

## Neutron emission characterisation at the FN-II Dense Plasma Focus

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**Abstract.** Plasma foci are efficient plasma based neutron sources, when deuterium is used as the filling gas. The dense plasma focus FN-II is a small device (4.7 kJ), in which the emission of deuterium fusion neutrons (2.45 MeV) are studied. The system produces an average neutron yield of  $(5.3 \pm 0.5) \times 10^8$  neutron/shot in  $4\pi$  sr at  $\sim 350$  kA peak discharge current and 2.75 torr deuterium operation. Three methods are currently used; silver activation counters and CR-39 nuclear track detectors, for time integrated and angular distribution studies, and BC 400 scintillators coupled to photomultiplier tubes for spectra studies. In the latter case, we compare signals due to neutron reflections in the laboratory with those obtained with a collimated beam in a paraffin shielded detector. Regarding the angular distribution of the neutron emission, it has been found to have isotropic and anisotropic components, the former giving the largest contribution. Also, the neutron spectrum, measured at  $90^\circ$  of the axis device, is broadened, peaking at energies slightly larger than 2.45 MeV. These can be interpreted as the consequence of coexisting neutron generation mechanisms, which will be discussed in this work. The correlation between neutron and hard X-ray yields is also discussed, and a possible interpretation in terms of different neutron generation mechanisms is attempted. There has also been a dosimetric study of the laboratory with TLD dosimeters, which will be presented in this paper.

### 1. Introduction

The mechanisms of neutron production in a plasma focus device are usually interpreted by both thermonuclear and non-thermonuclear (beam-target) mechanisms [1-6]. Several methods have been developed for the determination of the neutron generation mechanisms, including measurements of the neutron yield and its anisotropy [7-11] and the energy spectra of neutrons emitted from the plasma focus device [12-14]. Among these methods, the latter has advantages compared to the others. It provides information on the production mechanisms of neutrons and the energy distribution of reaction ions. The standard time of flight (TOF) spectroscopic method allows the determination of the emitted neutron energy and the number of the particles emitted from the source with high accuracy. Since the neutrons in question are not relativistic, in a pulsed neutron source their energy can be directly determined from  $E = 1/2mv^2$ , where the velocity  $v$  is obtained from the distance between the source and the detector, and time interval between the shot and the time at which they are recorded at the detector. This method can be used when the emitting source consists in a short pulse, even if there is a broad energy distribution, so long as the average energy of the neutrons is not too large.



## 2. Experimental setup

This work was performed using the FN-II small plasma focus device, operated at the Instituto de Ciencias Nucleares, UNAM, whose details have been described in Ref. 5. It was operated at 37 kV with 4.8 kJ stored energy. 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 on a squirrel cage configuration around a circle of 100 mm diameter. The insulator is an annular *Pyrex*® tube, 12 mm long, located at the base of the anode. As reported in Ref. 9, the neutron yield and its uniformity increased considerably when the diameters of the insulator and the inner electrode matched, probably due to an improvement of the current sheath breakdown, aided by the edge effect of the electrode close to the insulator. The energy storage is provided by four 1.863  $\mu\text{F}$  capacitors in parallel, and the discharge is triggered by a simple mushroom electrode spark gap. The device was operated in its neutron optimized regime, corresponding to a 2.7 torr pure deuterium gas pressure [9]. In this regime a peak focus current of 350 kA and an average yield of  $1.6 \times 10^8$  neutrons per shot have been routinely obtained.

The neutron absolute yield for each shot is measured by two Geiger-Muller (GM) activation counters. These are calibrated by counting in the saturation method [15-16] using an Am-Be neutron source with  $2 \times 10^{-6} \text{ ns}^{-1}$  intensity. Five detectors are used for neutron time of flight measurements and hard X-ray monitoring. They are placed at different distances from the device. They consist in cylindrical *Bicron*® BC-400 scintillators coupled to *Hamamatsu*® R1250, No. RA2457 photomultipliers, powered by two C4840 and three HTV C762-01 *Hamamatsu*® power supplies, through *Ortec*® 269 photomultiplier bases. The electronics, and the characteristics of each detector are as similar as possible. They are shielded from light and electromagnetic noise by custom made aluminum casing. Their time resolution is in the order of 5 ns. The signals of the detectors are displayed on two 300 MHz and one 500 MHz Tektronix oscilloscopes, along with the current derivative signal of the plasma focus circuit, obtained with a Rogowski coil.

## 3. Results and discussion

For the set of shots analysed in this work, the neutron average yield, as measured by GM-activation counters is about  $(5.3 \pm 0.5) \times 10^8$  neutron/shot into  $4\pi$  sr and the anisotropy (the neutron yield at  $90^\circ$  with respect to the neutron yield at  $20^\circ$  with respect to the device axis) is found to be 1.15.

