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Low and high energy deuterium ions emission in a 4.7 kJ plasma focus device and its variation with gas filling pressure

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Plasma Focus (PF) being a good source of electromagnetic radiations, ions and electrons, their characterization could be helpful in understanding the dynamics and various processes undergoing in this device. The emission of deuterium ions from PF at different filling gas pressures in the range 1-5 mbar has been studied in the present paper. An anti conical Faraday Cup (FC) has been designed and developed to detect ion flux. From the recorded signals, two peaks have been observed corresponding to low energy (a few eV) and high energy (few keV to hundreds of keV) ions. This study on measurement of poly energy ions flux at different filling gas pressures shows that the ratio of higher energy ions flux to lower energy ions flux increases with lowering the pressure and could be attributed to anomalous resistance in PF device.

Keywords: Plasma focus device, Faraday cup, Poly-energetic ion emission, Plasma instabilities

1 Introduction

Plasma Focus (PF) device has been the subject of intense experimental and theoretical investigations since it was discovered independently by Mather[1] and Fillipov[2] in early 1960's. It can be made operational in a compact and small as also in large devices and offers a cost effective source of pulsed poly-energetic ions, bursts of X-rays, electrons as well as neutrons, if deuterium is used as a filling gas. PF as ions source has potential applications in ion implantation, thin film deposition, material processing, inspection and modification etc. Though an unambiguous mechanism for ions generation and their acceleration has not been fully understood yet, but a few physical models have been developed and reported[3-5] to account for this. Measurement of ion flux at different operating conditions may reveal some aspects of its origin. Many researchers[6-8] have reported experiments on ion measurements for various gases at different filling gas pressures. Lim *et al*[9]. have recently measured the deuterium ions flux in PF device at filling gas pressures in the range 0.05-0.5 mbar by using a deuterated target. Their study correlates the effect of pressure on induced accelerating voltage due to plasma instabilities which is reflected in emission of ions. This type of study also helps in understanding the mechanism for acceleration of ions in this device.

The present study focuses on measurement of deuterium ions flux in a 4.7kJ PF device at different filling gas pressures (1-5 mbar) using a Faraday Cup (FC) developed by us. This FC is capable of covering a wide range of energy (few eV to hundreds of keV) of ions. Researchers[10-12] have looked for various emissions around the time of pinch only. A signal is recorded on a larger time scale much beyond the pinch phase which shows the presence of a burst of low energy ions during pinch phase. Such low energy ions could help in unravelling of processes occurring much beyond the main pinch apart from their practical application being found for ions implantation, surface modification and plasma coating etc. Effect of pressure on emitted ion flux and their energy in PF also show that the two emissions are originating as a result of focus effect. This work could also be helpful to optimize the filling gas pressure in PF device for ions flux emission for desired range of energy.

2 Experimental Set-up and Diagnostics

PF deployed here is Mather type in geometry. Various configurations of FC are developed but details of only the one used in present experiments as also the d*I*/d*t* and current measurement processes are briefly described in the following:

2.1 Faraday Cup

FC comprises of an inner core made out of graphite due to its secondary electron emission coefficient being relatively low. Inner electrode of anti-conical shape with narrower diameter at opening side has been designed for further enhancing the reduction in secondary electron emission. Inner electrode has been encircled by brass shield as outer electrode with Teflon insulator (dielectric constant ε =2.15) filled in between the two. Length of FC is 60 mm with opening diameter of 1.9 mm.

Design parameters of the FC have been decided using the following relation [Eq. (1)] to yield characteristic impedance (Z) of about 50 Ω which matches with the connected transmission line of RG58 coaxial cable.

$$Z = \frac{139}{\sqrt{\varepsilon}} \times \log\left(\frac{d_2}{d_1}\right) \quad \ldots(1)$$

where ε is dielectric constant. Inner diameter (d_2) of brass shield is 40 mm and outer diameter (d_1) of inner core is 12 mm at broader side of cup. Schematic of FC with biasing circuit is shown in Fig.1.

