A Neutron-Producing Mechanism in Transverse Pinches*

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Experiments performed on a transverse pinch assembly show that the presence of a longitudinal magnetic field inside of a conducting plasma and in the reverse direction to that of the external pinching field results in the generation of the $m=0$ (sausage) instability mechanism. This instability mechanism can generate high electrical fields which will accelerate deuterons to energies sufficient for neutron production in deuterium plasmas. Subsequent to the blowup of the instability, the plasma-field configuration is such that the accelerated deuterons can continue to circulate in stable orbits until lost by neutron-producing collisions or by diffusion out of the ends of the geometry.

ONE of the most attractive plasma containment configurations, by virtue of its neutral stability characteristics, is the transverse pinch in which a longitudinal magnetic field is generated external to a conducting plasma and employed in compressing and heating it. During the past three years extensive investigations[1–3] have been made on configurations of this general design. Characteristic with the high-power philosophy followed in fusion research, large high-energy condenser banks have been discharged through single-turn solenoids surrounding cylindrical columns of deuterium gas. The magnetic field configurations employed have been cylindrical, Helmholtz, and mirror. Longitudinal bias magnetic fields, either parallel or antiparallel, have sometimes been included in the plasma prior to the main discharge. The plasma is usually preionized to varying degrees by axial shock heating, rf ionization, or low-power pulsed longitudinal or transverse discharges.

The accepted criteria for the proper performance of these assemblies has been a high neutron yield. Neutrons, when produced in these configurations, occur near the peak of the sinusoidal field drive when there exists an antiparallel magnetic field within the plasma. Various explanations as to the production mechanism include thermonuclear reactions at fusion temperatures, heating due to field mixing, two-stream instabilities, etc. The detection of high-energy ($\sim$6–900 kev) x rays in Scylla[4] during neutron production time would seem to rule out true fusion temperatures.

The most consistent explanation, based on analysis of smear photographs, image converter snapshots, and magnetic probe signals obtained on a transverse pinch assembly, is that the accelerating action of the high electrical fields generated by the formation of $m=0$ (sausage) instabilities[5] can produce both neutrons and high-energy x rays. These same instabilities have been generated along with consequent neutron bursts in longitudinal pinches.[6–8] The field-trapping mechanism leading to these instabilities has been suggested by Samain *et al.*[9] The illustrations shown in Fig. 1 depict the origin and growth of the instability mechanism in a transverse pinch when a trapped reversed magnetic field is present. If one starts with a plasma and longitudinal magnetic field mixed as shown in (a), the application of an external magnetic field in the opposite direction will cause the internal field and plasma to form the configuration shown in (b) with surface currents as indicated generated on the plasma surface. If the solenoidal field is cylindrical and extended, this configuration will remain quasi-static except for pos-

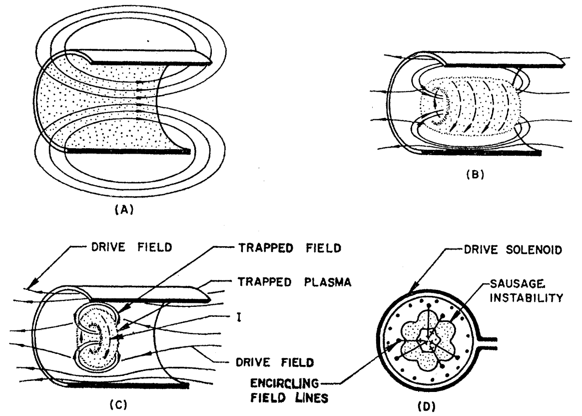

FIG. 1. Development of trapped plasma and field configuration leading to the growth of $m=0$ (sausage) instability.

