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Influence of diaphragms on measurements of ions emitted from dense magnetized plasmas

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Abstract The paper concerns the diagnostics of ions escaping from dense magnetized plasma (DMP) discharges. Particular attention is paid to the basic problem of the separation of such ions from the investigated plasma, under the condition that this process should not disturb the velocity (and energy) distribution functions of the measured ions.

Key words diagnostic of ions • energy distribution • plasma discharges • separate ions

Introduction

During studies of different plasma accelerators (so-called plasma guns), and particularly during investigations of plasma injectors, the most important characteristics concerns detailed mass- and energy-analysis of ions. For such purposes, analyzers of various types, e.g., time-of-flight (TOF) analyzers [2, 6, 13] and Thomson-type mass-spectrometers are applied [1, 5, 8, 10, 11]. Each measuring technique possesses some advantages and disadvantages and the choice depends on given experimental requirements. In all the systems mentioned above, it is necessary first to separate ions from the investigated plasma stream and this process must not deform the ion energy distribution function. This requirement is hardly to be fulfilled, in particular for dense plasma of the concentration above 10^{14}–10^{15} cm^{-3}. First – the separation of ions from a dense moving plasma object requires the application of relatively high voltage between separating electrodes, which in case of low-energy ions can induce a strong deformation of the energy distribution. Second – the transportation of the separated ion stream over a larger distance is difficult due to its large space electrical charge, which induces a divergence of the analyzed ion stream [3]. Such a spatial divergence of the ion beam can consequently induce widening of the registered energy distribution and an allusive increase in an ion temperature value.

Influence of electrical fields

The influence of axial electrical field, which is often used in multi-grid analyzers, was considered in several papers, which showed a maximal concentration of plasma (to be measured with such a technique) is about 10^{11}cm^{-3}.

A detailed analysis of electrical fields, which appear within a pulsed ion stream, was performed in [4]. On the basis of the computed electrical fields connected with the spatial

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electric charge critical values of ion concentration were estimated, below which the influence of the charges may be neglected. It was found that in a system with electrostatic fields, which is equipped with an input diaphragm of radius r_1, and an output diaphragm of radius r_2, the ion stream density at the entrance should be

$$n \le 5\times10^8 \frac{E_i}{L^2 z}\left(\frac{r_2}{r}\right)^2 \quad (1)$$

where E_i is the ion energy in kV, z is the ion charge number, and L is the distance between two diaphragms in cm. From this relation one can see that the critical ion concentration is relatively low and for the real experimental condition it amounts to $(10^8–10^{10})$ cm^{-3}. The upper limit value can be achieved only with the use of a wide-aperture detector (large $\frac{r_2}{r}$) and of relatively high ion energy values. Based on the above considerations, one can conclude that for the determination of a mass- and energy-spectrum of ions coming from a dense plasma it is necessary first to reduce the plasma concentration below $(10^8–10^9)$ cm^{-3} without any considerable deformation of its basic characteristics.

Three-step procedure

The three-step technique comprises: 1. The reduction of the investigated plasma concentration below $(10^8–10^9)$ cm^{-3} with a negligible disturbance of the ion energy distribution and the ion mass-spectrum; 2. The formation of a collision-less plasma stream and the separation of ions from the lower-density plasma stream; 3. The analysis of the separated ion stream (see Fig. 1).

That technique was proposed and elaborated in the 50s [7] in connection with research on the formation of free molecular streams. In some papers, e.g. [13], there were also analyzed possibilities to determine parameters of a primary plasma stream on the basis of mass- and energy-analysis of the ions separated from that stream.

In this paper, in the relation with studies of mass- and energy-distributions of ion streams produced by experimental facilities of the multi-rod plasma injector (RPI-IONOTRON) and Plasma Focus (PF) types, we consider mainly problems connected with the use of systems reducing concentration of the investigated plasma.

