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ORIGINAL PAPER

Comparison of characteristics of pulsed ion beams emitted from different small PF devices

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Abstract The paper concerns studies of pulsed ion beams emitted from different small-energy (5–50 kJ) devices of the plasma focus (PF) type. Emission characteristics of the ion beams as measured with nuclear track detectors (NTDs), Faraday-type collectors (FC), and Thomson-type analyzers, are summarized. Common features of the ion emission are considered and some differences are discussed.

Key words Faraday cups • ion-beams • plasma focus • Thomson analyzers • track detectors

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Introduction

Studies of pulsed ion beams, as generated by PF-type discharges, have been carried out in different laboratories for many years [2–5, 8, 10–12]. General characteristics of high-energy (>100 keV) ion beams, e.g. their angular distributions and energy spectra, have been investigated within PF devices of energy ranging from several kJ to above 500 kJ. Also investigated were energy spectra of impurity- and admixture-ions appearing in various ionization states [10]. Temporal characteristics of the ion pulses, and in particular the correlation of those with other PF phenomena, were also studied to some extent [1, 3–5, 8, 10–13]. Unfortunately, the emission features of different PF facilities differ considerably and it is necessary to perform some ion measurements within each device to be sure about the real emission characteristics. Since the fast ions can be applied for the ion implantation, a thermal treatment, and ion-assisted coating of various materials, particular attention has recently been paid to studies of the ion beams emitted from small-scale (5–50 kJ) PF devices. Such facilities are relatively simple and inexpensive and may be easily applied in different research and industrial laboratories.

The main aim of this paper has been to compare characteristics of the pulsed ion beams obtained from different small-energy (5–50 kJ) PF devices, which were investigated in IPJ, INFIP, and IFAS.

Studies of ions from small PF-devices in IPJ

Research on the ion emission from PF-type discharges was initiated in IPJ at Swierk, Poland, in the early 70s. Experimental studies of the pulsed ion beams were for the

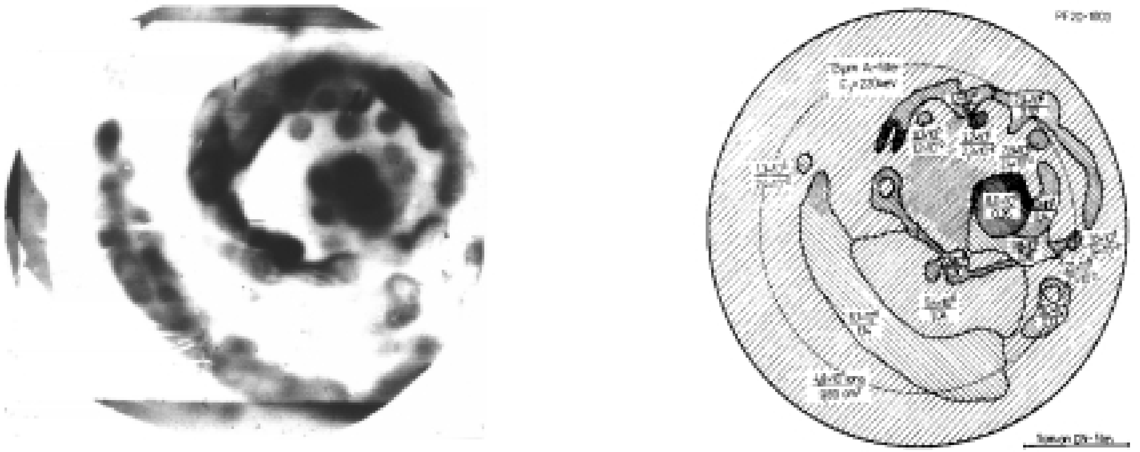


Fig. 1. The ion-pinhole picture, showing a complex structure of the pulsed ion beams (on the left), and a corresponding map of the ion fluxes (on the right), as measured for a single shot performed within the PF-20 device operated at 12 kJ, 34 kV [5].

