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Backward high energy ion beams from plasma focus

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High energy neutrons, more than 2.45 MeV from deuteron-deuteron fusion reaction, have been measured in backward direction of plasma focus devices in many laboratories. However the experimental evidence for high energy deuterons responsible for such neutrons has not been reported so far. In this brief communication, backward high energy deuteron beam from NX2 plasma focus [M. V. Roshan *et al.*, Phys. Lett. A **373**, 851 (2009)] is reported, which was measured with a direct and unambiguous technique of nuclear activation. The relevant nuclear reaction for the target activation is $^{12}\mathrm{C}(d,n)^{13}\mathrm{N}$, which has a deuteron threshold energy of 328 keV.
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Plasma focus (PF) devices are essentially a form of Z pinch, with a characteristic feature of producing short lifetime plasma with high density and temperature.[1] The density and temperature remain relatively constant for PF devices in a wide range of energies from 1 kJ to 1 MJ.[2] It is an efficient source of D-D fusion neutrons of up to 10^{11} (Ref. 3) and high energy ions of a few MeV.[4] This is in spite of the fact that the charging voltage is one or two orders of magnitude less than the induced voltage in the pinch. Plasma focus devices have been extensively studied in a large number of laboratories; however, there is as yet no fully satisfactory explanation for the mechanism of ion beam acceleration and consequently neutron production.

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 most of the neutron yield could not come from thermonuclear fusion.[5] 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 shape of the neutron spectra, and (iii) variation of mean neutron energy with direction.[6–9]

The experimental results of neutron production in plasma focus suggested that a substantial fraction of the neutrons are produced due to the axial acceleration of a comparatively small number of deuterons.[10] Based on experimental results, axial ion acceleration has been demonstrated by assuming a strong axial electric field.[11] However, the initial experiments showed that high energy ions are also generated in radial direction, and the angular distribution of deuterons with energies more than 328 keV was strongly forward peaked with anisotropy exceeding 10^2 (the ratio of deuterons yield in axial and radial directions).[12] Our experiments with NX2 plasma focus showed the anisotropy of high energy deuterons (more than 328 keV) in the range of 4–8.[13]

Ion acceleration mechanisms in the plasma focus device have been investigated assuming (i) particle motion in dynamically induced electromagnetic fields,[14] (ii) anomalous enhanced plasma resistivity,[15] (iii) rapid dynamic growth of sausage type pinch instability mode,[5] and (iv) fast magnetosonic shock wave produced during the pinch phase.[16] In the acceleration modeling, ions are considered mostly to be accelerated in forward direction although other directions are not excluded. Measurements of ion beam from NX2 plasma focus have employed a variety of techniques including nuclear activation of low-Z material,[17] activation yield ratio,[18] and magnetic spectrometer equipped with a Faraday cup (the results will be discussed in a future publication).

In this brief communication, we report ion beam measurements in the backward direction (more than 90°) of NX2 plasma focus using graphite activation. Nuclear activation is a direct and unambiguous diagnostic for deuteron measurements as graphite is activated by deuterons with threshold energy of 328 keV. Therefore, the activation is evidence of very high energy deuterons moving in backward direction. It is possible to rely on this simple method in the backward direction even where other methods like Faraday cups and magnetic spectrometer would fail for technical reasons.

The NX2 device is a high repetition rate small Mather-type plasma focus with a 27.6 μF capacitor bank coupled to the electrodes through four pseudospark switches.[19] The total system inductance is 26 nH. Throughout these experiments the NX2 was operated with 8 mbar deuterium gas and 12 kV charging voltage. Ion measurement is conducted with the activation of graphite target (20 mm in diameter) inserted on the anode tip. The schematic diagram of the experimental setup is shown in Fig. 1.