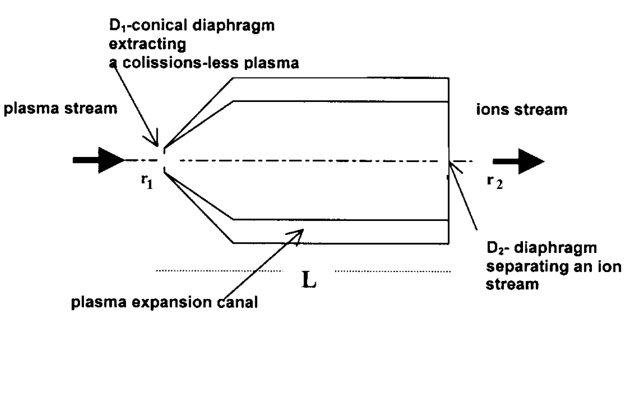

Fig. 1. Scheme of an input diaphragm system used for the extraction of ions from a dense plasma stream.

The formation of a collision-less plasma stream

During the preliminary reduction of a plasma density, by the extraction of a lower density plasma stream, in order to preserve the distribution function of ions, it is necessary to form a collision – less plasma beam. It can be achieved only if there is fulfilled the following relation

$$\lambda_D << d_1 < \lambda_{ii} \quad (2)$$

where d_1 is the input diaphragm diameter, λ_D is the Debye radius, and λ_{ii} is the mean free path for plasma ions. The range of plasma concentration and temperature values, for those the relation given above is fulfilled at different dimensions of the input diaphragm, is presented in Fig. 2.

The upper boundary of this region is described by an approximate formula [4]

$$T^2_i \text{ (eV)} = 3.8 \times 10^{-12}\, n \text{ (cm}^{-3}) \, d_1 \text{ (cm)} \quad (3)$$

From the above formula and diagrams shown in Fig. 2 one can conclude that the formation of collisions – less plasma beam is possible in majority of experiments with plasma injectors. During the impact of fast plasma stream upon the input diaphragm some undesirable effects may appear, e.g. before the diaphragm a reflected shock wave can be formed, which could propagate in the opposite direction and disturb the primary plasma stream. The bombardment of the input diaphragm with energetic plasma components could also produce a plasma cloud (pillow) containing particles pull out of the diaphragm surface. For a given ion temperature value and for a given average value of the parallel component of the ion velocity (energy), i.e. for a determined value of the Mach number, the effects described above depend on the input diaphragm dimensions [7], as shown in Fig. 3.

From Fig. 3 it can be seen that the effect connected with the primary plasma stream reflection may be neglected only if the outer angle Φ_1 of the input diaphragm is small enough. The influence of inner walls of the conical diaphragm may be neglected if the inner angle Φ_2 is large enough [7, 9].

The above requirements are contradictory and cannot be fulfilled simultaneously at small Mach numbers. For plasma

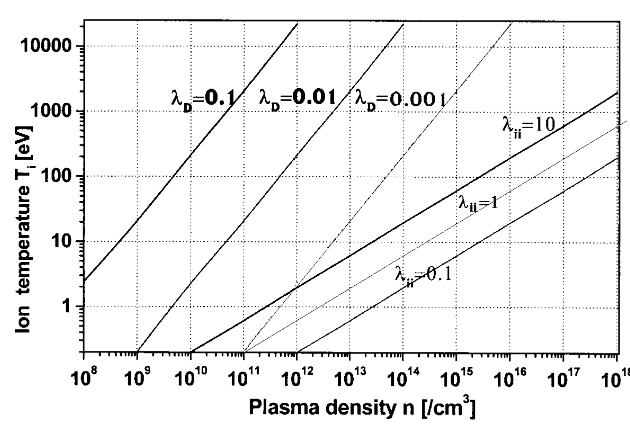

Fig. 2. Relation of the ion temperature (T_i) and the plasma concentration (n) for different values of the Debye radius (λ_D) and the ion free path (λ_{ii}).

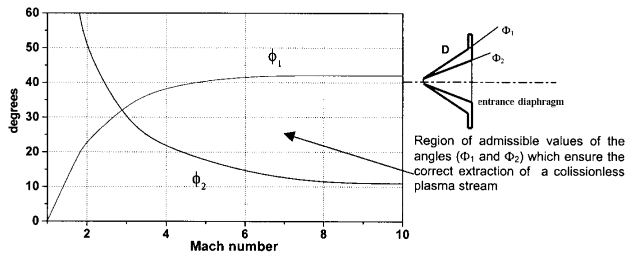

Fig. 3. Dependance of the outer angle (Θ_1) on the inner angle (Θ_2) of the input conical diaphragm on the Mach number (M) of the analyzed plasma stream [7, 9].

