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ORIGINAL PAPER

Time- and space-resolved measurements of high-energy ion beams emitted from PF-type discharges

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Abstract. The paper presents experimental studies of the spatial-microstructure and temporal-characteristics of fast ion beams, which are emitted from high-current plasma-focus (PF) discharges performed within the PF-360 facility at National Centre for Nuclear Research (NCBJ) at Otwock/Świerk, Poland. The spatial structure of the ion beams was investigated by means of pinhole cameras equipped with solid-state nuclear track detectors shielded by absorption filters made of Al-foils of different thickness. In order to perform time-resolved measurements there were applied miniature scintillation detectors placed at different points of the ion-image plane.

Key words: ion beams • miniature scintillation detectors • PF-360 facility

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Introduction

Z-pinch facilities of the PF type, which can generate dense magnetized plasma, have been investigated in different laboratories for many years [1–5]. Such a plasma, as produced within a small region located at the electrode symmetry axis, emits intense electromagnetic radiation, accelerated primary ions, as well as charged- and neutral-products of nuclear fusion reactions. Studies of the emitted ion beams can deliver important information about a spatial distribution of ion sources and about energetic characteristics of the investigated ion species. The main aim of the reported experimental study, which was performed with the PF-360 facility at the NCBJ [5], was to record ion beams emitted along the discharge axis using nuclear track detectors with different absorption filters and to perform time-resolved measurements of the emitted particles.

Experimental setup

During the experiments described in this paper, the PF-360 facility [4, 5] was equipped with coaxial electrodes of 300 mm in length. The outer electrode was a solid copper tube of 170 mm in diameter, while inner electrode was a copper tube of 120 mm in diameter, with a central 40 mm-diameter hole, as shown in Fig. 1.

In the described experiments a tubular ceramic insulator, embracing the inner electrode, was 80 mm in length. The experiments were carried out at the charging voltage equal to 30 kV, and at the energy level of 105 kJ. The initial deuterium filling was equal to 6 hPa. The maximum current amounted to about 1.8 MA.

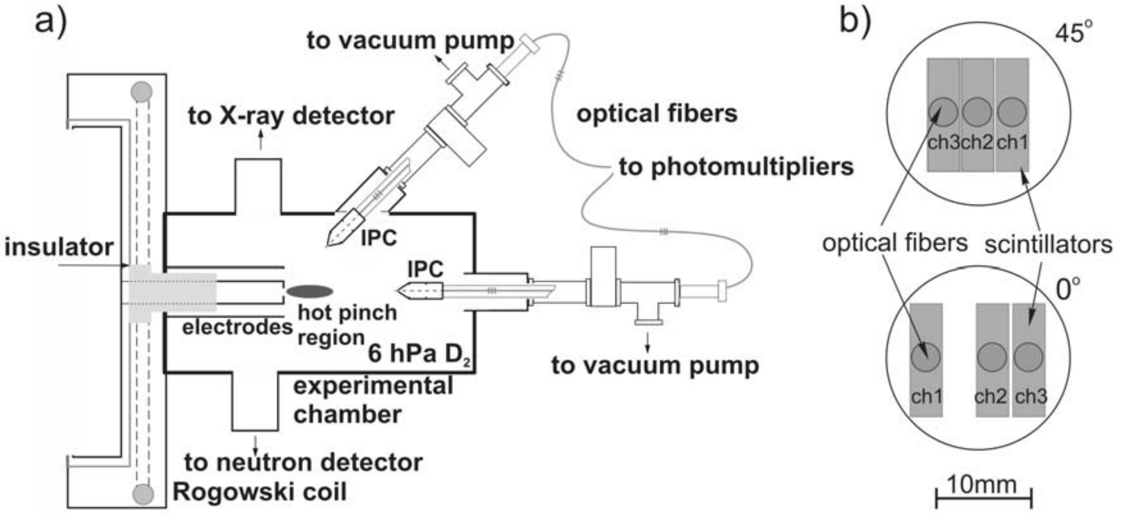

Fig. 1. Scheme of the PF-360 experiment (not to scale) which shows positions of ion pinhole cameras (a), and scheme of the scintillation detectors arrangement inside the camera placed at the angle of 45° to the axis (b, top) and along the axis (b, bottom).

