Track measurements of fast particle streams

from the pulse-discharge explosion-induced plasma

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Abstract

This paper reports the results of experiments with a plasma micropinch device performed at the Electrodynamics Laboratory Proton-21 which include the track registration of fast particles emitted from the hot spot sparked inside a metal target. In the ion pinhole camera, a magnetic analyzer and a Thomson mass-spectrometer were mounted in order to derive images of the hot spot and to define the spectra of fast particles. On the track detectors in the pinhole camera, we have obtained specific split images which have a form of three or more track stripes stretched in parallel to the diode axis. The "average etching rate ratio versus track length" locus for the groups of tracks is depicted by means of the asymptotic method of squared diameters. Our

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analysis shows that the majority of tracks belong to hydrogen nuclei. The track loci for the detectors from the pinhole or analyzers turn out to be split in two parallel streaks that have been interpreted as a proton-deuteron doublet, deuterons being abundant for the track range < 10 μm. The Thomson analyzer gives the evident demonstration of the numerical equality of protons and deuterons for some parallel parabola sections. The total number of deuteron tracks equals to 1% of the registered proton tracks with energy ≥ 0.3 MeV in the experiments without any preliminary deuterium concentration in the metal target.

Keywords: micropinch, hot spot, detector CR-39, track range, average etching rate ratio, locus, protons, deuterons.

1. Introduction

The pulse discharge studied at the laboratory PROTON-21 (Kiev) is a plasma diode micropinch **broken down** as a load of **the plasma erosion opening switch**. The diode parameters are: U_{diode} = 300-500 kV, I=30-40 kA, W_{diode} =100-300 kJ (Adamenko, 2004). Unlike the conventional plasma-diode or plasma-focus where a hot spot sparks in a gas-plasma medium, the hot spot in the PROTON-21's device occurs on the axis inside a solid, usually metal target. The breakdown process is fully self-organized and occurs due to a know-how design of the cathode-anode assemblage and is of a pulse form. The powerful X-ray and intensive fast-ion radiation observed in the process provides an evidence for the high hit efficiency and the target explosion power. This report presents the track registration data of the abundant radiation of fast hydrogen ions from the hot-spot under consideration. A noticeable deuterium component is detected in the abnormal proportion to protons of the registered part of the energy spectrum in experiments with usual metallic targets without preliminary hydrogen implantation.

The solid-state track detectors (STD) CR-39 display the presence of fast ions with velocities $\geq 10^8$ cm/s, while the powerful electromagnetic disturbances make it problematic to register the ion electric signals during 20 ns after the breakdown. Being placed behind a small pinhole not far (up to 4.5 cm inside the ion pinhole camera) or far (46-66 cm inside the magnetic or Thomson analyzer) from the hot spot, STD give opportunities to determine the trajectories of fast narrow beams and to consider the characteristics of individual tracks of fast ions. By counting the tracks on the STD situated inside the magnetic analyzer, we have determined the fast-ion energy spectrum expressed in the proton specific energy units. We supplement the trajectory analysis with the procedure of track identification by means of the "squared-diameter asymptotic method" (SDAM) (Somogyi, 1973) which allowed us to determine the length (R) and average etching rate ratio (V) for each track within the groups of craters chosen for measurements during the etching.

The pinhole camera track images of the hot spot obtained in our experiments are totally different from the ones known for discharges of the plasma- or laser-focus type. For each effective shot, we obtained a composite picture represented by the set of three or more track streaks parallel to the diode axis and slightly split azimuthally. Sometimes, the image is added by the track nebula chaos. We present the examples of such images and discuss a possible dynamical model of the hot spot.

The experimental "*VR*-locus" of the tracks occurs in a way suitable for the identification of light particles which appear mostly in the spectra of the fast ion streams going out of the hot-spot. Using this method, we have found that almost 100% of ions giving the hot-spot image in the pinhole camera are hydrogen nuclei. Moreover, this method allows us to see that the fine splitting of the loci of the groups of craters taken from different streaks from the pinhole camera or analyzers can be interpreted as a proton-deuteron doublet. The presence of a deuterium dose in the hot-spot radiation has been demonstrated visually by the track parabola on the detectors in a Thomson analyzer, and the track densities in the proton and deuteron parabola streaks can be comparable locally. The total number of deuterons is 1% of the number of protons in the visible part of the proton spectrum.

Here, we pay a main attention to the presence of deuterons in the exaggerated proportion to fast protons in the hot-spot output due to the fact that no published data exist on a like effect in the case of the micropinch, plasma- or laser-focus hot spots where targets or a working gas are not enriched preliminarily with deuterium (even for higher discharge energy inputs).