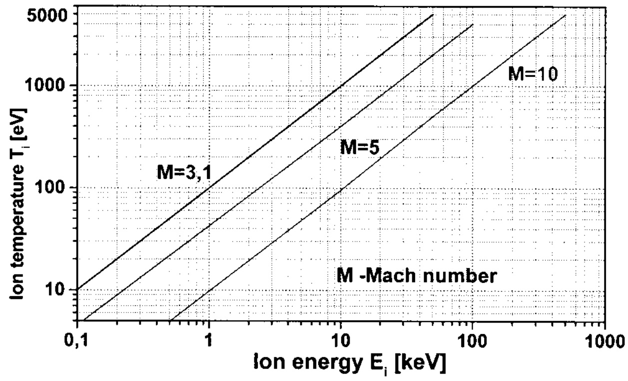

Fig. 4. Relation between the ion temperature (T_i) and a parallel component of the ion energy (E_{II}), as determined for plasma streams with different Mach number [14].

streams with Mach numbers M > 2.6, however, it is possible to determine some values of Φ_1 and Φ_2, which ensure that the plasma stream disturbance is negligible.

In Fig. 4 a diagram is presented showing lines corresponding to constant values of the Mach number (M) for the different values of ion temperature (T_i) and parallel (directed) component of ion energy (E_{ii}). A comparison of this diagram (Fig. 4) with the parameters of plasma streams, which are produced within different experiments, shows that the conical input diaphragm with appropriate dimensions can be used in many cases as an entrance system of ion analyzer.

Separation of an ion stream of reduced density

The extraction of ions from a collision-less plasma stream (of a reduced density) can be performed by means of an auxiliary electric field if an appropriate additional (second) diaphragm D_2 is placed at the distance L behind the input (first) diaphragm D_1. The separation of the lower density plasma into components (ions and electrons) is possible if there is fulfilled another relation

(4) $\lambda_D \geq d_2$

where λ_D is the Debye radius for the low density plasma, and d_2 is the diaphragm diameter. From diagrams shown in Fig. 2 one can see that the above condition can be fulfilled for different values of plasma concentration and temperature if the separating diaphragm has appropriate dimensions.

Taking into consideration all the described requirements, which refer to the formation and separation of investigated plasma streams, for experimental studies of ions from RPI-type facilities there were applied special entrance systems. In particular, a conical input (first) diaphragm with opening d_1 = 1 mm and the angles $\Phi_1 \approx 26°$ and $\Phi_2 \approx 18°$ was used. The separating (second) diaphragm had the diameter d_2 = 0.5 mm and was placed at the distance L = 70 cm behind the input diaphragm, as shown in Figs. 1 and 3. In Fig. 5 an example of results obtained within the experimental plasma facility of RPI type is presented [11, 12].

A more difficult aim is to perform ion measurements in experiments of the Plasma Focus (PF) type, in which the plasma stream concentration amounts to above 10^{18}–10^{19} cm^{-3}, at the operational pressure (within the discharge chamber) of the order of several mbar. Fig. 6 presents a special input diaphragm (the so-called plasma skimmer) with a differential pumping, which can be applied under such experimental conditions [5, 10]. Using such an input system [5] valuable quantitative results were obtained, some of which are shown in Fig. 7.

Conclusions

The main conclusion from the diagnostic studies described in this paper can be formulated as follows:

