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Plasma Focus Neutron Anisotropy Measurements and Influence of a Deuteron Beam Obstacle

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Abstract

The deuterium-deuterium (DD) fusion neutron yield and anisotropy were measured on a shot-to-shot basis for the NX2 plasma focus (PF) device using two beryllium fast-neutron activation detectors at 0° and 90° to the PF axis. Measurements were performed for deuterium gas pressures in the range 6–16 mbar, and positive correlations between neutron yield and anisotropy were observed at all pressures. Subsequently, at one deuterium gas pressure (13 mbar), the contribution to the fusion yield produced by the forwardly-directed D\textsuperscript{+} ion beam, emitted from the plasma pinch, was investigated by using a circular Pyrex plate to obstruct the beam and suppress its fusion contribution. Neutron measurements were performed with the obstacle positioned at two distances from the anode tip, and also without the obstacle. It was found that ~ 80% of the neutron yield originates in the plasma pinch column and just above that. In addition, proton pinhole imaging was performed from the 0° and 90° directions to the pinch. The obtained proton images are consistent with the conclusion that DD fusion is concentrated (~ 80%) in the pinch column region.

Keywords: plasma focus, DD fusion, neutron anisotropy, deuteron beam, beam obstacle

Introduction

Neutron anisotropy measurements are amongst the most informative of diagnostics for the deuterium-filled plasma focus (PF) as they afford explicit evidence of the nature of the fusion mechanism [1,2]. It is well known that thermonuclear fusion is characterized by isotropic emission of neutrons with a narrow spread (some keV) of energies around 2.45 MeV. However, numerous experiments conducted by different groups using PF devices covering a wide range of capacitor-bank energies [3-7] show that the emitted neutrons exhibit both fluence and energy
anisotropy: the neutron fluence is greater in the axial (0°) direction than in the radial (90°) direction, and the average neutron energy at 0° is significantly higher (~2.8 MeV) than it is at 90° (~2.5 MeV). The fusion cannot therefore be straightforward thermonuclear fusion within the hot plasma pinch column. In the moving-boiler model [8], ions and electrons within the ‘boiler’ are thermalized at energies of a few keV (typical of thermonuclear fusion), and the observed neutron emission anisotropy results from center-of-mass motion of the whole plasma-containing ‘boiler’. However, this model provides no explanation for the intense forwardly directed D+ ion beam that has been consistently observed for numerous PF devices. D+ ions ejected from the pinch have a wide spectrum of energies ranging up to a few MeV. However, deuterons with energies < 100 keV are responsible for the bulk of the neutron yield [9-11]. These observations are consistent with the beam-target mechanism [12-14] in which an intense forwardly-directed D+ ion beam bombards stationary deuterons within the pinch column and the surrounding deuterium gas.

As part of the present work we have investigated the fraction of the neutron yield produced downstream of the plasma pinch by using a circular Pyrex plate as an inert non-conducting obstacle to block the forward ion beam at varying distances from the anode tip. Previous studies show that solid obstacles positioned at least one anode-diameter beyond the anode tip do not appreciably alter the dynamics of plasma pinch formation [15-17]. Later, in the Discussion section, the beam obstacle neutron measurements of Steinmetz, et al. [15] and Moo, et al. [16] are reviewed and discussed in relation to results from the present experiments.

Our neutron detectors [18] are based on fast-neutron activation of beryllium via the $^9\text{Be}(n,\alpha)^6\text{He}$ reaction. This reaction has a maximum cross-section in the 2.8 to 3.0 MeV range, but a negligible cross-section below 1 MeV. Consequently, these detectors are sensitive to the direct ~2.5 MeV DD fusion neutrons, whilst being largely insensitive to room-scattered neutrons. Unlike thermalized/moderated neutron detectors (e.g. Ag activation), the Be activation detectors are compact, and can be placed close to the source with negligible mutual interference. The short half-life (0.807 s) of the $^6\text{He}$ beta-decay ensures that the detector foreground count is a factor of at least $\sim 10^2$ larger than the background count; (typically: foreground > $10^4$, background ≈ 60). Consequently neutron yield and anisotropy measurements with low statistical uncertainty can be made – even when the neutron yield is suppressed (as in this work) by an ion beam obstacle.
MCNP simulations [18] were performed to obtain the calibration factor for the beryllium activation detectors, assuming of a point source of neutrons located at centre of the pinch column. However our beam-obstacle experiments, described later, indicate that this point source assumption is of limited validity, as ~20% of the yield originates downstream of the pinch. For this reason the majority of our results are presented in terms of detector net-counts.