2. Pinhole imaging

A general scheme of measurements is shown in Fig. 1. (We conserved the dimension proportions of the upper Thomson mass-spectrometer and the pin-hole camera. The magnet with inner detectors *a-e* is used as a magnetic analyzer). We use a 20-μm tungsten foil for pinholes. Less firm foils are not appropriate even for a single shot in our experiments. The entrance hole of 20-50 μm in diameter is situated at a distance of 1.5 cm from the hot spot, so that the camera aspect ratio is 2:1. The pinhole axis is directed through the expected hot-spot center by the laser beam in the diode equatorial plane. Two examples of the pinhole track images of the hot spot are shown in Fig. 2. All studies were performed with a CR-39 TASTRAK STD produced by TASL. The processing of the detectors was carried out in 6.25 N NaOH at 70^{o}C. Up to now, we have obtained more than 200 sharp pinhole images under the described conditions.

The images in Fig.2 are oriented parallel to the diode axis with the upper position of the anode. The tops of streaks are located at a distance of 1-5 mm from the pinhole axis being depicted by the tracks of the fastest particles for a given streak. Tracks are degraded along the streak to the lower detector edge. The streak width is usually minimal at the top, being of the order of 100 μm. It increases as one moves down the streak; in other cases, it may be constant down to the lower edge. The use of different pinholes shows that the diameter of a hot spot is close to 100 μm which is $^1/_5$ or $^1/_{15}$ of the target diameter. The horizontal displacements of track streaks are also of the order of 100 μm, so the pinholes of 20-50 μm in diameter are suitable to see the split images. The set of three streaks – “triplet” - may be considered as a minimal complete set.

The nature of the hot spot should still be understood; however, a few statements can be made. It is clear that the basic magnetic field of the diode current is able to deflect protons of MeV energies on their 4.5-cm path from the hot spot through the pinhole toward the STD. The fields of 10 kGs are sufficient to give deflection to the degree observed. It is apparent that the vertical stretch of the track streaks corresponds to the cyclotron curvature distribution of ions in the dynamical magnetic field. The diode fields together with the pinhole camera serve as a natural Thomson analyzer of corpuscular fluxes emitted by a hot spot. In order to be valid, such a model must assume that the radiating hot spot exists simultaneously with the diode current, and the azimuthal magnetic field must be supplemented with an azimuthal electric field. Such a configuration arises under the helix magnetic mode excitation, the longitudinal field variation being sufficiently fast . There is an evidence for a helix-type instability which accompanies the explosion of a target.

3. Track analysis method

We have adopted the SDAM as most appropriate for the measurement of the shallow tracks of light nuclei. SDAM gives directly the integral characteristics of individual tracks: the full track length (R) and the average etching rate ratio (V) are described by the relations

$$R = a + k/16, \tag{1}$$

$$V = (a + k/16)/(a - k/16), \tag{2}$$

where a and k are the parameters entering the formula for the squared diameter of a track on the etched layer, $D^2(h) = k(h\text{-}a)$, established at the latest stage of the track etching. Relations (1), (2) take into account only normal-incidence tracks.

While SDAM has practical advantages in the identification of particles, we have faced with some difficulties in the interpretation of the SDAM results. This algorithm is too dependent on the limited resolution of the optical system at the detector surface where the curvature of an **etched track wall** impairs the **sharp** formation of the image. According to the Dorschel's data, the critical value D_c is defined as a value that has to be added to the measured diameter D_{ex} for the sum $D=D_{ex}+D_c$ to be zero in the limit $h \to 0$. D_c is about 0.4-1 μm for a 1-MeV proton in the case of a PERSHORE CR-39 detector (Dorschel, 1997, 1998). It would be reasonable to consider the D_c as a function of h under long-time etching. There are currently no models able to explain the $D_c(h)$ dependence.

By a simple analysis, one can find that the correction of the experimental locus "V_{ex} vs R_{ex}" must be carried out by the shifting to the lower values of R and to the upper values of V. The relative errors in the determination of V and R are, respectively, of about 10% and 20% in the case of protons with $R \approx 5$ μm, $V \approx 1.5$, and a crater diameter is 15 μm if we take $D_c = 1$ μm. This effect plays a more significant role in the case of shallow hydrogen pits which are measured in our locus constructions by SDAM.

Despite the difficulty described above, SDAM seems to be the only method able to analyze the shallow tracks of hydrogen nuclei in a range of about 10 μm, because only the track diameters are available for measurements, and the Dorschel's method of **STD breaking** is not applicable to our experiments. The effect of D_c produces systematic errors of RV-coordinates and cannot be a reason for the locus split. The spatial resolution of our optical system is about 0.25 μm at a magnification of 960 used in our measurements. The error bars are not given for our measured loci, because the RV-coordinates are calculated by using the method of least squares. Really, we see the domination of the effect of fluctuations of individual track parameters on the values R and V. So, the measurement errors are displayed by the statistical **expansion** of the RV-streaks with tracks of the same kind which attain 4% in the best case. It meets the requirements of resolution for the 10% locus split.