first time performed with a small PF-20 machine, operated with the D_2-filling at 12 kJ, 34 kV [11]. The device was equipped with coaxial electrodes of 60 and 100 mm in diameter, and about 160 mm in length. To study high-energy ions (mostly deuterons) the use was made of several pinhole cameras, which were equipped with NTDs and placed end-on and side-on the experimental chamber. The ion pinhole pictures, as taken end-on with an 8 cm long camera placed about 15 cm from the electrodes ends, delivered complex ion images composed of numerous microbeams, which formed the central ion stream and ring-shaped (tubular) ion bunches, as shown in Fig. 1. A detailed analysis of the ion tracks showed that individual ion microbeams are almost homogeneous and contain mainly deuterons ($<1\%$ impurity ions). The total flux of deuterons within energy range 220 keV $< E_D <$ 1 MeV was estimated to be 8×10^7 deuterons/10 cm^2, including some 5×10^7 deuterons in a quasi-homogeneous background. Using thicker Al-foil filters there were selected microbeams containing deuterons of higher energy. Within the energy range 1.7 MeV $< E_D <$ 2.5 MeV there were found only several distinct microbeams containing about 5×10^5 deuterons.

Energy distributions of the fast deuterons emitted from PF discharges were investigated e.g. by a German-Polish team in the IPF, Stuttgart [10]. Those spectra, as measured in a 56 kJ PF experiment, ranged from about 300 keV (the lower detection threshold) to about 3 MeV. They were well approximated by an exponential law exp $(-\alpha E_D)$, where α was 2 MeV^{-1} for lower energy deuterons and 4–8 MeV^{-1} for high-energy ones. Similar energy spectra were also observed in other small-scale PF experiments, although values of a were slightly different.

Considering the ion microbeams emitted from the PF region, one should take into account their slowing-down within the dense plasma column and a neutral gas volume (between the focus and the detection plane). An effect of the working gas might be a lateral spread of the ion microbeam caused by multiple scattering (elastic and ionizing collisions). The lateral broadening and natural divergence of the ion microbeams was measured experimentally by taking the ion pictures at different distances behind the entrance diaphragm, as shown in Fig. 2.

An angular distribution of the ion emission was investigated within a small 4 kJ PF device called the PGN (Plasma Generator of Neutrons), which was equipped with coaxial electrodes of 20 and 50 mm in diameter, and about 100 mm in length. Using CN- or CR39-films (nude and covered with

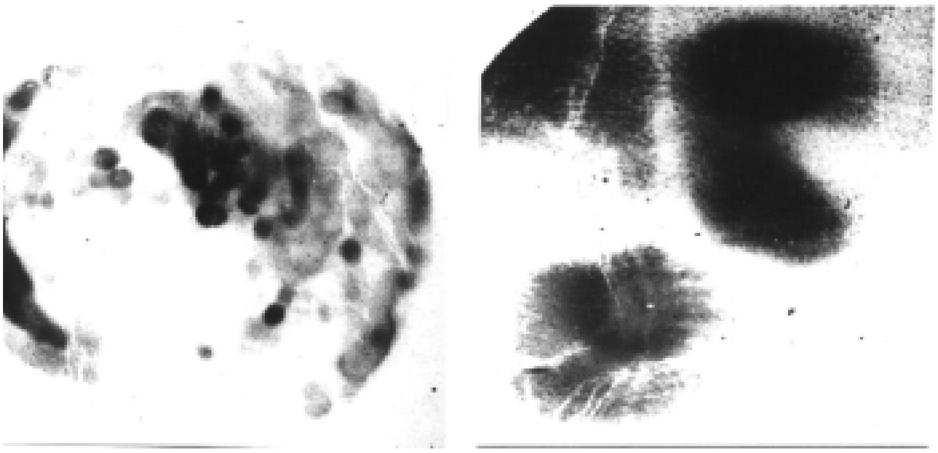


Fig. 2. Ion pinhole pictures taken at different distances behind the diaphragm, which demonstrate the natural divergence and lateral spread of the deuteron microbeams of energy $E_D > 380$ keV (registered behind 3.0 μm thick Al-filters). Measurement geometry: $l_p = 120$ mm, $l_1 = 90$ mm, and $l_2 = 650$ mm.

