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In-situ mass-spectrometer of magnetized plasmas

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ABSTRACT

Modified mass-spectrometer of magnetized plasmas (MSMP-03) was installed on the linear plasma device PSI-2 in support of plasma-material interaction studies. MSMP-03 was adapted for in-situ mass-spectrum measurements in high-power discharge regimes and equipped with advanced measurements system consisting of a double-collector system allowing to decrease both the secondary electron emission signal in the high-voltage measurement range and the influence of the angular distribution of ions. To verify the MSMP-03 functionality, measurements of plasma ions mass-spectra were carried out for different working gases and discharge conditions in PSI-2. Mass-spectra of deuterium, argon, helium and neon plasma at the edge of the plasma column for different discharge conditions are presented.

1. Introduction

Linear plasma devices are well suited for studying fusion reactor relevant plasma-material interaction (PMI) [1]. One of the advantages of the linear devices is the possibility of realizing mixed plasmas with arbitrary ion concentrations of the constituents. Typically spectroscopy is applied for the determination of the plasma composition [2,3]. However, in some cases the spectroscopic methods cannot deliver the information on all plasma species due to e.g. a low line intensity or limited spectral resolution. Also, the recalculation from the amount of photons, measured by the spectroscopy, to the amount of ions requires atomic data for the particular plasma conditions, which are not always available or are often of a poor accuracy. Residual gas analysis, for example by a quadrupole mass-spectrometer, can provide information of the neutral species in a vacuum chamber but it does not directly reflect the ion composition of plasma.

In-situ mass-spectrometry, a technique based on the mass separation and detection of plasma ions, can be applied for measuring the plasma composition. The omegatrone mass-spectrometer [4–6] requires an additional RF source of the electrical field and an ultra-high-vacuum differential pumping of the spectrometer for reducing the influence of collisions with the residual gas molecules. The plasma ions mass-spectrometer (PIMS) [7] developed on the tokamak DITE is based on the cycloidal focusing in the perpendicular electrical and strong magnetic fields for the mass-to-charge ratio ion separation.

A further possible method for the ion separation is the use of the magnetic field of the plasma device. Mass-spectrometer of magnetized plasmas (MSMP) is based on a classical scheme of static magnetic ion separator with 180° magnetic deflection of accelerated ions [8]. The earlier versions of the device MSMP-01 and MSMP-02 [9,10] were developed by MEPhI Moscow and employed on the linear plasma device PSI-2 in Berlin [11].

PSI-2 was moved to Forschungszentrum Jülich in 2009 and upgraded for advanced plasma-material interaction studies [12]. PSI-2 operates mostly in deuterium because of its relevance to the fusion research. Knowledge of the deuterium molecular ion composition is crucial for the PMI studies. Furthermore, the response of material samples to the mixed plasma exposure, e.g. a fraction of noble gases such as helium, neon and argon added to deuterium, is one of the foci of the PMI research in PSI-2 [13]. Information on the ion fraction of impurities in deuterium as well as on the charge states of the impurity ions is essential in these studies.

This paper describes the upgraded version of the in-situ mass-spectrometer MSMP-03 installed at the linear plasma device PSI-2 in Forschungszentrum Jülich. The mass-spectrometer was thoroughly refurbished and upgraded with respect to the earlier versions used on PSI-2 in Berlin. The modified design and working principles are described in Section 2. Section 3 provides examples of mass-spectra and evaluated data on the ion fluxes from in-situ measurements in PSI-2. A summary is provided in Section 4.

