Radiation Characteristics of the FN-II Dense Plasma Focus Device

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\textbf{Abstract.} The Fuego Nuevo II (FN-II) dense plasma focus device is a small machine (4.6kJ), operating at the Instituto de Ciencias Nucleares, UNAM, in which neutrons, as well as soft and hard X rays have been studied with a number of diagnostics. Neutrons are studied with silver activation counters, and scintillator-photomultiplier detectors, while their angular distribution inside and outside the discharge chamber have been studied with CR-39 plastic track detectors. The soft X rays are studied with a multiple-pin-hole camera and PIN diodes, while the hard X-rays are observed with the scintillator-photomultiplier detectors mentioned above. When a needle is inserted on the inner electrode, a bright spot of hard x-rays can be concentrated, and used for the production of high-contrast radiography. Dosimetric measurements have been made for X-rays crossing a 300 micron aluminum window, through the axis of the machine, showing an average dose of \(0.11 \pm 0.01\) mGy per shot. In contrast, the average dose with a hollow cathode is \(0.077 \pm 0.006\) mGy per shot.

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\textbf{INTRODUCTION}

Dense plasma focus machines have become ubiquitous as plasma based pulsed power radiation sources. While the interest of scaling them up for energy production purposes has faded, there is an increasing interest of scaling them down as portable and high repetition rate x-ray and neutron sources, for a wide range of applications [1]. On the other hand, while the physics of the plasma focus has been extensively studied through decades, it is still important to settle a number of questions, which include, among others, the precise neutron generation mechanisms [2].

This work reviews some of the results obtained in the Fuego Nuevo II (FN-II) dense plasma focus machine, which operates at the Instituto de Ciencias Nucleares, at the Universidad Nacional Autónoma de México. A full description of it has been given in Ref. [3]. In this work we review some of the recent results on the measurement of the angular distribution of neutrons and X-rays, as well as the use of
hard X-rays for high contrast radiography. In the latter case, we have performed dosimetry of the x-rays with calibrated TLD-100 dosimeters, and made a rough estimate of their energy using aluminum filters.

**EXPERIMENTAL SET-UP**

The results shown here, recently reported in Ref. 4, were obtained operating the FN-II device at 37 kV, with a stored energy of 4.6 kJ, and deuterium filling pressure of 2.7 torr. The anode is made of oxygen-free copper, 40 mm long, with a 50 mm diameter. The co-axial cathode is formed by twelve copper rods, 8 mm diameter each, arranged in a squirrel cage configuration around a circle of 100 mm diameter. The insulator is an annular Pyrex® tube, 12 mm long, with a diameter matching that of the anode. The current is 350 kA. CR-39 Lantrack® nuclear track detector chips, 1.8 \( \times \) 0.9 cm\(^2\), 500 μm thick, and separately, thermoluminescent TLD-200 dosimeters, were placed on a 13 cm radius semicircular Teflon® holder inside the chamber around the central electrode of the plasma focus, in order to measure the angular distributions of neutrons, protons and X-rays.

For the case of protons and neutrons, the CR-39s were mounted over and under a semi-circular holder, 13cm away from the column, inside the chamber. The upper ones were covered by a 15 μm Al foil, which is able to let through the 2.45 MeV neutrons and the 3.03 MeV protons from the fusion reactions, but stop the other charged reaction products; the 1.01 MeV \(^3\)H and the 0.82 MeV \(^3\)He nuclei. They are also able to stop the lower energy deuterons which are accelerated by the discharge, away from the axis, as well as impurity ions which result from the erosion of the electrode. This foil may not be enough, however, to stop some of the deuterons accelerated along the axis, if they have energies up to a few MeV. This renders measurements on the axis useless. A second set of detectors was placed on the bottom side of the Teflon holder, which is 1 cm. thick. Additional 1mm. thick polycarbonate sheets were placed in front of the neutron detectors, in order to enhance the n-p reaction rate. The detectors were placed at 0°, ±15°, ±40° and ±70°, and were exposed to 21 shots. Calibrated silver activation counters at 20° and 90° from the axis monitored the neutron yield for each shot.

