PRAMANA
— journal of
physics

Vol. 68, No. 4
April 2007
pp. 603–609

Detection of accelerated particles from pulsed plasma discharge using solid state nuclear track detector

G M EL-ARAGI[1], U SEDDIK[2] and A ABD EL-HALIEM[2]
[1]Nuclear Physics Department, Nuclear Research Center, Cairo, Egypt
[2]Plasma Physics Department, Nuclear Research Center, Cairo, Egypt
E-mail: usamasm@yahoo.com

MS received 7 June 2006; revised 25 December 2006; accepted 5 January 2007

Abstract. The ion beam of a Mather-type 23.25 J plasma focus device operated with air filling at 10 Torr was registered using CR-39 nuclear track detector. The irradiated samples were etched in NaOH solution at 70°C for 1 h. It is found here that plasma beam contains multi-components of microbeams. The individual track density of microbeams is estimated and the total current density of the plasma stream is measured to be 1.2 mA/cm^2. A model for counting the track density of individual microbeams is proposed here. Faraday cup measurements showed the ion pulse with energy ranging from 5.8 keV to 3.3 keV.

Keywords. Plasma focus; solid state nuclear track detector; ion tracks.

PACS Nos 52.70.Nc; 52.25.Jm; 52.20.Fs; 29.40.Wk

1. Introduction

Generation of pulsed ion beams with a broad spectrum of ion kinetic energy is interesting because of its technological applications [1]. Pulsed plasma coaxial accelerators are very attractive because of their relatively low costs and simplicity of their operation. The use of Faraday cup (FC) collector appeared to be a useful diagnostic technique to determine the main characteristic of ion pulses in the plasma devices [2,3]. Studies of the ion emission from plasma focus devices supply information about mechanisms of the ion acceleration and emission characteristics. These emitted ions as well as all charged particles deposit energy along their path when they travel through matter. In the case of organic plastic materials, this energy loss creates a submicroscopic cylinder of 50–100 Å which is known as latent track. The latent track is of course invisible under optical microscopes, but if one places the organic plastic material in a chemical etching solution (for instance NaOH) the volume around the latent track will be attacked preferentially. So the trail of the incident particle becomes visible under optical microscopes [4,5] as a cylinder or cone-shaped hole of 1 to 30 μm if we consider heavy ions. In this work, CR-39 is used as a solid state nuclear track detector (SSNTD) to study the structure of ion beams produced by a (plasma focus) PD-type device. In fact, the track caused by plasma is not that track of the previous meaning or characteristics. It is some kind of surface burning due to the large number of particles.

2. Experimental

Mather-type 23.25 J plasma focus device consists of an outer electrode which is formed of six copper rods, each of 130 mm length and 10 mm diameter as shown in figure 1. The diameter of the outer electrode is 90 mm. The inner electrode is made of stainless steel of 18 mm diameter. There is a hole of 5 mm diameter in the front of the inner electrode. The annular space gap between inner and outer electrodes is 36 mm. The cylindrical insulator flange is of 130 mm diameter and 35 mm thickness.

A stainless steel tank (expansion chamber) of 350 mm length and 100 mm diameter encloses the plasma focus. The condenser bank of plasma focus device consists of six condensers (Bosch MP model) of 40 kV and 0.31 μF low inductance condensers which are connected in parallel. The inner electrode is connected to the positive connection of high voltage supply via an air gap switch, whereas the outer electrode is connected to earth. The vacuum system consists of a rotary pump (Edwards single stage model 1 Sc.-150B) connected to an oil diffusion pump (Edwards model F 403). To avoid vapour from back-streaming, the specimen is washed by argon after evacuation by oil pump. Then a fore vacuum is reached using only the rotary pump. The gas was fed into the system via flow meter (OMEGA model). The pressure was measured using a thermocouple gauge (Edwards model). The detector is a 1×1 cm^2 sheet of CR-39 of 0.5 mm thickness, while the irradiated samples are etched in 6.25-N NaOH solution at 70°C for a time period of 1 h.

3. Theoretical

The image of plasma ion tracks shows a collection of several microbeams. Each individual microbeam has a circular cross-section of total area ranging from 9.6 to 28 μm^2. The bunches of microbeams contain a large number of fast ions which

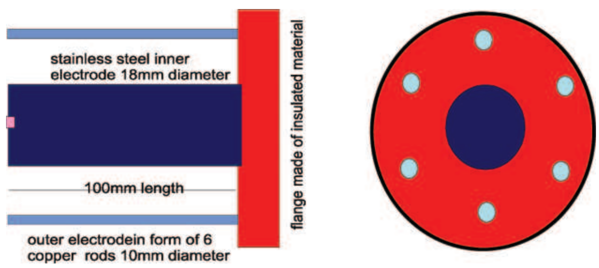

Figure 1. Schematic diagram of the construction details of plasma focus electrodes set-up. Left part shows the horizontal cross-section, while the right part shows the vertical cross-section.

