Probe measurements on the GOLEM tokamak

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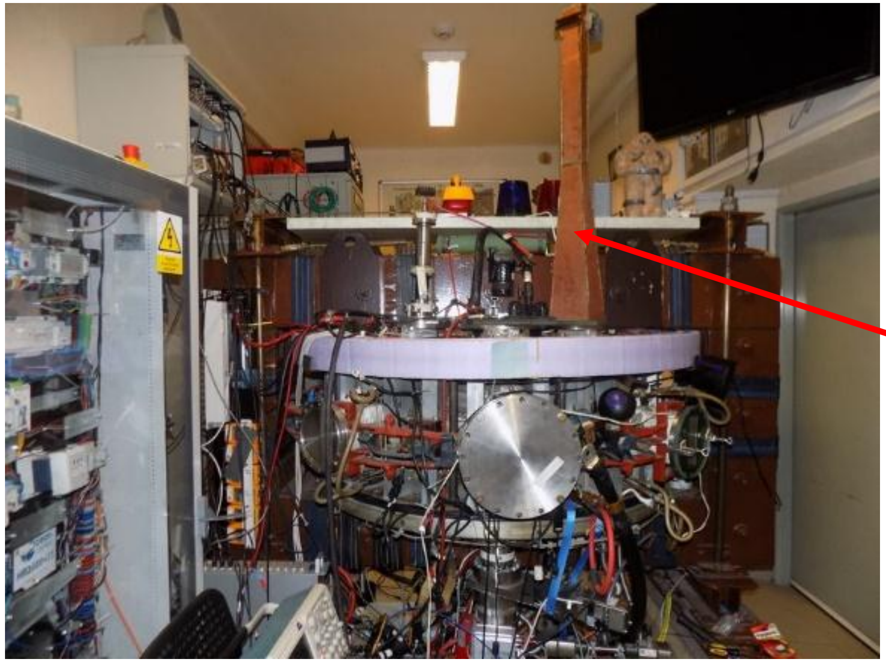
Motivation

- Probe measurements in tokamaks are essential for understanding of edge plasma parameters, such as electron temperature, density, floating and plasma potential as well as the electron energy distribution function
- These parameters are usually determined from the I-V characteristics of a single Langmuir probe
- However, duration of discharges on the GOLEM tokamak is relatively short – up to 15 ms and plasma is not steady state
- Therefore, the standard technique using sweeping probe voltage can’t be used, because the sweeping frequency is typically lower than 1 kHz. So, just a few characteristics can be collected during a single discharge, and consequently, the temporal resolution is not sufficient
- However, the discharges on GOLEM are quite reproducible. Therefore, we present here results of measurement of the probe characteristics on the shot to shot basis

The GOLEM tokamak

The GOLEM tokamak is a small and also the "simplest" tokamak, operational at the Kurchatov Institute since 1961 as TM-1, and at IPP Prague in the period 1997 – 2006 as CASTOR.
Location: Faculty of Nuclear Physics and Physical Engineering (Czech Technical University)
Mission: Education and training of students



Toroidal magnetic field	<0.5 T
Plasma current	<10 kA
Plasma density	$<10^{19}$ m^{-3}
Central electron temperature	<100 eV

Preionization

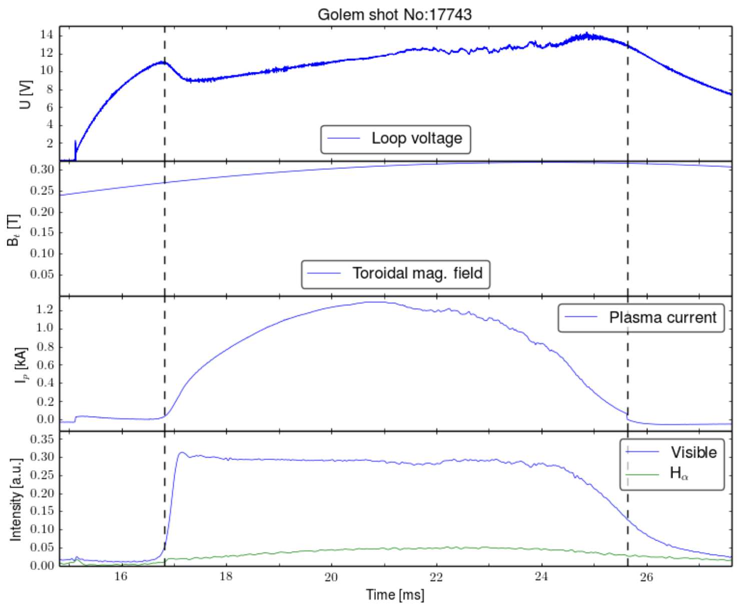
- Electron gun
- Microwave power at 2,45 GHz delivered by a horn antenna

- Discharges every 3 - 5 minutes

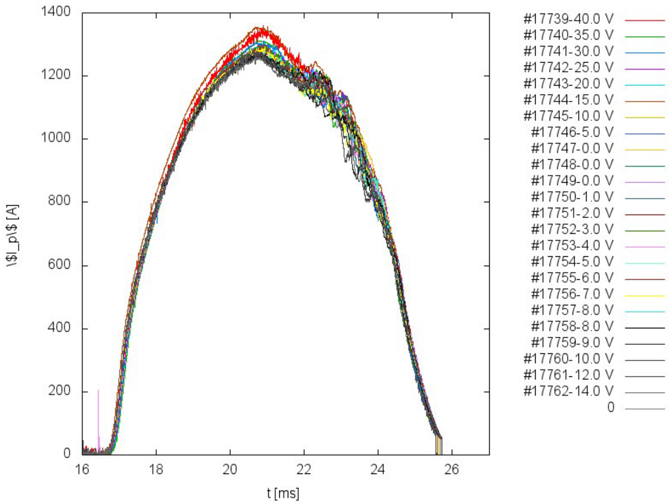
Unique feature of GOLEM: Operational remotely via Internet