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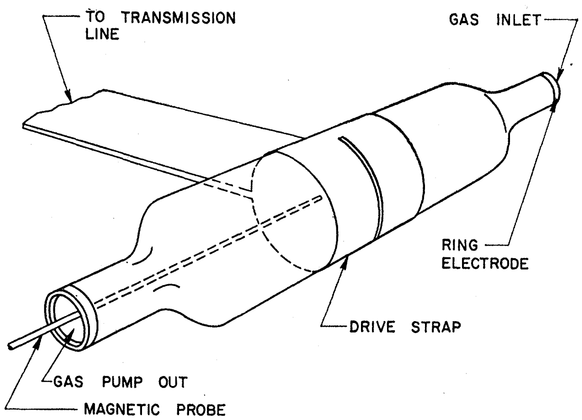

FIG. 2. Schematic diagram of discharge tube.

sible flute-like perturbations along the inner and outer surfaces. However, the encircling field lines will eventually deform to the configuration shown in (c). Mirrors or a Helmholtz-type drive will cause this configuration to form more rapidly. This plasma ring shown in (c) has the same magnetic field and current configuration as a linear torodial pinch (Perhapsatron, Zeta, Sceptre, etc.) and is subject to sausage-like ($m=0$) instabilities shown in (d), [the end view of (c)]. In this configuration, neutrons will be produced if sufficiently high electrical fields are generated by LdI/dt due to the plasma choke-off between sausages. In addition, when the current is interrupted by this choke-off action, the field on axis is cancelled and the external field can penetrate this nonconducting ring of sausages, thus accounting for the sudden field reversal observed by use of on-axis magnetic probes.

In longitudinal pinches (Columbus, etc.) deuterons will be accelerated by this instability mechanism and can produce neutrons before being lost to the end electrodes or, drifting to the walls due to field curvature in the case of longitudinal pinches in a torus. Neutrons will occur in bursts accompanying each instability blowup. This instability can form several times during the rising current cycle in longitudinal pinches, and has been adequately explained by Colgate.[10] In the present geometry, the instability blowup is accompanied by the cancellation of the trapped field resulting in a complete intermixing of plasma and external field. However, the deuterons accelerated by the instability mechanism can continue to circulate in stable orbits produced by the longitudinal field until lost by collisions. Thus, the neutron production time can be greater than the instability blow-up time. The use of sinusoidally varying magnetic fields undoubtedly further complicates the plasma dynamics.

Studies showing this plasma behavior have been made on an assembly using a 0.28-ohm transmission line energy source to drive a transverse pinch. The line, when charged to 18 kv, furnishes a 60 000 ampere pulse 10 μsec long with a rise time of 0.75 μsec to a single-turn solenoid 10 cm i.d. by 15 cm long enclosing a Pyrex cylinder filled with deuterium gas.[11] Figure 2 shows a schematic diagram of the assembly used. A linear discharge is used to pre-ionize the gas prior to the main discharge and *no* parallel field is present at the beginning of the transverse pinch. Consequently, the configurations shown in Fig. 1 form during the second 10-μsec reverse current period, the necessary reverse field remaining from the first 10-μsec period. On-axis (2 cm from solenoid mid-plane and viewing port) magnetic probe traces taken at vacuum, 25 microns, and 100 microns are shown in Fig. 3. During the first 10-μsec period, the drive field, although initially excluded from the plasma due to its conductivity, penetrates to full vacuum field near the end of the period. When the drive field reverses, this on-axis field decreases to near zero, then rises to and oscillates around a high value for a limited time, finally reversing suddenly to $\sim$ the full vacuum field of the drive. The disappearance of this trapped magnetic field has been ascribed to field mixing and annihilation, and also described as an artifact dependent on the presence of an internal probe.[12] One would expect that field mixing (if it can occur in this geometry) would be slower and annihilation would occur later in the case of the higher conductivity gas. Experiments show, in the case of the higher conductivity 25-micron pressure, that the annihilation occurs earlier and is more compatible with the observed instability growth rates and faster choking off of the plasma obtained with the higher pinch velocities at lower densities. Further, in these experiments, annihilation of the trapped field occurs when no probe is in the plasma to cool it. Figure 3(d) shows overlays of the fringing magnetic field outside of the solenoid with and without the plasma. Here, the effect of the trapping is to reduce the fringing field until the

