PERGAMON

Radiation Measurements 34 (2001) 315–318

Radiation Measurements

www.elsevier.com/locate/radmeas

Spatial structure and energy spectrum of ion beams studied with CN detectors within a small PF device

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Received 28 August 2000; received in revised form 14 February 2001; accepted 9 March 2001

Abstract

The paper reports the application of Solid-State Nuclear Track Detectors to study the pulsed plasma-ion streams emitted from plasma-focus (PF) type discharges, which were performed within a low-energy PACO device constructed at Instituto de Fisica Arroyo Seco. The PACO device was operated under static initial gas conditions or with dynamic gas puffing. Studies of the structure of the fast deuteron beams were carried out within an energy range from 80 keV to about 2 MeV. Studies of ion energy and an ion angular distribution were also performed. The measurements showed that the fast deuterons are emitted in many "narrow" micro-beams, as in other larger PF devices. The anisotropy of the deuteron angular distribution was explained by the stochastic character of the formation of local ion sources within the PF discharge column.

Keywords: Plasma-ion stream; Plasma focus; Ion pinhole camera; Solid-state nuclear track detector

1. Introduction

Studies of the ion emission from (plasma-focus) PF-type facilities supply information about ion sources and mechanisms of the ion acceleration. Ion emission characteristics are also of interest for applied research. Therefore, extensive experimental and theoretical studies of primary deuterons, as well as impurity or admixture ions, were carried out in various laboratories (Kelly et al., 1997; Mozer et al., 1982; Sadowski, 1996). Some ion emission studies were also performed with a small (2 kJ) Mather-type PACO device (the PF facility called PACO) operated at IFAS (Milanese et al., 1999; Sadowski et al., 1998).

The main aim of this work was to use of SSNTD to study the structure of ion beams of different energies, and to determine an angular distribution of ions emitted from the PACO device, which was operated with an initial static D_2-filling and dynamic gas puffing.

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2. Experimental setup

The PACO device was equipped with coaxial electrodes of 4- and 10-cm diameter, and it was powered from a small 4-μF condenser bank charged up to 31 kV. Most PF shots were performed using an initial static pressure of 2 mbar D_2. Some shots were carried out with the deuterium gas puffing.

In order to analyze the spatial structure of the ion beams, an ion pinhole camera, equipped with a diaphragm which is 0.5 mm in diameter, was used. It was placed at a distance of 12 cm from the electrode ends. Kodak CN films (LR 115) were used as SSNTD to register the ion beams. The LR 115 had a registration threshold for proton-like ions equal to about 30 keV. To facilitate the ion measurements at different distances from the electrode outlet, and to obtain ion images with different magnifications, an ion pinhole camera was fixed upon a special support, which could be shifted along the z-axis, as shown in Fig. 1.

Particular care was taken with relatively high-energy (> 80 keV) deuteron beams, those were emitted mostly along the symmetry axis of the electrode system. To

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PII: S1350-4487(01)00175-5

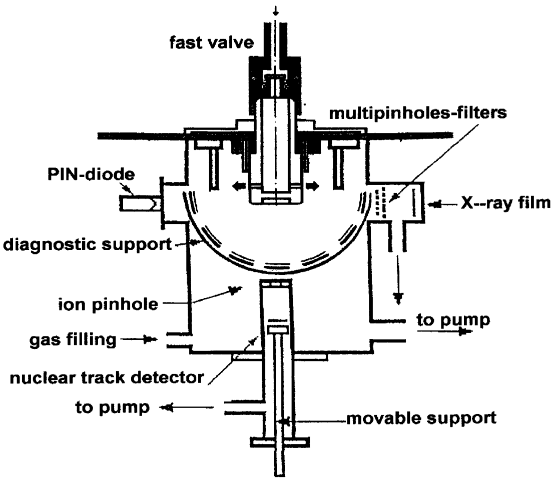

Fig. 1. Scheme of the PACO PF-device, equipped with a fast valve for gas-puffed experiments. Also shown is the diagnostics equipment used for ion and X-ray measurements.

register images of the ion beams of various energies, absorption filters of pure Al-foils of different thicknesses, ranging from 0.75 to 10 μm, were interposed between the beams and the SSNTD. In this way deuteron beams of energy above the corresponding detection threshold could be registered. When high-energy deuterons were analyzed, the low-energy deuterons were eliminated using thick filters. Deuterons of energies over 80, 220, 700, and 1300 keV, were detected by this methodology. The irradiated samples were etched in a 2.25-N NaOH solution at 60°C.