Probe measurements are performed in two different plasmas

Standard tokamak discharge



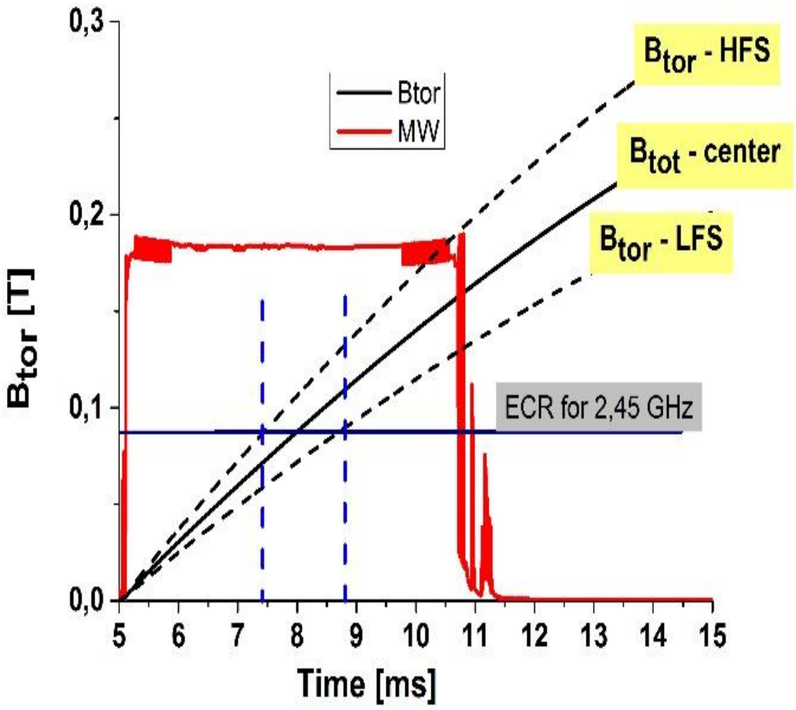
Reference discharge #17 743



Evolution of plasma current in series of 24 shots (#14739- 17762)

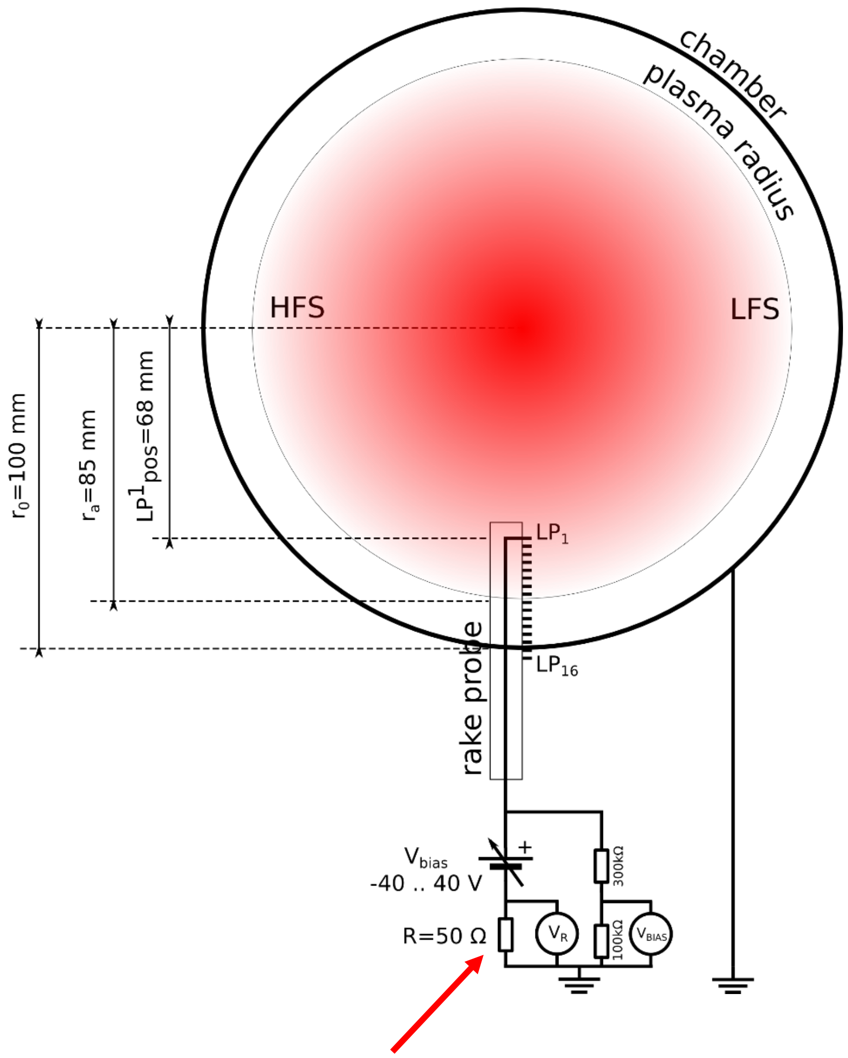
- reproducibility

Microwave plasma used for breakdown of the working gas



Electron Cyclotron Resonance appears in the vessel for the time interval ~1,5 ms, when the toroidal magnetic field is Bt = 0. 087 T