**Experimental Setup**

These experiments were performed on the NX2 Mather-type plasma focus device [11] operated with deuterium filling gas; using the hollow anode and squirrel-cage cathode configuration as described in Ref. [19]. The device is energized by a 27 µF capacitor bank and has a short-circuit inductance of 26 nH. Throughout these experiments it was operated at 11 kV charging voltage (1.63 kJ stored energy). A Rogowski coil was used to measure the (external circuit) discharge current derivative \( (dl/dt) \) and the signal traces were recorded by a digital oscilloscope. Integrating the \( (dl/dt) \) signals gave peak currents of ~300 kA for these experiments.
Two identical beryllium activation detectors were positioned at 0° and 90° to the PF axis respectively. The distance from the anode tip to the mid-point of each Be plate was 250 mm. The gross count was integrated over a 3.0 s interval (= 3.7 half-lives) following each PF shot, and the background count was subtracted to give the net count: denoted \( C_{nBe}^0 \) and \( C_{nBe}^{90} \) for the 0° and 90° beryllium detectors, respectively. A schematic diagram of the experimental setup is shown in Fig. 1. For the first series of experiment (scan of D₂ gas pressure) no Pyrex setup was present.

**Experimental Procedures and Results**

**Neutron measurements: scan of deuterium gas pressure**

During the first experimental series, the deuterium gas pressure was scanned from 6 to 16 mbar in 2 mbar steps, with 20 shots being fired at each pressure. For each shot, the beryllium-count-anisotropy \( A_{nBe} = \frac{C_{nBe}^0}{C_{nBe}^{90}} \) was calculated. And, hence, the average count-anisotropy \( \langle A_{nBe} \rangle \) was obtained at each pressure. Since the beryllium detectors are equidistant from the plasma pinch, the count-anisotropy is (to a first approximation) proportional to the neutron fluence anisotropy. However, the net count also has a weak dependence on neutron energy, over the range pertinent to DD fusion [18]. Figure 2 presents a group of plots containing the main results from this first experimental series. As seen in the top-right plot, the highest average neutron yield was obtained for a deuterium gas pressure of 12 mbar. The MCNP derived calibration indicates an average neutron yield of \( 3 \times 10^8 \) per shot at 12 mbar, but a sizeable yield was obtained over the whole 6 to 16 mbar pressure range. The top-left plot shows that the average count-anisotropy \( \langle A_{nBe} \rangle \) decreases steadily with increasing gas pressure. The other plots in Fig. 2 show that for each of the six experimental pressures there is a positive correlation between \( A_{nBe} \) and \( C_{nBe}^0 \) (i.e. higher yield shots tend to have higher count-anisotropy).

We previously reported evidence from experiments with a different PF device (UNU-ICTP), that a substantial fraction of the fusion takes place in a conic zone in front of the pinch [20]. However for the NX2 PF device employed in the present experiments, coded-aperture proton images showed the fusion to be concentrated in the pinch zone [21]. Therefore, in a second series of experiments, we aimed to investigate the fraction of fusion yield produced
downstream of the pinch by a different method: using a deuteron-beam obstacle to suppress the fusion contribution produced in front of the pinch.

