Measurements of Charged Particle Beams from Plasma-Focus Discharges

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Abstract: Experimental studies performed with many Plasma-Focus (PF) facilities have shown that simultaneously with the emission of X-ray pulses and intense relativistic electron beams (REBs) there also appears the emission of pulsed ion streams of a relatively high energy (up to several MeV). Such ions are emitted mainly along the z-axis of the PF discharge, although the ion angular distribution is relatively wide. From PF discharges with deuterium filling fast neutrons produced by nuclear fusion reactions are also emitted. The paper concerns studies of the energetic ion beams and their correlation with the pulsed REBs. Time-integrated measurements were performed with an ion pinhole camera equipped with solid-state nuclear track detectors (SSNTDs), and time-resolved studies were carried out with a scintillation detector, enabling the determination of an ion energy spectrum on the basis of the time-of-flight (TOF) technique.

1. Introduction

Inside the pinch column of a Plasma-Focus (PF) discharge, particularly when some admixtures of noble gases are applied, miniature regions of high-density and high-temperature plasma are formed. These miniature regions, called “hot spots”, are sources of intense pulses of X-ray and corpuscular emission [1,2]. Extensive studies of the X-ray emission from the hot spots performed during recent years have demonstrated that different spectral lines emitted by highly-ionized species have various polarization [2,3]. Such polarization effects can be explained by strong disturbances of the maxwellian distribution of electron velocities (e.g. by the appearance of directed e-beams) and/or the formation of strong local electric and magnetic fields. It should be noted that the emission of high-intensity relativistic electron beams (REBs) has been confirmed by numerous experimental studies, e.g. those reported at the conference BEAMS’98 [4].

It was proved experimentally that the REBs are emitted mainly in the upstream direction, i.e. toward the inner electrode (the anode). The REBs penetrating through an axial channel in the central electrode could be registered, e.g. by means of Čerenkov-type detectors. Recently, it has been shown that such REBs are well correlated with the emission of X-ray pulses emitted from individual hot spots [1, 4]. In general, the emission of fast e-beams and corresponding X-ray pulses might be induced by strong local electromagnetic fields, which are formed within dense magnetized plasma of the hot spots. It is evident that such processes can be accompanied also by the emission and acceleration of ion beams in the direction opposite to that of the REBs.

Detailed studies of X-ray and corpuscular pulses have demonstrated that high-intensity and high-energy deuteron beams are emitted mainly within a narrow solid angle to the z-axis (precisely speaking, to the magnetic axis of the PF discharge). The main aim of the recent studies at IPJ was the investigation of such pulsed ion beams, in order to determine the spatial distribution of ion sources, energy spectra of the emitted ions, and temporal characteristics of the observed pulsed electron and ion beams. Particular attention has been paid to research on the correlation of the investigated corpuscular beams.

The described studies have been performed within the MAJA-PF facility, which was equipped with two coaxial electrodes of 72 mm and 124 mm in diameter. The system was powered by a condenser bank, which was usually charged to 44 kJ at 35 kV. The maximum discharge current amounted to 500 kA. The working gas was pure deuterium or a mixture of deuterium and argon (5-20%).

2. Experimental results

The main aim of this work was to investigate the correlation between the appearance of hot spots and the emission of intense X-rays, REB pulses, and pulsed ion streams (beams). Therefore, use was made of an ion pinhole camera equipped with solid-state nuclear track detectors (SSNTDs). Tracks registered on SSNTDs (after their etching) were analyzed with an optical microscope and a digital camera. Made it possible to determine the spatial distribution of the investigated ions, and to estimate absolute values of the ion flux.

Simultaneously with the ion studies, space- and time-resolved measurements of pulsed REBs were also performed. Those measurements in many cases made it possible to assign individual ion pulses to electron-induced peaks originating from the determined hot spots. Using the time-of-flight (TOF) technique, the energy spectrum of the investigated ions was also estimated.

2.1 Time-integrated studies of ions by means of nuclear track detectors

For time-integrated and space-resolved measurements of pulsed ion streams a small pinhole camera was placed inside the MAJA-PF experimental chamber at a distance of 280 mm from the PF electrodes outlet. It was equipped with an input diaphragm of 0.8-mm diameter, and it ensured a magnification of 1.63:1. Ion images were registered upon SSNTDs of the CN type, which were covered with 10-µm-thick Al-foil filters, eliminating deuterons of energy below 1.3 MeV.