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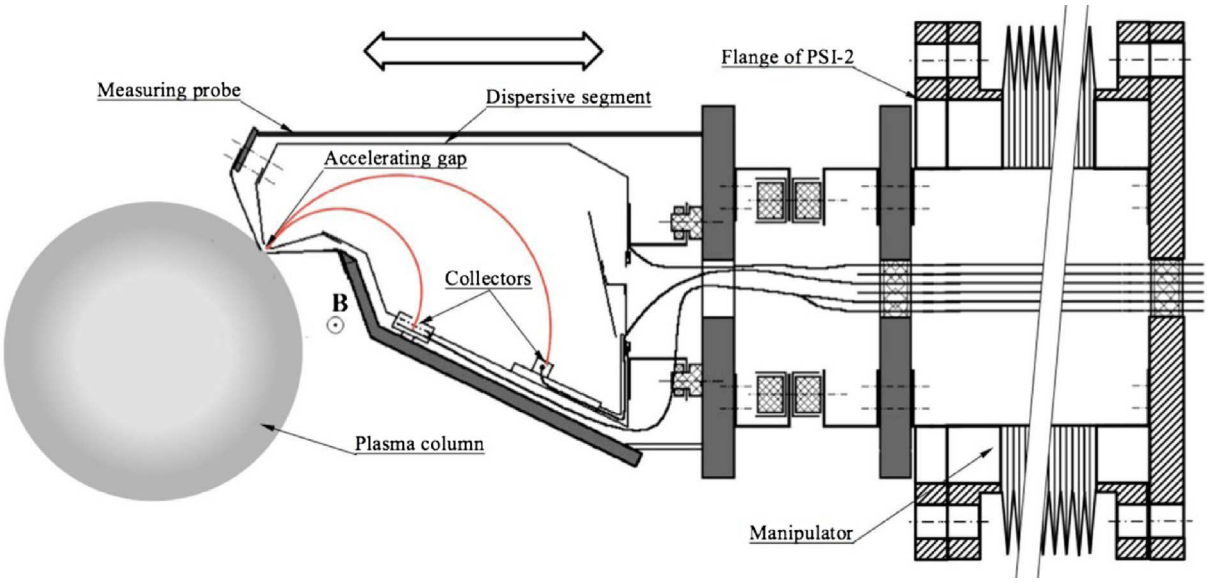

Fig. 1. Scheme of MSMP-03 measuring head.

2. Design and work principle of MSMP-03

Mass-spectrometer of magnetized plasmas was developed in MEPhI Moscow for the in-situ analysis of plasma ion composition by static magnetic ion separation. The version installed at PSI-2 in Forschungszentrum Jülich, MSMP-03, is also equipped with a single Langmuir probe for the measurements of the local plasma parameters and a Hall probe for monitoring the local magnetic field. MSMP-03 is mounted on a vacuum lock manipulator attached to a vacuum port of PSI-2, which is usually occupied by the side-fed sample manipulator (Fig. 1 in Ref. [12]). The sharing of the vacuum port restricts the operation of MSMP-03 to dedicated campaigns. On the other hand, it enables measurements at the position in the device where material samples are typically exposed. MSMP-03 can be operated in combination with the material testing programs using the other material sample manipulator, the target station. The use of the vacuum lock system allows for the installation of the MSMP-03 without affecting the vacuum of PSI-2. The linear drive can move the MSMP-03 measuring head to a position close to the centre of the plasma.

The measuring head of mass-spectrometer is shown on Fig. 1. MSMP-03 operates in the ion probe mode to extract ions directly from plasma. Ions reaching the entrance slit ($8 \times 0.5\,mm^2$) are accelerated by the electrical field applied in the accelerating gap of 1 mm width. They are then detected by the magnetic field of plasma device (~ 0.1 T) and as a result separated by the mass-to-charge ratio. Mass-spectrum of plasma ions is obtained by changing the accelerating voltage, and registered by two ion collectors placed at different radii of ion trajectories ($R_1 = 2.5$ cm, $R_2 = 5$ cm). This type of the collector system decreases both the secondary electron emission signal for the high accelerating voltage measurement range and the influence of the angular distribution of ions. The collector at the lower radius is used for a rough mass-analysis of typical light working gases (hydrogen, deuterium, helium). The second collector has a better mass resolution and is used for more accurate measurements in a heavier mass range.