Experimental setup



Load resistance

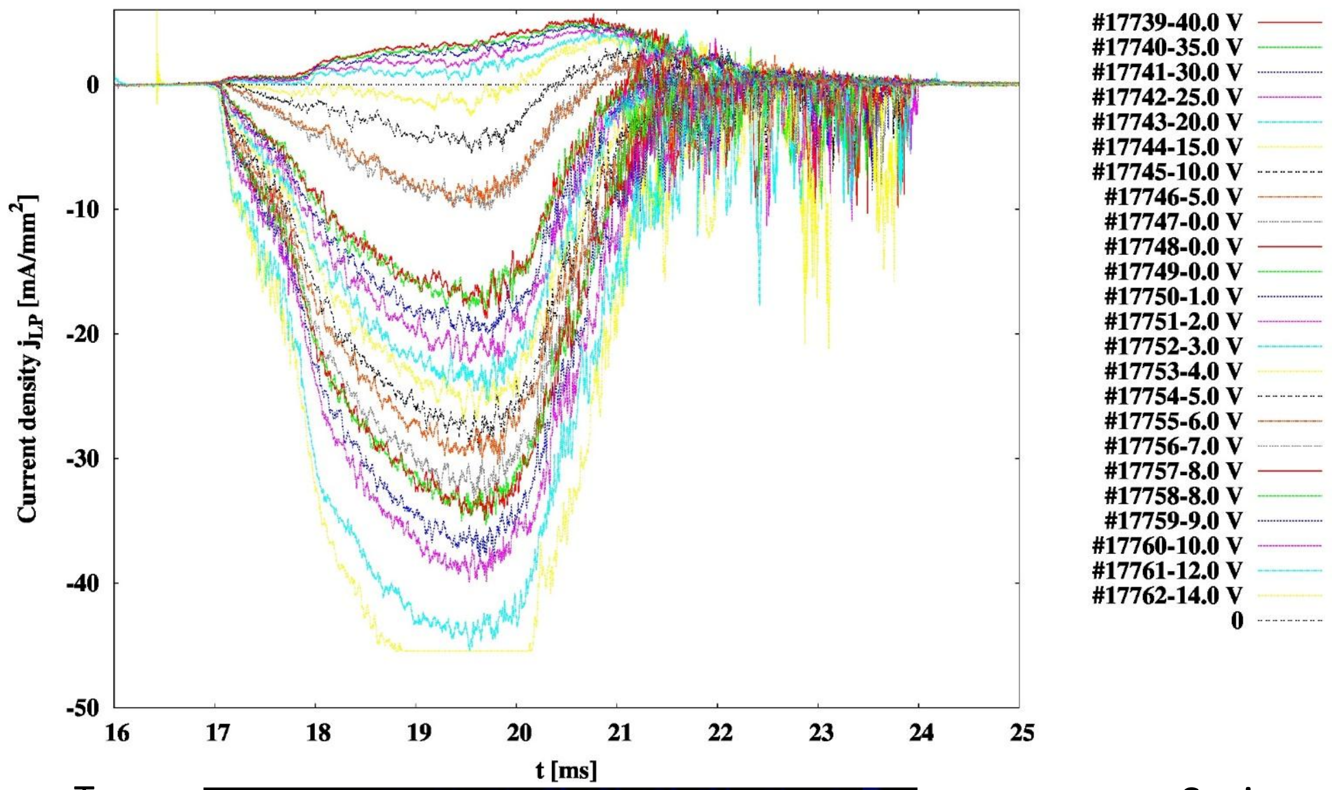
Radial array of 16 Langmuir tips is immersed in the plasma from the bottom of the tokamak vessel, movable on the shot to shot basis.

Tokamak discharge: Cylindrical probe diameter 0.7 mm, probe length 2 mm.
Load resistance = 50 Ω

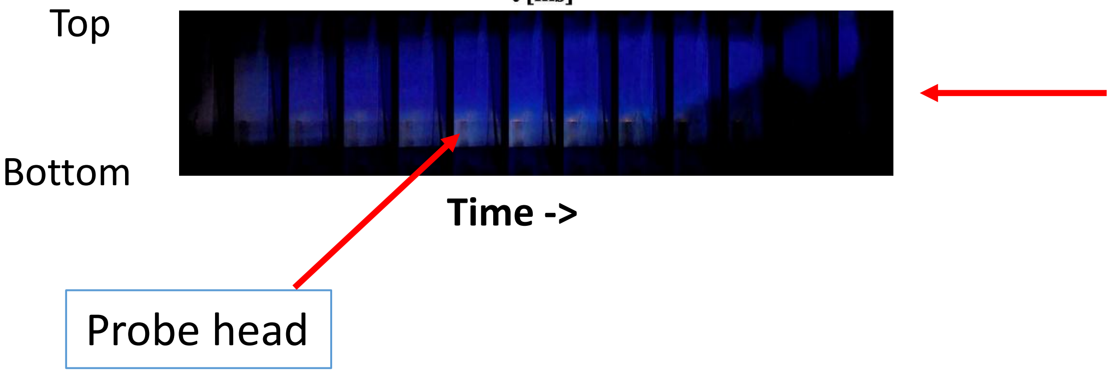
MW plasma: Planar probe 5 x 5 mm
Load resistance R_L = 50 kΩ (because of much lower plasma densities)

The DC voltage (from -40 to + 40 V) is applied to a probe (No 1) on the shot to shot basis and the temporal evolution of the probe current is recorded with sampling frequency 1 MHz i.e. with temporal resolution 1 μs.