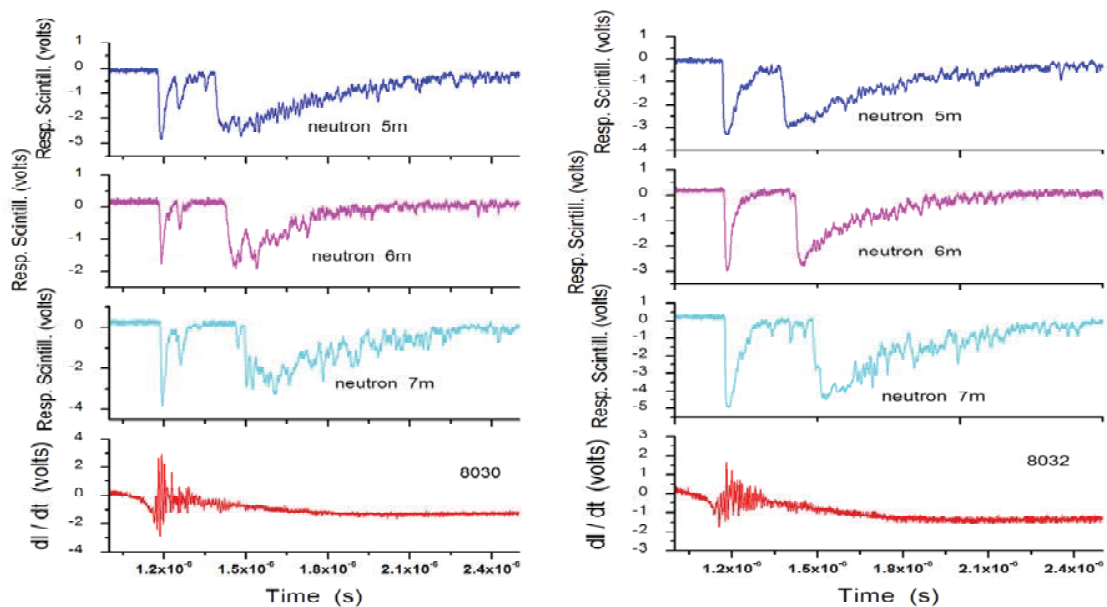
The time difference between the x-ray peak and the neutron signals, at a given distance is defined as the reference time for signal processing, taking into account a correction due to the time of flight of the hard X-rays. Also, the peak current derivative signal ( $dI/dt$ ) can be selected as the time reference for the neutron signal time analysis.

All detectors show the separation of the neutron and x-ray signals properly, as shown in Figure 1. At short distances, the x-ray and neutron signals may overlap each other. The environmental effects will change the detectors' signals, especially in the case of the detectors placed farther away. Neutron signals are recognized by the TOF between the anode and each detector.

### 3.1 Shielding

A problem that is always present, and is actually exacerbated in cases when the neutron yield is particularly high, is the effect of X-ray and neutron scattering by the laboratory. In fact, when the yield is particularly high, the X-ray peak widens and overlaps the neutron peak in such a way that the correspondence between the yield obtained from the GM-counters and that obtained from the integrated neutron signals is lost. It would therefore be strongly desirable to be able to shield the detectors from this effect. In Fig. 2 we show typical examples of some attempts in this direction. The three signals belong to the same shot (9726). The first signal on top left is for an unshielded detector. It can be seen how the X-ray signal slightly overlaps the neutrons one. The signal on top right, comes from a detector fully surrounded by blocks of paraffin, 8 cm. thick, with a 5 cm. hole, in order to collimate the neutron beam. As seen, this attempt is unsuccessful; rather than obtaining a collimate beam, the neutrons are thermalised by the paraffin, and the neutron signal is smeared. In the third

