Investigation of the ion beam emission from a pulsed power plasma device

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Abstract. Plasma Focus (PF) devices are well known as ion beam sources with characteristic energy among the hundreds of keV to tens of MeV. The information on ion beam energy, ion distribution and composition is essential from the viewpoint of understanding fundamental physics behind their production and acceleration and also their applications in various fields, such as surface properties modification, ion implantation, thin film deposition, semiconductor doping and ion assisted coating. An investigation from a low energy, 1.8 kJ 160 kA, Mather type plasma focus device operating with nitrogen using CR-39 detectors was conducted to study the emission of ions at different angular positions. Tracks on CR-39 detectors at different angular positions reveal the existence of angular ion anisotropy. The results obtained are comparable with the time integrated measurements using FC. Preliminary results of this work are presented.

1. Introduction
In plasma focus (PF), a high density, high temperature, short duration plasma column is formed, following the radial compression phase that characterizes PF discharges [1]. In addition to x-ray and neutron pulses, the PF is a well-known source of energetic ion beams, of characteristic energy from hundreds of keV to tens of MeV [2]. This characteristic energy range exceeds up to several hundred times the maximum energy to be expected from the capacitor bank voltage. Most of the earlier studies on ion beam emission in PF were carried out in deuterium medium, to investigate the correlation between neutron production and deuteron acceleration. Several properties of PF emitted ion beams have been measured, including their angular distributions and energy spectra [3]. A comprehensive characterization of the PF ion beams, in terms of energy, flux, spatial distribution and ion compositions is desirable in order to advance the understanding of the fundamental physical processes involved in their generation. Several theoretical and computational models have been developed on the ion production and acceleration mechanism for PF discharges [4], however a complete explanation of the ion emission mechanism of the different ranges of PF bank energies is still not available. Low energy PF operating in the few kilojoules range are characterized by a modest operational cost and allow easy modification. These particular features of PF devices, combined with the wide energy range and high characteristic flux of the emitted ion beams, together with the possibility of high frequency operation, have attracted the interest of several researchers, in view of the potential applications in different technological fields, such as surface properties modification, ion implantation, thin film deposition, semiconductor doping and ion-assisted coating [5, 6, 7]. In the past, studies have
been carried out on the general characteristics of ion beam emission in PF [3, 8, 9]. Sadowski et al [10] observed two to three separate ion pulses each having 20-60 ns full width at half maximum (FWHM), using Thomson parabola techniques. They reported that narrow bunches (with divergence less than 8°) of very high-energy ions are emitted among numerous low energy ion beams pulses. Visualizing the importance of energetic ions in the field of materials processing, we have performed an experimental analysis on the ion emission from a low energy PF device operating in nitrogen.

2. Experimental Apparatus

The experiment was conducted in a low energy, 1.8 kJ, Mather type [1] PF device. A schematic diagram of the experimental arrangements along with the discharge circuit is shown in figure 1. The electrode assembly of the PF chamber consists of a hollow central anode of length 10 cm and outer diameter 2.4 cm encircled by six cathode rods of length 9.7 cm and diameter 0.8 cm uniformly spaced coaxially at a diameter of 6.3 cm. The electrode material is copper. The two electrodes are separated by a 3 cm long Pyrex glass insulator sleeve fixed around the bottom of the anode as shown in figure 1. A hollow anode configuration was used in order to decrease plasma contamination with heavy ions resulting from anode ablation. The PF device is powered by a capacitor bank of 9 µF, at 30 kV maximum charging voltage. At 20 kV operating voltage the capacitor bank delivers a maximum current of 100 kA with 1.8 µs quarter period. The system inductance at the maximum current is around 146 nH. A resistive divider and a single groove Rogowski coil are used as voltage and current probes, respectively. Further details of the PF device were reported elsewhere [11]. In this case, high energy photon illumination of the collectors results in a positive polarity signal. A BPX65 PIN diode masked with a 3 µm thick aluminium filter is placed at the side port of the PF chamber, to record the x-ray signal from the side-on plasma emission. In PF operation, intense soft x-ray pulses are mainly emitted at the time of maximum radial compression, when a hot and dense plasma column is formed. Because of the negative biasing, the ion probes also act as x-ray detector (XRD). Thus, the x-ray emission recorded by the PIN diode and the x-ray signal in the ion probes can be used to establish a time correlation between plasma evolution and ion beam emission during the pinch formation process. The electrical signals from the voltage probe, current probe, PIN diode and ion probes are recorded on a four-channel, 500 MHz, 2 Gs s⁻¹ sampling rate oscilloscope. Ion beam measurements were performed in pure nitrogen, in the pressure range 0.25-0.55 Torr.

![Figure 1. PF configuration using CR-39 track detector at angles of 0, 10, 15 and 20 degrees from the anode axis.](image)

The measurements were done using solid state nuclear track detector (CR-39) at a distance of 15 cm from the top of the anode at different angles (0, 10, 15 and 20 degrees) respect to the anode axis. The shutter was removed after the achievement of optimum operational condition, without disturbing the in vacuum conditions and thereby exposing the track detectors to the energetic ions of a single shot. The samples were etched for 2.5 hours in 6.25 N NaOH solutions.
at (70±1) °C. The etched samples were investigated by Optical Microscope (OM) and Atomic Force Microscope (AFM).