3. Experimental results and discussion

Some examples of the ion pinhole pictures, showing a complex structure of the investigated deuteron beams, are shown in Fig. 2.

It can be easily observed that for 0.75-μm Al-filters the SSNTD registered numerous deuterons emitted along the axis of symmetry. With a 1.5-μm-thick Al-filter some deuteron beams of energy higher than 220 keV only were detected, and with a 6.0-μm-thick Al-filter a distinct decrease in a number of the registered beams was observed. In general, high-energy ion beams were well collimated, but they were irreproducible from shot to shot, possibly because of a stochastic mechanism in their generation.

3.1. Study of structure and energy of deuteron beams

A complex structure of the investigated ion beams could be observed when a magnified image of tracks was analyzed. An example of such an image, as registered behind a 1.5-μm-thick Al-filter, transmitting deuterons of energy $E_D > 220$ keV only, is shown in Fig. 3.

One can easily note that the high-energy (> 220 keV) deuteron beams constitute bunches of micro-beams, which contain large numbers of fast deuterons. Detailed measurements of track densities were performed upon the SSNTD irradiated behind a pinhole of 0.5-mm diameter and 0.5-mm wall thickness, which was placed at a distance of 12 cm from the electrode ends. At the pinhole camera magnification equal to 1 : 2 the ring-shaped track region of the investigated beam was registered, which was about 0.15 mm in width. Using an optical microscope, it was estimated that the corresponding ion flux density (upon the detector surface) amounted to 1.2×10^7 deuterons/cm^2, while the maximum density reached 1.5×10^7 deuterons/cm^2. There were also registered several micro-beams of about 1 mm in diameter, with the corresponding flux densities ranging from 0.5×10^7 to 1.5×10^7 deuterons/cm^2. It should be noted that the background ion flux was equal to about 8×10^4 deuterons/cm^2 only. Taking into account geometry of the measuring system, it was estimated that the average ion (mostly deuteron) flux density at the pinhole surface (placed 12 cm from the inner electrode outlet) was about 3.3×10^9 ions/cm^2 at the

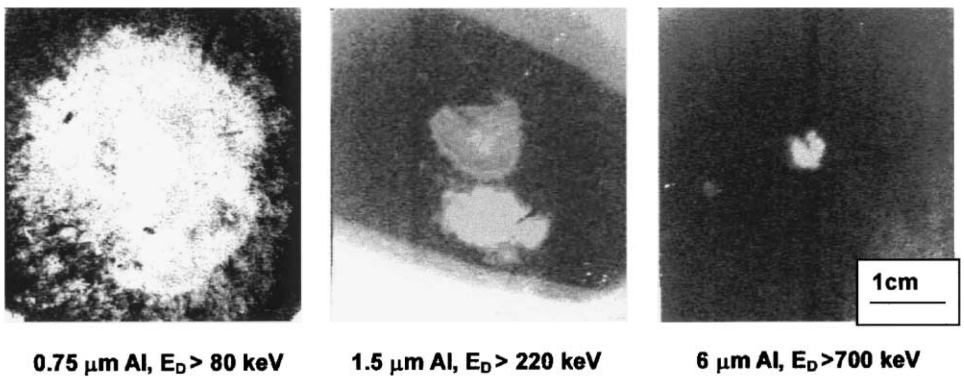

Fig. 2. Ion images registered by means of the CN-LR 115 SSNTD with different absorption filters. The results were obtained from 3 successive PF-shots performed under identical experimental conditions. The presented images have the same scale.

