RECENT STUDIES OF THE ION EMISSION FROM HIGH-CURRENT PF-1000 EXPERIMENTS

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The paper describes diagnostics of fast ion beams emitted from a large PF-1000 facility operated at 21…27 kV, 290…480 kJ. Those beams were measured with pinhole cameras and PM-355 nuclear track detectors, placed at different angles to the discharge axis. The measurements showed a complex spatial structure of the fast ion beams. Measurements behind an axial channel in the inner electrode have shown that some ion beams are emitted also in the upstream direction. The ion energy spectra were measured with a miniature Thomson-type spectrometer. Time-resolved measurements of ions were performed with miniature scintillation detectors placed behind a pinhole.
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1. INTRODUCTION

Experimental studies of plasma-ion streams emitted from high-temperature plasmas are of importance not only for plasma physics, but also for application-oriented research. Such studies have been carried out at the IPJ in Swierk and IPPLM in Warsaw, Poland, for many years [1-3]. The PF-1000 facility at the IPPLM has recently been modernized to increase discharge currents and neutron yields, and to produce plasma-ion streams of higher concentration and energy. The new diagnostic equipment has been designed and applied to study the emitted plasma-ion streams. This paper reports on recent time-integrated and time-resolved measurements of the ion beams as well as their energy spectra.

2. EXPERIMENTAL SET-UP

During experimental campaigns in 2009 the PF-1000 machine [4] was equipped with coaxial electrodes of 460 mm in length. The outer electrode consisted of twelve 40-mm-dia. stainless-steel tubes, which were distributed symmetrically around the cylindrical surface of 40 cm in diameter. The inner electrode was a 230-mm-dia. copper tube with a 40-mm-dia. axial opening. The end-on view of the electrodes and an example of an image of the ion beams (recorded end-on) are shown in Fig. 1.

The investigated PF-1000 discharges were triggered at the initial pressure p_0 = 1…3 hPa D_2, and they were supplied from a 1.32-mF condenser bank charged to 20…27 kV, 290…480 kJ. The maximum discharge current amounted to about 1.5…1.8 MA.

In order to investigate the spatial structure of the emitted deuterium streams the use was made of a miniature ion-pinhole camera equipped with PM-355 nuclear track detectors (NTD) and different absorption filters. The camera was placed at various angles to the discharge axis: at 0^0 (along that axis) at a distance of 160 cm from the electrode ends, at 60^0 and 90^0 - at a distance of 74 cm from the center of the pinch column (appearing at z = 4 cm), and at 180^0 (in the upstream direction) - also at a distance of 74 cm from the electrode outlets. Detailed measurements of the mass- and energy-spectrum of the emitted ions were performed by means of a Thomson-type spectrometer equipped with similar NTD.

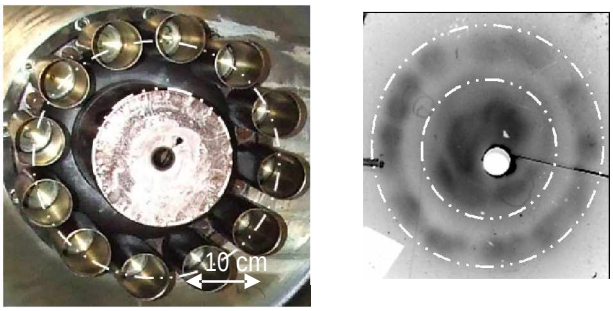

Fig. 1. View of the PF-1000 electrodes and an ion image recorded along the z-axis, at z = 160 cm, for two 290- kJ discharges with the total neutron yield $Y_n = 6.\times 10^{10}$

3. EXPERIMENTAL RESULTS

In order to analyze the spatial structure of the ion beams, the applied ion pinhole camera was equipped with a diaphragm of 0.5 mm in diameter, placed at a distance of 160 cm from the electrode outlet. The investigated ion beams were recorded with PM-355 detectors, which for deuteron-like ions have the low-energy threshold equal to about 30 keV. To obtain images of the ion beams of various energies, the applied detectors were shielded with absorption filters made of pure Al-foils of a different thickness (ranging from 1.5 to 80 μm), which determined various energy thresholds (for deuterons, from 220 keV to 3.9 MeV, appropriately). Lower-energy ions were absorbed by the filters, while higher-energy ions could penetrate those filters and be recorded. It enabled the ion beams of energies higher than the corresponding detection thresholds to be investigated. Samples of the detectors, which after their irradiation by PF-1000 shots were taken out the pinhole camera, were etched under the standard conditions [1]. Examples of the ion pinhole pictures, which show complex structures of the investigated ion beams, are shown in Fig. 2.