**Neutron measurements: with & without deuteron-beam obstacle**

A circular Pyrex plate (180 mm diameter, 6 mm thick) positioned perpendicular to the PF axis was used as an inert non-conducting obstacle to block the forward ion beam. As the inner diameter of the NX2 vacuum chamber is 190 mm, this Pyrex plate occupies 90% of the chamber cross-sectional area. The front (plasma-facing) surface of the Pyrex plate was positioned at either $z = 3.0$ or $6.0$ cm (where $z = 0$ corresponds to the position of anode tip) as indicated by the dashed lines in Fig. 1. Neutron data were collected over 40 shot series for each Pyrex plate position, and (for comparison) without the Pyrex plate. In the absence of the Pyrex plate, the ion beam extends to the surface of the chamber top-plate at $z = 11.8$ cm. A deuterium gas pressure of 13 mbar was used throughout these three series of shots. The gas was refreshed after each 20 shots.

Figure 3 shows the shot-to-shot variation of neutron anisotropy and the average anisotropy value (dashed horizontal line) for each 40 shot series; for the two plate positions $z = 3.0$ and $6.0$ cm, and without the Pyrex plate. The average neutron count and count-anisotropy values are summarized in Table 1. From the beam-target model of PF fusion we would expect the neutron yield (for which $C_{nBe}^0$ will suffice) and beryllium count-anisotropy $A_{nBe}$ to satisfy the conditions:

$$C_{nBe}^0(z = 11.8 \text{ cm}) > C_{nBe}^0(z = 6 \text{ cm}) > C_{nBe}^0(z = 3 \text{ cm}),$$

$$A_{nBe}(z = 11.8 \text{ cm}) > A_{nBe}(z = 6 \text{ cm}) > A_{nBe}(z = 3 \text{ cm}).$$

The data shown in Table 1 satisfy the second inequality, but not the first. The lowest $C_{nBe}^0$ was obtained for $z = 6.0$ cm. The reason for this low average yield value is not clear, but it might be that the shot-to-shot yields are not statistically independent; this could be due to the effect of ‘insulator conditioning’ over a series of shots [22]. Satisfaction of the $A_{nBe}$ inequality can be understood in terms of fusion produced by the forwardly-directed $D^+$ ion beam shifting the centre-of-gravity of neutron emission along the forward PF axis. The introduction of the obstacle reduces this centre-of-gravity shift. While fusion originating in the pinch will be due to trapped $D^+$ ions following convoluted trajectories (and possibly some thermonuclear contribution) for
which the neutron emission will be more isotropic than is the case for the straight-trajectory beam-target fusion occurring in front of the pinch.

Fig. 2: (top right) average Be detector count (0° and 90°) vs. D₂ gas pressure; (top left) average neutron count-anisotropy vs. D₂ gas pressure; (other panels) individual shot count-anisotropy for different D₂ gas pressures. Statistical uncertainties in $C_{nBe}^X$ values are $\cong \sqrt{C_{nBe}^X}$ (typically about 1%). Uncertainties for $A_{nBe}$ are typically $\sim$2%. Hence error bars are too small to be plotted.
Proton pinhole imaging of fusion source

Proton pinhole imaging was performed (without the Pyrex obstacle) to observe the fusion source shape and size, and to make an approximate comparison of proton-anisotropy and neutron-anisotropy. CR-39 nuclear track detectors were located within pinhole cameras positioned at 0° and 90° to the PF axis. The pinholes were of 1 mm² area, and at a distance of 95 mm from the anode-tip, giving a solid angle of \(1.11 \times 10^{-4}\) sr for each. The pinhole to CR-39 detector distances were 65 and 35 mm, for the 0° and 90° cameras respectively, giving

![Graph showing individual shot count-anisotropies (\(A_{nBe}\)) over 40 shot series, without- and with-Pyrex obstacle at positions: \(z = 3.0\) or 6.0 cm. Statistical uncertainties in \(A_{nBe}\) values are ~2%, and therefore too small to indicate as error bars.]

