NUKLEONIKA 2012;57(1):67–74 ORIGINAL PAPER

Research on spatial and energetic characteristics of the ion beams emitted in the PF-360 discharges

Roch Kwiatkowski,
Elzbieta Skladnik-Sadowska,
Karol Malinowski,
Marek J. Sadowski,
Krzysztof Czaus,
Jaroslaw Zebrowski,
Igor E. Garkusha

Abstract. Experimental results are presented on the spatial structure and energetic characteristics of the fast ion beams produced by high-current discharges in a PF-360 device operated at the National Centre for Nuclear Research (NCBJ, Otwock/Świerk, Poland). The 105 kJ discharges were initiated at the initial deuterium pressure around $p_0 = 6$ hPa and were powered from a 234 μF capacitor bank charged up to 30 kV. The spatial structure of the ion beams was recorded using pinhole cameras equipped with the solid-state nuclear track detectors of the PM-355 type, placed at two different angles (0°, 45°) relative to the discharge axis. The detectors were shielded by thin absorption filters made of pure Al foils of various thickness, which made it possible to record only ions with energies exceeding a chosen threshold value. Similarly as in other plasma focus (PF) experiments, energies of the emitted ions ranged from about 30 keV to about 3 MeV, i.e. they were much higher than the voltage applied to the electrodes. The recorded ion images showed a complex spatial structure of the fast ion beams, which consisted of many micro-beams of different energies. It is possible that these beams were emitted by various local micro-sources (e.g. plasma micro-diodes) the were formed inside the PF pinch column.

Key words: ion beams • PF-360 facility • ion pinhole images

R. Kwiatkowski✉, E. Skladnik-Sadowska, K. Malinowski, K. Czaus, J. Zebrowski
National Centre for Nuclear Research (NCBJ),
7 Andrzeja Sołtana Str., 05-400 Otwock/Swierk, Poland,
Tel.: +48 22 718 0417, Fax: +48 22 779 3481,
E-mail: Roch.Kwiatkowski@ncbj.gov.pl

M. J. Sadowski
National Centre for Nuclear Research (NCBJ),
7 Andrzeja Sołtana Str., 05-400 Otwock/Swierk, Poland
and Institute of Plasma Physics and Laser
Microfusion (IPPLM),
23 Hery Str., 01-497 Warsaw, Poland

I. E. Garkusha
Institute of Plasma Physics,
National Science Center, Kharkov Institute of Physics
and Technology (NSC KIPT),
1 Akademicheskaya Str., Kharkov, 61108, Ukraine

Received: 9 June 2011
Accepted: 19 December 2011

Introduction

The high-current discharges of the plasma focus (PF) type have been studied for many years at numerous laboratories around the world, located in USA, Russia, France, Germany, Italy, UK and other countries. A rich bibliography may be found in various summary and review papers, e.g. [1, 2, 4, 7, 9]. It was observed that PF discharges generate intense pulses of electromagnetic radiation and pulsed streams of high-energy charged and neutral particles, which consist of accelerated primary ions and electrons as well as products of nuclear fusion reactions. Measurements of the emitted deuterons and protons provide a valuable information on the spatial distribution of ion sources and the energetic characteristics of the investigated species. The emission characteristics of PF devices depend strongly on their operational parameters and cannot be determined theoretically. In this paper we report on an experimental study that was performed on the PF-360 device [9] in order to investigate ion beams emitted along the discharge axis and at an angle of 45° to this axis, using nuclear track detectors with different absorption filters. The 45° angle was chosen in order to collect some information on the ion emission anisotropy using the existing diagnostic ports.

Experimental setup

During the experiment described in this paper the PF-360 device [8, 9] was equipped with 300 mm long coaxial electrodes. The outer electrode was a solid copper tube 170 mm in diameter, which made it possible to operate the device at lower pressures due to the fact that the working gas from the inter-electrode region was not lost in the radial direction (as is the case with the transparent squirrel-cage electrode) and could be more effectively collected by a current sheath. The inner electrode was a copper tube 120 mm in diameter, with a 40 mm wide central opening. The inner electrode was surrounded by 80 mm long tubular ceramic insulator.

Plasma discharges were initiated at the initial deuterium pressure around $p_0 = 6$ hPa and they were powered by a 105 kJ pulse delivered from a 234 μF capacitor bank charged initially to 30 kV. The maximum discharge current was approximately 1.8 MA. Pulsed plasma streams were emitted mainly during a characteristic current dip that occurred approximately 5 μs after initiation of the discharge.

The ion beams under investigation were recorded with solid-state nuclear track detectors (SSNTD) installed inside small ion pinhole cameras (IPC), which were placed inside the PF-360 experimental chamber (shown in Fig. 1) at different distances from the electrodes, and at two different angles relative to the z-axis: 0° and 45°. To obtain ion images with a chosen magnifications the detectors may be mounted inside the cameras at various distances from the pinholes. To perform time-resolved ion measurements the IPC's were equipped with miniature scintillation detectors coupled to fast photomultipliers, as shown in Fig. 2. The scintillation detectors were 200 μm thick and their active surface had a diameter of 2 mm. They were shielded against the visible radiation by 1.5 μm thick Al filters. The centres of the scintillators for separate channels were placed at the distance of $x = 4$ mm, 3 mm, and 6 mm relative to the centre of the detector plane, respectively. It means that the channels 1 and 3 recorded ions arriving (behind the pinhole) at an angle of approximately 3° and 5° to the z-axis, respectively, while the channel 2 recorded ions arriving at an angle of approximately 2° to this axis.