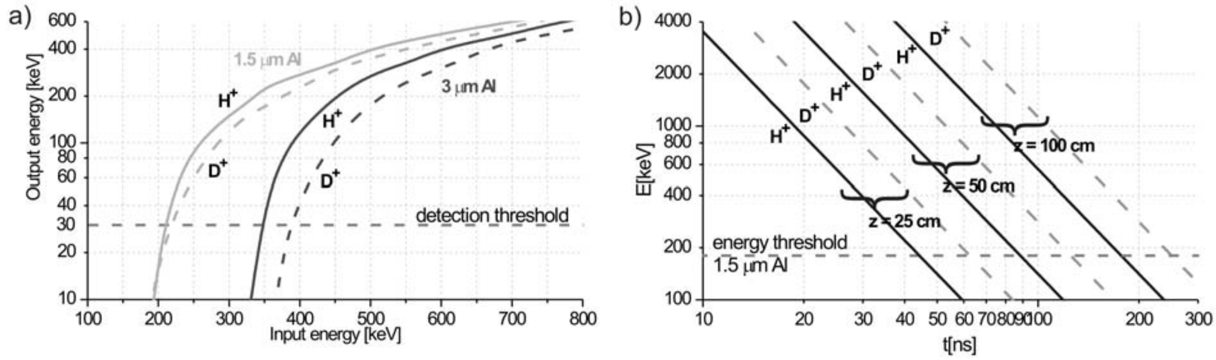

Fig. 2. Energy of protons and deuterons after their penetration through an Al-filter of different thickness (a), and TOF of the measured ions over different distances (b).

The investigated ion beams were recorded using solid-state nuclear track detectors (SSNTD) of the PM-355 type installed inside miniature ion-pinhole cameras (IPC). Those cameras were placed inside the PF-360 experimental chamber along the z-axis and at chosen angle, at different distances from the end of the electrodes (see Fig. 1). After the irradiation (by a single or few discharges), the detectors were etched under standard conditions and investigated with an optical microscope.

To perform time-resolved measurements of the investigated ions the IPC were equipped with miniature scintillation detectors of the NE102 type coupled with fast photomultipliers, as shown in Fig. 1. During earlier studies [2–4], it was proved that the PF-360 facility can emit bunches of accelerated primary ions (mostly D^+ and H^+) of energies up to 800 keV and secondary ions (mainly H^+) of energy about 3 MeV. To record ions of different energies, the SSNTD were shielded with filters made of pure aluminum foil of different thickness (e.g., 1.5 or 3 μm), which allowed to record deuterons of energies above 220 and 380 keV, respectively (see Fig. 2a).

Experimental results

Examples of the ion images obtained from PF-360 discharges are shown in Fig. 3. The left part of the figure shows the image recorded at a distance of 80 cm from the electrode ends. In that case the lower half of the detector was shielded by a 3 μm Al-filter. A comparison of the recorded tracks with electrode projections (marked as dashed circles) suggested that the investigated ions originated mainly from a pinch column and a region between the coaxial electrodes. The right part of Fig. 3 shows the ion image recorded at a distance of 100 cm from the electrodes, behind a 1.5 μm Al-filter, and a track-density map of the selected region. Below the described images there are shown corresponding density profiles, as measured along the dashed lines. The obtained profiles, fitted to the normal distribution, allowed to estimate a diameter of the ion-emitting plasma region. The width of those profiles was equal to about 1.2 mm, and taking into account magnifications of the recorded images, was consistent with the previous measurements [4, 5].

