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Ion mass spectrometry in a magnetized plasma

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Introduction

The direct identification of all ions present in a plasma is a valuable qualification of its properties. Such information is particularly needed to verify collisional radiative models, understanding the interchange processes of isotopes, and may play a role in the evaluation of other diagnostics such as Langmuir probe characteristics.

A mass spectrometer for magnetized plasmas (MSMP-02) [1] was installed at the linear plasma device PSI-2 [2]. The MSMP-02 is a static 180° magnetic mass-spectrometer which uses the intrinsic magnetic field for mass-to-charge separation of plasma ions. This allowed for the first time to measure relative densities of various ions in the PSI-2 plasma with good spatial resolution. Due to the large heat flux in case of high current discharges only scans over the boundary region of the plasma can be investigated, but for moderate discharge currents half of the plasma cross-section can be measured.

To our knowledge there are only two competing diagnostics which can stand similar plasma conditions: the omegatron mass spectrometer [3] and the plasma ion mass spectrometer (PIMS) [4]. The omegatron is driven by RF and the PIMS also uses an electric field to produce an $\vec{E} \times \vec{B}$ drift.

Experimental Setup

Plasma Generator PSI-2

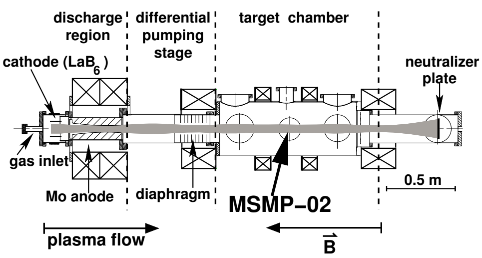

Figure 1: Plasma Generator PSI-2

PSI-2 is a linear plasma device with a stationary arc discharge. A steady discharge current in the range of 20 to about 500 A can be chosen. The plasma is produced in the discharge region which consists of a heated, hollow, cylindrical LaB_6-cathode and a cylindrically-shaped Mo-anode. This leads to a hollow profile in electron density and temperature. Guided by an axial magnetic field the plasma streams with a typical cross-section of 60 mm through a differential pumping system and a so called target chamber until it is terminated at a neutralizer plate (cf. Fig. 1). The MSMP-02 was mounted in the target chamber at a position where the magnetic field provides optimum homogeneity. The vacuum is sustained by up to eight turbo molecular pumps. Parameters prevailing during this work are: $I_{\mathrm{AC}} = 50\ldots260$ A, $B = 0.1$ T, $n_{\mathrm{e}} = 1\ldots5\cdot10^{18}$ m^{-3}, $T_{\mathrm{e}} = 2\ldots15$ eV, $T_{\mathrm{i}} = 0.5\ldots0.7\ T_{\mathrm{e}}$, $p_{\mathrm{neutral}} \approx 0.05$ Pa.

Mass Spectrometer MSMP-02

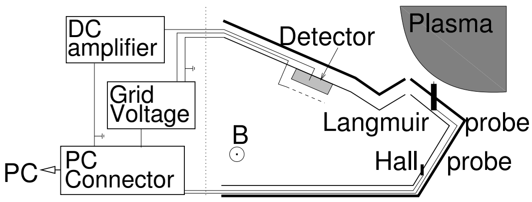

Figure 2: Scheme of the MSMP-02

The MSMP-02 uses the intrinsic B-field of the PSI-2 and an additional E-field to separate the ions. There is no distortion of the applied B-field. However, the range of the magnetic field strength is limited. The ions gyrate on radii typically in the range of 1 cm in the PSI-2. After passing the entrance slit (8×0.2 mm^2) of the measuring head, the ions are accelerated by the applied electric field between the inner and outer shell of the measuring head (cf. Fig. 2). The energy of the ion, and therefore its gyration radius r_{g} is changed by this acceleration process:

$$\frac{M}{2}v_{\perp}^2 = q(U+U_{\mathrm{Pl}}) \tag{1}$$

$$r_{\mathrm{g}} = \frac{Mv_{\perp}}{qB} \tag{2}$$

$$r_{\mathrm{g}} = \frac{1}{B}\sqrt{\frac{M}{q}}\sqrt{2(U+U_{\mathrm{Pl}})} \tag{3}$$

$$\Rightarrow \left(\frac{M}{Z}\right)_{\mathrm{i}} = \frac{r^2\cdot e}{2}\cdot\frac{B^2}{U_{\mathrm{i}}+U_{\mathrm{Pl}}} \tag{4}$$

where is U_{Pl} the plasma potential at the position of the slit, U is the applied voltage, r is the detector radius, e is the elementary charge, M, v, and Z are the mass, velocity, and charge of the ion. The subscript i denotes the values for the i-th peak in the spectrum which is obtained by varying the voltage U and recording the detector current.

In addition the MSMP-02 is equipped with a Langmuir probe located on the same magnetic field line as the entrance slit. This offers the possibility to diagnose electron temperature, density, and plasma potential at the same position. Measurement of magnetic field strength is provided by an InSb Hall probe located inside the measuring head. To ensure an operation in the bulk of the plasma the head is water cooled and its temperature is measured by a thermocouple.