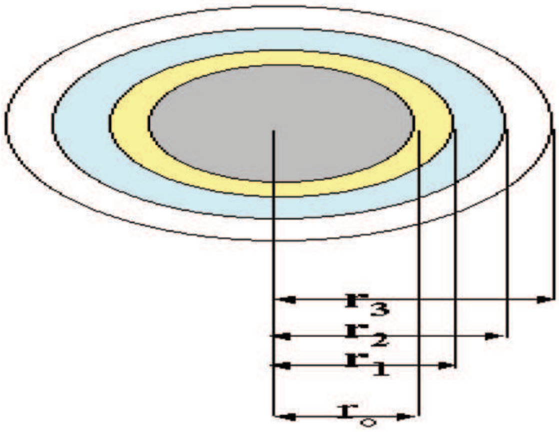

Figure 2. Schematic diagram of the CCZ model, where r_0 is the radius of the core, r_1, r_2 and r_3 are the radii of the first, second and third zones, respectively.

are distributed uniformly or quasi-uniformly over the beam cross-section. To estimate the ion flux density of an individual microbeam, a model consisting of *a core surrounded by co-central zones* (CCZ model) is proposed. The model assumes that the beam cross-section consists of a main core of highest track density surrounded by several co-central zones of lower densities (see figure 2). The nearest the zone to the core the highest is its track density, while the track density of each zone is assumed to be uniform.

The number of tracks ($n_{\rm tr}$) inside a predefined small area (δ) is first counted for the core and each zone. The total number of tracks ($N_{\rm tr}$) inside an individual microbeam is then given by

$$N_{\rm tr} = \pi r_0^2 \frac{(n_{\rm tr})_0}{\delta_0} + \sum_{i=1}^{n} (r_i - r_{i-1}) \times 2\pi r_i \frac{(n_{\rm tr})_i}{\delta_i}, \quad (1)$$

where $(n_{\rm tr})_0$ is the number of tracks inside a small area δ_0 of the core, $(n_{\rm tr})_i$ is the number of tracks inside a small area δ_i of the ith zone, r_0 is the radius of the core, r_i is the radius of the ith zone and n is the number of zones.

The ion flux density ($\rho_{\rm tr}$) of an individual microbeam is given by

$$\rho_{\rm tr} = \frac{N_{\rm tr}}{A_{\rm mb}}, \quad (2)$$

where $A_{\rm mb}$ is the area covered by the microbeams in $\rm m^2$.

The microbeams of the present plasma image (see figure 3) are classified into two main categories according to their track density distribution: (1) a majority of quasi-uniform ion density microbeams (the density of ions is distributed) tend towards the beam center. The total number of tracks for this kind of microbeams is estimated using eq. (1). (2) A small number of uniform ion density microbeams. Here, the microbeam is considered to be a core without zones, i.e. eq. (1) is reduced only to the first term.

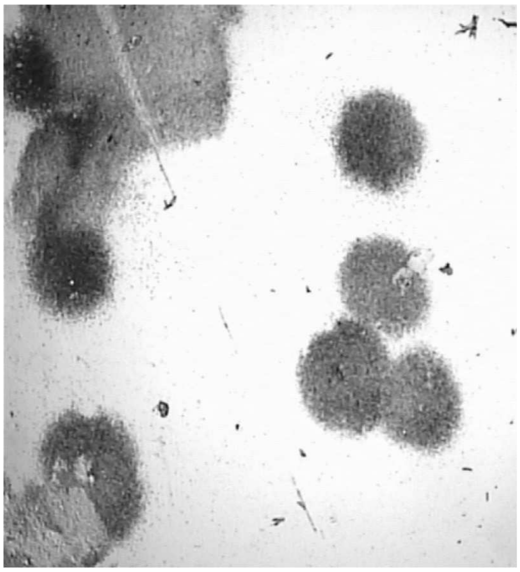

Figure 3. Photo of a collection of microbeams of plasma ion tracks developed by chemical etching.

There is, however, a very rare third category where the core has a sided crescent shape and the rest of the beam is a uniform density area. To estimate the number of tracks, we consider that it consists of a core and a single zone. The ratio of core radius and the single zone radii was considered however to be equivalent to the ratio of core and zone areas.

