# Characterisation of the WEGA plasma

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## I. Introduction

The WEGA (Wendelstein Experiment in Greifswald für Ausbildung) is a classical stellarator, which serves for studying the fundamental properties of low power density plasmas. Basic tasks of the research program at WEGA are the characterisation of plasma profiles and of plasma confinement.

The WEGA plasma is mainly diagnosed by Langmuir probe measurements. Furthermore, the results obtained by the electrostatic probe are cross-checked with results from an interferometer and a spectrometer.

The WEGA device is presented in section II. Section III. treats the Langmuir probe measurements and the obtained characteristics. The interferometer and spectrometer measurements are described in the following two sections. The last section contains the conclusions.

## II. WEGA machine

The WEGA stellarator has 40 planar toroidal field coils and 4 helical field coils in a $l = 2$, $m = 5$ configuration. Major and minor radius of the vessel are $R = 0.72$ m and $r = 0.19$ m, respectively. $H_2$, He, Ar were used as working gas. The plasma is ignited and heated by ECRH with a maximum power of 6 kW at a frequency of 2.45 GHz and a resonant magnetic field of $B_0 = 87.5$ mT. The heating wave is an O-mode wave. The toroidal magnetic field ($B_t$) was varied in different measurements between 40 – 100 mT, the rotational transform ($\iota_0$) on the axis between 0.1 –0.6 .

## III. Langmuir Probe Measurements

### III.1. Experiment and method

The Langmuir probe is a basic diagnostics tool at the WEGA. It can be used to measure plasma parameters as electron temperature ($T_e$), electron density ($n_e$) and plasma potential ($V_p$) throughout the whole cross-section of the plasma.

The used probes are cylindrical graphite probes and have the following dimensions: $l_1 = 2.5$ mm, $d_1 = 0.9$ mm; $l_2 = 2$ mm, $d_2 = 0.9$ mm and $l_3 = 5$ mm, $d_3 = 5$ mm. There were made some measurements with a double probe, too ($l_4 = 2$ mm, $d_4 = 0.9$ mm).

All current-voltage characteristics show one common feature: the ion current does not saturate. One possible explanation for this is the presence of a fast electron component in the plasma. Stangeby derived a formula for a current collected by a probe in a plasma with a two-temperature Maxwellian distribution of electron energies [1]. Making the assumption that the ion temperature ($T_i$) is much less than $T_e$ - which is an appropriate assumption in the case of WEGA – the expression derived by Stangeby is:

$$I = I^{i}_{sat}\left\{1-\frac{\sqrt{(2m_i)/(\pi m_e)}}{1+f_n}\cdot\left[(1-\sigma_s)\cdot\exp\left(\frac{e(V-V_p)}{kT_{es}}\right)+(1-\sigma_f)\cdot f_n\cdot\sqrt{f_T}\cdot\exp\left(\frac{e(V-V_p)}{kT_{es}f_T}\right)\right]\right\} \tag{1}$$

where: I is the measured current; $I^{i}_{sat}$ is the ion saturation current; $m_{i,e}$ is the mass of an ion and an electron, respectively; $f_n$ is the ratio of density of the slow electron component related to the density of the fast electron component; $f_T$ is the ratio of temperatures of the two electron components; V is the biasing voltage; $\sigma_{s,f}$ is the secondary electron emission coefficient for the slow and fast electrons, respectively; e is the elementary charge; $T_{es}$ is the temperature of the slow electrons.

The characteristics from the WEGA plasma were successfully fitted with this expression. Fig. 1. shows a fitting example.