The angular distribution of X-rays was measured in a separate set of 10 batches of shots, placing TLD-200 dosimeters on top of the holder, at 0°, ±10°, ±20°, ±30°, ±40°, ±50°, ±60°, and ±70°. In one of those batches, a set of CR-39 plastic track detectors was placed below the holder, at the same angular positions. The TLD-200s were also covered by 15 μm aluminum and 350μm Mylar foils, in order to protect them from the expanding plasma, with the purpose of detecting X-rays above 15 keV (Transmission of 15 keV X-rays is .992 for 350 μm Mylar and .999 for 15 μm aluminum).

Time integrated images of soft x-rays are obtained with a 5-pin-hole camera, using Al filters, 5, 10, 15, 20 and 25 μm thick, while the time-resolved behavior is observed with a PIN diode, inside the chamber, using a 500 μm Be filter. Time-resolved monitoring of neutrons and hard X-rays, is performed by five photomultiplier-scintillator detectors, placed at different distances [5].
Figure 1 shows the evolution of the signals from two of the photomultiplier-scintillator detectors, the current derivative $dI/dt$, measured by a Rogowski coil, and the PIN diode signal. The hard X-ray peak has shown to be very persistent, even when heavy water shielding (0.23 m in water bottles) around the detector is used. When high performance shots are obtained, the X-ray peak widens, “blinding” the photomultiplier to appropriately detect the neutron pulse. Therefore this system has serious shortcomings when the detectors are too close to the experiment.

![Figure 1](image)

**FIGURE 1.** Time evolution of the signals from the photomultiplier-scintillator detectors, the current derivative $dI/dt$ from the Rogowski coil, and the Be filtered PIN diode.

**ANGULAR DISTRIBUTIONS OF NEUTRONS, PROTONS AND X-RAYS**

Once the CR39 detectors are developed, the density and size of the tracks are measured. The ones above the holder show a much higher density of small tracks
between 1 and 3 µm, than large tracks between 5 and 8 µm. In contrast, the detectors on the lower side of the holder, show a single distribution of tracks (Figure 2). Thus, since the 15 µm foils are enough to block the 1.01 MeV ³H and the 0.82 MeV ³He fusion products, it can be fairly assumed that the distribution of smaller tracks in the upper detectors correspond to protons, which can be detected more efficiently, while the larger tracks are produced by kick-off products of neutron reactions. Since all protons from the fusion reactions would be absorbed by the 1 cm thick holder, it is clear that only neutrons can be registered by the lower detectors.

![Figure 2](image.png)

**FIGURE 2.** Developed CR-39 plastic track detectors. The one on the left was placed over the holder, while the lower one was shielded by the 1 cm thick Teflon® holder.

Although the angle span is smaller, the neutron angular distributions are consistent those found in Ref. 6; they show both an isotropic and an anisotropic component, in which the isotropic one is usually below the 30% of the total yield, which for the cases studied here was in the order of $10^7$ neutrons per shot. The estimated detection efficiency of the CR-39 detectors is in the range of 1-6 $\times 10^{-3}$. The proton distribution, on the other hand, is peaked on the axis. Typical results are shown in Fig. 3. The details on the experimental procedure and the analysis can be found in Ref. 4.

![Figure 3](image.png)

**FIGURE 3.** Angular distributions of track density for neutrons (larger tracks), on the left, and protons (smaller tracks), on the right.

Figure 3 shows the resulting angular distribution of X-ray doses registered by the TLD-200 (CaF₂:Dy) thermoluminescent dosimeters, placed above the holder,
where the statistics of 10 batches of shots have been used. These dosimeters cover a wide spectrum, being more sensitive in the 20-200 keV energy range, with a pronounced peak at 30 keV. The 15 µm Al and 350 µm Mylar foils over them are practically transparent for x-rays above 15 keV. The dosimeters were exposed to 15-20 shots, trying to have similar number of counts in the silver activation counters for each batch. It is interesting to note that, quite differently form the proton or neutron angular distributions, the X-ray distribution is bi-modal, peaked approximately at ± 20°. It is reasonable to believe that the main source of this radiation is the bremsstrahlung due to the collimated electron beam which is accelerated towards the electrode, when it impinges upon its surface. The best evidence for this is the straight cylindrical hole, 5 mm wide, bore into the solid electrode. From pinhole camera soft X-ray images, we know that the width of the plasma column itself is slightly smaller than this (~4.5 mm) [3].

