# Measurements of ions emission using ToF method and CR39 SSNTD in a Small Plasma Focus device of Hundreds of Joules

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**Abstract.** Ion beam emission in plasma focus (PF) discharges was originally investigated to explain the strong forward anisotropy observed in the neutron emission when $D_2$ is used as filling gas in the PF devices. Several properties of emitted deuteron beam, including its angular distribution and energy spectra in PF devices operating at energies from 1kJ to 1MJ, have been measured. At present there is a growing interest in the development of very small PF devices operating under 1kJ. As part of the very low energy (< 1kJ) PF devices physics characterization program carried out at the Chilean Nuclear Energy Commission, the charged particle emission is being studied when hydrogen ($H_2$) and mixture ($H_2$+ %Ar) is used as filling gas in the PF device. The experiments have been performed in a plasma focus device of 400 joules (PF-400J). In order to estimate the ion beam energy spectrum and its ionization degree, by means of the time of flight method, a graphite collector system operating in the bias ion collector mode was constructed. On the other hand, measurements of the energy and flux of the ions have been corroborated using CR39 SSNTD. Preliminary results mainly show the presence of hydrogen ions with an average energy of 40keV. Also, in some cases, copper (from anode) and aluminum (from insulator) ions with energies lower than 1keV have been observed.

## Introduction

It is an interesting phenomenon that high energy ions with an energy of more than 1 MeV are produced in plasma focus devices [1,2]. The energy of these ions is sometimes larger than hundred times the charging voltage of the capacitor bank, (table 1). The mechanism of the production of these ions has been investigated for several decades [3,4]; however, the physical mechanism of the production of these ions remains unclear. These 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 [5,6]. The determination of ion beam characteristics is very important not only in understanding the mechanism of production of high-energy ion or neutron, but also for their potential applications.

In general, the studies of ions beam have been performed in plasma focus devices that operate with energies from 1kJ to 1MJ. In this work, preliminary results of some characteristics of the emitted ions from a plasma focus devices of 400 joules [5] are presented. In particular, the ion energy and ion current density is measured with a graphite, biased ion collector [6]. Furthermore, a magnetic spectrometer is used to obtain preliminary images of ion beams on a film of SSNTD, CR39, with a pinhole that enables differential vacuum to be performed between the PF and spectrometer chambers. The CR39 is used in the focal plane of the spectrometer to detect the ions passing through the magnet. The special feature of this method is that the ions produce tracks in two particular regions on the CR39: neutral band and the ions spectrum. The neutral position is used as reference to obtain the ions energy spectrum, since they travel through the magnet without deflection. The CR39 detector is etched to enlarge and develop ion tracks, so that they can be viewed under and optical microscope.


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**Table 1**. Measurements of ion beams at different PF devices.

| Device | Energy of the Bank | Gas | Pressure | Ionic State | Ion Energy | Technique |
|---|---|---|---|---|---|---|
| PF_UC | **1.8kJ** | methane<br>hydrogen | 0.2-0.45Torr<br>0.5-1.3Torr | C+4<br>C+5<br>H+ | **0.4-0.6MeV**<br>**0.9-1.1MeV**<br>**0.2-0.4MeV** | ToF |
| | **4.75kJ** | nitrogen | | N+1,N+2,N+3 | **0.17-4.0MeV** | ToF |
| Bostick et al. | **5.4kJ** | deuterium | | | **0.3 to 0.5MeV**<br>**1-9MeV** | ToF |
| Gullickson & Sahlin | **76kJ** | deuterium | | | **8MeV** | |
| Krompholz et al | **1kJ** | deuterium | | | **0.1 to 0.4MeV** | ToF & Mspec |
| Takao et al | **19kJ** | hydrogen | | | **0.15 to 2MeV** | |
| PGN (Kucinski et al.) | **3.6kJ** | deuterium | 2 - 6 torr | | **> 0.05MeV** | SSNTD<br>CN y CR-39 |
| PFIPS (Heo & Park) | **0.6kJ** | argon | 0.1-0.7Torr | | **<E>=0.2MeV** | |
| PF-20 IPJ, Poland | **12kJ** | deuterium | | | **0.22-1.0MeV**<br>**1.7 to 2.5MeV** | NTD |
| IPF (Stuttgart) | **56kJ** | deuterium | | | **0.3 to 3.0MeV** | |
| PGN | **4kJ** | deuterium | | | **0.08 to 0.5MeV** | CN ó CR39 |
| PF-II | **4.75kJ** | nitrogen | | | **0.05 to 1MeV** | |

