Ion Beam Emission within a Low Energy Focus Plasma (0.1 kJ) Operating with Hydrogen

Gamal M. El-Aragi

Plasma Physics and Nuclear Fusion Dept., Nuclear Research Center, AEA, P. O. Box, 13759 Cairo, Egypt

Reprint requests to G. M. E.; E-mail: elaragi@gmail.com

Z. Naturforsch. **65a,** 606 – 612 (2010); received October 19, 2009

An investigation of energetic ion beam emission from a low energy plasma focus (0.1 kJ Mather type) device operating with hydrogen gas is studied. The ion beam emission is investigated using time-integrated and time-resolved detectors. The present plasma focus device is powered by a capacitor bank of 1 μF at 18 kV maximum charging voltage. The correlation of ion beam intensity with filling gas pressure indicates that the beam emission is maximized at the optimum pressure for the focus formation at peak current. Energy of ions is determined with a time-of-flight (TOF) method, taking into account distance from the center electrode to the detection plane.

Key words: Energetic Ions; Plasma Focus Time of Flight; Charging Voltage.

1. Introduction

The plasma focus is not only a suitable device for detailed studies of fundamental plasma physics, but also one of the complementary fusion devices low-β tokamak and high compression inertial fusion. High energetic ions are considered to play an important role in the production of the intense neutron flux in the plasma focus device when using deuterium gas [1]. Ion diagnostics of high-temperature plasma objects are considered to be very important, because they provide essential data about plasma parameters. Ion beams emitted from the high-temperature plasma objects are an abundant source of valuable information about fusion reaction yields, plasma ion temperatures, as well as spatial distribution of fusion reaction sources.

Studies of high-energy ions emitted from plasma focus devices provide information on the ion acceleration mechanisms and are also important for various plasma focus technology. Gerdin et al. [2] employed a Faraday cup in a time-of-flight technique to measure the ion spectrum and a careful study of the ion-neutral interactions allowed the observation of deuteron energies down to $\sim$ 25 keV.

Inside the pinch column of a plasma-focus (PF) discharge, particularly when some gases are applied, miniature regions of high-density and high-temperature plasma are formed. These miniature regions, called ‘hot spots’, are sources of intense pulses of X-ray and corpuscular emission [3]. Most of the earlier studies on ion beam emission in plasma focus were carried out in a deuterium medium to investigate the correlation between neutron production and deuteron acceleration. Several theoretical and computational models on ion production and acceleration mechanisms have been developed for plasma focus discharges [4].

The generation of ion beams from the plasma focus and their applications have been studied by various researchers [5 – 7].

The main aim of this work is to study the ion beam characteristics (time-resolved using Faraday cup and time-integrated using pinhole camera with LR-115A film).

2. Experimental Setup

Mather-type 112.5 J plasma focus device consists of an outer electrode, which is formed of eight copper rods, each of 130 mm length and 10 mm diameter as shown in Figure 1. The outer diameter of the center electrode is 18 mm and the inner diameter of the squirrel cage (outer electrode) amounts to 55 mm. A hole of 5 mm diameter and 8 mm depth was drilled in the front of the inner electrode in which different metals were filled. The cylindrical insulator ring is of 130 mm diameter and 35 mm thickness. The electrode system is enclosed in a vacuum chamber made of a stainless steel tank of 350 mm length and 100 mm

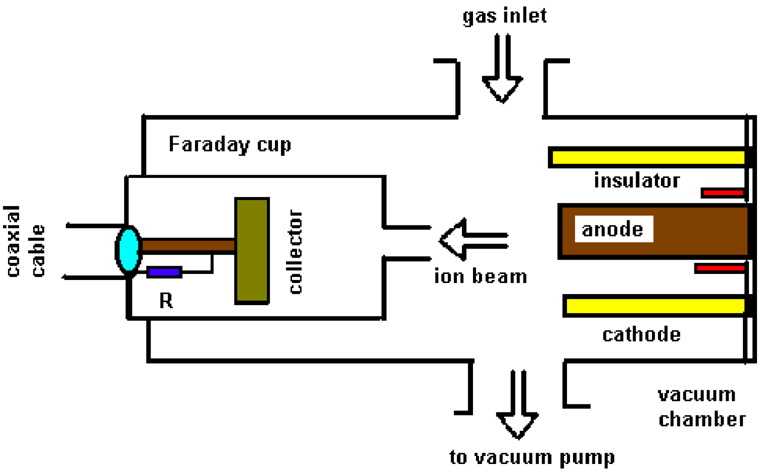

Fig. 1. Scheme of experimental setup.