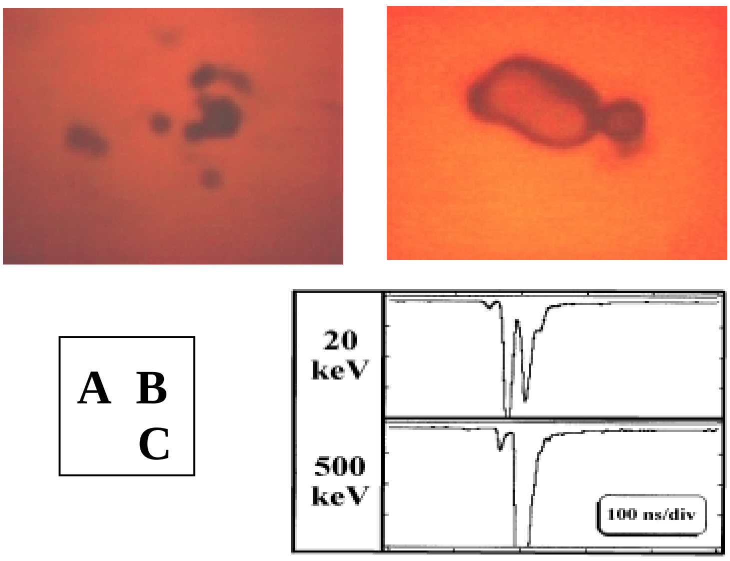

FIG.1. Ion beam images obtained from many PF discharges (A) and from a single PF discharge (B) in the presence of hot spots emitting REBs (C).

Some examples of the ion images registered on the irradiated SSNTDs are presented in Fig.1. In Fig.1A there is shown a time-integrated ion image obtained from a series of 11 successive PF discharges with an average neutron yield equal to $Y_n = 4 \times 10^8$ neutrons/shot. In Fig.1B there is presented the ion image from a single PF discharge with a relatively high neutron yield equal to $Y_n = 1.2 \times 10^9$ neutrons/shot. All the investigated discharges were performed under the identical experimental conditions.

From the ion picture obtained for the series of shots one can conclude that plasma sources emit many collimated ion beams (in Fig. 1A one can identify more than a dozen narrow beams). One can suspect that such beams are generated in different miniature (point-like) sources distributed within the PF pinch column. That hypothesis has been confirmed by Fig. 1B, obtained from a single PF discharge in which several hot spots were formed, as one can conclude from an analysis of the time-resolved REB-induced signals presented in Fig. 1C. It should be noted that several ion beam spots, visible in Fig. 1B, correspond to several REBs producing the distinct peaks shown in Fig. 1C. The large (over-exposed) ion spot was possibly produced at the same time as a high (saturated) REB signal, which corresponded to a high-energy (> 500 keV) electron beam of a relatively high intensity (see the description of oscillograms given in Section 2.2).

Estimated values of the ion flux density, for deuterons of energy above 1.3 MeV, emitted in a narrow solid angle oriented along the z-axis, amounted to 3.9×10^{11} deuterons/sr in case (A), and to 2.5×10^{12} deuterons/sr in case (B).

2.2 Time-resolved measurements of electron- and ion-beams

In order to investigate REBs, which in the case of PF discharges are emitted mainly in the up-stream direction, use was made of a 10-mm-diameter opening drilled in the front plate of the inner electrode. The pulsed REBs were registered by means of Čerenkov-type detectors made of rutil crystals, which were placed at a distance of 50 cm from the plane of the electrode outlet. Čerenkov light signals were transmitted through appropriate optical cables and registered with fast photomultipliers. The preliminary electron measurements in the MAJA-PF device showed that the REB-induced signals last about 7 – 10 ns and are correlated with X-ray pulses, which are emitted from different hot spots [3]. To investigate the energy spectrum of the pulsed REBs use was made of a miniature magnetic analyzer with a deflection angle equal to 180^0. The analyzer, which was placed behind the main collector plate, enabled fast electrons to be registered through their conversion in X-rays causing the blackening of an X-ray film. On the basis of the irradiated films it was possible to determine the electron energy spectrum. It was found that the spectrum extends from about 5 keV to about 600 keV, with the maximum appearing near 50 keV. In many cases electron energy spectra were obtained with several distinct peaks. This proved that the REBs are emitted as bunches of beams within relatively narrow energy ranges [4].

In order to make possible time-resolved measurements of REBs by means of the magnetic analyzer, it was equipped with several miniature scintillation detectors, which were placed in a chosen point corresponding to different energy values. These detectors enabled measurements of the electron energy value with an accuracy of ±10%, which was determined by the geometrical dimensions of the scintillators. Several series of time-resolved measurements proved that the hot spots (formed successively along the z-axis) can be identified as local sources, which emit the REBs within different and rather narrow energy bands (see Fig. 1C). Individual hot spots (and REBs) can appear in time intervals of the order of 100 ns, and their number can reach about a dozen in a single PF discharge. The emission of the short-lasting REBs, with FWHM < 10 ns and a maximum energy above 500 keV, proves that very strong local electromagnetic fields are generated inside or close to hot spots. If REBs are accelerated in such fields, there should also appear energetic ions.

