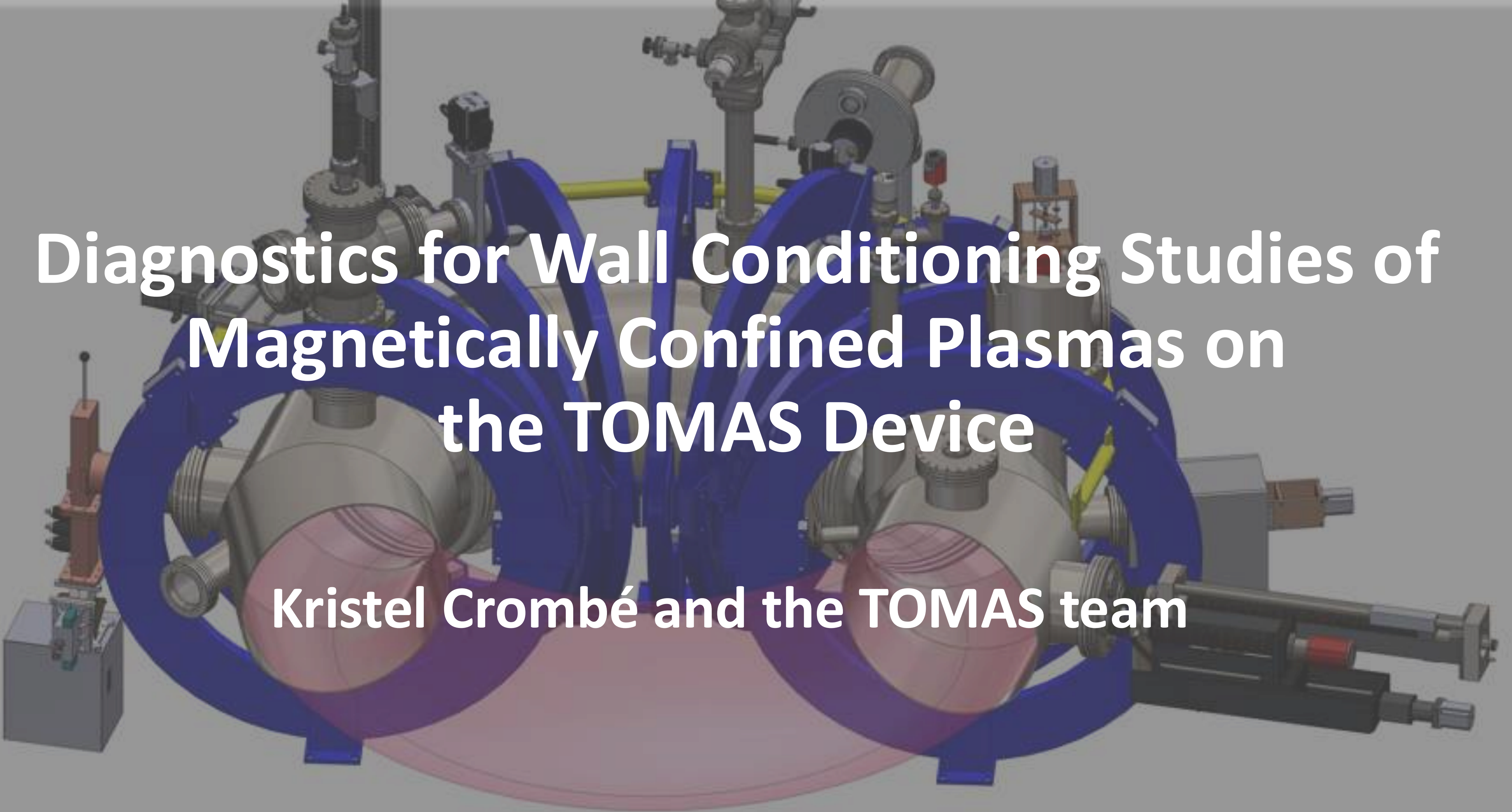


Diagnostics for Wall Conditioning Studies of Magnetically Confined Plasmas on the TOMAS Device

Kristel Crombé and the TOMAS team

TOMAS international collaboration

K. Crombé[1,2], J. Buermans[1,2], S. Brezinsek[3], D. Castaño-Bardawil[1], A. Goriaev[1], D. López- Rodríguez[1,2], L. Dittrich[4], Yu. Kovtun[5], Ch. Linsmeier[3], J. Ongena[1], P. Petersson[4], T. Wauters[6]

[1] Laboratory for Plasma Physics, LPP-ERM/KMS, Brussels, Belgium

[2] Department of Applied Physics, Ghent University, Belgium

[3] Institute for Energy and Climate Research, Forschungszentrum Jülich GmbH, Germany

[4] Fusion Plasma Physics, KTH Royal Institute of Technology, Sweden

[5] Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine

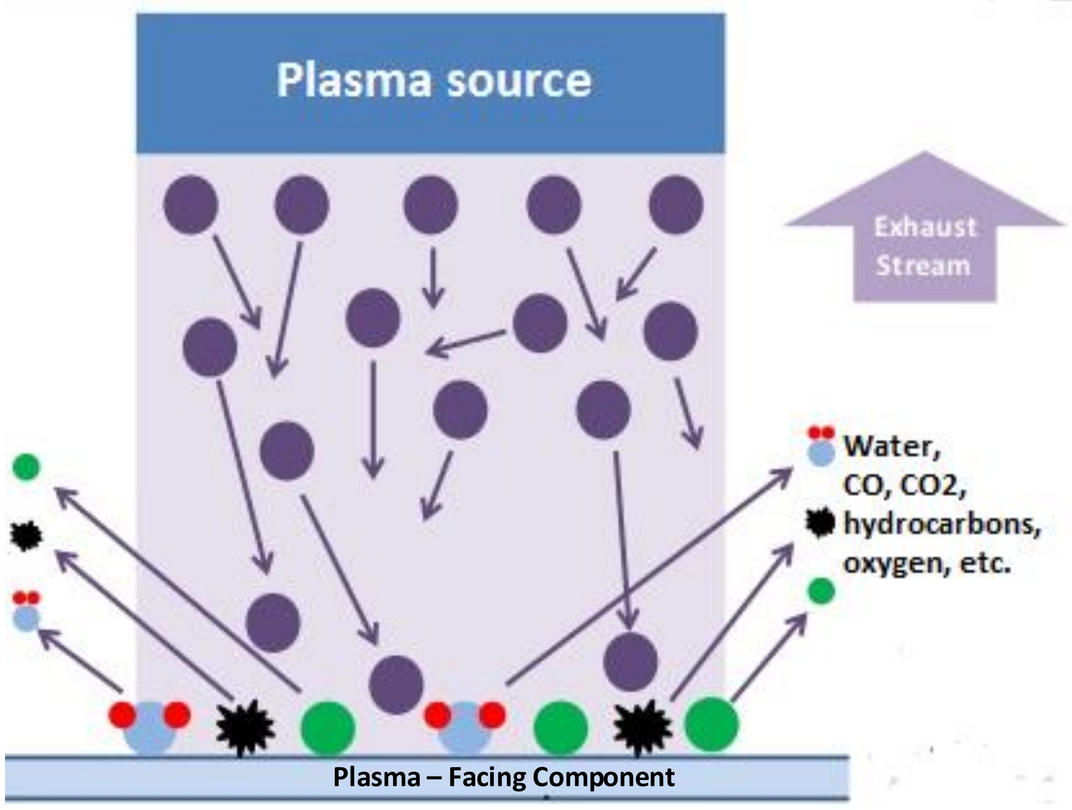
[6] ITER Organization, St. Paul-lez-Durance, France

Wall conditioning in fusion devices

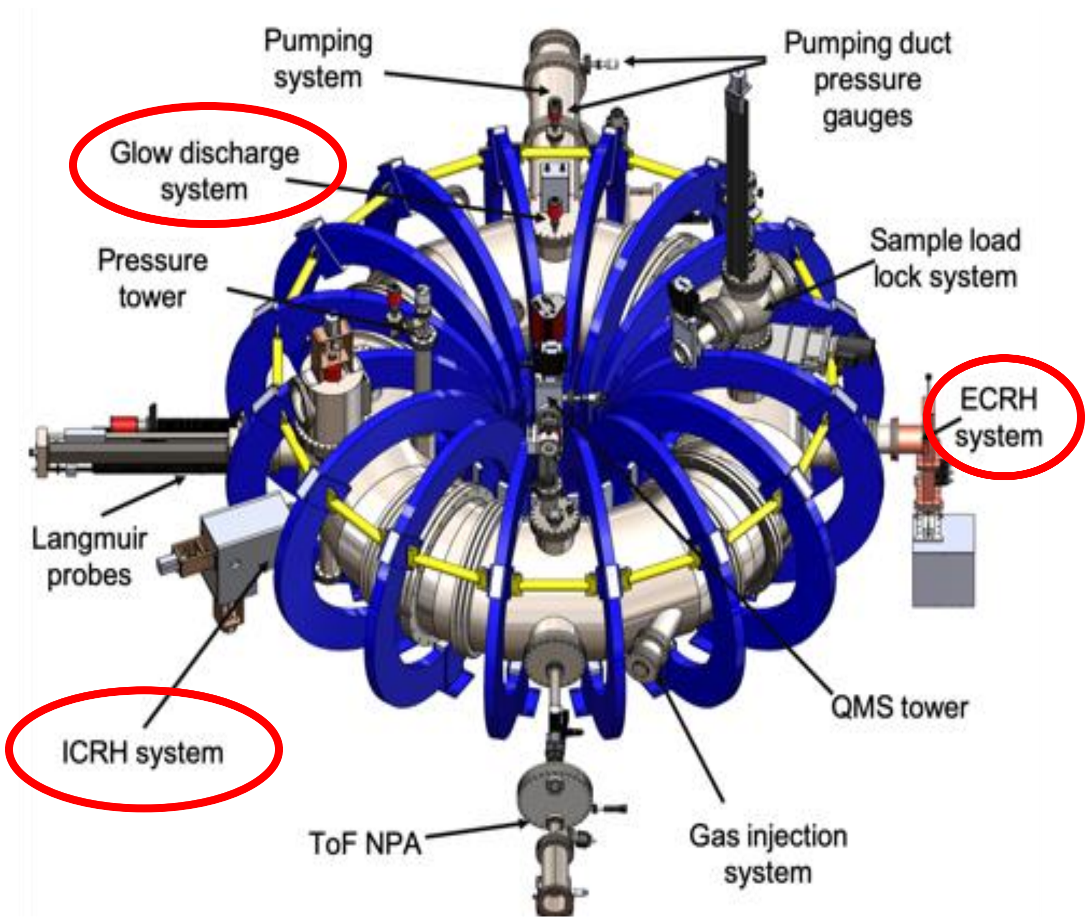
Influence fuel and impurity recycling

Improve plasma performance and reproducibility

- Control surface state of plasma facing components (PFCs)
    - Remove impurities
    - Prevent impurities to enter plasma
    - Control isotopic ratio (H/D/T)
- Ease plasma startup
- Prevent/recover from radiative collapses, disruptions
- Improve plasma performance (density limit, stored energy)
- Improve discharge reproducibility



