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Calibration and applications of modern track detectors CR-39/PM-355 in nuclear physics and high temperature plasma experiments

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Abstract. Solid-state nuclear track detectors (SSNTDs) have been used for the registration of charged particles practically since the beginning of the 1960s, when a new class of detectors, called dielectric track detectors, were discovered. The paper describes applications of the SSNTDs type PM-355 for diagnostics of fusion-reaction protons and other ions emitted from plasma focus (PF) devices, tokamaks and laser facilities. Such detectors were also used in biomedical experiments for beam profile measurements. The results of our calibration studies of SSNTDs as well as charged particle- and biomedical measurements, which were carried out within different facilities, are presented.

Key words: PM-355 detectors • corpuscular diagnostics • nuclear-fusion applications

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Introduction

SSNTDs have been used for corpuscular diagnostics in high-temperature plasma experiments in facilities such as plasma focus (PF), tokamak, laser plasma experiment, etc.

The main advantages of these detectors are that they are easy to use, they need no electronics and can be operated under rough experimental conditions [3]. Additionally, SSNTDs are immune to electromagnetic noise, and they are practically insensitive to fast electrons and electromagnetic radiation pulses (at reasonable doses). These detectors do not disturb high-vacuum conditions, and they are very easy to use in various experimental applications, except for the time-consuming etching process required after their exposure.

To use such detectors in an optimal way and to exploit new detector plastics, detailed calibration studies of different SSNTDs (e.g. CR-39, PM-355, PM-500, PM-600) have been performed at the Soltan Institute of Nuclear Studies (SINS), Świerk, Poland, for several years. Samples of the detectors were exposed to beams of different mono-energetic ions and the produced micro-craters were measured by means of an optical microscope, and recently also by an electron microscope. Track dimensions (mainly their diameters) were determined for light- and heavy-ions (i.e. protons, deuterons, He-, C-, and S-ions) as a function of ion energy and etching time. The detectors calibrated in this way were used in many high-temperature plasma experiments, especially: 1) to measure 3 MeV fusion reaction protons emitted from PF discharges (the experiments were carried out with the PF-360 facility, Świerk, Poland); 2) in experiments performed within the TEXTOR tokamak (Juelich, Germany) to measure fusion reaction protons; 3) in experiments conducted at the LULI Laboratory (Palaiseau, France) to measure primary ions emitted from laser-produced plasmas. Such detectors were also used in biomedical experiments for beam profile measurements.

Magnetic confinement (Tokamak, Stellarator), *Z*-pinch and laser-driven inertial confinement fusion-experiments have reached a point where substantial populations of fast ions are created. Ion diagnostics are fundamental for understanding the mechanisms of the physical processes which drive the particle acceleration. In inertial confinement experiments such diagnostics will be needed to understand the physical phenomena and to guide target development necessary to achieve the ignition and burn-up of a fusion pellet. In magnetic confinement experiments measurements of plasma parameters, such as: ion temperature, ion velocity function, relative concentration of the fuel ions, are of crucial importance.

General properties of the detectors

To perform the calibration measurements quasi-monoenergetic ion species provided by particle accelerators were used [5]. In the energy range from 0.1 MeV up to 2.0 MeV irradiations with light ions were performed by means of the LECH electrostatic Van de Graaff accelerator operated at SINS, Poland, whereas higher energy ions of energy up to 100 MeV were provided by the Tandem Van de Graaff accelerator operated at the Erlangen-Nürberg University, Germany, and by the Heavy Ion Cyclotron in Warsaw, Poland. The main aim of these measurements was to observe changes of track dimensions as a function of ion energy and etching time. After the irradiations the detector samples were etched under standard conditions (i.e., in a 6.25 N water solution of NaOH, at a temperature of 70 ± 1°C). The etching procedure was stopped every 2 h, and the samples were scanned with an optical microscope for track diameter determination. The obtained calibration characteristics of the PM-355 detectors irradiated with mono-energetic protons are presented in Fig. 1.