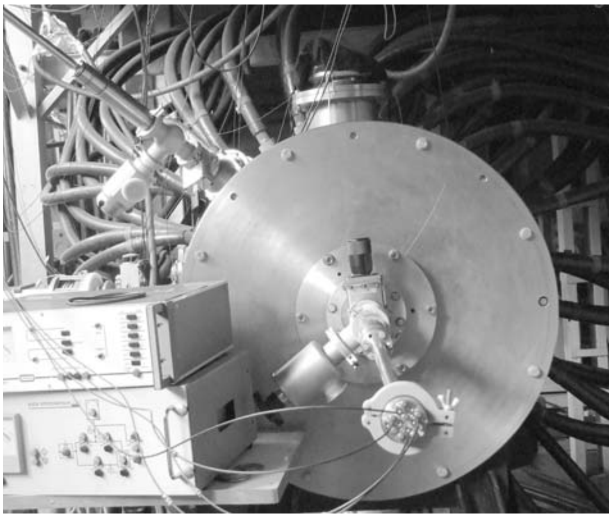

Fig. 1. End-on view of the PF-360 experimental chamber.

In earlier studies [8, 9] it was proved that the PF-360 device can emit bunches of accelerated primary ions (mostly deuterons and protons) with energies up to 700 keV, as well as secondary ions (mainly fusion-produced protons) with energies around 3 MeV. The primary protons were evidently originating from the hydrogen remnants occluded and absorbed in the metallic electrodes and the chamber walls during previous experiments. Some heavy ions from heavier impurities were recorded as well [8].

The IPC's were equipped with solid-state nuclear track detectors (NTD) of the PM-355 type. After irradiation the detectors were etched under standard conditions and analyzed with an optical microscope. To discriminate between different ion energies, the SSNTD were shielded with filters made of pure aluminium foil of different thickness (0.75, 1.5 or 3 μm), which eliminated most of the deuterons with energies below 120, 220, and 380 keV, respectively (see Fig. 3).

It should here be noted that while studying ions emitted during PF discharges one has to take into account the effects of absorption and dispersion of ions in the dense plasma region, in the low-density plasma surrounding the pinch, in the neutral gas layer, and in the absorption filters (as described above). In this paper we report characteristics of ions recorded by the detectors arranged for specific experimental conditions. This information is

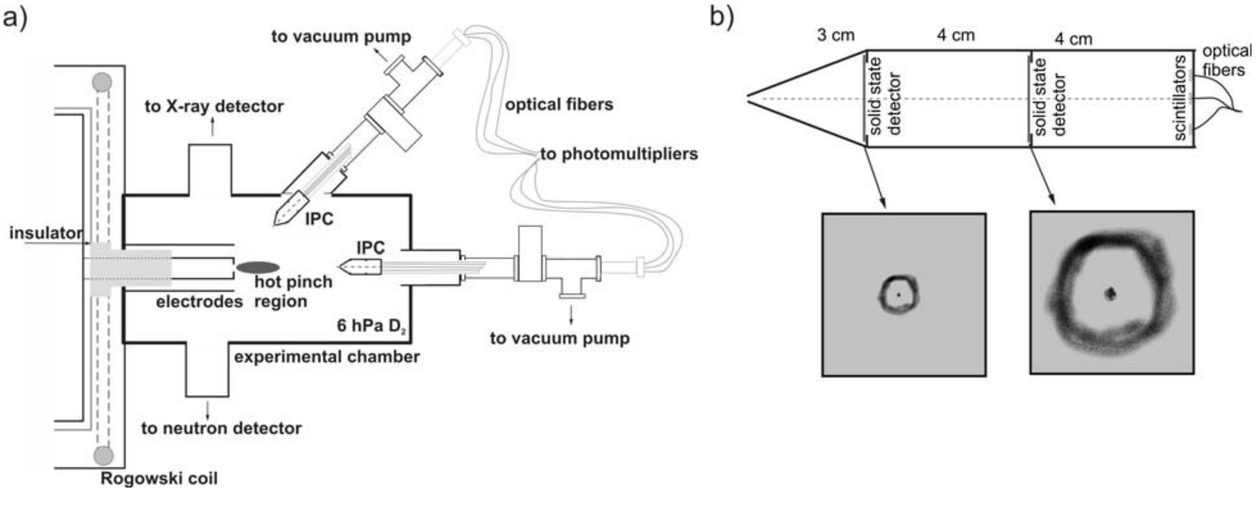

Fig. 2. (a) Schematic view of the PF-360 experiment, showing (not to scale) positions of two ion pinhole cameras; (b) a schematic drawing of the ion pinhole camera with exemplary ion images of different magnification.

