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NEUTRON AND X-RAY PRODUCTION IN A FOCUSED Z-PINCH

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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract F04695-67-C-0158 and documents research carried out from January 1967 through August 1967. It was submitted on 22 December 1967 to Captain Ronald J. Starbuck, SMTAG, for review and approval.

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Approved

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Ronald J. Starbuck

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Project Officer

ABSTRACT

Diagnostic studies were made of the neutrons and x rays produced by a paraboloidal geometry Z-pinch device (700 mTorr D_2, 15 kJ). The neutron energy spectra at 0 and 180 deg relative to the electric field applied at the pinch axis were obtained by nuclear emulsion techniques; they resemble the spectra obtained for linear pinches. The energy anisotropy can be explained in terms of a 90- to 130-keV deuteron beam that strikes stationary deuterons. Ross filters reveal complex x-ray spectra from 7 to 88 keV, while absorber studies reveal x radiation up to 350 keV. The spectrum from 7.11 to 29.2 keV is insensitive to neutron yield and fits the function $\omega^{-1.7}$, as does plasma bremsstrahlung from the electron energy distribution $E^{-2.2}$. The relationship between the power-law spectrum and current MHD turbulence theories is discussed. The presence of energetic x rays and fast deuterons is not consistent with the boiler model of neutron production recently proposed by the Fillipovs.

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FIGURES

I. INTRODUCTION

Pulsed high-density deuterium plasmas with kilovolt temperatures may be generated by coaxial accelerators[1,2] or metal-walled discharges.[3,4] Despite extensive diagnostic studies of such devices,[1-6] the mechanisms of neutron and x-ray production are not well understood. For example, early work at the Kurchatov Institute[3] indicated the generation of fast deuterons by an acceleration mechanism, while later work there[4] points toward a traveling thermonuclear reaction ("boiler" model), and recent work at Los Alamos[2] lends support to the model of a stationary thermonuclear reaction. This paper discusses measurements of neutron and x-ray energies that were performed in the exploration of these questions. The results of these measurements are in accord with an acceleration mechanism.

II. APPARATUS

The paraboloidal pinch geometry[7] is shown in Fig. 1. Deuterium gas fills the volume between the inner copper anode and the outer copper cathode. Closing the air gap switch introduces the voltage of the 15-kJ capacitor bank across the electrodes. A current sheet develops across the pyrex insulator at the base of the anode and is driven toward the apex of the apparatus by $J \times B$ forces. Maximum compression of the quasi-cylindrical imploding shock-front occurs 3 to 5 μsec after breakdown, in agreement with snow-plow theory.[1] A peak current of 300,000 A is achieved during the maximum compression.

Three events are observed within 50 nsec of the current peak: (1) a discontinuity in the current, (2) a burst of neutrons, and (3) a burst of x rays. Typical operation at 18 kV and 700 mTorr gives neutron yields between 5×10^7 and 10^9 n/burst with an average value of 3×10^8. The neutron yield is reduced by the substitution of a hollow, constant radius, cylindrical inner electrode containing a nuclear emulsion. The x-ray flux measured 50 cm from the 0.125-in.-thick beryllium window is 55 erg/cm^2.

III. NEUTRON ENERGY SPECTRUM

The neutron energy spectrum was measured for the purpose of identifying the mechanism responsible for the production of neutrons. The energy of the neutron in MeV from the $D(d,n)He^3$ reaction can be approximated from

$$E_n = 2.45 + 1.1E_d^{1/2} \cos\theta \qquad (1)$$

where E_d is the energy of the incident deuteron, and θ is the angle between the velocity vectors of this deuteron and the neutron. In a thermonuclear reaction, there is not a preferred direction and the resultant spatially isotropic neutron energy distribution has a maximum at 2.45 MeV. Conversely, when there is a preferred deuteron energy and direction, the observed anisotropic neutron energy distribution allows calculation of E_d from Eq. (1) if θ is known.

Moving thermonuclear reactions also produce anisotropic energy distributions.[4] The energy of a neutron produced by a translating D-D reaction is given by

$$E_n = 2.45 + 2.2E_{d'}^{1/2} \cos\theta' \qquad (2)$$

where $E_{d'}$ is the energy of a deuteron pair moving with the translational velocity of their center of mass, and θ' is the angle between the velocity vectors of the center of mass and the neutron.

