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A MEASUREMENT OF THE DISTRIBUTION OF VERY ENERGETIC IONS IN THE PLASMA FOCUS DEVICE

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MASTER

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A MEASUREMENT OF THE DISTRIBUTION OF VERY ENERGETIC IONS IN THE PLASMA FOCUS DEVICE

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ABSTRACT

The $C^{12}(d,n)N^{13}$ reaction was used to monitor the distribution of deuterons in the plasma focus device having energies exceeding 330 keV, the reaction threshold. Carbon discs, placed at various angles and distances from the anode of a plasma focus device having a stored energy of 75 kilojoules at 18 kV, were analyzed following the shot to determine the N^{13} activity. Low pressure operation (1 torr deuterium) produced a substantially greater number of energetic deuterons than did high pressure (5 torr D_2) operation with the low pressure distribution more sharply peaked in the forward direction. This is consistent with previous data which showed that low pressure operation maximized electron acceleration as determined by hard x-ray measurements.[1] Using a thick target yield of 2.86×10^{-7} N^{13} atoms per incident deuteron,[2] the calculated number of deuterons above 330 keV for the highest intensity shot was 2×10^{15} (the neutron yield on this shot was 1.2×10^{13}). In contrast the largest deuteron yield on a high pressure shot was 4.3×10^{13} (neutron yield = 2.4×10^{10}). The ratio of 0° to 90° deuterons normally exceeded 100 and was greater than 10^4 on high yield shots. The intensity and anisotropy of high energy deuterons showed a positive correlation with the amount of material

removed from the anode insert by energetic particle bombardment, and the total hard x-ray yield as monitored by a silicon "PIN" detector with titanium filter. Pulse width of the hard x-ray signal was typically less than 10 nanoseconds for high deuteron yield low pressure shots. These measurements suggest that beam-target reactions contribute a significant fraction of the neutron yield in the low pressure mode of operation of the plasma focus device, and also that more than 0.2% of the stored capacitor bank energy can be converted into a deuteron beam with $E \gtrsim 330$ keV.

INTRODUCTION

The plasma focus device is a form of linear pinch discharge which produces a dense, magnetically compressed plasma at the end of a coaxial electrode system.[3] The plasma focus device has produced neutron yields exceeding 10^{12} per shot (operating with deuterium)[4] and is an intense pulsed x-ray source. The plasma focus device can be operated so as to produce high electric fields at the termination of the dense pinch phase, resulting in the acceleration of electrons and ions to many times the energy of the capacitor bank charging voltage. Maisonnier has suggested that the bulk of the neutron yield in the plasma focus device may arise from a low density plasma ($n \lesssim 10^{18}$ cm^{-3}) turbulently heated to 10 keV by an energetic electric beam generated at the time of the disruption of the dense pinch phase.[5]

In previous work at this laboratory the characteristics of this energetic electron beam were evaluated by x-ray measurements.[1] The work reported here describes intensity and angular distribution measurements of high energy deuterons in a Mather geometry plasma focus device as evaluated by a nuclear activation technique. These experiments are motivated by the suggestions of Sahlin[6] and Freeman et al.,[7] that the high energy electron and ion beams in the plasma focus device, focused in space and time, may have applications in the heating and ignition of fusionable pellets.

EXPERIMENTAL

The plasma focus device employed in these experiments has a 10 cm diam hemispherically ended copper anode with an interchangeable insert. The cathode is 15 cm in inner diameter and is made from twelve 1.2 cm diameter copper rods. The anode extends 29 cm from the base of the cathode, the pyrex insulator, 13 cm. The capacitor bank consists of 32 14.7 microfarad capacitors having a total stored energy of 76 kilojoules at 18 kV. Vacuum spark gap switches are used to switch 4 capacitor modules to the parallel plate transmission line upon which the load is mounted. Maximum current into the load is 900 kiloamps at 18 kV and the quarter cycle time is 3.5 microseconds.