**Table 1: Average neutron count (beryllium detector) and anisotropy for different Pyrex obstacle distances, and without Pyrex obstacle, over 40 shot series.**

<table>
<thead>
<tr>
<th>40 shot series</th>
<th>without Pyrex</th>
<th>(z = 6.0) cm</th>
<th>(z = 3.0) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\langle C^0_{nBe}\rangle)</td>
<td>24,621</td>
<td>14,642</td>
<td>17,557</td>
</tr>
<tr>
<td>(\langle C^{90}_{nBe}\rangle)</td>
<td>12,596</td>
<td>8,867</td>
<td>12,813</td>
</tr>
<tr>
<td>(\langle A_{nBe}\rangle)</td>
<td>1.95 ± 0.02</td>
<td>1.65 ± 0.02</td>
<td>1.37 ± 0.02</td>
</tr>
</tbody>
</table>

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magnification values of 0.684 and 0.368. The detectors were covered by a 75 µm Kapton film to stop deuterons with energies $E_d \leq 3$ MeV (which for the great majority of shots is effectively all deuterons). The DD fusion protons, however, have sufficient range to pass through the Kapton film and produce latent tracks in the CR-39 detectors. The detectors were exposed to 2 consecutive PF shots. The beryllium detectors at 0° and 90° were used simultaneously to measure the neutron yield and anisotropy for these shots. The CR-39 detectors were then etched for 8 hours in 6.25n NaOH at 70°C. The detectors were then scanned using an automated optical microscope; the acquired images were processed using Image-Pro software; and the spatial distribution of recognized proton tracks was obtained.

The proton pinhole camera images (i.e. scatter plots of proton track positions) obtained from the two CR-39 detectors are shown in Fig. 4. The total number proton tracks on each detector are 1890 for 0°, and 667 for 90°. However, as a hollow anode was used in this experiment, approximately half of the pinch fusion source will be geometrically inside the copper anode and therefore obscured from the 90° pinhole camera. Moreover, the fraction of the pinch source obscured from the 90° camera is increased by the bending of proton trajectories by the magnetic field around the pinch. Nevertheless, an estimate of the proton anisotropy $A_p$ can be obtained by doubling the number of protons observed by the 90° camera. In this way, an approximate proton anisotropy value of $A_p = 1.4$ is obtained. Also, averaging the proton counts for the 0° and 90° cameras, and extending the result to $4\pi$ sr, gives a 2-shot proton yield of $Y_p = 1.83 \times 10^8$. The corresponding neutron values, for these 2 shots combined, are: neutron yield $Y_n = 1.55 \times 10^8$ and count-anisotropy $A_{nBe} = 1.63$. The (Fig. 4) proton pinhole images show: a nearly circular disc distribution for the end-on view, and an elongated (along $z$) conical distribution for the side-on view, with higher proton density in the $0 \leq z \leq 7$ mm region (corresponding to the part of the plasma pinch not obscured by the hollow anode). The side-on view Fig. 4(b) is consistent with results from the ion-beam obstacle measurements as the Pyrex obstacle at $z = 3$ cm will cut ~20% of the total fusion yield.
Discussion

There are two factors which cause the beryllium count-anisotropy $A_{nBe}$ measured here to be greater than the anisotropy values due purely from reaction kinematics and the DD differential cross-section ($d\sigma/d\Omega_n$). Firstly, as discussed in Ref. [18], the beryllium activation detector response is about 30% greater for neutrons in the energy range 2.8–3.0 MeV than it is for 2.45 MeV neutrons; and it is known that average neutron energy is higher at 0° than at 90° to the PF axis. Secondly, the forwardly-directed $\text{D}^+$ ion beam shifts the fusion source centre-of-gravity along the forward PF axis. For neutron detectors placed relatively close to the PF (as in this experiment), this centre-of-gravity shift increases the measured count-anisotropy.