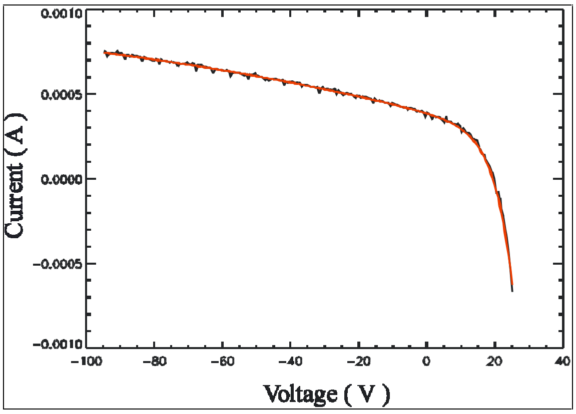

Fig. 1. Typical fit of a measured characteristic: black line – experimental data; red line – fit.

From such a fit we can obtain five parameters: $T_{es}$ , $I^{i}_{sat}$ , $V_p$, $f_n$ and $f_T$. Finally the temperature of the fast electrons can be calculated by mutiplying $T_{es}$ by $f_T$ and $n_e$ can be determined from expression (2):

$$I^{i}_{sat} = \frac{1}{2}\cdot n_{i0}\cdot c_s\cdot A \tag{2}$$

where $n_{i0}$ is the ion or electron density of the plasma far away from the probe, $c_s$ is the ion acoustic velocity and A is the collecting probe area.

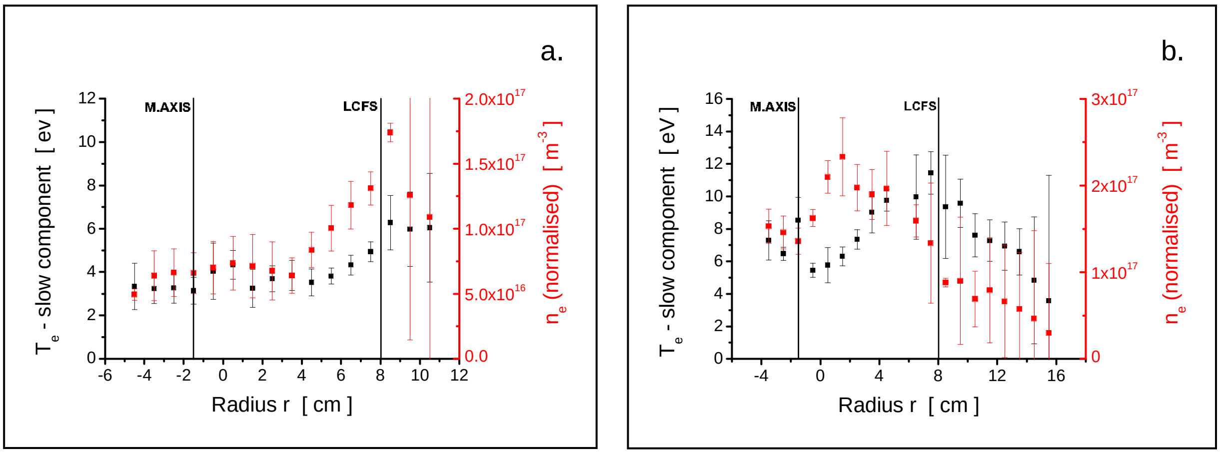

Fig. 2. $T_e$ , $n_e$ profiles in the case of the 90° antenna: a. first harmonic heating; b. Second harmonic heating.

### III.2. Results

During an optimisation process of the plasma heating we made measurements in plasmas generated by different types of microwave antennas. At the beginning the antenna was a metallic cylinder emitting the heating wave perpendicularly to the magnetic field lines (90° antenna). Heating the plasma with first harmonic heating ($B_t = 1.0 \times B_0$) we obtained hollow profiles of $T_e$ and $n_e$ with maxima outside the last closed flux surface (LCFS) (Fig. 2.a). The maximum density was above the cut-off density ($7.5 \times 10^{16}$ $m^{-3}$). Using second harmonic heating ($B_t = 0.5 \times B_0$) the maxima of the profiles moved inside the LCFS (Fig. 2.b).

