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THE HARD-CORE PINCH. II

D.H. Birdsall, S.A. Colgate, and H.P. Furth

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D.H. Birdsall, [*]S.A. Colgate, and H.P. Furth

Lawrence Radiation Laboratory, University of California
Livermore, California, U.S.A.

ABSTRACT

The toroidal version of the hard-core pinch tube is created by levitating a ring conductor inside a toroidal shell. The magnitude of induced $\underline{H_\theta}$ necessary for levitation is small in terms of field strengths normally desired for energetic pinches. In a 3-in. glass-and-copper toroid of square cross section, a 3/4-in. hollow copper ring has been levitated with a 60-cycle current of 3 kiloamperes. A 12-in. stainless steel tube of round cross section is being built.

The stability of near-vacuum field hard-core configurations is best investigated in toroidal geometry. At high power levels and low plasma densities, the conventional toroidal "stabilized pinch" is subject to an anomalous plasma energy leakage to the wall, which cannot be explained by the observed ultraviolet radiation alone. A critical question is, therefore, whether the relative stability of some hard-core pinches, as reflected by the smoothness

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[†] This work was performed under the auspices of the U.S. Atomic Energy Commission.

[*] Paper to be presented by this author (Colgate).

and reproducibility of magnetic probe traces, is reflected by an improved containment of the plasma energy leading to high temperature.

A toroidal hard-core tube is also useful in studying the nature of the nonhydromagnetic instabilities observed in the linear "inverse stabilized pinch". The presence and condition of electrodes appear to have a substantial effect on the magnitude of these instabilities, as would be expected if they were, for instance, of electrostatic origin.

In order to complement the plasma study of the hard-core pinch, we have developed an analogue method using sodium tubes to simulate the current-carrying layer. In this way the purely hydromagnetic aspect of the plasma behavior can be isolated.

1. Introduction

A toroidal pinch has two major virtues through which it may yield information additional to what can be obtained from the analogous linear pinch, namely, increased symmetry and improved plasma-energy containment.

The degree of symmetry in a toroidal configuration is higher, in the sense that uniformity must exist along the discharge column, due to the geometry. In a linear discharge there are special effects occurring at the electrodes, and there may also be an anode-cathode asymmetry. This possibility is illustrated by Fig. 1, which presents magnetic probe traces taken on our linear hard-core tube (cf. Fig. 1 of ref. 1) with an axially oriented glass probe inserted through a hole in one electrode, 11 cm out from the tube axis. The configuration studied is the conventional "stabilized pinch". The $\underline{H_z}$ field is seen to rise initially and then to drop again as the current-carrying front sweeps by. The sharpness of the front has been found consistently greater near the cathode than near the anode, under a wide variety of conditions, including, of course, tube voltage and $\underline{H_z}$ field reversal. In addition, one notes the presence of small, erratic oscillations near the cathode only. At higher power levels, these high-frequency disturbances grow mainly near the cathode, while much larger disturbances of lower frequency occur towards the anode. If these disturbances are produced or propagated by an electron flow phenomenon, a linear discharge can be expected to have quite different symmetry properties from a toroidal one.

The second major difference between linear and toroidal pinches relates to the containment of plasma energy. From a toroidal pinch, energy can leak only in the form of radiation or particle convection across the magnetic field. It has been shown experimentally in the case of a "stabilized pinch" losing 500 eV per particle per μsec during its first quarter cycle[2] that the observed vacuum ultraviolet radiation power is quite inadequate to account for the loss rate. One suspects, therefore, that an anomalous particle transport effect, presumably involving energetic electrons, appears at high power levels, by virtue of the small-scale pinch instabilities. The further study of this mysterious leakage phenomenon promises to contribute new theoretical insight into the general problem of plasma containment.

2. The "Levitron"

A toroidal ring conductor can be levitated inside a toroidal conducting shell (Fig. 2) by induction of a transient or alternating current. The magnitude of induced H_θ required to levitate such a ring core in typical cases of practical interest is considerably smaller than the magnitude of H_θ that is desirable for plasma-containment purposes. Specifically, the balance magnetic field $H_{\theta b}$ at the core is given by

$$H_{\theta b}^2 = (2\pi/\Delta r)\rho g(R^2 - r_0^2),$$

where R and r_0 are the tube and core radii, Δr is the displacement from center due to gravity, ρ is the mass density of the core, and g is the gravitational acceleration. For a copper core of 5 cm radius inside a tube of 15 cm radius, $H_{\theta b}$ = 2000 gauss for Δr = 2.5 cm.

