Nuclear track methodology for the analysis of isotropic components in a plasma focus neutron yield

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The average angular distributions of neutron emissions have been measured in the Fuego Nuevo II (FN-II) dense plasma focus device (5kJ) by means of CR-39 plastic nuclear track detectors. When pure deuterium is used as the filling gas, the data can be adjusted to a Gaussian function, related to anisotropic emission, superposed on a constant pedestal, related to isotropic emission. When deuterium-argon admixtures are used, the anisotropic contribution is best represented by a parabola. The neutron flux at these two angles are used, along with the angular distribution obtained from the track detectors, in order to estimate the absolute neutron yield of both the isotropic and the anisotropic contributions. From examining different groups of shots, it is found that the shape of the angular distribution is important in the estimation of anisotropy, and that the value usually reported, as the ratio of the neutron flux head on and side on, as measured by activation counters, may be misleading.

Keywords: Plasma focus; neutrons; protons; nuclear track detectors.

La distribución angular promedio de la emisión de neutrones ha sido medida en el foco del Dispositivo de Plasma Denso (5kJ) Fuego Nuevo II (FNII) mediante detectores plásticos de Trazas Nucleares (CR-39). Cuando se usa deuterio puro como gas de llenado en el dispositivo, los datos se pueden ajustar a una función Gaussiana, relacionando la emisión anisotrópica, superpuesta sobre un pedestal. Cuando se usa una mezcla de deuterio-argón, la contribución anisotrópica está mejor representada por una parábola. Se usó el flujo de neutrones a dos ángulos, a lo largo con la distribución angular obtenida por los detectores de trazas, con objeto de estimar el campo absoluto de neutrones en ambas contribuciones, isotrópica y anisotrópica. Examinando los diferentes grupos de disparos del FNII, se encuentra que la distribución angular es importante en la estimación de la anisotropía, y que el valor usualmente reportado, es una relación de los flujos principales y secundarios de neutrones, como los medidos con contadores por activación.

Descriptores: Plasma; neutrones; protones; detectores por trazas nucleares.

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1. Introduction

The plasma focus was devised during the early days of fusion research [1,2], and immediately attracted the interest of researchers, due to the intense bursts of neutrons it emitted, from ^{2}H(d,n)^{3}He fusion reactions, when operated with deuterium gas. To date, it is arguably the most cost-effective plasma-based neutron source, and although it is hardly a candidate for energy generation, it is attractive for other applications. A large number of experimental investigations have been conducted with the aim of better understanding the nature of the fusion mechanisms, and especially to test the validity of the *thermonuclear model* and various complementary models based on *supra-thermal* mechanisms, such as the beam-target [3,4] and gyrating-particle models [5]. These studies have concentrated mainly on the neutron fluence characterization, including the neutron yield and anisotropy, the neutron energy spectra, and the temporal pulse duration and shape [4,6,7]. In particular, the neutron pulse duration ($\leq$100 ns) and the observed neutron anisotropy provide compelling evidence that supra-thermal mechanisms play an important role. However, in earlier work we found that there are both isotropic and anisotropic contributions in the neutron angular distribution, the former being the most important [8,9]. Although it has been established that there is more than one fusion mechanism, a detailed understanding of them is still lacking. In contrast to the neutron measurements, a paucity of experimental data exists on the charged fusion products: protons, tritons and ^{3}He. As pointed out by Jäger *et al.* [10], such studies could provide much needed additional information on the fusion mechanisms. In the present work, in addition to the study of the neutron angular distribution, that of protons from the ^{2}H(d,p)^{3}H reaction channel is also studied, using a semi-circular holder. The fusion protons, with energies of 3.02 MeV, are far more penetrating than any of the other charged particles, except for the deuterium beam, which is axially accelerated by the focus. Therefore, they can be easily studied. The adverse environmental conditions encountered during a PF shot include: strong electromagnetic noise, intense emissions of light, ultra-violet, x-rays and energetic electrons. As mentioned above, there is also a strong axially directed deuteron beam, which is followed by the expansion of hot plasma. The charged particle emission occurs in a time scale shorter than 10^{-7} s, so the count-rate requirement for an electronic detector would be extremely high. In view of these considerations, it is apparent that polymer solid-state nuclear track detectors are well suited for time integrated diagnostics for neutrons and charged particles studied in plasma focus devices. Earlier work on the diagnostics of fusion neutrons, using CR-39 nuclear track detectors, was done by Collopy *et al.* [11], Frenje *et al.* [12], and Castillo *et al.* [9]. Charged particles incident on a polymer track detector, such as CR-39, deposit their kinetic energy as dense trails of ionisation and excitation resulting in numerous polymer chain scissions. These damage trails represent latent particle tracks which can be made visible by chemical etching after the exposure [13]. Counting etched tracks by eye, using an optical microscope, has been the most frequently employed method for many years. Naturally, the tedious and laborious nature of such work is not convenient for the high accuracy required in the analysis of a large number of detectors. If the spatial distribution of the tracks is required, rather than simply a gross count, the task of manual analysis becomes extremely time-consuming and inconvenient. In the present work, an automated track measurement system has been employed, which overcomes the limitations of manual counting [14].