4. The energy spectrum

Fig. 3 shows the energy spectrum of fast ions determined by the direct count of tracks on the detectors inside the external magnetic analyzer, whose entrance pinhole of 60 μm in diameter is situated at a distance of 36 cm from the hot spot. In these experiments, the beam passes along the diode axis to minimize the effect of the diode fields on the ion **run**.

The spectrum presents **the distribution of ions on ion gyroradii written through the specific energy** $E^* = EM/Z^2$ (M and Z are the mass and charge ion number, respectively). The high-energy edge of the energy spectrum has a sharp steep of the beam type. (The highest energy measured is 2.7 MeV for proton groups with track lengths of about 100 μm in other shots). It is the most fast hydrogen nuclei that give the tracks in the tops of streaks on the pinhole images. The main body of the energy distribution is low-energy and enriches to the low-energy margin E^*=100 **keV**, where the counting was ended. The average ion energy is roughly 0.25 MeV. In the given case, the total number of particles registered inside the magnetic analyzer is about $4.2\cdot10^5$, which corresponds to the total hot-spot output about 10^{14} particles taking into account all the distances, entrance hole diameter, and angle distribution of radiation. The spectrum represented in Fig. 3 is appropriate for arbitrary ions. Sometimes, the tracks of heavy particles **go over the spectrum** (an example is shown below), but, in this case, **the number of hydrogen tracks is given by the same estimation**.

5. The locus analysis

Through the selective analysis of the track groups from the middle of the spectrum, we have found that the contributions of protons and deuterons are comparable in a certain track range. First, this result was derived from the track analysis of a "triplet" observed in shot No. 6512 shown in Fig. 4, *a*. One hundred tracks from 10 groups were chosen for the analysis: groups 1, 4, 7 are taken from the left streak, 2, 5, 8 from the middle streak, and 3, 6, 9, 10 from the right streak.

The *VR*-locus of 100 tracks is shown in Fig. 4, *b*. The split into two streaks is characteristic of the locus. Note that the upper streak in the locus is generated by the tracks from groups 3, 6, 9, 10, while the rest of groups generate the lower streak. Since all tracks are processed and measured in the same way, it is appropriate to assume that the track streaks in Fig. 4, *b* are made of different kinds of particles. Hydrogen nuclei are the only likely candidate, because the condition V<2 is valid only for them in the interval 4<R<12 μm. (In Fig. 4, *b,* we plot the curve for molecular hydrogen ions H_2^+ which is closest to the *p-d-t* theoretical hydrogen **set** to show the increasing of V for heavier ions).

The streak split in Fig. 4, *b* achieves 10%, which is somewhat higher than the theoretical split of $V(R)$ curves for protons and deuterons. However, the experimental streaks appear to be shifted down by the same 10%, respectively, to *p-d* curves. Earlier, we explained the displacement of the measured V, R values by the optical effect of reducing the visible track diameter and by increasing the error of the determination of V, R by SDAM in a long-time etching.

We have confirmed these conclusions in other measurements. Fig. 5 shows tracks and their locus registered inside a magnetic analyzer in the same scheme of the spectrum measurement as that described above, but with the use of a very little entrance pinhole of 5 μm in diameter. In all measurements with the magnetic or Thomson analyzer, we use only one entrance pinhole. This is due to the fact that a two-pinhole collimator used normally reduces or even eliminates entirely the ion signal because of the split effect of ion streams induced by a hot spot. In other words, our upper **object** in Fig.1 is a big pinhole camera with its own inner magnetic and electric fields.

Even for such a little pinhole and a low-density track packing, three streaks are noticeable. 80 tracks were chosen for the analysis, as shown in Fig. 5, *a*. Fig. 5, *b* demonstrates the streak split into a doublet like in Fig. 4, *b*.

Finally, Fig. 6, *a* shows the parabolic track streaks on detectors inside the Thomson analyzer which present the results of a successful shot. The M/Z=1 parabola is marked with the proton tracks nearest to the zero line **observed easily**; with this calibration, we obtain a simple identification of the deuteron M/Z=2 parabola. Deuterons are presented on detectors 4 mainly, and the sharp edge corresponds to the maximal deuteron energy of about 350 keV. The track ranges for such a level of energy are about 2-3 μm, but the determination of a good locus proves problematic because of the high density of tracks at this place. However, the deuteron parabola has the 1-cm continuation from detector 4 onto detector 3, as is visible in a microscope. Fig.6, *b* shows the corresponding locus of 40 tracks with ranges in the 2-6 μm interval. This clearly demonstrates that the tracks belong to the hydrogen family. It is sufficient for the complete identification of the deuteron component.

Fig. 6, *a* reveals that the sections of track streaks in the analyzers may be in the rough ratio 1:1 for protons and deuterons. The total numbers of tracks contained in the deuteron and proton parabolas are given by proportion 1:100. In the case under consideration, the Thomson mass-spectrometer can analyze protons only with energies >300 keV.