The interaction of high energy deuterons with the graphite target results in the production of nitrogen-13. The threshold energy for this reaction is 328 keV, although the cross section remains very small below 600 keV. The graphite activation is therefore caused by the high energy tail of the deuteron distribution. ^{13}N is a short-lived radioisotope, and decays with the half-life of 9.96 min and produces positron. The positrons slow down in the graphite and annihilate with electrons. Two oppositely directed 511 keV gamma rays are produced by each positron annihilation event. Bismuth ger-

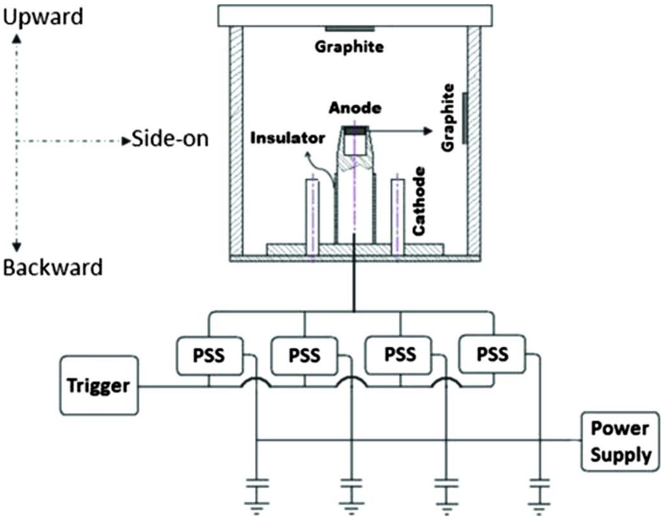

FIG. 1. (Color online) Schematic of NX2 plasma focus and the experimental setup. PSS stands for pseudospark switch.

manate (BGO) scintillation detector (with a radius of 3 in. and thickness of 1 in.) and multichannel analyzer (MCA) system are used to detect the 511 keV gamma rays. The efficiency of the BGO and MCA system for 511 keV annihilation gamma-ray measurement is obtained by Monte Carlo simulations with MCNPX.[20] Simulations show that the BGO system has an efficiency of 52% for detection of positron annihilation events, using an integration window from 400 to 600 keV.

The experiments comprise a sequence of 30 shots fired at 1 Hz repetition rate. NX2 chamber is filled with deuterium at 8 mbars, which is comparatively lower than the optimum pressure for neutron production (14 mbars). At low pressures, neutron yield decreases while the probability of high energy deuteron production is much higher.[17] The discharge voltage in these experiments is 12 kV. Results show significant activation of graphite by high energy deuterons in backward direction as it is shown in Fig. 2.

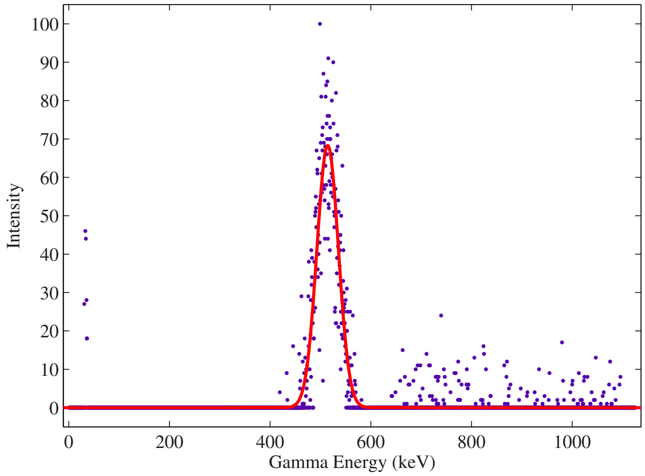

FIG. 2. (Color online) Typical background subtracted spectrum from graphite activation with high energy deuterons.