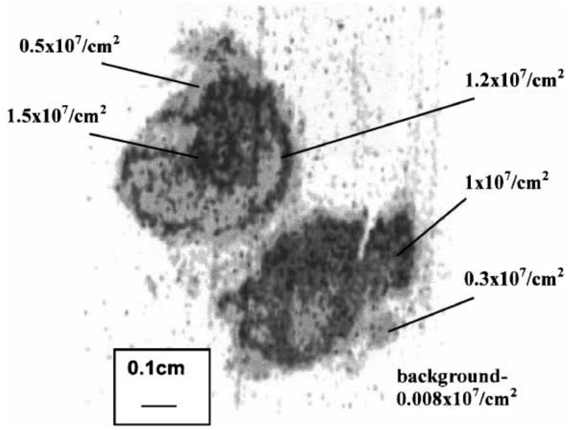

Fig. 3. Magnified image of fast deuteron tracks registered on the CN-type detector, which was covered with a 1.5-μm-thick Al-filter. It corresponds to the central picture in Fig. 2. The description gives number of the tracks registered per cm^2. The picture shows the fine structure of deuteron beams of energy $E_D > 220$ keV, which were emitted from the PACO device operated at $p_0 = 2.0$ mbar D_2, $U_0 = 30$ kV, $I_{max} = 280$ kA.

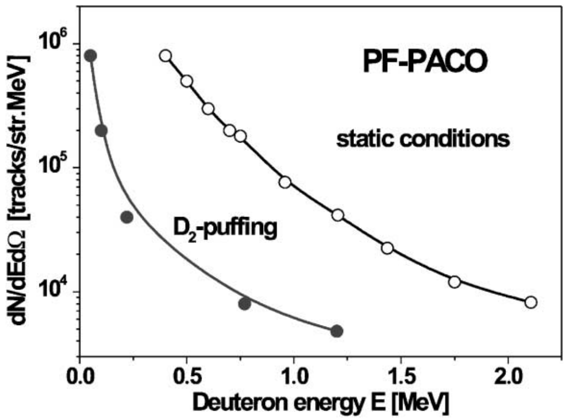

Fig. 4. Energy distribution of deuterons emitted from the PF-PACO device, which was operated with the deuterium puffing and under static initial gas conditions ($U_0 = 31$ kV, $I_{max} = 280$ kA).

static deuterium-gas filling. It was estimated that at dynamic deuterium gas puffing the average deuteron flux density was 3.7×10^9 ions/cm^2.

In order to determine an energy distribution of the deuterons emitted from the PACO device, the CR-39 detectors were used as SSNTD, because their calibration characteristics were determined with a good accuracy (Sadowski et al., 1995). To perform a rough energy analysis of the total ion flux (behind the pinhole), composed of multi-step Al-absorption filters were placed upon the CR-39 detectors. A detailed quantitative analysis of the irradiated and etched CR-39 detectors made it possible to determine ion fluxes in selected points of the detector plates. Taking data from several points corresponding to the same filter thickness, it was possible to estimate an average flux of ions (with energies higher than the threshold energy value). In order to verify the data by a comparison with the calibration curve of the CR-39 detector (Sadowski et al., 1995), the diameters of the etched micro-craters were also measured. On the basis of those results an approximate energy distribution of the investigated deuteron beams could be determined. An example of the characteristic energy spectrum of deuterons is presented in Fig. 4.

The obtained deuteron energy spectrum of ions demonstrated that the PACO device (in spite of its low energy) is able to generate relatively intense beams of high-energy deuterons.

3.2. Studies of angular distribution of deuterons

In order to investigate an angular distribution of the ion emission the CN-LR 115 SSNTD were fixed upon a special semi-circular diagnostic support, placed in front of the electrode outlet (as shown in Fig. 1). As in the previous case, to perform a rough energy analysis of investigated ions, the SSNTD were covered with narrow strips of the absorption filters of different thickness. The total numbers of ion tracks, as registered at different angles and behind various absorption filters, have been measured and compared. It enabled the angular distributions of ions within different energy ranges to be determined. Some examples of the angular distributions of high-energy deuterons are presented in Fig. 5.

