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ORIGINAL PAPER

Measurements of electron and ion beams emitted from the PF-1000 device in the upstream and downstream direction

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Abstract. In this paper we report on measurements of the energy spectra and other properties of the electron and fast ion beams emitted in the upstream and downstream direction along the *z*-axis of a large plasma focus device PF-1000, that was operated at 21–27 kV, delivering 290–480 kJ pulse. Measurements of the electron beam (EB) properties were performed using a magnetic analyzer. Properties of the ion beams were measured by means of pinhole cameras equipped with PM-355 nuclear track detectors and placed at various angles (0, 60 and 180°) to the discharge axis. Measurements revealed a complex spatial structure of the fast ion beams. The ion measurements behind the PF-1000 collector proved that some fast deuterons are emitted also in the upstream direction. Measurements of the EBs emitted in the upstream and downstream direction revealed electron energies in the range from approximately 40 keV to approximately 800 keV. These spectra confirm that in localized regions within the PF-1000 plasma column there appear strong fields accelerating charged particles in different directions along the discharge axis.

Key words: electron beam (EB) • ion beams • PF-1000 facility • magnetic analyzer • ion pinhole cameras (IPC)

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Introduction

Research on high-current discharges of the plasma focus (PF) type has been carried out in different laboratories for many years [1, 2, 5, 7]. It was observed that such discharges are sources of intense pulsed beams of high-energy charged particles, which consist of accelerated primary ions and electrons as well as charged products of nuclear fusion reactions. Experimental studies of the emitted particles (deuterons, protons, and electrons) are an important source of information concerning electromagnetic fields in the discharge column, which are responsible for the acceleration of these particles, and the spatial distribution of ion sources as well.

The main aim of the experimental study reported below, which was performed using the PF-1000 device [5], was to record electron and ion beams emitted along the axial acceleration direction of the current sheath, both in the upstream and downstream direction.

The experimental setup

At the time when the experiments reported in this paper were being performed, the PF-1000 device was equipped with 460 mm long coaxial electrodes. The outer electrode (cathode) of the squirrel-cage type consisted of 12 stainless steel tubes 80 mm in diameter, which were positioned symmetrically in the form of a cylinder with the diameter of 400 mm. The inner electrode (anode) was a solid copper tube 230 mm in

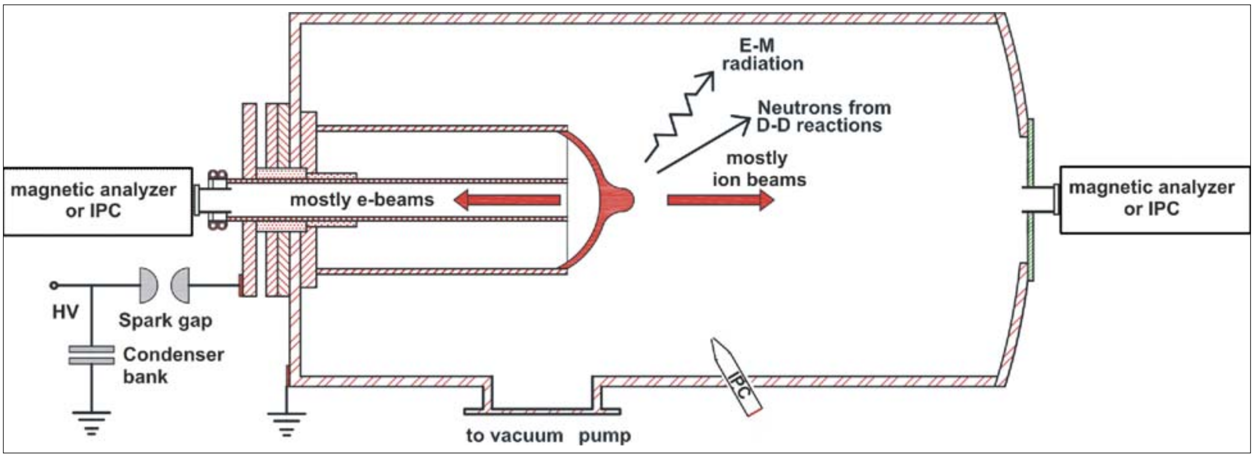

Fig. 1. Schematic drawing of the PF-1000 device (not to scale). Positions of the magnetic analyzer during measurements of EBs are indicated, as well as positions of ion pinhole cameras used for measurements of ion beams.

diameter, with a 40 mm wide central opening [5]. In all the experiments reported here the plasma focus discharges were triggered at the initial pressure of 1 hPa D_2, and they involved a release of 290–480 kJ of energy from a 1.32 mF condenser bank charged initially to 21–27 kV. The maximum discharge current was approximately 1.5–1.8 MA.

