Microwave plasma on the GOLEM tokamak

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Plasma, generated by the microwave power was studied by means of Langmuir probe in 18 reproducible discharges (#18480 – #18 497). Description of experiment and some data processing can be found on http://golem.fjfi.cvut.cz/wiki/Experiments/BesidesMainStream/MWplasma/sessions/0115VAcharMeasurementIntro/index

The temporal evolution of the toroidal magnetic field and the microwave power is shown in Fig. 1.

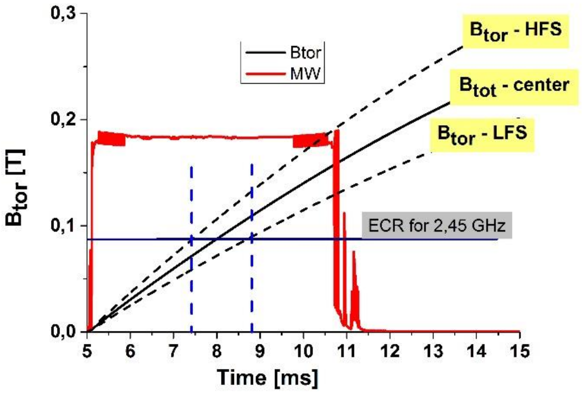

Fig. 1. Temporal evolution of the toroidal magnetic fielsd and the microwave power

The toroidal magnetic field power supply and the microwave power are switched on simultaneously at t = 5 ms. The toroidal magnetic field increase and reaches the ECR resonance in the vessel in the time interval t = 7.4 – 8.8 ms, as shown in Fig. 1. The resonance layer occurs at first at the High Field Side of the vessel, crossing its center, and disappears at the Low field side of the vessel. The B_{tor} at the LFS and HFS is derived from the data from the database B_{tor}^0, corresponding to the center according formulae:

$$B_{tor}^{LFS} = \frac{B_{tor}^0}{R_0+a} \qquad B_{tor}^{HFS} = \frac{B_{tor}^0}{R_0-a}$$

where R_0 = 0.4 m is the major radius of the vessel, and a = 0.085 m is the radius of the poloidal limiter. The MW power is switched off at t = 10.8 ms.

The Langmuir probe used in this experiment is planar, 5x5 mm. oriented perpendicularly the magnetic field lines. So, the effective collecting area is 50 mm^2.The radial position of the probe in the vessel is not known, but it was located somewhere close to the edge. The probe voltage is changed on the shot-to shot basis from -20 V to +26.3 V. The typical IV characteristic constructed at t = 12 ms is shown in Fig.2.

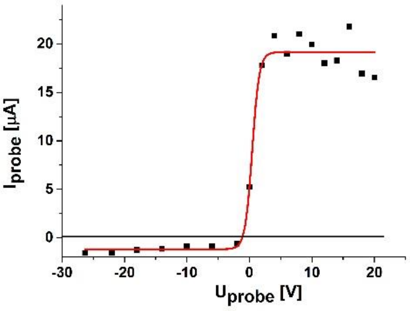

Fig. 2. IV characteristics constructed at t = 12 ms, when the toroidal magnetic field is B_0 = 0.188 T.

Black squares – experiment

Red line - fit

The experimental data are fitted by an analytic function proposed by AA Azooz in [1] (Review of Scientific Instruments 79, 103501 (2008); doi: 10.1063/1.2976755).

$$I_{probe} = \exp\left[a_1 \tanh\left(\frac{V_{probe}+a_2}{a_3}\right)\right] + a_4 \qquad (1)$$

With four fitting parameters a_1, a_2, a_3 and a_4, explained in Appendix. As it is seen, the fit is quite reasonable. The fitting function was used (by Megi) to calculate plasma parameters by using technique proposed by Ts Popov et al in [2]. The resulting temporal evolutions of the main parameters like the electron temperature, plasma potential, electron density and the ion saturation current are plotted in Fig. 3.

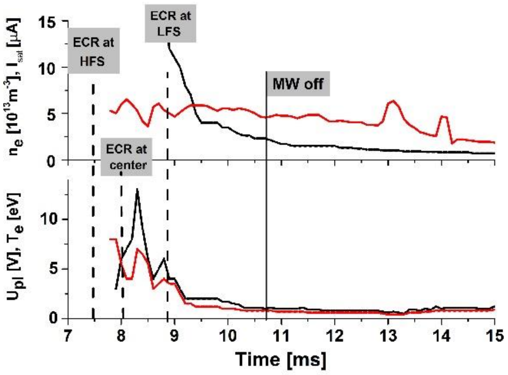

Fig. 3. Temporal evolution of selected plasma parameters with temporal resolution 100 μs in series of 17 reproducible discharges (#18480 – #18 497).