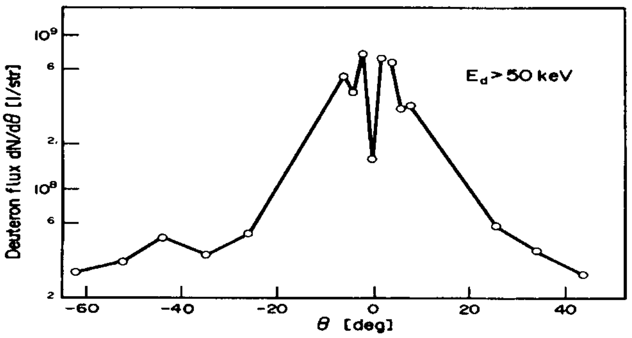


Fig. 3. Typical angular distribution of fast deuterons, as measured within the PGN device, which was operated at p_0 = 5 torr D_2, U_0 = 40 kV, W_0 = 3.6 kJ, Y_n = 1.4×10^8 [12].

additional Al-foil filters) a rough energy analysis was also performed. The measured angular distribution of fast deuterons (of energy > 50 keV) revealed that the emission is confined mainly within the 80° solid angle, but there appear some local minimum at the z-axis, as shown in Fig. 3. That effect was also observed later on in larger PF experiments, e.g. in the PF-360 facility operated initially at 126 kJ [5]. It was explained by a lack of accelerated primary ions within a hole of a diameter equal to about an ion larmor-radius, which might be caused by trapping of the deuterons within a conical tunnel of the collapsing current-sheath [12]. This hypothesis could hardly be proved since plasma parameters in ion micro-sources are not known exactly.

The energy spectra of deuterons from small-scale PF experiments were also measured within the PGN device and (for a comparison) within the PF-360, operated at lower energy levels. Within the investigated energy range (from about 80 to about 500 keV) the deuteron spectra could be approximated by the power law $dN/dE \approx E^{-a}$ where $a = 3\pm1$, as shown in Fig. 4. It was not stated whether this approximation can be used for low energy (<50 keV) and very high energy (>500 keV) deuterons.

Some time-resolved measurements of the fast ions, as performed in IPF (Institut für Plasmaforschung, Universität Stuttgart) and in IPJ (Institute for Nuclear Studies) [10, 11], demonstrated that the ion pulses have a coarse (≈30 ns) and a fine (≈2 ns) temporal-structure. In some cases there was observed also a multi-spike structure of the ion pulses, e.g. quasi-monoenergetic deuterons were emitted in 3–4 subsequent spikes separated by 30–40 ns intervals. The whole ion emission time was estimated to be about 150–200 ns.

Although the general features of the ion emission from the PF discharges were determined and explained in the 80s, more detailed time-resolved measurements and particularly correlation studies were needed. Also needed were detailed measurements of the ion beams from other small-scale PF devices, designed and constructed in different laboratories.

Ion beam studies in INFIP

Investigations of the pulsed ion beams emitted from PF discharges were also performed in the INFIP in Buenos Aires, Argentina. The use was made of a small PF-II device powered by a 4.75 kJ, 30 kV, condenser bank. The ion studies were concentrated on measurements of ion fluxes within a lower energy part of the spectrum (<50 keV).

To measure low-energy ions there was applied a Faraday-type collector (FC), placed about 100 cm from the focus region. The FC was equipped with an entrance grid, two miniature permanent magnets (used to produce a transverse magnetic field), and a ring-shaped collector electrode, located inside a solid metallic housing [6, 7]. There were applied biasing voltages of -200 V to the grid, and -700 V to the collector, respectively. The large measuring basis allowed to use the time-of-flight (TOF) method and to discern various effects upon obtained FC signals, e.g. those due to electromagnetic (X-ray) pulses and fast particles. An evaluation of the secondary-electrons effects on the collector signals was performed, and the detailed analysis of the registered FC waveforms made possible the determination of the ion energy spectrum under different experimental conditions [6, 7], as shown in Figs. 5 and 6.