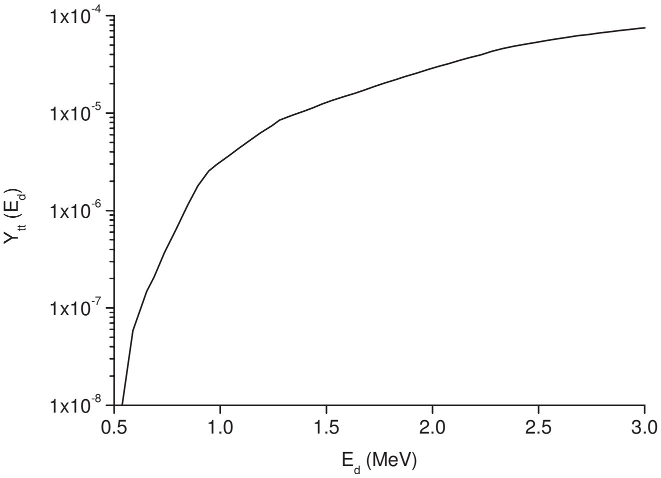

FIG. 3. Thick target yield for $^{12}\mathrm{C}(d,n)^{13}\mathrm{N}$ nuclear reaction.

The total number of ^{13}N nuclides produced in the target by deuteron bombardment can be obtained from

$$N_{^{13}\mathrm{N}} = k\int_0^{E_{\max}} E_d^{-m} y_{tt}(E_d)\,dE, \tag{1}$$

where the deuteron energy distribution follows an empirical power law of the form $(dn_d/dE_d)=kE_d^{-m}$ (Ref. 21) and $y_{tt}(E_d)$ is the thick target yield

$$y_{tt}(E_d) = \int_0^R n\sigma(E)dx = n\int_0^{E_d} \frac{\sigma(E)}{|dE/dx|}dE, \tag{2}$$

where E_d is the incident energy of deuterons, $\sigma(E)$ is the reaction cross section, n is the target nuclei per cm^3, dE/dx is the stopping power, and R is deuterons range in the target. Figure 3 displays the calculated thick target yield as a function of deuteron energy.

The total number of ^{13}N nuclides obtained from 511 keV gamma-ray measurements with BGO and MCA system is estimated to be 5.7×10^4. The activation yield-ratio technique gives the value of m to be about 9.[18] The characteristic deuteron energy activating the graphite target is in the range of 650–750 keV. The value of k determined from Eq. (1) is 1.7×10^{10} MeV^{-1}, which gives 1.3×10^{11} *backward deuterons* per shot per steradian with energies higher than 500 keV. The backward deuterons are about one order of magnitude less than the forward ones.[13] For an $\sim E^{-9}$ spectrum, the distribution of ^{13}N yield with deuteron energy is shown in Fig. 4.

The graphite target in current experiments was drilled by electrons at the center (a hole with 0.9 mm depth and 1.5 mm radius) and most of the activated particles were sputtered. A plasma jet drills the target as well. Therefore, the activation in the target which is measured by the BGO and MCA system is much less than the real activation caused by high energy deuterons. Hence, the total number of ^{13}N nuclides produced by high energy deuteron activation of the graphite was underestimated.

Bernstein has reported high energy neutrons (more than 2.45 MeV) at 180°, so it was assumed that some high energy ions have high velocities in the backward direction.[14] How-

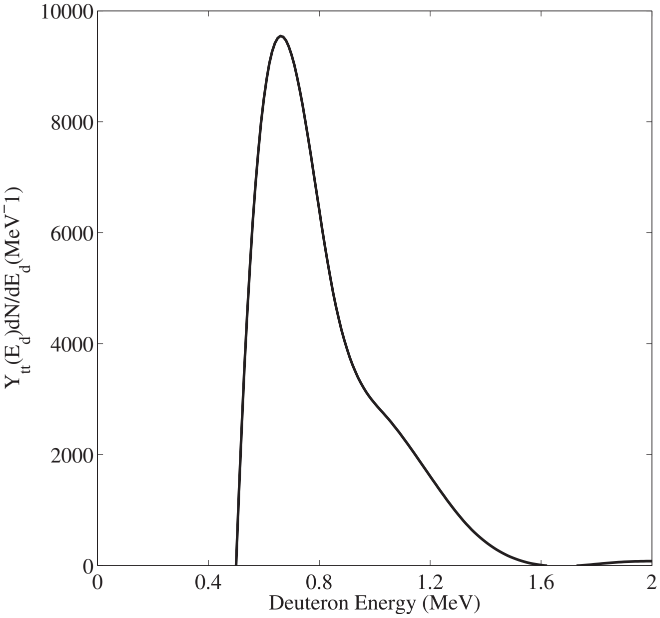

FIG. 4. Nitrogen-13 yield distribution for a deuteron spectrum of $dn_d/dE = kE^{-m}$ $(m=9)$.

ever, the experimentally measured high energy deuterons have not been reported so far, and our experiments could justify the backward high energy neutrons production.