It is evident from the figure that plasma is confined in the vessel long time after switching-of the MW power at t = 10.8 ms. Since that time, the ion saturation current, and electron density decay exponentially, as it is more apparent in Fig.4.

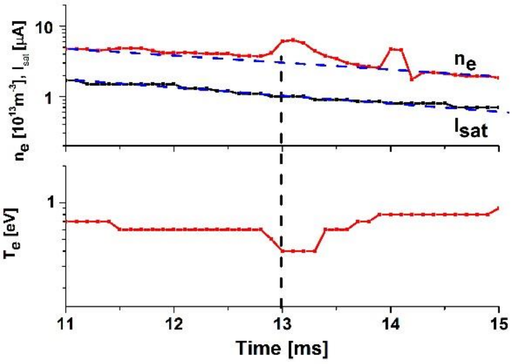

Fig. 4. Evolution of selected plasma parameters in the time interval when MW power is swithed off. The Isat and ne decay exponentially with the characteristic time constant

τ = 1.25 ms

The electron temperature remains constant during this period T_e = 0.6-0.8 eV. Note a bit strange behavior t = 13 ms, where a drop of the electron temperature is well seen.

We also may calculate the ion density from the measured ion saturation current and electron temperature using formula.

$$n_i = \frac{2I_{sat}^{+}}{eAc_s}$$

where $$c_s = \sqrt{\frac{2kT_e}{M_i}} = 1{,}4 \cdot 10^4 \sqrt{T_e} \qquad \text{[m/s, eV]}$$

is the ion sound speed (assuming $T_i = 0$ eV)

The collecting area of the probe is 64 10^{-6} m^2, therefore

$$n_i = \frac{2I_{sat}^{+}}{eAc_s} = \frac{1.79 \cdot 10^{19} I_{sat}}{\sqrt{T_e}} \qquad [m^{-3}, A, eV] \qquad (2)$$

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This yields to the ion density $n_i \sim 2.3\ 10^{13}\ m^{-3}$ at t = 12 ms.

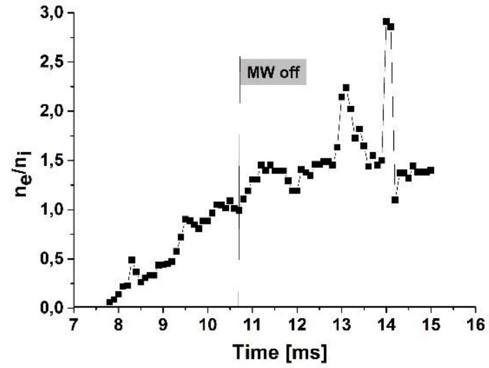


Fig. 5. Ratio of the electron and ion densities determined from data processing of Megi. The ion density saturation is calculated by formula (2)

We observe a quite reasonable agreement ($n_e \sim n_i$) after t = 10.8 ms, when the MW power is already switched off. However, $n_i \ll n_e$ during the time period, when the ECR occurs inside the tokamak vessel. This may indicate that the formula (2) is not valid at the microwave heating (Non-Maxwellian plasma?).

More detail analysis of probe data

Let us look on the IV characteristics shown in Fig 1 in more detail.

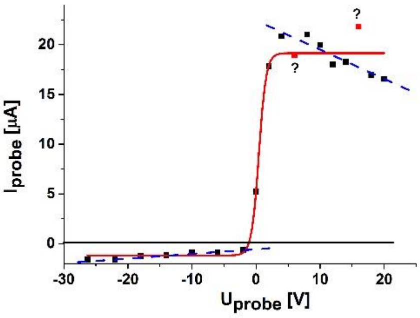


Fig. 5. IV characteristic at t = 12 with emphasized peculiarities.

We can recognize several peculiarities:

Discharges of this shot series are not fully reproducible, as seen from data points at U_{probe} = 6 and 16 V (marked by question marks), which are evidently out of the trend. This unpleasant feature can be avoided in future experiments by measuring the I_{sat} by an additional probe (as the reference one) located in vicinity of the planar probe. The measured data from the planar probe should be normalized to the I_{sat} signal of the reference probe.