The theory has been well confirmed by means of several preliminary models. The largest of these contains a 3/4-inch diameter hollow copper core in a 3 × 3 inch toroidal shell of square cross section. Levitation can be achieved with 3 kiloamperes rms (60 cycle), and 6 kiloamperes suffice to center the core within 10%. The toroid is lined with a glass and Micalex vacuum chamber. For pinch experimentation, both 60-cycle and pulsed levitating currents can be used. A larger discharge tube, with a 12-inch diameter stainless steel liner and a 4-inch diameter core, is being prepared.

The Levitron affords the possibility of starting with a large Stellarator-like vacuum magnetic field (initial $\underline{H}_z$ being added to the levitating $\underline{H}_\theta$) and then superimposing an arbitrary plasma current density $\underline{j}_\parallel$ along magnetic field lines. Since a wide range of such near-vacuum field pinches have theoretical hydromagnetic stability, and since their linear analogues have been found to yield stable magnetic probe signals,[1] there will be considerable interest in studying the dependence of plasma energy leakage on $\underline{j}_\parallel$.

The fundamental time constant of the Levitron is set by the resistive decay of the current circulating in the toroidal core. Since copper has a conductivity corresponding to deuterium plasma of 1 KeV temperature, the time constant of the Levitron does not impose a serious limitation on present-day pinch experimentation and is also compatible with burnup times of useful thermonuclear plasmas, should these prove realizable in the future.

The question naturally arises whether it would not be much simpler and almost equally effective to suspend the ring core of the Levitron by means of small wires,[†] which incidentally would serve to create the current in the core.

[†]The use of a ring core suspended from wires to produce a poloidal ($\underline{H}_\theta$) vacuum field for particle containment is discussed in ref. 3.

This question has been considered at some length in a preliminary report.[4] Our tentative conclusion is that, while current lead-in wires can be shielded to some extent by their own magnetic field, there are always traces of null magnetic field, extending indefinitely outward from the core, or regions of dubious stability, or both. Such arrangements seem unsuitable if the object is to create a pinch configuration of high symmetry, or one where energy-leakage rates are to be studied rigorously.

3. Sodium Analogue Experiments

A number of sodium experiments have been initiated with a view to isolating the purely hydromagnetic aspect of pinch phenomena, and perhaps gaining some insight into nonlinear hydromagnetic effects, which are difficult to calculate. A technique has been developed, using rf magnetic fields, liquid sodium, and an oil of comparable specific gravity, to create and study equilibrium configurations. The hard-core configuration, where internal $\underline{H_\theta}$ pressure is balanced against external sodium pressure, has been tried and found stable, unless the rf is applied in bursts, in which case $\underline{m} = 0$ instabilities can be made to develop.

A second technique makes use of a solid sodium sheath, which is formed by high pulsed magnetic fields. This technique has been tried, first of all, on a conventional "stabilized pinch" (Fig. 3). A uniform $\underline{H_z}$ is generated by an external coil, and then a large current is passed through the electrodes and the cylindrical sodium tube. The pressure of the fields far exceeds the mechanical strength of the solid sodium, so that the tube is compressed and flows radially inward, compressing the entrapped axial field, provided the tube remains intact. The dynamic compression time at the highest fields is small (100 μsec) compared to the resistive decay time of the entrapped axial field (a few milliseconds). This is even more true of the time for Alfvén speed traversal of the layer (20 μsec). Thus there is ample time for instabilities to grow under conditions of equilibrium and high conductivity.