Ion energy, velocity vector, and the mechanism in which they are accelerated, are required to be taken into account for ion acceleration in the pinch. If ions are upward directed and the acceleration is in the same direction, they are accelerated in upward with increasing curvature radius, because the magnetic field depends on the position as shown in Fig. 5.

The pinch current in NX2 plasma focus is about 200 kA and the pinch radius is 1 mm. The magnetic field in the pinch is estimated to be 40 T, which is maximum on the pinch surface and minimum on the axis. Deuterons with the energy ≤ 40 keV, have got the chance to gyrate within the pinch volume, and it is interesting to mention that vast majority of neutrons are produced from deuterons with the energy range of 30–60 keV.[22] However, the curvature radius for deuterons with higher energy is more than the pinch radius, which results in the deuterons to move in the upward direction. This is the case when we assume that deuterons are accelerated with any mechanism and the initial velocity vector is oriented in the upward.

With this assumption, which is considered by most of the authors, it is concluded that none of the deuterons (even with energies much less than the deuterons activating the graphite) are produced in nonaxial directions. So it is required to introduce a mechanism in which the deuterons can be accelerated in different directions. Currently we are working on the possible mechanisms for ion acceleration, including the acceleration in nonaxial directions, in order to clarify the idea based on the experimental measurements.

Comparing the current results with the one reported in Ref. 13, it is concluded that the acceleration of deuterons to very high energies occurs not only in one direction in plasma focus, a fact that is required to be considered in any experimental and theoretical investigation of the mechanism in which the ions are accelerated in the pinch plasma devices. It may also be concluded that the works which search to relate the neutron production to the thermonuclear mechanism, with anisotropy measurements, take into account that the present results strongly suggest that nonthermal mechanism is still dominant in plasma focus.

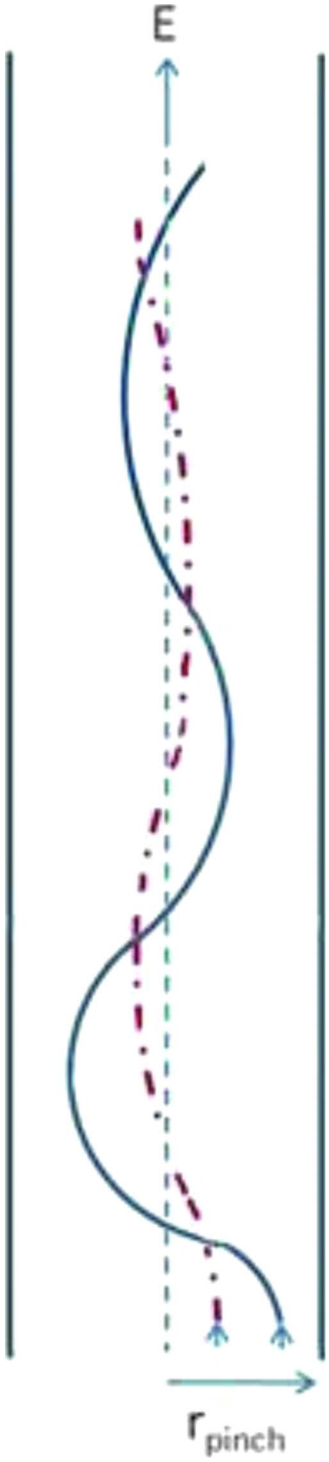

FIG. 5. (Color online) Conceptual drawing of ion trajectories in a constant electric field and magnetic field. Dashed line is the path for high energy ion and solid line for lower energy ion.

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