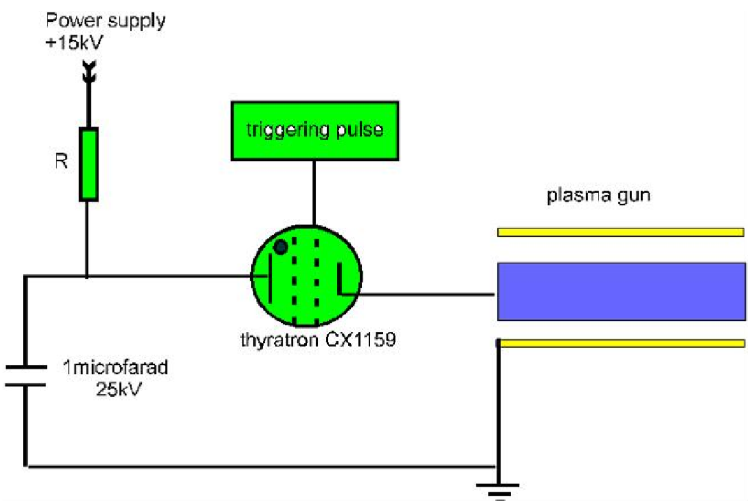

Fig. 2. Circuit diagram of the trigger pulse.

diameter. There are several ports in the vacuum chamber for diagnostic purposes. The condenser bank of the plasma focus device consists of one 25 kV and 1 μF low inductance condenser. A capacitor bank charged at 15 kV (112.5 J), giving a peak discharge current of about 5 kA, powered the focus device.

The inner electrode is connected to the positive pole of the high voltage supply via a triggertron-type vacuum tube (CX1159) serving as a switch, whereas the outer electrode is grounded.

The vacuum chamber was evacuated up to 10^{-2} mbar pressure by a rotary pump (Edwards single stage model 1 Sc.-150B) before filling with gas (hydrogen). To avoid vapour from back streaming, the vacuum chamber is washed by gas after evacuation. The gas was fed into the system via a flow meter (OMEGA model). The circuit diagram of the trigger pulse for the plasma discharge is shown in Figure 2. The external inductance of the system including the capacitor, the thyratron switch, the connecting cables, and the coaxial electrodes (cathode and anode) is measured to about 6.5 μH.

In order to register the particle radiation within the pinhole camera, nuclear track detectors of the LR-115A type were used. After irradiation those detectors were etched under standard conditions (in a 6.25-N solution of NaOH, at a temperature of 70 °C) for a period ranging from one hour to several hours. To perform time-resolved measurements there were used Faraday-type collectors: a single cup (FC) and a so-called double-cup system (DFC), which used two ring-shaped collectors placed at a given distance (time-of-flight basis), but adjusted along the common z-axis.