Both energy and gyration radius of the ions in the mass-spectrometer depend on the acceleration process according to following expression [10]:

$$\left(\frac{M}{Z}\right)_i = \frac{K}{U_i + U_{pl}}$$

where K is a coefficient depending on the mass-spectrometer geometry and the magnetic field strength; U_{pl} – the local plasma potential; U_i – the accelerating voltage. The subscript i denotes the value of the i-th peak in the spectrum. The calibration of the peak position in the experimental mass-spectrum is determined by two peaks with known M/Z, for example by ions of the usual working gases.

MSMP-03 is mounted on the linear manipulator allowing to change the position of the measuring head and to obtain the radial distribution of the ion composition in the plasma column. However, the range of possible positions close to the plasma centre is limited by overheating of the measuring head. That is controlled by a thermocouple mounted close to the entrance slit. The overheating can lead to both the thermoelectron emission from the slit surface and a damage of the spectrometer by the local melting in high power discharge regimes. On the other hand, the mass-spectrometer, when inserted into the plasma, can also influence the plasma parameters and affect the results of the measurements. Therefore, in most cases the measurements by MSMP-03 are conducted at the plasma periphery. The radius of the hot and dense plasma region in PSI-2 is about 3 cm (Fig. 2 in Ref. [12]). The MSMP-03 is usually positioned at a radius between 4 and 5 cm.

In the ideal case, the extracting electrical field between plasma and MSMP-03 should be constant during the measurement to simplify the consideration of the extraction process. Therefore, the local plasma potential is monitored by the Langmuir probe installed at MSMP-03. The mass resolution R of the static mass-spectrometer can be evaluated from the following expression [9]:

$$\frac{1}{R} = \frac{S_i + S_0}{r} + \frac{2\Delta B}{B} + \frac{\Delta U}{U} + \alpha^2$$

where S_i is the entrance slit width, S_0 – the image width, r – the radius of the ion trajectories, ΔB – the fluctuation of the magnetic field strength B, ΔU – the fluctuation of the accelerating voltage U and α – the angular spread. The mass resolution of MSMP-03 is shown on Fig. 2. A general scheme of the static mass-spectrometer with one ion current detector has a good mass resolution for ions of working gases and light impurities ($M < 10$ a.m.u., cf. Fig. 2 (black curve)). Mounting of a second ion collector allows improving the mass resolution in a heavier mass range (cf. Fig. 2 (red curve)). The theoretical value of the minimal resolved mass (cf. Fig. 2) is in a good agreement with experimental

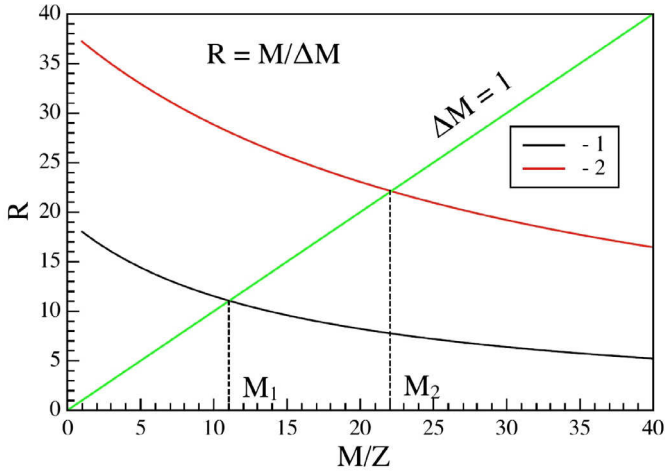

Fig. 2. Theoretical resolution versus mass-to-charge ratio and values of minimal resolved masses for two collectors: 1 – collector at r = 2.5 cm ($M_1 = 11$) and 2 – collector at r = 5 cm ($M_2 = 22$). The straight line corresponds to the critical resolution, when two adjacent peaks with $\Delta M = 1$ can just be resolved.

Table 1
The experimental conditions for deuterium plasma.

