Characterization of neutron emission and measurement of the electronic density in a plasma focus device of 400J

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Abstract. Experimental results of anisotropy in the distribution of neutron flux and his mean energy in the radial direction (90º), and measurements of the electron density in a very small plasma focus device, PF-400J (880 nF, 30 kV, 120 kA, 400 J, 300 ns time to peak current, dI/dt~4x10$^{11}$ A/s) are presented. The following diagnostics were applied in deuterium: Time of Flight (ToF) to estimate the neutron mean energy. An array of CR-39 (C$_2$H$_2$O$_7$) nuclear track detectors covered with polyethylene located radially at several positions (between -90º to 90º) in order to determine the angular distribution of the neutron emission. The measurements of the electron density were realized in hydrogen, and the plasma discharge was synchronized with a pulsed Nd-YAG laser (~6ns FWHM at 532nm) in order to obtain interferometric diagnostics. Discharges were performed with a charging voltage of 30±2 KV (~400J).

1. Introduction

Plasma focus (PF) is a high voltage discharge that happens between two coaxial cylindrical electrodes inside of a chamber at low pressure. These devices have been studied in a wide range of energies, MJ to kJ [1-3]. It is characterized by forming a column of plasma of high density and short duration in the superior end of the central electrode, together with emit ion and electron beams, and ultrashort x-ray pulses. Using deuterium gas, plasma focus devices produce fusion D-D reactions, generating fast neutron pulses (~2.5 MeV) an protons (leaving behind $^3$He and $^3$H). Recently the studies in PF devices have been expanded to energies lower than 1kJ[1,3,5].

The mechanisms of nuclear fusion and the subsequent neutron production in pinch discharges are still an open and controversial field. It is widely accepted the participation of two main processes in the total neutron yield, $Y$, produced by a pinch discharge: thermonuclear fusion and ion beam-target fusion. Thus, the total neutron yield is $Y=Y_{th}+Y_{bt}$, where $Y_{th}$ is the thermonuclear component and $Y_{bt}$ is the beam target component. If the fusion mechanism is thermonuclear an isotropic emission is expected. Experimentally, more emission is observed in the axial direction (0º) than in the radial direction (90º).

In this work we present the characterization of the neutron emission and measurement of electronic density in the PF-400J (880 nF, 30 kV, 120 kA, 400 J, 300 ns time to peak current, dI/dt~4x10$^{11}$ A/s). The diagnostics used were: 2 silver counter detectors in axial and radial position, several CR-39
nuclear track detectors angularly distributed, 5 plastic scintillators with photomultipliers at different radial distances, and an optical refractive system in order to measure the electron density.

2. Experimental Setup

Details of the PF-400J appears in reference [5]. The dimensions for anode and its insulator are: radius of the anode $r_a = 6\text{mm}$; inner radius of the cathode $r_c = 15.5\text{mm}$; overall length of the anode $z = 28\text{mm}$; length of the alumina insulator $l = 21.5\text{mm}$. The discharge chamber was filling with deuterium at pressures of 6 to 10 mbar, and a charging voltage of 30 kV. Voltage and derivative current signals was measured.

The neutron yield was measured by using two activated silver counters, previously calibrated with an Am-Be source. These detectors were placed in two angular positions, 0º (axial) and 90º (radial). In addition the fast neutrons (>1 MeV) and hard x-ray were directly detected with a set of scintillator-photomultiplier systems (five systems).

The angular distribution of the neutron flux, was measured with CR-39 nuclear track detectors covered with polyethylene [6]. These detectors were arranged on a circular frame of 50 cm radius, centered at the focus, outside the discharge chamber, at nine different angles relative to the gun axis: 0º, ±22.5º, ±45º, ±67.5º, ±90º.

And finally, the plasma discharge was synchronized with a pulsed Nd-YAG laser (~6ns FWHM at 532nm) in order to obtain the electron density. A Mach-Zehnder interferometer was implemented.

![Figure 1. Angular distribution of the track population obtained from the neutron emission, normalized to the maximum count obtained for 0º. CR-39 chips covering a 1.9cm ×0.9cm area were placed 0.5m away from the focus at 0º, ±22.5º, ±45º, ±67.5º and ±90º from the axis.](image)

3. Results

A maximum neutron yield, of $(1.06 \pm 0.13) \times 10^6 \text{ n}$/ was measured previously at 9 mbar [5]. This maximum occurs close but after the current peak.