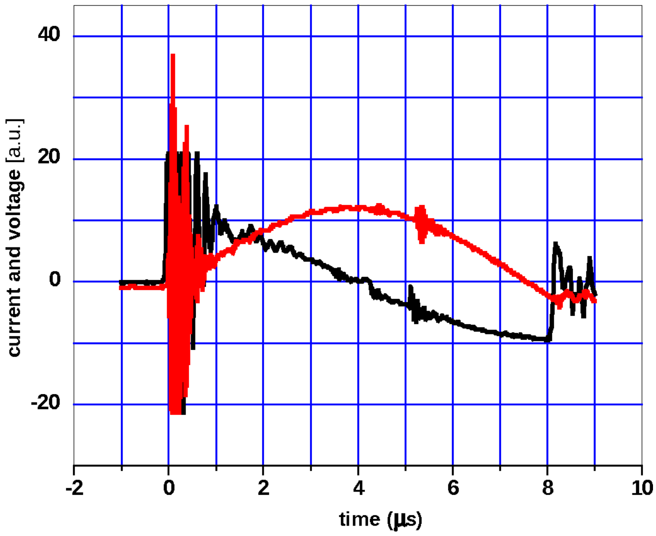

Fig. 3. Discharge current (grey) and voltage (black) signals from the plasma device.

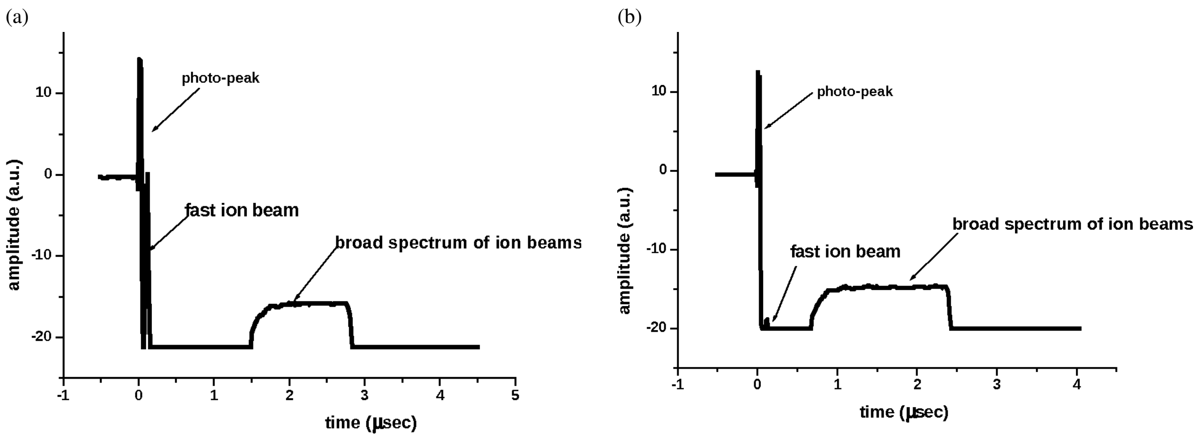

Fig. 4. Typical Faraday cup signals obtained from a single discharge. The left signal (a) indicates a good peak of fast ions while the right signal (b) shows less fast ions.

The applied voltage to and the discharge current through the discharge chamber were measured using a voltage divider (home made), which was connected between the two electrodes, and a current monitor, which can be located upon returning to the ground. The signals from the voltage divider and the current monitor were recorded in a digitizing oscilloscope (Lecroy, USA) with 200 MHz bandwidth.

The peak value of the measured discharge current was approximately 5 kA during the pulse. Figure 3 shows the current and voltage waveforms characterizing the pulsed low energy plasma focus device. Current and voltage were measured as a function of time at an input energy of 112.5 J (maximum applied voltage 15 kV).

3. Results and Discussion

3.1. Time-Resolved Measurements

Preliminary time-resolved measurements of the ion pulses were carried out by means of an ion collector, which was placed at a distance of 10 cm from the top of the anode. The collector plate was polarized negatively, and the whole measuring circuit was shielded against electromagnetic noise. Time-resolved studies of ions were performed by means of a double-collector of the Faraday type, which was designed especially for TOF measurements of pulsed charged-particle streams. This detector was equipped with two separate collectors (collector and grid) adjusted along the same z-axis. The