Standard diagnostics include silver activation neutron detectors,[8] a neutron time of flight detector,[9] current and voltage monitors, x-ray pinhole cameras, silicon "PIN" detectors with Ross filters,[10] and thermoluminescent dosimeters.

Primary diagnostic technique in these measurements was the activation of high purity carbon by energetic deuterons by the reaction $C^{12}(d,n)N^{13}$. This reaction has an absolute threshold of 330 keV and the nitrogen 13 is a beta emitter which decays with a half life of 9.97 minutes. Various authors[11-17] have measured the cross section and/or thick target yield from this reaction. A thick target yield value of 3.5 x 10^6 incident deuterons per N^{13} atom for a deuteron energy of 700 keV was used in all absolute yield calculations in this report, as it was the lowest energy value found.[2]

The $O^{16}(d,n)F^{17}$ reaction with an absolute threshold of 1.84 MeV was also used to place an upper limit on deuteron energy.[18]

A gas flow proportional counter with a counting geometry of 2π was used to measure the N^{13} activity. The efficiency was measured with a calibrated strontium-90 source and found to be 40 ± 5%.

SUMMARY OF OTHER DATA

Measurements of high energy ions in plasma focus geometries have been made by Belyaeva and Filippov[19] and by Conrads et al.[20] Using nuclear emulsions Belyaeva and Filippov measured 10^{13} deuterons per shot with an energy between 0.3 and 1 MeV distributed in a cone with a half angle of 25-30°, in a Filippov geometry plasma focus device. Conrads et al., used neutron time-of-flight and a deuteron reaction on lithium in a hybrid Filippov-Mather geometry plasma focus device to measure more than 10^{15} deuterons with $E \geq 1$ MeV, directed away from the anode. Bernard et al.,[21] compare measured neutron time-of-flight spectra with calculated values generated from a deuteron acceleration model[22] and finds good agreement, concluding that beam-target reactions may account for the neutron yield in his Mather geometry plasma focus device.

The calculation of energetic deuteron distributions has been accomplished by Bernstein and Comisar[22] and by Gary.[11] In the first reference an electric field generated by a rapidly constricting current discharge is calculated, causing an ion acceleration to axial energies in excess of 400 keV. The ions initially move with a substantial angle to the axis, becoming more parallel to the axis as the energy increases. Since the total path length travelled by such high energy deuterons is much longer than the displacement from the anode, beam target reactions could account for a higher neutron yield than might be evident from a simple calculation, and the neutron distribution could be relatively isotropic. In the second reference an anomalous resistivity caused by a microinstability is assumed, and the resulting electric and magnetic fields calculated. A resistivity of 4×10^{-15} $\sec^{-1}$ was necessary to account for experimental observations of field penetration to a depth of 1 mm in 30 ns. The author comments that this is the same magnitude required for ion-acoustic turbulence and Buneman two-stream turbulence, and his calculations show deuterons can have substantial radial velocities.

A variety of authors have speculated on the mechanism which apparently causes the rapid disruption of the current in the plasma focus device with the resulting high electric fields and particle acceleration. Direct measurements of this "anomalous resistance" have been made using laser scattering[21,23] and electrical data.[24] In addition to the microinstabilities mentioned in the previous paragraph, it has been proposed that the explosive decay of magnetic structure in localized filaments can result in the observed acceleration.[25] Impurities may have an important role in triggering microinstabilities through increased resistivity from ionizational cooling.[26] Sahlin has suggested that high Z impurities may cool the plasma from radiative losses to the point where the electron thermal velocity is less than the directed velocity, triggering the microinstability.[27] Bazdenkov et al.,[28] propose that dense neutral vapor from the anode lowers the plasma conductivity, permitting magnetic field diffusion through the current sheath, causing particle acceleration.