Later the antenna tube was cut under an angle of 45° (45° antenna). In this case the $n_e$ profile became flat or peaked and the $T_e$ profile just slightly hollow (Fig. 3.a). The achieved maximum densities were more than a factor of 10 above the cut-off density. The last step was to use a round antenna which has two slots on opposite sides of the antenna (two-slot cylindrical antenna). The density profiles again were peaked or flat, the temperature profiles slightly hollow (Fig. 3.b). With this antenna we obtained even higher density values than with the 45° version. For details of the antenna see [3].

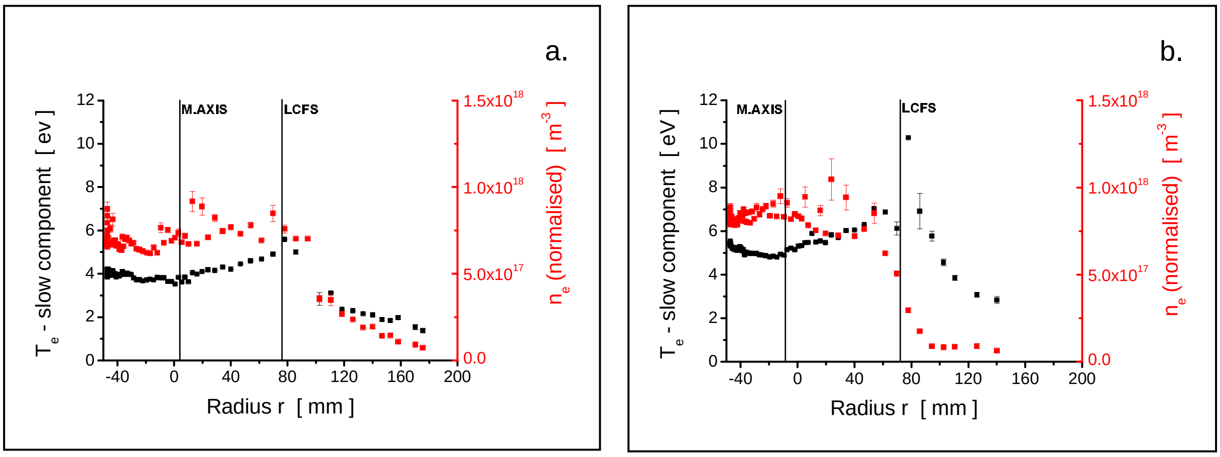

Fig. 3. $n_e$ , $T_e$ plotted versus minor radius in the case of: a. 45° antenna; b. Two-slot cylindrical antenna.

## IV. Interferometry

The average electron density is measured by a Mach-Zehnder type, single channel microwave interferometer. The probing wave is an O-mode wave with a frequency of 80.605 GHz. Thus the critical density is $8 \times 10^{19}$ $m^{-3}$ . The phase resolution is 0.1°, so the line density resolution is $1.66 \times 10^{14}$ $m^{-2}$. The interferometer has a vertical line of sight through the centre of the torus.

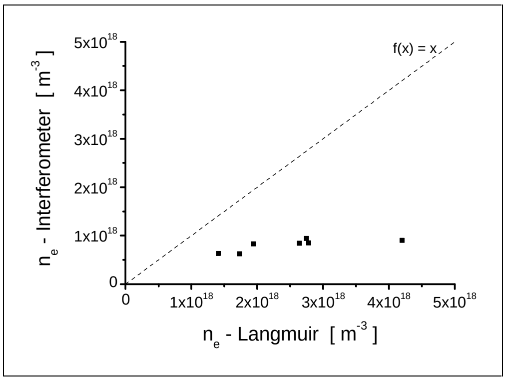

Fig. 4. Comparison between average electron density values obtained from interferometry and Langmuir probe measurements.

In Fig. 4. the $n_e$ values measured by the interferometer are plotted versus the Langmuir probe data. The results from the probe are higher than the results from the interferometer.

## V. Spectroscopy

Another way to measure electron density ($n_e$) and temperature ($T_e$) is to use optical spectroscopy. In the case of WEGA the average $n_e$ , $T_e$ values were obtained with the help of an Echelle spectrometer, which is able to detect simultaneously a spectral range of 200-780 nm. $n_e$ was determined by the line intensity ratio technique [2], $T_e$ was calculated from absolute intensities. In the case of $H_2$ gas the gas temperature ($T_{gas}$) was determined from the rotational temperature of the molecule (Fulcher spectrum).