Fig. 6, *a* contains the parabolas of heavier ions. The preliminary analysis of their tracks gave us the values V>10. Such values are characteristic of particles with Z>4. We see almost 20 parabolas.

6. Conclusion

It is worth discussing two aspects of our results. Firstly, the hydrogen yield of 10^{14} per shot is surprisingly high, because the result is obtained with a lead target. The superficial organic and aqueous contaminations may explain only 1% of this output. The hydrogen solubility in Pb is very low and thus cannot explain such high amount of hydrogen. Moreover, we did not use hydrogen as a working gas and operated with a vacuum micropinch. Previously, the experiments with a laser focusing had produced the proton output of the order of 10^{10} per shot.

With the help of a Thomson analyzer, we have registered the enhanced content of deuterium in the corpuscular emission from a target. In addition to the quantitative deuteron abnormality against the background of fast protons, deuterons have a bump in the spectrum near E=300 keV (which corresponds to 600 keV for protons on their parabola), as follows from the distribution of tracks in the deuterium parabola in Fig. 6, *a*. Our intention is to undertake further investigations to clarify the situation.

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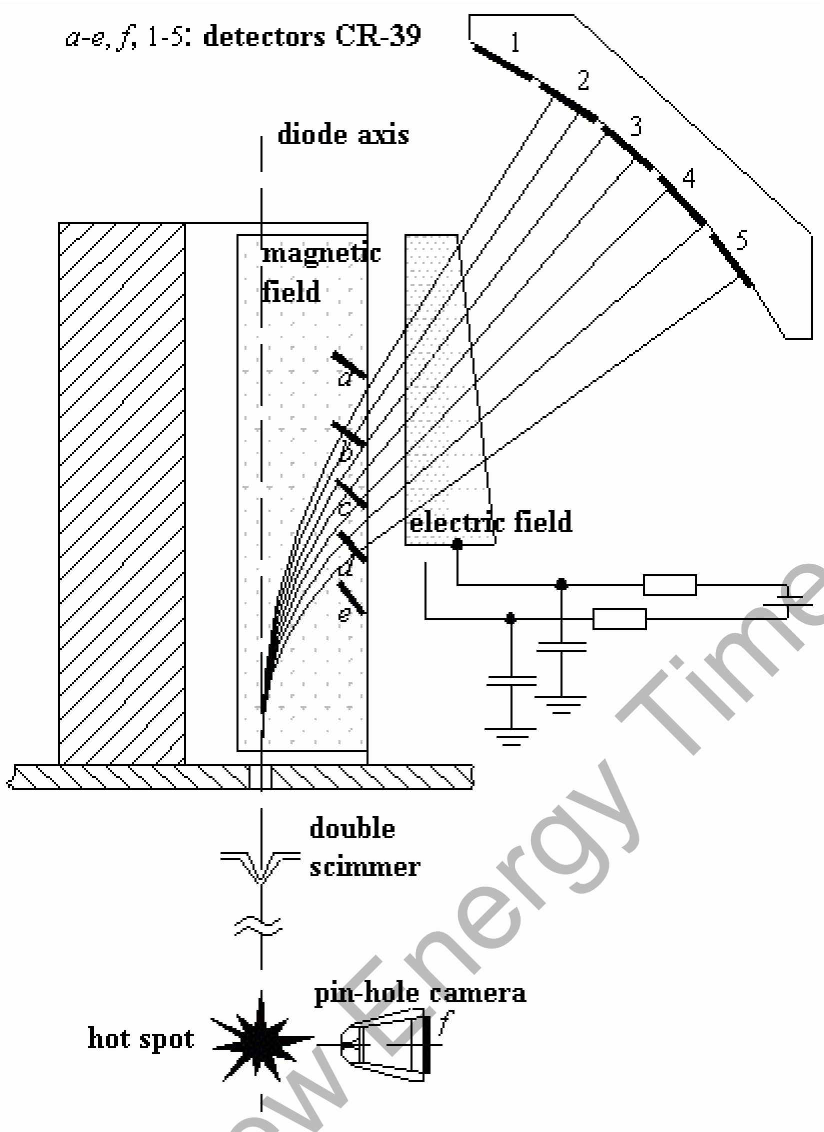

Fig. 1 Scheme of the experimental set-up.