Regime	Power, kW	Pressure, mbar	Plasma parameters	
			T_e, eV	n_e, cm^{-3}
D-I	6.7	$5.8 \cdot 10^{-4}$	10.4	$7.1 \cdot 10^{11}$
D-II	0.26	$7.2 \cdot 10^{-4}$	9.2	$5.6 \cdot 10^{10}$
D-III	0.24	$1.3 \cdot 10^{-3}$	8.6	$9.4 \cdot 10^{10}$

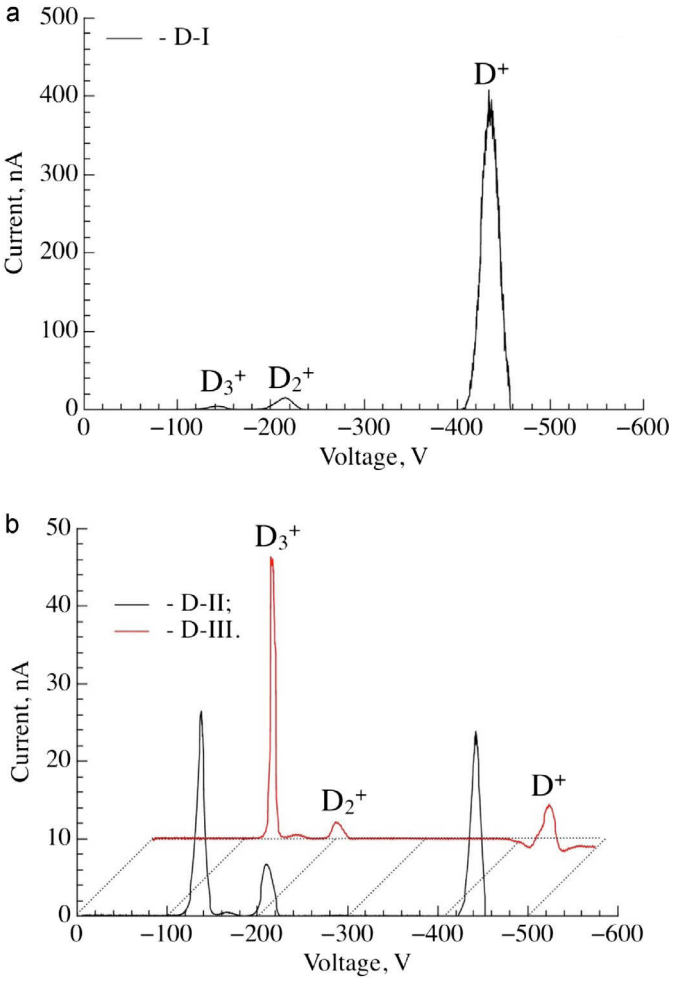

Fig. 3. Mass-spectra of deuterium plasma in various discharge regimes indicated in Table 1.

results and limits the range of *M/Z*–ratio in which MSMP-03 can be used for the ion fraction analysis. MSMP-03 works in the detector regime for lower *M/Z*.

The theoretical resolution of MSMP-03 depends on different parameters and can be improved, for example, by increasing the radius of ion trajectories or the magnetic field in the plasma device. However, these parameters are often restricted by the geometry and technical capabilities of a particular plasma device.

The measurements of the plasma mass-spectra reveal, that there are constraints on the neutral gas pressure for the operation of MSMP-03. A decrease and a high distortion in the ion current signal are observed when the gas pressure is above 2.0×10^{-3} mbar. This is probably caused by the particle scattering and charge exchange processes inside the body of the mass-spectrometer. This issue can be in principal improved by the differential pumping of the measuring head.

3. Application of MSMP-03 on PSI-2

The MSMP-03 functionality was tested for various operational regimes of PSI-2, i.e. different working gases (deuterium, helium, neon and argon), arc discharge power and neutral gas pressure. Changing the discharge power and the gas flow into the vacuum chamber results in a variation of plasma properties such as the electron density and temperature monitored by the Langmuir probe.

