Neutron and high energy deuteron anisotropy investigations in plasma focus device

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The anisotropies of neutron and high energy deuteron emissions from the NX2 plasma focus device [M. V. Roshan *et al.*, Phys. Lett. A **373**, 851 (2009)] are studied. The nuclear activation of graphite targets is used to measure the fluences of high energy deuterons in the axial and radial directions. Two bismuth germanate scintillation detectors connected to multichannel analyzer systems are used for the detection of 511 keV gamma rays resulting from positron annihilation in the two targets. In addition, fast neutron activation detectors are employed to measure the axial and radial fluences of fusion neutrons. These detection systems are calibrated using the simulation code MCNPX [L. S. Waters *et al.*, AIP Conf. Proc. **896**, 81 (2007)]. Two distinct regimes of neutron and deuteron anisotropies are observed for the NX2 device. For deuterium gas pressures below 10 mbar, the neutron anisotropy increases with increasing pressure, while the overall neutron yield remains low. For gas pressures of 10–14 mbar, the neutron anisotropy is essentially constant, while, with increasing pressure, the neutron yield rises rapidly and the deuteron anisotropy falls. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3133189]

I. INTRODUCTION

Early observations of neutrons from pinched plasma devices were initially interpreted in terms of thermonuclear fusion. However it soon became clear that the observed neutron yields were much higher than the predictions of simple calculations based on plasma temperature, volume, and duration. Moreover, various experimental results from different plasma focus devices proved that an important part of the neutron yield could not come from thermonuclear fusion.[1] The evidence for their nonthermal origin came from observations of (i) neutron anisotropy (i.e., neutron fluence is higher in the axial direction), (ii) spread in neutron energies (away from 2.45 MeV as expected from thermonuclear fusion), and (iii) variation in mean neutron energy with direction.[2–5]

One of the most generally credited explanations of the neutron production relates to $m=0$ sausage instabilities in the pinched plasma column. Rapid dynamic growth of this instability results in a rapid change in the pinch inductance. The resulting axial electric field across the instability accelerates a group of deuterons. The collision of these deuterons with other deuterons within or near the pinch column gives rise to the neutron production. This is the essence of the beam-target model.

Neutron flux anisotropy measurement is an important tool for the determination of the roles played by different neutron production mechanisms in plasma focus. Anisotropy investigation provides an indication of deuteron acceleration process occurring in the compressed plasma column of the plasma focus device. According to Castillo *et al.*[6] neutron anisotropy measurements show a high anisotropy of about six which falls quickly within a narrow cone with an angle of 10°. It is also shown that the half width of neutron emission in end-on direction is longer than that of side on. The anisotropy significantly increases when a doping gas is added.[7] Neutron anisotropy measurements with CR-39 showed that the distribution can be fitted with a Gaussian function. So both the isotropic and anisotropic mechanisms for neutron production coexist.[8] The experiments with different electrode configuration show the geometry influence on the neutron anisotropy.[9]

Neutron yield of plasma focus device is strongly dependent on the energy of the reacting deuterons as the cross section for deuteron-deuteron fusion reaction is dependent on the energy. It is required to define the correlation between neutron production and deuteron acceleration in plasma focus to comprehend the mechanism of neutron generation.

In this paper the anisotropy of neutrons and high energy deuterons emitted from NX2 plasma focus is studied using nuclear activation methods as opposed to that of CR39 which suffers from low sensitivity to fast neutrons in order to advance the understanding of the fundamental physical process involved in neutron production and deuteron acceleration in plasma focus devices.

II. EXPERIMENTAL SETUP

The NX2 plasma focus device is a high repetition rate (up to 16 Hz) medium energy Mather-type plasma focus device.[10] Energy storage is provided by a 27.6 μF capacitor bank coupled to the plasma focus electrodes through four pseudospark switches. The total system inductance, short circuit, is measured to be 26 nH. The hollow copper tapered anode has an effective length of 40 mm. The cylindrical section (within the insulator sleeve) has a diameter of 31 mm, which tapers down to 23 mm at the top of the anode over the last 25 mm length. A Pyrex insulator sleeve of 35 mm in diameter and 60 mm in height is used. The insulator sleeve plays an important role in ensuring the symmetry of the initial gas breakdown and current sheath formation. The coaxial cathode comprises eight copper cathode rods arranged in a