TOMAS (TOroidal MAgnetized System) device



Parameter	Value
Major radius	0.78 m
Minor radius	0.26 m
Volume	1.2 m^3
Inner surface area	8.5 m^2
Wall material	Stainless steel (5 mm)
Baking	80 °C
Toroidal coils	16
Maximum field on axis	0.125 T
Glow Discharge	9 kW
ECRH	6 kW
ICRH	6 kW

- Study wall conditioning techniques : Baking, Glow Discharge Cleaning (GDC), ion and electron cyclotron wall conditioning (IC and ECWC)
- Test bed for plasma wall interaction and plasma production research in tokamaks and stellarators (ITER, W7-X, JT-60SA)
- Excellent training tool for students and young researchers to obtain the necessary skills and experience in experimental plasma physics

A. Goriaev et al., RSI 92 (2021) 023506

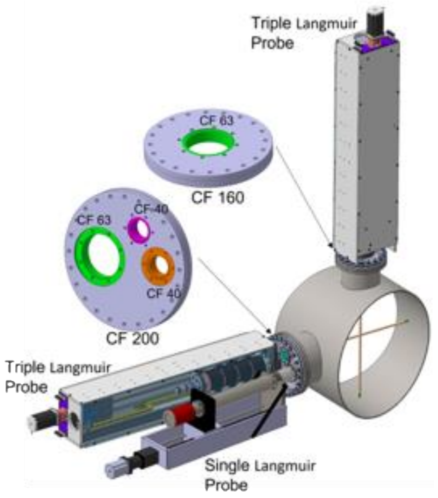
Strong efforts in diagnostic capabilities

Diagnostics are **strength** of the TOMAS device

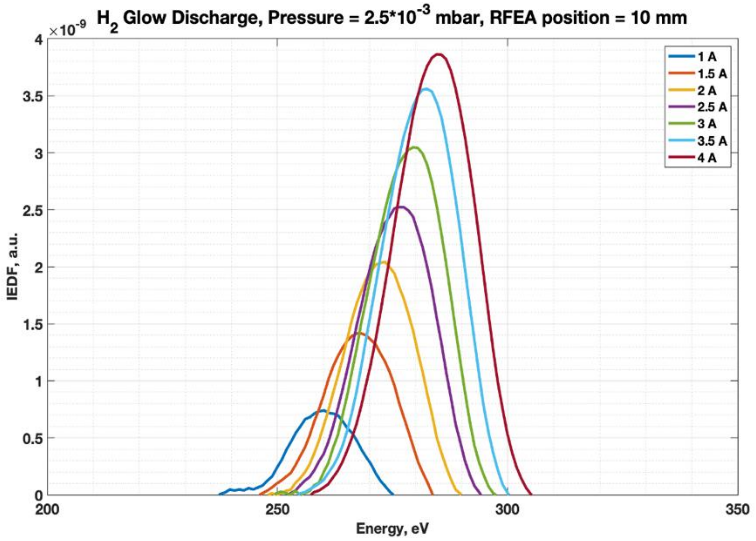
- Detailed characterisation of plasma parameters
- Comparison wall conditioning methods

Available diagnostics

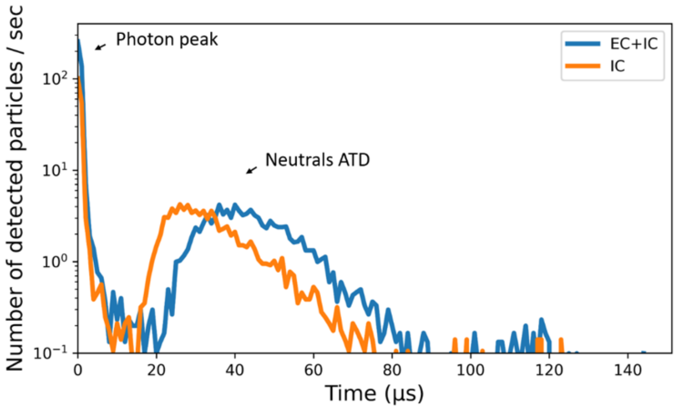
- Retarding Field Energy Analyzer – ion energy distribution
- Movable Langmuir probes – electron temperature, density, floating potential
- NIR/VIS/UV spectrometer – density, temperature, impurities
- Visible cameras – density
- Time-of-Flight Neutral Particle Analyzer (NPA) – neutral energy distribution
- MW interferometer – line integrated electron density
- Quadrupole Mass Spectrometer - Residual Gas



Horizontal and vertical probe system



Ion energy distributions in GDC plasmas

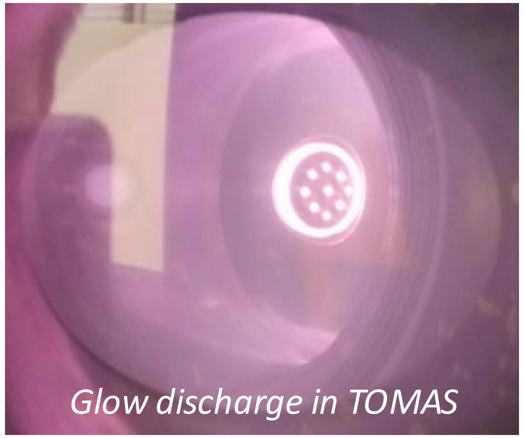


NPA results

Glow Discharge Cleaning (GDC)

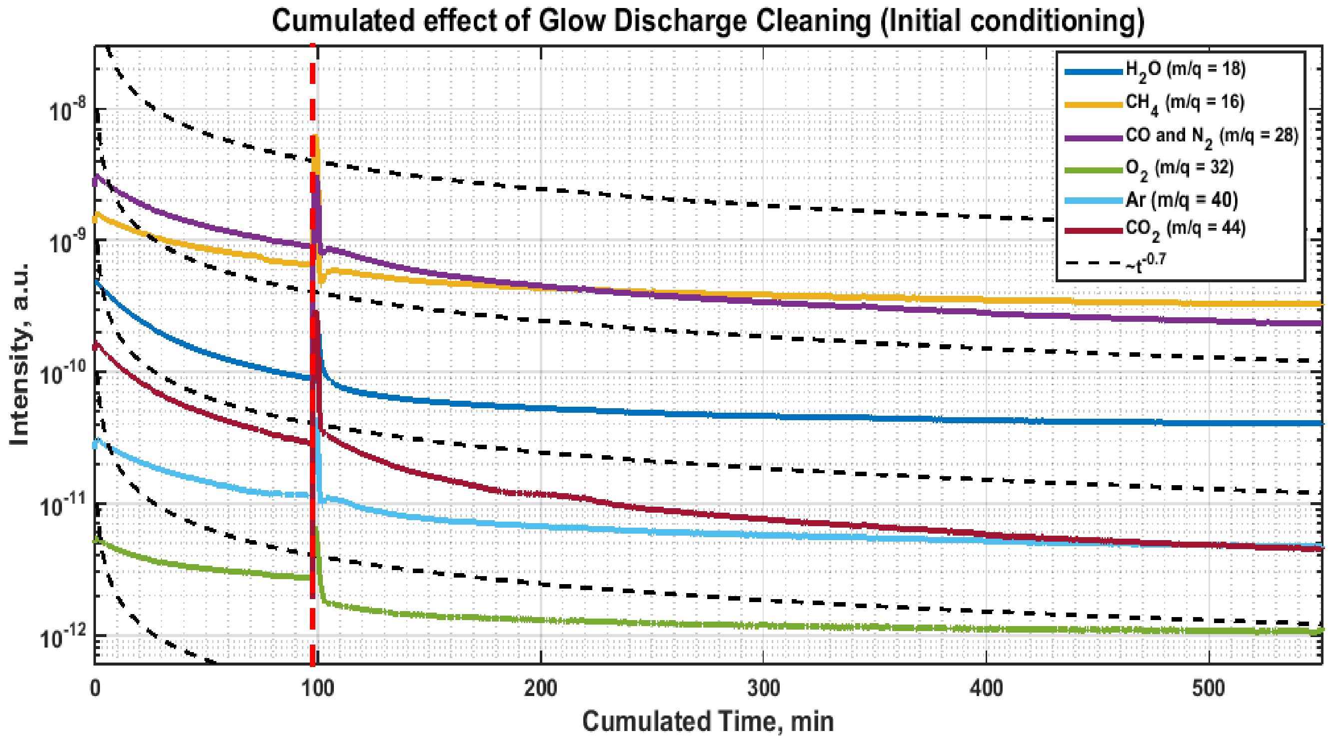
- TOMAS glow discharge system similar to W7-X and ASDEX-Upgrade
- Graphite anode, up to 1.5 kV, 6 A, current densities 0.1 – 0.7 A/m²