Particular attention was paid to the studies of PF discharges performed with the N_2 filling, since nitrogen ions can be used for different technological applications. In order to determine the actual energy spectrum of the nitrogen ions arriving at the entrance diaphragm (or pinhole) there were taken into account also elastic scattering processes within the neutral gas. The spectra obtained from FC measurements were compared with those measured with the Thomson analyzer, and good agreement was observed. The total flux of the nitrogen ions within the energy range from 50 keV to about 1 MeV, was estimated to be about 3.2×10^{13} ions/sterad.

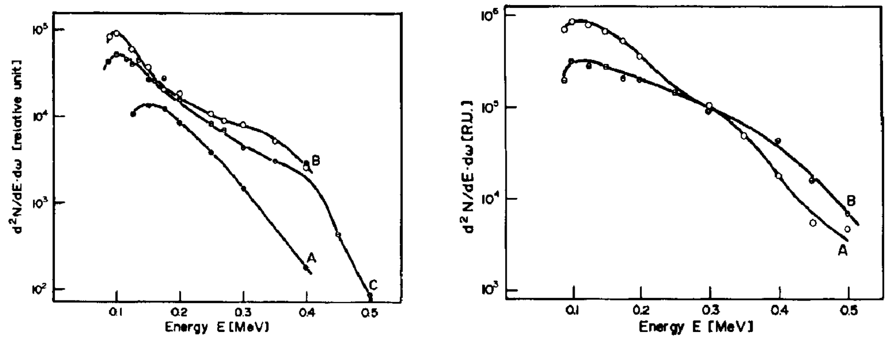


Fig. 4. Comparison of energy distributions of deuterons emitted along the z-axis, as measured in the PGN device (on the left; A – at p_0 = 5 torr, W_0 = 3.6 kJ; B – at p_0 = 2 torr, W_0 = 3.9 kJ; C – at p_0 = 2 torr, W_0 = 4.5 kJ) and in the PF-360 facility (on the right; A – at p_0 = 3 torr, W_0 = 126 kJ; B – at p_0 = 4 torr, W_0 = 143 kJ) [5, 12].

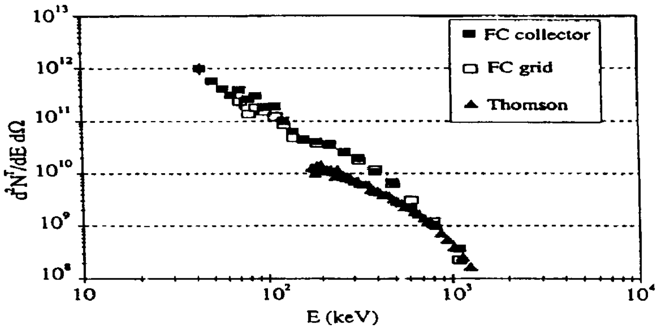


Fig. 5. Energy spectra of the nitrogen ions emitted from the PF-II device, as estimated on the basis of FC signals taken from the polarized collector or grid [6]. For a comparison there are also shown results of the previous measurements performed with the Thomson-type spectrometer.