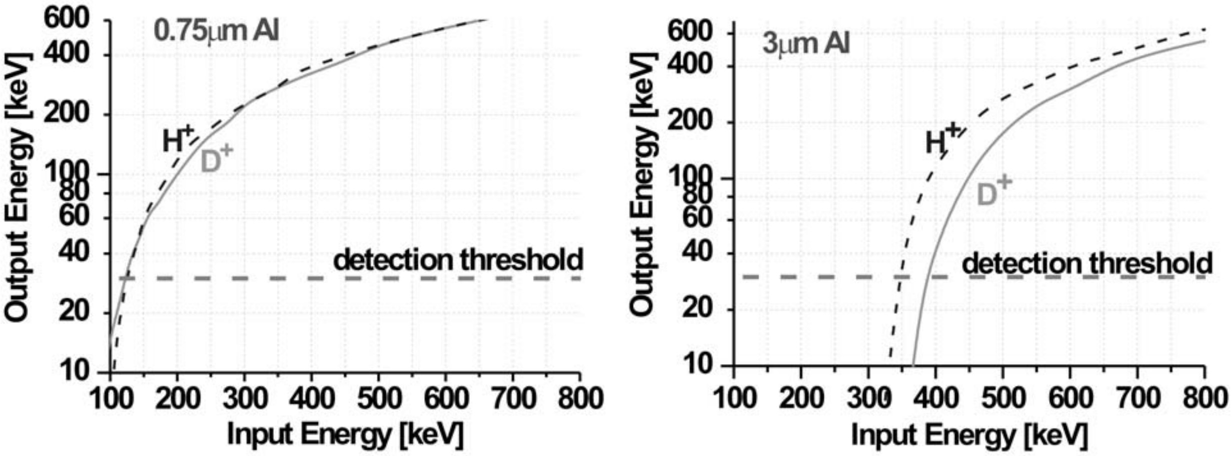

Fig 3. Energies of ions after their penetration through Al-foil filters with the thickness of 0.75 and 3 μm, computed using the SRIM software [6].

of particular importance for practical applications, i.e. for the use of such ion beams in material studies. The recorded ion energies refer to those measured at the detector surface, but since the filters and gas conditions in front of the detectors are known, they may be easily converted into ion energies at the pinhole input. In order to estimate energies of ions leaving the plasma column one can use the SRIM software described below, but due to unknown values of the local plasma density, local magnetic and electric fields, and rapid changes that occur in pinch column microstructures, an exact calculation of these energies is impossible. It should be mentioned that the NTD's used in this experiment cannot record ions with energies below certain minimum value, but they record all ions above the energy threshold. Energies of the recorded ions can also be estimated from dimensions of the etched tracks (micro-craters), provided that the detector calibration curves are known, as is the case with the PM-355 detectors.

The PM-355 detector did indeed record distinct tracks of some ion beams. An estimate of the number of recorded ions and their energies could be obtained via a quantitative analysis of the recorded tracks (micro-craters), performed with an optical microscope. Unfortunately, the calibration characteristics of the NTD's used in this experiment were not known with a precision sufficient for an accurate determination of the ion energies after the tracks had been etched for 2 h. A more precise determination of ion energies could be obtained by extending the etching time, but then it would be impossible to obtain any information from detector regions with high density of tracks. The overlapping of craters could be avoided by using a smaller pinhole, but then the density of the registered tracks would be too low to provide clear images of the ion beams. For this reason during the experiment only the pinholes with the diameter of 0.5 mm were used.

Experimental results

The measurements performed with IPC's during the PF-360 discharges demonstrated that the emitted high-energy ion beams have a complex spatial structure. A comparison of an ion image obtained in this PF-360 experiment with those obtained from the earlier PF-20 and PF-360 experiments [8] is presented in Fig. 4. One can easily notice that despite the differences in experimental conditions the ion images show similar structure, i.e. they are composed of many micro-beams of different energies. This is true not only for the central part of the ion image (recorded at the electrode symmetry axis or close to it), but also for the ring-shaped images produced by micro-beams deflected by the azimuthal magnetic field surrounding the pinch column. It should be noted that the emission of ions in numerous micro-beams has also been observed in many other PF experiments, as described in the known review paper [1] and other publications, e.g. [5, 8].

A comparison of the obtained ion images with the electrode projections has shown that recorded ions originated mainly from the pinch column and the region between the coaxial electrodes. This may be seen in Fig. 5, where the number of ions per square cm recorded in the detector area is shown.

Ion images obtained from two successive PF-360 discharges, recorded at a distance of 100 cm from the electrode ends, are shown in Fig. 6. In this case only ions emitted from the pinch column were detected. In order to estimate a diameter of the ion emitting plasma region (the pinch column), the measured profiles of the ion track densities were fitted to the normal distributions (see Figs. 6a and 6b). The width (FWHM) of these distributions was equal to 1.3 mm for deuterons with energies $E_D > 30$ keV, and 1.2 mm for those with energies $E_D > 225$ keV, respectively. Taking into account the magnification of ion images, the measured FWHM values corresponded to the pinch column diameter, which is approximately 2 cm. These results are consistent with the measurements of the X-rays and the visible radiation performed in previous experiments [8, 9]. One could notice that the ion beam images in Fig. 6 were smaller in size compared to those presented in Fig. 5. This may be attributed to the fact that the ion beam emission has a stochastic character and that there is some jitter in the operation of PF-360. For these reasons the images of the ion beams emitted from PF-360 discharges are irreproducible on a microscopic scale.

