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Investigation of properties of the WEGA plasmas

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I. Introduction

The WEGA stellarator is a classical stellarator originally built in Grenoble (France). The machine is used since 2001 in Greifswald for educational training, testing of new diagnostics and basic plasma research.

The main goal of the work being presented in this paper is the characterisation of WEGA plasmas - that means low-temperature, but overdense, toroidally confined plasmas - and to determine the optimum discharge conditions. Overdense here means that the electron density (n_e) values measured in the WEGA plasmas are above the cut-off density of the heating microwave (7.45×10^{16} m^{-3}).

The technical parameters of the WEGA device are presented in [1]. The basic diagnostics and data processing methods involved in this work are described in Section II. of this paper. Section III. and IV. contain information about the magnetic and energy confinement of WEGA plasmas. The last section is a summary of the results.

II. Basic diagnostics

The main diagnostics at the WEGA is the electrostatic (Langmuir) probe. Because the WEGA plasmas have a low power density, the probe can be used throughout the whole cross-section of the torus to measure electron density (n_e), temperature (T_e) and plasma potential (V_p). The two other diagnostics which will be presented are the microwave interferometer and the optical spectrometer.

1. Langmuir probes

Single cylindrical graphite probes were used for profile measurements. Usually the dimensions of the probe were: $l = 2$ mm and $\varnothing = 0.9$ mm, but some measurements with a larger probe were made, too ($l = 4.8$ mm, $\varnothing = 5$ mm).

The measured current-voltage characteristics showed a common feature: the non-saturation of the ion current (Fig.1.a). Some possible reasons for this anomaly could be eliminated on theoretical or experimental grounds [2], but one possible cause remained: The shape of the plot of the natural logarithm of the electron current divided by the ion saturation current indicates that a two-temperature distribution of electron energies can be the reason for the non-saturation of the ion current (Fig.1.b). In order to determine the plasma parameters from the measured data the characteristics has been fitted with a formula proposed by P. Stangeby [3] assuming a two-temperature Maxwellian distribution:

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

where: I is the measured current; I^{i}_{sat} is the ion saturation current; $m_{i,e}$ is the ion/electron mass; $f_{n,T}$ are the ratios of density and temperature of the slow electron component related to the fast electron component; 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. $\sigma_{s,f}$ were assumed to be 0. Figure 1.a shows an example of the fit results. Usual values of parameters determined in this way are: $3\ \mathrm{eV} < T_{es} < 12\ \mathrm{eV}$; $1 \times 10^{17}\ \mathrm{m}^{-3} < n_e < 5 \times 10^{18}\ \mathrm{m}^{-3}$; $15\ \mathrm{V} < V_p < 60\ \mathrm{V}$; $20\ \mathrm{eV} < T_{ef} < 400\ \mathrm{eV}$; $f_n < 5\ \%$.

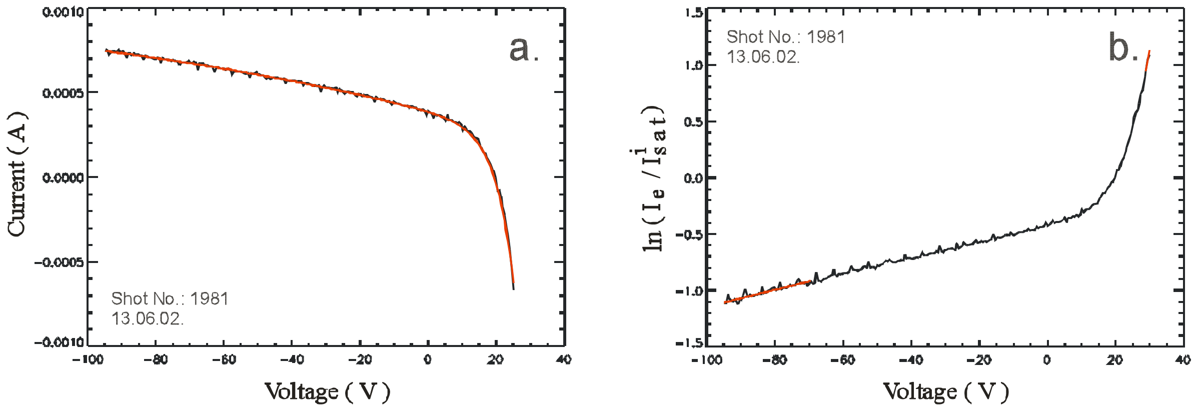

Fig.1. a. Typical I-V characteristic measured in a WEGA plasma. The red line is the fit of the characteristic with (1). b. Plot of $\ln(I_e / I^{i}_{sat})$ *versus V indicating a two-temperature electron distribution.*

The obtained electron density values were compared with the interferometer and spectrometer data. The probe gives to high n_e values, but the overestimation of n_e can be explained with the possible violation of some assumptions in the probe model: i. $T_i << T_e$ (T_i – ion temperature); ii. singly charged ions. Also the large ion Larmor radius compared to the probe radius can be a cause of too high n_e values. Therefore the electron density values measured by the Langmuir probe are calibrated with those from the interferometer measurements.

