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Electron Heating and Plasma Production in Helicon Plasma

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1. Introduction

Time-resolved emission and absorption spectroscopy in combination with Langmuir probe diagnostics and 4 mm interferometry was applied on a pulsed helicon discharge to investigate electron heating due to helicon wave absorption on a helicon source. Among the various absorption mechanisms we favour anomalous absorption due to parametric excitation of small-scale fluctuations [1] as compared to collisional absorption. Resonant absorption (wave-electron resonance) is also not likely to play a role as was verified by time-resolved ArII line emission measurements revealing no modulation with the helicon phase.

2. Experimental

The investigations were carried out on the helicon source HE-L (r_p = 73 mm, l_p = 1.1 m, τ_{pulse} = 2 – 4 ms, f_{pulse} = 25 – 100 Hz, $P_{RF} < 2$ kW, f_{rf} = 13.56 MHz, m = 1 helical antenna coupling, $n_e < 2 \times 10^{19}$ m^{-3}, $T_e \approx 3$ eV, $B_0 < 0.1$ T, p = 0.2 – 0.5 Pa argon gas [2]). Absorption and emission spectroscopy was used to determine the evolution of the electron temperature (Fig. 2a). In both cases, we applied a collisional-radiative (CR) model to evaluate the spectroscopic data assuming a Maxwellian EEDF. From the measured density of the $^3P_0$ metastable argon atoms as well as the electron and gas densities we deduced the electron temperature.

3. Results

Fig. 1a shows the temporal evolution of the ion saturation current and ArI line intensity. After 0.5 ms there is a sharp peak of both quantities over the whole radius. After that, the electron density increases till 1.5 ms and stays then nearly constant: Simultaneously the helicon wavelength (see Fig.5) and damping length decrease so that the location of plasma heating and production shifts to the antenna. In contrast, the line intensity steadily increases after the first peak as the electron temperature increases slightly due to heating and rarefaction of the gas.- In the nearly stationary stage of the helicon discharge, we achieved good agreement between the electron temperatures obtained from the absorption spectroscopy measurements and those deduced from the ratio of the Ar763 and Ar750 line intensities on the axis (Fig. 2). The values correspond to those obtained from Langmuir probes. Note that application of the stationary CR model requires $n_e < 5 \cdot 10^{17}$ m^{-3} so that T_e can only be determined for $t > 0.5$ ms.

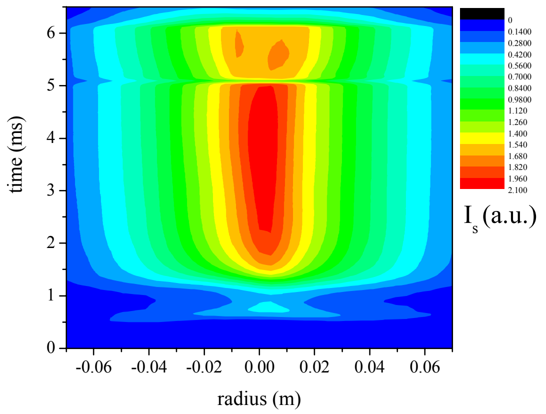

Fig.1a: local measurements of ion saturation current in the main and second pulse over the radius 0.5 m from the antenna centre

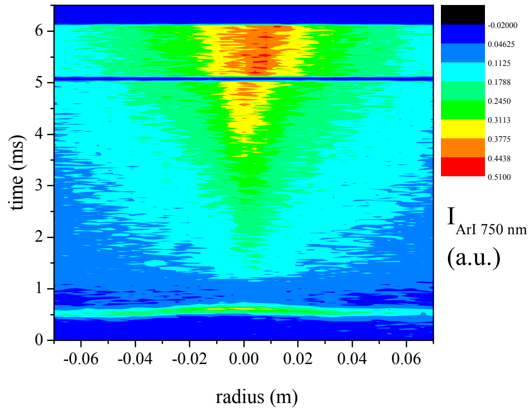

Fig.1b: local intensity of ArI 750 nm line in the main and second pulse (B= 40.5 mT, P = 0.6 Pa, delay 40 µs, P_{rf} = 1.4 kW)

To study electron heating we applied a *double pulse* technique, i.e., a high-power pulse (P_{rf} ≈ 1 kW) producing the helicon plasma was followed by a second pulse of variable *rf* power with a delay of 20 - 40 µs (Fig. 3a). We thus provided a *target* plasma of low temperature, but nearly unchanged electron density at the beginning of the second pulse. After the target pulse T_e drops to values below 2 eV, and the argon line emission decreases as well. The line intensity and, thus, the electron temperature rises about 1-2 µs after the beginning of the second pulse independently of the *rf* power and reaches a stationary value after about 15 µs. For *rf* powers below 200 W the signal is too small to see an increase of intensity. The intensities of the ion line start to increase with a delay of 0.5 - 1 µs. This observation proves that the electrons are first heated in the bulk of the EEDF until energetic electrons with energies above 20 eV are produced via thermalisation. The spectroscopic results fit reasonably with the probe measurements.