In previous experiments at this laboratory the acceleration of energetic electrons was evaluated by x-ray measurements. It was determined that operating in the low pressure mode (1 torr) about 2% of the capacitor bank energy could be delivered in an electron burst less than 20 nanoseconds in width with an average electron kinetic energy of 150 keV.[1]

EXPERIMENTAL RESULTS

The carbon discs used to monitor energetic deuterons were 3.8 cm in diam and 0.79 cm thick. Nine of these discs were mounted on a bar perpendicular to the axis of the electrodes and 23 cm from the end of the anode. Three additional discs were mounted on the side of the chamber (radial distance = 23 cm) at axial positions ranging from 0 to 29 cm from the end of the anode (Fig. 1). On some shots the carbon discs were replaced with aluminum oxide, copper, or aluminum targets.

To study the effect of anode material upon the acceleration of deuterons an interchangeable anode insert was used (Fig. 2). The anode inserts consisted of 1.3 cm diam tantalum, tungsten, copper deuterated polyethylene, or titanium placed in the center of the anode. Most shots in these experiments used the copper insert. On one copper insert the weight loss was evaluated to provide an estimate of the number of copper atoms removed per shot. For 26 shots producing neutron yields above 10^9 an average of

7.7×10^{20} copper atoms per shot were removed. No direct measurement of weight loss was made on the other insert materials, but the number of atoms removed is estimated to be a factor of 10 lower with the titanium and tantalum inserts. The tungsten insert often fractured irregularly with large chunks removed on a single shot.

Wide variations were evident in the activation of the carbon targets. Following some low pressure shots beta activities in excess of 50 mr/hr (off scale) were measured on the 0° target with a portable geiger tube survey instrument. Chamber filling pressure was the most important parameter in determining the high energy deuteron yield. Shots at one torr produced up to 1.4×10^{8} N^{13} atoms on the 0° pellet at shot time (neutron yield was 1.2×10^{10}) whereas at 5 torr the neutron yield was higher (2.4×10^{10}) but the maximum number of N^{13} atoms on the 0° disc was 2.8×10^{6}, a factor of 50 higher for the low pressure operation. Normalized to neutron yield the low pressure shots produced a factor of 100 times more deuterons in the 0° direction above 330 keV than did high pressure operation. The deuteron distribution was strongly forward peaked with the anisotropy increasing with intensity. The ratio of 0° to 90° deuterons (0° is aligned with the axis of the electrodes and points away from the anode) exceeded 10^{4} on some shots and commonly was greater than 100. On the highest intensity shots the deuterons were distributed in a cone with half of the intensity inside a half angle of 7°. On some high intensity, low pressure shots the angular deuteron distribution was found to be a good fit to an exponential distribution, i.e., $D(\theta) = D(0) \exp(-\alpha\theta)$ which facilitated calculations of the total yield. In Fig. 4 the deuteron distribution from shot 1661 is shown and compared with an exponential distribution with a coefficient $\alpha = .076 \text{ deg}^{-1}$.

The deuteron distribution was normally centered at 0°; however, on some low yield shots the center of the distribution was displaced as much as 11° from zero. In no case was a "hollow" distribution found, with maxima on both sides of zero. Figure 5, shot 1688, shows one such example of an asymmetric distribution. Note that the absolute maximum is about 86 times less than on shot 1661, Fig. 4.

A strong correlation was found between the intensity of high energy deuterons and the magnitude and duration of the hard x-ray pulse. The low pressure shots which produced the maximum number of high energy deuterons produced the highest intensity hard x-ray yields and the narrowest pulses. The hard x-ray signal as monitored by a 250 micron thick silicon detector with a .044 cm (18 mil) thick titanium filter is shown in Fig. 3 for both high and low pressure shots. On low pressure shots producing high deuteron yields the x-ray pulse was commonly less than 10 ns in width (FWHM).

These experiments were conducted primarily with copper and titanium anode inserts. The previous experiments emphasizing x-ray measurements[1] used primarily tantalum and tungsten. Sahlin suggested that deuterium adsorption on the anode could provide ions for acceleration,[27] and titanium, becomes of its high adsorptivity, was selected as an anode insert to determine if this effect was important. On the limited number of anode materials tested no appreciable difference was noted between various materials on the number and distribution of high energy deuterons. This phase of the experiment ended before a wide variety of different materials could be evaluated, following an electrical breakdown in the insulation between the transmission plates in the capacitor bank, on a low pressure shot.