## The Device and Diagnostics

The experiments presented here were conducted in a plasma focus device operating at the energy level of hundreds of joules (PF-400J, 880nF, 20-35kV, 176-539J, ~300ns time to peak current, dI/dt ~ $4x10^{11}$ A/s)[5]. This device was designed and constructed at the Chilean Nuclear Energy Commission, CCHEN. The dimensions for copper anode and its alumina insulator, in PF-400J, were: radio of the anode $r_a$ = 6mm; inner radio of the copper cathode $r_c$ = 15.5mm; overall length of the anode z = 28mm; length of the alumina insulator l = 21mm. The discharge chamber was filled with hydrogen at pressures of 5 to 12mbar, and mixture (hydrogen + 5% of argon) at pressure of 1 to 9mbar. A charging voltage of 27 kV was used. Diagnostics include voltage and current derivative usual probes, a BPX-65 PIN diode masked with 10μm thick aluminium filter radially located at 100mm from upper end of the anode to record the x-ray signal from the side-on plasma emission, and a Faraday Cup used as an ion collector. The ion collector is a conical probe designed to maintain an impedance of 50Ω[6]. It is composed by a conical inner electrode of graphite of 15mm in length with base diameter 7mm to reduce the secondary electron emission (SEE) and a brass external electrode separated by Teflon insulator. The ion detector chamber, which acts as a drift tube, is separated from the PF chamber by a 0.5mm diameter hole. In order to minimize the ion beam attenuation in the background gas medium the ion detection chamber was kept at a lower pressure (~$10^{-2}$ mbar) than the main chamber, using additional pumping on that particular zone. The graphite collector inside the drift tube was used to detect the axial ion beams emitted from the PF and it was placed 222mm away from the anode tip. The collector is negatively biased to a dc -200V. Due to the negative biasing, the ion probes also act as XRD. Thus, the x-ray emission recorded by the PIN diode and the x-ray signal in the ion probe can be used to establish a time correlation between plasma evolution and ion beam emission during the formation process.

The magnetic spectrometry was performed mainly in hydrogen discharges. In these experiments, it was used an arrangement consisting in two rounds bar ceramic magnets (NdFeB) of 2.22 cm diameter and 2.54 cm long, which are clamped by two disks maintaining a certain pole gap as shown in figure 1a. The magnets are also separately connected to a high voltage power supply to produce a DC electric field parallel to the magnetic field in the gap. In the figure 1b is shown a radial distribution of magnetic field.

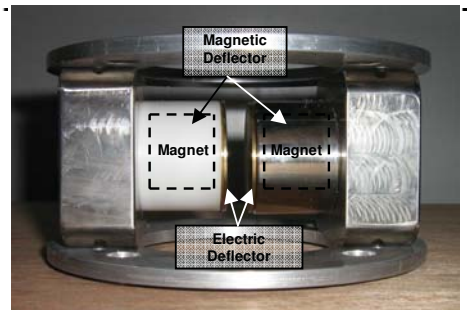


**Figure 1a.** Electro-Magnetic deflector.

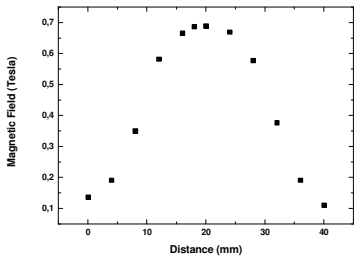


**Figure 1b.** Radial distribution of magnetic field.

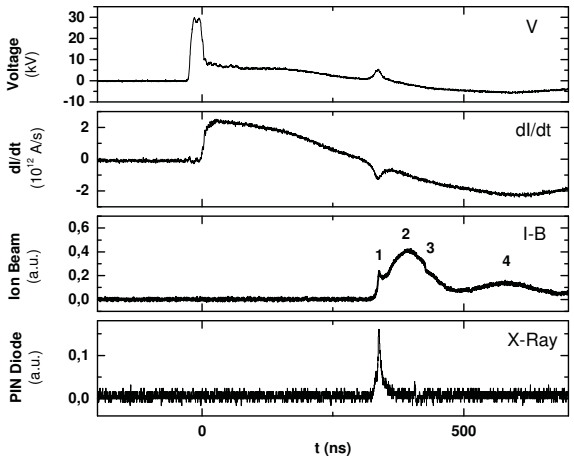


**Figure 2.** Characteristics signals at 7 mbar of mixture, $H_2$ + Ar(5%). From top to bottom: voltage, time derivative of the discharge current, ion probe signal (FC) and PIN diode signal. Label 1 represents x-ray signal in FC, and labels 2, 3 y 4 identify three distinctive ion peaks.