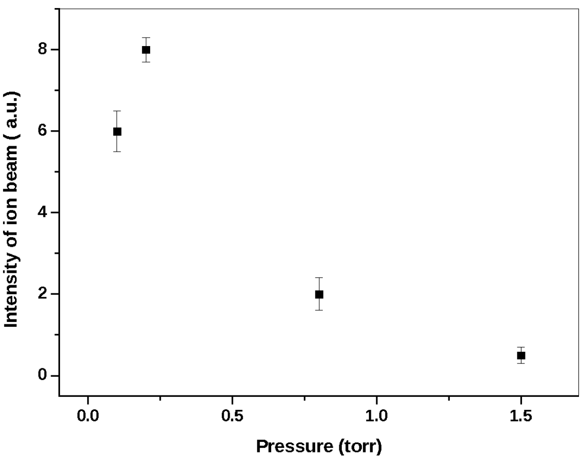

Fig. 5. Ion beam intensity as a function of the operating pressure at charging voltage 15 kV.

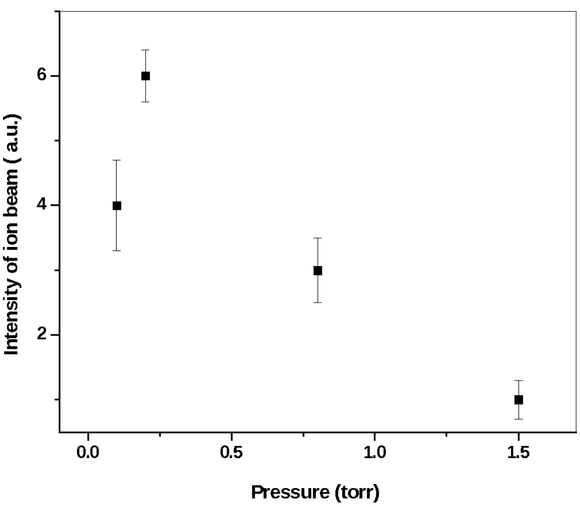

Fig. 6. Ion beam intensity as a function of the operating pressure at charging voltage 12 kV.

first ring-shaped collector (grid) was placed at a distance of 8 cm from the focus pinch, and the second one was situated about 2 cm behind the first collector. Some examples of the registered traces of the collector signals are presented in Figure 4.

The Faraday cup (FC) signals showed that the first peak could be explained by the intense pulses of the electromagnetic radiation interacting with the surface of the entrance grid or the collector themselves and inducing an intense photo-effect. As a result, the obtained signals were caused by the photoemission followed by the second peak of fast ion beam and then the bulk of thermal ion beam of about 1.6 microsecond duration (Fig. 4a) and approximately 2.5 microsecond duration (Fig. 4b).

Figures 5 and 6 show the ion beams with highest intensities per shot recorded when the plasma focus was operating at a H_2 filling pressure of $P = 0.1 - 1.5$ torr, with a maximum value of the beam intensity at 0.2 torr at a charging voltage of 15 kV and 12 kV, respectively.

The energy of the ions is determined with a time-of-flight (TOF) method, taking into account the distance from the center electrode to the detection plane. It is found that the energy of fast ions and the bulk of broad spectrum ion beam is ranging from 0.045 to 75 keV at 15 kV charging voltage and 0.2 torr hydrogen gas pressure.

3.2. Time-Integrated Measurements

These emitted ions as well as all charged particles deposit energy along their path when they travel through matter. In case of organic plastic materials, this energy loss creates a submicroscopic cylinder of 50 – 100 Å, which is known by 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 [8, 9].

In order to register an image of the investigated ion beams which were emitted from the plasma focus discharges, there was used a special diagnostic system. The images of the ion beams which were obtained after etching of the irradiated solid-state nuclear track detectors (SSNTDs) of the LR-115A type were analyzed with an optical microscope equipped with a CCD camera coupled with a special interface and a fast (Pentium-4) computer. An example of the ion beam images is presented in Figure 7. The emitted ions have too low energy to be registered directly with SSNTDs.

The LR-115A film was irradiated with hydrogen gas at pressures of 0.1, 0.2, 0.8, and 1.5 torr at 15 kV at a distance of 10 cm from the end of the central electrode.