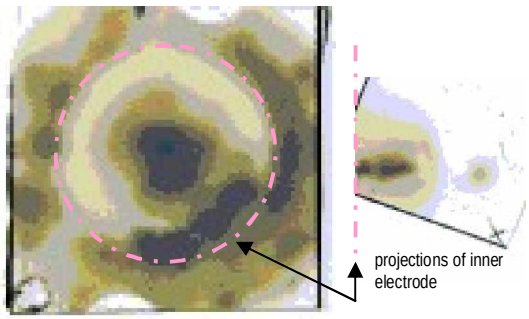

Fig. 2. Images of ion beams, which were recorded on the z-axis (left– IPCII10) and at 60^0 (righ– IPCII10").These detectors were irradiated in PF-1000 during three 290-kJ discharges with the total neutron yield $Y_n = 4. \times 10^{11}$

The etched PM-355 detectors, demonstrated that the emitted ion beams have a complex spatial structure and they consists of many micro-beams. A comparison of the electrode projections with the ion images suggest that the recorded ion beams originated mainly from the pinch column and regions between the outer electrode tubes. To study the spatial structure of the high-energy deuterons and protons beams, the pinhole cameras were equipped with PM-355 track detectors shielded with absorption filters made of different Al-foils, as described above. Some examples of the obtained ion beams images are presented in Fig. 3.

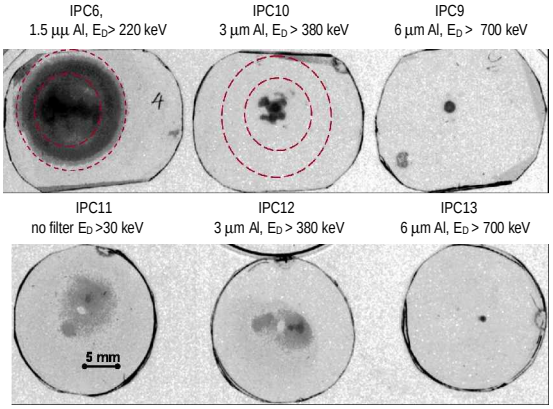

Fig. 3. Images of the ion beams emitted from similar 290-kJ PF-1000 shots, as recorded at 0^0, at a distance of 162 cm (upper row), and at 60^0, at a distance of 74 cm (lower row). Ion images were obtained behind different filters and showed deuterons of different energies E_D

From the quantitative analysis of the recorded tracks it was found that a single PF-1000 shot emits along the z-axis intense deuteron micro-beams. At z = 160 cm there was recorded about $2{,}4\times10^9$ deuterons in micro-beams of energy > 380 keV and 1 x 10^9 deuterons of energy > 700 keV, while at 60^0 – above 9×10^9 cm^{-2} and $1{,}2\times10^8$ cm^{-2}, respectively. An analysis of macro-photographs of the obtained tracks delivered information about the spatial micro-structure of the investigated deuteron beams, as shown in Fig. 4.

On the presented macro-pictures one can easily see that the tubular bunch of highest-energy deuterons (>700 keV) and protons (>525 keV) was surrounded by many high-energy micro-beams. Some results of the quantitative analysis of the ion-pinhole image are shown in Fig. 5.

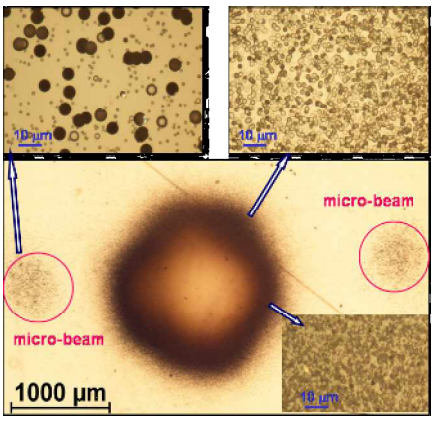

Fig. 4. Enlargement of the IPC9 ion- image (see Fig. 3) which shows the highest-energy (> 700 keV) ion beams recorded at 0^0. Inserts show different parts of the image with the larger magnification

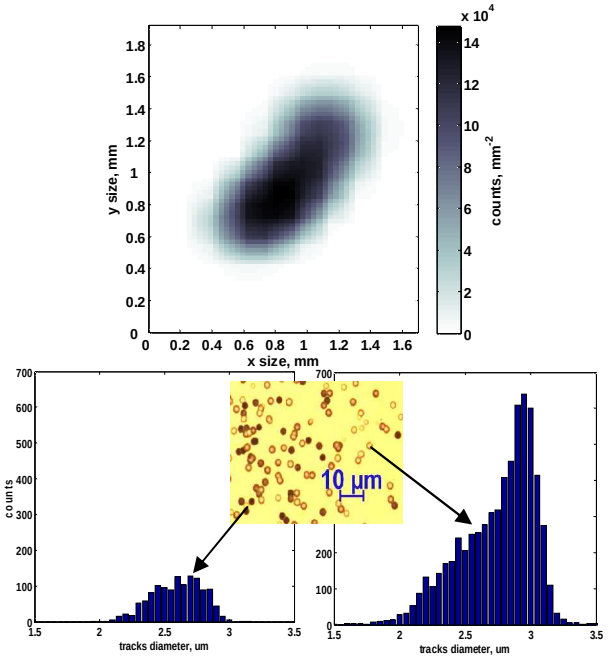

Fig. 5. Iso-density map of an ion image and histograms of high-energy protons and deuterons, which were recorded with a pinhole camera IPCII7 placed at 60^0 and equipped with PM-355 detector and a 10-μm-thick Al-filter