**Results and Discussion**

Figure 2 shows simultaneous characteristic oscilloscope signal of voltage, current derivative, ion probe and PIN diode corresponding to operation in mixture at 7 mbar (H2+Ar(5%)). Even though the electrode geometry is not the optimal to obtain a good pinch, it is possible to observe the dip in the voltage and current derivative signals, which is seen to coincide with both the x-ray pulse in the FC and the PIN diode signals. This kind of peak on these detectors has been reported earlier as x-rays emitted during pinching [6,7]. Time of flight (TOF) measurements performed using two ion probes indicate that the time delay between probes for the different beam components with simultaneous emission at a time which, within the time resolution, coincides with the emission of the x-ray pulse. These facts allow single ion probe signals to be used for the ion energy spectrum measurements [7].

The time correlation between x-ray and ion beam emission indicates that in PF discharges ion acceleration takes place at some time close to the maximum radial compression phase. Therefore, it is reasonable to assume that ion acceleration takes place in existing plasma, with a multi-charged ion

composition. Under these conditions, all ions are accelerated by the same electric field and the energy gained in the acceleration process is proportional to the ion charge. This assumption allows using the following relation between the TOF of hydrogen ions, $t_H$, and other species ions (X) of charge state n, $t_X$:

$$t_X = t_H \sqrt{M_X / nM_H} \quad (1)$$

where $M_H$ and $M_X$ are the mass of the hydrogen and unknown ions, respectively.
Using equation (1), and assuming that the first ion peak, labelled 2, in the ion probe signals corresponds to hydrogen, the charge state of the different subsequent ion peak was determined from the average values of the different measured TOF.
The velocity, energy and density of ions were estimated using TOF technique [2,8]. The ion velocity is estimated by taking the ratio of the distance to the flight time of ions from source to detector. The time of flight of ions is deduced by correlating the FC signal with voltage or current derivative probe. A statistical procedure was used to assign a characteristic TOF to the different peaks in the ion probe signals, prior to charge state identification [7]. First, a peak deconvolution routine was applied to the ion probe signal, assuming a gaussian shape for the different peaks. Second, characteristic TOFs were assigned to the onset and maximum value of the deconvolved peaks. Third, using equation (1) and assuming that the first ion peak, after x-ray peak, in the ion probe signals corresponds to hydrogen, the charge state of the different subsequent ion peak was determined from the average values of the different measured TOF. A detailed explanation on the analysis procedure appears in the reference 7. The ion velocity (v) thus obtained can be used to calculate the energy associated with the ions, which are reaching the FC at different instant, by the simple formula:

$$E = \tfrac{1}{2} M_X v^2 \quad (2)$$

where $M_X$ is the atomic mass of unknown ion. The number density of ion having velocity $v$ and charge $q$ is given by

$$n_i = \frac{V}{RqAv} \quad (3)$$

where $V$ is the maximum voltage of the ion pulse, $R$ is the resistance across which the output of the ion pulse is taken (50Ohm) and $A$ is the area of the aperture.
The figure 3 shows the distribution of the ions energy for all data obtained in hydrogen ($H_2$) and mixture ($H_2$ + 5% of Ar). In hydrogen, it is clearly observed that the ions energy is distributed in three narrow regions with an energy maximum around of 50keV. The region of higher energy, R3, should correspond to hydrogen ions, the middle region (R2), in relation to the equation (1), should be $Cu^{+8}$ ions, and the first region (R1), should be $Cu^{+}$ ions. These copper ions appear form the electrode erosion made by the plasma. On the other hand, when hydrogen-argon mixture is used, the energy range is larger and an energy maximum of 270keV is obtained. In this case, the determination of the ion species is more complicated, due to the greater difficulty in measuring the dip time in the voltage or current derivative signal. However, it is possible to distinguish a first region, lower than 1keV, that could correspond to $Cu^{+}$ or $Cu^{+2}$ ions. It is also possible to observe a second wide region of greater energy. On this wide region, it is possible to find ions of hydrogen and/or $Al^{+3}$ (aluminium are eroded from the alumina insulator). However, additional data and/or diagnostics are needed to discriminate these ions. .