Probe measurement in tokamak discharges - 1



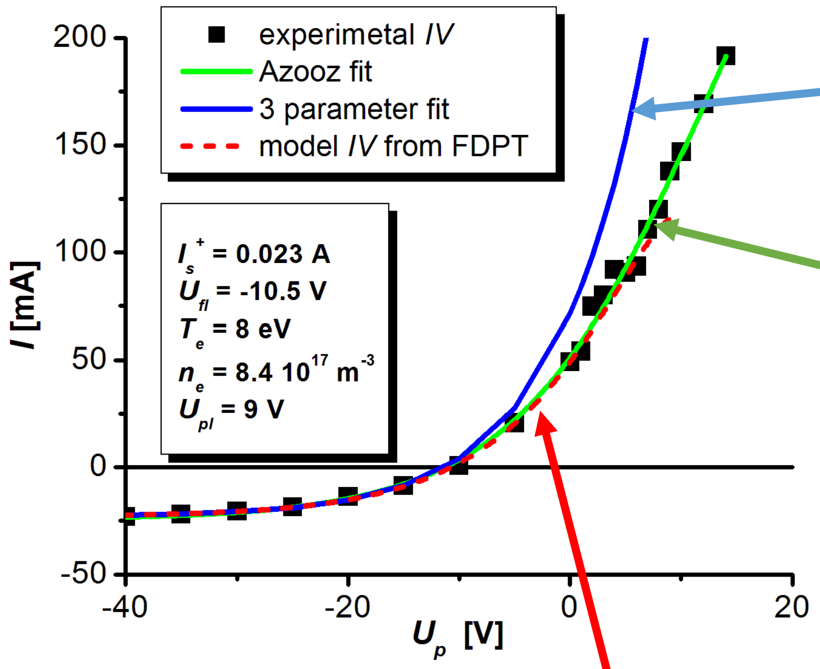
Evolution of the probe current in 24 reproducible discharges (#17 739- 17 762)



Series of pictures taken by visible camera viewing The plasma column through the horizontal port. Vertical movement from the bottom to the top of the tokamak vessel is apparent. Consequently, the probe appears to be out of plasma from 22 ms until end of the discharge

Probe measurement in tokamak discharge - 2

Experimental IV characteristics are processed by three techniques:



1. Classical technique (3 parameters fit)

$I_p = I_{sat}$ (1-exp[(U_{fl} - U_p)/T_e]

The electron branch is not taken into account (V_{probe} < V_{fl} +T_e)

2. Empirical fit according empirical formula proposed by Azooz)

I_p = exp[a_1 * tanh (U_p + a_2)=a_3] + a_4

where a_1-a_4 are linked to plasma parameters

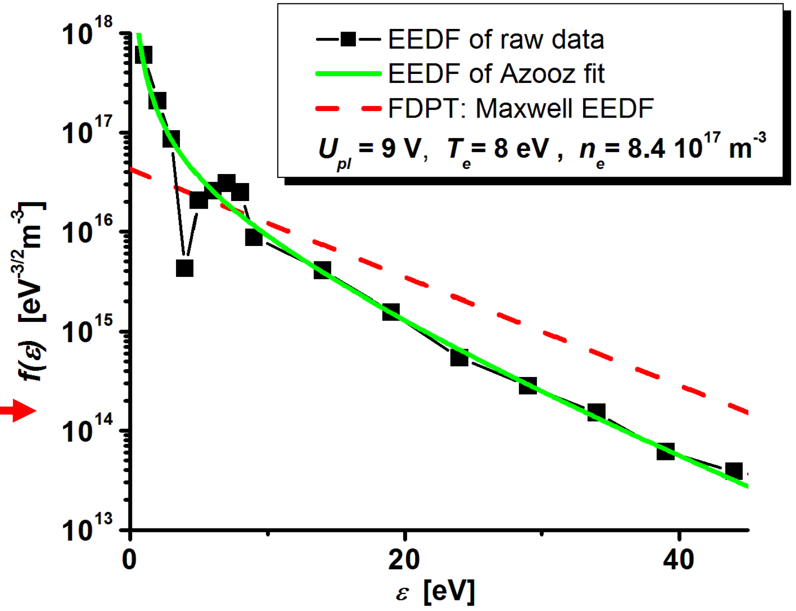
A. Azooz, *Four free parameter empirical parametrization of glow discharge Langmuir probe data*, Review of Sci. Instr. 79. 2008, 103501

3. First derivative technique according (see talk of Tsv. Popov)

$$I_e(U) = -\frac{2eS}{3\sqrt{2m_e}} \int_{eU}^{\infty} \frac{(\varepsilon - eU) f(\varepsilon) d\varepsilon}{\gamma(\varepsilon)\left[1 + \frac{(\varepsilon - eU)}{\varepsilon}\psi(\varepsilon, B)\right]}$$

$$f(\varepsilon) = \frac{3\gamma\sqrt{2m}}{2e^3 S} \cdot \frac{\psi(\varepsilon, B)}{U} \cdot \frac{dI_e(U)}{dU}$$

Tsv. K. Popov et al, *Electron energy distribution function, plasma potential and electron density measured by Langmuir probe in tokamak edge plasma* Plasma Phys. Control. Fusion, 51 (2009)