In order to perform time-resolved measurements, and to estimate energies of ions incoming to the detector plane, there was applied also another method, i.e., miniature scintillation detectors. Those detectors were placed inside the pinhole camera and coupled with fast photomultipliers through separate optical cables. To eliminate the visible radiation of plasma the scintillation detectors were shielded with a 1.5 μm Al-foil, which blocked ions (protons and deuterons) of energies lower than 180 keV. That arrangement allowed to perform

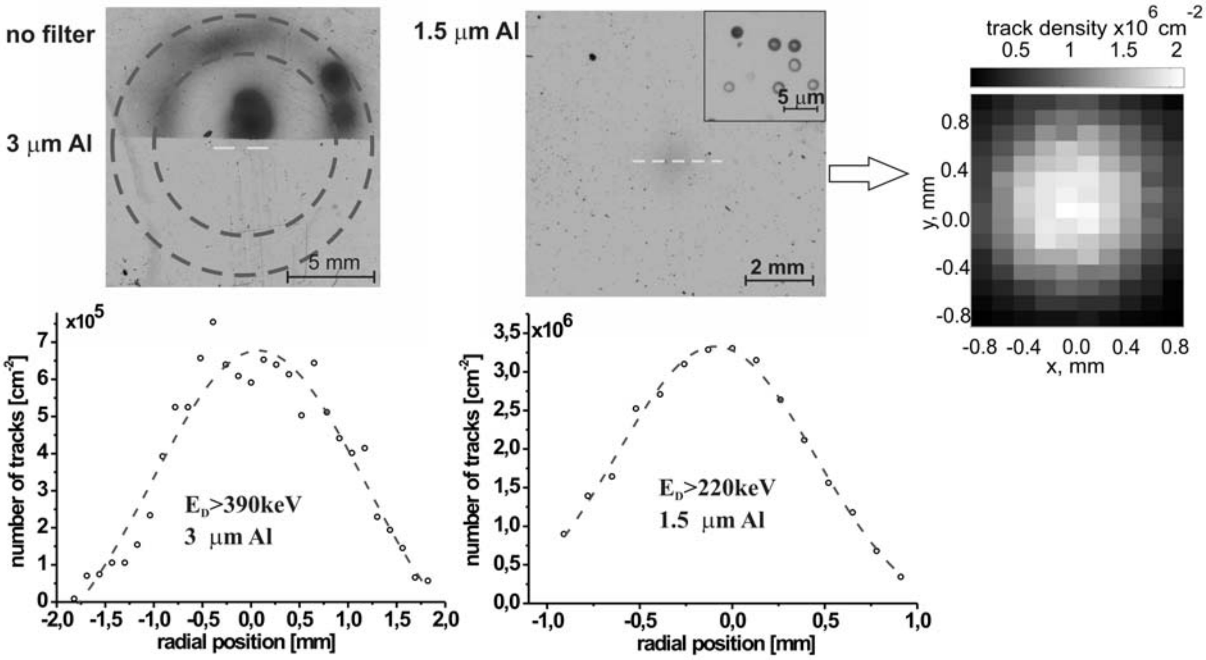

Fig. 3. Ion images, density profiles (obtained with different absorption filters) and a track-density map, as recorded with the IPC placed at a distance of 80 cm (left) or 100 cm (right) from electrodes outlets.

time resolved measurements of ions which were emitted from different pinch regions. Due to relatively large dimensions of the applied scintillators ($3 \times 12\ mm^2$) and a stochastic character of the ion beams emission, the recorded signals varied considerably in amplitudes.

The obtained signals were recorded by means of a digital oscilloscope. In order to investigate time correlations, the use was made of a neutron probe, which recorded hard X-rays and neutron signals. The previous measurements showed [4, 5] that the neutron emission is always accompanied by the hard X-ray emission. Comparing signals from the neutron probe and scintillation detectors, it was possible to identify time-resolved signals produced by the incoming ions. The neutron-produced peaks were identified using the time-of-flight (TOF) method. For the given experimental conditions a difference between signals of hard X-rays and 2.5 MeV neutrons was equal to about 110 ns. For better identification of the X-ray and ion signals, the use was made of two cameras placed at two different distances from the electrode outlets. When the hard X-ray signals were registered by the two cameras simultaneously, the ion signals were recorded with different delays, as shown in Fig. 4.