2. Experimental set-up

This work was performed using the FN-II small plasma focus device, operated at the Instituto de Ciencias Nucleares, UNAM [15]. It is a 5 kJ device at 37 kV, with an oxygen-free copper anode, 40 mm long, with a 50 mm diameter. The co-axial cathode is formed by ten copper rods arranged in a squirrel cage configuration at a radius of 50 mm. The insulator is an annular *Pyrex*®tube located at the base of the anode, matching its diameter. The energy storage is provided by four 1.863 μF capacitors in parallel, and the discharge is triggered by a simple mushroom electrode spark gap. Throughout the present work the plasma focus was operated in its neutron optimised regime, corresponding to a 2.75 torr deuterium gas pressure. In this regime a peak focus current of 350 kA and an average neutron yield of $\sim 3 \times 10^8$ per shot are obtained. The evolution of the current derivative is obtained with a Rogowski coil. Two silver foil activation counters, one on axis, and the other at 90°, were used to measure the neutron yield.

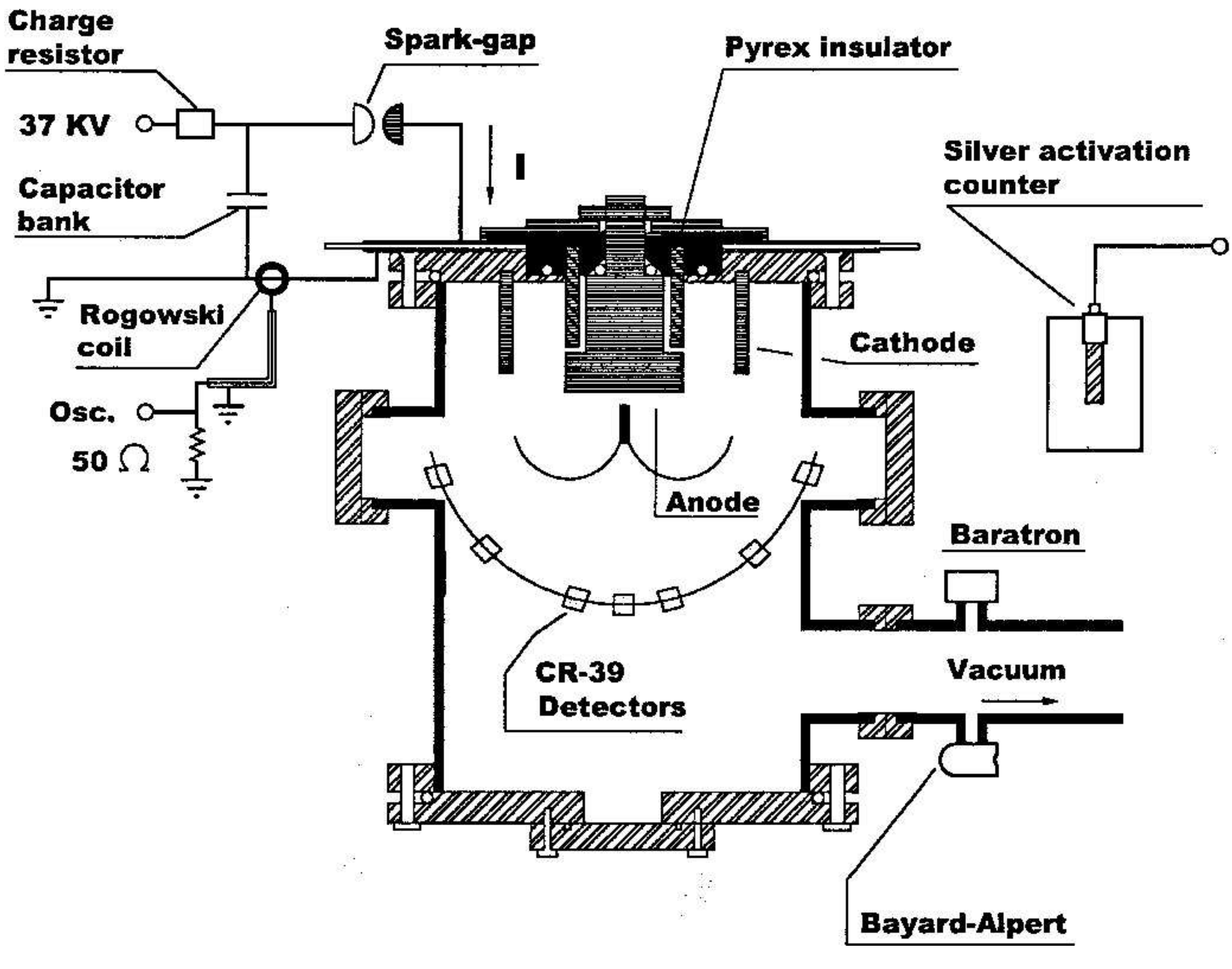

FIGURE 1. Diagram of the *Fuego Nuevo II* PF-device. Also shown is the diagnostic equipment used for ion and neutron measurements.

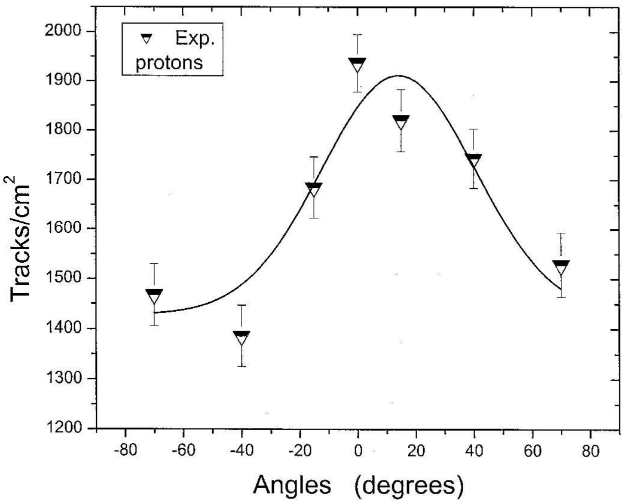

FIGURE 2. Angular distribution of the track density for the detectors on top of the holder. Both proton and neutron tracks are included.

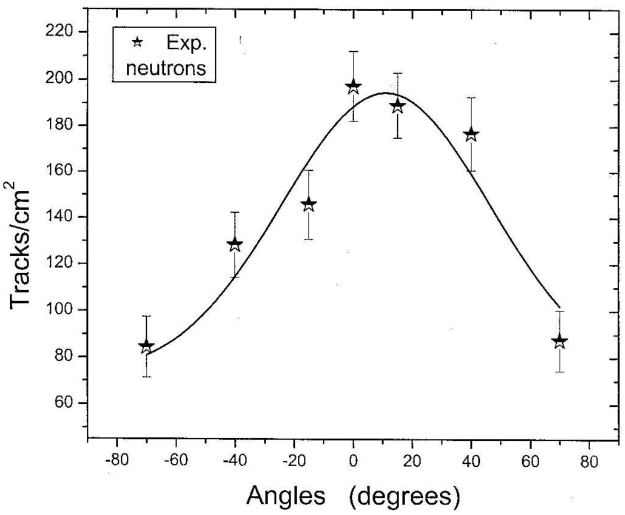

FIGURE 3. Angular distribution of the track density for the detectors below the holder. Only neutrons can be detected in this case.