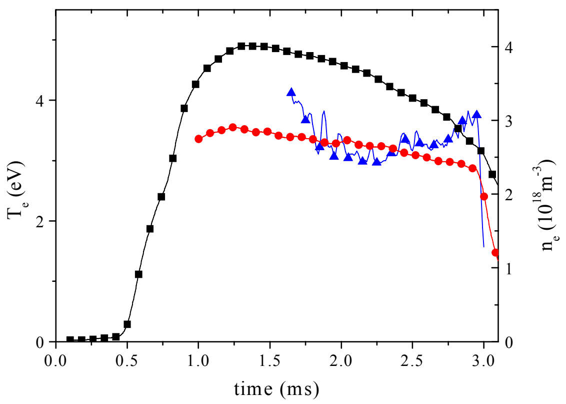

Fig.2a: Electron density and electron temperature determined from metastable density ($^3P_0$ niveau)

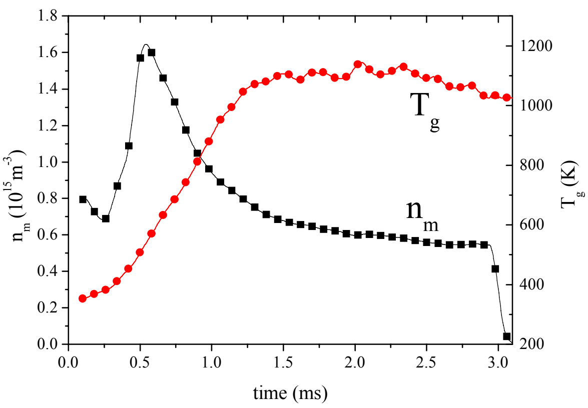

Fig.2b: $^3P_0$ density and gas temperature determined from Doppler absorption profile (B = 40.5 mT, P = 0,3 Pa, L = 1.4 kW)

Apart from the CR model for argon we developed a model for helium that takes account of 19 niveaus. Thus, we are able to determine the electron temperature from the line ratio of two nearby argon and helium lines (no calibration necessary!). These measurements were also best evaluated by assuming a Maxwellian EEDF (Fig. 3b). The measured rise time of the electron temperature T_e (measure of electron heating) is in accordance with the energy balance equation if we account of the measured *rf* power absorption (deduced from the helicon wave damping decrement), the peaked density profiles, the power P_{rf} deposited in the plasma core and the length of the discharge [3].

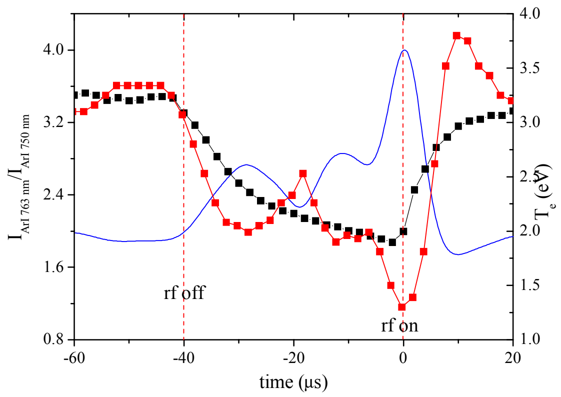

Fig.3a: Ratio of Ar 763 nm and Ar 750 nm line intensities and electron temperature in the afterglow and the second pulse; for comparison, T_e from probe measurements.

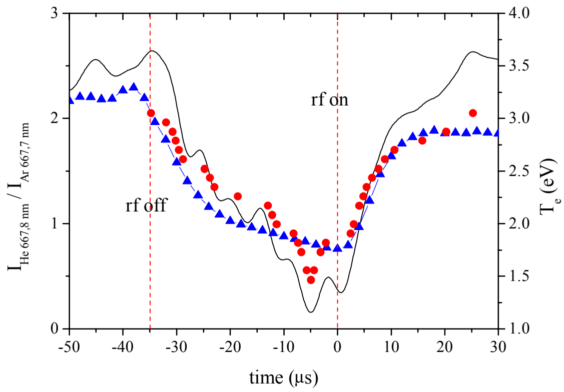

Fig.3b: Ratio of He 667,8 nm and Ar 667,7 nm line intensities and electron temperature in the afterglow and the second pulse.

In Fig.4a we compare the ratio of the ArII and ArI line intensities in the second *rf* pulse obtained from local (optical fiber probe on axis) and diameter-integrated measurements. For the ArI 750,4 nm line emission (T_g =1000 K, p = 0.3 Pa) we used again the CR model, while for the ArII 480.6 nm line only excitation from the ground level was taken into account.