4. Results and discussion

The discharge current of the plasma focus device was measured using Rogowski coil and its peak value is approximately 1.2 kA at the first half cycle. Figure 4 shows the current and voltage waveforms of the plasma focus capacitor bank discharge. Current and voltage were measured as a function of time at an input energy of 23 J (applied voltage 5 kV) and air pressure of 10 Torr. The value of maximum current varies shot by shot, but the variation of the period is very small, although same condition of applied voltage and gas pressure was used. From these measurements, the power transfer and impulse transfer into the gun can be calculated. They were also obtained as a function of time as shown in figures 5 and 6 respectively.

It is well-known that for photon energies below 100 keV, the dominant interaction with the matter is the photoelectric effect. When a beam of X-rays ($h\nu = 100$ keV) impinge on a metal surface, many of the ejected photoelectrons will be stopped within the bulk of the material, and the others will lose a fraction of their kinetic energy before leaving the metal surface. Hence the kinetic energy of the ejected particles represents the maximum energy limit for the photoelectrons leaving the metal surface. The metal plate was maintained at negative potential by an R-C biasing circuit. A wire grid placed in front of the metal plate collects the resulting

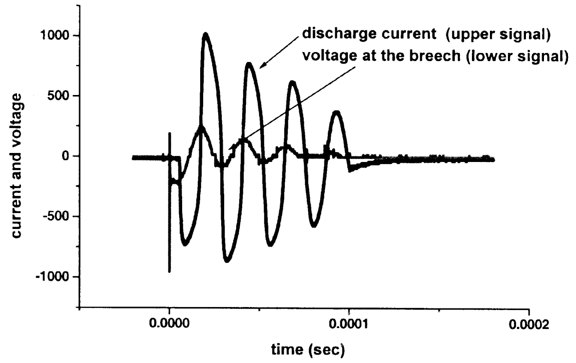

Figure 4. Discharge current and voltage signals from the plasma device.

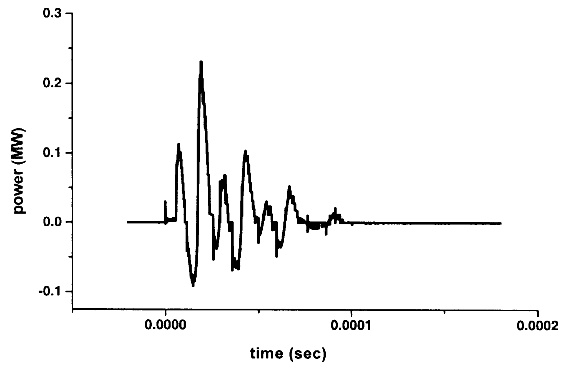

Figure 5. Time variation of the power.

photoelectrons, which is positive relative to the negatively biased plate (maintained at ground potential), giving rise to a current signal through the detector.

The resulting voltage signal as shown in figure 7 was recorded by an oscilloscope (Lecroy model). The efficiency of photoelectric effect depends on the material of the target (we choose copper as the target material for the detector plate) and the absolute energy spectrum of the X-ray source. The emission of X-ray was accompanied by acceleration and emission of pulsed ion streams in the direction opposite to electron beams. Time-resolved measurements of soft X-rays and ion streams are performed by means of Faraday cup (FC) coupled with digital oscilloscope, soft X-ray is measured by time-integrated X-ray film (Kodak model). The FC signal as shown in figure 7 showed that, the first peak could be explained by secondary electrons knocked out from FC collector by energetic X-ray followed by the second peak of fast ion beam and wider ion pulse of about 1.6 μs duration. Energy of ions was determined with a time-of-flight (TOF) method, taking into account the distance from the center electrode to the detection plane. The FC signal showed that the first peak lasts for about 90 ns. It was followed by the second wider ion pulse (of about 1.6 μs) corresponding to nitrogen ion with kinetic energy ranging from 0.025 to 5.8 keV.

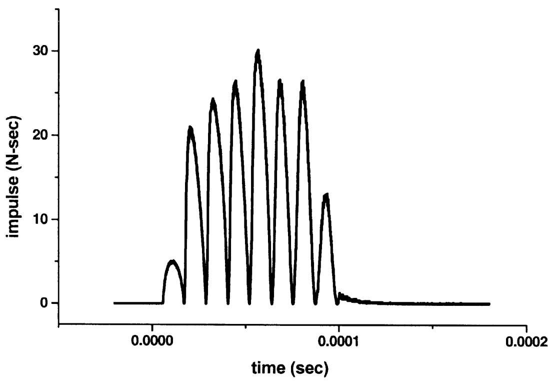

Figure 6. Time variation of impulse.