The initial experiments were primarily concerned with the time scale and manner of the breakup of the current-carrying layer by the interchange instability. Consequently, the most interesting experimental pinch configuration was one which was expected to be stable against the gross $\underline{m} = 0$ and $\underline{m} = 1$ modes, but contained a zero in shear (radial logarithmic derivative of the pitch of magnetic field lines) within the current-carrying layer. Accordingly, a pinch ratio close to unity (1.16) was chosen (Fig. 4). During single pinches the situation remained stable, and the sodium tube was re-expanded symmetrically to the outer wall. In one case a second pinch was attempted, leading to escape of the trapped $\underline{H_z}$ during the pinch cycle and conversion of the sodium tube into a "rope" (Fig. 5). The helical slot in the rope, somewhat obscure in the photograph, extends along its full length. The slow growth rate and narrow width of the slot may be interpreted in terms of an interchange instability. By way of comparison, the same breakup was observed to take place in 1/2 the time, during a single pinch cycle, when twice the original magnetic field strengths were used. A pinch equilibrated by internal gas pressure (without axial magnetic field) broke up in less than 1/40 the time. A hard core version of the sodium analogue is being built, and may permit verification of the expected hydromagnetic stability of the "inverse stabilized pinch" in a situation free from the possibility of more complex instabilities.

References

1. D.H. Birdsall, S.A. Colgate, and H.P. Furth, "The Hard-Core Pinch. I", a paper presented at this conference by H.P. Furth. This paper is also Lawrence Radiation Laboratory report No. UCRL-5599, July 1959.
2. S.A. Colgate, J.P. Ferguson, and H.P. Furth, "The Stabilized Pinch", Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, Paper No. 369.
3. B. Lehnert, "Confinement of Charged Particles in a Magnetic Field", Nature 181, 331 (1958).
4. S.A. Colgate and H.P. Furth, "Small-Scale Instabilities of the Pinch and a Suggested Remedy — The Levitron," Lawrence Radiation Laboratory report No. UCRL-5392, November 1958.