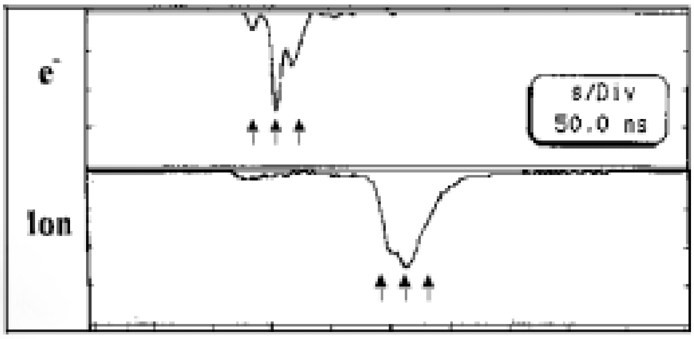

Fig.2. Time-resolved signals from the ion detector (ion), which are correlated with corresponding electron-induced signals (e$^-$).

In order to perform time-resolved measurements of the ion emission a special scintillation detector was placed on the z-axis at a distance of 70 cm from the PF electrode outlet. It was equipped with an input diaphragm of 1.0-mm diameter, which limited the measured ion stream. In addition, a thin absorption filter made of a pure Al-foil of 1.5-µm thickness was placed in front of the scintillator, which eliminated deuterons of energy lower than 220 keV. During the described studies PF discharges were carried out in deuterium with a small (about 5%) Ar admixture, under a total initial pressure $p_0 = 1.7$ hPa.

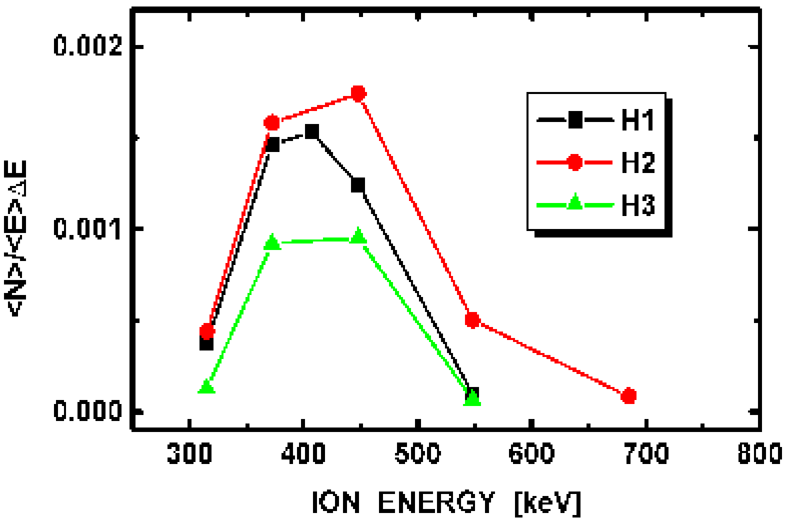

Fig.3. The deuteron spectra emitted from individual hot spots.

The registered ion pulses, which are presented in Fig. 2, have been correlated with different REB-induced peaks registered with the magnetic analyzer within the energy range of 50 ± 5 keV. One can observe that three successive REB-induced peaks (denoted e$^-$) can be assigned to three successive (but superimposed) ion peaks (denoted ion). Taking into account the distance (l) and a time shift (t), corresponding to the time-of-flight of ions from the PF region to the detector plane, and using a simple formula $W_d = m_d l^2/2 t^2$, energy values for deuterons emitted from different hot spots were calculated. The results of those calculations are presented in Fig. 3, which shows energy spectra of deuterons emitted from individual hot spots simultaneously with the emission of REBs (in the opposite direction). One can see that the obtained energy spectra of deuterons extend from about 300 keV (due to the elimination of lower energy deuterons by the applied absorption filter) to about 700 keV. The distinct maxima appear within the range of 400 - 500 keV. Analogous measurements and calculations, performed for other PF discharges, show similar energy spectra extending even above 1000 keV.

3. Summary and conclusions

The most important results of the recent experimental studies can be summarized as follows:

1. PF discharges emit pulsed collimated ion beams, which produce images within an ion pinhole camera. Such ion images can supply information about local micro-sources (hot spots) inside the dense plasma column, which emit the fast ions.
2. The observed ion beams of energy higher than 1.3 MeV, are usually emitted within a narrow cone oriented along the axis of the PF discharge. The ion current density upon the measuring diaphragm reaches several mA, and particle flux density amounts to 2.5×10^{12} deuterons/sr.
3. The FWHM value of the ion pulse (in the registration plane) amounts to about 20 ns. The energy spectrum of accelerated deuterons extends up to about 1 MeV, and its maximum appears within the range of 400-450 keV.

On the basis of the experimental results described above, one can suspect that the fast ion beams emitted along the PF discharge axis, as well as the pulsed REBs emitted in the upstream direction, are generated within the micro-sources (hot spots). Such hot spots, constituting miniature short-lived pinches, are formed successively (starting from the electrode ends), when the current-sheath collapse region moves along the PF pinch axis. The correlation of fast ion pulses and pulsed REBs requires still more detailed investigation under different experimental conditions, as well as an appropriate theoretical modeling.

References

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