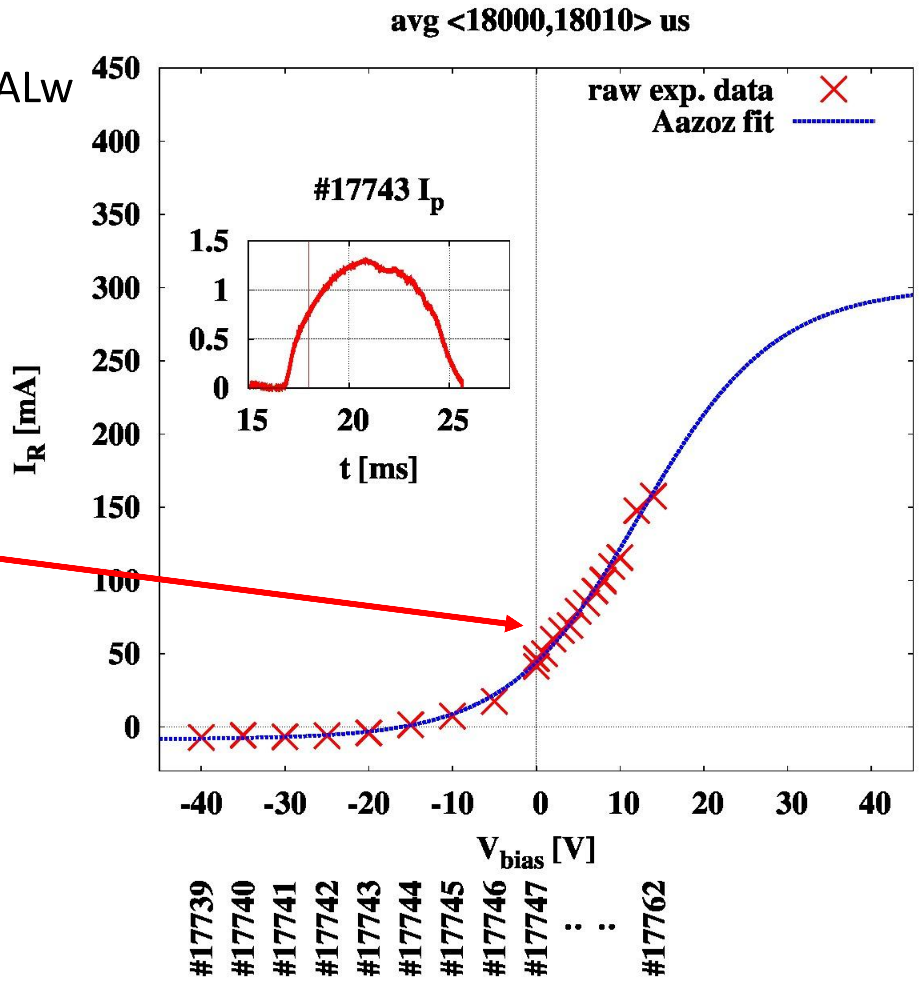


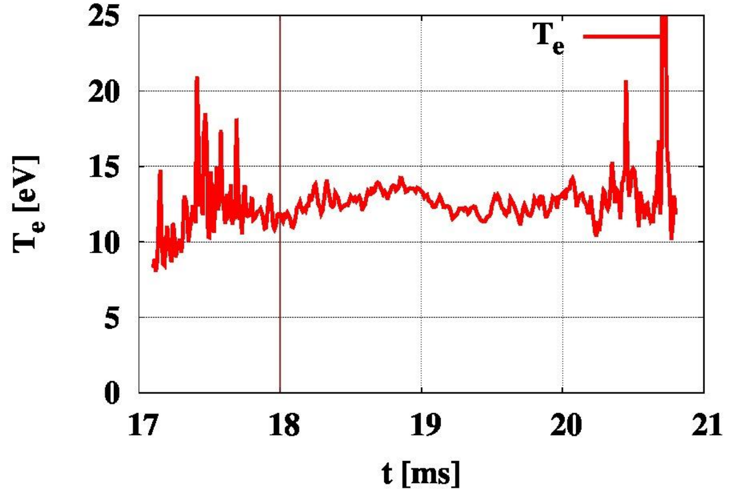
Probe measurement in tokamak discharge - 3

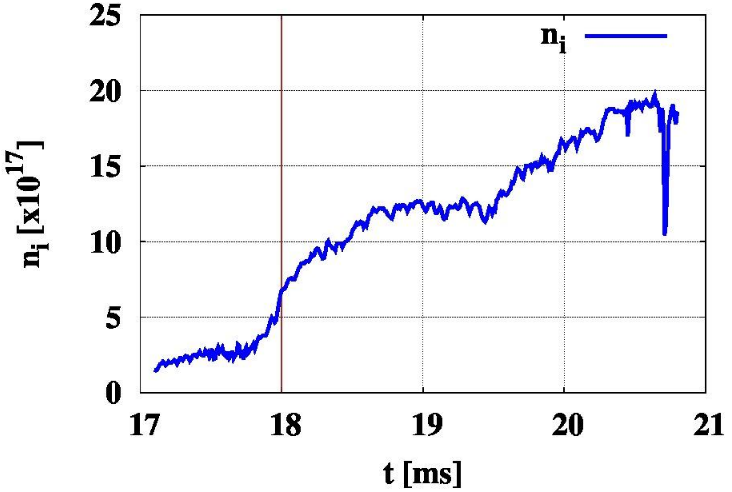
Temporal evolution of the shape of the IV characteristics during the series of reproducible discharges #17 739- 17 762 with the temporal resolution 10 μs (video)