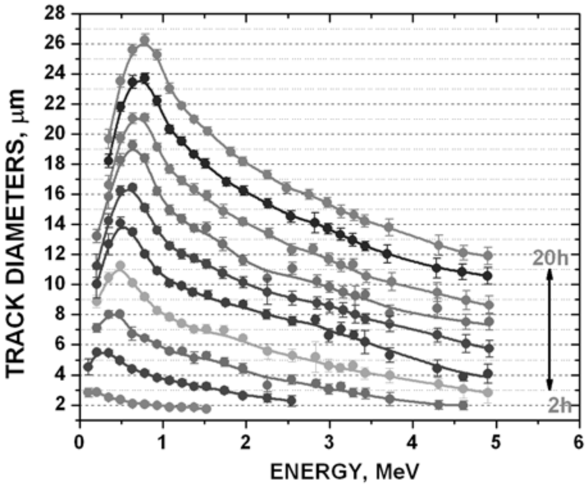

Fig. 1. Calibration diagrams presenting the evolution of track diameter as a function of proton energy and etching time.

The calibration diagrams demonstrate a typical dependence of track diameters on proton energy and etching time. Therefore, the obtained characteristics made possible the determination of proton energy on the basis of the diameters of the tracks formed in the detector samples, which were irradiated in the plasma experiment.

Application of track detectors PM-355 in nuclear physics

Measurements of fusion protons emitted from a PF type facility

The fusion protons of the ^{2}H(d, p)^{3}H reaction were studied within plasma-focus devices by means of SSNTDs of the PM-355 type. The PF facility is a high-voltage plasma discharge system which belongs to the class of the *Z*-type pinches [4]. The PF facility can produce hot magnetized plasma, which emits neutrons, X-rays, electron- and ion-beams. SSNTDs have been used in experiments performed within the PF-360 facility, operated in SINS, Świerk, Poland. For time-integrated measurements (angular and spatial distributions) of fusion-reaction protons we used several miniature pinhole cameras equipped with the PM-355 detector samples. The input pinholes were 3 mm in diameter. In order to eliminate streams of primary deuterons and accelerated impurity heavy ions, the PM-355 detectors were protected with Al-foil absorption filters of 80 μm in thickness. These filters cut protons below 3 MeV and slowed down the high energy protons, but enabled such protons to be recorded. Figure 2 presents angular distributions of protons obtained from several shots performed at a D_2-gas filling pressure equal to 6.2 hPa.

In Fig. 2 one can easily see that the angular distributions, as determined for the PF-360 facility, were strongly anisotropic. This means that the recorded proton flux depended on the observation angle measured in relation to the electrode axis. The fusion-reaction protons were emitted mainly into a narrow cone, with the maximum emission oriented along the electrode axis. Such a big anisotropy cannot be understood on the basis of nuclear-reaction mechanisms, but it can be explained by the influence of local (azimuthal and axial)

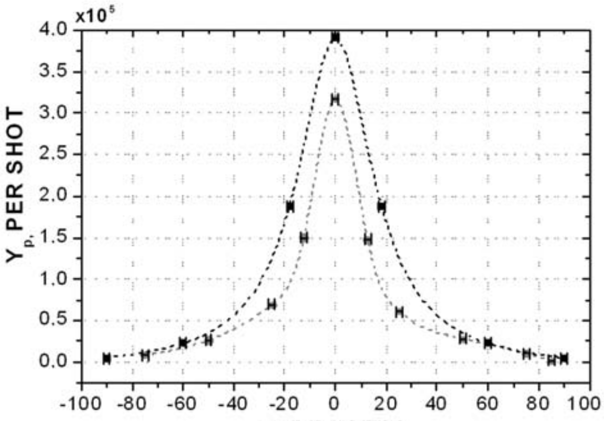

Fig. 2. Angular distributions of fast protons, determined for two different the PF-360 discharges.

