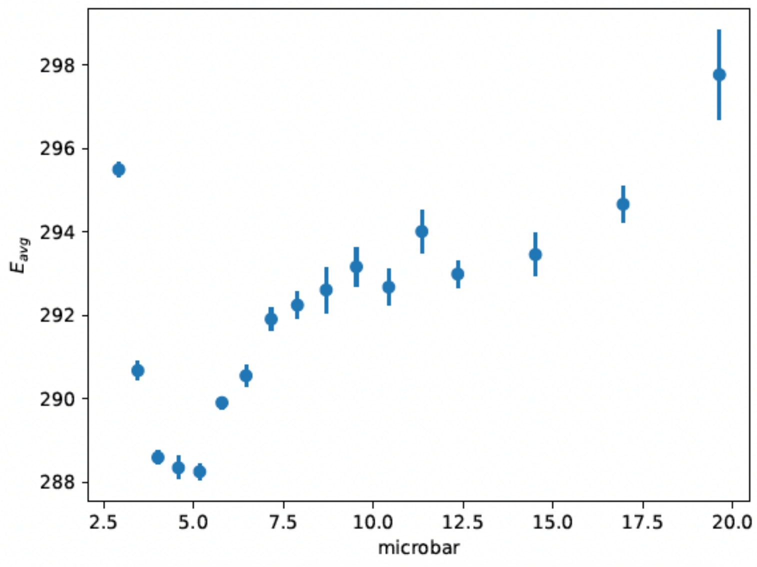
Current ECRH launching port



Port for tangential launching

- Extension of the ECRH system
  - Addition of a 2 kW gyrotron to increase the total power
  - Use of the tangential port
  - Installation of waveguide tuners, mode convertors, polarizers, vacuum windows, cooling elements
  - Integration of the new gyrotron to the control system

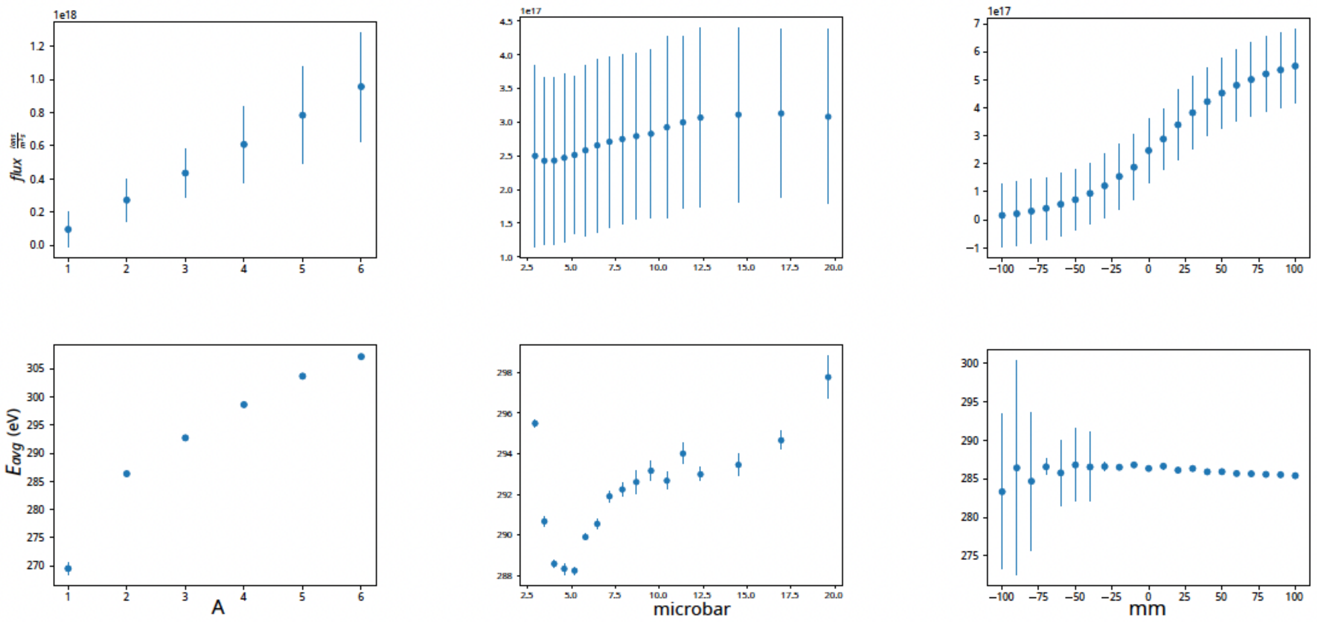
Erosion rate calculations

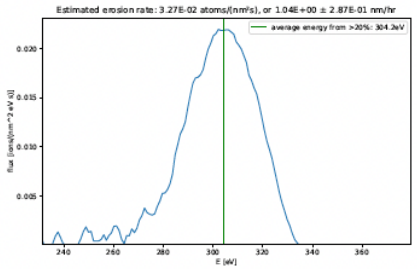


Average ion energy I.f.o gas pressure

H2 GDC Plasma Characterization using a RFEA

5 µbar,0mm varying current | 0mm, 2A varying gas | 5 µbar, 2A, varying position





Sputtering estimate for chosen (left) distribution:

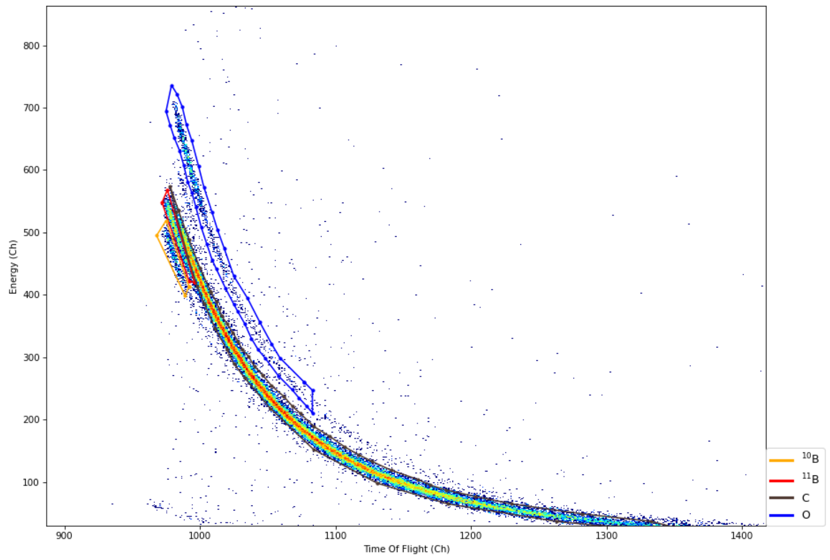
$$\mathcal{E} \approx \frac{1}{N}\sum_{\theta:1-89}\sum_{E} Y(E,\theta)\times \mathfrak{F}(E)\Delta E \quad \frac{\text{particles}}{\text{s m}^2}$$

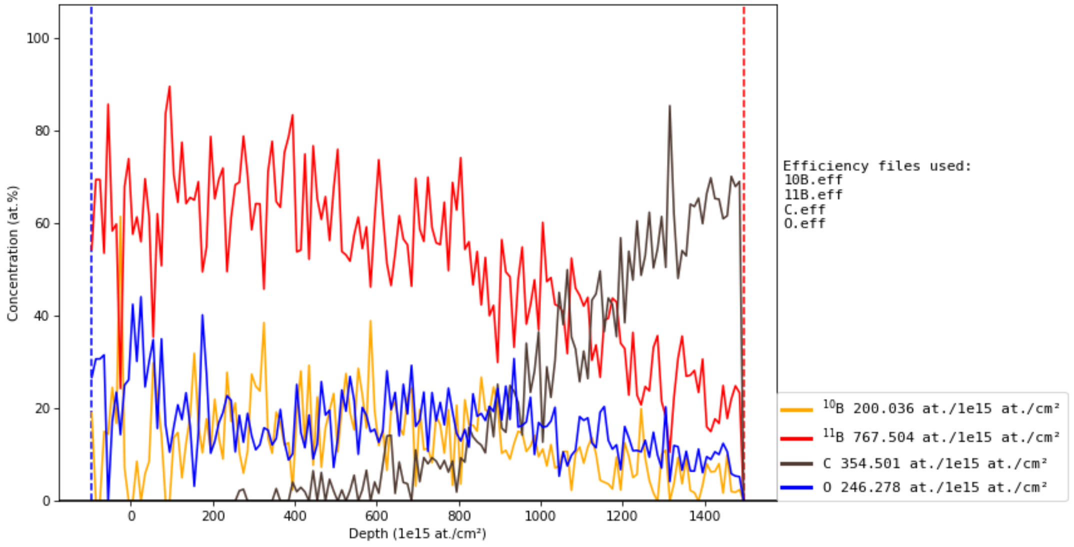
$$\Delta D \approx \frac{\mathcal{E}_{H2}}{\rho_B}\frac{\text{m}}{\text{hr}} = 1\pm 0.3\frac{\text{nm}}{\text{hr}}$$

With $Y(\theta, E)$ the angle of incidence and energy-dependent yield (computed using the code rustBCA), $\mathfrak{F}(E)$ the flux per energy bin and N the amount of angles considered (assumed homogeneous). As the layer is 100nm thick, 2 hours of exposure should leave 98% intact.

Studies of boron layer erosion

- Pre-characterization and post-mortem analysis
  - Boron coating thickness by Focused Ion Beam Scanning Electron Microscope (FIB/SEM) and ellipsometry
  - Boron coating roughness by profilometry
  - Boron coating elemental composition by ion beam analysis
  - ➢ Elastic Recoil Detection Analysis (ERDA)
  - ➢ Nuclear Reaction Analysis (NRA)
  - Analysis of composition by Thermal Desorption Spectroscopy (TDS)
  - Monitoring of impurity release during exposure by Quadrupole Mass Spectrometry (QMS) and optical spectrometry





Results obtained by ERDA