2. Interferometry

At WEGA a single-channel Mach-Zehnder type interferometer is installed. The probing O-mode wave has a frequency of 80.605 GHz. The line of sight is vertical and points approximately through the centre of the vessel.

A common method for interferometer data evaluation is to determine the average n_e value in the magnetically confined plasma region by dividing the measured line integrated n_e with the path length of the wave inside the LCFS (last closed flux surface), because usually n_e outside LCFS is negligible. In the case of WEGA plasmas this assumption does not hold. Hence we could obtain only the average n_e value along the whole minor diameter of the vessel by dividing the line integrated n_e with the diameter of the torus.

3. Spectroscopy

An Echelle spectrometer is installed at the WEGA, which is able to detect simultaneously a spectral range of 200 to 780 nm. The method used for determination of n_e is the line intensity ratio technique [4]. The principle of this technique is to compare the intensity ratios of certain lines with results of model calculations. Theoretical calculations show that some line intensity ratios have a strong dependence on n_e and depend just weakly on T_e. At WEGA the following pairs of lines were used for n_e determination: ArII 480.6 nm, ArII 480 nm and HeI 667.8 nm, HeI 728.1 nm. T_e is calculated from measured absolute intensities [4].

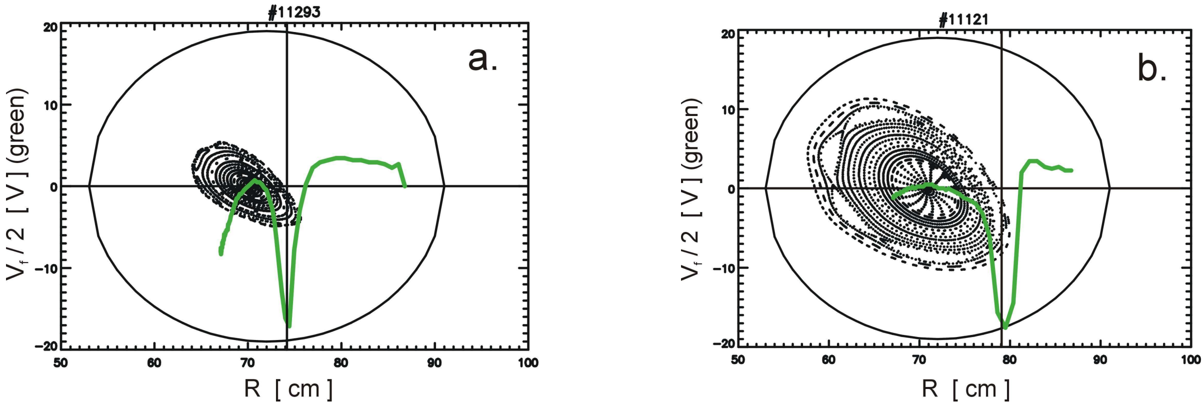

Fig.2. Flux surface plots and V_f profiles (green) in the case of : a. separatrix plasma, b. limiter plasma (the limiter is the heating antenna).

III. Magnetic confinement

The measured parameter profiles were compared to calculated flux surface configurations. Figure 2. shows the flux surface plot and the overlaid floating potential (V_f) profile in the case of a small separatrix plasma and a limiter plasma. The minima of the V_f profile always are at the same radial coordinate as the LCFS. The position of the LCFS is also indicated by the highest gradient of the pressure profiles.

IV. Energy confinement

To calculate the confined energy (W) we proceeded as follows: The pressure profiles were transformed from the geometrical to a magnetic coordinate system. The confined energy is the volume integral of the pressure inside the LCFS. If the pressure depends only on the radial magnetic coordinate – what is assumed – the volume integral of the pressure can be written as:

$$W = \int_V p dV = 4\pi^2 R \int r_{eff}\, p(r_{eff}) dr_{eff} \tag{2}$$

Here R is the major radius of the vessel, p is the pressure of ions and electrons and r_{eff} is the radial magnetic coordinate. The obtained W values are below 1 J.

The energy outside the confined plasma region (W_{out}) was calculated with the same formula, but in this case the line integration was performed over a distance which is an average of the distances between the LCFS and the wall. To do this it was assumed that the pressure decreases uniformly outside the LCFS: independently on the direction in the poloidal plane. It was found that $10\% \times W < W_{out} < 75\% \times W$.

The energy confinement time (τ_E) is the ratio: W / P_{abs}, where P_{abs} is the power absorbed in the confined plasma. Since the value of P_{abs} is not known, instead of it the total heating power (P_{mw}) was taken, which is an upper limit. Therefore τ_E is underestimated: $\tau_E < 0.5$ ms.

V. Summary

The plasma parameters used in the characterisation of WEGA plasmas are taken mainly from Langmuir probe measurements. The non-saturation of ion current can be explained only with a two-temperature electron energy distribution. The interferometer and spectrometer are used for testing of probe data and calibration of them.

The shape of the measured profiles yields an evidence for magnetic confinement of plasmas.

The calculated τ_E values are very small compared to the predictions of the ISS95 scaling: $10 < \tau_{ISS95} / \tau_E < 80$. A possible explanation of this is that just a part of the input power is absorbed in the plasma centre. Hence in calculation of τ_E taking P_{mw} instead of P_{abs} the resulted value will be an underestimation.

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