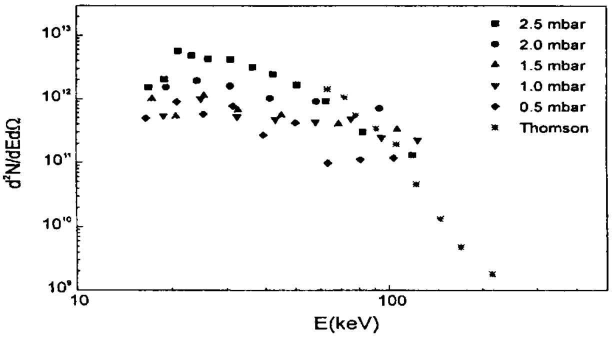


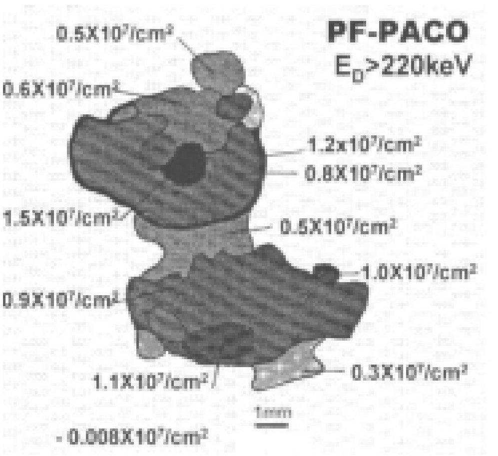
Fig. 6. Energy spectra of deuteron beams emitted from the PF-II device, as measured at different initial pressures [7]. For a comparison there are also shown the data obtained with the Thomson-type spectrometer.

For a comparison there were also performed measurements of the deuteron beams from PF shots carried out with the D_2 filling. In that case the total flux of deuterons was estimated to reach $3\times10^{13} - 3\times10^{14}$ deuterons/sterad. It should be noted that the deuteron energy spectra (see Fig. 6) could not be fitted with a single scaling law of the $E^{-\alpha}$ type. For higher (>70 keV) energies the fitting gave $\alpha = 4–5$, while for lower (<70 keV) energies it gave a smaller value $\alpha = 2–3$, and some saturation was observed. This can be explained by the fact that lower-energy deuterons are stronger trapped within the pinch column and some of them undergo the fusion reactions, while the higher-energy deuterons can easily escape from the dense plasma region.

Ion beam measurements in IFAS

The emission of pulsed ion beams from PF discharges was also investigated within a small PACO device operated in the IFAS in Tandil, Argentina. That device was equipped with coaxial electrodes of 40 and 100 mm in diameter. It was powered from a 4 μF condenser bank charged up to 31 kV. To study high-energy deuteron beams there were used NTDs fixed upon a semicircular support (at different angles to the z-axis) or placed inside a pinhole camera, which was adjusted axially. To enable an energy analysis of the observed deuterons the NTDs were covered with Al-foil filters of different thickness.

Measurements of the angular distribution of very fast (>700 keV) deuterons revealed a strong anisotropy and in particular the local minimum close to the z-axis (probably on the symmetry axis of the collapsing current sheath). That result was in good agreement with measurements performed within the other small-scale experiments, e.g. PGN and PF-360 (at lower energy input). The ion pinhole pictures, as taken behind a 0.5 mm diameter diaphragm placed 16 cm from the electrode ends, demonstrated also a complex microstructure of the registered ion beams, as shown in Fig. 7. Similar to the other small-scale PF experiments, within the PACO device there were registered numerous microbeams emitted along the z-axis (forming the central image) and those deflected by an azimuthal magnetic filed (forming some ring-shaped images) [14–16]. The ion pictures taken at different distances behind the pinhole, which were varied from 6 to 35 cm, confirmed that the deuteron



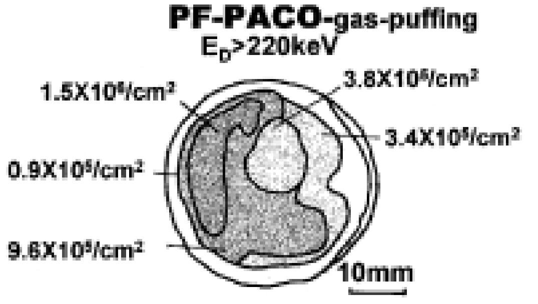


Fig. 7. Ion flux density maps obtained from the pinhole camera pictures, which were taken within the PACO device under different experimental conditions. On the left – the flux of high-energy deuterons emitted at the static initial pressure, and on the right – the central part of the ion picture taken at the gas puffing.