Since the distance between ion sources (the pinch column) and the scintillation detectors was known, using a TOF method and assuming the instant (T) of the ion emission it was possible to estimate values of ion energies (see Fig. 2b). In the analysis it was necessary to take into account that these energies should be greater than the given thresholds (for the applied absorption filters) and be smaller than the maximum value dependent on the experimental conditions (for PF-360 it was about 800 keV [4]). It should however be noticed that the exact time of ion generation was not known, and the calculated energies could be determined with a low accuracy.

The experimental data (waveforms) presented in Fig. 4 were obtained from two IPC (placed at a distance of 100 cm on the discharge axis, and at a distance of 50 cm, 45° to this axis, respectively). In the ion signals

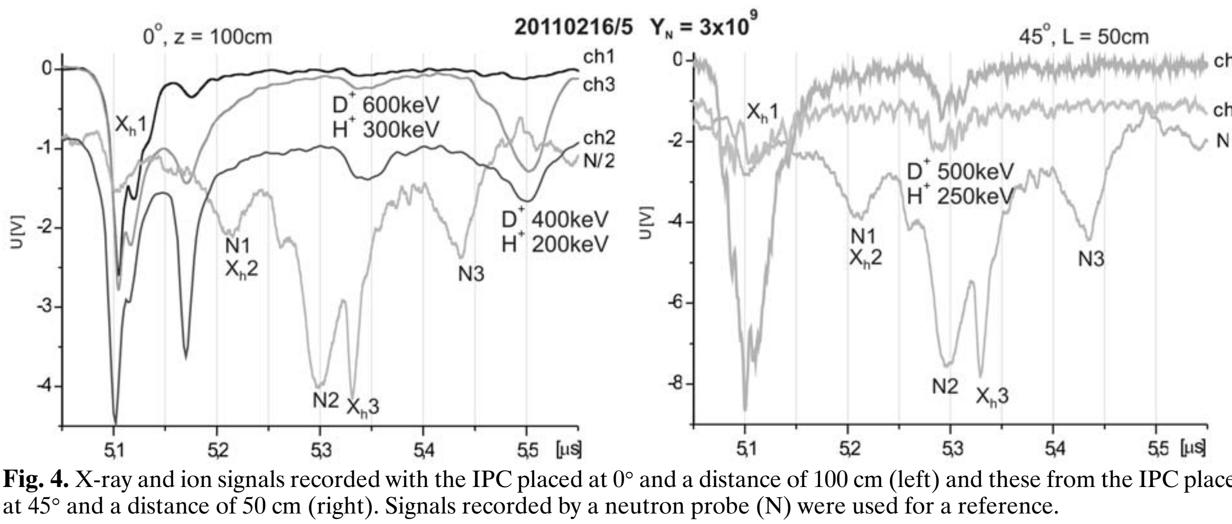

Fig. 4. X-ray and ion signals recorded with the IPC placed at 0° and a distance of 100 cm (left) and these from the IPC placed at 45° and a distance of 50 cm (right). Signals recorded by a neutron probe (N) were used for a reference.