The decision to use nuclear emulsions for energy spectrum measurements was based on the success other groups have had in using this technique on plasma devices.[3] Ilford K2 200-μ emulsions mounted on. 1-in. × 3-in. glass slides were positioned as indicated in Fig. 1. Each emulsion was surrounded by lead shielding with a minimum thickness of 0.3 in. to prevent x-ray fogging of the emulsion. The pinch was then fired 100 times for a total yield of 6×10^9 neutrons. (Largest single burst yield: 2×10^8 neutrons.) After development, according to the procedure outlined in the Appendix, both emulsions were scanned over 1-mm × 12-mm strips along their axes.

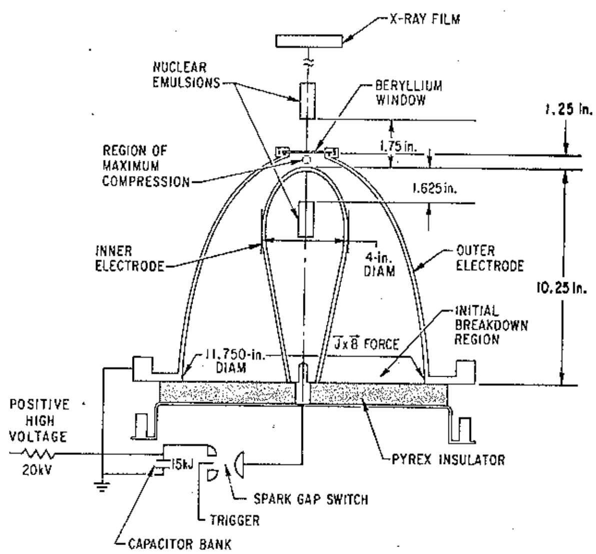

Fig. 1. Paraboloidal Pinch Geometry

The energy spectrum of recoil protons whose tracks made an angle ψ of 30 deg or less with the accelerator's axis is shown in Fig. 2 with the theoretical spectrum that would result from a monoenergetic neutron beam at 2.45 MeV. A substantial anisotropy is shown to exist in the neutron energy distribution. By assuming that the neutrons were produced on the accelerator's axis, the neutron energy is obtained from that of the recoil proton from the relationship $E_n = E_p \sec^2 \psi$. The corresponding neutron energy spectra is also shown.

The inherent experimental error is smaller in the recoil proton spectra than in the neutron spectra, due to the dependence of E_n on ψ. Neutrons that are scattered before entering the emulsion correspond to a true value of ψ which is not the same as that calculated by assuming all of the neutrons originated on the axis. However, the scattered neutrons could not gain energy in the scattering process. Since the recoil proton energy E_d depends only on the track length observed in the emulsion and is independent of ψ, the proton energies above 2.45 MeV are a clear indication that a substantial number of the neutrons produced with 0-deg velocities had energies greater than 2.45 MeV.

The measured spectra negate the possibility of neutron production by stationary thermonuclear reactions. Assuming that individual deuterons were accelerated to an energy E_d before striking stationary target deuterons allows one to estimate $\overline{E}_d$, the deuteron energy corresponding to the peak energy $\overline{E}_n$ of the neutron energy spectra. Equation (1), $2.75 \lesssim \overline{E}_n$ (0 deg) $\lesssim$ 2.85 MeV, and $2.05 \lesssim \overline{E}_n$ (180 deg) $\lesssim$ 2.15 MeV give $90 \lesssim \overline{E}_d \lesssim 130$ keV. Although the peak for the 0-deg spectrum appears to be somewhat higher than 2.85 MeV, this does not affect the conclusion that many deuterons must have been moving along the axis with energies of ~100 keV in order to produce the observed spectra.

The Fillipov model of a plasma "blob" with thermonuclear temperature that moves axially with high velocities must also be considered. The estimates of $\overline{E}_n$ and Eq. (2) give $\overline{V}_t = (2E_{d'}/M)^{1/2} = 2 \times 10^8$ cm/sec, which is a rather high velocity since it corresponds to the velocity of the "blob." X-ray pinhole camera pictures do not show the smearing that is expected from a hot plasma moving at 10^8 cm/sec.

The measured neutron and recoil proton energy spectra therefore indicate a mechanism that accelerates deuterons axially to energies on the order of 100 keV.