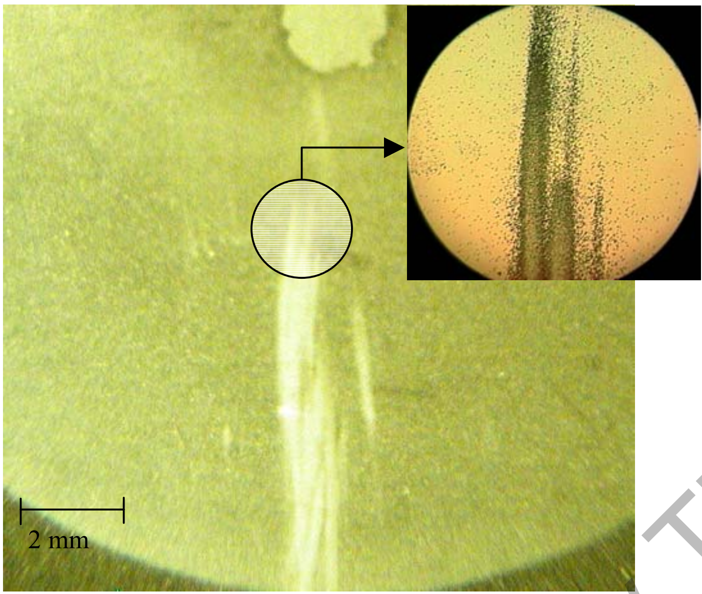

Fig. 2a Pin–hole images of the hot spot.

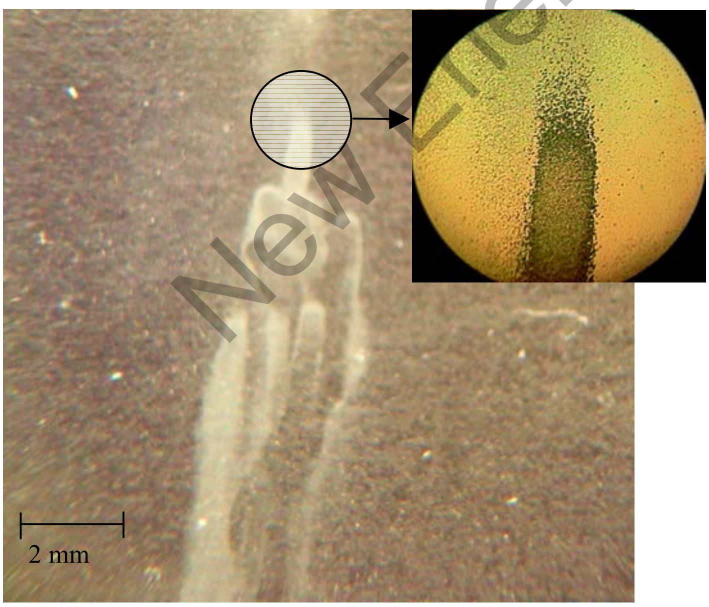

Fig. 2b Pin–hole images of the hot spot.

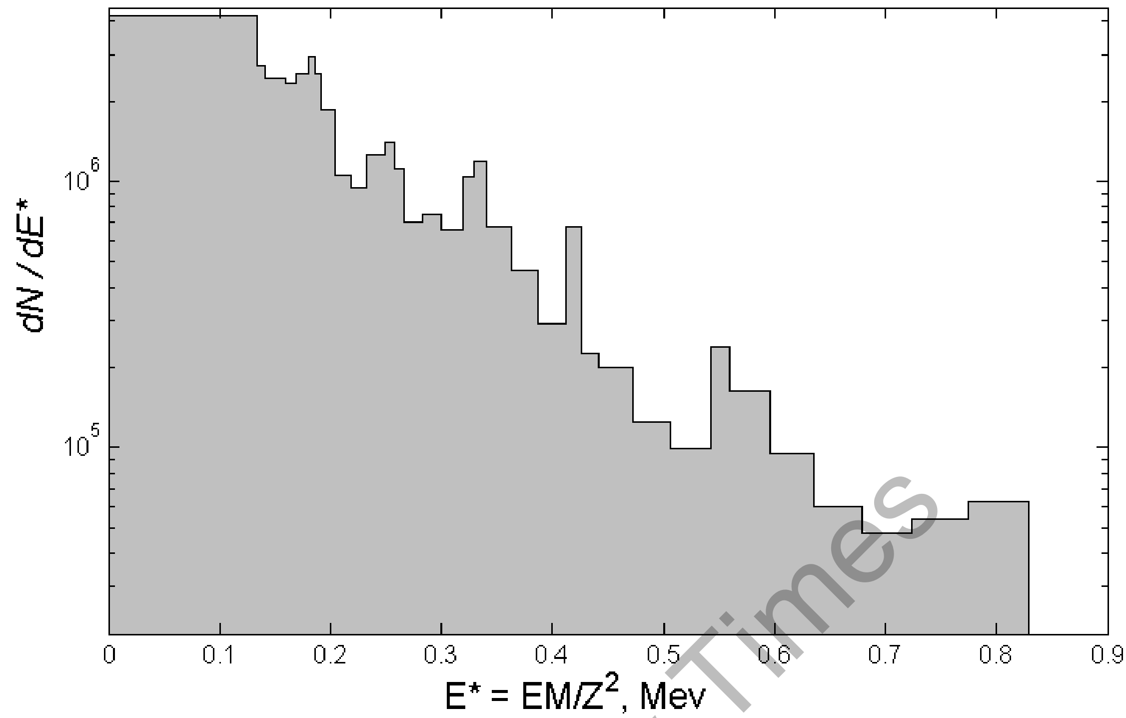

Fig. 3. Energy spectrum of track-creating particles in terms of the specific energy $E^*= E\mathrm{M}/\mathrm{Z}^2$ (*M* and *Z* are the mass and charge ion numbers).