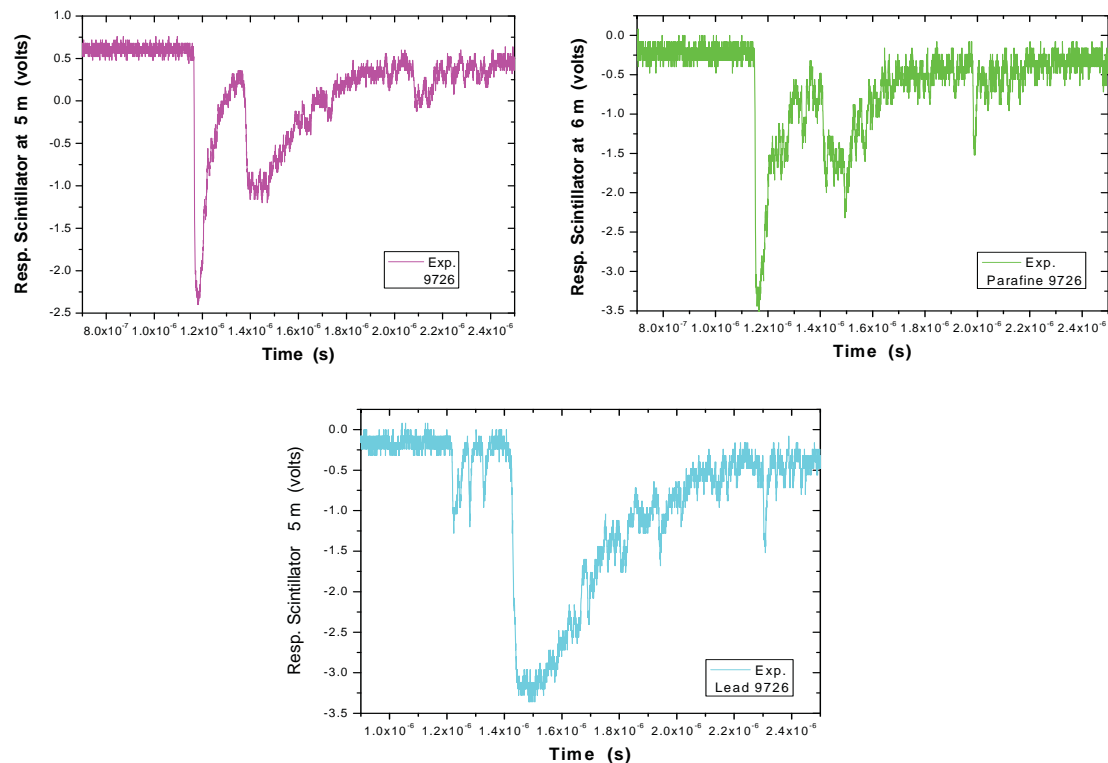
signal, below, the detector is shielded by blocks of lead, 5 cm. thick. This shows to be a good means of reducing the hard X-rays, and allows for good time-of-flight measurements, since the difference between the first X-ray peak and the arrival of the first neutrons is clearly seen.



**Figure 1.** Scintillator-photomultiplier signals at 5, 6 and 7 m from the source, along with the Rogowski coil (current derivative) signal. The shot on the left shows the case of a double pinch. While it remains well resolved for the hard X-rays with increasing distance, the double neutron peak is smeared at 7 m.

### 3.2 Neutron spectra

Since deuterium is being used as filling gas, the fusion neutrons obtained should have 2.45 MeV energies, coming from a thermonuclear source. By taking the time difference between the first X-rays and the first neutrons to reach the detector, it is possible to have a good estimate of the neutrons energy. Fig 3 shows histograms of the energies obtained from a series of shots, for detectors placed at 5, 6 and 7 m. from the source. The peaks are clearly placed at 2.45 MeV, which probably indicates a strong thermonuclear component. However, the energies are widely spread from 1.7 up to 3.2, and in some case, up to 4 MeV. These deviations need to be explained by means of the existence of a strong beam-target effect. Since the detectors are placed at 90° from the axis of the plasma column, in this case we are not talking about the beam-target effect due to axial acceleration of deuterons, which gives rise to the well known anisotropy in these devices. This means there must be an azimuthal acceleration of deuterons, so the spread in energies is due to Doppler shifts from collisions from both approaching and receding accelerated ions, with background ions. The fact that the peak still remains close to the expected 2.45 MeV energy is consistent with the earlier finding that the neutron yield has both isotropic and anisotropic components. At 90° the isotropic component, which might be due to thermonuclear effects, would be expected to prevail.