In the work reported by Steinmetz, et al. [15], a study of the influence of an inert non-conducting obstacle on neutron emission characteristics was performed on the large ‘1-MJ’ Frascati PF device. The diameter of the obstacle was 11 cm, but the material is not specified. The main operating parameters were: 20 kV, 250 kJ and 3 torr (= 4 mbar) $\text{D}_2$ gas. The main conclusions from this study were that: (i) the neutron yield was level (i.e. unaffected) for obstacle positions $z > 12$ cm (note: PF top plate located at $z = 30$ cm), (ii) the neutron yield

![Fig 4: CR-39 proton pinhole camera images as viewed from: (a) 0° and (b) 90°. Magnification factors have been accounted for, i.e. dimensions on axes pertain to the source plane. The red rectangle indicates the down-stream half of the pinch column (of 10 mm length and 2 mm diameter) in front of the anode.](image-url)
decreased as the obstacle $z$ was reduced further – and about 60% of the neutron yield originated from the ‘main source’ ($0 \leq z \leq 6$ cm), (iii) the neutron anisotropy decreased as the obstacle distance was reduced, and (iv) the neutron anisotropy reached unity (i.e. isotropic emission) at the shortest obstacle distance $z = 6$ cm. The neutron anisotropy was $\cong 1.1$ without the obstacle.

For a small PF device (of UNU-ICTP design) Moo, et al. [16] used a copper obstacle placed at various $z$ positions. The main operating parameters were: 15 kV, 3.3 kJ and 3 torr (= 4 mbar) D$_2$ gas. The diameter of the copper obstacle was 4 cm. The neutron yield was level for obstacle positions $z > 5$ cm (note: PF top plate located at $z = 13$ cm). Again, the neutron yield decreased as $z$ was reduced. However, it was found that only about 15% of the neutron yield originated from the pinch column ($0 \leq z \leq 2$ cm). Hence $\sim 85\%$ of the neutron yield was associated with the forwardly emitted D$^+$ ion beam. Neutron anisotropy measurements were not performed by Moo, et al.

One caveat to note is that the obstacles used in [15] and [16] had relatively small diameters by comparison with the inner diameters of the PF vacuum chambers, and they therefore obstructed a smaller solid angle on the forward PF axis than is the case for the present experiment. Consequently, the obstacles in [15] and [16] may be blocking only a fraction of D$^+$ beam ions when $z >$ obstacle diameter; moreover, the fluence and energy of the D$^+$ ions will vary as a function of angle $\theta$ w.r.t. the forward PF axis. These factors complicate the interpretation of their results. By contrast the Pyrex obstacle used in the present work blocks the beam almost up to the cylindrical wall of the chamber.

The general trend of decreasing neutron yield and anisotropy with decreasing obstacle $z$, are observed in [15], [16] and the present work. The data in Table 1 and the images in Fig. 4 indicate that, for the NX2 PF, a large fraction $\sim 80\%$ of the neutron yield is produced within the pinch zone (and just above that, in the range of $z<3$ cm); which is more similar to the situation for the 1-MJ Frascati PF than to the small UNU-ICTP device. Our interpretation of these results is as follows.

For low energy (and low pinch-current) devices, such as the UNU-ICTP, the pinch magnetic field is insufficient to trap D$^+$ ions with energies relevant to DD fusion ($E_d > 30$ keV). The D number density ($n_d$) within the pinch column is greater than that for the cold D$_2$ gas by a factor of roughly 20 (being $10^{19}$ cm$^{-3} \div 5 \times 10^{17}$ cm$^{-3}$). If the D$^+$ ions are emitted in a wide-
angled cone (e.g. ~45°) then their path-length ($l_d$) within the pinch can be roughly estimated as the pinch diameter (~0.2 cm). Then the ratio between D+ ion path-lengths through the D$_2$ gas and through the pinch is about 100 (being 20 cm ÷ 0.2 cm). Consequently the fusion produced ($\propto n_d l_d$) in the cold D$_2$ gas will represent ~ $100/120 \approx 85\%$ of the overall neutron yield. For this rough estimation, we neglect the energy-loss of D+ ions (due to their stopping-power = $-dT/dx$), and the resulting decrease in reaction cross-section along each ion trajectory. By contrast, for the higher pinch-current devices (1-MJ and NX2) the magnetic field within the pinch is sufficient to trap a large fraction of the D+ ions with $E_d > 30$ keV within the pinch column, and so the neutron yield originates mainly within the pinch column. Table 2 compares the parameters of the three PF devices. For the NX2 PF, the maximum pinch current and therefore magnetic field are almost double that of UNU-ICTP (with almost the same size of pinch region) which is sufficient to confine most of the D+ ions with $30$ keV $< E_d < 100$ keV involved in DD reaction. For the Frascati PF, the pinch volume is about 700 times larger than NX2, and therefore for Frascati, 60% of the fusion source is located in the pinch region, whereas, in NX2, more than half of the fusion reactions happens just above that in $1 \text{cm} < z < 3 \text{cm}$ (pinch plasma has a length of 1 cm and half of that is inside the anode tip).