In addition to maximizing particle acceleration, low pressure operation produced an undesirable side effect. Shots at one torr resulted in the puncture of the mylar insulation between the transmission plates on two occasions, the breakage of the pyrex insulator in the plasma focus assembly, the explosive failure of a vacuum spark gap switch, and on a number of occasions the breakage of the small pyrex insulator rings in the vacuum switches. On no high pressure shot (5 torr) did damage to the capacitor bank or plasma gun occur, except for the occasional fracture of a switch insulator ring. As a result maximum operating voltage at 1 torr was limited to 16 kV, and all the low pressure data given in this report was for this voltage. High pressure shots were all at 18 kV.

On some shots deuterated polyethylene anode inserts were used both to note any effect upon the total neutron yield, and to see if any activation of the carbon in the CD_2 occurred. No N^{13} activity was detectable on any of these shots and no increase in total neutron yields was evident. Apparently no appreciable collective acceleration (in the direction of electron flow) of ions was produced on any of these shots.

The total number of deuterons accelerated to $E \gtrapprox 330$ keV was calculated by using the thick target yield value of Amaldi[2] for the $C^{12}(d,n)N^{13}$ reaction (3.5×10^6 incident deuterons per N^{13} atom at $E_d \approx 700$ keV) and by fitting the observed angular distribution to an exponential function and integrating over the entire solid angle. The total deuteron yield is given by

$$D_{TOTAL} = \int_0^{2\pi} d\phi \int_0^{\pi/2} D(\theta) SIN\theta \, d\theta$$

where $D(\theta)$ is

$$D(\theta) = D_o \, e^{-\alpha\theta}$$

with α determined by the experimental fit. The coefficient D_o was evaluated from the thick target yield and the measured number of N^{13} atoms in the 0° target, D_1, corrected for radioactive decay to shot time. That is

$$D_1 = 2\pi\, D_o \int_o^{4.8°} e^{-\alpha\theta} \mathrm{SIN}\ \theta\ d\theta$$

where 4.8° is the half angle subtended by the zero degree target. Not all the shots produced an exponential angular distribution but the highest intensity shots did. Maximum high energy deuteron yield for a low pressure shot was 2×10^{15} (shot 1536), shot 1661 (Fig. 4) had a total yield of 7×10^{14}; the best high pressure shot (1600) had a total deuteron yield of 4×10^{13}.

The $O^{16}(d,n)F^{17}$ reaction, with an absolute threshold of 1.84 MeV, was used to look for higher energy deuterons. No F^{17} activity was detectable on any shot, but an appreciable quantity of an isotope with a half life, $t_{1/2} = 2.5 \pm .5$ min was present. Speculating that this activity was Al^{28} ($t_{1/2}$ = 2.24 minutes) a stack of two aluminum discs, each 247 milligrams thick (36 mils), and also a stack of two copper discs, each 226 mg (10 mils) thick, were placed in the target holders at minus 11° and 21°. The copper and aluminum targets, in addition to the usual carbon targets, were irradiated on shot 1914. The number of radioactive atoms corrected to shot time on the top aluminum disc was 1.64×10^6, the bottom disc was 5.0×10^5. A carbon disc placed at the same angle had 8.16×10^7 N^{13} atoms produced. The copper discs were also radioactive with a half life of 14 ± 3 minutes with the top disc having 7.5×10^5 radioactive atoms; the bottom, 3.2×10^4. The difference in activities between the top and bottom targets for both aluminum and copper suggest that a charged particle reaction was responsible for both. Also a simple calculation was made to see if thermal neutrons could produce the measured activity on the top aluminum target, and it was determined that more neutrons than the entire yield on the shot (1.2×10^{10}) would have to be thermalized and all incident upon the aluminum disc at 23 cm from the focus, to account for the observed activity.

