Argon ion velocity distributions in a helicon discharge measured by laser induced fluorescence

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Abstract. A Helicon discharge in argon at low gas pressure of 0.1 Pa is generated with a flat coil antenna operated with 13.56 MHz. The power coupled into the discharge is around 1 kW which leads to an electron density of $10^{12}$ cm$^{-3}$. The velocity and temperature of the argon ions is measured by laser induced fluorescence (LIF) spatially resolved in radial and axial direction. Ambipolar diffusion accelerates the ions out of the heating region of the discharge with velocities up to 800 m/s. Due to homogenisation of the kinetic energy, the ion temperature increases from 0.15 eV in the centre to 0.4 eV at the edge of the plasma volume.

1. Introduction
Helicon discharges are driven by right-hand circularly polarised Whistler waves in bounded systems. An overview of physics and applications may be found in [1, 2]. The wave propagates along a static magnetic field of ten to 100 mT. Much higher plasma densities can be achieved with helicon discharges compared to other kinds of radio-frequency (RF) discharges operated with similar power densities. The neutral gas pressure is fairly low which makes helicons interesting for many kinds of applications. Although there are a lot of research activities on helicon discharges, the power coupling mechanism is still under discussion [2, 3, 4]. Here measurements of the argon ion velocity are performed in order to obtain the velocity profiles radially and axially resolved. Similar measurements have been performed before [5, 6] but not yet in this kind of flat coil helicon discharge.

2. Experiment

2.1. Helicon discharge
The plasma generating wave is launched by the induced electric field of a flat coil antenna [7, 8]. Details of the setup are described in [9]. Langmuir-probe measurements of the plasma density and B-dot measurements of the wave field will be described in [10]. A scheme of the setup is shown in figure 1. The chamber is 50 cm high with a diameter between 35 and 50 cm. The antenna has a diameter of 20 cm and is separated from the discharge volume by a quartz jar. A solenoid is located 13 cm below the antenna outside the vessel and can provide a magnetic field of up to 30 mT. The antenna is powered by a 2 kW RF power supply at 13.56 MHz. With no current through the solenoid, the discharge is operated as a standard inductive discharge. With a magnetic field, a helicon discharge requires that the longitudinal wave vector $k_l$ fulfills the condition $k_lL = m\pi$, with $L = 0.53$ m being the length of the field lines between the antenna and the bottom and $m$ being an integer.
With the assumption, that the electron density scales linear with the power $P$ and the electron cyclotron frequency $\omega_c$ scales linearly with the magnetic field and therefore the current through the coil $I$, the following relation holds:

$$k_r \sqrt{k_r^2 + k_r^2} \propto \omega_c^2/\omega_c^2 \propto P/I \ [9],$$

with $k_r$ being the radial wave number. This means that only discrete ratios of power to magnetic field lead to a helicon mode of the discharge instead of a magnetised inductive discharge. Typical operation conditions are DC currents of 52 A providing a magnetic field of 9 mT in the plane of the coil and an RF power of 1 – 2 kW. The plasma density is a few $10^{12}$ cm$^{-3}$, measured with a Langmuir-probe [10]. In addition, B-dot probe measurements have been performed to determine the electromagnetic field of the helicon wave. An analytical model which contains Landau and collisional damping confirms these measurements indicating that these are the dominating coupling processes of the wave to the plasma [10]. The helicon is operated in the azimuthally homogeneous $m = 0$ mode.

2.2. Laser induced fluorescence setup

The spectroscopic scheme shown in figure 2 is used to excite metastable argon ions with photons of 661.5 nm and observe the fluorescence at 459 nm. The laser system used is a 20 Hz frequency doubled Nd:YAG laser with 8 ns pulse length, pumping a narrow band dye laser (figure 3). The bandwidth of the dye laser radiation is 1.0 pm and the pulse energy is around 5 mJ. The laser beam is split into two parts, one beam is send from the bottom to the top of the discharge chamber in the radial centre allowing for axially resolved measurements, the other one is spread to a sheet of 5 cm height by a cylindrical telescope and then passing radially through the plasma. In order to avoid saturation the intensity is reduced to 15 W/cm$^2$. Perpendicular to both beams an intensified CCD camera observes the fluorescence (figure 1) providing spatial resolution. The strong background emission is suppressed by an interference filter together with gating the camera synchronously to the laser pulses.