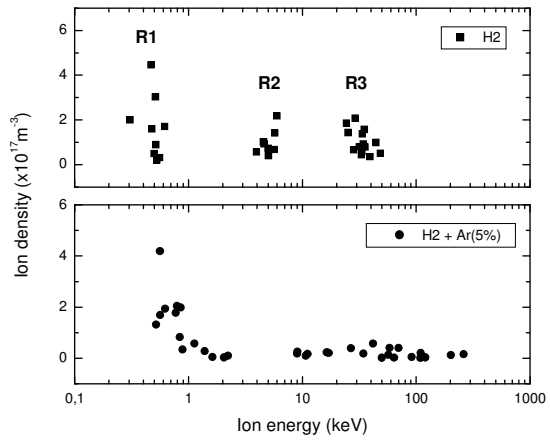


**Figure 3.** Ion density distribution in function of the ion energy to measurements in hydrogen ($H_2$) y mixture ($H_2$ + 5% de Ar).

The track signals obtained after a series of 500 discharges in hydrogen gas on CR39 detector through magnetic spectrometer (figure 4) show different distinct areas of the spectrum. These areas can be defined as: neutral band (1), non-hydrogen charged particles (2) and hydrogen spectrum (3) [9].

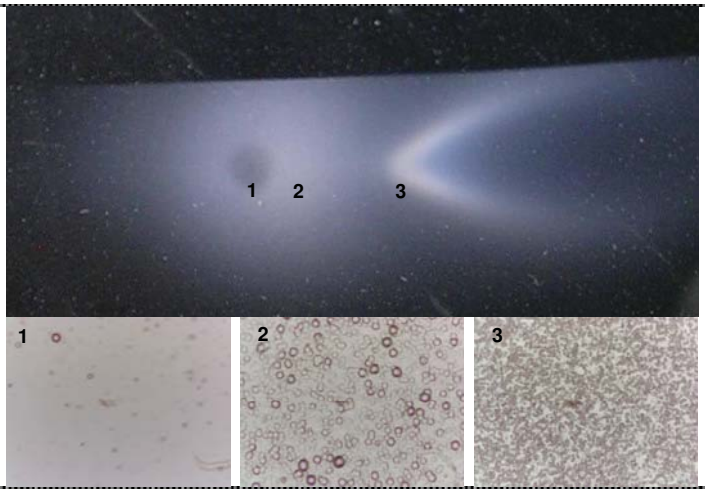


**Figure 4.** Typical image of ion spectrum on the CR39 detector obtained with a series of 500 discharges in hydrogen operating to 27kV. 1) Neutral band, 2) non-hydrogen charged particles and 3) hydrogen spectrum.

The result of spectral analysis of these zones is shown in the figure 5, where it is possible to observe that the highest distribution of ions is lower that 250keV and it corresponds to the hydrogen spectrum (zone 3 on figure 4). This is in agreement with the results obtained with the ion energy distribution using Time of Flight method in hydrogen discharges previously discussed. In this case, the energies of hydrogen ions are over the 40keV.

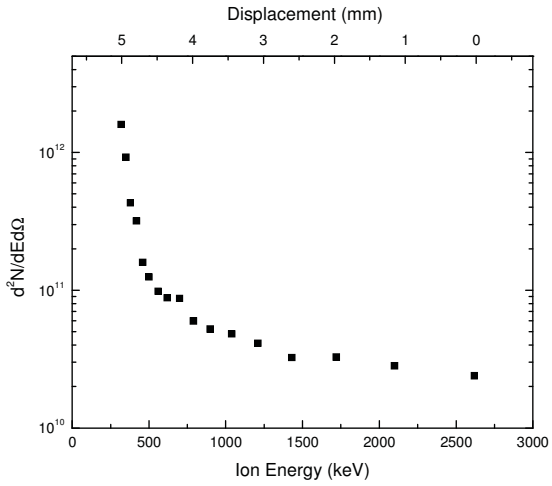


**Figure 5.** A plot of typical individual ion spectrum emitted from the plasma focus pinch, for a hydrogen working gas pressure of 12 mbar. The displacement is considered from zone 1 to zone 3 in figure 4

Two complementary diagnostic techniques were used to study high energy ion beams form a very small PF device (PF-400J). The obtained ranges of energies vary according to the operating gas of the discharge. In the case of hydrogen discharges, the ion energy range is from 0.5keV to 50keV; and in discharges using gas mixtures ($H_2$ + Ar) the ion energy range increases from 0.5keV to 270keV. When pure hydrogen is used, narrow energy beams of copper ions coming from electrode erosion are measured with the Faraday cups; which are not identifiable with the CR39 detector. Even though the charging voltage is lower than 30kV, it was possible to measure ion beams with energies larger than 200keV, indicating the presence of an acceleration mechanism inside of the pinched plasma as observed in larger machines. However, it is necessary to increase the statistics, mainly in the case of mixture, and the analysis method of the CR39 detector in order to obtain further conclusions.

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