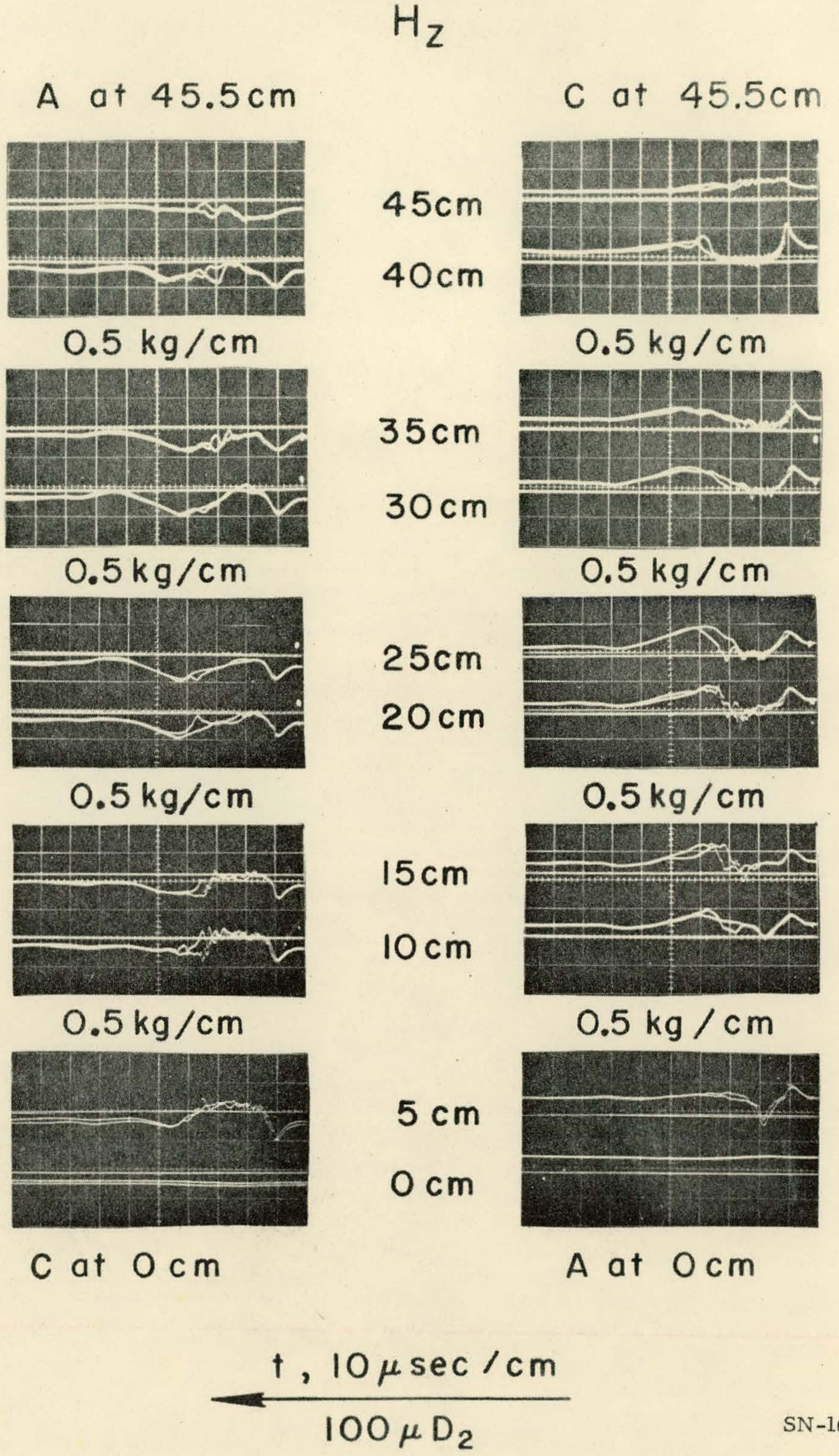

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Fig. 1. Magnetic probe traces in linear pinch tube, showing anode-cathode asymmetry, which is preserved when tube voltage and $\underline{H_z}$ is reversed.