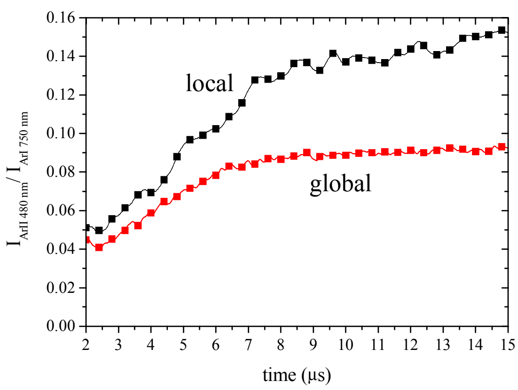

Fig.4a Local (optical fiber probe on axis) and diameter-inegrated measurements of ratio of ArII and ArI line intensities in second rf pulse (delay 40 μs, P_{rf} = 1.4 kW).

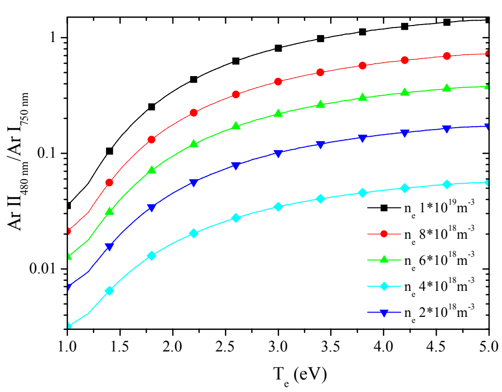

Fig.4b: Calculated Ratio of of ArII 480,6 nm and ArI 750,4 nm line intensities (Tg = 1000K, P = 0.3 Pa).

To clarify whether or not resonant electron heating plays a role in our helicon discharge we also performed time-resolved emission spectroscopy measurements on the time-scale of the *rf* fields. In several experiments ([4,5]) strong modulation of the ArII emission with the local helicon wave period was observed. This finding is explained by fast non-Maxwellian electrons accelerated by the wave field. For excitation of the argon ion lines the parallel helicon wavelength should be longer than about 20 cm (threshold energy for excitation of the Ar^+ niveau ≅ 20 eV) while for ionisation $\lambda_z = 17$ cm is sufficient ($E \cong m_e(f_0\lambda_z)^2/2$). Due to the increasing density in the first stage of the helicon discharge λ_z decreases simultaneously. Modulation effects are expected in the time interval 0.8 – 0.9 ms (Fig.5a). However, no significant modulation of the ArII intensity over one *rf* period was observed (two spectroscopic measurements over 4000 pulses under the same parameters shown in Fig.5b).

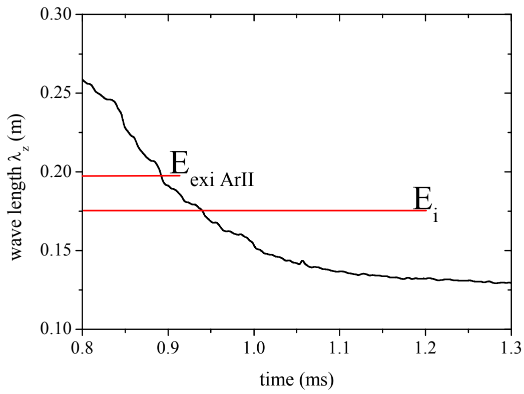

Fig.5a: Variation of the helicon wave length in the beginning of the plasma pulse

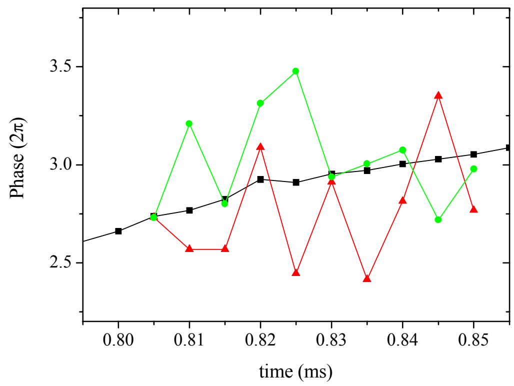

Fig.5b: Phase from modulation of ArII emission and B_z phase from B-dot probe

4. Conclusions

Various spectroscopic methods were applied to measure the temporal evolution of the electron temperature. All observations on our helicon source are best described by a Maxwellian energy distribution function. At least in the range of higher densities, the electrons are thus heated in the bulk of the EEDF (most likely via parametric excitation of short electrostatic fluctuations [1]). In particular, no modulation of the ArII line emission was observed so that resonant electron heating can be excluded or it plays only a minor role in our helicon discharge.

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References

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