Graphite anode


Glow discharge in TOMAS

Optimisation of glow discharge wall conditioning

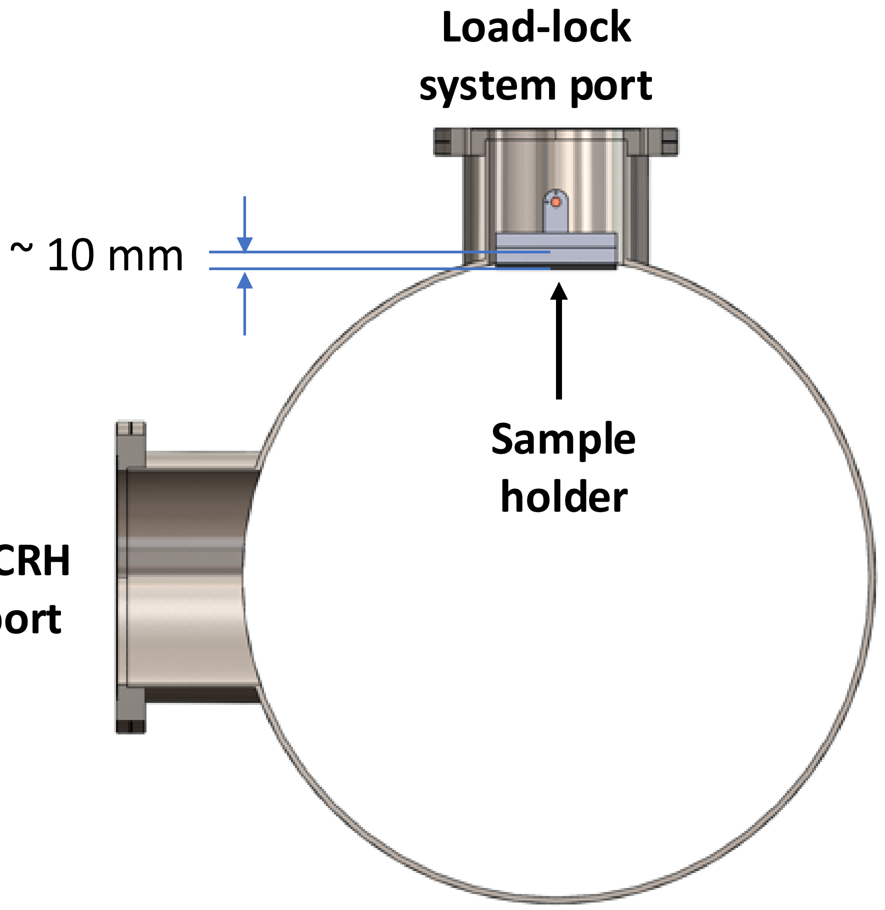
- Discharge homogeneity and stability
- Maximum impurity removal

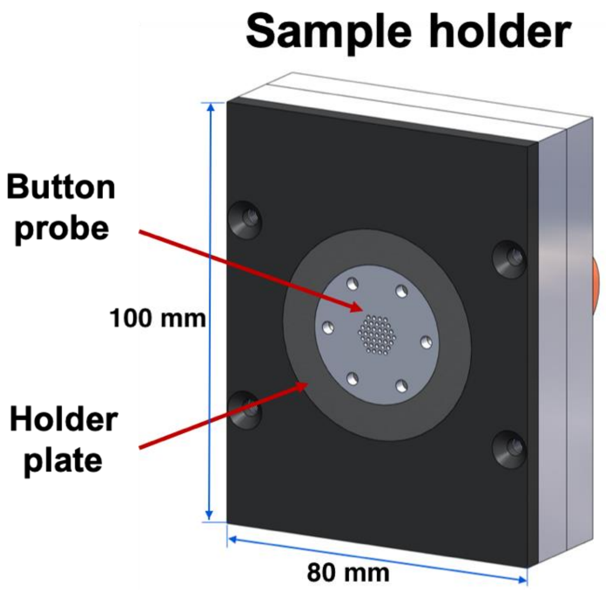


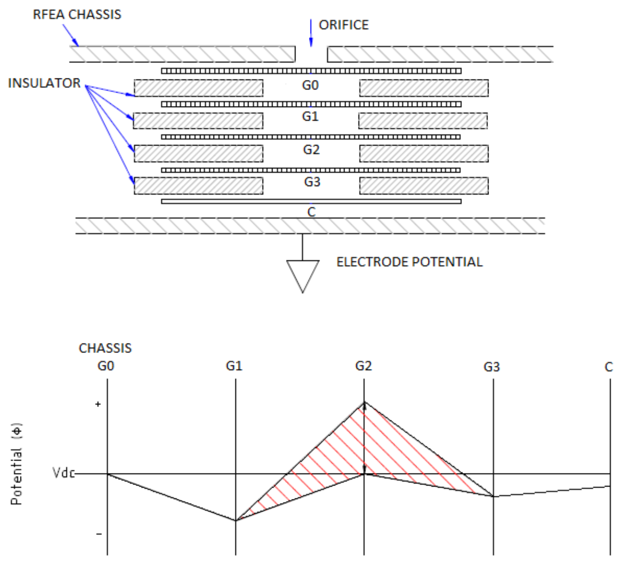
Practical Example on W7-X

- Hydrogen GDC before start of experimental campaign to reduce impurities
- Helium GDC to desaturate the walls from hydrogen

Ion energy distribution functions measured by Retarding Field Energy Analyser (RFEA)







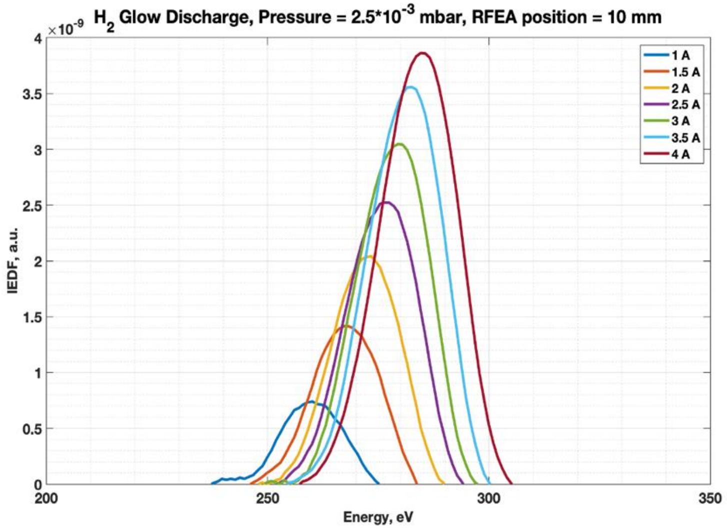
Ion energy distribution functions in glow discharges

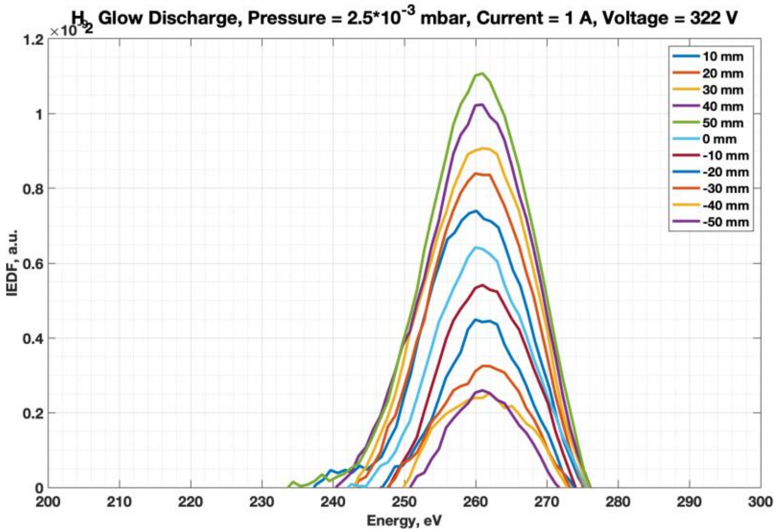
Constant pressure 2.5 10^{-3} mbar

Constant detector position (10 mm inside plasma)

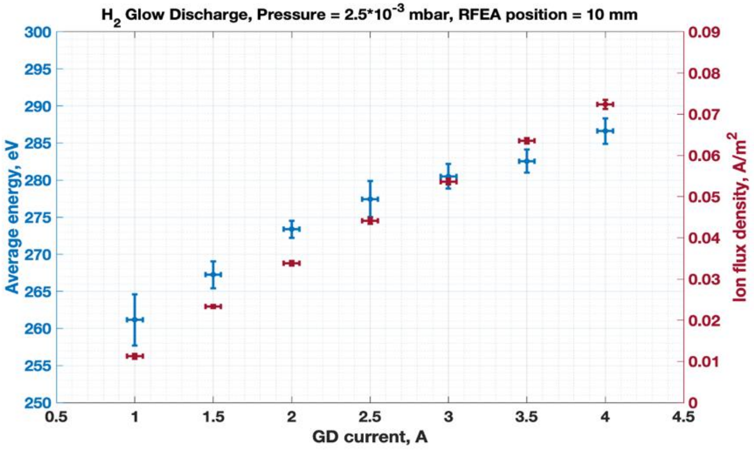
Varying anode current: 1 – 4A

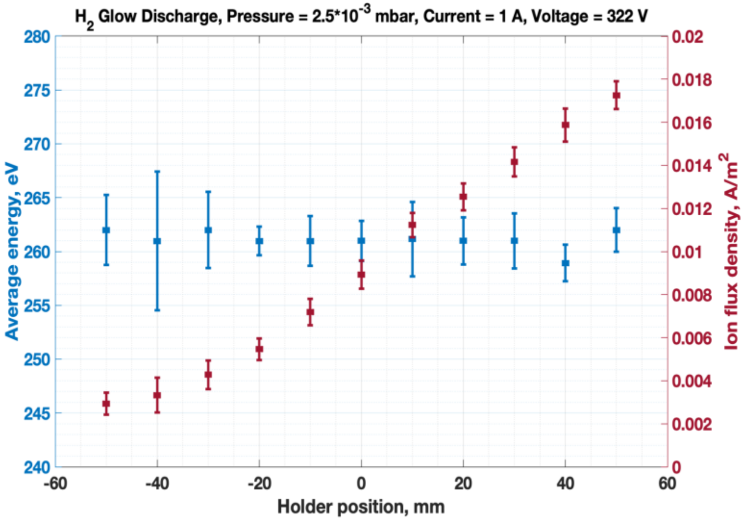
- Increased average energy
- Increased ion flux





