interact with the minimum-B magnetic well to produce electron- and ion-temperature variations. The ion-temperature variation should not be sufficient to seriously effect the density measurement; however, the electron-temperature variations could have a serious effect on the potential measurements and these measurements should be treated accordingly.

These measurements demonstrate that the potential and density structures observed in the octupole are strongly correlated with the anomalous plasma loss to the wall. The measured properties of these structures indicate that they are in large part due to azimuthal asymmetry in the magnetic surfaces. These structures are likely responsible for a large part of the losses, and their elimination should greatly improve the containment time of the octupole.

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[1]D. M. Meade, Phys. Rev. Letters 17, 677 (1966).

[2]S. Yoshikawa, M. Barrault, W. Harries, D. Meade, R. Palladino, and S. von Goeler, in Proceedings of the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 403.

[3]J. A. Schmidt and G. L. Schmidt, to be published.

[4]M. Yoshikawa, T. Ohkawa, and A. Schupp, Phys. Fluids 12, 1926 (1969).

[5]H. Forsen, D. Kerst, D. Lencioni, D. Meade, F. Mills, A. Molvik, J. Schmidt, J. Sprott, and K. Symon, in Proceedings of the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 313.

[6]W. L. Harries, S. Yoshikawa, and R. W. Palladino, Phys. Fluids 12, 1115 (1969).

[7]A. W. Molvik, Bull. Am. Phys. Soc. 14, 1032 (1969).

DEUTERON ACCELERATION AND NEUTRON PRODUCTION IN PINCH DISCHARGES*

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Deuteron trajectories have been calculated for the crossed electric and magnetic fields generated by a rapidly constricting current distribution in a z-pinch discharge. The results show that many ions are accelerated to high energies with a large value for their time-averaged axial velocity. A neutron-production model based upon nuclear collisions by these deuterons easily accounts for the observed characteristics of neutron emission.

Average energy shifts of up to 250 keV were exhibited by the axially emitted neutrons from deuterium-filled linear pinches.[1-3] To explain this energy shift, a beam-target model was introduced in which linearly accelerated deuterons strike stationary ions. For example, in one analysis the deuterons are accelerated axially by the electric field generated along the neck of each $m=0$ sausage instability.[1] Presently plasma-focus types of z pinches emit more than 10^{10} d-d neutrons per discharge, and average energy shifts greater than 400 keV have been measured.[4,5] Such an energy shift corresponds to the reacting deuterons having an axial velocity averaging 2×10^8 cm/sec, which is an order of magnitude greater than the maximum velocity of the radially collapsing plasma. However, neutron-flux measurements have shown that the flux anisotropies in plasma-focus devices are much smaller than that predicted by the simple beam-target model.[5-7] This has led to the currently popular model of a moving thermal plasma, but recent observations give evidence that the neutron source is not thermonuclear.[8] In this Letter, I report a new acceleration model based on computing deuteron trajectories in a pinched plasma discharge. The resulting velocities show that many high-energy deuterons can be produced by acceleration in the crossed electric and magnetic fields generated by a rapidly constricting current distribution. Most important is the result that the deuteron velocities are not linearly directed along the axis; therefore the neutron production based on these calculated deuteron velocities is consistent with the characteristics of neutron emission.

One important assumption in these calculations is that ion-ion collisions can be neglected during the acceleration phase. This is justified since the plasma density appears to be less than 10^{20} cm^{-3} so that the usual Spitzer expression gives a collision time on the order of 10 nsec for deuterons having an energy of several keV. Electron-ion collisions are not neglected and it is assumed that the plasma resistivity becomes very significant when the plasma constricts to a radius of a few millimeters. This leads to my key assumption that within the small plasma column the current distribution undergoes a rapid transition from a boundary concentration to an axial concentration. The generation of very hard x rays at the right time indicates that such a transition does take place.