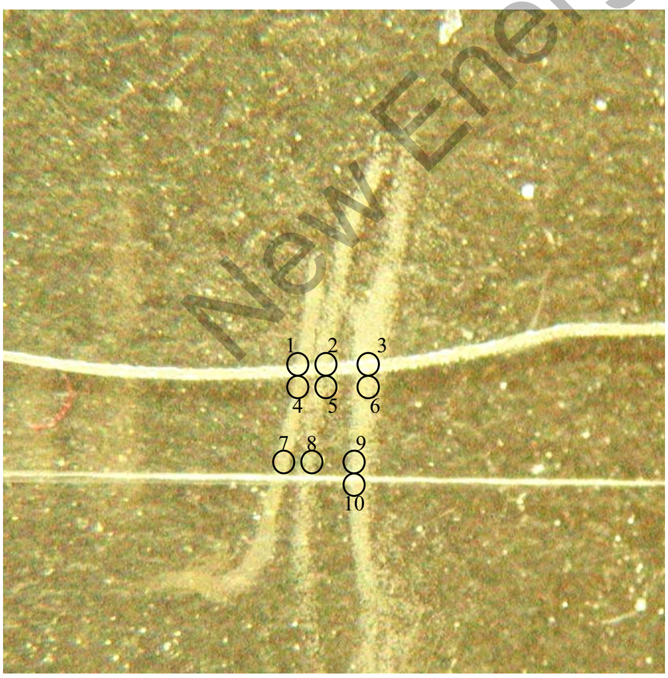

Fig. 4. *a* - the triplet pinhole image (2 horizontal lines are drawn artificially only for the measurements and are not a part of the hot spot image).

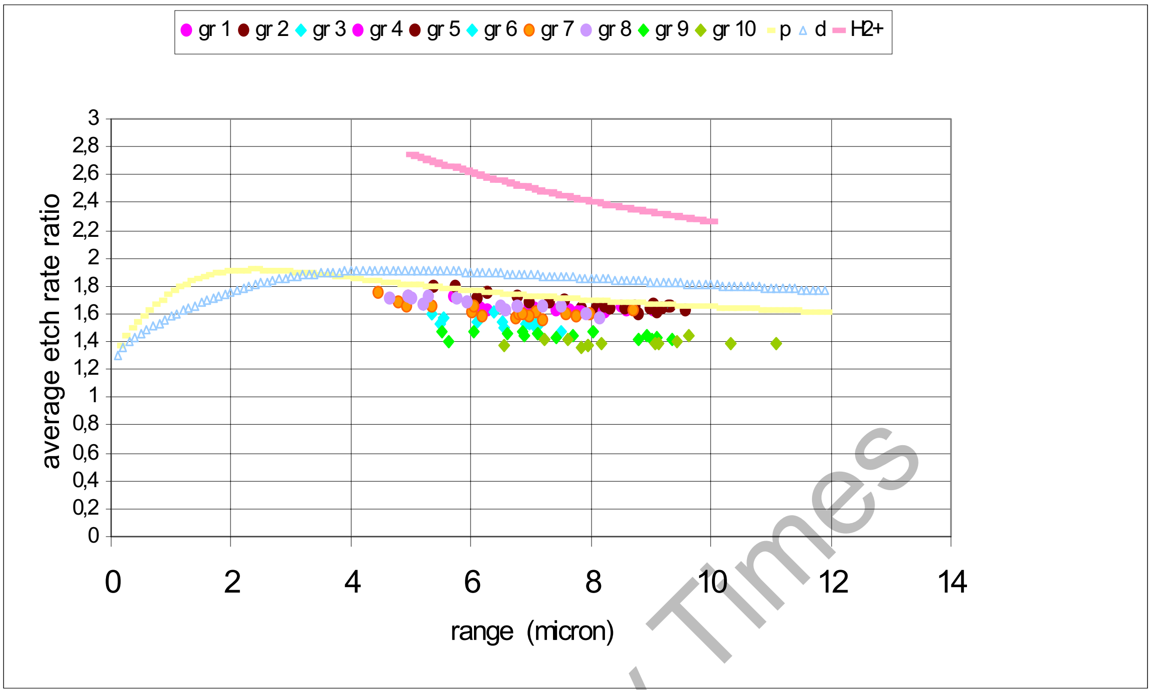

Fig. 4. *b* – its locus (shot No. 6512).