In order to investigate the anisotropy of the ion emission and to estimate the dimensions of the pinch

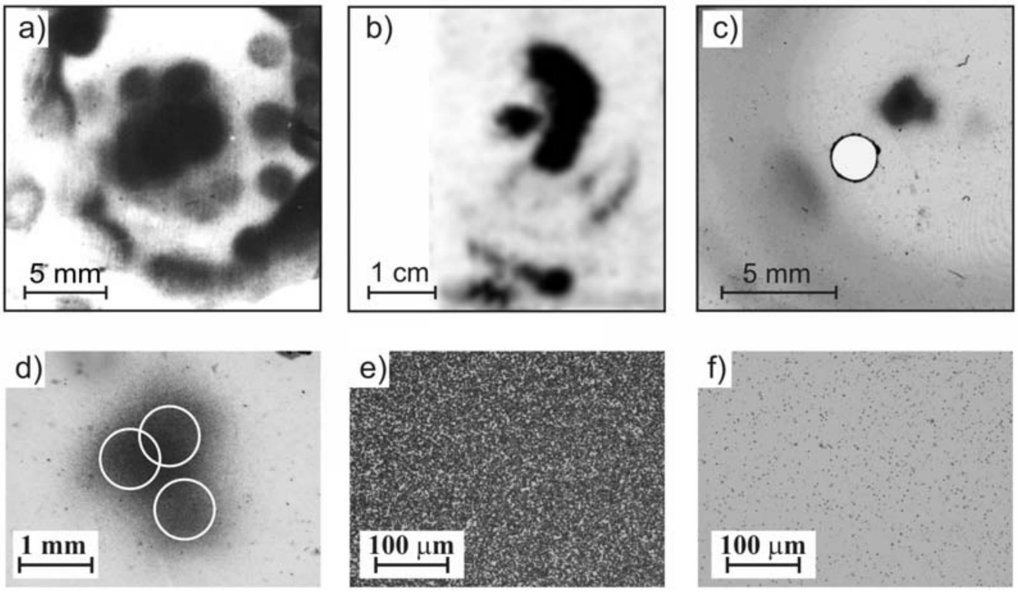

Fig. 4. Top row: (a) The ion images obtained in earlier experiments with a small PF-20 device [8], compared with (b) the ion images from the previous PF-360 experiments [8], and (c) the ion images from the recent PF-360 experiments (a complex ion beam recorded at a small angle relative to the z-axis). In spite of different magnifications (due to the differences in experimental arrangements), one can easily notice that the ion images are not uniform and that they are composed of some micro-beams, as observed in many PF experiments [1]. The bottom row presents a magnified view of the image (c), which shows the appearance of three micro-beams (d), and magnified images of the ion tracks taken in the micro-beam centre (e) and outside of it (f).

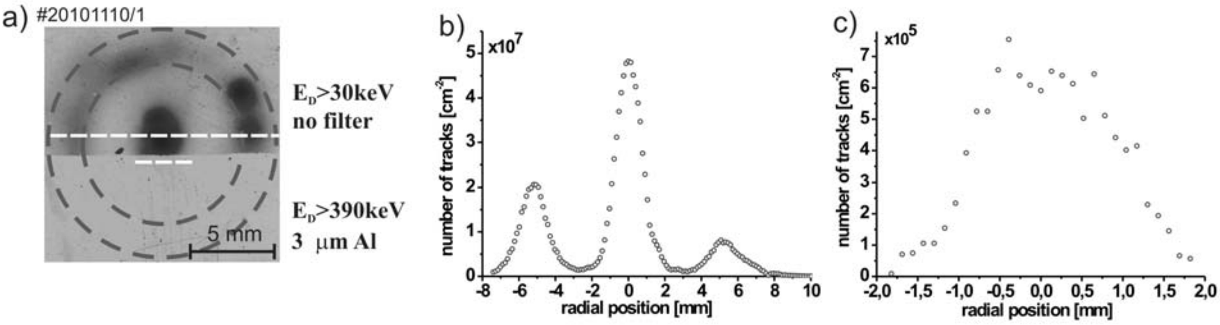

Fig. 5. Images and profiles of the ion beams recorded with the IPC's placed at a distance of 80 cm from the electrode ends. Half of the detector surface was shielded with a 3 μm thick Al foil: (a) the ion image on the detector located 3 cm behind the pinhole (dashed circles show projections of the electrode ends on the detector plane); (b) the ion track density measured along the upper dashed line; (c) the ion track density measured along the lower dashed line (note a different linear scale).