The conditions of the discharge regimes in pure deuterium plasma experiments are presented in Table 1. In standard discharge regimes, similar to D-I in Table 1, more than 90 % of the ion flux is carried by deuterons (Fig. 3(a)). Value of the proton (H^+) current signal is negligible (<1%) compared with the deuterium components, underlining the purity of deuterium plasma. All mass-spectra of deuterium plasma were measured at a radial position of the MSMP-03, at the edge of the plasma column (4 cm from the center of the column).

Reducing the power of the arc discharge and increasing the gas flow leads to a cooling of the plasma and to the recombination regime of the plasma discharge [14,15]. It is reflected in the redistribution of the ion composition of the discharge (Fig. 3(b)). The molecular ion fractions increase significantly in the regime D-II and become dominant in the regime D-III.

Measurements of ion mass-spectra for noble gas plasmas (He, Ne and Ar) were carried out at a radial position of MSMP-03 of 4 cm for different values of the discharge power and therefore different plasma parameters. The gas flow into the ion source is constant in each series of the presented experiments. The conditions of the discharge regimes used in the experiment (Table 2) are typical for noble gas plasmas in PSI-2.

The mass-spectra of He plasma presented in Fig. 4 were obtained for 150 sccm gas flow and four different discharge regimes. The working pressure in the vacuum chamber during the experiments was about 10^{-4} mbar. The double charged ion fraction in the plasma ion flux weakly increases with the discharge power and the electron temperature. In the regime with the highest discharge power (He-IV in Table 2) it reaches up to 2 %.

The behavior of Ne ions was studied with 150 sccm gas flow (a working pressure about 1.5×10^{-4} mbar) and three different plasma source settings. The range of discharge power for the measured cases was limited by overheating of the MSMP-03 head. The

Table 2
The experimental conditions for noble gas plasmas.

Regime	Power, kW	Plasma parameters		$\Phi_{X^{2+}} / \sum_i \Phi_{X^{i+}}$, %
		T_e, eV	n_e, cm^{-3}	
He-I	2.7	10	$9.5 \cdot 10^{11}$	0.4
He-II	6.3	11	$1.4 \cdot 10^{12}$	0.9
He-III	10.5	12	$1.6 \cdot 10^{12}$	1.3
He-IV	15.5	14	$1.6 \cdot 10^{12}$	1.7
Ne-I	1.4	5.8	$7.4 \cdot 10^{10}$	0.0
Ne-II	3.3	8.0	$4.3 \cdot 10^{11}$	1.2
Ne-III	5.6	9.0	$9.3 \cdot 10^{11}$	3.4
Ne-IV	8.1	9.6	$1.2 \cdot 10^{12}$	10.0
Ar-I	0.7	2.0	$4.0 \cdot 10^{11}$	1.4
Ar-II	1.8	2.7	$1.5 \cdot 10^{12}$	12.2
Ar-III	3.0	2.9	$2.9 \cdot 10^{12}$	28.0
Ar-IV	4.8	3.0	$4.4 \cdot 10^{12}$	54.0

