

## Neutron and Soft X-ray Emission from Plasma Focus

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### Abstract

This paper reports some of the results of our experiments aimed to investigate the emission of radiation from the pinch phase of a 3 kJ @ 15 kV Mather-type plasma focus device. In order to study the emission of neutrons and X-rays, a large number of diagnostics are performed simultaneously. The discharge and plasma parameters are monitored with 1 nanosecond resolution. The element of novelty of this work is the calculation of the neutron flux anisotropy in a time-of-flight arrangement. Two focus evolution regimes are observed. One is the single-compression regime, which leads to high neutron output. The other one is the multiple-compression regime, which is more favourable to the soft X-ray production. Average neutron energies of 2.48 MeV in the radial direction and 3 MeV in the axial direction support the idea of the dominant effect of the beam-target mechanism for the neutron production. The soft X-ray and the neutron emissions are also correlated. Lower operating pressures favour the soft X-ray production. As the pressure increases, the soft X-ray yield decreases and the neutron emission gets enhanced.

### Introduction

Plasma focus acts as an efficient radiation (ions, X-rays and neutrons) source. In this device a hot ( $\sim 1\text{keV}$ ) and dense ( $\sim 10^{19}\text{ cm}^{-3}$ ) plasma is created with a lifetime of 50-300 ns [1].

Our time-resolved measurements enable us to establish a correlation between the discharge parameters, emission parameters of hard X-rays, soft X-rays, neutrons and the characteristic time periods of the focus. The neutron energies both in the axial and the radial direction are also measured using time-of-flight peak to peak method of analysis. A particular attention is paid to the neutron anisotropy measurements. A correlation between the neutron and the soft X-ray production, discussed in this paper, provides information about the neutron or soft X-ray optimization conditions for the plasma focus device.

### Experimental Set-up

Our Mather-type plasma focus (NIE-SSC-PFF) is energized by a  $30\mu\text{F}/15\text{kV}$  capacitor charged at 14.5 kV giving a peak discharge current about 180 kA. A simple parallel plate sparkgap with a swinging cascade configuration is used as a switch. The following diagnostics were employed: Rogowski coil ( $dI/dt$  measurement), voltage probe (V measurements), Indium foil activation detector (total neutron yield measurement),

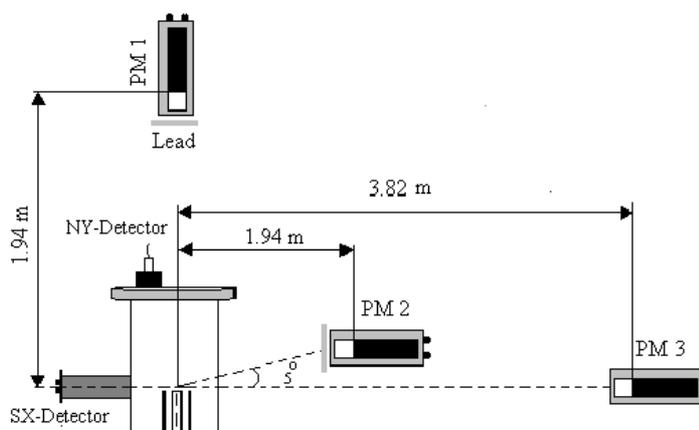


Figure 1: Experimental set-up.

scintillator-photomultiplier system ( $dY_n/dt$ ,  $dY_{HX}/dt$  measurements) and two filtered PIN diodes ( $dY_{sx}/dt$  measurements).