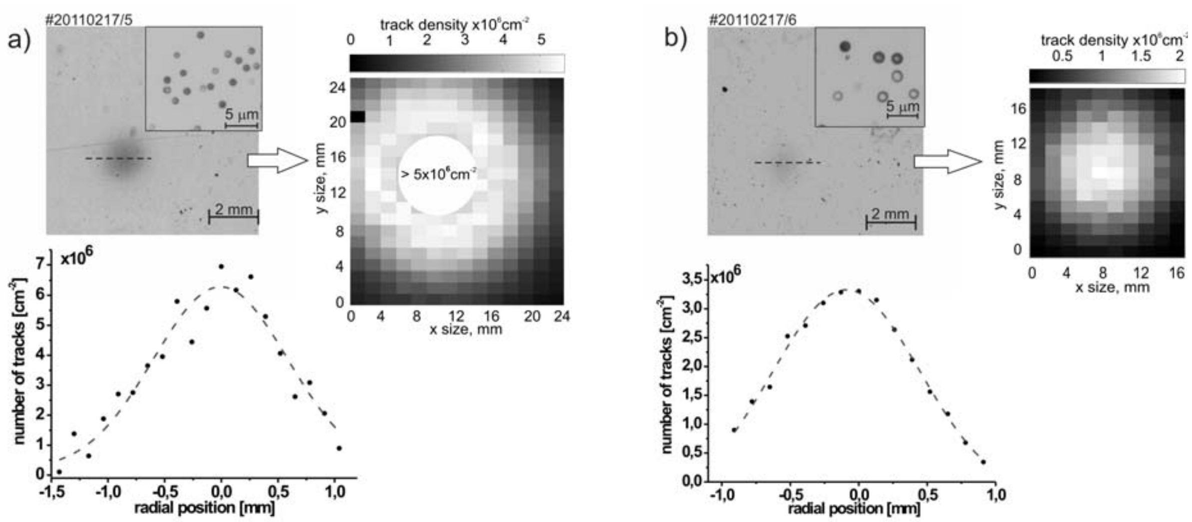

Fig. 6. The ion images recorded with the IPC's placed at a distance 100 cm from the electrode ends: (a) using the detector without any filter; (b) using the detector shielded with a 1.5 μm thick Al filter. The diagrams on the right and at the bottom present results of quantitative analysis and corresponding profiles of the ion track densities, as measured along the dashed lines and fitted to the Gaussian distributions.

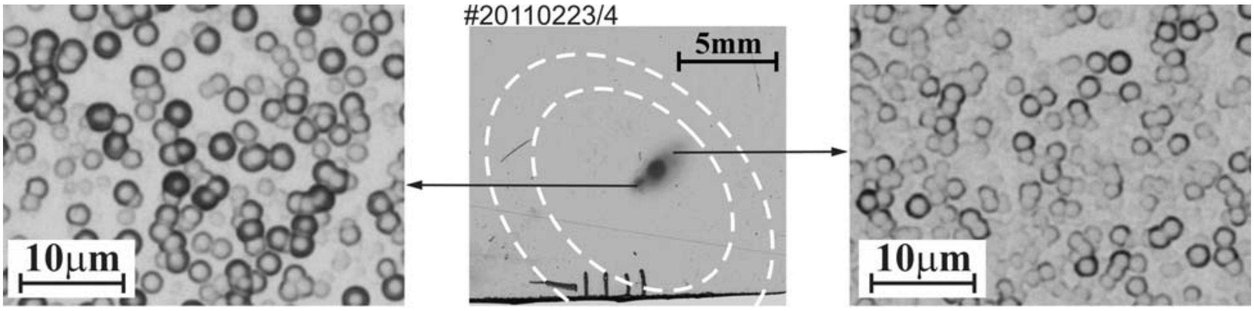

Fig. 7. An ion image recorded with the IPC's placed at an angle of 45° relative to the PF-360 axis, and magnified images of the ion tracks obtained with an optical microscope. The dashed ellipses (marked on the central ion image) correspond to projections of the electrodes outlets.

column, further measurements were performed with the IPC's placed at an angle of 45° relative to the discharge axis (i.e. using the available diagnostic port). In this case no ion images were recorded behind the Al filters of 1.5 and 3 μm thickness, which is attributed to the anisotropy of the ion emission. A clearly visible ion image was recorded only behind the 0.75 μm thick Al filter, as shown in Fig. 7. However, because of the non-perfect light-tightness of the applied Al-foil one cannot exclude that some incoming ions could pass through micro-holes in the Al-foil and create micro-regions with increased track density on the recorded image. Therefore, the obtained result is only of qualitative value. The pinch image recorded on the detector surface was about 3 mm long, which corresponds to the approximately 4 cm long plasma column. This result is consistent with earlier measurements performed in the X-ray and visible electromagnetic spectrum [8]. The magnified images of ion tracks presented in Fig. 7 show certain distribution in track dimensions, which corresponds to a distribution of ion energies (as determined by the PM-355 detector calibration).

It should be noted that local magnetic fields affect the ion trajectories mostly inside the pinch region and in its close proximity. Within this region ions travel along curved paths, while at larger distances from the pinch column they move along straight lines. The trajectories of ions moving along the discharge symmetry axis (z-axis) are nearly straight lines, which makes it possible to estimate the size of the plasma column on the basis of the size of the central ion image. The estimate obtained in this experiment is in a rough agreement with the estimates obtained from measurements of the electron density, which were performed by means of a laser interferometer during early experiments on PF-360 [2]. Unfortunately, in the experiment reported here it was impossible to use this interferometer alongside with other diagnostics.