Average ion energies and ion flux densities





Constant pressure 2.5 10^{-3} mbar

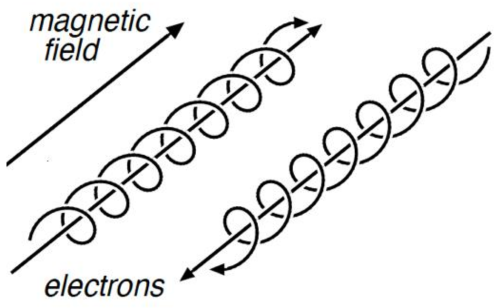
Constant anode current = 1A

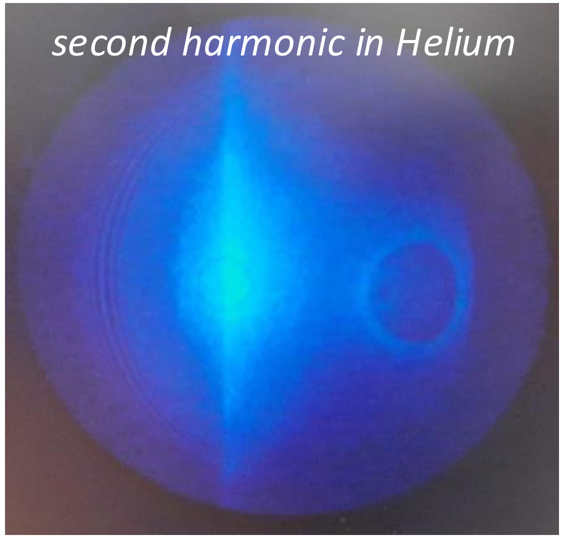
Varying vertical position detector plate: -50 to +50 mm

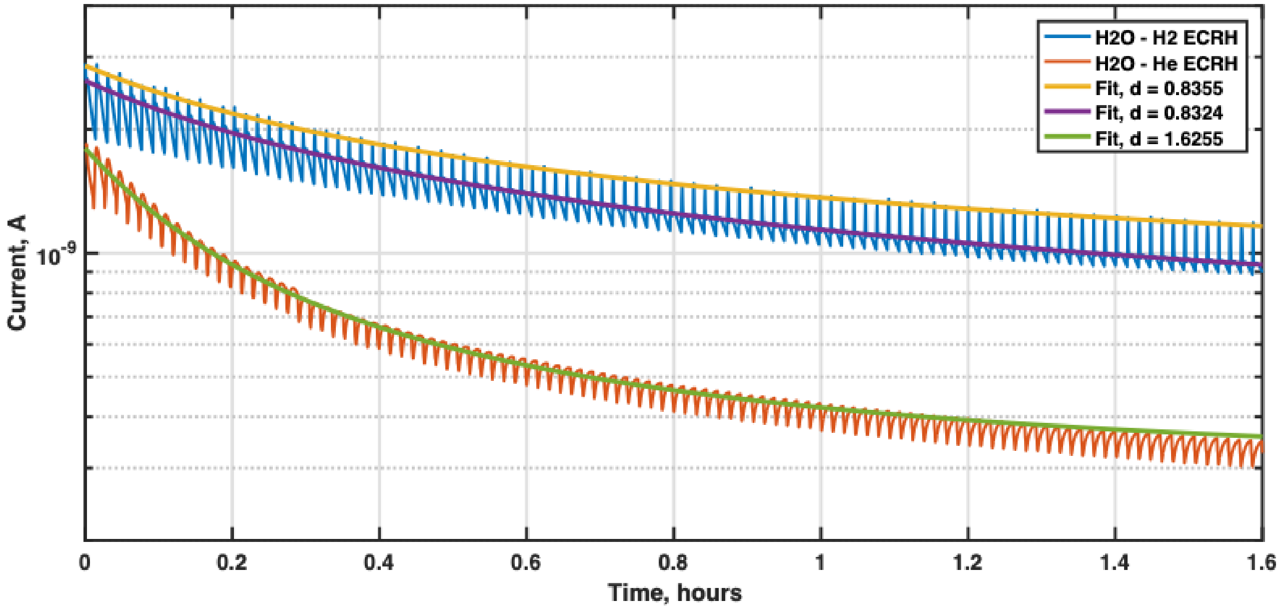
- Increased ion flux
- Average energy constant

Electron Cyclotron system

- Magnetron at 2.45 GHz with 0.6 – 6 kW power
- Steady state operation and pulsed regime down to 1 s of pulse length

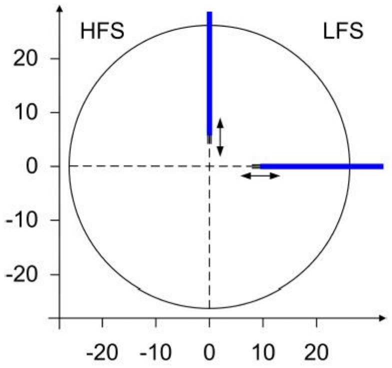




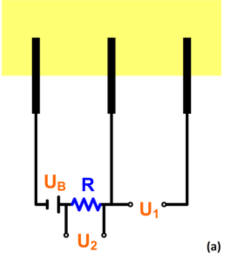


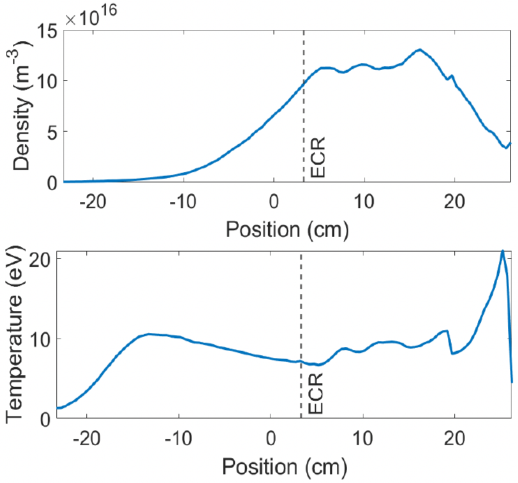
- Pulse train with 5s on and 55s off time
- Purpose removal of retained H_2O
- H_2 and He plasmas different removal efficiency

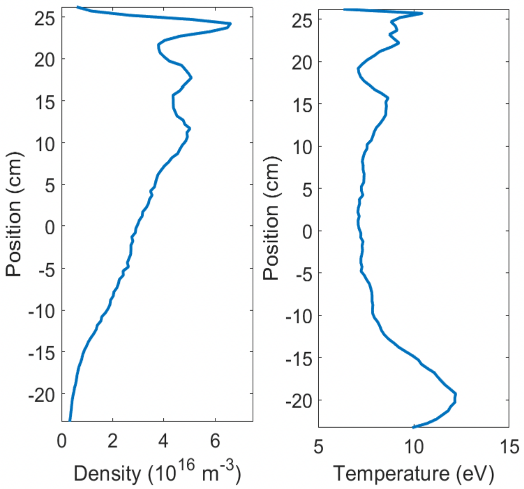
EC plasma characterisation by triple Langmuir probes



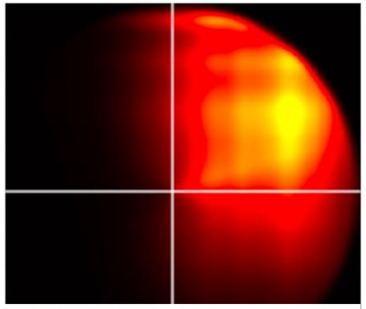
- 2D scans by triple Langmuir probes (TLP) (vertical + horizontal)
- Variations power, B_t, pressure, EC mode
- Supported by theory of EC wave propagation



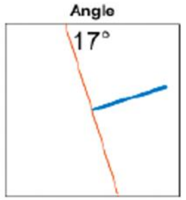




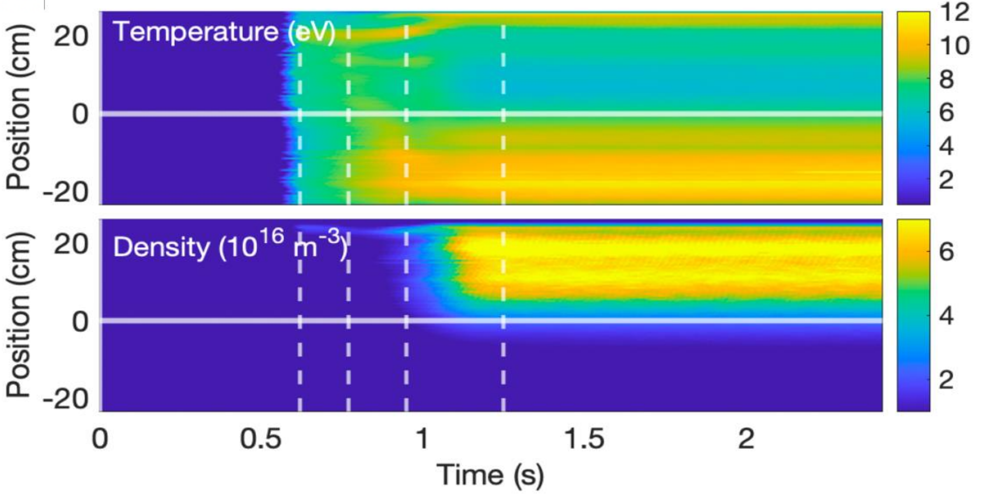
J. Buermans et al., Phys. Plasmas 31, 052510 (2024)



P = 1200 W , B_0 = 91.2 mT

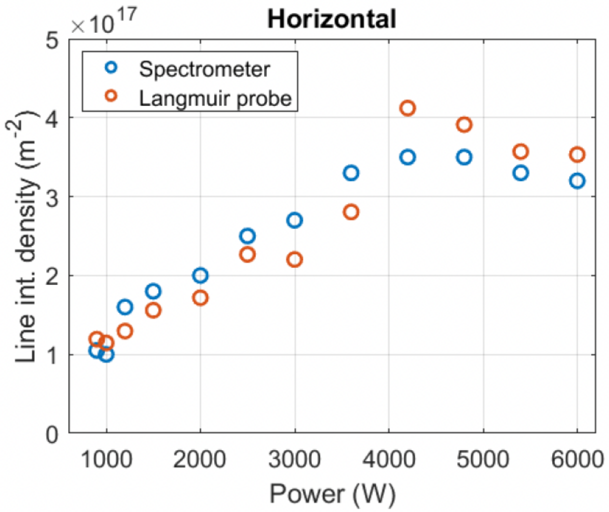


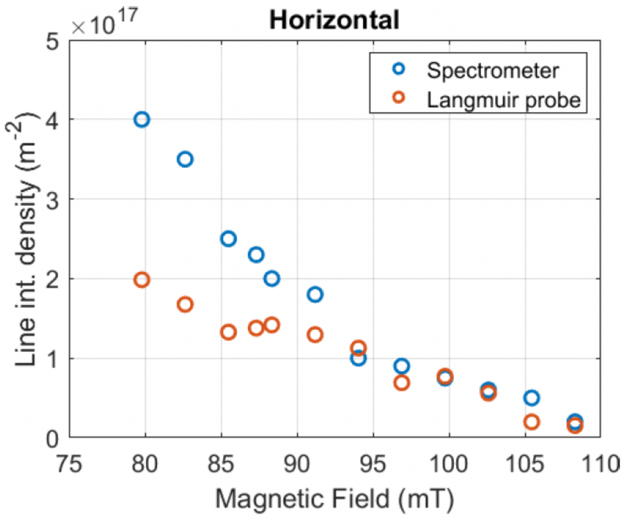
2D extrapolation of density
Plasma drift visible in purely toroidal field