Measurements of the fast ion beams were carried out by means of ion pinhole cameras (IPC) equipped with PM-355 track detectors and various absorption filters. The cameras were placed at the angles of 0, 60 and 180° relative to the z-axis, at distances z = 162, 74 cm and –74 cm, respectively (negative values of z correspond to the upstream region). The cameras were introduced into the PF-1000 chamber through a T-pipe and a valve, which made it possible to replace detectors without compromising the vacuum conditions.

Measurements of the electron energy spectra were performed with a magnetic analyzer, which was positioned on the z-axis behind the main collector plate, at a distance of –160 cm from electrode outlets (i.e. in the upstream direction) or alternatively on the end-plate of the vacuum chamber, at a distance z = 200 cm (i.e. in the downstream direction), as shown in Fig. 1.

The magnetic analyzer was equipped with an input collimator and permanent magnets deflecting the incoming electrons. In order to record the deflected electrons the use was made of an X-ray film, shielded with a thin metal (Al) foil, which converted the electron signals into X-rays. A schematic drawing of the analyzer is presented in Fig. 2.

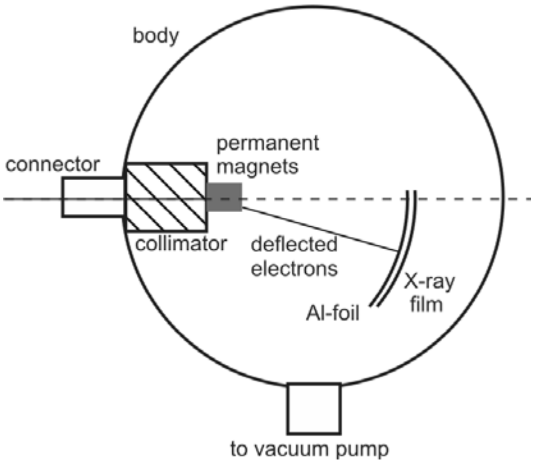

Fig. 2. Schematic drawing of the magnetic analyzer used for electron measurements.

The pinhole cameras were equipped with internal supports, which made it possible to place the PM-355 track detector at different distances behind the input diaphragm, as shown in Fig. 3.

Experimental results

In this section we present most important experimental results on the ion and EBs, obtained via measurements performed both in the upstream and downstream locations.

Measurements of the accelerated ions

The signals recorded by the PM-355 detectors indicated that the ion beams have a complex spatial structure and consist of many micro-beams. Such micro-beams might be generated in numerous micro-regions inside the pinch column, where strong electric and magnetic fields are produced due to a local instability. A comparison of the electrode projections with the ion images suggests

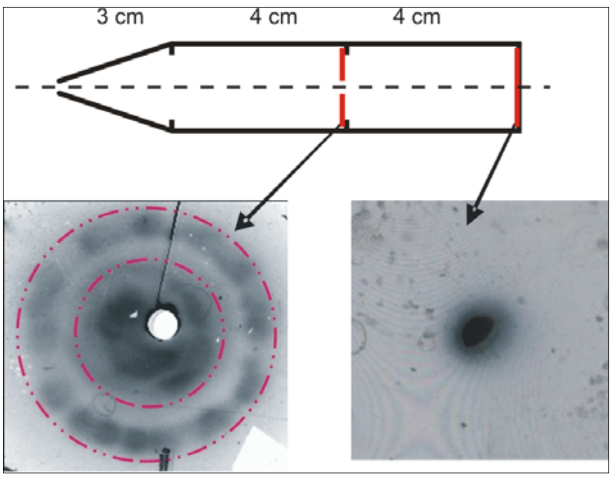

Fig. 3. Schematic drawing of the IPC and the images of ion beams recorded along the z-axis for two different positions of the detector. Circles drawn with a broken line show projections of the electrodes.