Analysis of the experimental results

A quantitative analysis of the ion tracks displayed in Fig. 5 showed that the mean ion-flux density recorded 80 cm from the electrode ends was approximately $3 \times 10^7\,\mathrm{cm}^{-2}$ for deuterons with energies above 30 keV, and $4 \times 10^5\,\mathrm{cm}^{-2}$ for those with energies above 380 keV. Analysis of the ion tracks recorded at a distance of 100 cm (Fig. 5) the ion-flux density was approximately $4 \times 10^6\,\mathrm{cm}^{-2}$ for deuterons with energies above 30 keV, and $2 \times 10^6\,\mathrm{cm}^{-2}$ for those with energies above 220 keV. It should be noted that in both cases the distance between the pinhole inlet and the PM-355 detector was identical (7 cm).

The differences in ion flux densities reported here (Figs. 5 and 6) could result from different distances of the pinhole from the electrode outlets, i.e. from the difference in the viewing angle of the ion pinhole camera. Such a discrepancy could be also caused by a difference in thickness of the gas-filled region, which could result in stronger ion stopping and reduce the number of ions arriving at the pinhole inlet. The fact that all the recorded ions had to pass trough a pinhole of a known diameter was taken into account. Some results of this analysis are displayed in Table 1, in which deuteron flux densities at the pinhole inlet are compared for different energy thresholds. The images registered behind the 1.5 μm Al foil filter and images registered without a filter were recorded at a distance of 100 cm, while the image behind the 0.75 μm filter was recorded at a distance of 60 cm. In order to compare the flux densities (at the pinhole inlet) the results of measurements were normalized to the distance of 100 cm, neglecting the influence of the gas layer. The stopping of ions by the gas layer will be discussed below.

In order to estimate how the gas filling the PF-360 chamber could affect the ion energies some numerical computations of the ion stopping were done. A Monte-Carlo (MC) simulation was performed by means of the SRIM software [6], which takes into account the two-body collisions, with some additional assumptions concerning the mean free path and the inter-atomic potential. This code is well known and had been shown to generate predictions consistent with numerous experimental data for a large range of ion masses and energies.

The curves illustrating the dependence between the initial ion energy and its energy after passing through a given gas layer are shown in Fig. 8. From the presented diagrams one can easily see that a 100 cm thick layer of deuterium under a pressure of 6 hPa can eliminate most of the protons and deuterons with energies below 80 and 100 keV, respectively. A gas layer 80 cm thick can stop most of the protons and deuterons with energies

Table 1. Normalized averaged deuteron flux density (number of particles per cm^2) in a single shot, as calculated at the pinhole inlet on the basis of measurements performed with different filters and for deuterons of different energy

Thickness of Al filter (μm)	0	0.75	1.5
Deuteron energy E_D (keV)	> 30	> 125	> 220
Flux density (cm^{-2})	4×10^9	2.3×10^9	1.3×10^9

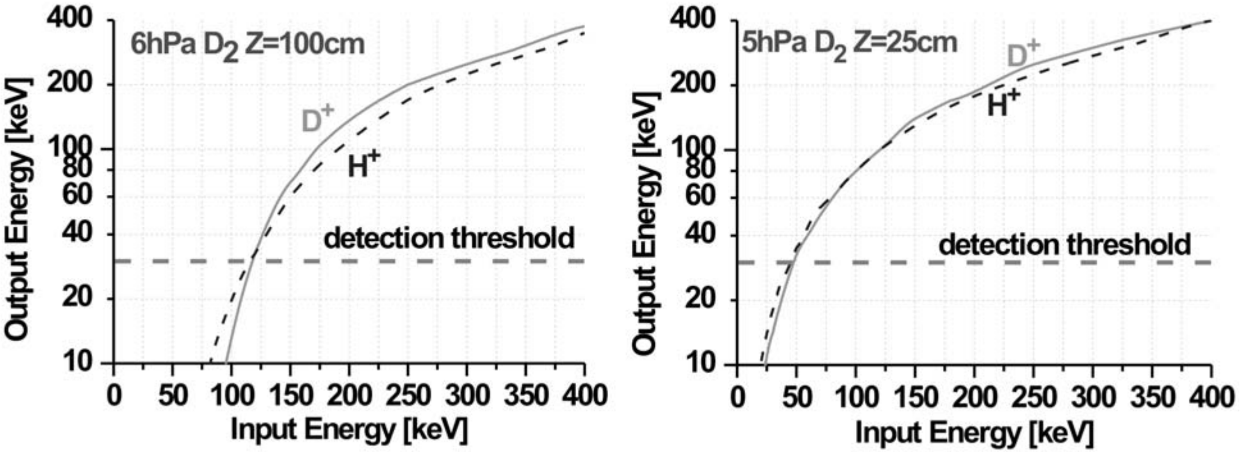

Fig. 8. Energies of protons (H^+) and deuterons (D^+) after their penetration through a layer of deuterium gas (D_2) of different pressure (p_0) and thickness (Z), as computed using the SRIM Textbook [6].

below 50 and 80 keV, while for a 50 cm thick layer these values are reduced to 30 and 50 keV, correspondingly.