For this model, I assume an axisymmetric, radially varying current density $j(r, t)$ which is axially uniform. Then from Maxwell's equations in cylindrical coordinates, we have only azimuthal and axial components for the magnetic field B_θ and electrical field E_z, respectively. A convenient current distribution, which represents both a contraction and a transition to an axial concentration, is the following one:

$$j(r, R) = j_a + (j_b - j_a)(r/R)^\alpha, \quad 0 \leq r \leq R,$$

where j_a is the current density on axis, j_b is the current density at the boundary R, and the constant $\alpha > 0$. The discharge current (about 700 kA) is assumed to be confined within this boundary and I have further assumed that j_b remains constant during the contraction while j_a increases from an initial value of zero in such a manner as to conserve the total current. The time dependence is introduced by a constant velocity for the boundary $dR/dt = -V_R$. Radial distributions of current density, magnetic field, and electric field are shown in Fig. 1 for two different times, assuming $\alpha = 1$.

In these computations of ion trajectories, I assumed motion to be only in the r-z plane; motion in the θ direction enters the calculations only when collisions are considered and would not alter the important aspects of the results. Under this assumption, Newton's equation reduces to two simultaneous linear equations which were solved on a computer to obtain the trajectories. Just before maximum plasma compression, the plasma boundary has a velocity of about 3×10^7 cm/sec and I assumed that collisions produced a random distribution of ion velocities, many of which were greater than 4×10^7 cm/sec. Corresponding to the rise time of the neutron production and other observations, suitable values for the initial radius and velocity of the boundary were 5 mm and 3×10^7 cm/sec. However, the results did not vary greatly when other reasonable values were used.

The trajectories of the accelerated ions can be divided into two categories: (case I) those which do not reach the axis, and (case II) those which reach the axis and oscillate back and forth through the axis. Figure 2 illustrates these two trajectories. In actuality, because of three-dimensional motion, no trajectories will pass exactly through the axis. But this division in two dimensions serves to illustrate how the electric field accelerates different ions. For the representative pair of examples shown in Fig. 2, we display in Fig. 3 the time histories of the positions and velocities. The initial positions and energies (2 keV) were the same for both ions, but their axial velocity components were initially oppositely directed. In case I, a deuteron gains considerable energy within a fraction of a gyro-orbit and then gradually gains more energy during subsequent orbits. We find case II to be far more interesting, though, for then the energy gain on succeed-

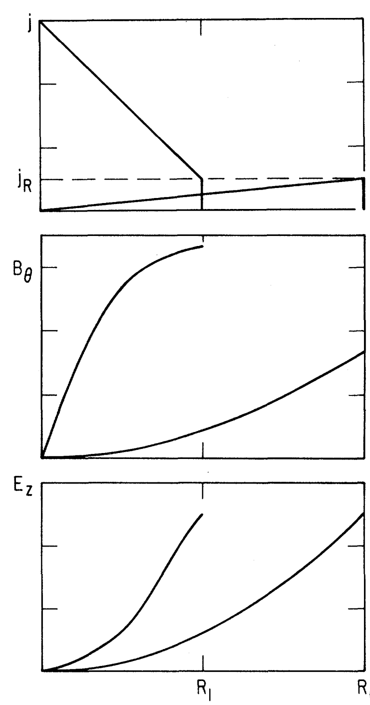

FIG. 1. Radial dependence of current density $j(r, R)$, magnetic field $B_\theta(r, R)$, and electric field $E_z(r, R)$ for initial boundary R_0 and at later time, $R_1 = \frac{1}{2}R_0$. Arbitrary linear scales.