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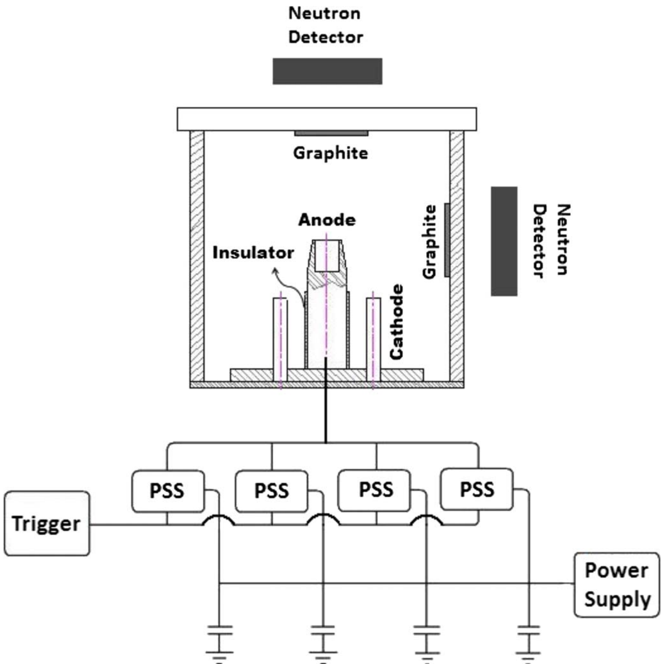

FIG. 1. (Color online) Schematic diagram of NX2 plasma focus along with graphite targets and the neutron detectors (PSS: pseudospark switch).

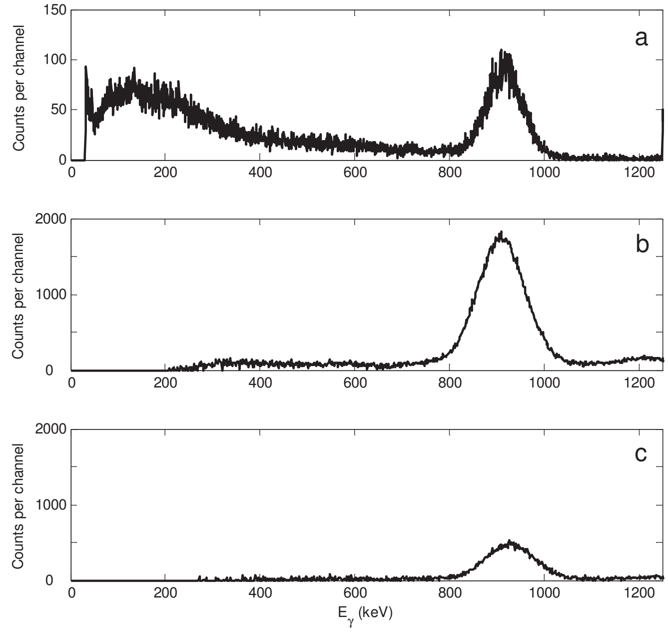

FIG. 3. Gamma ray from neutron activation detector (a) with background, (b) high neutron yield background subtracted, and (c) low neutron yield background subtracted.

squirrel cage configuration. The whole assembly is shown in Fig. 1. The capacitor bank was charged to 12 kV with the stored energy of about 2.0 kJ.

Lee's model[11] has been applied to the analysis of the voltage and current traces obtained for these operating conditions. The current trace obtained by calibrated Rogowski coil has been used to measure the peak discharge current of 300 kA and then fitted using Lee's model to estimate other parameters such as pinch current, dimensions, duration, and temperature. The main parameters resulting from Lee's model analysis are plasma pinch column dimensions of 2 mm diameter and 11 mm length, pinch duration of 70 ns, plasma pinch temperature of 0.5 keV, and a peak pinch current of 190 kA. A typical current derivative signal from NX2 plasma focus is shown in Fig. 2.