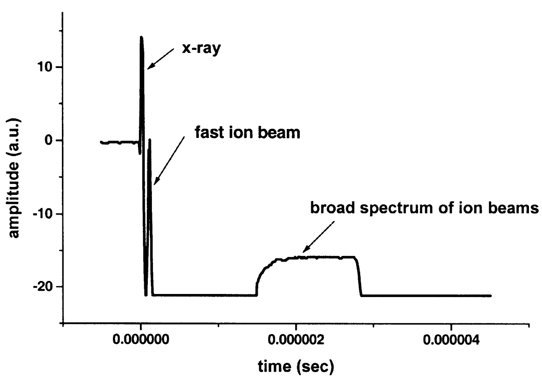

Figure 7. Typical Faraday cup signal obtained from a single discharge.

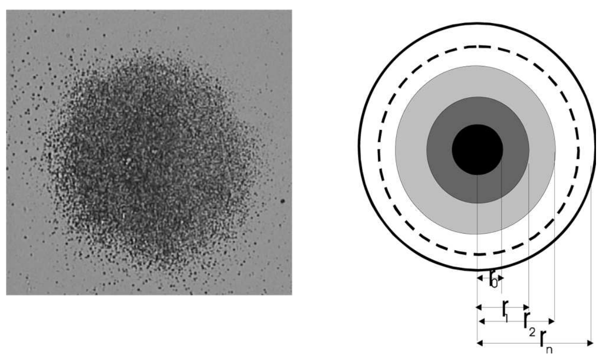

Figure 8. Photo of an individual microbeam (left) and schematic diagram of the equivalent CCZ model (right).

Most ion trajectories are twisted by B-field, forcing the ions to whirl within the pinch column. The ion beams are a mixture of fast ions or suprathermal ions [6,7] (defined as ions with characteristic velocities much larger than the characteristic local thermal velocity and the free energy in fast ions can derive plasma instabilities) and bulk ion streams. The bulk ion beams escape axially, particularly after the column is disturbed. The rotating plasma has the distribution of the θ-component of the ion velocity according to the following equation:

$$f(\nu_\theta) = n_i \left(\frac{M_i}{2\pi KT}\right)^{3/2} \mathrm{e}^{\frac{M_i \nu_\theta^2}{2KT}}. \quad (3)$$

For plasma of Maxwellian distribution, the number of faster particles is less than that of slower particles. In other words, in thermodynamic equilibrium the distribution function always decreases monotonically with velocity (Landau damping). Consequently, more particles take energy from the wave field and the wave is damped.

According to CCZ model, it is possible to estimate the total number of tracks (ions) of an individual microbeam. For instance, figure 8 shows a photo of a microbeam of total cross-sectional area of 22 $\mu\mathrm{m}^2$. The estimated total number of tracks (using eq. (1)) is equal to 915 tracks. The ion flux density (using eq. (2)) is 4.15×10^9 track/cm^2.

5. Conclusion

Particle beam diagnostic tools involving an ion beam Faraday cup and solid state nuclear track detectors have been used to measure the parameters of the particle beams generated by a Mather-type plasma focus. Faraday cup measurements showed that the average kinetic energy value of the ion beam was 3.3 keV using time-of-flight (TOF) method. The ion current density amounts to 1.2 μA/cm^2. The proposed CCZ model is used to estimate the total number of tracks and the ion flux density for a selected microbeam. More extensive study is needed to improve the proposed model.

References

[1] J J Curomo, S M Rosagent and H R Kanfiman, *Handbook of ion beam processing technology* (Noyes Publishers, Park Ridge, New Jersey, 1989)
[2] J S Pearlman, *Rev. Sci. Instrum.* **48**, 1064 (1997)
[3] W Stygar, G Gerdin, F Venneri and J Mandrekas, *Nuclear Fusion* **22**, 1161 (1982)
[4] R L Fleisher, P B Price and R M Walker, *Nuclear tracks in solids* (University of California, Berkeley, 1975)
[5] S A Durrani and R K Bull, *Solid state nuclear track detection* (Pergamon Press, Oxford, 1987)
[6] L Jakuboweski, M Sadowski, J Zebrowski and E O Baronova, *J. Tech. Phys.* **40**, 1137 (1999)
[7] L Jakuboweski, M Sadowski and J Zebrowski, *J. Tech. Phys.* **38**, 141 (1999)