Thus the aluminum 28 activity appears to be produced by the $Al^{27}(d,p)Al^{28}$ reaction. While this reaction has no threshold, the cross section is less than 2 mb below 3 MeV. Also to penetrate the first disc and activate the second, the deuteron energy would have to be at least 15 MeV. No good candidate was found for a reaction to explain the activity in the copper. To penetrate the first copper disc and activate the second, deuterons of 10 MeV or more would be required. These results may indicate that deuteron energies appreciably in excess of 330 keV are present, or another explanation may be found. When the experiment resumes a gamma spectral analysis will be performed on the aluminum and copper targets to positively identify the isotopes produced.

DISCUSSION

Up to 2×10^{15} deuterons above 330 keV have been produced on a single shot at low pressure. This represents approximately 100 joules of high energy deuterons, about 0.2% of the capacitor bank energy. If the ion burst is accelerated for the same duration as the electron burst that produces a 10 ns x-ray pulse, then the current of high energy deuterons on this shot was 32 kiloamps, 4% of the peak total current.

Fitting the number of high energy deuterons to a power law distribution with an exponent of 3, as suggested in Ref. 22, normalized to a total yield above 330 keV of 2×10^{-5}, the number of deuterons as a function of energy is $N_d(E_d) = 4.4 \times 10^{14} E_d^{-3}$. Assuming a lower cutoff of 50 keV the integral of this function from E_d to infinity gives the total number of high energy deuterons above any selected energy, e.g.,

E_d	$N_d(E \geq E_d)$
50 keV	8.8×10^{16}
100	2.2×10^{16}
330	2.0×10^{15}
1000	2.2×10^{14}
5000	8.8×10^{12}

Considering only those deuterons with an energy above 330 keV on shot 1536, what total neutron yield would be produced in beam target reactions? The total yield should be $Y_n = N_d N \sigma L$, where N_d is the total number of high energy deuterons (2×10^{15}), N the deuterium density at 1 torr (7×10^{16}), σ is the d-d cross section (0.1 barn at 400 keV), and L is the length of the vacuum chamber ahead of the anode (68 cm). These numbers give $Y_n = 9 \times 10^{8}$, 7% of the measured total neutron yield on this shot. This crude calculation neglects all those deuterons less energetic than 330 keV, the increased density in the focus region, and the observation made in Ref. 22 that the total path length for an accelerated deuteron can be many times the displacement from the anode. However it does show that even neglecting these points an appreciable fraction of the yield is generated by beam-target reactions.

These measurements illustrate that the plasma focus device can be operated in two distinctly different modes, with low pressure operation resulting in the acceleration of deuterons and electrons to many times the capacitor bank charging voltage. In this low pressure mode of operation energy stored inductively is converted to directed particle energy on a time scale of 10 nanoseconds or less. It may be possible to account for most of the neutron emission in the low pressure mode from beam target reactions. In the high pressure mode the neutron yield is at least a factor of 2 larger and the maximum number of high energy deuterons a factor of 35 smaller. The characteristic time scale for radiation pulses is hundreds of nanoseconds. The plasma focus device, operated in the low pressure mode, appears to be a natural inductive storage device with a microinstability-triggered fast switch, capable of delivering energy with reasonable efficiency to high intensity electron and ion beams, focused in space and time.

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FIGURE CAPTIONS

Figure 1. One hundred kilojoule plasma focus device with activation targets.

Figure 2. Plasma Focus Anode Insert. The large insert is made of tantalum. The center section, which extends through the end of the anode, is 1.27 cm in diameter and was made of copper, titanium, tungsten, tantalum, or deuterated polyethylene.

Figure 3. Comparison of hard x-ray pulses for high and low pressure operation. A 250 micron thick silicon "PIN" detector with 0.044 cm (18 mil) thick titanium filter was located 75 cm from the end of the anode, at an angle of about 5°.

Figure 4. Angular Distribution of High Energy Deuterons. Experimental data for shot 1661, a low pressure shot, is compared with an exponential distribution. The total neutron yield on this shot was 7×10^{9}. The calculated number of deuterons with energy greater than 330 keV was 7×10^{14}.