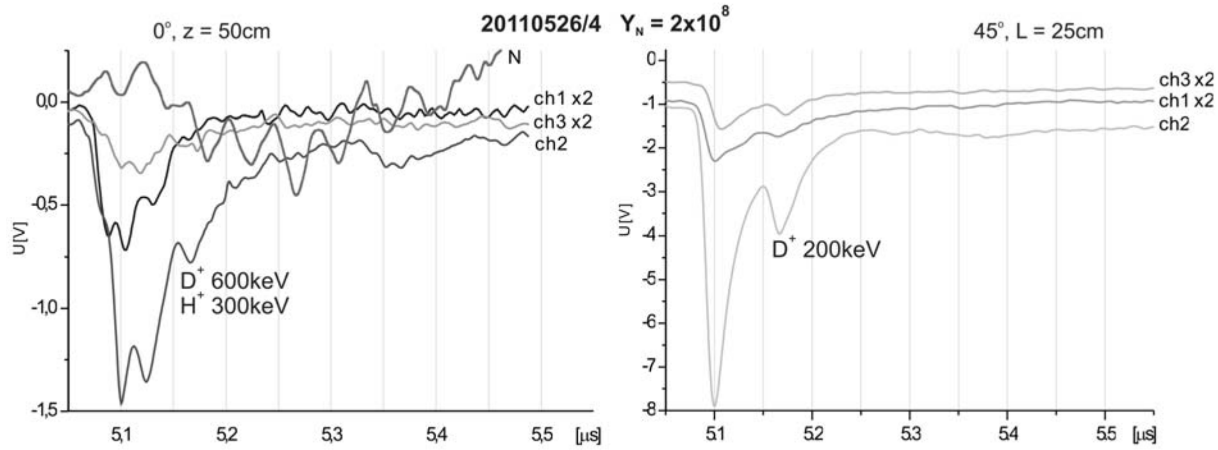

Fig. 5. X-ray and ion signals recorded with the IPC placed at 0° and a distance 50 cm (left) and these from the IPC placed at 45° and a distance of 25 cm (right). For a comparison there are also shown signals from a neutron probe (N) or a Rogowski coil (I).

(ch1–ch3) on the left graph one could easily distinguish four peaks. The first peaks in each channel corresponded to X-rays. The second peaks (after about 70 ns) could correspond to 3 MeV fusion-produced protons because the number of very fast primary ions was negligible. The consecutive pulses could be explained as signals from accelerated primary ions. In this shot we recorded three X-ray pulses (X_h1–X_h3), and the corresponding neutron pulses (N1–N3). Taking into account correlations of the ion detectors signals with X-ray and neutron pulses, one could deduce that the applied scintillation detectors of ions could react to intense X-ray pulses, but they were practically insensitive to fast fusion neutrons. Therefore, the third peaks (at $T = 5.35$ μs) on the ion signals could partly be induced by the X-ray pulses, while the fourth peaks (at $T = 5.5$ μs) were evidently induced by fast ions only. In this cases the calculated ion energies (assuming ion emission during X_h2 and X_h3 pulse) amounted to about 400–600 keV for deuterons (or 200–300 keV for protons). In the ion signals (ch1–ch3) on the right graph one could distinguish two distinct peaks. In this case the first peaks corresponded also to X-ray pulses. The second peaks (at $T = 5.3$ μs) were induced by fast ions. The calculated ion energies (assuming ion emission simultaneous with the X_h2 pulse) amounted to about 500 keV for deuterons.

For a comparison, the signals obtained from two cameras placed at distances of 50 cm and 25 cm from the electrodes ends are presented in Fig. 5.

In these case the calculated energies of deuterons amounted to 200–600 keV, but it should be noted that in this shot the neutron yield was very small and no signal from the neutron probe was recorded. Therefore, in order to determine a time reference, it was assumed that the first registered peak corresponds to an instant of the ions generation.

Summary and conclusions

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

1. The ion measurements in the PF-360 facility, as performed without absorption filters, confirmed a complex spatial structure of the emitted ion streams, which consisted of many microbeams.
2. It was concluded that these microbeams originated mainly from the pinch column and a region between the electrodes.
3. The described time-resolved measurements of ion beams showed that high-energy ions are emitted in a few bunches and they correlate with hard X-ray pulses.
4. The TOF method confirmed, that the ion streams emitted from PF-360 discharges contain 200–600 keV deuterons and 200–300 keV protons.

In order to improve the accuracy of ion measurements one might decrease an energy threshold for the investigated ions (using thinner absorption filters or a magnetic deflector of ions). In order to identify the neutron and hard X-ray signals more precisely one might use two or more neutron probes.

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