For  $dY_n/dt$ ,  $dY_{HX}/dt$  measurements three detectors (PM1, PM2 and PM3), each consists of a plastic scintillator (NE 102A) and a photomultiplier (EMI 9813B) tube, are used. The internal transient time of the photomultiplier is compensated by introducing appropriate delays to the other diagnostics. A temporal accuracy of 1 ns is obtained. Two ( $X_3$  and  $X_4$ ) BPX-65 PIN photodiodes with filters of 24  $\mu\text{m}$  Aluminized Mylar and 24 $\mu\text{m}$  Aluminized Mylar +10  $\mu\text{m}$  Cu, respectively, are used for the time-resolved soft X-ray measurements (SX-Detector in fig.1). The copper is chosen specifically to check the extent of copper contamination. The whole experimental arrangement is shown in figure 1.

## Results and Discussion

The focus is operated at 14.5 kV using deuterium as a working gas at 4.0 mbar (optimum pressure). Based on  $dI/dt$  and  $V$  signal profiles, two distinct regimes or patterns are identified for the plasma focus discharges.

The first one is the regime in which the voltage probe signal exhibits a single, sharp and fast rise time spike, which indicates a single-compression of the plasma column. The corresponding  $dI/dt$  signal has a distinct and sharp negative spike. Almost all the shots in this regime give very high neutron yield and a low emission in the soft X-ray region. The time reference (see figure 2) is taken at the instant ( $t = 0$ ) when the plasma column reaches the minimum radius, i.e. at  $t=0$ ,  $r=r_{min}$ . Here  $t_{comp}$  represents the time when the plasma sheath enters the radial compression phase. It is determined from the current derivative signals, correlated with the beginning of the rise time of the voltage spike. The pinch life time  $t_p$  is defined as the duration from the instant  $t=0$  to the instant corresponding to the development of the  $m=0$  instability.

Figure 3 presents a 500 ns time window of the waveforms of the signals exhibiting single-compression. The first hard X-ray burst has two peaks and a sharp rise time of 6 ns with 40 ns FWHM. The first peak is related to the first compression to the minimum radius and the second is associated with the onset of the  $m=0$  instability. The neutron signals have a small peak on the leading edge, which is associated with the first hard X-ray pulse that appears at the instant of maximum compression. The second peak is related with

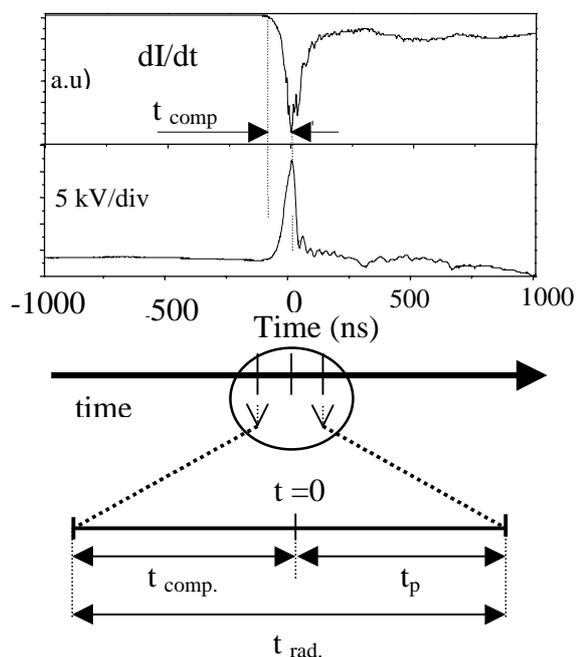


Figure 2: Time reference diagram.

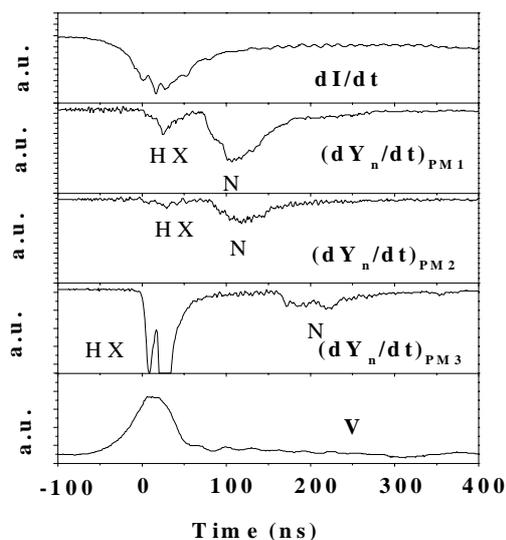


Figure 3: Signal Profiles of  $dI/dt$ ,  $dY_n/dt$ ,  $dY_{HX}/dt$  and  $V$ .