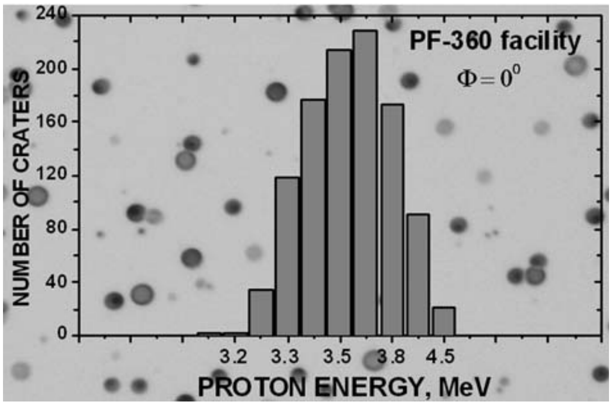

Fig. 3. Energy spectrum of protons obtained from the PF-360 facility.

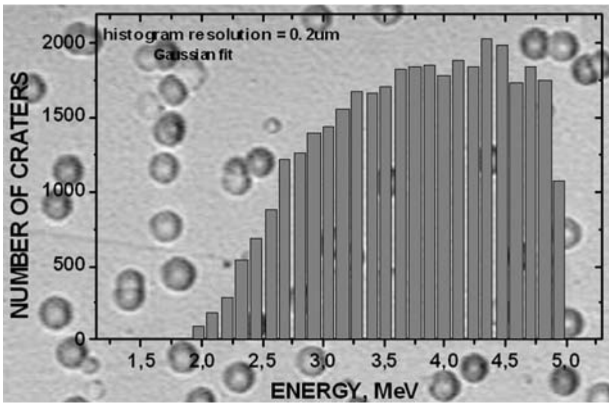

Fig. 5. Energy spectrum of protons obtained from the TEXTOR tokamak.

magnetic and electric fields on the proton trajectories.

The SSNTDs of the PM-355 type were also used for measurements of fusion-proton spectra. Figure 3 presents a diagram of the number of recorded proton tracks vs. proton energy, which were determined from the detectors exposed within the PF-360 facility on the electrode axis.

One can see that the fusion-protons, which were emitted from deuterium discharges had energies within the range from 3.2 MeV to 4.5 MeV. Such high-energy protons could be produced only by energetic deuterons, which had undergone nuclear-fusion reactions ^{2}H(d, p)^{3}H. Such energetic beams can be generated by different plasma instabilities. Products of the nuclear reactions, which are created by the beam-target mechanism, are expected to have energy spectra shifted towards higher energy values, even by hundreds of keV (up to 4.5 MeV). In fact, the nuclear reaction mechanisms, which are responsible for the fusion-neutron and -proton emission from PF-type discharges, have not so far been satisfactorily explained.

Measurements of fusion protons emitted from tokamak-produced plasmas

The detectors have also been used in experiments performed within the TEXTOR tokamak to measure 3 MeV fusion reaction protons. In a medium size tokamak (like TEXTOR), the fusion charged products are not confined within a magnetic field [6]. They escape from the plasma in a few microseconds, bearing valuable information about plasma parameters. In order to place the detector inside the TEXTOR vacuum vessel a small ion camera was used. That camera was equipped with an input pinhole of 0.3 mm in diameter. The detector sample was located inside it, at a distance of 40 mm from the pinhole. To keep the detector at a relatively low temperature a special water-cooled manipulator was used. The measuring assembly (consisting of the camera and detector) was attached to the manipulator, which could be located in a chosen position within the plasma boundary. The measurement was performed with the pinhole camera located at a distance of 49 cm from the plasma center. The camera was aligned such that its input pinhole was oriented along the major radius, opposite the torus centre (i.e. at $\gamma = 0°$). In Fig. 4 surface distributions of crater density, as measured on the PM-355 detector sample which was irradiated in the TEXTOR experiment, are presented.

Figure 5 presents a histogram of measured track diameter values. It is evident that several populations of protons with different energies were registered. Probably together with the fast 3 MeV protons also lower energy primary protons were detected by the PM-355 samples.