Both the neutron and proton CR-39 detectors were placed on a 13 cm diameter semicircular holder inside the chamber around the central electrode of the plasma focus (Fig. 1). The proton detectors, with dimensions 1.8 $\times$ 0.9 cm^2, 500 μm thick, were placed on the top side of the holder, covered with 100 μm Al filters, which are able to let through the 2.8 MeV protons from the fusion reactions, and stop other charged reaction products, such as 1 MeV tritons and 0.8 MeV ^{3}He. They should also be able to stop the lower energy deuterons that are accelerated in the discharge, and impurity ions which result from the erosion of the electrode. Indeed, they can still detect neutrons which result from n-p reactions within the detector. For this reason, the analysis is made over the top surface of the chips. The neutron detectors are placed on the bottom side of the *Teflon* holder, which is 1 cm thick. Additional 1 mm thick polycarbonate sheets were placed in front of the neutron detectors, for an enhanced n-p reaction rate. In our earlier work, the neutron angular distribution was measured 1m away from the focus, outside the chamber [9], which has the advantage of being able to treat the plasma column more as a point-like source, and allows measurements over a wider angular range, but at the cost of neutron fluence, and consequently a larger number of shots are necessary. On the other hand, charged particle diagnostics can only be possible inside the chamber. The detectors were placed at 0, $\pm$15, $\pm$40 and $\pm$70°. The detectors were exposed to 50 shots.

After exposure, the nuclear track detectors were etched by the standard procedure, in KOH solution at controlled temperature (60$\pm$1°C). The track density and track diameter distribution were measured with a digital image analysis system [14].

3. Results and discussion

The proton detector placed at 0° deserves special attention, since it shows a 5mm diameter blotch, where an extremely high density of tracks is observed. This is due to the high energy deuteron beam accelerated by the plasma column. However, outside this blotch, it is still possible to measure the track density. The number of tracks per cm^2, counting only the circular ones, at each angle, is shown in Fig. 2. These results were obtained with 12 hours of etching. Their average diameter is 3 $\pm$ 1 μm, which suggests a mono-energetic distribution of a single kind of particle. The angular distribution for the detectors below the holder, showing roughly a tenth of the density of those above the holder, is shown in Fig. 3. In this case 16 hours of etching were necessary. In both cases the maximum is observed close to the axis, but slightly shifted in the positive direction.

A reasonable doubt can be cast regarding the fact that the detectors on top of the holder can detect both neutrons and protons. For this reason, it is necessary to obtain the neutron distribution simultaneously, in order to compensate for this effect. A comparison between Figs. 2 and 3 suggests that the tracks due to n-p reactions could at most be a tenth of those observed on top, since all other charged particles are stopped by the holder.

4. Conclusions

The possibility of measuring the angular distributions of both neutrons and protons from d-d reactions, inside the chamber of a dense plasma focus, was explored. This is done by placing the detectors on the top and bottom sides of a holder around the plasma column. While the ones on top can in principle detect both protons and neutrons, those below the holder can only detect neutrons. This simultaneous measurement is necessary, in order to estimate the compensation necessary in order to obtain the proton distribution. It is found in this work that the neutrons can account for at most one-tenth of the observed density. Both the angular distributions of protons and neutrons show a maximum close to the axis, and decay monotonically for larger angles. The nature of the array unfortunately forbids the possibility of exploring the yield at angles beyond 90°.

Although the well collimated deuteron beam, accelerated by the plasma column, was clearly observed on the 0° detector on top of the holder, its study was beyond the scope of this work, so it was not further studied, but there is indeed a potential for the use of this kind of detectors for such purpose. This has indeed been explored by other authors in the past [16].

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