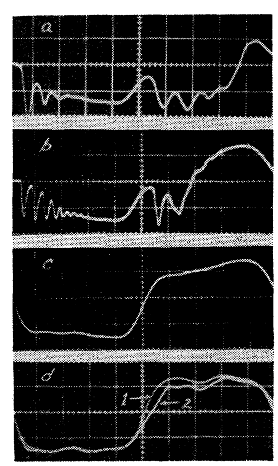

FIG. 3. Scope traces (2 μsec/cm) of (a) on-axis B_z, 100μ D_2 (b) on-axis B_z, 25μ D_2, (c) on-axis B_z, vacuum, and (d) fringing B_z for (1) vacuum and (2) 100μ D_2.

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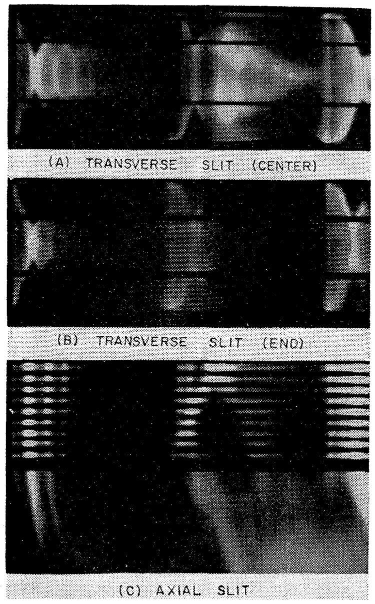

FIG. 4. Smear photos showing plasma escape during first 10-μsec interval and plasma trapping during second 10-μsec interval.

trapped field disappears, at which time the fringing field increases to full vacuum value.

Smear photos taken through a transverse slit (a) at the center of the solenoid and (b) at the end of the solenoid, and a smear photo of an axial slit extending from the solenoid center to 8 cm outside of the solenoid are shown in Fig. 4. Here, during the first 10-μsec current period, plasma appears to be ejected at high velocity in multiple bursts. During the second reverse current period, however, after the trapping configuration is formed, no external luminosity is visible until the sudden field reversal, thus confirming the plasma-trapping action of the internal reverse field. The axial slit smear also shows rapid ejection of plasma during the first period but a reverse motion inside of the solenoid during the second period, confirming the rapid transformation of the plasma cylinder into a plasma

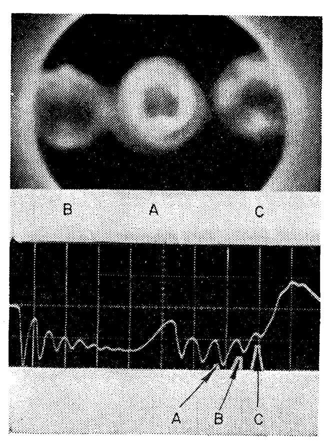

FIG. 5. Image converter snapshots of trapped plasma ring with trace showing timing.

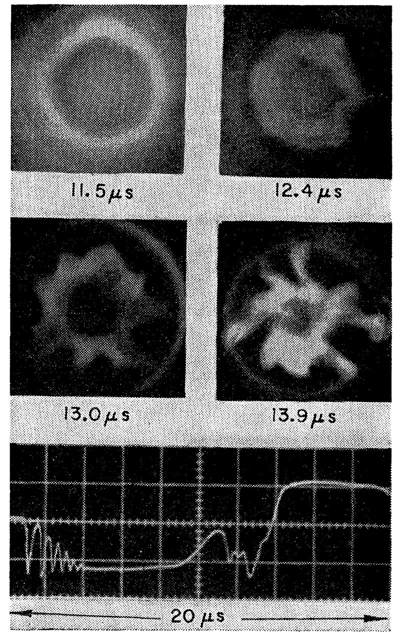

FIG. 6. Kerr cell photos showing growth of instability and plasma blowup.

doughnut as postulated in Figs. 1(b) and (c). Only the fringing magnetic field was monitored in these experiments and *no* internal probes were in the discharge region.