3. Experimental results

3.1. Radial measurements

LIF spectra are obtained by accumulating the fluorescence of typically 100 laser pulses at each
Figure 4. Fluorescence spectra at different radial positions. $P = 1500$ W, $p = 0.1$ Pa argon and 52 A coil current.

Figure 5. Radial velocity profiles. $p = 0.1$ Pa argon, 52 A coil current. Negative positions correspond to the left side of the axis in figure 1.

wavelength. From the series of pictures, spectra at different spatial positions are generated (figure 4). Gaussian profiles are fitted to the measurement to obtain the temperature from the Doppler width:

$$k_B T_i = \frac{m c^2}{8 \ln 2} \frac{\Delta \lambda_{\text{FWHM}}}{\lambda_0}$$

and the drift velocity $v$ from the shift of the distribution:

$$v = c \frac{\Delta \lambda}{\lambda_0}.$$  

Here $m$ is the ion mass, $\Delta \lambda_{\text{FWHM}}$ the full width at half maximum of the spectrum, $\lambda_0$ the unchanged wavelength of the transition and $\Delta \lambda$ the shift of the central wavelength due to a drift. A clear shift of the ions is observable. Due to radial symmetry, the spectra in the centre are assumed to be unshifted, marking the spectrally unchanged transition $\lambda_0$. With this assumption, outward directed drifts with velocities of 500 – 800 m/s are observed. This drift is assumed to be caused by ambipolar diffusion since the discharge is operated in the $m = 0$ mode so the plasma generation is mainly concentrated on the axis given by the static magnetic field. Due to thermalisation the ion temperature increases from 0.24 eV in the centre to 0.3 eV 7.5 cm outside the radial centre.

Figure 5 shows radial velocity profiles taken in the axial centre at different RF powers for the helicon and in case of 1750 W for the inductive discharge. From 1000 W to 1500 W a strong increase in the measured velocities is observed while the profile at 1750 W stays more or less the same. This indicates that the condition of standing waves might not be perfectly fulfilled so it is no longer a pure helicon. The profile belonging to the ICP is clearly below the helicon ones, caused by the different power coupling. While the helicon is excited along the whole discharge length the ICP is generated only close to the antenna and after a few cm the electromagnetic field is strongly damped.

3.2. Axial measurements

With the laser passing along the axis from the bottom to the top, also a change of the line profiles is observed. In figure 6 three spectra are shown, all taken in the radial centre but at different axial positions: in the axial centre (0 cm), 6.8 cm and 13.5 cm below this centre. Again a shift and broadening is observed, the corresponding values are given in the legend. Assuming that the plasma is radially homogeneous in the centre the axial drift can be described in a one dimensional way by ambipolar diffusion which leads to a velocity $u$ of the ions out of the axial centre given by [11]:

$$u = \frac{q B}{m c} \frac{\Delta \lambda}{\lambda_0}.$$
\[ u = u_0 \tan(kz) \quad \text{with} \quad u_0 = \sqrt{D_a \nu_{iz}} \quad \text{and} \quad k = \frac{\nu_{iz}}{D_a}, \]

with \( D_a \) the ambipolar diffusion coefficient and \( \nu_{iz} \) the ionisation frequency of the electrons.

In figure 7 the ion temperature and velocities are shown with increasing distance to the centre. A tangent function is fitted to the measured velocities as described before and from the fit \( u_0 \) and \( k \) are obtained. From these values the ambipolar diffusion coefficient and the electron ionisation frequency are determined to be: \( D_a = 21 \text{ m}^2/\text{s} \) and \( \nu_{iz} = 1300 \text{ s}^{-1} \) respectively.

Conclusions

Ion drifts and temperatures in a helicon \( m = 0 \) mode discharge have been measured. A strong radial acceleration and weaker axial acceleration is observed. Parallel to the gain in drift velocity also a substantial increase in temperature occurs. The axial drift profiles agree well with a one-dimensional ambipolar diffusion model.

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