2.2 Plasma Focus

PF device has been designed and developed indigenously in our Lab[13]. Its schematic is shown in Fig. 2. It comprises of a squirrel cage electrode configuration of the cathode with cylindrical anode in its centre. The whole assembly is housed in a vacuum chamber. A 41.8 µF/25 kV capacitor bank is connected to electrode assembly through an open air spark gap. Inductance of this device has been estimated to be around 85 nH. In the present experiments, the system has been operated at 15 kV (4.7 kJ) with deuterium as filling gas and pressure varying in the range 1-5 mbar.

2.3 Diagnostics and Measurements

Time derivative (d*I*/d*t*) of the discharge current signals has been recorded with the help of a pick-up loop in which a sharp dip signifies the instant of maximum pinching. This time is taken as the reference for emission of radiations and considered as t=0 for Time of Flight (TOF) method which has been used here to infer the energy of ions.

FC has been used to characterise the ion beam emission from the PF device. FC was located at a height of 220 mm from anode top in the vacuum chamber and biased to 145 V (negative). It has been positioned at an angle of around 5° from axial direction as ion flux has been reported to be maximum at small angular positions[7]. Output has been monitored across 50 Ω resistor via 100 pF capacitor to get fast rise time. Voltage drop across 50 Ω resistance is proportional to ion flux intensity.

All signals have been recorded in 2 GS/s digital oscilloscope housed in a Faraday cage to minimise electromagnetic interference.

3 Results and Discussion

Typical signals of the time derivative of discharge current (d*I*/d*t*) and corresponding ion current in FC for two shots in the present plasma focus are displayed in Fig. 3(a). Both the shots show double pinch in current and corresponding two early peaks in the FC signals indicative of two bursts of high energy ions followed by very clean peaks suggesting association of low energy ion bursts. There are no ions observed corresponding to the time interval in between these two sets of peaks as reflected in signals of FC in Fig.3(a).

The late peaks are not artifact of experiments since it has been observed that low energy ions corresponding to these peaks were associated with plasma focus pinch phase only. We have taken shots at higher filling gas pressure of 15 mbar [Fig.3 (b)] also where no focus was formed and there were no

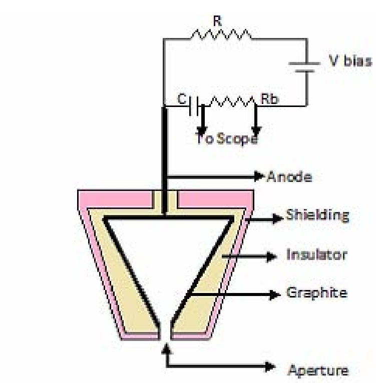

Fig. 1 — Schematic of Faraday Cup and biasing circuit

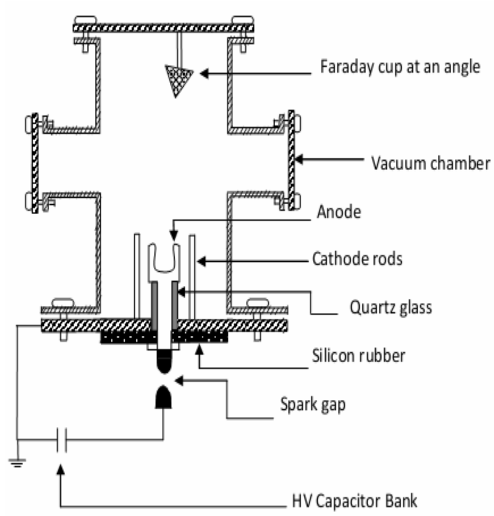

Fig. 2 — Schematic of Plasma Focus with Faraday Cup

peaks of ions in either of the energy regimes in FC signal. It may be concluded that both sets of peaks appear only when there is PF pinch which is origin of accelerating potentials.

Further, the effect of pressure on FC signals observed in the present experiments can be seen in Fig. 4 in which complete temporal profiles of the ion signals registered by the FC at different pressures are plotted. It is evident from here that two sets of peaks have consistently been observed in every shot whenever focus has been formed.