https://youtu.be/AGaqU0q2ALw

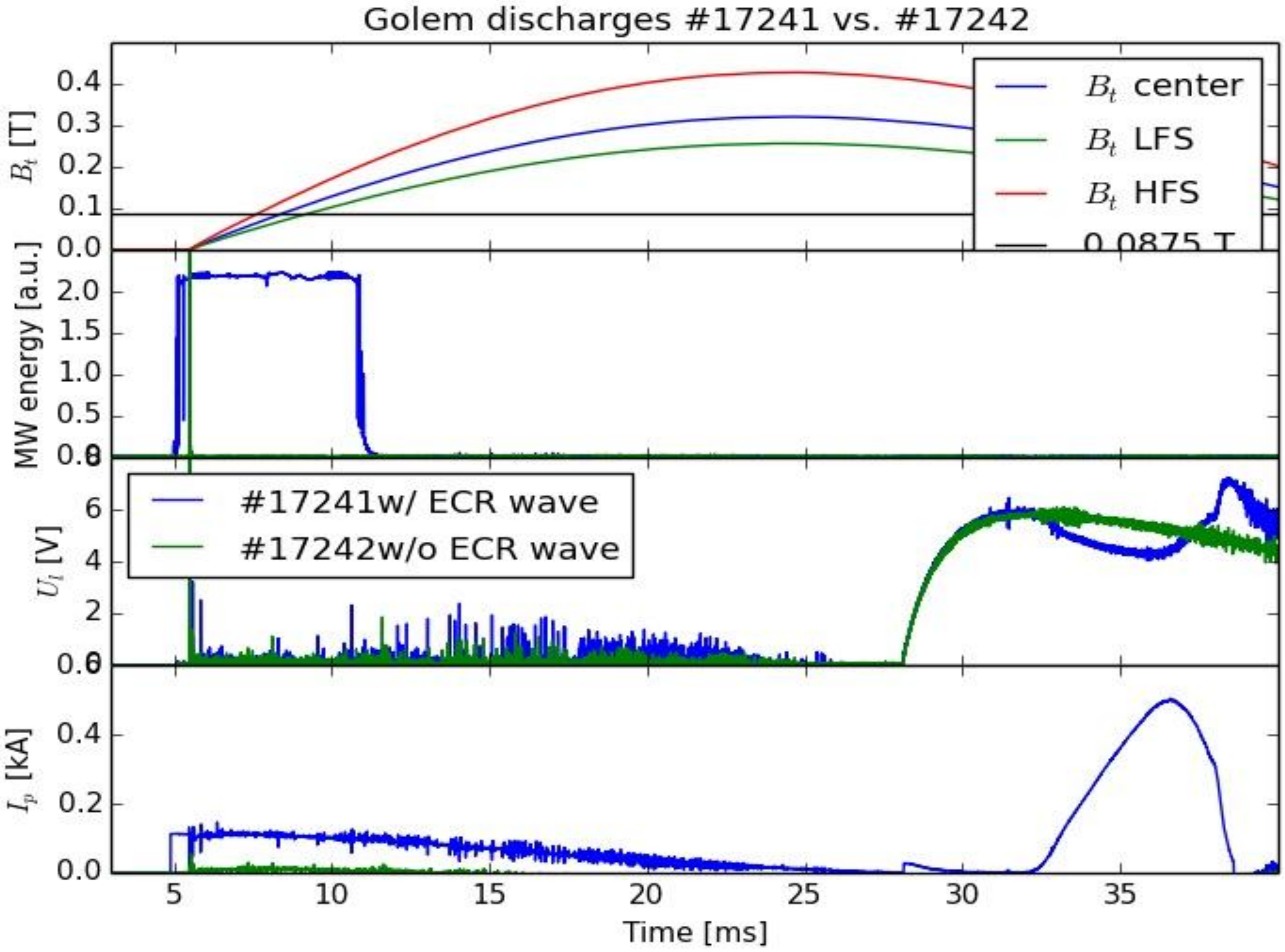
Fit of IV characteristics according the Azooz empirical formula





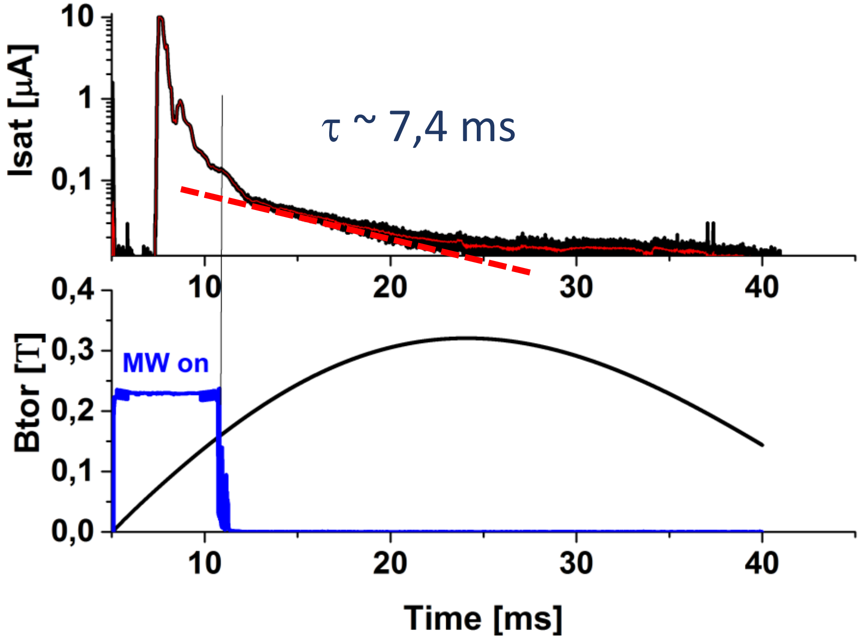


Probe measurements in microwave plasma – motivation breakdown conditions persistence