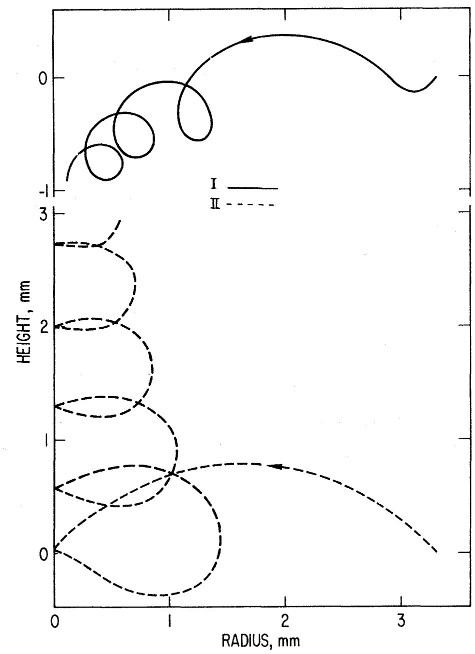

FIG. 2. Deuteron trajectories for two cases of ion acceleration. Reflections from $r=0$ in case II represent passage through the axis.

ing orbits is much greater. Even more important is the fact that these ions not only reach very high energies, but their average axial velocity reaches a very high value. Discontinuities in the plot of the radial velocity occur when the trajectory passes through the axis. As already mentioned, consideration of the azimuthal motion of the ion would give a similar motion, but without the sharp discontinuities in the plots. The orbiting motion of the ions in the first case is probably typical for most of the ions during the earlier stages of the plasma collapse regardless of the distribution of the current density. Notice that these ions exhibit a $\vec{B}\times\nabla\vec{B}$ drift in a direction opposite to the electric field force.

The calculated trajectories for different initial velocities and positions indicate that a small but significant fraction of the plasma deuterons are accelerated to very high energies with a large axial velocity. Consequently, the observed neutron emission most likely comes from collisions between these ions and low-energy ions. This is not a beam-target model in the usual sense, because the ion velocities are not directed but are constantly changing in the magnetic field. Thus, in fusion collisions, the center-of-mass velocities have large axial components but the relative collision velocities are randomly oriented. This would account for the observations of a relatively

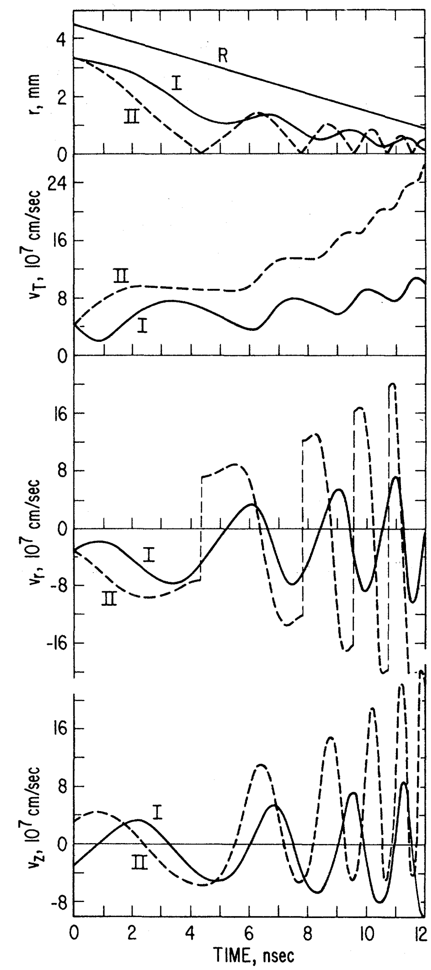

FIG. 3. Time dependence of ion radius r, total velocity v_T, radial velocity v_r, and axial velocity v_z for two cases of ion acceleration. Energy proportional to v_T^2. Discharge current I is 700 kA.

isotropic neutron emission as compared with the anisotropy expected for a linear beam-target model. To account for the measured spectrum of neutron energies, the high-energy deuterons would need axial velocities ranging up to 6×10^8 cm/sec and the ion energies would be as high as 400 keV. My calculations show that some deuterons can reach these high energies within 20 nsec, corresponding to the observed rise time of the neutron pulse. Estimates on the fraction of ions which could be accelerated to very high energies range from 1 to 10% of all the ions in the plasma column. If we assume an average ion density in the column of 3×10^{19} cm^{-3} and an average energy of 150 keV for the accelerated deuterons, then a beam-target model with an ion current of about 50 kA will give a neutron yield of 10^{10}. This represents less than 10% of the total discharge current and about 0.3 % of the total ion number in the dense column. Now when the orbiting motion of the ions is also taken into account, the current due to these accelerated ions will be appreciably smaller than the above value.