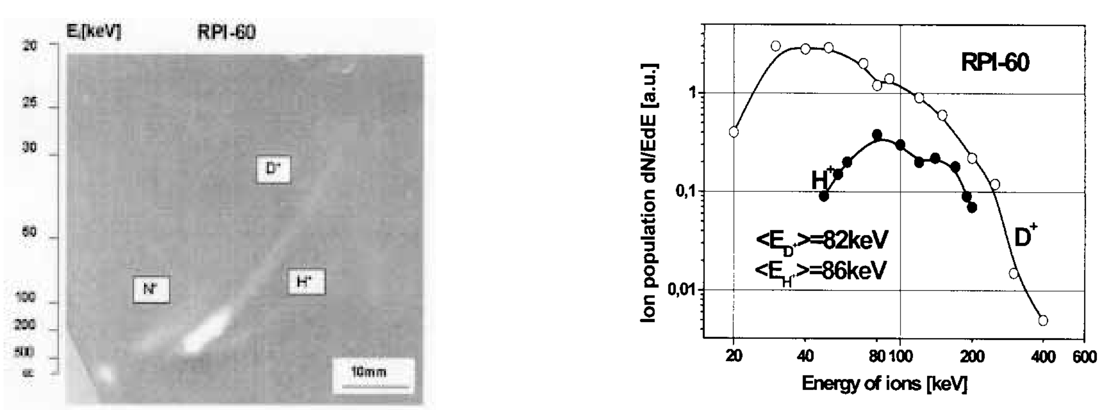

Fig. 5. Thomson-type ion parabolas and corresponding energy spectra of deuterons and protons, which were obtained during a single discharge performed within the RPI-60 device.

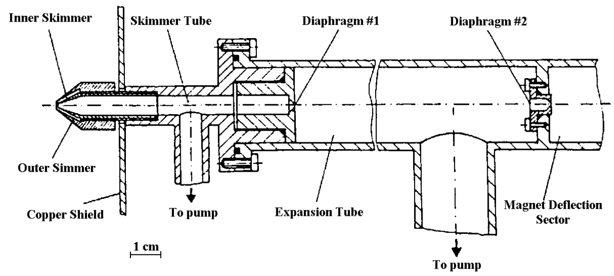

Fig. 6. Scheme of an ion extractor system used for studies of ion beams generated by a plasma-focus machine [5].

- During measurements of an ion component of the dense plasma stream it is of primary importance to apply an appropriate input diaphragm system, as described above.

It should be noted that in some cases an additional acceleration electrode system can be applied [12]. If the separation of the ion component is achieved by means of the second (extracting) diaphragm, the application of such an additional acceleration system enables the energy threshold for ion measurements to be lowered to about 20 keV. If the separated ions are additionally accelerated by the known voltage (e.g. 25 kV), they can easily be registered by means of solid-state nuclear track detectors (NTDs), e.g. plastic foils of the CR-39 or PM-355 type, which are sensitive above 45 keV.

In general, the described diaphragms (and eventual acceleration systems) make possible quantitative studies of ions emitted from experimental facilities producing dense plasma-ion streams (e.g. devices of the PF- and RPI-type).

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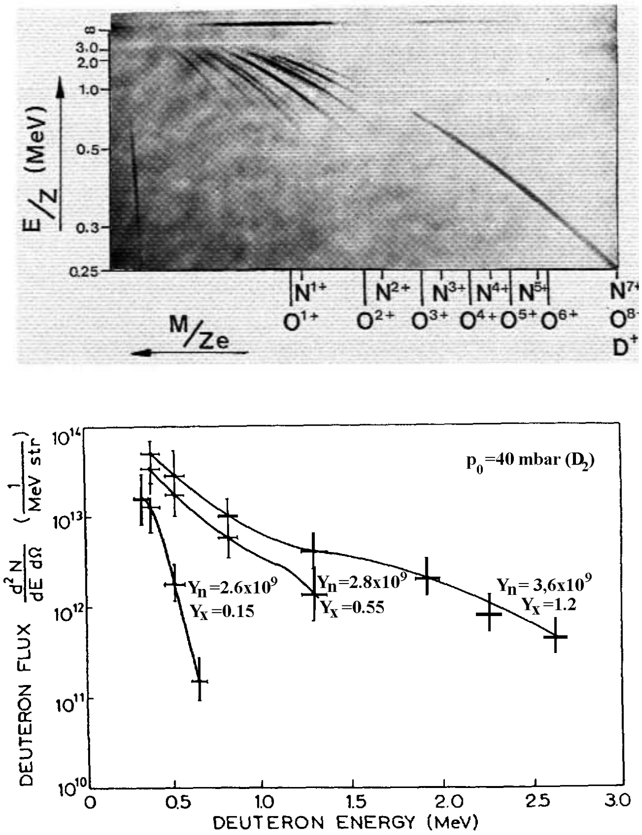

Fig. 7. Examples of the Thomson spectrograms and energy spectrum of deuterons, as determined from the measurements performed within the Nessi plasma-focus machine [5]. Y_n denotes the neutron yield, and Y_x is the hard X-ray output (in arbitrary units).

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