First group of peaks indicates emission of high energy ions from the pinch. Although FC may be sensitive to X-rays also but the time difference between the pinch and initial peaks observed in the signal is significantly too large (~200 ns) to be attributable to interaction of X-rays. Though very small amplitude kinks in FC signals [marked with arrows in Fig. 5(a)] merged in high energy ions peak have appeared at the instant matching with dips in dI/dt which could be attributed to X-rays. But these do not appear very distinct because of their low coupling efficiency with Faraday Cup.

Double peaks have also been registered in some shots as may be seen in Figs 4 and 5. Reason for dual peaks corresponding to high energy ions can be pointed to double pinching in PF device as evident in Fig. 5(a), displaying the time profile of dI/dt from pick up loop along with the signals of Faraday Cup.

Though behaviour of PF device is known to be quiet random but tendency for multiple pinches increases with lowering of the filling gas pressure[6,14] as a consequence of plasma instabilities only. This behaviour is also observed here [Fig. 5(b)] so that at higher pressures multiple pinching is seen to be less prominent.

It is also found in these experiments that number of peaks in high energy regime of FC signal is proportional to number of dips in dI/dt at the time of pinching. However, peaks in low energy regime are independent of number of dips in dI/dt signal as can be seen in Fig.3(a) showing two different shots.

The origin of low energy ions is not well understood but a possible process appears to be that high energy ions get escaped from pinch while low energy ions get trapped in azimuthal magnetic field of dense pinches, as suggested by Yousefi *et al*[15]. It seems that PF emits ions of wide spectrum of energy from eVs to hundreds of keV or more but the difference lies in release time only with respect to pinch formation. Moreover, ions with energy lying between about 60 eV to a few keV lose their energy while travelling a distance of 22 cm (the position of FC) as briefly discussed below.

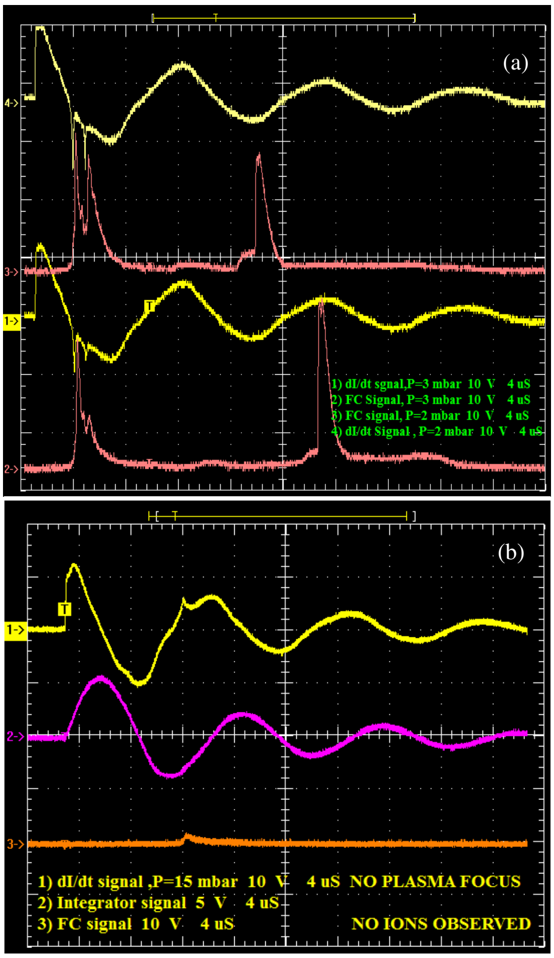

Fig. 3 — (a) dI/dt signals for discharge current and FC signals showing high and low energy ions at P=2 and 3 mbar, (b) dI/dt and FC signals observed at P=15 mbar