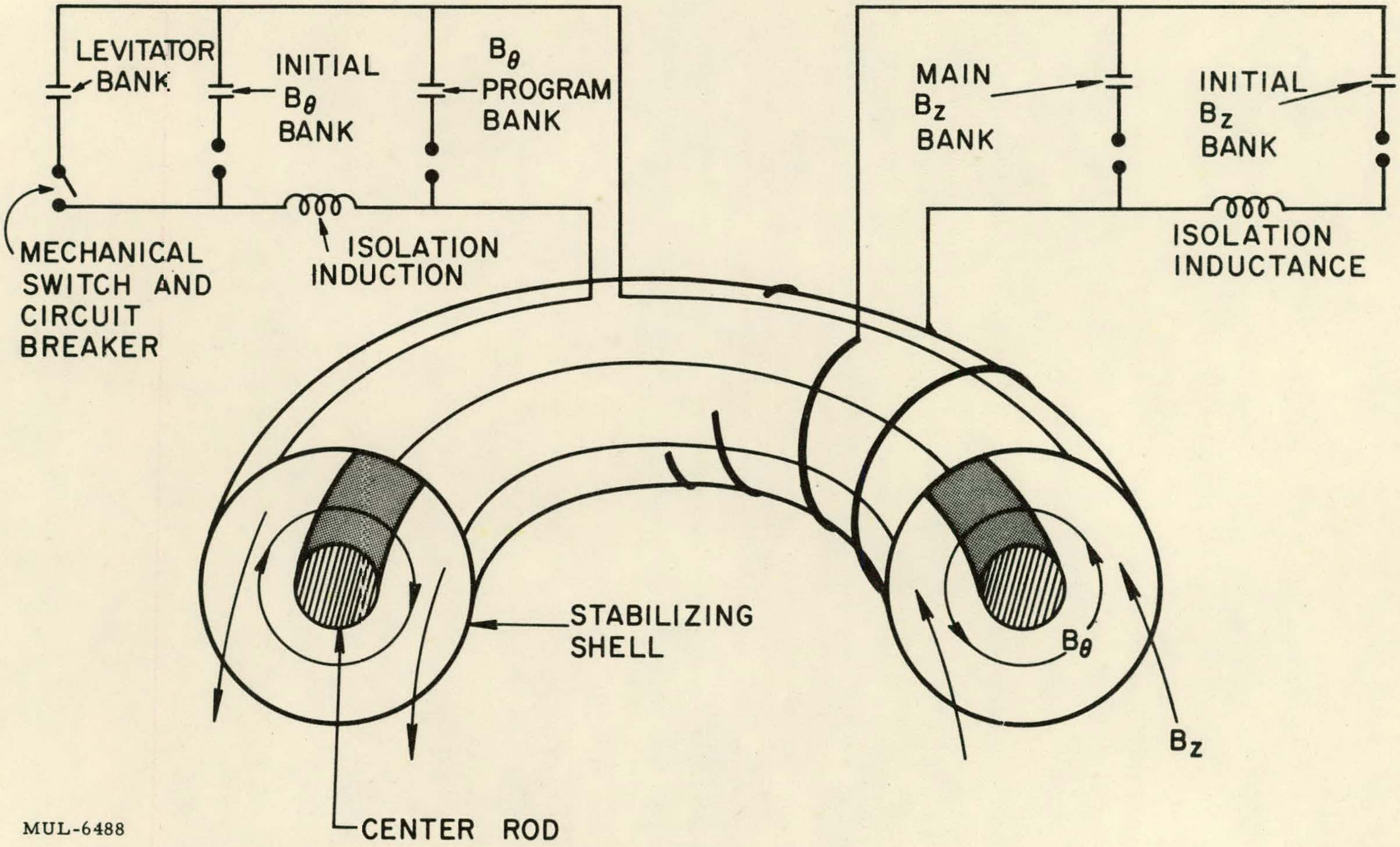

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Fig. 2. The Levitron.

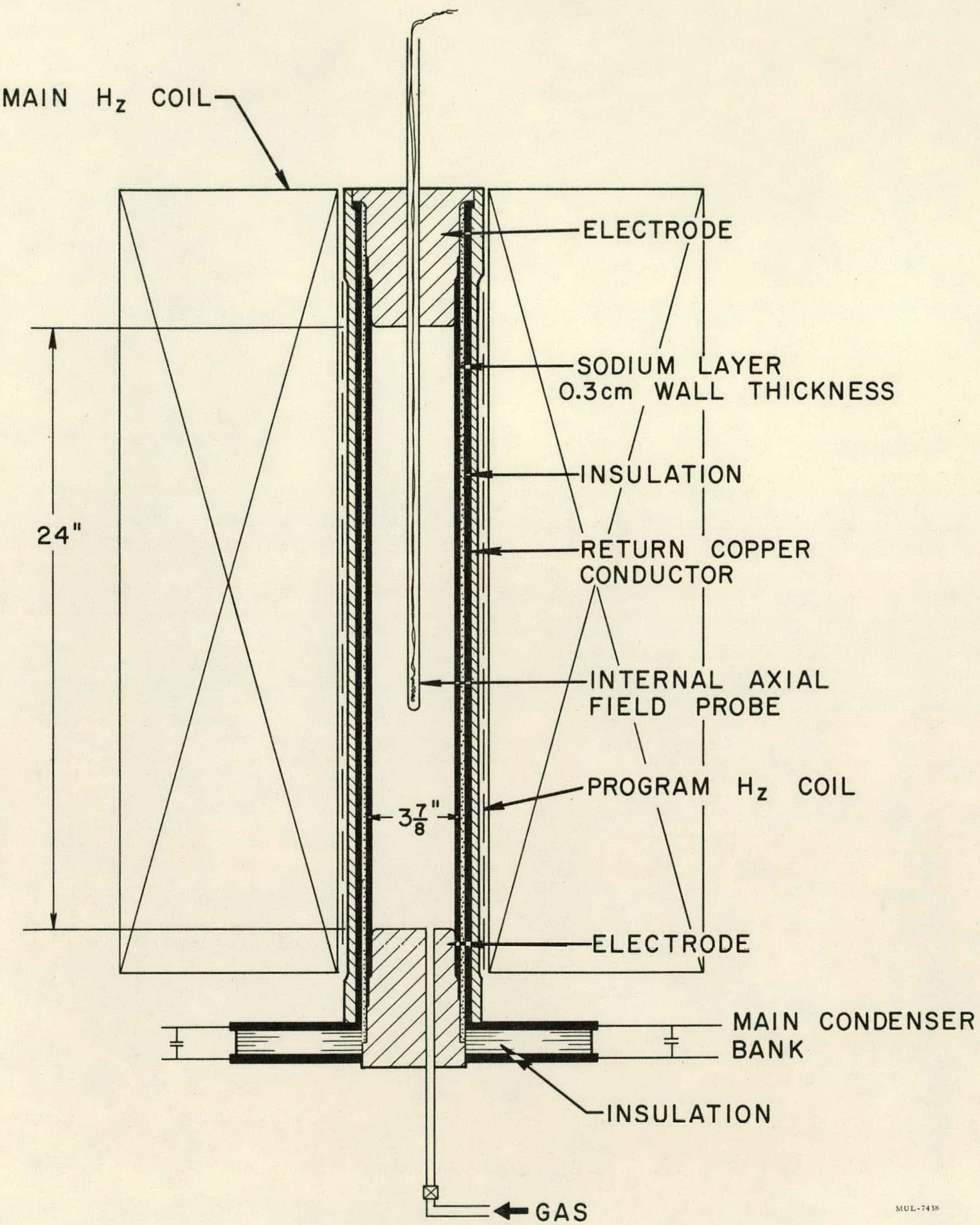

Fig. 3. Apparatus for sodium analogue pinch.