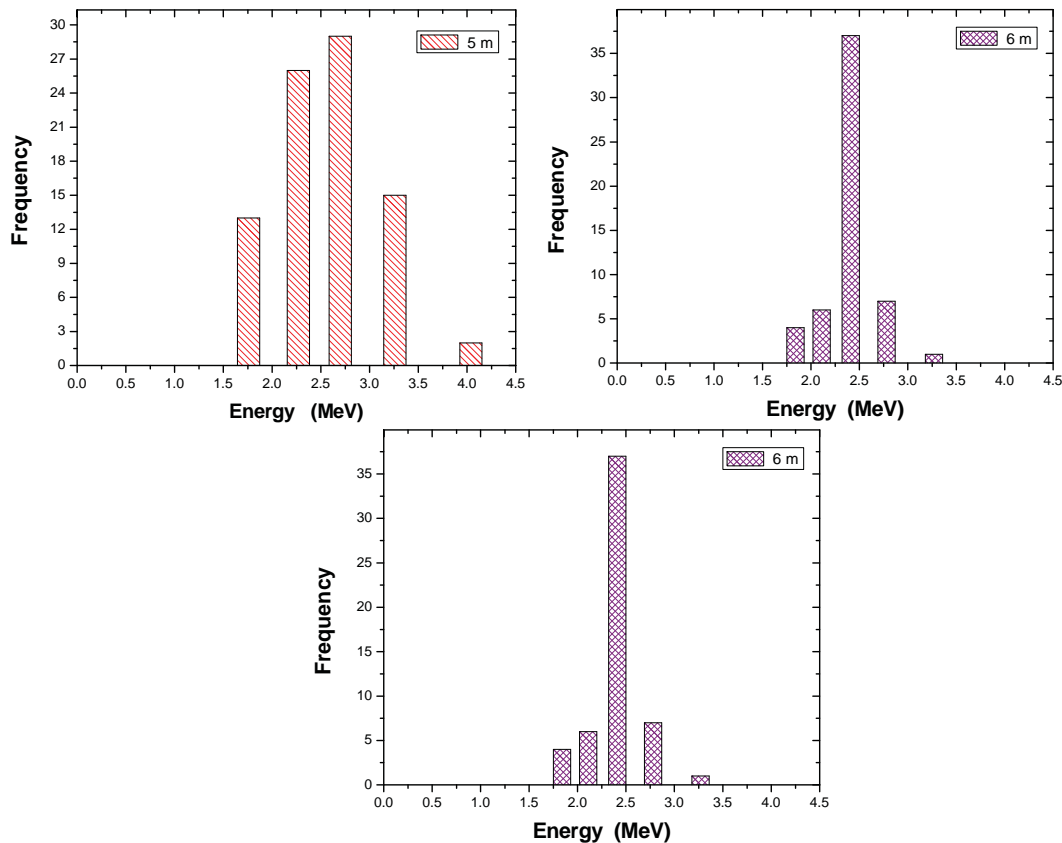
**Figure 2.** Signals from three different detectors with different shielding, for shot 9726. The signal on top left is from an unshielded detector. The one on top right is from a detector shielded with 8 cm. thick paraffin with a 5 cm. hole. The idea was to have a collimated neutron beam, but the neutron signal is actually smeared by thermalisation. The signal in the bottom is from a detector shielded by 5 cm. thick lead blocks. The hard X-ray peak is successfully reduced, allowing better conditions for time-of-flight measurements.

### 3.3 Dosimetric measurements

For safety reasons, dosimetric measurements have been made, placing thermoluminescent dosimeters (TLD) at five different locations in the laboratory, both close to the device, and away from it, behind a 80 cm. thick concrete brick wall. Both TLD-600 and TLD-700 dosimeters have been used. The results are shown in Table 1. The doses are found to be rather small, but above the background radiation. Further study of this should be made.

	Gamma rays	Neutrons	
Package (distance m)	Dose (mGy)	Equivalent dose (mSv)	Equivalent dose per shot (mSv/shot)
1 (2.54)	0.23	5.65	0.019
2 (2.40)	0.21	4.95	0.017
3 (4.81)	0.20	3.06	0.010
4 (7.62)	0.21	3.80	0.013
5 (7.10)	0.20	3.24	0.011

**Table 1.** Dosimetric measurements using TLD-600 and TLD-700 dosimeters placed at different locations in the laboratory and distances from the source.



**Figure 3.** Neutron energies measured in detectors at 5, 6 and 7 m from the source. While the peak of the 2.45 MeV neutrons is clearly seen in the 6 and 7 m cases, the energies are widely spread between 1.7 and 3.2 MeV for some of the shots.

#### 4. Conclusions

The use of the time-of-flight technique is very useful for a better understanding of the neutron spectra, and therefore the neutron generation mechanisms in plasma focus devices. However, some technical problems arise, which need to be addressed. The main one is that the neutron peak comes both from neutrons which travel directly from the source to the detector, as well as from neutrons scattered by the laboratory. Therefore, in this work only the first neutrons (the beginning of the neutron peak) are used. Even in of only the early neutrons are used, the X-ray peak tends to overlap the neutron one, specially in the cases of high performance shots. This requires the use of shielding. Shielding with paraffin in order to collimate the incoming neutrons has turned out to be unsuccessful, since the paraffin tends to thermalise the scattered neutrons, rather than stopping them. Probably boron should be added to obtain the necessary effect. On the other hand, lead is useful to reduce the X-ray peaks, and to allow good time-of-flight measurements.

It was found that at  $90^\circ$  the early neutrons are mostly around the 2.45 MeV energy, although in a few cases lower and higher energies are obtained, revealing azimuthal beam-target effect.

From dosimetric measurements, it was found that the radiation levels in the laboratory, while relatively small, are above the background radiation. It may be important to conduct similar studies in other plasma foci laboratories, in order to asses their safety.

### Acknowledgement

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