Figure 7 represents a part of the irradiated LR-115A detector etched for 1 hour and analyzed with an optical microscope operating at a large (1200×) magnification. In this picture one can easily discern two types of particle tracks: small micro craters and larger ones. During the analysis of these micro craters, one should take into consideration that in the described experiment the integral electromagnetic radiation (broad spectrum) was very intense. Such pulse radiation could ionize the

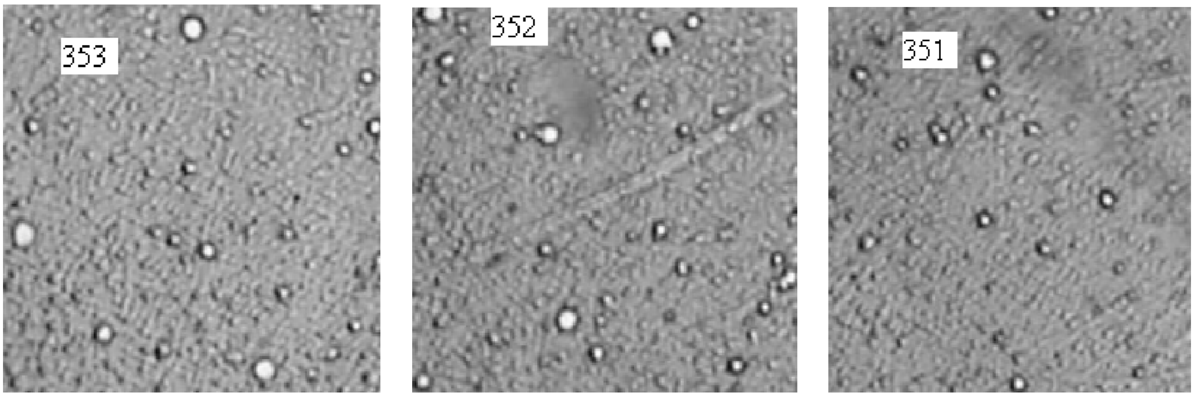

Fig. 7. Images of the ion tracks as obtained from focus plasma discharges which were registered with the LR-115A detectors at different conditions of pressure.

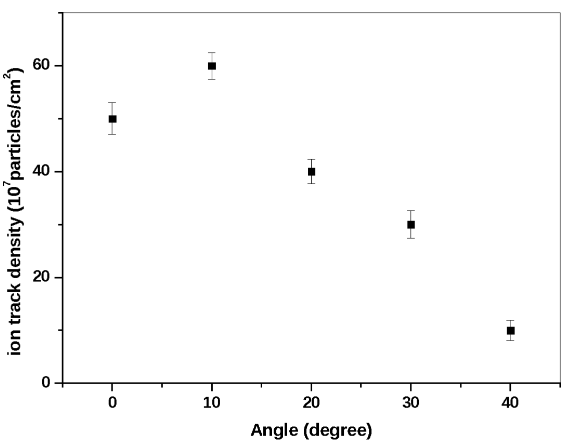

Fig. 8. Angular distribution of protons as measured for several discharges performed with hydrogen filling.

working gas and admixtures (impurities). Hence, one might suspect that the small micro-craters could be produced by hydrogen ions, and the larger ones could be generated by heavier ions of copper, iron, carbon, and oxygen.

Ion angular distributions were measured with a set of small SSNTDs samples placed upon a circular disk at constant distance from the electrode outlet, but at different angles to the electrode axis. The SSNTDs samples were irradiated with hydrogen ions (protons), produced by several plasma focus discharges performed under the same experimental conditions. In Figure 8 an angular distribution of the protons is presented as measured for a series of PF discharges performed with 0.1 torr hydrogen filling. The distribution shows a peak at an angle of about 10 degree to the z-axis, i.e. a track density close to the z-axis (zero degree) has a relatively low ion emission along the electrode axis.

According to a core surrounded by co-central zones (CCZ) model, it is possible to estimate the total number of tracks (ions) for a selected microbeam [10]. A flux density of the investigated corpuscular radiation at a distance of 10 cm from the center electrode was estimated to be about 6.0×10^8 particles/cm^2 at an angle of 10 degree from the central electrode.