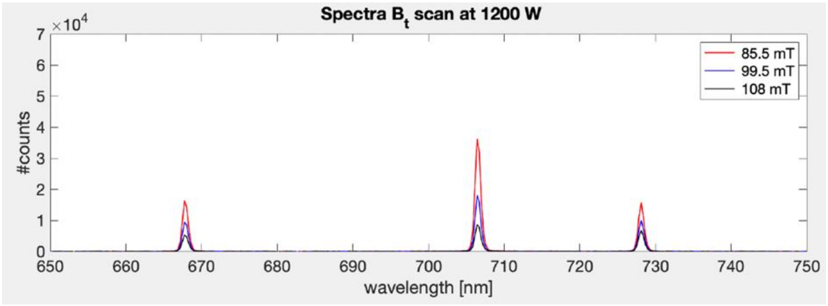
EC plasma characterisation by spectroscopy

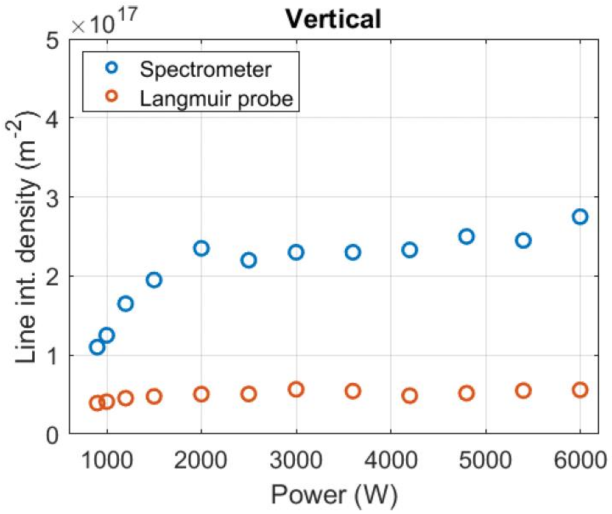
K. Crombé et al., IAEA FEC 2023, London, 15 – 21 Oct 2023

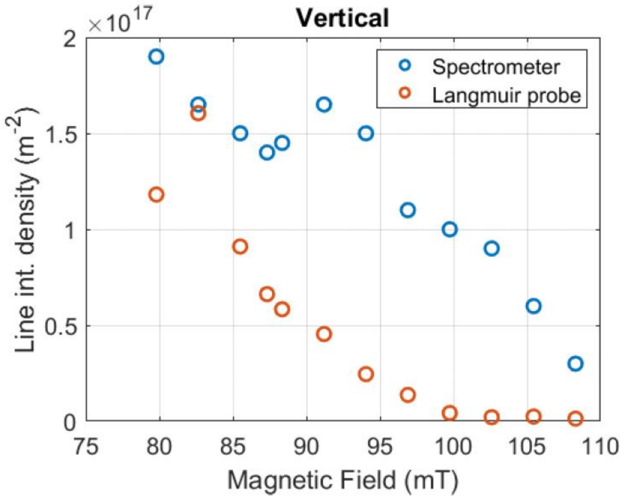




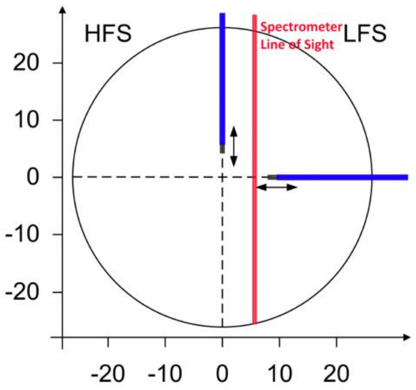
He spectral line ratios (AvaSpec-ULS4096CL-EVO-UA-10, fibre optic spectrometre) → electron density



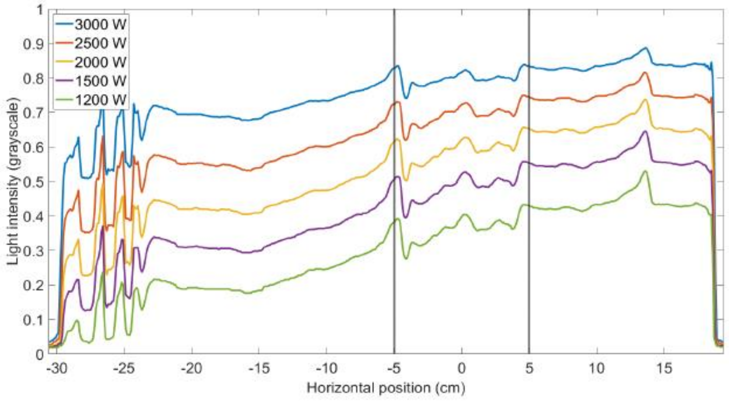


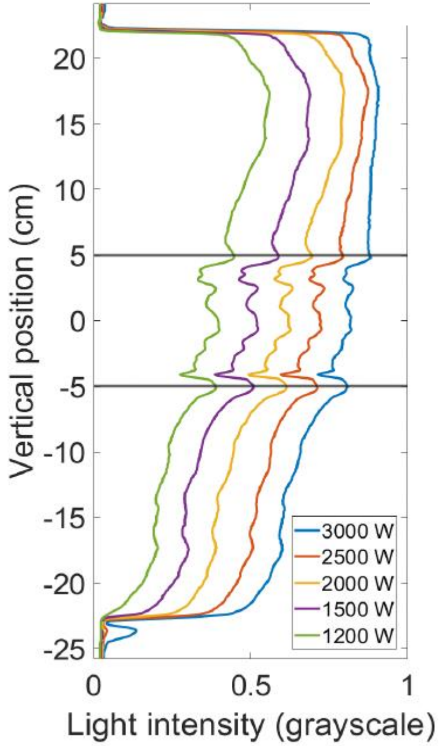


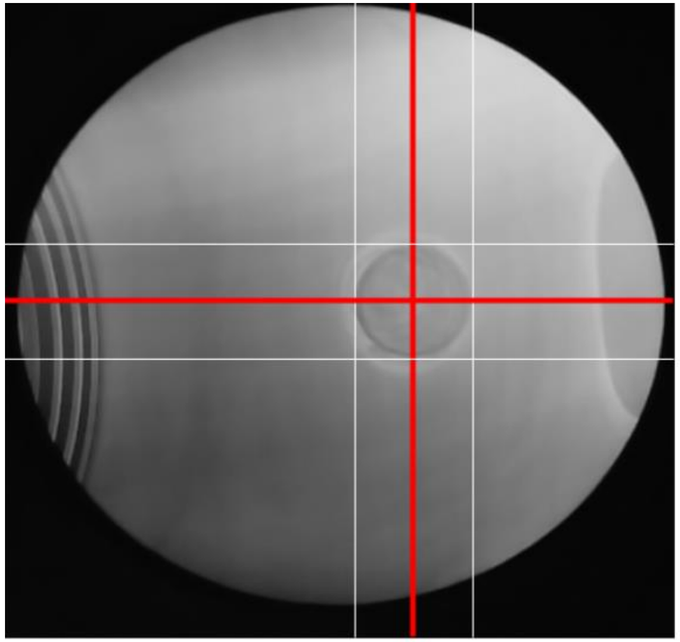
- Reasonable agreement with TLP for horizontal orientation
- For vertical orientation the position of TLP is not the same as the line of sight spectrometer (Δx = 5.4 cm to LFS)
- Higher values measured by spectrometer due to ExB drift, directed outwards



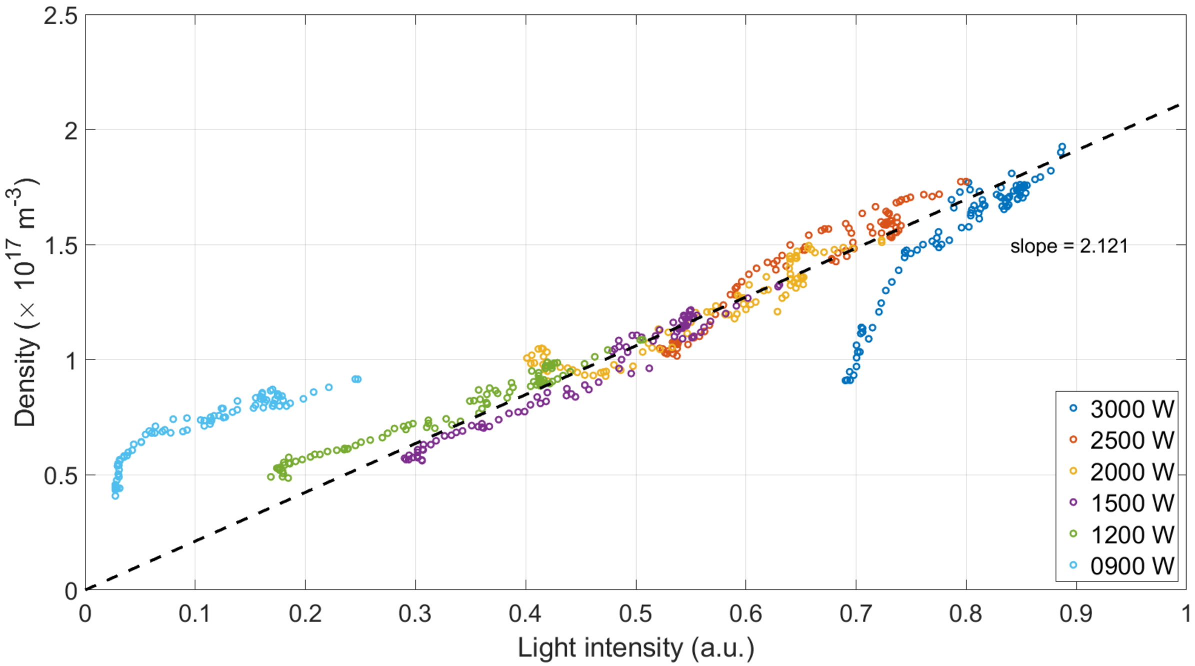
EC plasma characterisation by camera images