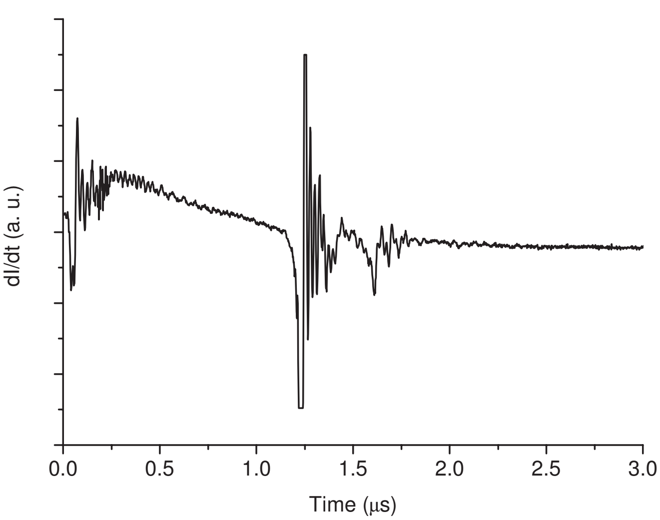

FIG. 2. Typical current derivative oscillogram of NX2 plasma focus.

Anisotropy of the accelerated deuterons was investigated using two graphite targets of 75×75 mm^2 area, 10 cm away from pinch, and positioned at 0° and 90° with respect to the plasma focus axis. These targets are activated by the deuterons through the $^{12}C(d,n)^{13}N$ reaction. The produced ^{13}N β + decays with a half life of 9.96 min and two back-to-back 511 keV gamma rays are produced from each positron annihilation event. After each series of plasma focus (PF) shots, comprising 30 shots fired at 1 Hz repetition rate, the graphite targets were removed from the chamber. The use of two scintillation detectors and two multichannel analyzer systems enabled a gamma-ray spectrum for each of the two graphite targets to be accumulated simultaneously. The bismuth germanate (BGO) crystals were of 76 mm diameter with a 0.5 mm thick aluminum front window. The graphite targets were placed in contact with the aluminum detector window. The photoelectric interaction of the gamma ray with the BGO crystal gives the number of counts in the photo peak. Thus, the number of activating deuterons is inferred from the number of gamma rays (annihilation radiation) associated with the absorption of positron (β^+) produced from the decay of ^{13}N. The threshold energy of $^{12}C(d,n)^{13}N$ reaction is 328 keV. Therefore, all the deuterons activating the graphite are high energy deuterons which are accelerated in the pinch phase of plasma focus. Simulation in MCNPX (Ref. 12) is performed to obtain BGO efficiency for 511 keV gamma rays, which is 52%.

Neutron yield measurements are performed with new activation neutron detectors (patent pending). The experimental setup as well as graphite targets and neutron activation detectors are shown in Fig. 1. The typical signal with background *a* along with the typical signal for "high neutron yield" *b* and "low neutron yield" *c* regimes are shown in Fig. 3. It can be seen that there is no problem of differentiating

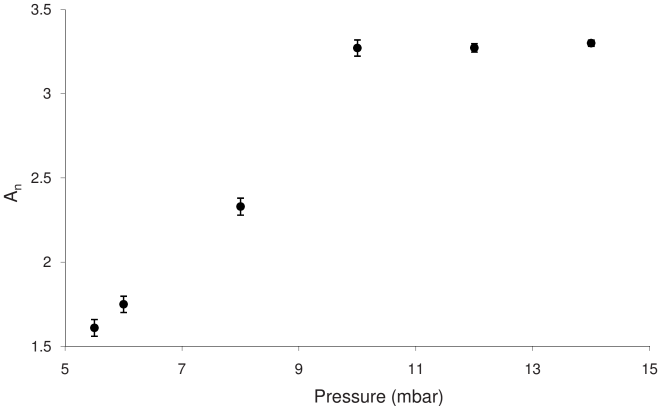

FIG. 4. Neutron anisotropy vs deuterium pressure showing the two neutron anisotropy modes.

the background contribution from the signal of low neutron yield regime indicating accurate anisotropy measurement even for low neutron yield regime.

III. RESULTS AND DISCUSSION

The neutron anisotropy A_n, which is the ratio of axial to radial neutron fluence at different deuterium filling gas pressure of NX2 plasma focus, is shown in Fig. 4. For pressures up to 10 mbar, it can be seen that the anisotropy A_n increases with increasing pressure, whereas, for gas pressures of 10–14 mbar the neutron anisotropy is essentially constant. These results are different from the neutron anisotropy results of various plasma focus devices. Bernard *et al.*[13] also observed a variation in neutron anisotropy for different filling pressures. However, Lee *et al.*[14] found no significant dependence of the anisotropy of neutron fluence upon the deuterium filling pressure for 1–10 torr.