It should be added that some ion pinhole measurements at 60^0 (e.g. IPCII7) were performed simultaneously with a mass- and energy-analysis of ions along the z-axis, which was performed by means of a Thomson spectrometer [5]. The use of a miniature spectrometer, which could be placed inside the large PF-1000 chamber, facilitated to record mass- and energy spectra of ions emitted along the z-axis. During the investigated discharges there were recorded Thomson parabolas of protons and deuterons [5]. The quantitative analysis of those parabolas made possible to determine energy distributions of the investigated ions, as shown in Fig. 6.

The measurements showed that the accelerated deuterons (escaping along the z-axis) have energies in the range of 25…1000 keV, while protons (originating from hydrogen remnants) have the population of about 2 orders smaller and energies within the range of 35…300 keV.

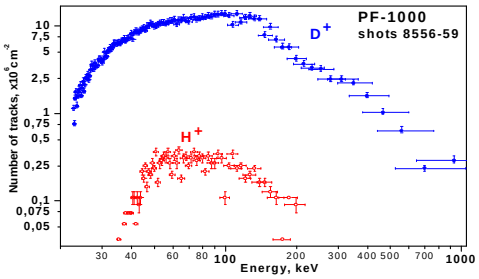

Fig. 6. Energy spectra of deuterons and protons emitted from PF-1000 along the z-axis

To study dynamics of the ion emission there were performed preliminary time-resolved measurements. For this purpose the use was made of miniature scintillation detectors, which were placed within the pinhole camera. The measurements, along the z-axis at a distance of 162 cm from the electrode outlet, delivered distinct signals corresponding to deuterons of energy < 1 MeV and protons of energy < 300 keV, as shown in Fig. 7.

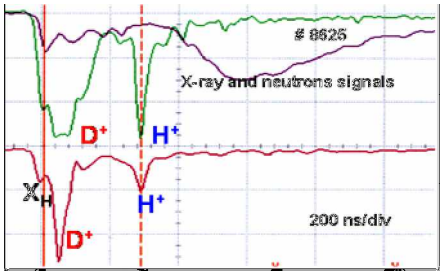

Fig.7. Time-resolved signals of deuterons and protons in a comparison with X-ray and neutron signals

5. SUMMARY AND CONCLUSIONS

The recent experimental studies of the ion emission from the PF-1000 facility confirmed that it emits intense ion beams mostly along the z-axis. These beams have a complex structure and contain many micro-beams of energies > 30 keV and some micro-beams of energy > 380 keV. Some ion beams are also emitted in the upstream direction. The deuterons emitted along the z-axis have energies from about 25 keV to about 1000 keV, and some protons have energies in the range of 35…300 keV. The preliminary time-resolved ion measurements have shown distinct signals identified with deuterons of energy < 1 MeV and protons of energy < 300 keV. To study acceleration processes in the PF discharges it is necessary to perform more detailed time-resolved measurements of ion beams.

ACKNOWLEDGEMENTS

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НОВЕЙШИЕ РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТОВ ПО ИССЛЕДОВАНИЮ ИОННЫХ ПУЧКОВ, ЭМИТИРУЕМЫХ НА ПФ-1000

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Представлена диагностика быстрых ионных пучков, эмитируемых установкой ПФ-1000, работающей при 21...27 кВ, 290...480 кДж. Измерения, проведенные с помощью камеры обскура и ядерных трековых детекторов РМ-355, расположенных под различными углами к оси системы, показывают сложную пространственную структуру быстрых ионных пучков. Так, измерения за аксиальным каналом внутреннего электрода показывают, что некоторые ионные пучки эмитируются также в направлении потока. Ионные энергетические спектры измерены миниатюрным спектрометром томпсоновского типа. Измерения с временным разрешением проведены с помощью сцинтилляционных детекторов, установленных за камерой обскура.

НОВІТНІ РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТІВ ПО ДОСЛІДЖЕННЮ ІОННИХ ПУЧКІВ, ЩО ЕМІТУЮТЬСЯ НА ПФ-1000

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Представлена діагностика швидких іонних пучків, що емітуються установкою ПФ-1000, яка працює при 21...27 кВ, 290...480 кДж. Виміри, які проведено за допомогою камери обскури і ядерних трекових детекторів РМ-355, розташованих під різними кутами до осі системи, показують складну просторову структуру швидких іонних пучків. Так, виміри за аксіальним каналом внутрішнього електрода показують, що деякі іонні пучки емітуються також у напрямку потока. Іонні енергетичні спектри виміряні мініатюрним спектрометром томпсоновського типу. Виміри з часовим дозволом проведено за допомогою сцинтилляційних детекторів, розташованих за камерою обскурою.