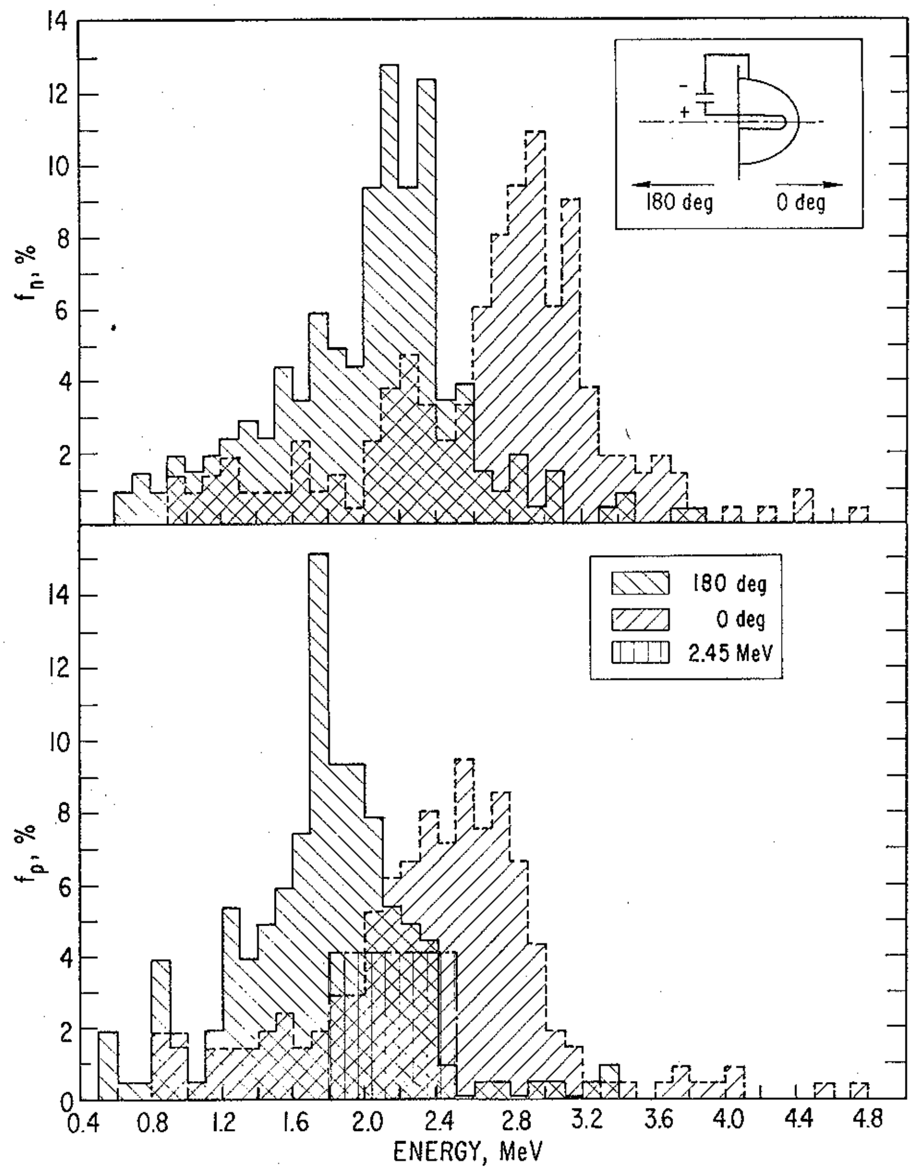

Fig. 2. Energy Spectra of Recoil Protons and Corresponding Neutron Energy

IV. X-RAY MEASUREMENTS

Preliminary x-ray measurements made using aluminum absorbers with Kodak Type F film as the detector revealed the presence of soft x rays with photon energies < 15 keV and hard x rays with energies between 29 and 41 keV. (X rays with energies higher than ~350 keV were also detected.) The intensity of the hard component was proportional to the neutron yield of the shot.

Ross x-ray filters were designed to measure the x-ray spectrum in the following intervals: 7.1 to 8.3, 8.3 to 9.0, 14 to 20, 20 to 25.5, 25.5 to 29.2, 40.4 to 67.4, and 67.4 to 88 keV. The gaps in spectral coverage occur because of the difficulty in obtaining thin foils of certain elements. During exposure, the filters and film detectors were on the device axis 53 cm from the anode.

The intensity and spectral distribution between 7.1 and 29.2 keV was not a function of neutron yield. The standard deviation of the x-ray intensity in each of the measured photon energy intervals between 7.1 and 29.2 keV was about 30%, while the standard deviation in the neutron yield was over 90%. Also, the spectrum showed no significant change when hydrogen was substituted for deuterium.