The energy losses of ions emitted from the pinch column may be reduced by placing the pinhole inlet closet to the electrodes and reducing the initial deuterium filling pressure, but this could have adverse effect on the formation and dynamics of the PF discharge, making a direct comparison questionable. Nevertheless, during the experiments one should take into account that in order to be able to observe protons with energies down to 20 keV and deuterons with energies down to 30 keV the thickness of the deuterium gas layer under the pressure of 5 hPa should be at most 25 cm. These energies are, however, close to the minimal energy threshold for the PM-355 detectors.

It follows from the simulations that in order to obtain a clear image of the ion (deuteron) beam and to record the low-energy ions, the distance between the pinhole and the ends of the electrodes (Z) – as well as that between the pinhole inlet and the detector plane (L) – should be as small as possible. Also the initial pressure inside the experimental chamber should be reduced, but it may change the operation conditions and the discharge characteristics. The only solution might be the reduction of the gas pressure inside the ion pinhole camera, but this requires an additional pumping system and makes the camera construction more complicated.

The ion pinhole camera used in this experiment allowed to perform measurements at the minimal distance Z equal to 25 cm, with the internal distance L equal to 3 cm, and the initial gas pressure within the PF-360 chamber reduced to only 5 hPa only, because of the safety precautions. The reduction of the working gas pressure allowed less energetic ions to penetrate through the gas volume inside the PF-360 chamber.

In order to perform preliminary time-resolved measurements of the ions, and to estimate the energies of ions hitting the detector plate, we applied also a different method, based on miniature scintillation detectors. Such detectors were placed inside the pinhole camera and shielded with a 1.5 μm Al foil (in order to eliminate the effect of visible radiation), and then coupled with fast photomultipliers through separate optical cables. Such an arrangement allowed us to perform time-resolved measurements of ions emitted from different pinch regions. The signals were recorded by means of a digital oscilloscope. Knowing the distance between ion source (the pinch column) and the scintillation detector, and making some assumptions regarding the duration of the ion emission (on the basis of hard X-ray peaks) it was possible to estimate ion energies by means of the time-of-flight (TOF) method. An exemplary result is presented in Fig. 9a.

In the recorded time-resolved ion waveforms (in all three channels) one could discern four peaks. The weakest signals were obtained from the channel 1, which was sensitive to the anisotropy in the ion emission. The primary peaks in each channel corresponded evidently to X-rays. Unfortunately, from the scintillation signals alone one could not discern the fast primary deuterons from the primary and secondary protons. The secondary peaks (appearing after about 70 ns) might correspond to 3 MeV fusion-produced protons, because the number of very fast deuterons was negligible. Since from other measurements performed with a Thomson analyzer [3] it was known that the population of primary protons (originating from remnants of occluded and absorbed hydrogen) was two to three orders of magnitude lower than that of primary deuterons, the subsequent pulses could be explained as signals from the accelerated primary deuterons (and partly from the fast protons).

In the PF-360 discharge considered here three distinct X-ray pulses were emitted, accompanied by neutron pulses which were recorded by the neutron probe after each X-ray pulse with a delay (TOF) of about 120 ns, as shown in Fig. 9b. Analyzing the correlations of the ion detector signals with the X-ray and neutron pulses, as recorded by the neutron scintillation probe (see Fig. 9b), one could deduce that the thin and small scintillation detectors used to record ions were practically insensitive to the fast fusion neutrons, but they showed some sensitivity to intense X-ray pulses. Therefore, the tertiary peaks on the ion signals could be partly induced by the X-ray pulses, while the quaternary peaks on these waveforms were evidently induced by fast ions only. In future experiments we plan to use a Thomson-type analyzer [3] adapted for the time resolved measurements, which would eliminate unknown input from the primary protons, thus facilitating the analysis of correlations with X-ray and neutron pulses.