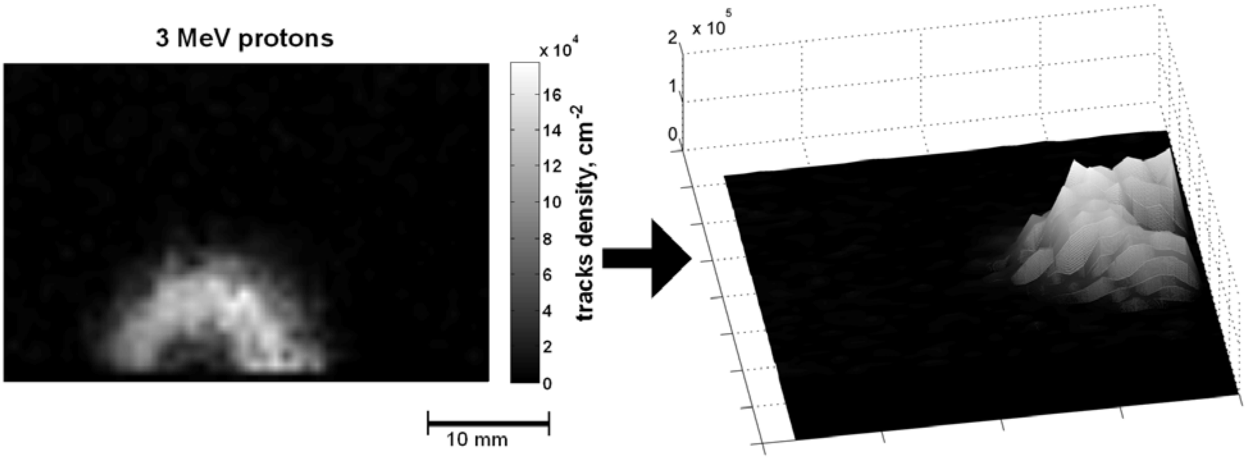

Fig. 4. Surface distributions of craters of diameters in the range 6–8 μm, which were induced by fusion-reaction protons as measured on the PM-355 detector sample.

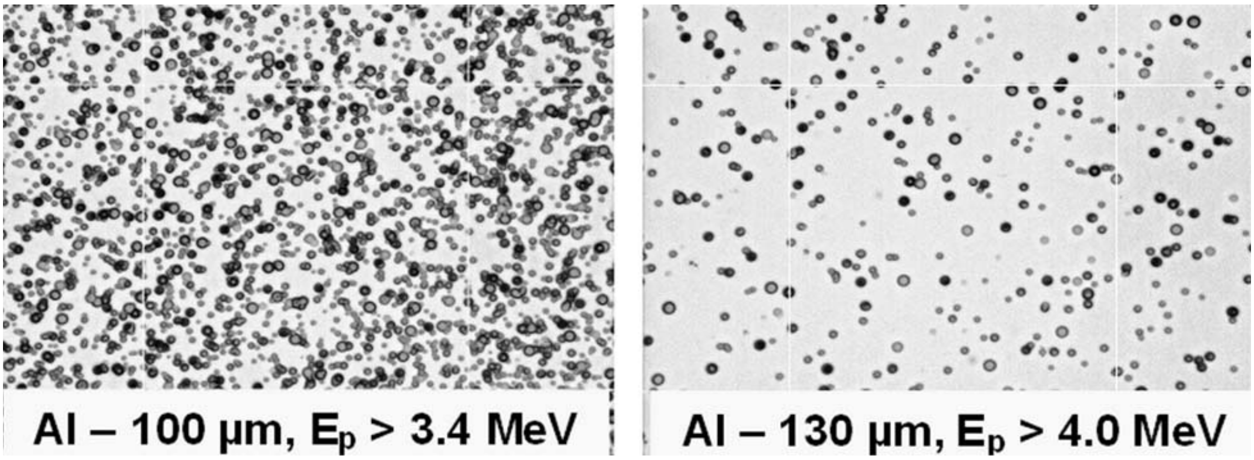

Fig. 6. Examples of ion tracks, which were recorded in PM-355 detectors covered by aluminum filters of different thickness.