It is also seen that electron and ion saturation currents are not constant. The ion saturation current increases with the probe voltage. This is consequence of well - known phenomenon – probe sheath expansion. Figure 6 shows the ion branch of IV characteristics in more detail.

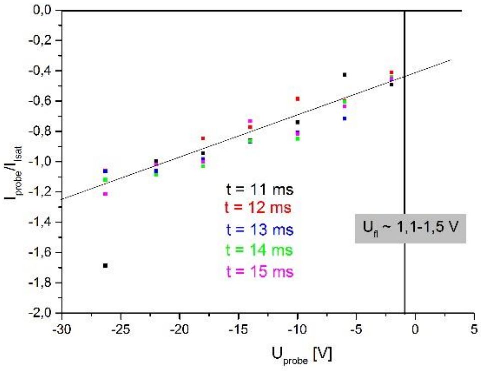
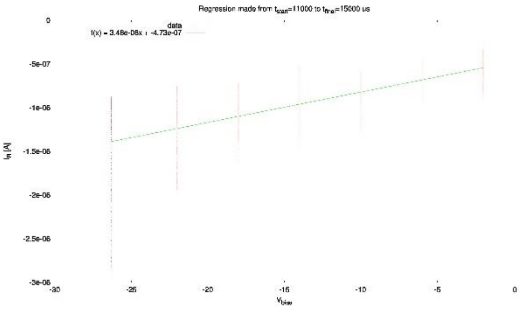


Fig. 6. Ion branch of IV characteristics at t = 12, 13, 14, and 15 ms, normalized to the I_{sat} resulting from the analytic fits.



We see that the ion current depends linearly on the probe voltage. Note that the slope is independent on the magnetic field. To clarify, if the sheath expansion influences processing of the IV characteristics we remove the slope from the raw data by using the linear fit

$$I_{probe} = 3.48\ 10^{-8}\ U_{probe} \qquad [A, V]$$

For all probe data for U_{probe} < 0 V, see figure below.

The sheath expansion is usually observed by cylindrical probes. We have to check, if this phenomenon was already observed in the case of planar probes in magnetized plasmas (Tomaz Gyergek!!).

An example of the raw (red symbols) and corrected (green symbols) IV characteristic is shown in figure below

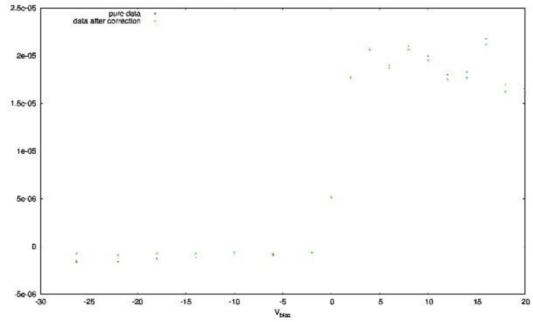


Figure 7 compares several IV characteristics constructed at different time of the discharge, so at different values of the toroidal magnetic field. Characteristics are again normalized to the I_{sat} resulting from the fits.

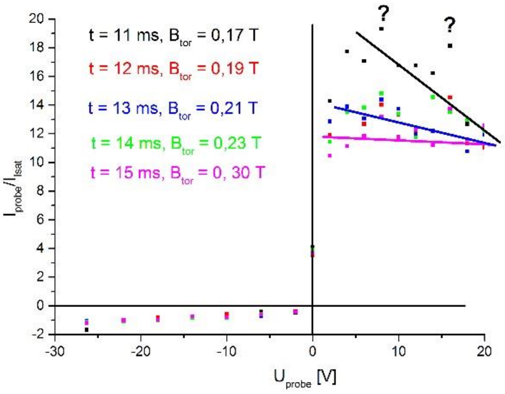


Fig. 7. IV characteristics at t = 12, 13, 14, and 15 ms, normalized to the I_{sat} resulting from the analytic fits. Experimental points marked by ? are evidently out of the trend, probably consequence of non-reproducible discharge.