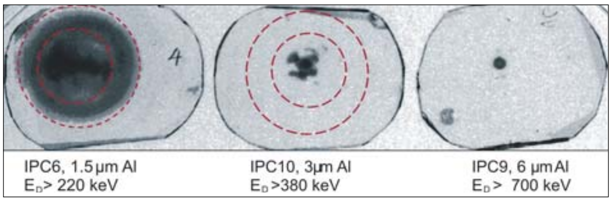

Fig. 4. Images of ion beams emitted during 290 kJ shots, as recorded at 0°, at a distance of 162 cm. These images were obtained with different filters and showed the presence of deuterons of the following energies: left – E_D > 220 keV; middle – E_D > 380 keV; right – E_D > 700 keV.

that the recorded ions originated mainly from the pinch column and the regions between the electrodes. To study the spatial structure of the high-energy deuteron and proton beams, the pinhole cameras were equipped with PM-355 track detectors shielded with absorption filters made of Al foil of various thickness. Some examples of the recorded signals are shown in Fig. 4.

The quality of the PF-1000 discharge was estimated on the basis of the total neutron yield (Y_n). Unfortunately, no clear correlation between Y_n and the parameters of the studied ion beams had been observed. This might be explained as follows: the deuterons which are responsible for the production of fusion neutrons have energies mostly in the range from 10 keV to about several dozen keV, and they are lost in the fusion reactions. It is only the high energy ions (deuterons) which can penetrate the plasma and contribute to the signal recorded by the track detectors.

From an analysis of the recorded tracks it was determined that for a single PF-1000 shot and the pinhole inlet placed at a distance of 162 cm along the z-axis the deuteron flux for deuteron energies above 380 keV was approximately 2.4×10^9 deuterons/cm^2, while for the deuteron energies above 700 keV it was approximately 1.0×10^9 deuterons/cm^2. The deuteron fluxes along the line of sight inclined at an angle of 60° to the z-axis and the pinhole inlet placed at a distance of 74 cm) were found to be approximately 9×10^8 deuterons/cm^2 for the deuteron energies above 380 keV, and 1.2×10^8 deuterons/cm^2 for the deuteron energies above 700 keV. An information on the spatial microstructure of the deuteron beams could be gleamed from the macro-photographs of the recorded tracks, as shown in Fig. 5.

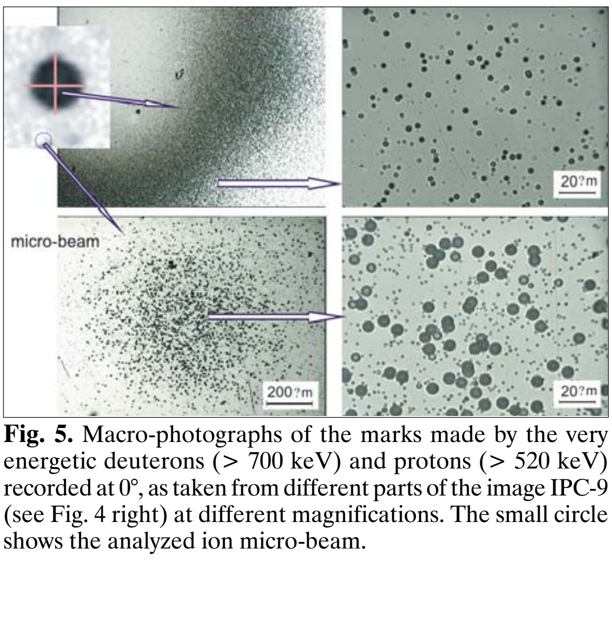

Fig. 5. Macro-photographs of the marks made by the very energetic deuterons (> 700 keV) and protons (> 520 keV) recorded at 0°, as taken from different parts of the image IPC-9 (see Fig. 4 right) at different magnifications. The small circle shows the analyzed ion micro-beam.

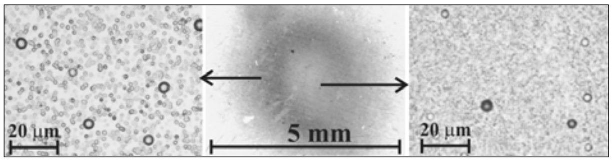

Fig. 6. Ion pinhole image (center) provided by the camera placed at z = –74 cm (behind the axial channel in the inner electrode) during a single shot #8408 with $Y_n = 1.5 \times 10^{11}$. Parts of the image (shown on left and right) were analyzed at a larger magnification.