Measurements of ion beams emitted from laser-produced plasmas

The PM-355 type detectors, were also used for measurements of the characteristics of ion beams emitted from laser-produced plasmas [1]. The experiment was performed at LULI, Ecole Politechnique (Palaiseau, France), within the 100 Tera-Watt laser facility. The parameters of the laser beam were as follows: energy E_L = 0.5–15 J, pulse duration τ_L = 0.35 ps, intensity $I_L = (5 \times 10^{16})–(2 \times 10^{19})$ W/cm^2. During the experiments different targets were used, in particular: polystyrene (PS) of thickness 0.6–5.0 μm and double-layer targets of Au/PS of thickness 1–3 μm. The SSNTDs appeared to be especially useful for the experimental analysis of energetic protons (E_p > 3 MeV). To measure effectively the proton emission efficiency and to estimate proton energy spectra about ten samples covered with different Al foils were used in each laser shot.

In general, some samples irradiated with protons from the same laser shot appeared to be overexposed, especially those covered with thinner Al foils. But others, masked with thicker foils, showed craters regular in shape well separated one from another (Fig. 6). Therefore, it was possible to estimate the flux of relatively fast protons impinging upon the surfaces of some samples. Samples with thicker and thicker foils revealed fluxes of more and more energetic protons. In this way the proton flux was determined as a function of the filter thickness, i.e. vs. proton energy. Knowing these counting rates (track densities) it was possible to estimate the proton energy spectrum.

Characterization of accelerator ion beams using nuclear track detectors

The irradiation of living matter with charged particles has become increasingly interesting for medical applications like radiotherapy, radioprotection and space radiobiology. In this field, particle accelerators are helpful owing to the wide range of available ions, energies and flux or dose fractionation. Usually, two types of configuration are used: micro/nano beams and broad beams. A micro-beam can precisely target a defined point on a cell or a group of cells. The broad beams allows us to irradiate a thousand of cells simultaneously. In the set-up, the beam must have a special uniformity of ± 3% over an approximately 1 cm^2 surface and be stable during the irradiation. In 2005–2006 the SINS, Institute of Physics of Kielce Academy and Institute of Experimental Physics of Warsaw University decided to develop an "in vitro" irradiation station using ion beams from the heavy ion cyclotron U-200 of Warsaw University [2]. A schematic view of the set-up for radiobiological studies, with the horizontal beam line installed at the Heavy Ion Laboratory of the Warsaw University cyclotron, is presented at Fig. 7.

In the present studies $^{12}C^{2+}$ ions were accelerated to energies in the range 50–100 MeV. The ion beam was transported from the cyclotron area to the exposure set-up, the collimated beam was spread out by scattering from gold foils with a thickness of 9–17 mg/cm^2. The gold foils allowed the desired ion energy and a homogeneous radiation field over an area 10 × 10 mm^2 of the exit window to be achieved. The ion beam intensity was controlled on-line by an integral monitoring system consisting of a Si detector placed inside the scattering chamber at an angle of 20° detecting scattered projectiles. The beam extraction into air occurred through a 1 × 1 cm^2 square window, sealed by a Havar (Fe, Ni)

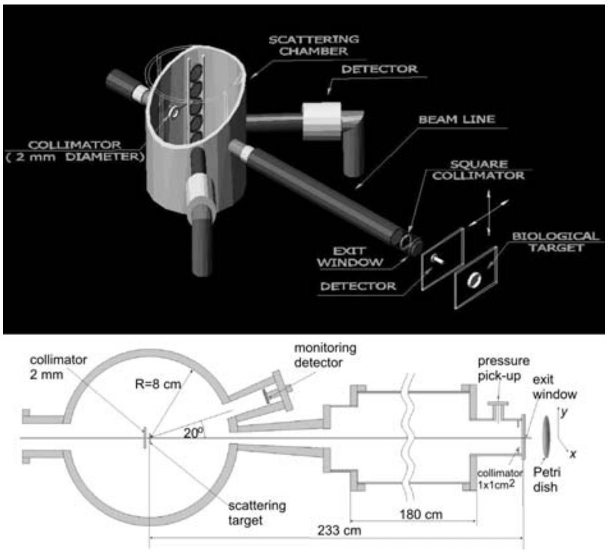

Fig. 7. Schematic view of the set-up of the horizontal beam line installed at the cyclotron.