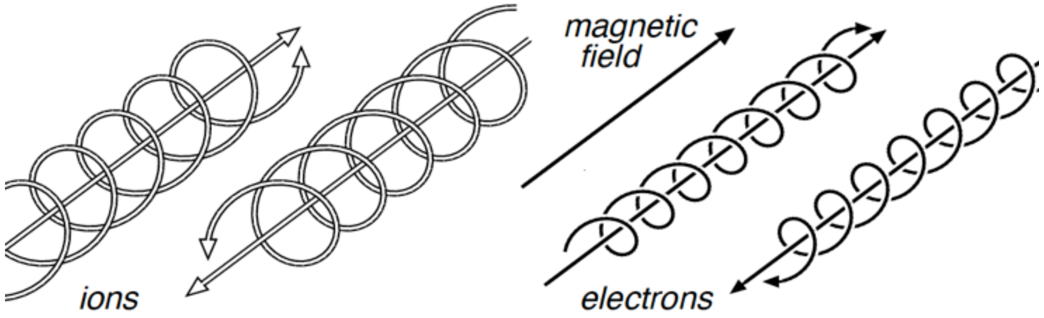


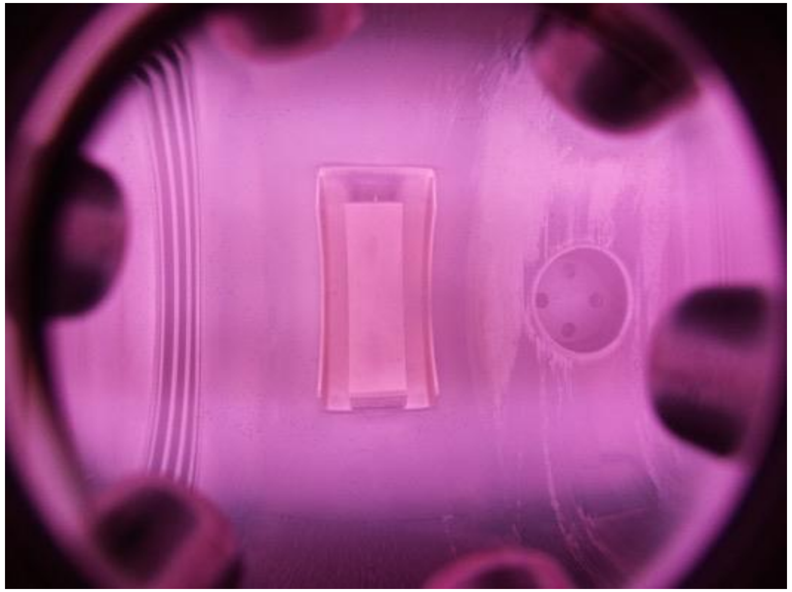
- Comparison of probe measurements of horizontal and vertical densities with visible light intensities of webcam
- Linear fit found in broad parameter domain for various power EC level
- This allows for a quick estimate of the density in 2D without the need to insert a probe



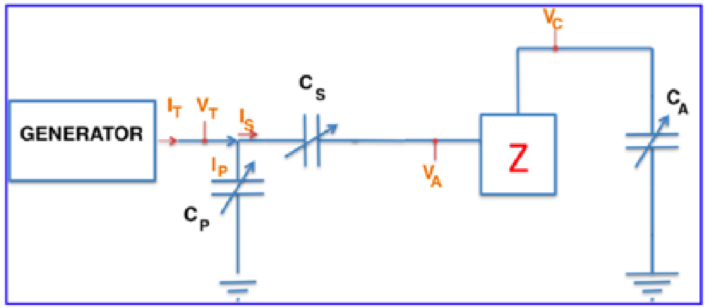
Ion Cyclotron system on TOMAS

- Single strap antenna
- 10 – 50 MHz
- up to 6 kW
- 3D printed antenna in Iinconel and coated by copper





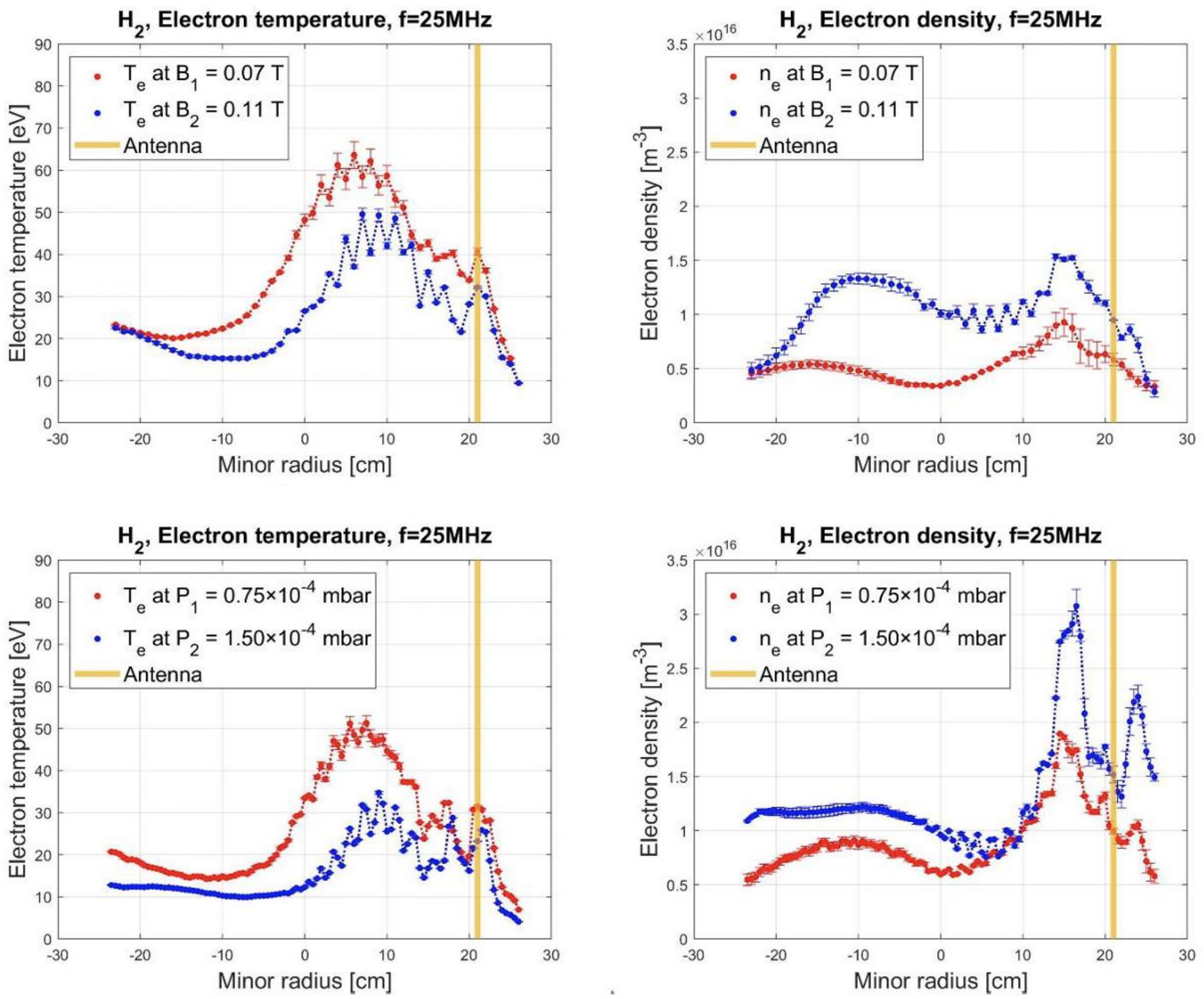
View on the ICRF antenna



ICRF matching circuit

IC characterisation by triple Langmuir probes

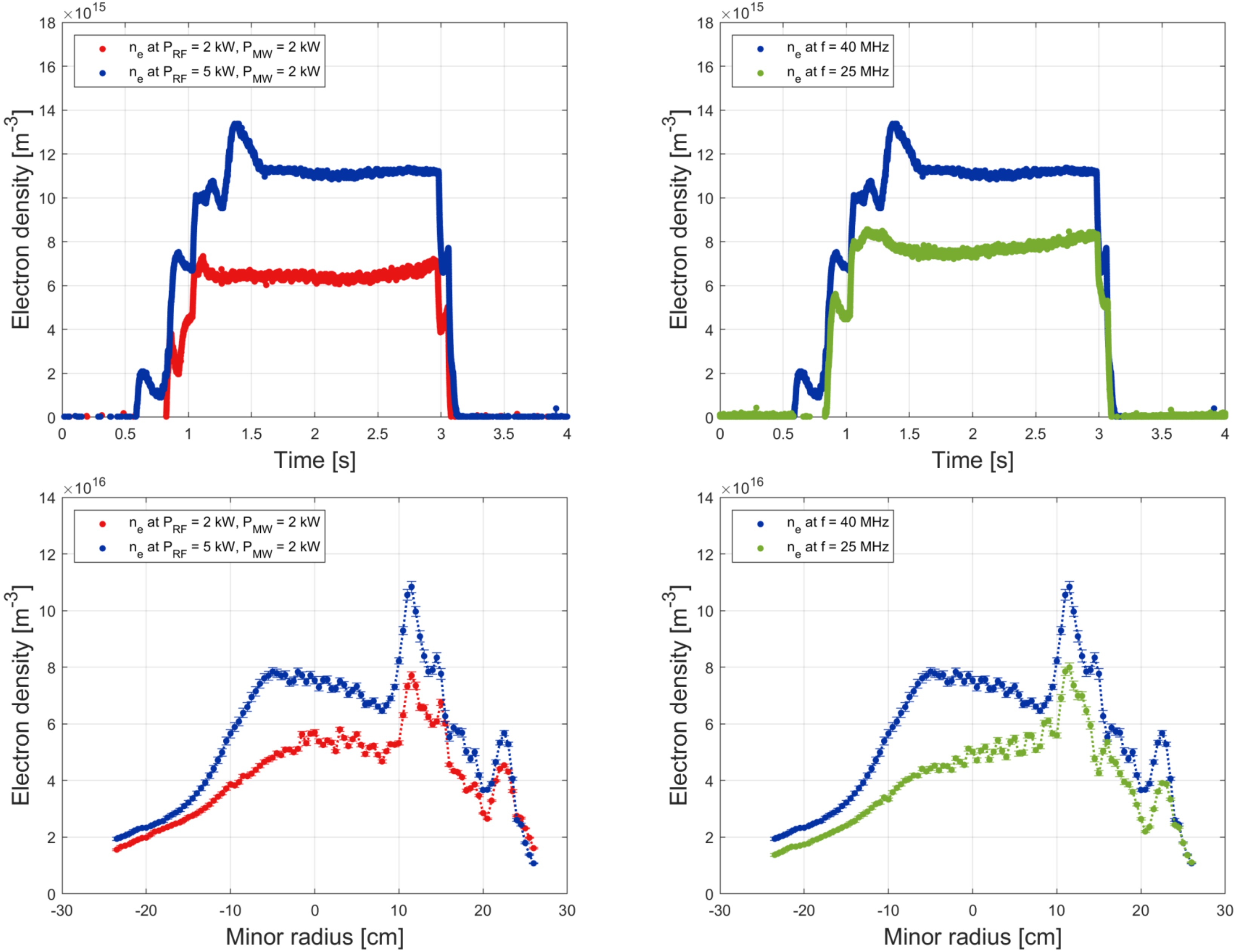
D. Lopez et al., Rev. Sci. Instrum. 95, 083542 (2024)