We propose that two distinct modes of PF operation are associated with the different behaviors of A_n seen in Fig. 4, which can be termed "A_n rising mode" and "A_n plateau mode." As can be seen from Fig. 5, in the A_n rising mode, the total neutron yield is comparatively low, although increasing gradually with A_n. The minimum neutron anisotropy in this mode is A_n=1.6 and the maximum is A_n=3.3.

In the A_n plateau mode, anisotropy remains invariant at optimum deuterium pressure range of 10–14 mbar (see Fig. 4), but the neutron yield is high and increases to maximum, as shown in Fig. 5. The average neutron anisotropy in this mode is A_n=3.2.

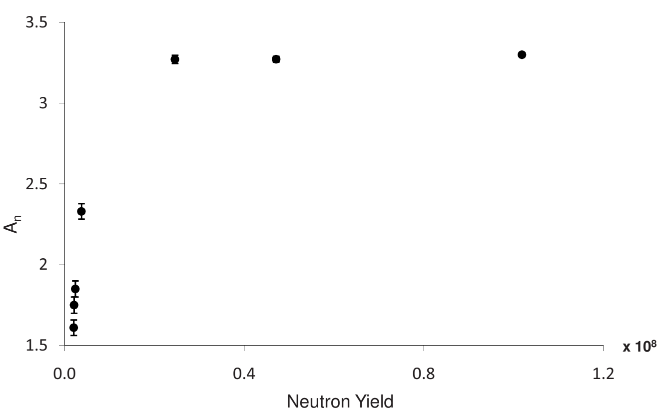

FIG. 5. Neutron anisotropy as a function of total neutron yield.

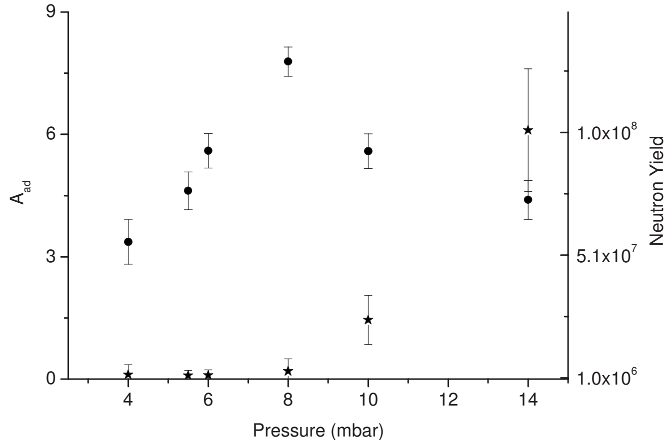

FIG. 6. High energy deuteron distribution A_{ad} (circle) and neutron yield (star) vs pressure.

With a simple analysis of the A_n rising mode, in Fig. 5, it is noticed that there is a very significant increase in neutron anisotropy at lower deuterium gas pressure pointing to the fact that at lower filling gas pressure the contribution of beam-target mechanism increases with the increase in the pressure and then saturates at optimum pressure. Comparing Figs. 4 and 5, and considering that the optimum pressure range for neutron production in NX2 plasma focus is in the range of 10–14 mbar,[15,16] it is observed that the significant number of neutrons is produced when a constant anisotropy is obtained. At this invariant anisotropy, the neutron yield reaches to the highest yield regime. Once the optimum neutron yield regime is achieved, the ratio of neutron production in radial and axial directions is found to be in equilibrium. Hence, we conclude that the higher neutron yield does not depend merely on the axial neutron production, as in that case we would have observed the continuous increase in anisotropy.

The NX2 plasma focus experiments with graphite target show that high energy deuteron anisotropy (A_{ad}) is in the range of 4–8. The average anisotropy of the energetic deuterons is double of the neutron anisotropy in the plateau region. The anisotropy of high energy deuterons is observed at all the pressures from 4 to 14 mbar.