The ion accelerations achieved with various current distributions will be discussed in a future publication along with more details on the neutron production.

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[1]O. A. Anderson, W. R. Baker, S. A. Colgate, J. Ise, Jr., and R. V. Pyle, Phys. Rev. 110, 1375 (1958).

[2]A. M. Andrianov et al., in Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy (United Nations, Geneva, Switzerland, 1958), Vol. 31, p. 348.

[3]J. W. Mather and A. H. Williams, in Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy (United Nations, Geneva, Switzerland, 1958), Vol. 32, p. 26.

[4]D. A. Meskan, H. L. L. van Paassen, and G. G. Comisar, in Proceedings of the Conference on Pulsed High Density Plasmas, Los Alamos Scientific Laboratory Report No. LA-3770 (unpublished).

[5]M. J. Bernstein, D. A. Meskan, and H. L. L. van Paassen, Phys. Fluids 12, 2193 (1969).

[6]N. V. Filippov, T. I. Filippova, and V. P. Vinogradov, Nucl. Fusion: Suppl. Pt. 2, 277 (1962).

[7]P. J. Bottoms, J. P. Carpenter, J. W. Mather, K. D. Ware, and A. H. Williams, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. II, p. 67.

[8]M. J. Bernstien and F. Hai, to be published.

TRANSPORT PROPERTIES OF CHROMIUM THROUGH THE NÉEL POINT

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We have measured precisely the transport properties of a pure polycrystalline specimen of chromium, with a residual resistivity ratio of 380, from 300 to 320 K. We have found no evidence whatsoever for the 5% peak in the thermal conductivity recently reported by Meaden, Rao, and Loo.

In a recent letter, Meaden, Rao, and Loo[1] (henceforth referred to as Meaden) have reported their measurements of the thermal conductivity of a specimen of chromium, with a residual resistivity ratio of 178, which showed a peak at 313.5 K of about 5 %. Previous work, done by a group at the Oak Ridge National Laboratory[2] (ORNL), on two different specimens of chromium with residual resistivity ratios of 58 and 280 showed no such peaks, a failure which Meaden somewhat gratuitously ascribes to a lack of precision. In an attempt to resolve this discrepancy, we have borrowed the purer of the two specimens from ORNL. Its properties were fully characterized before[2]; since then, however, it has undergone extensive annealing (4 days at 1100 K, followed by 1 day at 1200 K), and its residual resistivity ratio increased from 280 to 380, which is more than twice as large as the value reported by Meaden for their specimen. Briefly, the results that we have obtained for this specimen in its annealed condition confirm none of the "peaky" features reported by the latter, and elsewhere, by Meaden and Sze.[3]

Two separate experiments were performed on the specimen. In the first, we determined very precisely its electrical resistivity through the Néel point in an oil bath used for the calibration of platinum resistance thermometers. The temperature of the oil bath was uniform and stable to within 1 mK, and was measured with a primary standard resistance thermometer to ±1 mK. The electrical resistivity was measured by a precise ac technique[4] at 7 Hz to eliminate any possible errors stemming from the high thermoelectric power of chromium, which could easily affect dc measurements.[5] The absolute accuracy of our measurement was ±0.2 % and the precision ±0.003 %. There was no discernible frequency effect within that precision.

The results of this experiment are shown by a solid curve in Fig. 1. This curve, taken on a heating cycle, was synthesized from 68 points, none of which departed from the smooth curve by more than the imprecision of the measurements.[6] The cooling curve coincided with the heating curve above the Néel point, but below it was somewhat lower, about 0.15 % at 300 K.

The specimen was then mounted in a thermal conductivity apparatus described elsewhere in