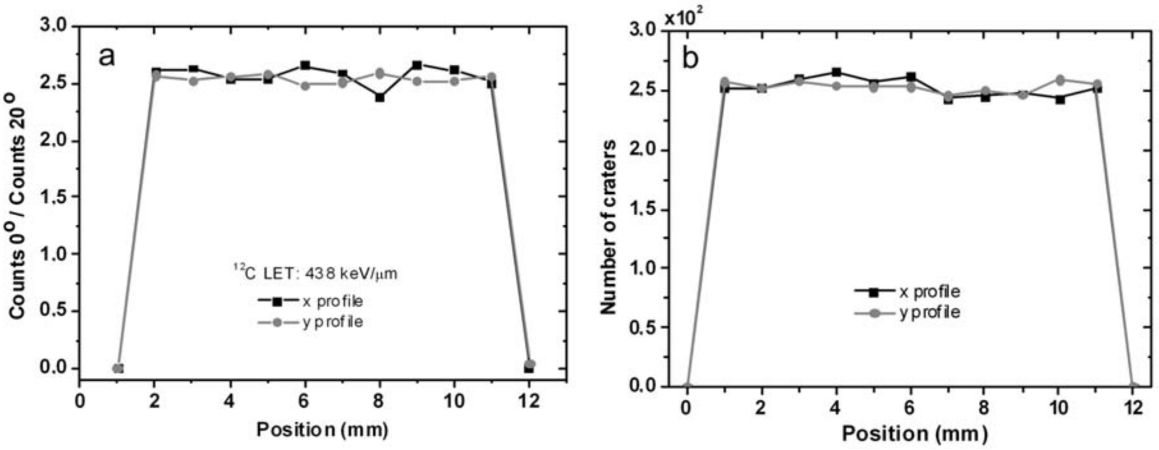

Fig. 8. Profiles of ion beams measured using: a – Si detector; b – PM-355 detector.

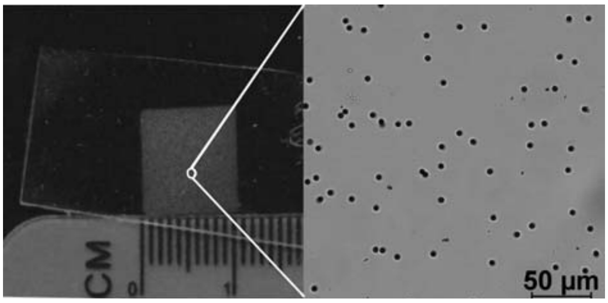

Fig. 9. Picture of ion beams profiles measured by the PM-355 detector.

foil of 2.3 mg/cm^2 thickness. The intensity and distribution of the scattered ions was measured outside the exit window by means of a surface-barrier Si detector with a 0.5 mm collimator. The Si detector was fastened to a *x*-*y*-*z* sliding table moving across two dimensional array centers. The ion beam profiles, as measured by the 0° Si detector in two dimensional (x, y) intensity distribution over the 1×1 cm^2 exit window, are presented in Fig. 8a. The measured beam uniformity was better than ± 2.5%. The beam uniformity was also checked also by using a nuclear track detector of the PM-355 type. The SSNTD sample was located in air a few mm from the exit window. The irradiation time was about 20 s. After the irradiation the detector sample were etched under standard conditions for 2 h. In Fig. 9 one can recognize a clear 1×1 cm^2 collimated beam.

The measured beam profile distribution in two axes (x, y) are presented in Fig. 8b. The achieved beam uniformity was about ± 3%, in quite good agreement with the results obtained using a time-consuming surface barrier silicon detector.

Summary and conclusions

The most important results reported in this paper can be summarized as follows:

1. Different plastic SSNTDs, and particularly PM-355 type detectors, have been calibrated by means of quasi-monoenergetic ions. The obtained calibration diagrams can be used for the identification of ion species under known experimental conditions.
2. It was demonstrated that the SSNTDs are very useful for ion measurements in different high-temperature plasma experiments, and particularly for studies of fusion-protons emitted from PF-type facilities, Tokamak-type facilities and in laser-target experiments.
3. The SSNTDs appeared also to be useful for measurements of ion beam profiles for medical applications like radiotherapy, radioprotection and space radiobiology.

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