the onset of the  $m=0$  instability. The two neutron pulses (for each detector) are merged together due to a small pinch lifetime. The neutron pulse associated with the  $m=0$  instability is larger indicating that the majority of the neutrons are produced at and after the instant of development of the  $m=0$  instability. It can be explained by saying that the ion beams are generated in the axial direction due to the presence of strong electric fields in the  $m=0$  instability zones. Therefore, the neutron production is generally assigned to the axial beam-target mechanism.

The average energy of 2.48 MeV of the neutrons in the radial direction (signals from PM2 and PM3) is calculated using the neutron time-of-flight peak to peak method of analysis. The peak of PM1 (forward direction) corresponds to the neutrons of average energy of 3 MeV. For  $D(D, n)He^3$  reaction, the energies of the neutron moving in the forward direction (beam-target) for a single interaction are calculated [2] using 3.31 MeV as  $Q$  value for the reaction. The graph in figure 4 justifies the fact that the neutrons having high energy in the axial direction are attributable to the high mean energy of the reacting deuterons moving in the axial direction.

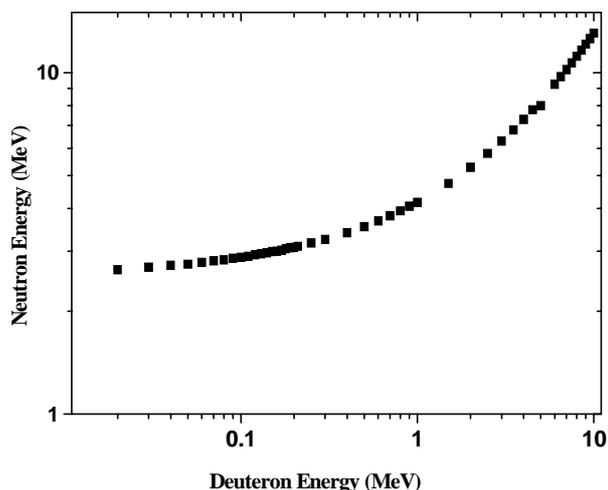


Figure 4: Energy of the neutrons (beam-target) as a function of the deuteron beam energy.

The calculated value of the neutron anisotropy define as  $\alpha = \frac{(Y_n)_{PM_1}}{(Y_n)_{PM_2}} = \frac{Y_n(0^\circ)}{Y_n(90^\circ)}$  is

1.5.

Figure 5 illustrates the dependence of the anisotropy on the neutron yield. Since the neutron yield increases with the increase in the energy of the reacting deuterons [3], the increase in the anisotropy may be related to the increase in the energy of the axially moving reacting deuterons for the shots with the high neutron yield.

Figure 6 is a 500 ns time window of signal profiles of  $dI/dt$ ,  $V$  and  $dY_{SX}/dt$  from the two PIN diodes. Usually, three peaks of  $dY_{SX}/dt$  signal associated with the first burst are observed [4]. The first peak with a sharp rise time of 1 ns and approximately 3 ns FWHM, corresponds to the plasma focus compression to the minimum radius. The second one, associated with the quiescent phase, has a rise time of 3 ns with approximately 10 ns FWHM. Its peak is related with the onset of the  $m=0$  instability.