The plasma parameter values measured with the spectrometer are compared in Fig 5. to results obtained from electrostatic probe measurements. The probe gives higher values for $n_e$ and $T_e$ than the spectrometer.

$T_{gas}$ is around 500 K for $H_2$ gas.

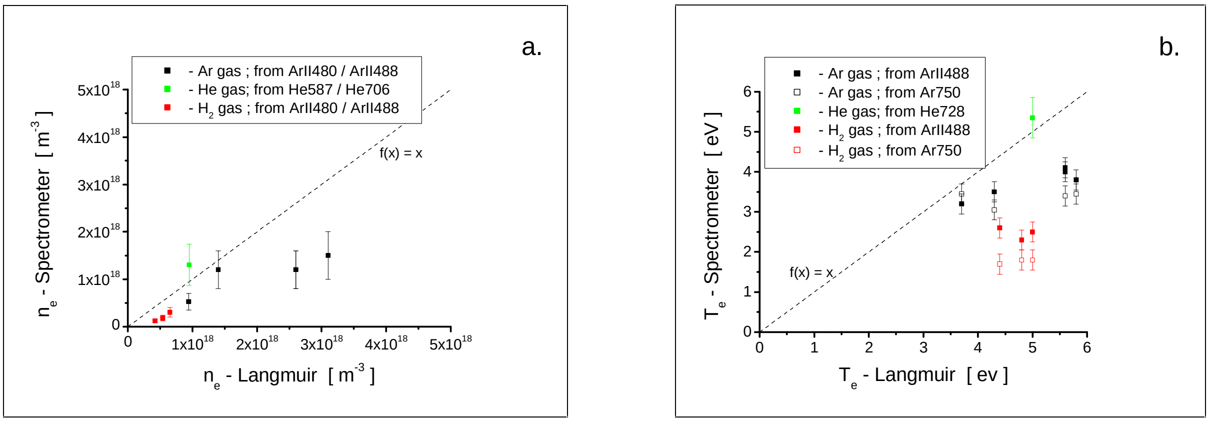

Fig. 5. a. $n_e$ values obtained from spectroscopy versus $n_e$ from Langmuir probe measurements; b. The same comparison for $T_e$ values.

## VI. Conclusions

The WEGA plasma has been diagnosed by three different diagnostics. The Langmuir probe gives higher $n_e$ values than the interferometer and spectrometer. Given the uncertainties in the knowledge of the collecting probe area, the interferometer is believed to be more accurate than the Langmuir probe as regards absolute values of density. In the same time the electrostatic probe measures whole profiles of densities. Thus the electron density profiles resulted from the Langmuir measurements have to be normalised to the interferometer data. $T_e$ values obtained from probe measurements are higher than the spectrometer $T_e$ values. The reason for this is still under investigation.

We made measurements using different type of microwave antennas. It was observed that by launching the heating wave perpendicularly to the magnetic field the heating power is absorbed mostly outside the LCFS. Changing the launch direction of the wave the profiles become peaked, flat or just slightly hollow, what shows that in this case more power is absorbed in the plasma centre. Possibly this is caused by the OXB process [3].

During the optimisation process of the heating an improvement in the plasma confinement can be observed: the estimated confined energy is increased from ~0.025 J to ~0.3 J, the confinement time from ~0.005 ms to ~0.1 ms, ionisation degree from ~0.5 % to ~80 % and $\beta$ from ~$2 \times 10^{-5}$ to ~$8 \times 10^{-4}$.

**References:**

1. P.C. Stangeby, Plasma Phys. Control. Fusion 37, p. 1031 (1995);
2. M. Brix, Berichte des Forschungszentrums Jülich, 3638 (1998);
3. Y. Podoba et al., P.Mo27.