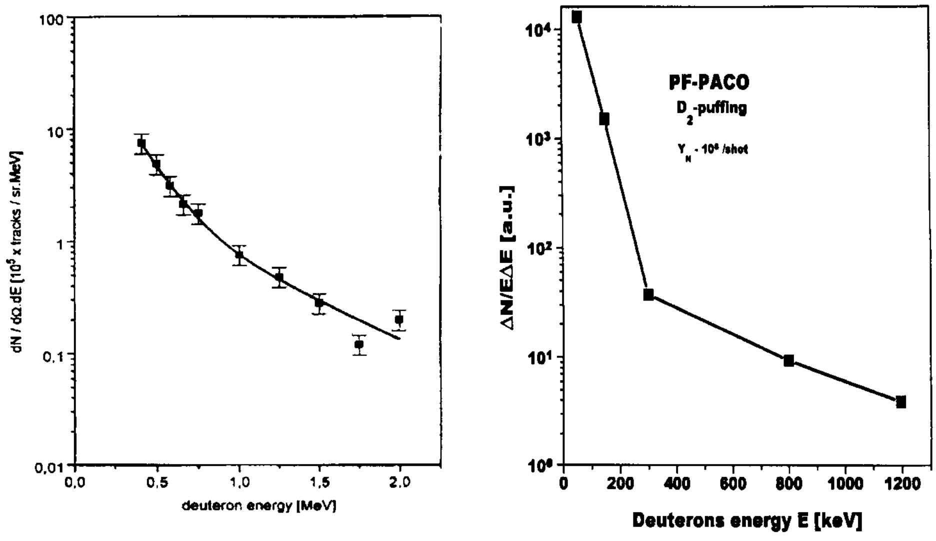


Fig. 8. Deuteron energy spectra measured within the PACO device under different initial gas-conditions: on the left – for the static initial filling, on the right – for the dynamic filling [9].

microbeams have a small divergence and are irreproducible from shot to shot. The deuteron microbeams can, however, form ion bunches of high intensity. Inside such bunches one can observe individual microbeams of considerably higher energy, e.g. at a 31 kV charging voltage deuterons of energy >700 keV were registered. That was confirmed by detailed measurements of deuteron energy spectra, which are shown in Fig. 8.

Summary and conclusions

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

1. PF-type devices can generate high-intensity ion beams. The fast (>100 keV) deuterons, as well as impurity- and admixture-ions, are emitted within a wide solid angle (within 60–80° to the z-axis), and their energy spectra (ranging up to several MeV) demonstrate a strong spatial modulation.
2. Intensity of the ion emission depends on electrode geometry and energy supplied as well as on other experimental conditions, i.e. the working gas, the initial pressure, etc. In general, the PF facilities emit numerous ion microbeams, which form pulsed ion bunches. The ion pinhole pictures show usually many ion-spots, distributed at the z-axis and within ring-shaped regions.
3. The characteristic ring-shaped ion images can be explained by deflections of the ion microbeams within an azimuthal magnetic field surrounding the pinch column. The effects of the ion deflections are intensified when current filaments appear and local magnetic fields become stronger.
4. For small-energy (<50 kJ) PF devices the local flux of high-energy (>100 keV) ions within the microbeams spots amounts to 10^6–10^8 ions/cm^2 at a distance of 6 cm behind the pinhole. One can estimate that the total ion flux at a distance of 10 cm from the electrode ends reaches 10^{10}–10^{11} ions/cm^2.
5. To obtain a considerable modification of a solid surface (e.g. of a constructional steel) one must implant above 10^{13} ions/cm^2. Hence, using a small PF device one needs 10^2–10^3 shots. With an increase in a number of shots, non-uniformity of the ion irradiation can be considerably reduced.
6. Since the ion bunches from the PF device can deposit high-power (10^{10}–10^{12} W) locally, the surface of a solid target can be considerably eroded, e.g., a 3 μm thick Al-foil can be melted and completely vaporized. Therefore, such high-power ion bunches can be used for investigations of different constructional materials, e.g. those for nuclear fusion facilities.

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