3. Experimental Results and Discussion
Figure 2 shows simultaneous oscillograms of voltage, current derivative and PIN diode. The singularities seen in the voltage and current derivative signals around 1.6 µs indicate strong PF action, which means that a tight, hot and dense plasma column has formed. Earlier we have investigated the anisotropy of ion emission with Faraday cups (FC), in which case the emission instant of ions was considered at the moment of the appearance of x-ray peak in the x-ray PIN diode. In this measurements, the CR-39 detectors were irradiated by the incident ion beam for single discharge and its depth profile are investigated.

![Figure 2](image)

Figure 2. Characteristic electrical signals. From top to bottom: voltage, time derivative of the discharge current and x-ray pin diode.

Figures 3-6 shows AFM images and depth profile of ion exposed CR-39 detectors at different angular position with respect to the anode axis. The grayscale on the AFM images indicates the depth profile of ions. Depth profile for some selected tracks of each AFM images are shown in figures 3b, 4b, 5b and 6b. The variations in the ion tracks are clearly visible on the AFM images, particularly track intensities and track diameters. AFM analysis of the CR-39 detectors at different angular positions shows the variation in track’s number density, heights and diameters, indicating the different ion flux and ion energy. The penetration depth of the ions is related to the incoming ion beam energy. The track diameter and track height are the crucial parameters for the ion energy calculation. The different depth and diameter of the tracks are the evidence of the existence of different group of ions in the PF ion beams with different ion spectrum. This result is in agreement with earlier published works [8] that shows an angular anisotropy of the ion beam emission which can be explained in terms of ion Larmor radius effects during the characteristic z-pinch like plasma formation phase.

Measurements of the ion energy distribution in a 4.75 kJ PF operating with nitrogen, performed with a Thomson analyser, shows that the main ion species are N$^+1$, N$^+2$ and N$^+3$, with a characteristic energy in the range 0.17-4.0 MeV, and total (time integrated) average ion flux $8 \times 10^{12}$ ions/stereorad [12]. In our case, the estimated track density on the detector is $\sim 10^{12}$ ions/m$^2$ and considering an ion irradiation time over the samples of about 1 µs, it can be estimated an ion flux of $I_F \sim 10^{18}$ ions/m$^2$s.

The figure 7 shows the ion flux as a function of the penetration depth of the ion beam. The histograms indicate a Gaussian distribution, irrespective of the angular positions respect to the PF axis. The estimated maximum ion penetration depth is of the order of 1800 nm, whereas ion fluxes are maximum for the energy range 200-800 nm. At 0° the maximum flux of ions is observed at around 600 nm depth, whereas at 10° it is around 376 nm. This indicates that
maximum ion energy is on the axis on 0° whereas maximum ion flux is observed at 10°. This result is in well agreement with the previous results obtained with FC in the same PF, where
the angular distribution of hydrogen and carbon ions shows a highly anisotropic character[3]. The flux of hydrogen ions is found to be maximum at the PF axis, whereas in the case of carbon species it is seen to maximize off-axis. Maximum ion emission is confined within a solid angle of 15°. The nitrogen ions detected within a solid angle of 15° emitted from a 2.2 kJ PF, using time of flight (TOF) technique, revealed that the ion flux is maximum at an angle of 5° and minimum at an angle of 0° with respect to the PF axis [13].

Despite the available experimental data, the exact mechanism for ion acceleration is still not clear. Basically, four different possibilities have been proposed to explain the ion beam formation. The first one is a re-distribution of current at the end of the radial compression phase, changing from an annular distribution to a centre peaked one, giving rise to intense, high gradient, axial electric fields [4], the second is an axial voltage increase due to a fast inductance change in the
radial collapse phase [14], the third is ion runaway during the radial compression phase [15] and the fourth is the formation of $m = 0$ MHD instabilities in the plasma column, which result in magnetic field energy being transferred to the kinetic energy of the ions [16]. Bhuyan et al [9] have measured the basic properties, charge states, energy spectrum and flux, of ion beams generated in a low energy PF operating with methane using FC in time of flight technique. The dominant charge states of the carbon ions appear to be consistent with a model in which ion acceleration takes place before the high density, high temperature phase of the PF discharge.

4. Conclusions
We have investigated the ion emission of a 1.8 kJ PF device operating in nitrogen at different angular positions, using CR-39 track detectors. From the depth histogram at different angular positions it is observed that the ion beam emission clearly depends on the angular position. The maximum ion emission is confined within a solid angle of $\sim 20^\circ$. We observe an ion flux of $\sim 10^{18} \text{ ions/m}^2\text{s}$. The mass dependence of the ion Larmor radius, together with scattering with neutrals in the background gas, might cause the observed angular anisotropy. In addition, various complex phenomenon like heterogeneity of local electro-magnetic field, energy exchange between different species of ions and electrons etc, which might also affect the ion emission processes. Further works are in progress.

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