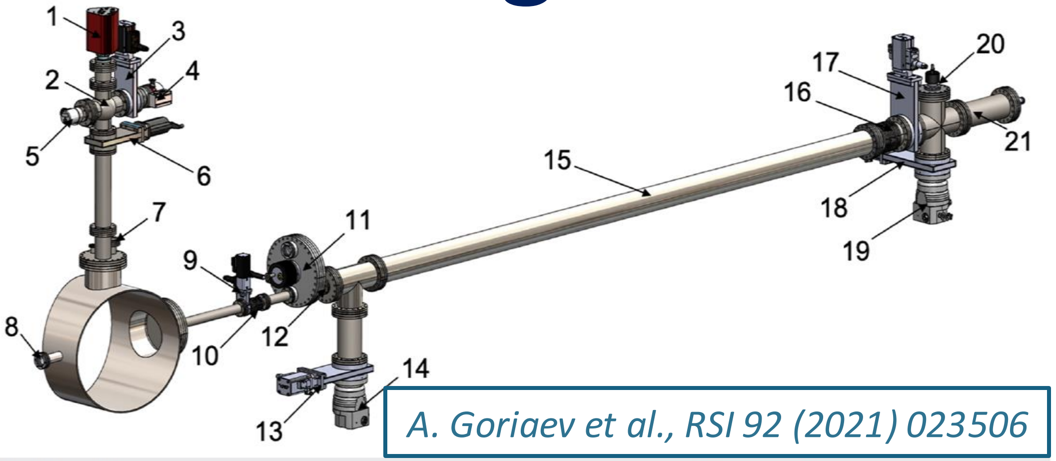
- Profiles n_e and T_e by movable triple Langmuir probe
- Two levels of B_t = 0.07 T and 0.11 T at constant pressure = 1.0 10^{-4} mbar
- Higher n_e and lower Te for higher magnetic field
- Two levels of pressure = 0.75 and 1.50 10^{-4} mbar at constant B_t = 0.08 T
- Higher ne and lower Te for higher pressure
- Comparison with IC power deposition models ongoing

Interferometer – Langmuir probe comparison

- Miwitron 2650
- Frequency 26.5 GHz
- Line integrated n_e
- Good qualitive agreement for various IC and EC power levels and RF frequencies
- Quantitative differences : further investigation needed

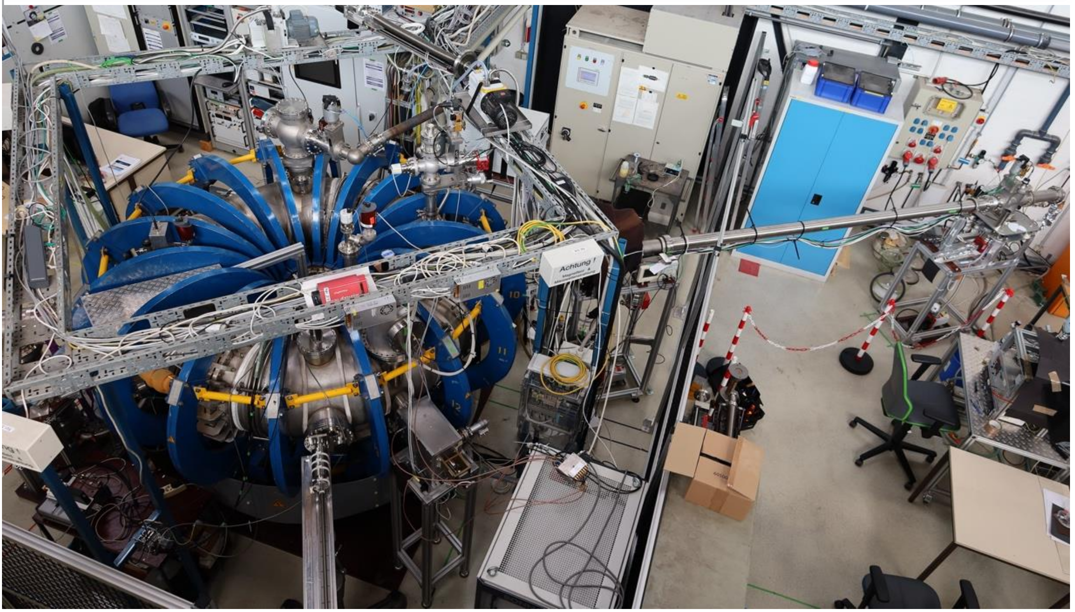


Time-of-Flight Neutral Particle Analyser

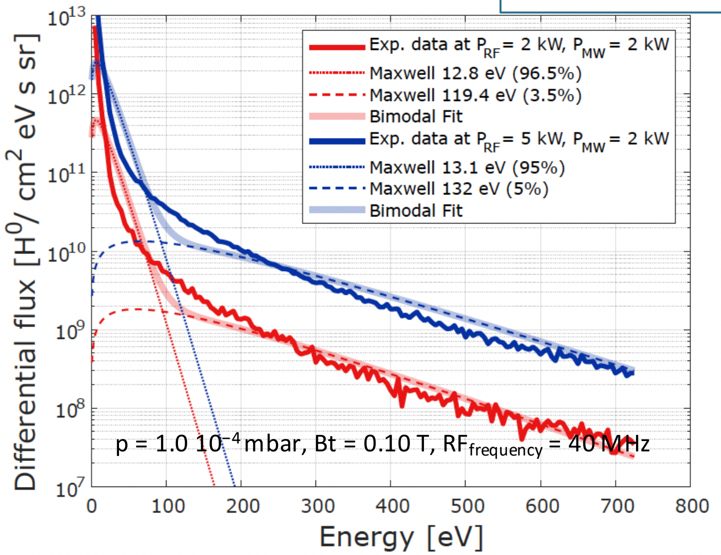


A. Goriaev et al., RSI 92 (2021) 023506

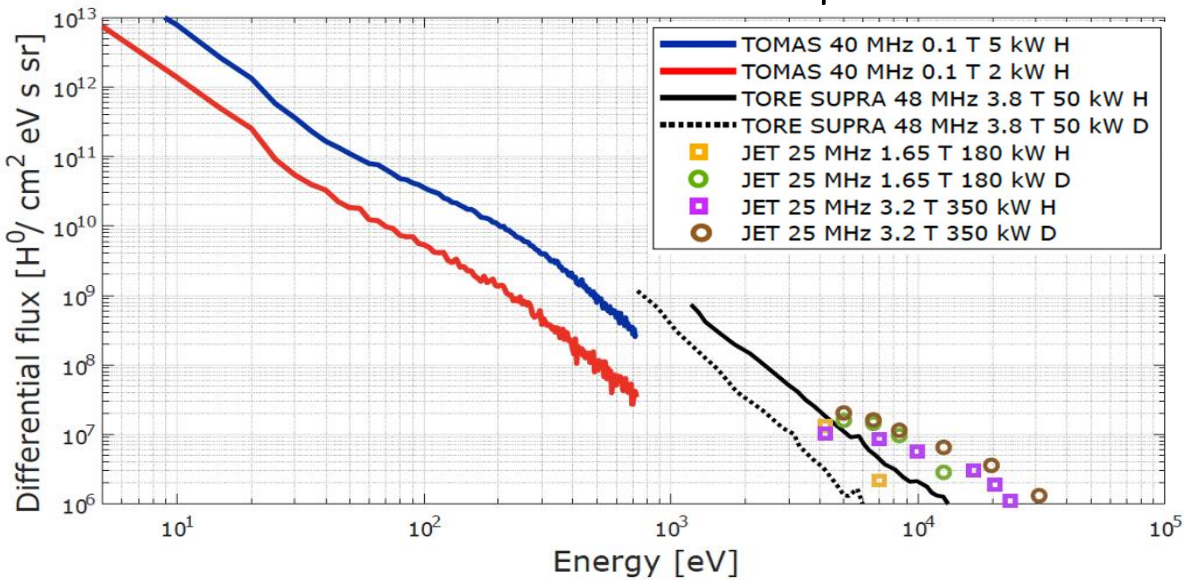
FIG. 16. Time-of-Flight neutral particle analyzer and residual gas analyzer. (1) Quadrupole Mass-Spectrometer (QMS), (2) by-pass DN16 angle valve, (3) DN63 electro-pneumatic gate valve, (4) Pfeiffer HiPace 80 turbomolecular pump, (5) Pfeiffer IKR 270 cold cathode gauge (Penning gauge), (6) DN63 manual gate valve, (7) DN40 viewport, (8) DN40 viewport, (9) DN40 electro-pneumatic gate valve, (10) DN40 bellows, (11) chopper, (12) Leybold PENNINGVAC PR 27 pressure gauge, (13) DN100 electro-pneumatic gate valve, (14) Pfeiffer HiPace 300 H turbomolecular pump, (15) DN100 flight distance pipe, (16) DN100 bellows, (17) DN100 electro-pneumatic gate valve, (18) DN100 electro-pneumatic gate valve, (19) Pfeiffer HiPace 300 H turbomolecular pump, (20) Leybold PENNINGVAC PR 27 pressure gauge, and (21) detector pipe.