Finally, image converter framing camera snapshots taken looking along the axis of the discharge tube show patterns similar to those in Fig. 1(d). These patterns vary from flute-like to sausage depending on the time of observation, with the sausage configuration in evidence immediately prior to trapped-field cancellation. Typical examples are shown in Fig. 5 along with an indication of their time of appearance. Figure 6 shows 0.1-μsec Kerr cell photos taken on successive discharges along with the indicated viewing times and a representative on-axis B_z probe signal. The shot-to-shot reproducibility permits viewing the instability growth and plasma blowup at various stages.

While this mechansim is possibly of interest as a heating mechanism since it does give energy to the ions, the small number accelerated, and the uncertainties in the energy to which the ions are accelerated and in the plasma density and composition would make this heating mechanism uneconomical unless it can be controlled and programmed. In the experimental assembly studies here, a more desireable plasma containment configuration is generated during the first compression cycle, starting with a field-free conducting plasma of known density and composition. A plasma in this configuration would be subject only to neutrally stable flute instabilities or Taylor instabilities, and it is theoretically possible to control these by orthogonal ac fields.[13] The major containment effort would of necessity be in capping the geometry ends.

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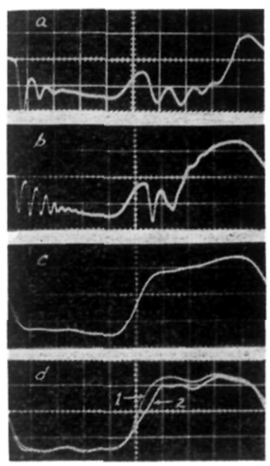

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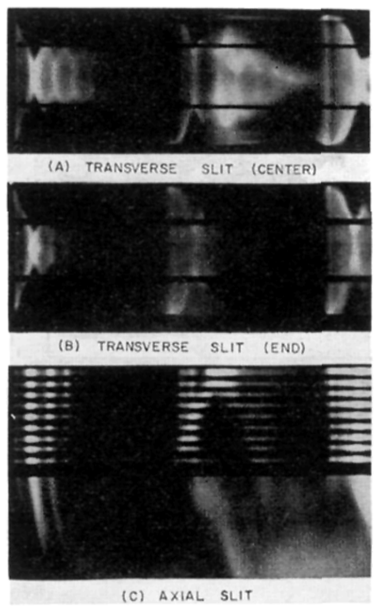

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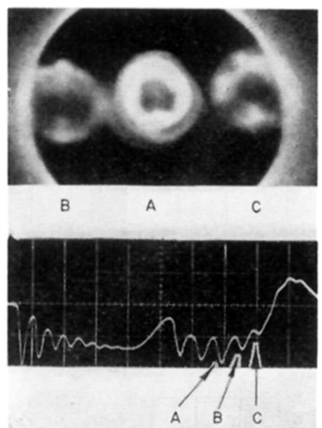

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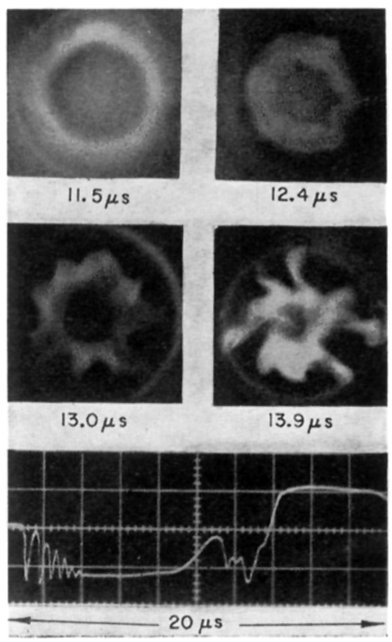

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