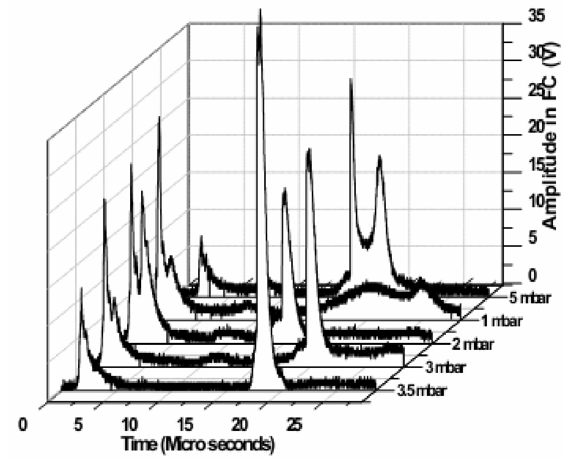

Fig. 4 — Faraday Cup signals at different filling gas pressures (1-5mbar)

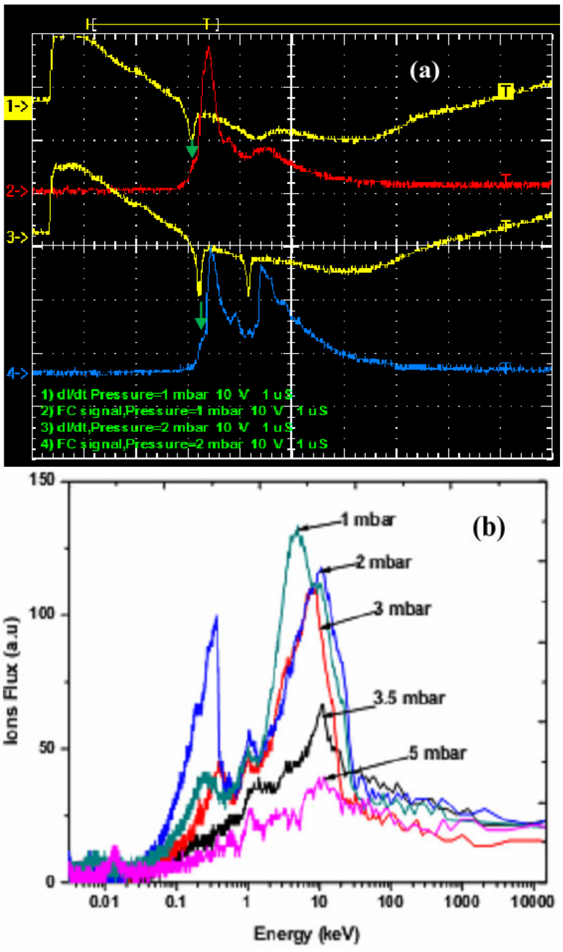

Fig.5 — (a) d*I*/d*t* and FC signals at *P*=1 mbar and *P*=2 mbar, (b) High energy ions flux versus energy at different filling gas pressures (1-5 mbar)

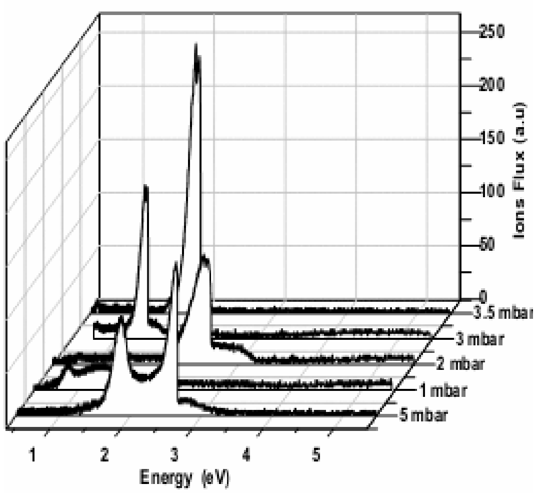

Fig. 6 — Low Energy ions flux versus energy at different filling gas pressures (1-5 mbar)