Figure 6 shows the correlation between neutron yield and high energy deuteron anisotropy. At 8 mbar, the anisotropy of high energy deuterons is highest. This is probably due to the following reason. Since the magnetic field at the central part of the pinch is weak, deuterons are accelerated in axial direction without too much change in their path. The inverse of collision frequency of deuterons is given by[17]

$$t_{ii} \approx 1 \times 10^7 \times \frac{E_d^{3/2}}{n \ln \Lambda} \text{ sec}, \quad (1)$$

where E_d is the deuteron energy in electron volts, n is the density in cm^{-3}, and $\ln \Lambda$ is the usual logarithmic factor of order 10. Deuterons with an energy as low as 10 keV have got the collision time of about 90 ns. Therefore, within a few nanoseconds, a significant number of ions run away and undergo fusion reaction with the deuterons surrounding the compressed plasma column. However, in the peak region, the neutron yield is still very low because the fusion reaction does not take place in the dense region of the plasma column (pinch).

Beyond 8 mbar, the anisotropy of high energy deuterons decreases. It may be due to the deuteron entrapment in the pinch where the magnetic field is very strong.

The estimation of Larmor radius

$$r_l = \frac{m_d v_d}{eB} \tag{2}$$

shows that r_l for some of the high energy deuterons is less than the pinch radius. If the magnetic field in the pinch is assumed to be given by[17]

$$B = 2 \times \frac{I_{\text{pinch}}}{r_{\text{pinch}}} \quad \text{(tesla)} \tag{3}$$

for the pinch current of 200 kA and pinch radius of 2 mm, Larmor radius for a deuteron energy of 300 keV is $r_l = 0.56$ mm. Gyration time of the deuterons in the magnetic field is obtained by

$$\tau = 2.57 \times 10^{-13} r_l E_d^{-1/2}, \tag{4}$$

where r_l is in centimeters and deuteron energy is in joule. This time is estimated to be 65 ns, which is in the order of pinch time duration in NX2 plasma focus that is 70 ns. Therefore, these high energy deuterons have got the chance of entrapment in the pinch during the pinch life time and undergo the fusion reaction in the compressed plasma column. In such conditions, deuterons gyrate in the region of strong magnetic field and could be accelerated in every direction. Hence the number of deuterons accelerated in axial direction is less and the deuteron anisotropy decreases, although it is still not less than four. Since the density of gas is significantly high and the fusion reaction takes place in the dense part of plasma column (pinch), in this region the neutron yield increases to the optimum conditions.

In the region where the pressure is less than 8 mbar, deuterons are gyrating in the strong magnetic field and accelerate in every direction, therefore the deuteron anisotropy is low. Here, the neutron yield is very low due to the lower density of deuterons owing to the lower operating pressure of deuterium gas in the chamber. From Figs. 4–6 it is evident that neutron anisotropy increases up to 10 mbar and does not change after that; the significant neutron yield is produced after 10 mbar; deuteron anisotropy at 10 mbar is in the decreasing manner. At the high enough pressures, there are a significant number of deuterons in the pinch, therefore, the number of deuterons in the surface of the pinch will also be higher and, as mentioned above, they gyrate in the strong magnetic field. Therefore, the anisotropy of deuterons decreases down to four and the neutron anisotropy increases to an equilibrium state of about 3.3. In this condition, the neutron yield increases to the maximum.

At lower pressure, deuterons are accelerated in the axial direction at the center of pinch. In these pressures, the neutron yield is very low.

IV. CONCLUSION

Neutron anisotropy in NX2 plasma focus has shown two modes of operation: rising and plateau. In the rising mode the anisotropy increases to 3.3 and remains invariant at this point. However, the neutron yield is very low in the first mode and only increases in the region of plateau mode where both the axial and radial components of neutron yield increase simultaneously. The activation technique was used for high energy deuteron distribution study, in which the graphite targets are placed in side-on and end-on positions. MCNPX simulation code was used for calibration of the detection system comprising BGO scintillator and multichannel analyzer. Deuteron anisotropy measurements show that at 8 mbar deuterons are not deviated much in the low magnetic field at the central part of plasma column (pinch) and also less collision takes place in the pinch, hence the axial component of deuteron yield is higher than the radial one. Beyond that, due to deuteron entrapment and gyration in the high magnetic field at the surface of pinch, high energy deuteron yield increases in other directions, which results in the less contribution of axially directed deuterons. Finally, at the significantly high pressures, in which the deuteron anisotropy decreases down to four and neutron anisotropy does not change any more at 3.3, the neutron yield increases to the maximum.

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