In the case of PF discharges performed with the gas puffing, the conditions of the plasma stream propagation are evidently different from those observed at the static initial gas filling. The distinct maximum in the beam emission along the symmetry axis of the system, and a characteristic ring-shaped ion emission, can be identified. The latter one is possibly caused by ion deflected within the azimuthal magnetic field, which appears around the pinch column. It should be noted that the results are different from those obtained for the static gas conditions, when a characteristic local minimum in the emission was observed close to the axis.

4. Summary and conclusions

The main results of this research can be summarized as follows:

- The measurements, performed with the ion pinhole camera and the SSNTD, confirmed that inside relatively intense ion fluxes (see Section 3.1) many “narrow” micro-beams are emitted.
- Energy of deuterons within the micro-beams, as produced in the PACO device, reached about 2 MeV (see Fig. 3), similar to larger PF experiments. This result could be related to the fact that inside the PF column there are local

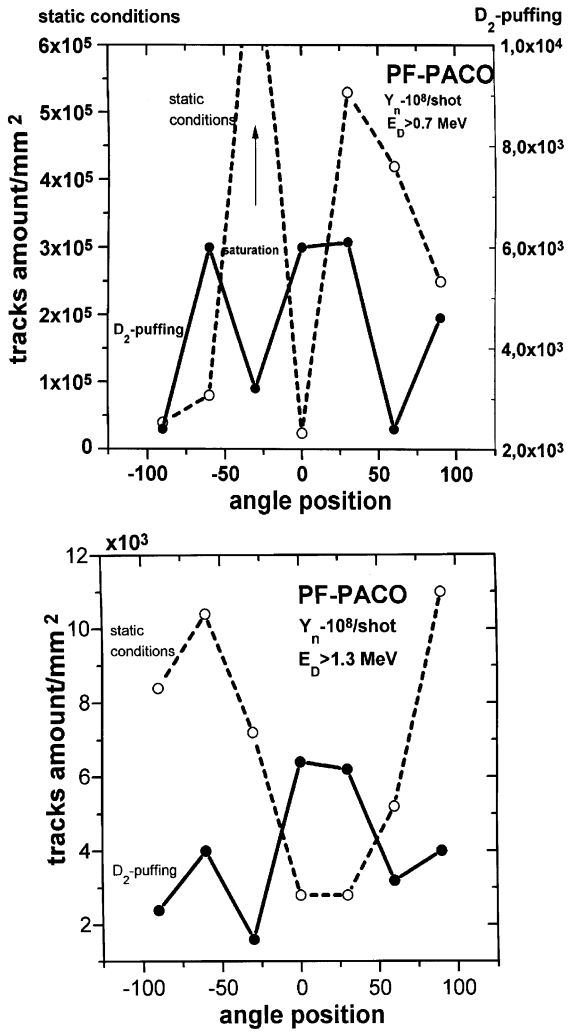

Fig. 5. Comparison of angular distributions of deuterons with energies $E_D > 0.7$ MeV and $E_D > 1.3$ MeV, as obtained at the static initial gas conditions (broken lines) and at the dynamic gas puffing (solid lines).

strong electric fields, because of the local separation of charges and non-linear phenomena.

- The anisotropic angular distribution of fast deuterons can be explained by a stochastic jitter in the formation of ion micro-sources within the PF column. The two local minima, as observed near the z-axis, could be interpreted by a lack of accelerated deuterons within a plasma tunnel (of an ion Larmor radius), where medium energy (10–100 keV) deuterons can be trapped by the collapsing PF current sheath (Sadowski et al., 1988).

The SSNTD proved to be very useful in the investigation of the pulsed ion streams emitted from high-temperature plasma. They made it possible to determine the spatial structure as well as energy spectra of the investigated ions, what is of interest for basic plasma studies as well as for applications. However, more detailed measurements are needed to investigate the mechanisms involved in the ion acceleration and formation of ion micro-sources in PF pinch columns.

Acknowledgements

This work was partially supported by the Argentine CONICET organization and the Polish State Committee for Scientific Research within a frame of the bilateral scientific cooperation agreement.

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