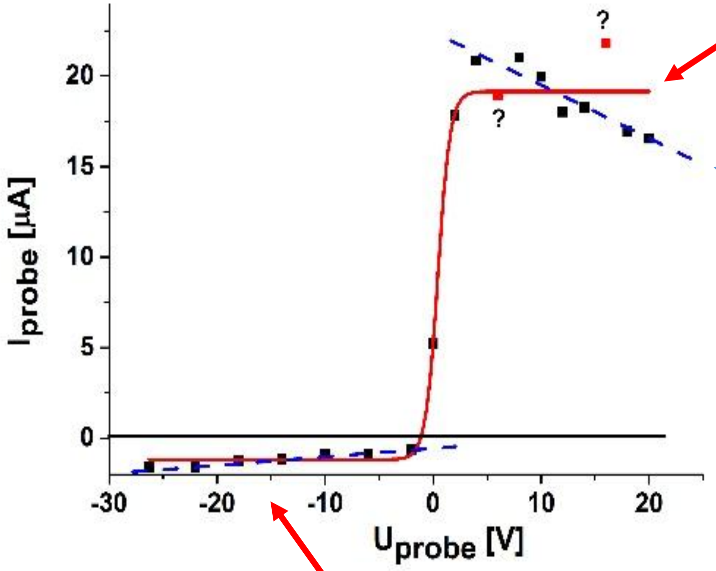
Probe measurements in microwave plasma – 1

Evolution of the toroidal magnetic field/MW power and the ion saturation current



- MW plasma is confined during whole duration of the toroidal magnetic field!
- The ion saturation current decays with the time constant ~7,4 ms after switching of the MW power
- **What are the plasma parameters??**

The typical IV characteristic recorded at t = 12 ms, when the MW power is already switched off



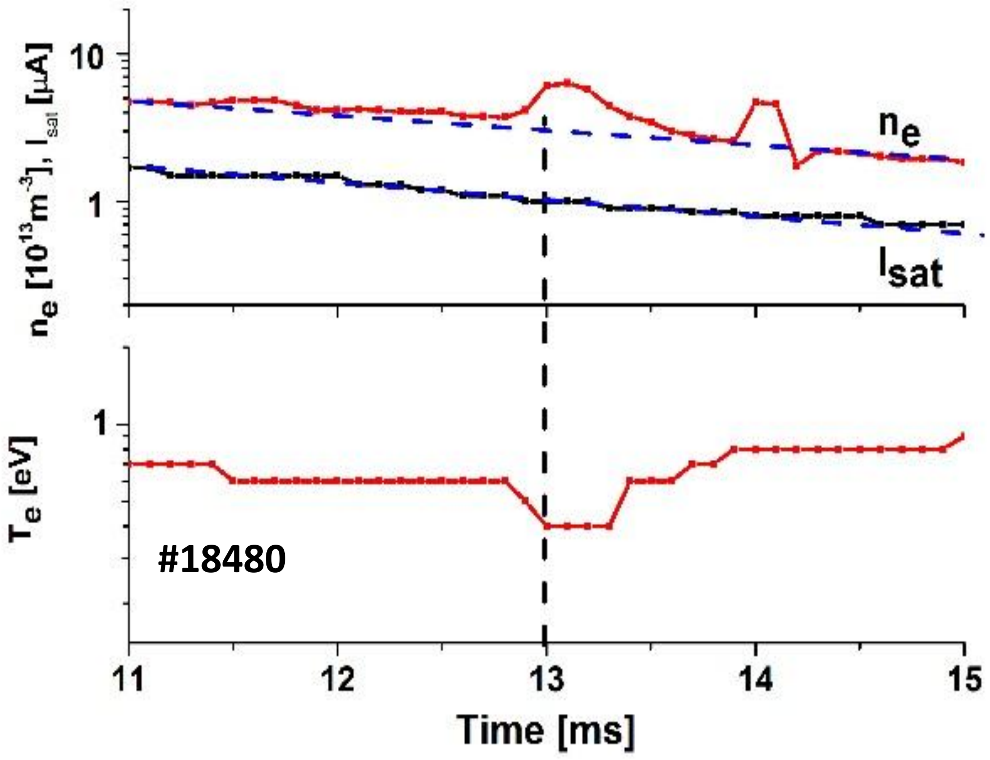
4 parameter fit – A.A Azooz

The electron saturation current decreases with the probe voltage – no explanation yet
Speculation: large probe acts as the biasing electrode => vertical electric field => ExB drift towards the Low field Side

The ion saturation current increases with the probe voltage – probe sheath expansion

Probe measurements in microwave plasma – 2

B_{tor} is still on, but MW power switched off



Evolution of the electron density and temperature during MW plasma decay in toroidal magnetic field

- n_e decays with a characteristic time constant 7,4 ms
- T_e is constant, remaining at < 1 eV

-> Low temperature plasma can be confined in toroidal magnetic field for a relatively long time (in the range of 1 -10 ms), if the electron temperature is sufficiently low.