Mass resolution from $\frac{\Delta M}{M} = 2\ldots6\%$ were experimentally found for masses ranging from $M = 1$ to 40 a.m.u.. This is sufficient to distinguish the ions of relevance in plasma surface interactions (isotopes of hydrogen, hydrocarbons) and the noble gases He, Ne and Ar.

Experiments

Argon

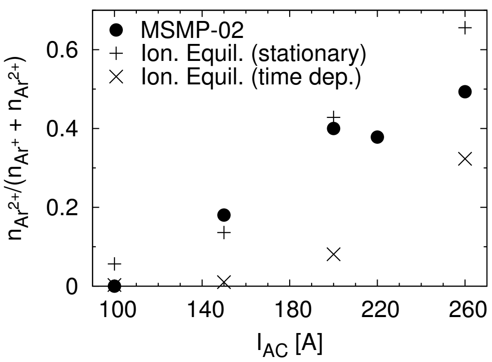

Figure 3: Ar-ion ratios as a function of the discharge current

In a series of experiments the measuring head was set at a fixed position at the edge of the plasma cross-section while the discharge current (I_{AC}), and hence the discharge power, was varied. A proportionality between doubly ionized Ar^{2+}-ions and the discharge current is found (cf. Fig. 3). The percentage of Ar^{2+} increases up to 50% of the total amount of ionized argon for a discharge power of $P_{AC} = 7$ kW ($I_{AC} = 260$ A). An assumed stationary corona ionization equilibrium [5] with a constant T_e measured in the target chamber reproduces the measured ratios quite well. In contrast, a time-dependent treatment that takes into account the finite dwell time of the ions within the discharge region and a constant n_e (target chamber) yields too low Ar^{2+}-concentrations. However, assuming a higher T_e or/and n_e in the discharge region increases the ratios and would hence improve the time-dependent ansatz. For example, in an isothermal plasma with a ten times higher n_e in the discharge region the time-dependent ratios approach the stationary ones.

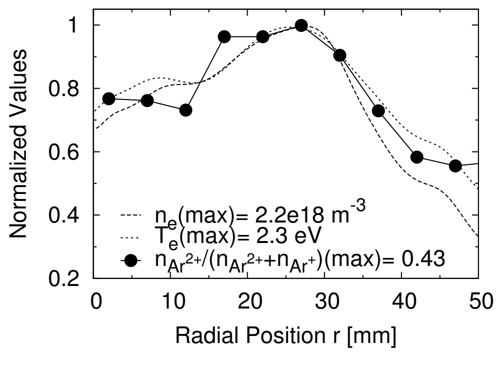

Figure 4: Radial profiles in Argon

While changing the radial position of the measuring head, it can clearly be seen that the Ar^{2+}-concentration attains maximum at the edge of the visible plasma column ($r = 25$ mm). This fits nicely with the course of electron temperature and density profiles as measured by a Langmuir probe (cf. Fig. 4).

From the experiments in argon we can conclude that ionized species in PSI-2 are in a stationary equilibrium characterized by hollow density profiles.

Helium and Hydrogen

Again the discharge current (I_{AC}) was varied while the position of the measuring head was fixed at the edge of plasma. A mixture of two gases (H and He) is blown into the discharge. Starting with a small amount of hydrogen and going up to a mixture of equal fluxes of both gases. The different exhaustion rates of the turbo molecular pumps for H and He [6] were taken into account to correct the ratio of the fluxes of gases ($\Gamma_{H_2}/(\Gamma_{H_2}+\Gamma_{He})$) taken as the abscissa in Fig. 5.

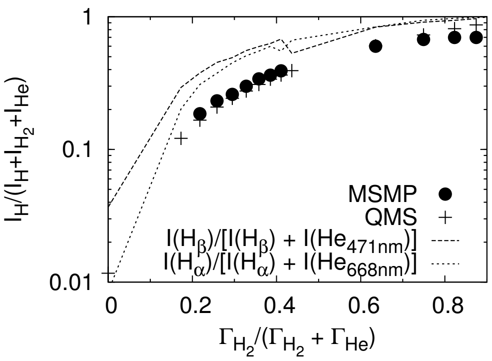

Figure 5: Ratio of signals vs. ratio of fluxes

The current signals from MSMP-02 are in a good agreement up to a ratio of 0.7 with those from quadrupole mass diagnostics (QMS) located in the exhaust duct and spectroscopy in particular. For higher fluxes of hydrogen there is an underestimation of the ratio by the MSMP-02 due to the smallness of the He-signal. For the spectroscopic data spectral lines H_α (656.3 nm), H_β (486.1 nm) and two He-I lines (667.8 nm, 471.3 nm) were taken into account.

Conclusion

It was shown that a new type of mass spectrometer (MSMP-02) can give valuable information on densities and charge states of the ions in a magnetized plasma. The measurements can be done with good spatial resolution. The results can (with respect to the ratios of ion densities) be well reproduced by invoking a simple ionization equilibrium model.

Besides the repeatability and reliability of the measurements, the compact design of the various diagnostics inside the measuring head and the automated evaluation allows to use the MSMP-02 as a standard diagnostics.

Acknowledgement

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