Figure 5. Angular Distribution of High Energy Deuterons. The angular distribution on this high pressure shot (5 torr) was asymmetric, peaked at 11° off axis. Total neutron yield on this shot was 2.8×10^{10}. Calculated total number of deuterons with energy greater than 330 keV was 1.3×10^{13}.

100 Kilojoule Plasma Focus Device

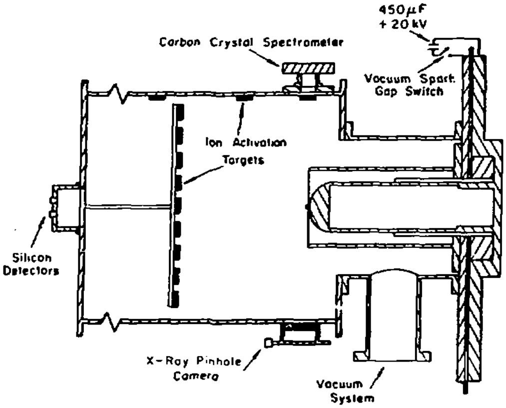
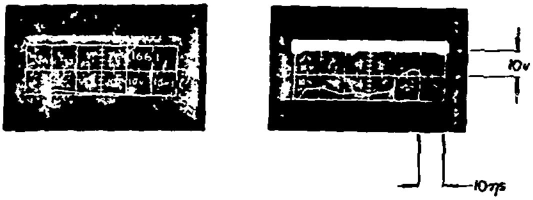


Figure 1

PLASMA FOCUS ANODE INSERT

Figure 2



Shot 1661, 1.0 torr D_2

Shot 1600, 5.0 torr D_2

COMPARISON OF HARD X-RAY PULSES FOR HIGH AND LOW PRESSURE OPERATION

Figure 3

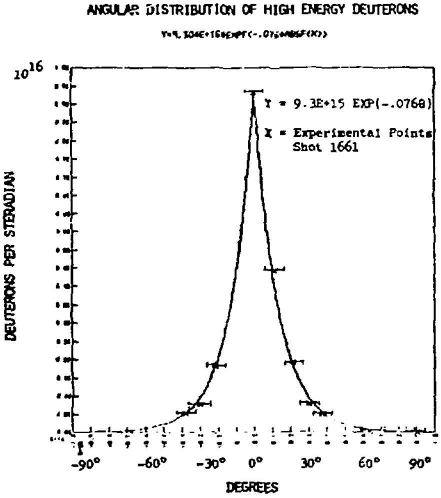

ANGULAR DISTRIBUTION OF HIGH ENERGY DEUTERONS
10^{16}
DEUTERONS PER STERADIAN
Y = 9.3E+15 EXP(-.076θ)
X = Experimental Points
Shot 1661
-90°
-60°
-30°
0°
30°
60°
90°
DEGREES

Figure 4

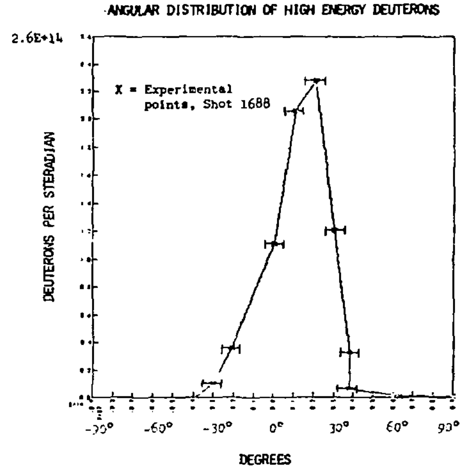

ANGULAR DISTRIBUTION OF HIGH ENERGY DEUTERONS
2.6E+14
X = Experimental points, Shot 1688
DEUTERONS PER STERADIAN
-90°
-60°
-30°
0°
30°
60°
90°
DEGREES

Figure 5

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