In many PF experiments a very strong anisotropy of the fusion-neutron and ion emission was observed. Some researchers suspected that a portion of the fast deuteron population might be accelerated and emitted also in the upstream direction. To clarify this issue a particular attention has been paid in this experiment to the ion pinhole measurements at 180°, i.e. behind the collector plate in the upstream direction. Some results are presented in Fig. 6. Figure 6 constitutes the first experimental evidence that in the high-current PF-1000 discharges the high--energy deuterons are emitted also in the upstream direction. On the basis of the recorded tracks it was estimated that at the pinhole inlet placed at z = –74 cm the fluxes of deuterons for the deuteron energy in the range above 30 keV, above 380 keV and above 700 keV amounted to approximately 1.4×10^8 cm^{-2}, 9.2×10^7 cm^{-2} and 2.2×10^6 cm^{-2}, respectively, i.e. they were about two orders of magnitude smaller than the fluxes of deuterons emitted along the z-axis.

Measurements of the accelerated electrons

Measurements of electrons accelerated in the PF-1000 device were performed both in the upstream and the downstream direction. In the case of the measurement in the upstream direction the use was made of two X-ray films arranged in the form of a sandwich, so that the first film worked as an absorption filter for the second one. In this way the saturation effect was eliminated. Both films were wrapped up in a non-transparent 30-μm-thick Al foil, supported in the analyzer by several thin tungsten wires and irradiated there during a single shot or several PF discharges. After developing the films it was possible to determine the energy spectra of the recorded electrons. Some examples are presented in Fig. 7.

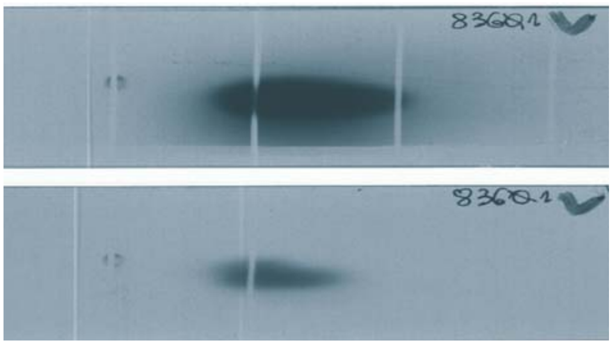

Fig. 7. Electrons emitted in the upstream direction, as recorded with the magnetic analyzer on the first film (up) and on the second one (down) for the shot #8361, with $Y_n = 1.9 \times 10^{11}$.

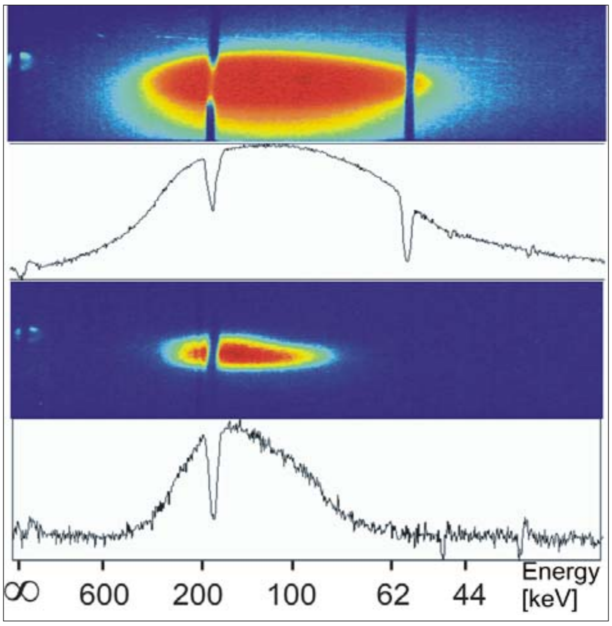

Fig. 8. Color enhanced isodensity profiles of the electron images and energy spectra determined for electrons emitted in the upstream direction, recorded at $z = -74$ cm during the PF-1000 shot #8361. The 1st film (top) showed some saturation, but the 2nd one (bottom) showed a distinct maximum. The local minima corresponded to positions of the thin tungsten wires.