When the data from each shot were plotted, it was found that the flux in erg/cm^2-keV could be represented by $F = a\omega^{-s}$ where $\hbar\omega$ is the photon energy in keV. The composite spectrum in Fig. 3 includes data from 26 deuterium firings. This spectrum, typical of the spectra from individual shots, is described by $F = 430\omega^{-1.7}$.

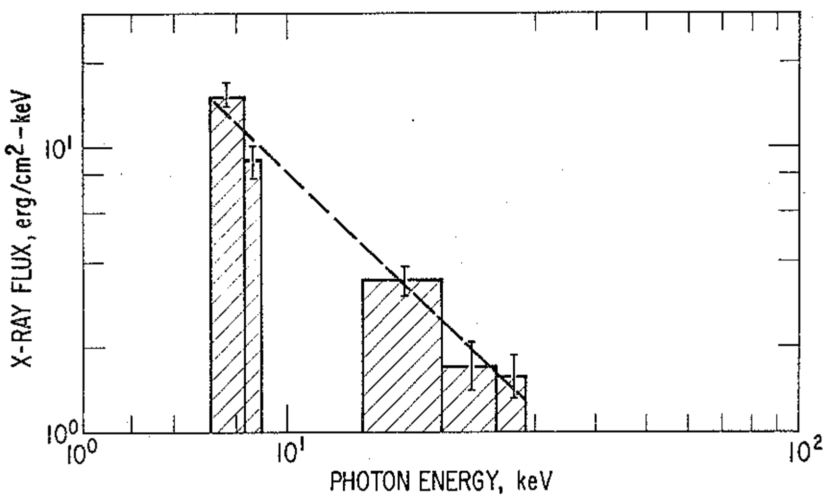

Fig. 3. Composite X-Ray Spectrum for 26 Shots at 18 and 19 keV with Deuterium at Pressures Between 650 and 780 mTorr.

Only one of the 26 shots in this series had sufficient intensity for Ross filter analysis above 29.2 keV and yielded more than 10^9 neutrons. Its spectrum differed from that of the other shots in two respects: a 45-keV radiation peak was superimposed on the ω^{-s} distribution, and the 7.1 to 8.3 and 8.3 to 9.0 keV filters detected an increase in fluorescence radiation.

A multiple pinhole x-ray camera with Ross filters was used to measure the position, distribution, and spectrum of the x-ray source. The source, a thin sheet of variable and complex structure that at times resembled a stellar nebula was located within 0.05 in. of the anode surface. The small point sources are believed to be associated with irregularities in the granular surface of the anode.

The radiation from any region of the anode surface is anisotropic with minimum intensity in the direction of the surface normal. Radiation at 45 deg is typically 3.5× greater than at 90 deg. A spectral map of the surface could not be made since the images made by pinholes with different Ross filters were at different angles relative to the anode surface.

V. DISCUSSION OF THE POWER-LAW SOFT X-RAY SPECTRUM

The ω^{-s} variation of the described continuous x-ray energy spectrum may indicate turbulent plasma heating. An electron distribution f(E) produces the bremsstrahlung power spectrum[8]

$$I(\omega) = C\int_{\hbar\omega}^{\infty} f(E)\, \log_e \left\{\left(\frac{E}{\hbar\omega}\right)^{1/2} + \left[\left(\frac{E}{\hbar\omega}\right) - 1\right]^{1/2}\right\} E^{-1/2}\, dE \qquad (3)$$

A non-Maxwellian electron distribution of the power law form $f(E) \propto E^{-\gamma}$ gives

$$I(\omega) = c'\omega^{-\gamma + 1/2}\int_{1}^{\infty} \chi^{-\gamma - 1/2} \log_e \left[\chi^{1/2} + (\chi - 1)^{1/2}\right] d\chi \qquad (4)$$

where the integral has a finite value for $\gamma > 1/2$. Comparison of Eq. (4) with the soft x-ray data ($s = 1.7 \pm 0.3$) leads to the identification $\gamma = s + (1/2)$, and, consequently, the electron distribution $f(E) \propto E^{-2.2 \pm 0.3}$.