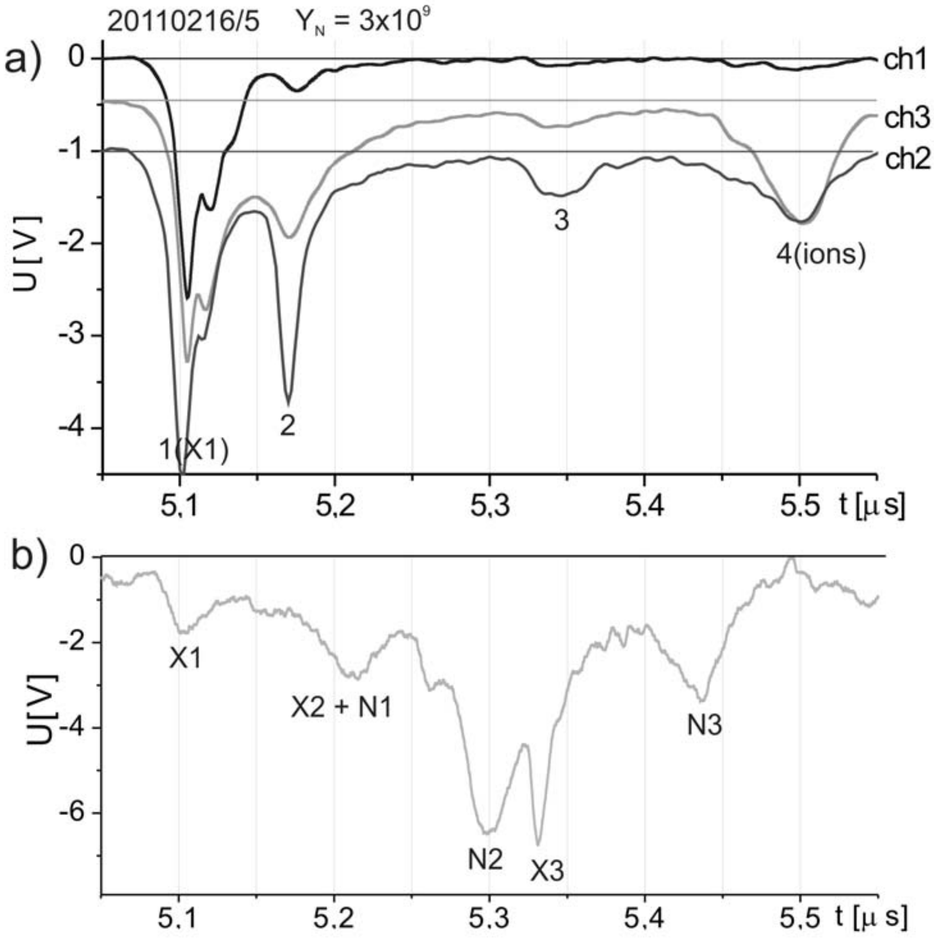

Fig. 9. Time-resolved signals obtained from three miniature scintillation detectors (a), which were placed inside an ion pinhole camera located on the z-axis at a distance of 100 cm from the PF-360 electrode outlet. For comparison the time-resolved signals obtained from the neutron scintillation probe are shown below (b), with marked hard X-ray (X) and neutron signals (N). The neutron probe was placed end-on, at a distance of 2.5 m from the pinch centre.

Summary and conclusions

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

- The measurements of ions generated in the PF-360 discharge, which were performed without the absorption filters, confirmed a complex spatial structure of the emitted ion streams, which consisted of many micro-beams (as may be seen in Fig. 3). It was concluded that these micro-beams originated mainly from the pinch column and the region between the electrodes.
- The ion images obtained behind different filters, recorded along the discharge axis and at a 45° angle to it, made it possible to estimate the dimensions of the pinch column, which came out to be consistent with results from VR and X-ray images. The earlier measurements with a laser interferometer [2] gave similar values of the pinch dimensions during the *quasi*-stable phase.
- The numerical simulation of ion propagation showed that in order to obtain sharp images of ion beams and to record low energy ions, the distance between the electrode ends and the pinhole inlet should be reduced, and the initial gas pressure inside the experimental chamber should be made as small as possible. Such a change of the experimental conditions may however modify the pinch dynamics and the ion emission characteristics.
- The time-resolved measurements of the ion beams should be continued, but to discern fast deuteron signals from the accelerated primary protons and fusion-produced protons one should apply a Thomson-type analyzer equipped with appropriate ion detectors placed upon different parabolas.

References

1. Bernard A, Bruzzone H, Choi P *et al.* (1998) Scientific status of plasma focus research. J Moscow Phys Soc 8:93–170
2. Herold H, Jerzykiewicz A, Sadowski MJ, Schmidt H (1989) Comparative analysis of large plasma focus experiments performed at IPF, Stuttgart, and IPJ, Swierk. Nucl Fusion 29:1255–1269
3. Sadowski MJ, Czaus K, Malinowski K, Skladnik-Sadowska E, Zebrowski J (2009) Mass- and energy-analyses of ions from plasma by means of a miniature Thomson spectrometer. Rev Sci Instrum 80:053504 (4 pp)
4. Scholz M, Bienkowska B, Ivanova-Stanik IM *et al.* (2006) Studies of pinch dynamics and fusion-products emission within megajoule plasma-focus facility. Rus Phys J 49:161–164
5. Skladnik-Sadowska E, Baranowski J, Milanese M *et al.* (2001) Spatial structure and energy spectrum of ion

beams studied with CN detectors within a small PF device. Radiat Meas 34:315–318

6. SRIM Textbook, http://www.srim.org
7. Steinmetz K, Hubner K, Rager JP, Robouch BV (1982) Neutron pinhole camera investigation on temporal and spatial structures of plasma focus neutron source. Nucl Fusion 22:25–30
8. Zebrowski J (2006) Studies of corpuscular and X-ray radiation emitted from plasma-focus discharges. PhD Thesis, Institute for Nuclear Studies, Otwock/Świerk, Poland
9. Zebrowski J, Sadowski MJ, Czaus K, Paduch M, Tomaszewski K (2004) Peculiar features of plasma-focus discharges within PF-360 facility. Czech J Phys 54:643–659