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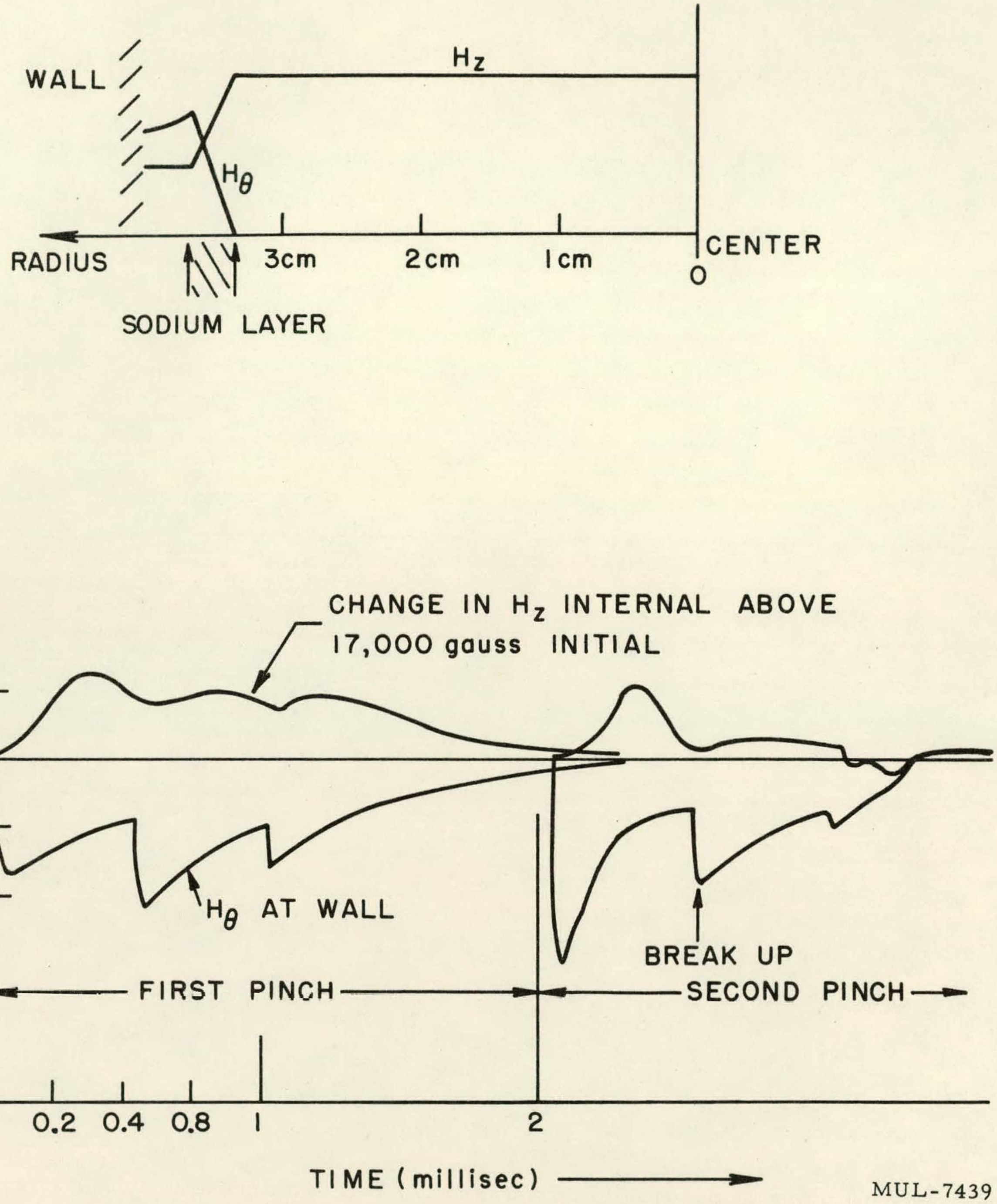

Fig. 4. Time history and magnetic field distribution of sodium analogue pinch.