Syrovatskii[9] has recently developed a general model for turbulent heating of electrons. This model considers a volume of high-temperature plasma with a total energy density $W_t = W_m + W_k + W_f$, where $W_m = H^2/8\pi$ is the magnetic energy density, $W_k = 1/2\, \rho u^2$ is the kinetic energy density of the turbulent background plasma, and $W_f = NE$ is the energy density of N fast particles of average energy E. A steady state is maintained if the loss of dN fast particles is compensated by an energy gain $dW_t = E\, dN$. The balance relation obtained by assuming $W_f/W_t = \epsilon$ is

$$1/\epsilon \;\; d(NE) = 1/\epsilon \;\; (E\, dN + N\, dE) = E\, dN \qquad (5)$$

which has the solution $N = CE^{-1-\delta}$, where $\delta = \epsilon/(1 - \epsilon)$ is the ratio of the fast particle energy to the remaining energy. The corresponding differential energy spectrum is

$$dN = f(E)\ dE = CE^{-\gamma}\ dE$$

where $\gamma = 2 + \delta$. At this point, Syrovatskii assumes strict equipartition of energy between the three modes and sets $\delta = 1/2$ to get $\gamma = 2.5$. This value is an excellent agreement with cosmic ray data. However, the theory of magnetohydrodynamical turbulence is presently in an uncertain state with regard to the question of energy equipartition.[10] For example, the work of Chandrasekhar[11] indicates a fine-scale mode of turbulent energy transfer for which $W_m = 2.6W_k$. This gives $\delta = (1 + 2.6)^{-1} = 0.28$ and $\gamma = 2.28$, in good agreement with the $\gamma = 2.2 \pm 0.3$ electron energy distribution inferred from the soft x-ray data.

Theories based upon general thermodynamic considerations[9] yield $\gamma = 2 + (\kappa - 1)^{-1}$, where $\kappa = 2$ or $5/3$ corresponding to two- or three-dimensional adiabatic processes, respectively, leads to $\gamma = 3$ or $\gamma = 7/2$, in apparent disagreement with the bremsstrahlung interpretation. Likewise, Kurchatov's hypothesis[12] concerning the presence of acceleration mechanisms of the Fermi type[13] leads to $\gamma = 1 + (\alpha\tau)^{-1}$, where the parameters α and τ are sensitive to local plasma conditions, contrary to the experimental observation that the spectra are quite insensitive to neutron yield. Consequently, these electron heating theories seem less appropriate than the described turbulent mechanism.

VI. CONCLUSIONS

It has been shown that the production of neutrons in the paraboloidal Z-pinch can be best described in terms of acceleration of deuterons to energies on the order of 100 keV. Plasma instabilities have been postulated by numerous investigators as the source of the electric fields that cause this acceleration.

It has also been demonstrated that models of turbulence exist that can explain the observed x-ray spectrum. The same plasma instabilities required for the acceleration of deuterons could also be the source of turbulence. It is thus concluded that under present operating conditions, a mechanism that gives rise to plasma instabilities and results in an extremely turbulent plasma, not a thermonuclear reaction, is operative.

Important questions remain unanswered. Recent x-ray absorber and Ross filter measurements have indicated a change in the spectrum as the neutron yield increases above 10^9 n/burst. Does this mean that the conclusions reached here are valid only for relatively small energy inputs and low neutron yields? What are the details of the instabilities? What are the dynamics of the pinch during all phases of the discharge and how does it differ from right cylindrical coaxial focused pinches?

All of these questions will be studied with the aid of a new device being constructed that will have a similar geometry, 5 times greater energy input, and much greater diagnostic accessibility.

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APPENDIX

NUCLEAR EMULSION PROCESSING

The following procedure, adopted from Ref. 14, was found satisfactory for the development of the 200-μ K2 emulsions.

1. Presoak in distilled water at $50^{\circ}F$ for 20 min

2. Develop in Kodak D-19 developer (diluted 1:6) at $68^{\circ}F$ for 30 min

3. Stop development by soaking in 0.2% acetic acid at $50^{\circ}F$ for 15 min

4. Fix in a solution of 300 g of sodium thiosulfate and 2.25 g sodium metabisulfate with 1 ℓ distilled water at $59^{\circ}F$ for 5.5 hr with gentle agitation (If necessary, extend the fixing time an additional 50% of the time required to clear the emulsion.)

5. Wash in flowing water at $59^{\circ}F$ for 3 hr

6. Soak in 100% glycerin at $69^{\circ}F$ for 40 min

7. Soak in 190 proof alcohol with 5% gylcerin at $69^{\circ}F$ for 40 min

8. Dry