![Graph](image)

**FIGURE 4.** X-ray angular distributions measured with the TLD-200 dosimeters inside the chamber.

**RADIOGRAPHY**

Hard X-rays which come through a 300µm Al window placed on the axis of the machine, 0.5 m from the electrode, have been used for high contrast radiography. Recent work in this direction has been done by the authors [3], as well as by other groups [7-8]. Both a hollow electrode, and a solid one with needles on the tip have been used. The purpose of the latter is to produce a well localized bright spot. When the hollow inner electrode is used, the diameter of the hole is 32 mm in diameter, and 107 mm deep. Two different stainless steel 304 needles were tried; one 1 mm wide and 6 mm long, and another one 2 mm wide and 6 mm long. The filling gas was deuterium at 2.6 torrs.

The length of the needles was monitored by a five-pin-hole camera, in which the 100 µm pin-holes are covered with 5, 10, 15, 20 and 25 µm aluminum filters [3]. The bright spot at the tip of the needle can clearly be seen in the image in Fig. 5. The needles were found to erode down to 1 mm after approximately 65 shots, although the thicker one is more resistant.

A significant example is that of a tangerine placed 0.50 m away from the focus, shown in Fig. 6. In the radiograph obtained with the needle, segments can be
clearly appreciate. Several other small samples were successfully radiographed, such as electronic chips, pencils, scorpions, flowers, seeds and tree leaves.

FIGURE 5. Multi-pin-hole camera images of the plasma column with a needle, filtered by 25, 15, 5, 10, and 20 μm of aluminium foil, respectively. The bright spot is clearly seen to persist with the thicker filter.

FIGURE 6. Radiographs of a tangerine obtained with the hollow electrode (left) and the needle (right).

Nine TLD-100 dosimeters, whose calibration factor was previously measured using a $^{60}$Co source, were placed 1 m away from the electrode, down the axis. The batch used to test the radiation of the hollow electrode was subjected to 60 shots, and the one with a 1mm needle to 79 shots. This choice was made on the basis of getting similar accumulated neutron yields in both cases. The average results were $0.077 \pm 0.006$ mGy per shot for the hollow cathode, and $0.11 \pm 0.01$ mGy per shot, for the needle. The spectrum has been studied using arrays of 9 dosimeters at the same distance, covering each with 4 μm Al, plus 0.0, 0.5, 1.0 and 2.0 mm Al filters, showing a wide range. Eliminating the softer part of the spectrum with 5 mm acrylic sheets, the first three points can be adjusted with an exponential decay of the form $I = I_e \mu x$, with $\mu = 0.74$ mm$^{-1}$, which yields an estimate for the effective energy of 20 – 25 keV. The fourth point, for the 2.0 mm filter falls above the fit, which means that higher energies should not be ruled out. A deeper study of the spectrum, as well as a more detailed discussion of the radiographs will be provided elsewhere.
CONCLUSIONS

The FN-II is a typical example of the plasma focus as a plasma based radiation source. It has been possible to obtain angular distributions of neutron, proton and X-ray emissions within the chamber. Although the angle span for which the neutron measurements can be made is smaller than in the one studied earlier outside the chamber (± 70° as opposed to ± 170°) [6], the results are consistent, and confirm the existence of anisotropic and isotropic components in the neutron yield, the anisotropic component being less than 30% of the total yield. The proton distribution, on the other hand, is strongly peaked around the axis, and falls rapidly for angles greater than ± 40°, which probably means that they are focused by strong magnetic fields. The X-ray distribution, on the other hand, is bimodal.

Hard X-rays can be used for high contrast radiography. Since the key is being able to have a sufficiently small point-like source, it is useful to concentrate the bright spot of hard X-rays on a needle placed on the tip of the inner electrode. The dose measured down the axis, 1m from the focus, is around 0.1 mGy per shot, which is equivalent to that of a typical torax radiograph. This is only slightly higher than for the case of the hollow cathode. The spectrum of the X-rays observed through the 300 μm Al window is complex. Eliminating the softer part, an equivalent energy of 20-25 keV is estimated, however higher energies are not ruled out. Further investigation in this respect is underway.

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