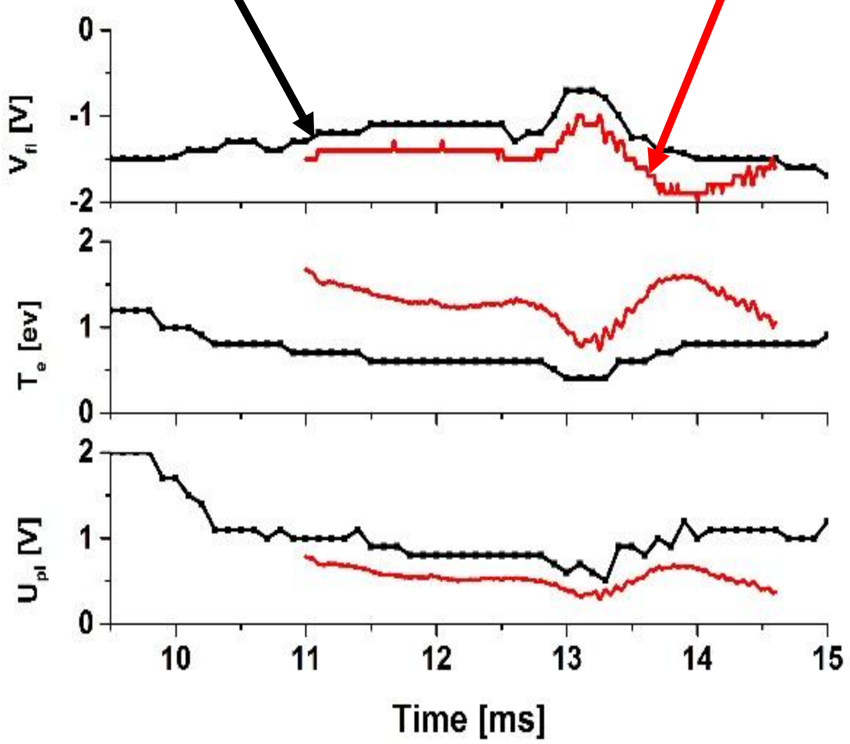
-> Particle losses due to the centrifugal and **B** x **grad B** losses in inhomogeneous magnetic field are reasonably low in this case

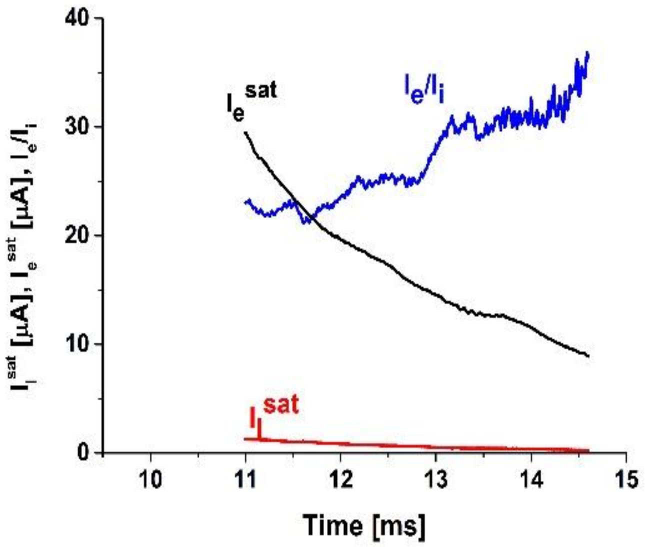
Probe measurements in microwave plasma – 3

Comparison of different fitting techniques

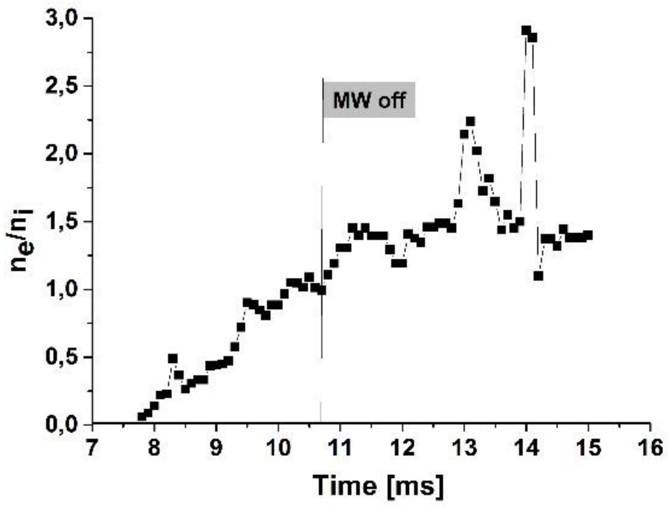
FDPT fit - black lines

4 parameter fit (empirical) – red lines





Electron and ion saturation currents in hydrogen plasma and their ratio



Ratio of electron and ion densities – Reasonable agreement, when the MW power is switched off

Conclusions

Discharges on the GOLEM tokamak are quite reproducible => IV characteristics of a single Langmuir probe can be recorded on shot – to shot basis

Therefore, temporal evolution of the plasma parameters is determined with a high temporal resolution (~10 μs)

Surprisingly, the whole IV characteristics are very well fitted by the empirical analytical expression proposed by Azooz

Probe date are fitted by several ways and the T_e, n_e, U_{pl} and the Electron Energy Distribution Function can be determined

- Tokamak discharge – edge electron temperature ~ 10 eV, densities ~10^{17} m^{-3}, Electron Energy Distribution Function is Maxwellian
- MW plasma used for breakdown: Electron temperature < 1eV, plasma density n_e ~ 10^{13} m^{-3} after switching off the MW power, plasma is confined in toroidal magnetic field for ~ tens of milliseconds, EEDF is Maxwellian