We see that the electron saturation current decreases when the probe voltage increases. The decrase I_e^{sat} is well pronounced at t = 11 ms (B_{tor} =0.17 T), while the saturation is almost constant at t = 15 ms, i.e. at B_{tor} = 0.3 T. An intermediate case is seen at B_{tor} =0.21 T. We have to search in publications (or ask probe experts), is similar behavior was ever observed. One can speculate that the probe acts as a biasing electrode, which generates the vertical electric field. Consequently, the ExB drift velocity v_{EXB} = E/B removes particles outwards, to the Low Field Side of the torus (check direction!!). In this model, the particle losses are proportional to the probe voltage and inversely proportional to the value of the toroidal magnetic field. This is consistent with experimental result shown in Fig.7. For E = 20 V/0.02 m = 1000 V/m, and B = 0.17 T, the resulting ExB velocity is v_{EXB} = 5900 m/s!! This is a huge value in comparison with other drift losses (B x gradB and curvature drift).

The opposite effect should be observed (an improved confinement), when the orientation of B_{tor} is reversed. We has to check it experimentally.

To avoid above mentioned peculiarities, we corrected experimental data by removing:

- Sheath expansion (as shown above)
- Experimental data for U_{probe} > 10 V

Then, we apply the new fitting according (1) for calculation of plasma parameters. Comparison is shown below.

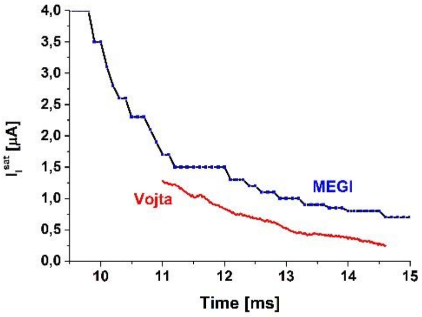


Fig. 8. Comparison of the ion saturation currents determined either from original fits (Megi) or from new fits (Vojta). The difference is significant – by a factor of 2.

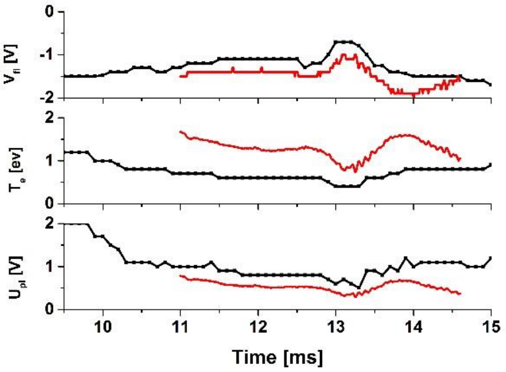


Fig. 8. Comparison of the floating potential, electron temperature, and the plasma potential.

- Original fits (Megi) – black lines
- New fits (Vojta) – red lines.

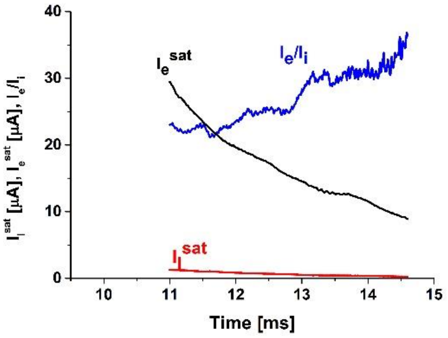


Fig. 9. Electron and ion saturation current and their ratio, as determined from the new fits (Vojta).

This is surprisingly too low value in comparison with the electron density, $n_e = 20 \times n_i$! **This huge difference has to be understood**.

Conclusions and actions

Repeat measurements by using a reference cylindrical tip of the rake probe as a reference to remove the issue of reproducibility. Maybe, not so many shots is required to construct the IV characteristics. The range of probe voltages could be from -15 V to + 10 V. More data should be measured in the exponential part of the IV characteristics, i.e around V_{probe} = -1 V – 6 V

Perform experiment with reversed orientation of the toroidal magnetic field

Appendix

Fitting formula according Azooz is

$$I_{probe} = \exp\left[a_1 \tanh\left(\frac{V_{probe} + a_2}{a_3}\right)\right] + a_4$$

With four fitting parameters a_1, a_2, a_3 and a_4

The ion saturation current is $I_{is} = \exp(-a_1) + a_4$

The electron saturation current is $I_{es} = \exp(a_1) + a_4$

The floating potential is $V_{fl} = a_3 tanh^{-1}[\ln(-a_4)/\, a_1] - a_2$

The plasma potential $V_{pl} = a_3 tanh^{-1}[(\frac{(1+a_1^2)^{\frac{1}{2}}-1}{a_1}\ ] - a_2$