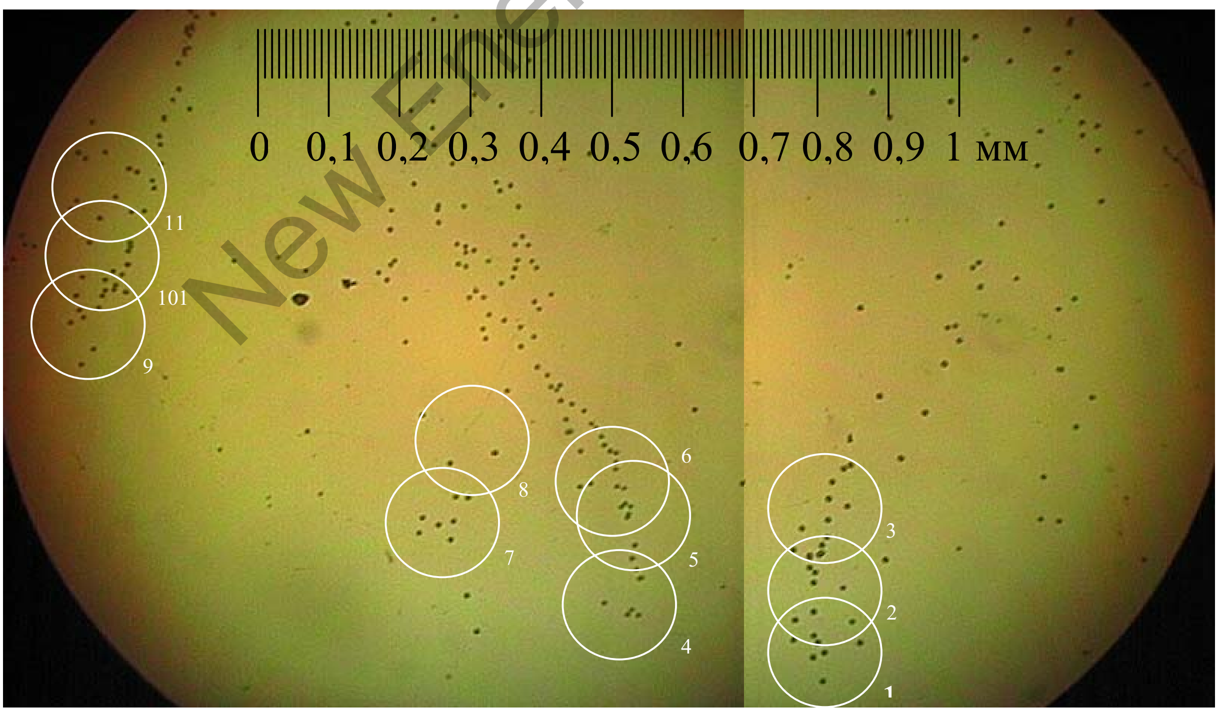

Fig.5. *a* - tracks on a detector in the magnetic analyzer (shot No. 7496).