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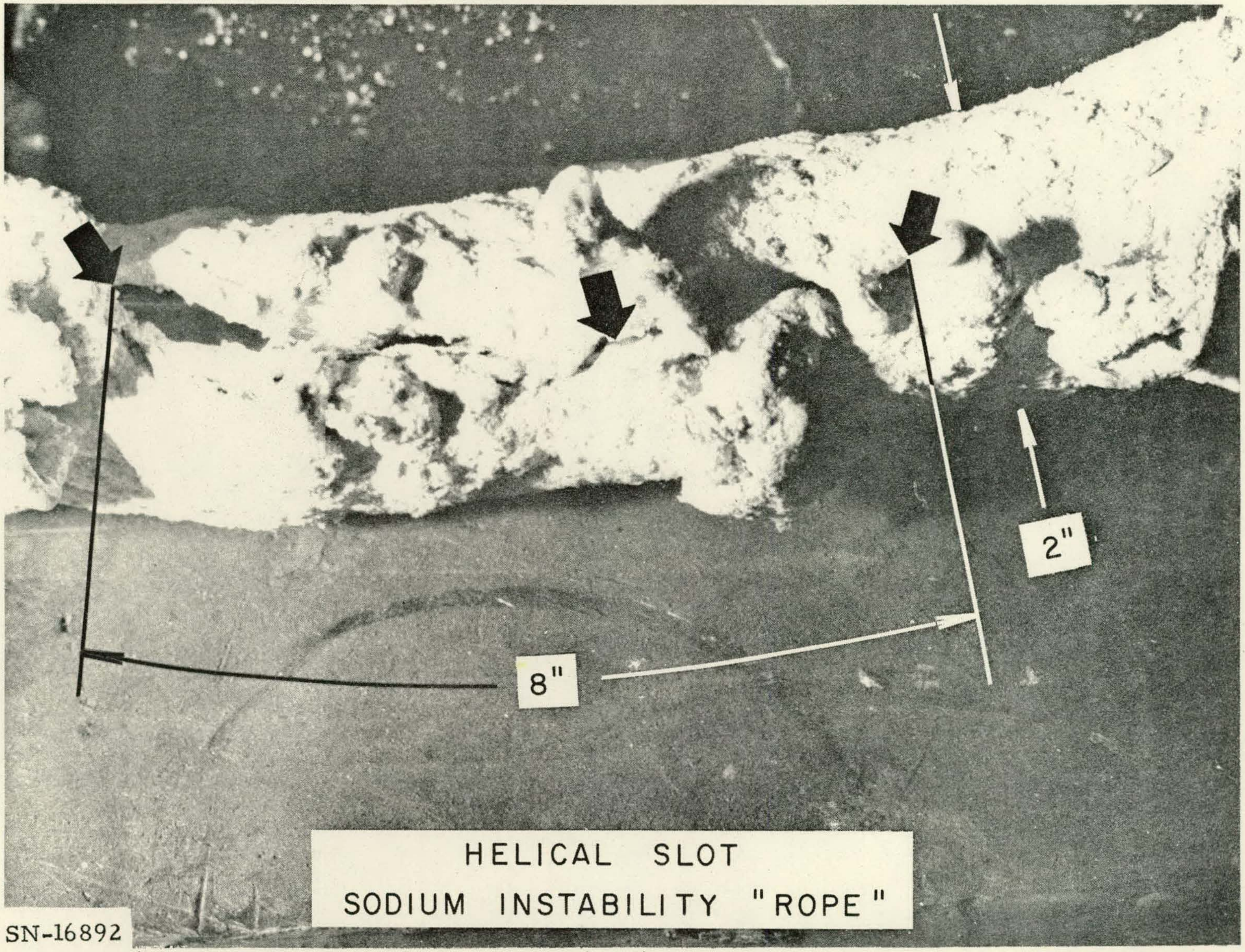

Fig. 5. Ruptured sodium tube, after development of helical slot during pinching.