Energy range of ions registered in FC is around 1keV-1 MeV on higher energy side and 1-5 eV on lower energy side. Energy loss mechanism of ions is different in different energy ranges. Deuterium ions of energy even 1MeV have β values of around 0.033 where Bethe Bloch Theory[16] fails. In this case, formulation of Lindhard[17,18] can be applied to have approximate value of energy loss per unit distance travelled by the deuterium ions produced in PF at given molecular density of deuterium molecules in experimental chamber. Consequently, it emerges that ions with energy less than 3.5 keV may not be able to travel up to FC location. Though Lindhard theory fails at low energies[18] of tens of eVs, an interesting observation is reported[19] that deuterium ions with energy less than 65 eV have no inelastic collisional cross-section in deuterium gas. It appears that such low energy ions through elastic collisions result in a flux of ions with a few eV of energy at FC observed in the present case. Further, experimental as well as theoretical investigations are needed to understand this process of low energy ions.

The effect of pressure on total ion flux in different energy regimes has been studied. The high energy (a few keV to hundreds of keV) ions flux decreases with increase in pressure as can be seen in Fig. 5(b). This temporal record of high energy ions at various filling gas pressures tends to support the existence of anomalous resistance as reported by Bahbahani*et al*[6,8]. for argon ions. This anomalous resistance is collectively due to various types of plasma instabilities and it is also responsible for acceleration of more number of ions at lower filling gas pressures. This process is further discussed below.

Plasma column pinch gets disrupted because of unavoidable magneto hydrodynamic instabilities only, which change the local electric field in unstable phase. Induced electric field due to change in inductance is responsible for acceleration of ions. This change in inductance is in turn caused by change in radius of plasma column formed while undergoing compression. Plasma instabilities are also responsible for extra induced voltages. If induced electric field due to change in inductance because of compression of plasma column was the only reason of acceleration then highly energetic ions emitted would not have energy more than a few tens of keVs. However, ions with energy more than hundreds of keVs have been observed in various experiments[7,11,15] including present ones. Though possible acceleration mechanisms of ions are still the topic of research, theoretical work by Horacio Bruzzone[20] presents the effect of anomalous resistivity on discharge current in PF devices. Even Lee *et al*[4,21] had to introduce an extra parameter in Lee's latest six phase model to account for anomalous resistance in this device. According to this model[21], if static inductance of PF device is around 100 nH then anomalous resistance is responsible for major consumption of energy. These instabilities have more probabilities to grow at lower pressures[22] and lead to enhanced induced electric field which accelerates the ions. It is expected that more high energy (a few keV to hundreds of keV) ions will be generated in PF at lower pressures as observed in the present experiment also. On the other hand, low energy (1-5 eVs) ions flux increases with pressure as can be seen in Fig. 6.

4 Summary and Conclusions

We have studied the emission of poly energetic deuterium ions from a 4.7 kJ PF device at various filling gas pressures (1-5 mbar) using a Faraday Cup. This FC is able to register a wide range of energy (eVs to hundreds of keV) of ions. Measurement of ions over long time scale has brought into picture the emission of ions with quite low energy of a few eVs only which does not appear to have been experimentally noticed and reported till now.

It has been widely reported in literature that anomalous resistivity is dominant at lower pressures[6,8]. This anomalous resistivity is thought to be a cause of major consumption of energy as electrical energy is being exhausted in plasma instabilities[14,15] like local micro-instabilities etc. These processes in turn give rise to higher induced electrical potentials leading to production of more ions with higher energy (tens of keV to hundreds of keV). This justifies the observed results. Hence, more ions with high energy are emitted at relatively lower pressures. Low energy (1-5 eVs) ions flux is found to be more prominent at higher pressures where pinch tends to be comparatively more stable. Their origin however requires further investigations.

The variation of the two components with pressure shows that the fraction of high energy ions reduces with increase in the operating gas pressure. This could be important from the point of view of understanding the behaviour of PF mechanism especially the relative role of thermonuclear and beam target fusion processes in the overall neutron yield from such devices.

This experimental study may help in optimizing pressure for required ions flux in desired range of energy for practical applications.

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