3.3. Acceleration Mechanism

The magnetic mirror was first proposed by Enrico Fermi as a mechanism for the acceleration of cosmic rays. Protons bouncing between magnetic mirrors approaching each other at high velocity could gain energy at each bounce. The confinement of charged particles in the Van Allen belts, where the magnetic field of the Earth at the poles is stranger than at the equator, form a natural mirror.

In plasma focus, especially in the pinch phase, the plasma gets more compressed at the onset of hydrodynamic instabilities ($m = 0$) as shown in Figure 9. The charged particles (ions and electrons) are trapped between two layers of plasma current sheath which act like two moving magnetic mirrors with radius R. The particles initially have a velocity V_i.

During the compression each mirror (current sheath) moves toward the midplane with a radial velocity $\mathrm{d}R/\mathrm{d}t$. By using the loss cone formula and the invariance of μ the energy to which the charged particle will accelerated before it escape can be calculated. The final velocity V_f depends on the initial velocity and the radius of the core. The mirrors (current sheaths) can be

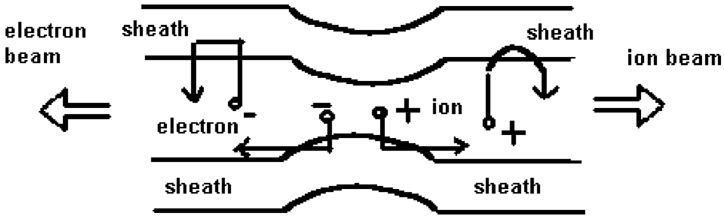

Fig. 9. Plasma pinch and emission beams of charged particles onset of instability inducing micro instabilities.

treated as flat piston. A particle with velocity $V_i > 0$ hit the piston moving at velocity $V_P < 0$. In the frame of the piston the particle bounces elastically and comes off with its initial velocity, but in the opposite direction. By transforming back to the laboratory frame the final velocity V_f is given by

$$V_f = -V_i + 2\,V_P.$$

At each bounce, the change in momentum is

$$\delta P = 2M|V_P|,$$

where M is the mass of the particle.

The number N of bounces depend on the initial velocity of the particle (initial momentum) and the piston velocity and is given by

$$N = V_i/2\,V_P.$$

Since high-temperature plasmas are nearly collisionless, i. e. the particle velocities obey approximately a Maxwellian distribution function (velocities of particles are distributed randomly around the average velocity).

A Maxwellian distribution function has more slow particles than fast ones, in other words, the number of particles with velocities slightly less than the wave phase velocity is greater than the number of particles with velocities slightly greater. Consequently, there are more particles taking energy from the wave and the wave is damped.

Faraday cup signals show that the plasma has an ion distribution function composed of a Maxwellian distribution of plasma bulk ion streams with density n_p and temperature T_p at rest in the laboratory and a Maxwellian distribution of beam (fast) ions with density n_b and temperature T_b. If n_b is very small ($n_b < n_p$), plasma oscillations travelling in θ direction experience a Landau damping, i. e. are in thermodynamic equilibrium (for example Fig. 4a). If n_b is large ($n_b > n_p$), i. e. in non-thermal equilibrium (Fig. 4b), there exist free energy used to excite waves. There will be two stream instabilities so that different species have drifts relative to one another. The drift energy is used to excite waves and oscillation energy is gained at the expense of the drift energy. There is a critical beam density n_b at which instability sets which depends on the velocity of the particles escaped from the pinch column after short time and the density of bulk ion streams (n_p).

The same results were reported by Bhuyan et al. [11] for a 2.2 kJ plasma focus device. Their Faraday cup measurements showed that the ion number density of lower energy ions was in excess of 4×10^{18} m^3, whereas the number density of high energy ion was of the order of 5×10^{17} m^3.