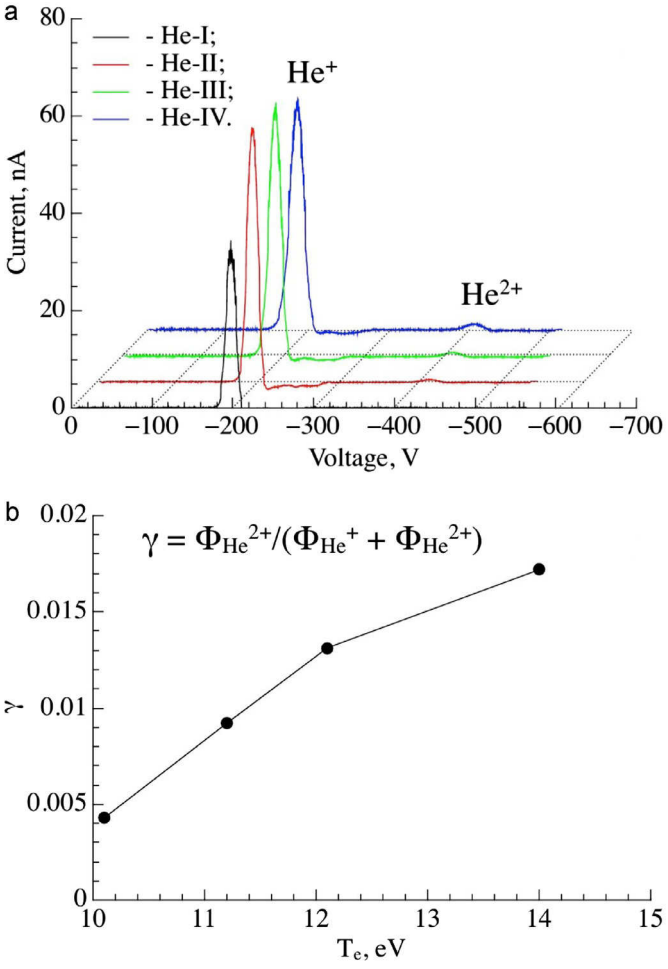

Fig. 4. Mass-spectra of helium plasma (a) and relative value of the He^{2+} ion flux for different discharge parameters (b).

obtained mass-spectra and relative flux of double-charged ions versus electron temperature are presented in Fig. 5.

As for helium, the double charged ion fraction increases with the discharge power and the electron temperature, but it reaches a higher value in lower power/temperature cases. The value of Ne^{2+} relative flux can reach up to 10 % at an electron temperature of less than 10 eV.

Fig. 6 shows the redistribution of the ion composition in argon plasma for different discharge conditions and a gas flow of 100 sccm. The working pressure during the experiments was about 10^{-4} mbar. Double-charged ion fraction strongly increases with

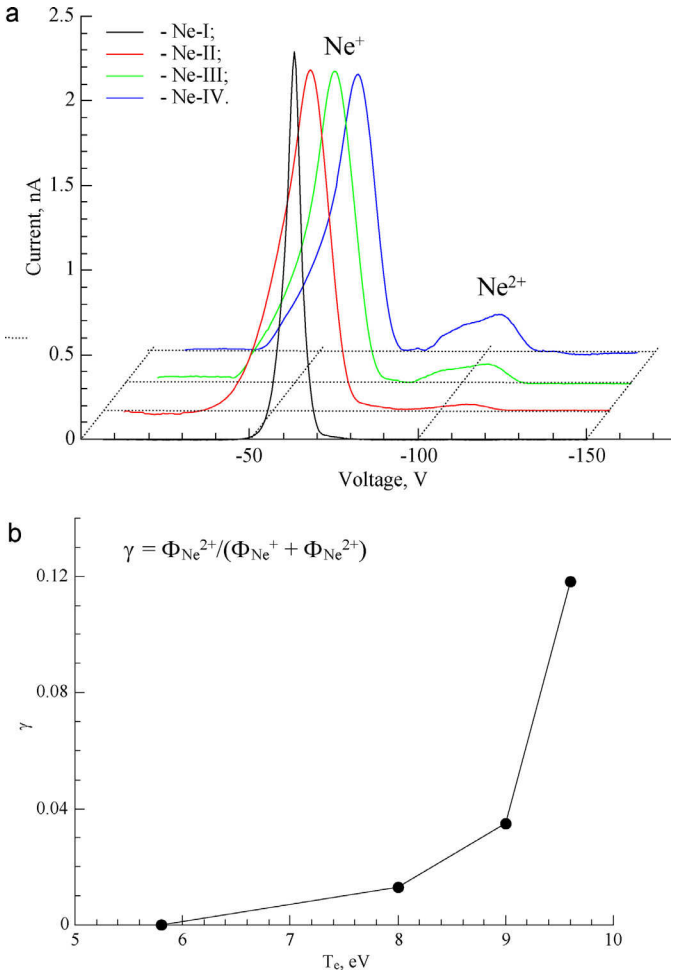

Fig. 5. Mass-spectra of neon plasma (a) and relative value of the Ne^{2+} ion flux for different discharge parameters (b).

discharge power and reaches 50 % of the total ion flux at the discharge power 5 kW.