D. Lopez et al., Rev. Sci. Instrum. 95, 083542 (2024)

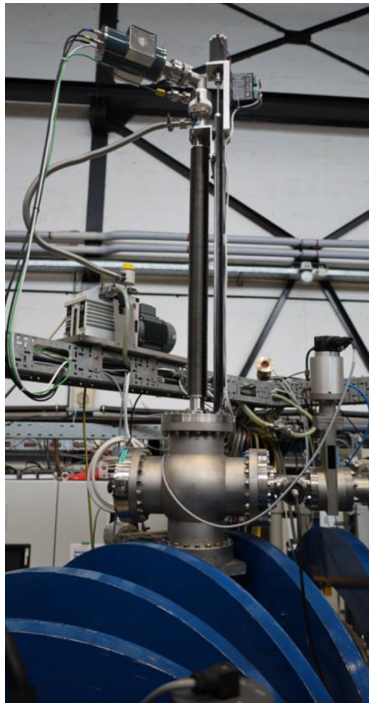


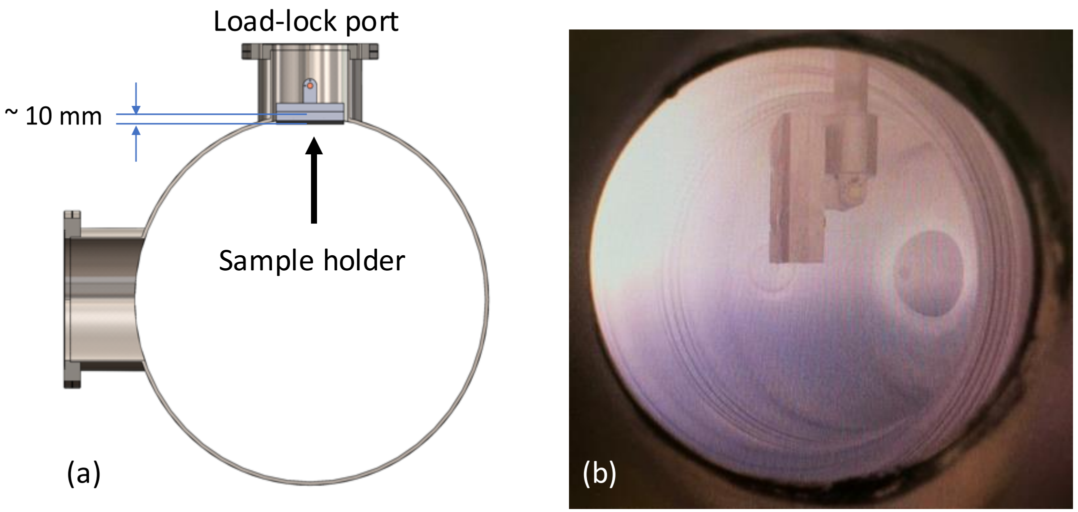
- more RF power (blue) increases ion energy and, after charge exchange, also energy of neutrals
- TOMAS data : neutral fluxes at low energies, complementary to TORE SUPRA and JET
- Operation in Deuterium is planned



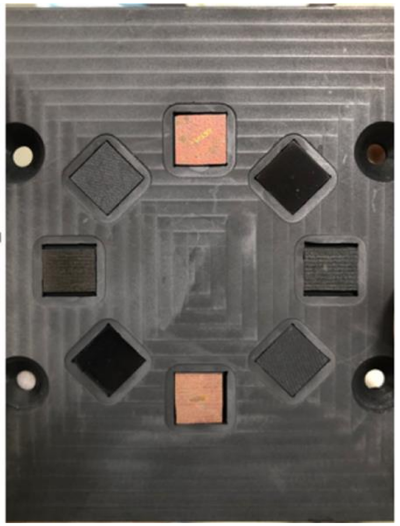
Sample exposure studies

- Exposure at desired radial distance from plasma centre and with a chosen surface orientation w.r.t. magnetic field (0° → 90°)
- Samples 10 mm x 10 mm, tungsten, stainless steel, graphite, …
- Samples can be heated up to 600 °C





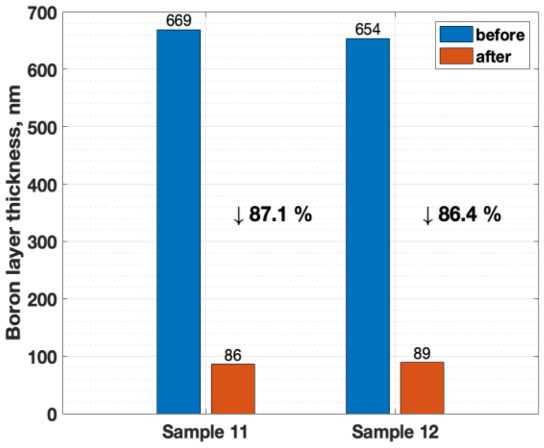
Position of the sample holder: (a) horizontal as PFC, (b) vertical inside the plasma core



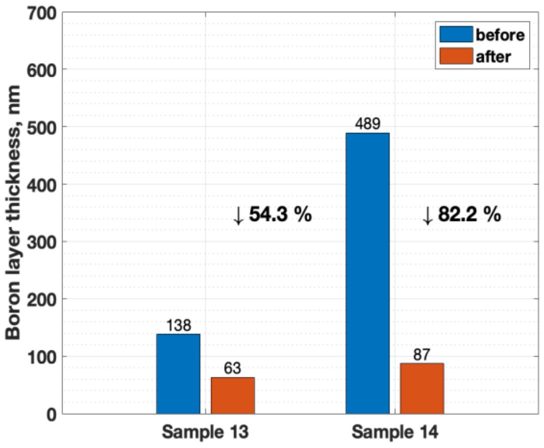
Sample exposure studies

Boron erosion rate evaluation (He)

Horizontal sample holder



Vertical sample holder



- ICWC exposure 24 min, 2kW
- Plasma inhomogeneity along vertical axis ➞ erosion rate variation
- On TOMAS studies will be performed for ITER and W7-X on various substrates (tungsten, graphite)

Impurity and deuterium content modification by GDC, ECWC and ICWC plasmas

- Samples from TEXTOR with co-deposits
- Nuclear Reaction Analysis (NRA) pre- and post-exposure ($^3He^{2+}$ beam at 3.5 MeV)
- D content decreased for IC power > 4 kW

Exposure number	Sample I D content	Sample II D content
ICWC 4	-15.0%	168.4%
ICWC 5	-68.3%	-32.9%
ICWC 7	-15.5%	-35.8%
ICWC 8	-3.4%	-13.2%
GD 1	7.3%	-2.5%
GD 3	-63.0%	-17.8%
GD 4	-6.8%	-14.8%

Summary

- In fusion machines a good control of the conditions of the inner vessel wall necessary for high plasma performance operation and stability
- Different wall conditioning techniques, combination and optimisation for best results
- TOMAS device : ideal testing environment for wall conditioning studies
- GDC, ECWC and ICWC systems available
- Various diagnostics are operational to provide a detailed knowledge of the plasma parameters
- Sufficient machine time available
- Present collaborations include LPP-ERM/KMS, Ghent University (Belgium), IPP (Germany), KTH (Sweden), KIPT (Ukraine), ITER, Australia National University
- Opportunities for master and PhD theses in physics, mechanical and electrical topics, software development and data analysis tools

Recent publications

[1] A. Goriaev et al., "The upgraded TOMAS device: A toroidal plasma facility for wall conditioning, plasma production, and plasma–surface interaction studies," Rev. Sci. Instrum., 92, 023506 (2021).

[2] S. Moon et al., "Characterization of neutral particle fluxes from ICWC and ECWC plasmas in the TOMAS facility", Phys. Scr. 96, 124025 (2021).

[3] Yu. Kovtun et al., "Overview of TOMAS Plasma Diagnostics", Journal of Instrumentation, 18, C02034 (2023).

[4] D. López-Rodríguez et al., "Characterisation of plasma parameters on Radio Frequency discharges in the upgraded TOMAS device", AIP Conf. Proc. 2984, 040006 (2023).

[5] A. Goriaev et al., "Study of local ion fluxes in Radio Frequency plasmas for Ion Cyclotron Wall Conditioning applications in the TOMAS device", AIP Conf. Proc. 2984, 040007 (2023).

[6] J. Buermans et al., "X-mode Electron Cyclotron Heating Scenarios Beyond the Cut-off Density", AIP Conf. Proc. 2984, 110003 (2023).

[7] Yu. Kovtun et al., "Measurement of Hydrogen Plasma Parameters of the Combined ECR+RF Discharge in the TOMAS Facility", AIP Conf. Proc. 2984, 110001 (2023).

[8] K. Crombé et al., "Radio Frequency Plasma Production on the TOMAS Device", AIP Conf. Proc. 2984, 040005 (2023).

[9] P. Petersson et al., "The influence of plasma parameters and electrical connection on the efficiency of wall conditioning plasmas in TOMAS facility", presented at 19th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Bonn, 22 – 26 May 2023.

[10] J. Buermans et al., "Characterization of ECRH plasmas in TOMAS", IAEA FEC 2023, London, 15 – 21 Oct 2023.

[11] J. Buermans et al., "Triple Langmuir probe calibration in TOMAS ECRH plasma", AIP Advances 13, 055125 (2023).

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

[13] K. Crombé et al., " Plasma characterisation and wall conditioning studies on the TOMAS device", IAEA FEC 2023, London, 15 – 21 Oct 2023.

[14] D. López-Rodríguez et al., "Characterization of plasma parameters and neutral particles in microwave and radio frequency discharges in the Toroidal Magnetized System", Rev. Sci. Instrum. 95, 083542 (2024).

[15] J. Buermans et al., "Characterization of ECRH plasmas in TOMAS", Phys. Plasmas 31, 052510 (2024).