High energy ions in the plasma are usually considered to be an indication of thermodynamic non-equilibrium of the pinch, a state in which a beam of charged particles is formed in the plasma. The energy distribution function in the pinch compression is determined by two processes, the escape of particles through the ends of the pinch and the plasma heating under compression. The escape of particles from the ends of the pinch reduces their number in the tail of the energy distribution function, as it are precisely energetic ions which the plasma loses first. Plasma heating during pinch compression leads to a redistribution of particles into the high energy region and compensates to some extent for the loss of fast particles from the plasma region.

During the second pinch compression, two processes occur in the plasma. Compression is induced by the azimuthally magnetic field H_θ and rarefaction as the result of particles escaping through the ends of the pinch.

It was found that the energy distribution of ions which escaped through the ends of the pinch is in agreement with the downstream ion flux distribution in the plasma focus observed in the experiment, although no measured distribution of ion flux in the up stream is available.

At the beginning the pinch initially has a Maxwellian plasma distribution, i. e. is in thermodynamic equilibrium. Assume that the pinch is in equilibrium, i.e. the plasma kinetic pressure is equal to the magnetic pressure and after short time, some particles will escape from the pinch and the distribution will take another form. The escape of particles from the pinch column will upset its equilibrium and the pinch will continue to be compressed until equilibrium is restored. Without collisions between particles the portion of fast particles in the distribution is higher than with collisions. If collisions occur, then the Maxwellian distribution is restored, but at lower temperature and thus with a much smaller number of fast particles in the tail of the distribution.

4. Conclusion

Studies of the ion emission from plasma focus devices supply information about mechanisms of the ion acceleration and emission characteristics.

The ion emission of a hydrogen-filled Mather-type plasma focus device was characterised by utilising a Faraday cup and a pinhole camera with LR-115A film.

From time-resolved measurements of ion beam using a Faraday cup, the ion beam is a mixture of a fast ion beam with energy greater than 70 keV and a bulk ion stream that, after slowing down on the cold plasma target, escape down stream after disruption of plasma column. Also, from time-integrated measurements using solid state nuclear track detectors LR-115A, it was found that the flux density of the investigated corpuscular radiation was estimated to be about 6.0×10^8 particles/cm^2 at an angle of 10 degree from the central electrode using the CCZ model. Also, from angular distribution of protons approximately in the center, the density of protons is higher than the off-center one.

[1] M. Zakaullah, I. Akhtar, G. Murtaza, and A. Waheed, Phys. Plasma **6**, 3188 (1999).

[2] G. Gerdin, W. Stygar, and F. Venneri, J. Appl. Phys. **52**, 3269 (1981).

[3] L. Jakubowski, M. Sadowski, and E. O. Baronova, Experimental studies of hot-spots inside PF discharges with argon admixtures, Vol. 2, Proc. Int. Conf. Plasma Phys., Nagoya 1996, p. 1326.

[4] M. J. Bernstein, Phys. Fluids **13**, 2858 (1970).

[5] R. S. Rawat, P. Arun, A. G. Vedeshwar, Y. L. Larn, M. H. Liu, and P. Lee, Materials Research Bulletin **35**, 477 (2000).

[6] B. B. Nayak, B. S. Acharya, S. R. Mohanty, T. K. Borthakur, and H. Bhuyan, Surface and Coatings Technology **145**, 8 (2001).

[7] R. Gupta and M. P. Srivastava, Plasma Sources Sci. Technol. **13**, 371 (2004).

[8] R. L. Fleisher, P. B. Price, and R. M. Walker, Nuclear Tracks in Solids, University of California, Barkeley 1975.

[9] S. A. Durrani and R. K. Bull, Solid State Nuclear Track Detection, Pergamon Press, Oxford 1987.

[10] G. M. EL-Aragi, U. Seddik, and A. Abd EL-Haliem, Pramana J. Phys. **68**, 603 (2007).

[11] H. Bhuyan, S. R. Mohanty, T. K. Borthakur, and R. S. Rawat, Indian J. Pure Appl. Phys. **39**, 698 (2001).