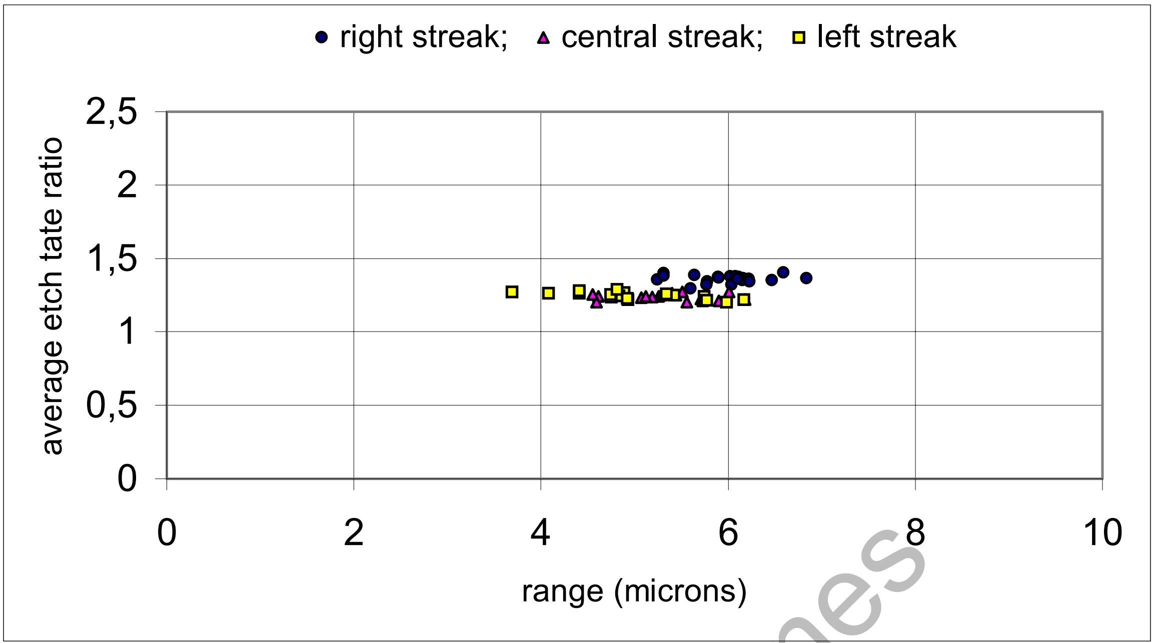

Fig.5. *b* - locus of tracks on a detector in the magnetic analyzer (shot No. 7496).

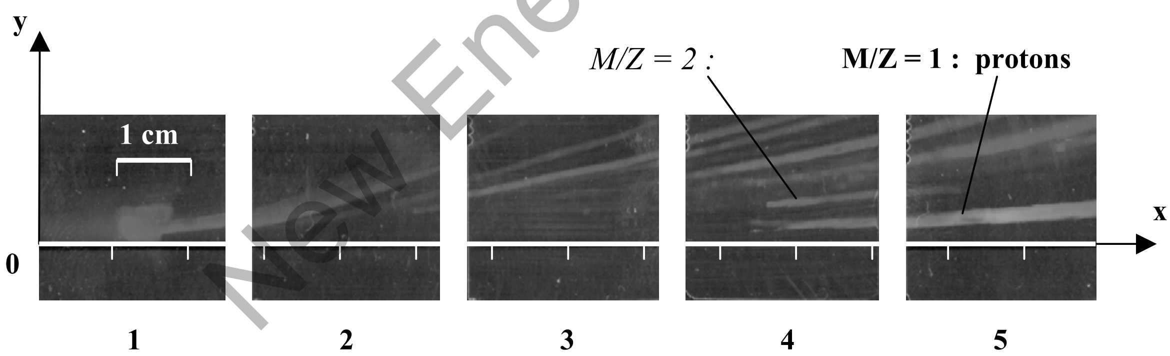

Fig. 6. *a* - track parabolas in the Thomson analyzer (shot No. 8527).

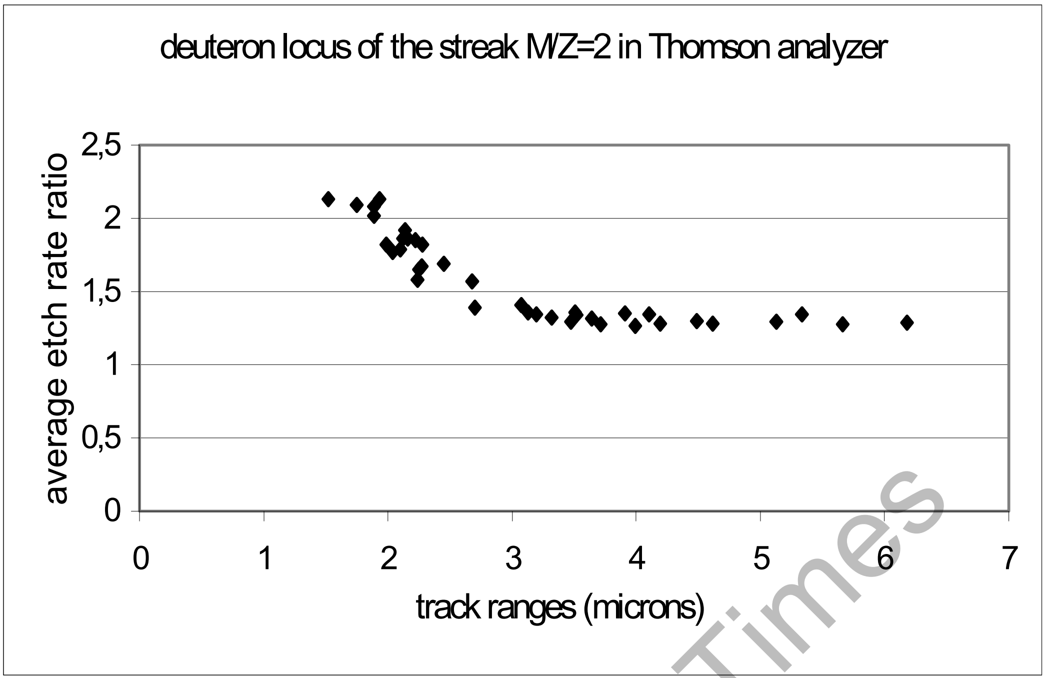

Fig. 6. *b* – the locus of the deuteron parabola (shot No. 8527).