The experimental results for noble gas plasmas show that an increased discharge power and a higher electron temperature lead to a redistribution in the plasma composition from single charged to multi charged ions in accordance with equilibrium state of plasma-chemical processes. The effect is more pronounced for Ar then for Ne and He, presumably due to a lower second ionization potential of 27.6 eV compared to 41.0 eV and 54.4 eV, correspondingly.

The amount of triple charged ions was below the detection limit for all cases investigated in this paper. We cannot exclude, that triple charged ions are produced in high power discharge regimes. However, for a discharge power of higher than ~ 10 kW the noise level of the MSMP-03 signal becomes too high to detect low-amplitude peaks.

4. Conclusions

An upgraded version of the in-situ static mass-spectrometer of magnetized plasmas MSMP-03 was installed on the linear plasma device PSI-2. MSMP-03 is equipped with an advanced measurements system consisting of a double-collector system, allowing to improve the mass resolution in a heavier mass range. The upgraded device was successfully used in experiments for the direct determination of the species ion fluxes in plasma. Mass-spectra for different working gases and discharge conditions were obtained. In the standard regime of deuterium plasma the deuteron ion

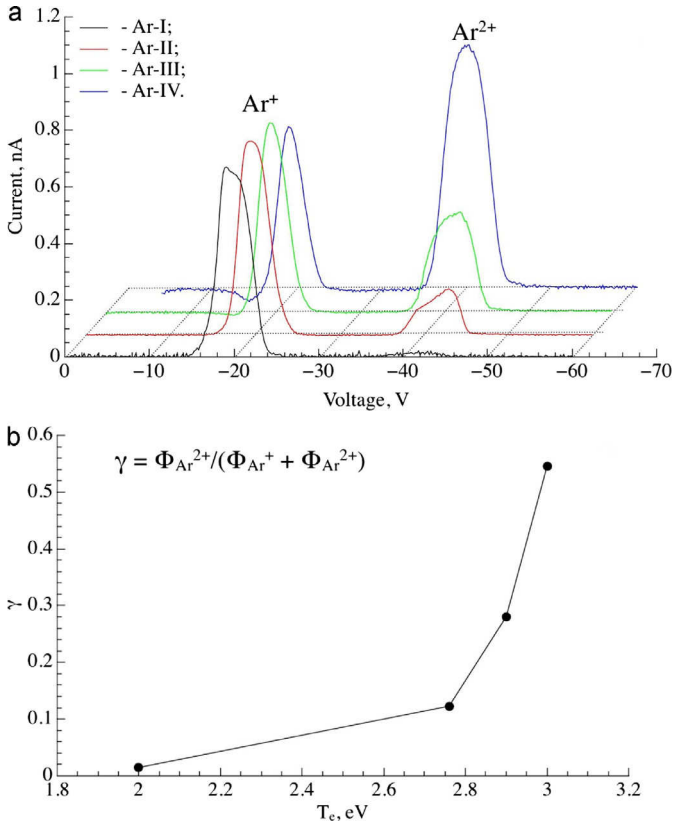

Fig. 6. Mass-spectra of argon plasma (a) and relative value of the Ar^{2+} flux for different discharge parameters (b).

fraction D^+ prevails over the molecular ion fractions of D^{2+} and D^{3+}. In the regimes with a low discharge power and a high deuterium inflow, the fractions of molecular ions can significantly raise. For noble gas plasmas, He, Ne and Ar, the fraction of double charged ions increases with the discharge power and electron temperature. While in He the fraction of double charged ions is at maximum of a few percent, for Ne it can reach over 10 % and for Ar more than 50 %. The difference is attributed to different ionization energies of He, Ne and Ar, but also changes in plasma-chemical kinetics of the discharge, which is of special interest for plasma physics. The presence of the multi-charged ions is critical for plasma-material interaction studies, i.e. due to a higher incident energy of double charged particles on the target. The data provided by MSMP-03 will lead to a better interpretation and understanding of PMI experiments in PSI-2.

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