3.1. Measurements of anisotropy with two detectors.

The total neutron yield, $Y_n$, obtained for axial (0º) and radial (90º) positions: activated silver detectors in the PF-400J was obtained. In general, for the different pressures the neutron emission at 0º is greater than at 90º. In this work, an average ratio $Y_0/Y_{90} = 1.3\pm0.26$ was obtained.
3.2. Angular array with CR-39 nuclear track detectors.
The average angular distribution of the track density, obtained with around 330 shots at 7mbar, is shown in figure 1, normalized to the average value at 90º. The data obtained for positive angles can be adjusted by a Gaussian function superposed on a pedestal;

\[ f(\theta) = B + \frac{C}{\sigma \sqrt{2\pi}} \exp\left(-\frac{\theta^2}{2\sigma^2}\right), \]  

where \( \theta \) is the angle in radians, \( B = 0.189 \), \( C = 1.285 \) and \( \sigma = 0.644 \). Thus, in this case, the isotropic pedestal contributes 57.5% of the neutron yield, while the anisotropic gaussian distribution accounts for the 42.5%.

![Figure 2](image)

**Figure 2.** Characteristic signals of the scintillation systems and the current derivate in PF-400J. Also, It is observed hard ray-X (\( \sim 100 \text{keV} \)), which are shown by arrows.

3.3. Time of flight.
Five scintillator + photomultiplier 0.5m separated in radial orientation with the discharge were used. Characteristic signals like ones showed in the figure 2 were obtained. In this figure is observed the signals of two scintillate systems (FM1 and FM2), and different pulses exist which are associated to the X-rays and neutrons. The pulsed X-rays are indicated by means of arrows. In this case, for the used experimental conditions and for the analyzed data set, an neutron energy range between 2 and 3.1 MeV could be found for the PF-400J device, with an estimated mean value of \( (2.55 \pm 0.45) \text{ MeV} \).

3.4. Electron density.
Figures 3 and 4 show interferograms obtained for discharges in hydrogen at 7 mbar and 30kv charging voltage. The times correspond to 4ns and 12ns after of the minimum in the \( \text{di/dt} \) (dip).
Figure 3. Interferogram obtained (4 ± 4) ns after the minimum in the current derivative dip. The anode (at center) has a diameter of 12 mm.

Figure 4. Interferogram obtained (12 ± 4) ns after the minimum in the current derivative dip. The plasma column is practically disrupted. The anode (at center) has a diameter of 12 mm.

Figure 5 shows the radial electron density profile obtained from the Abel inversion, it corresponding to the interferogram of the figure 3. The pinch radius is 0.74 mm and the electron density, \( n_e \), on the axis of the plasma column is \((0.83 \pm 0.25) \times 10^{23} \text{ m}^{-3}\). The number of particles per unit length, line density \( N \), can be obtained directly from the interferograms [7], thus \( N = 8.8 \times 10^{19} \text{ m}^{-1} \). The value of the current, \( I \), for the time of the interferogram was 117 ± 5 kA. Thus the temperature can be estimated from the well known Bennett relation. The Bennett temperature is \( T_B [\text{eV}] = 1.56 \times 10^{11} \frac{I^2}{N} \), with \( I \) and \( N \) in SI units. Thus \( T_B \) is estimated in ~240 eV. This value is of the same order that the Bennett temperature obtained for devices operating in the energy range of 1kJ - 1MJ. However a direct measured of the temperature is necessary.

Figure 5. Electron density profiles from the interferogram of figure 3. They are obtained to \( z = 0.6 \text{ mm} \) and \( z = 1.5 \text{ mm} \) over anode.
4. Conclusion
A neutron emission characterization in a plasma focus operating at hundreds of joules was done. With the results of the TOF measurements a mean neutron energy of (2.55 ± 0.45) MeV was obtained. The angular measurements were compared with the total neutron yield (the angular integral of the measurements) and the results are consistent with an angular uniform plateau (isotropic emission) plus a shape peaked in the direction of the axis of the discharge (anisotropic emission). Isotropic components accounts for 57.5% of the accumulative emission, while the anisotropy component accounts for the remaining 42.5%. Anisotropic component appears between +50º and –50º approximately. The result obtained with only two detectors, that is the usual way to estimate the anisotropy, give Y90/Y0 = 1.3±0.26. With the results obtained in this investigation it was not possible to conclude the kind of process that has more influence in the neutron radiation, however a characterization of the neutron emission in a small device of only hundreds of joules have been performed. At lower energy range operating conditions, the development and use of sensible and more efficient detectors is needed.

Finally, according with our measurements, the electron density in a small plasma focus that operate at hundred of joules (~400J) is of the same (10²⁵m⁻³) order that the density measured in bigger devices operating in the energy range of 1kJ - 1MJ.

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