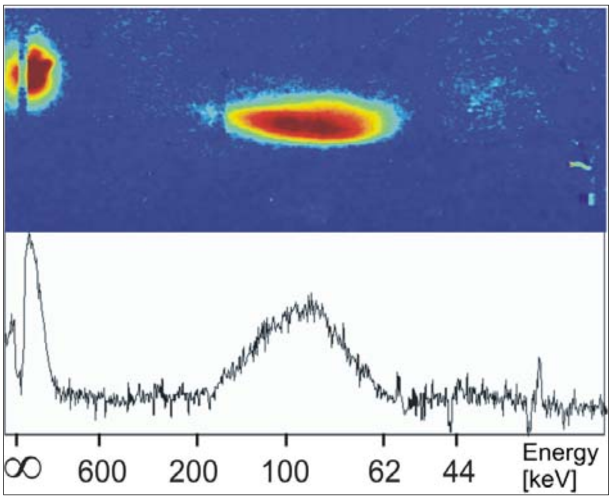

Fig. 9. Electrons emitted in the downstream direction at $z = 200$ cm, recorded on the 1st film, and a corresponding color-enhanced densitogram with the corresponding energy distribution, as measured for three successive shots with the total neutron yield $Y_n = 2.5 \times 10^{11}$.

The elliptical shape of the spots recorded on films is a result of the applied detection method. The electrons after being deflected by the analyzing magnetic field were converted into X-rays inside a thin Al foil filter, which was placed on top of the sensitive X-ray film. The X-rays generated in this way had a slight divergence, which resulted in the broadening of the recorded picture, proportionally to the X-ray intensity. Zero points on the exposed films were produced by fast neutral particles and they corresponded to electrons of extremely large energy. Bright vertical lines on the films coincide with the positions of the thin tungsten wires; this fact may be used to determine the spatial scale of the images. The energy scale was determined on the basis of the known magnetic field and the analyzer dimensions. Darker areas on the exposed X-ray film correspond to higher intensities of the recorded EBs. In this way it was possible to determine the energy spectra of the recorded electrons, as shown in Fig. 8.

It was found that the energy spectrum of the electrons emitted from PF-1000 device in the upstream direction extended from approximately 40 keV to approximately 800 keV. This confirms that accelerating fields in the PF plasma are considerably higher than the voltage applied to the electrodes (21 kV), a phenomenon whish was also observed in other PF experiments [1–3, 6, 7].

As mentioned above, measurements of fast electrons were also performed with the analyzer placed along the z-axis, i.e. in the downstream direction. Sample results are shown in Fig. 9. Those measurements provide a new experimental evidence that fast electrons may be emitted also in the downstream direction, as observed in some previous experiments [4].

A quantitative analysis of the exposed films showed that the number density of the fast electrons emitted in the downstream direction is considerably smaller than in the upstream direction, and that their energy spectra extend from approximately 60 keV to approximately 200 keV.

Differences in the spectra of electrons emitted in upstream and downstream direction may be explained by the fact that electrons emitted upstream have to penetrate only through the plasma and the neutral gas in the inner electrode channel, while those emitted downstream must pass through an extended plasma region (i.e. through the ejected plasma stream). Another reason might be the influence of strong local electric (and magnetic) fields, which are generated inside the PF pinch column.

Summary and conclusions

The most important results of our experiment may be summarized as follows:

1. The experimental studies of the ion emission from the PF-1000 device confirmed that during high current PF discharges intense ion beams are emitted mostly along the z-axis. These ion beams have a complex spatial structure and they consist of many micro-beams of energies exceeding 380 keV and some micro-beams of energy exceeding 700 keV.
2. The ion measurements behind the main collector of the PF-1000 device provided the first experimental evidence that some ion beams are also emitted through the axial opening of the inner electrode in the upstream direction. The ion fluxes in such emission are about two orders of magnitude smaller than in the case of beams emitted in the downstream direction.
3. The studies of the electron emission performed by means of the magnetic analyzer placed upstream and downstream of the PF-1000 device showed that during the high-current PF discharges beams of fast electrons are also emitted. These beams are to some degree attenuated by the plasma and the neutral gas. Despite that the electrons recorded in the upstream

direction (behind the inner electrode channel) have energies reaching 800 keV. The number of fast electrons emitted along the *z*-axis is considerably smaller and such electrons appear to be less energetic, which may be due to the fact that they need to penetrate larger plasma (and gas) volume.

One may conclude that experimental studies of the electron and ion beams generated in the PF-1000 device should be continued in order to investigate their spatial structure in more details. It would be of particular interest to perform time-resolved measurements, which could provide insight into the temporal characteristics of the emission processes. Such studies should be complemented with numerical modeling of the acceleration process and the tracking of charged particle trajectories in high-current PF discharges.

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