The third peak is detected during the unstable or decay phase. The total duration of the first X-ray burst (radial phase plus the pinch phase until the onset of the  $m=0$  instability) is 55 ns. A second X-ray burst is observed 80 ns after the first burst and lasts for 45 ns. This pulse is related to the breaking up of the remnant plasma filaments into small

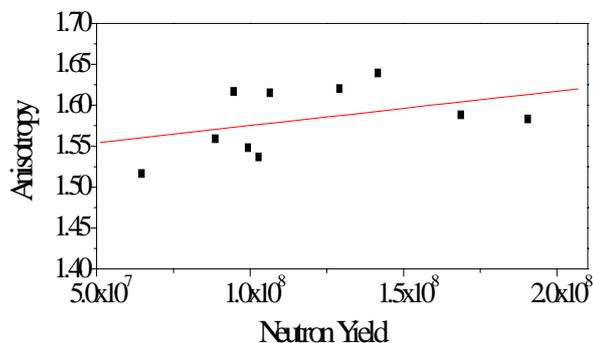


Figure 5: Anisotropy as a function of neutron yield.

structures. The third X-ray emission period starts 160 ns after the first burst and lasts for 100 ns. This pulse is associated with the vaporised copper jet emitted from the anode [5].

A correlation between the soft X-ray production and the neutron yield shows that the soft X-ray yield decreases with the increase of the neutron yield for a given operating pressure. This indicates that the plasma focus can be optimized either for the soft X-ray production or for the neutron output. Our measurements on the dependence of the soft X-ray production on the operating pressure show that soft X-ray production increases for lower operating pressures.

Our measurements of the plasma electron temperature using the filter ratio method show values ranging from 1 keV to 2 keV.

### Conclusions

The optimum neutron production pressure is 4 mbar of deuterium. The correlation of the emission of the hard X-rays and neutrons from the plasma focus with the characteristic time periods of the focus reveals that the emission of the hard X-rays and the neutrons starts at the instant at which plasma reaches the maximum compression (minimum radius). The major portion of the yield is emitted at the onset of the  $m=0$  instability. Two plasma focus regimes are identified operating in deuterium. One is the single-compression regime corresponding to a single-compression of the pinch. The other one is the multiple-compression regime associated with two or more compressions of the focussed column. The neutron yield is greater in discharges exhibiting the single-compression regime. Multiple-compression regime is favourable for the soft X-ray production.

Average neutron energy of 2.48 MeV in the radial direction is determined. The average neutron energy of 3 MeV estimated in the forward direction together with the high value of the flux anisotropy show the dominant effect of the beam-target mechanism responsible for the neutron production. The anisotropy is higher for the discharges exhibiting high neutron yield regardless of the pressure.

The soft X-ray and the neutron emissions are also correlated. Lower operating pressures favour the soft X-ray production. As the pressure increases, the soft X-ray yield decreases and the neutron emission gets enhanced.

### References

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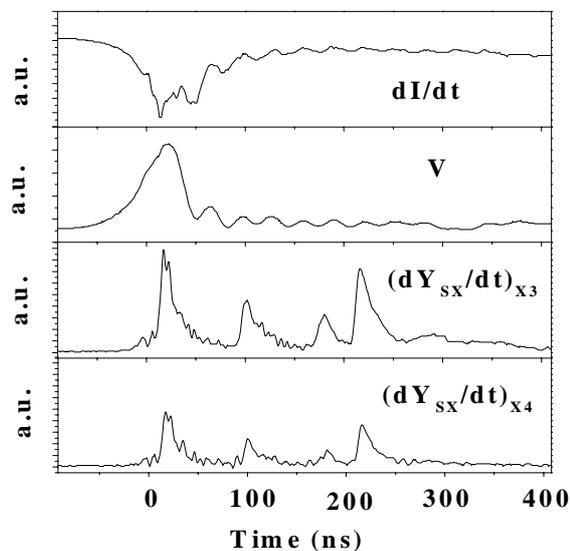


Figure 6: Signal profiles of  $dI/dt$ ,  $V$  and  $dY_{SX}/dt$ .