<table>
<thead>
<tr>
<th></th>
<th>Anode diameter (mm)</th>
<th>Pinch plasma column radius (mm)</th>
<th>Maximum pinch plasma current (kA)</th>
<th>Magnetic field at edge of pinched column (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NX2</td>
<td>18</td>
<td>0.9</td>
<td>300</td>
<td>67</td>
</tr>
<tr>
<td>UNU-ICTP</td>
<td>20</td>
<td>1</td>
<td>180</td>
<td>36</td>
</tr>
<tr>
<td>Frascati</td>
<td>160</td>
<td>8</td>
<td>1000</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2: comparison of between different devices for their pinch plasma parameters.

**Conclusion**

Two beryllium fast-neutron activation detectors were employed at 0° and 90° orientations, with respect to the PF axis, to investigate the neutron yield and anisotropy in the NX2 plasma focus device. These detectors enabled neutron measurements of good statistical accuracy to be made, even when the neutron yield is suppressed by an ion beam obstacle. By scanning the deuterium gas pressure from 6 to 16 mbar the optimum pressure for high neutron yield was found; giving an average neutron yield of $\sim 3 \times 10^8$ per shot at 12 mbar. A positive
correlation between neutron yield and anisotropy was observed for all deuterium gas pressures in the 6–16 mbar range. The average count-anisotropy $\langle A_{nBe} \rangle$ decreases steadily with increasing gas pressure.

Another series of experiments were performed, with 13 mbar deuterium, to investigate the extension of the fusion source in front of the plasma pinch, by using a circular Pyrex plate as an inert non-conducting obstacle to block the forward ion beam at a distance $z$ from the anode tip. These beam obstacle measurements indicates that $\sim80\%$ of fusion originates in the pinched plasma column and above just that $(0<z<3)$. Since the NX2 PF anode is hollow, the centre of the pinch should nearly coincide with the axial $z = 0$ position. As the beam obstacle is moved closer to the anode tip the average count-anisotropy decreases from $\langle A_{nBe} \rangle = 1.95$ without the obstacle, to $\langle A_{nBe} \rangle = 1.37$ with the obstacle located at $z = 3.0$ cm. This observation is consistent with significant beam-target fusion being produced by a forwardly directed $D^+$ ion beam.

Proton pinhole imaging of the fusion source was also performed for comparison with the neutron measurements, using CR-39 detectors and pinhole cameras located at $0^\circ$ and $90^\circ$ orientations. The wall of the hollow anode partially obscures the view of the pinch for the $90^\circ$ camera, making quantitative analysis difficult. However, the obtained proton images are consistent with $\sim80\%$ of fusion occurring in the vicinity of the pinch, and the roughly estimated proton yield and anisotropy were $Y_p = 1.83 \times 10^8$ per shot, and $A_p = 1.4$. Given the rather rough approximation resulting from the partial obscuration (at $90^\circ$), these values are consistent with the results obtained from the neutron measurements.

Lastly, the use of a beam-obstacle is found to be a reasonably simple and direct method for investigating the fraction of the PF neutron yield produced by the forwardly-directed $D^+$ ion beam. It does however require detectors with the capability to measure the neutron fluence for individual PF shots with good statistical accuracy – even when the neutron yield is suppressed by the action of the beam-obstacle. The beryllium fast-neutron activation detectors employed in this work are well suited to performing such measurements.

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