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THE HARD-CORE PINCH. I

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ABSTRACT

It is well known that a pinch column with internal $\underline{H_z}$ and external conducting shell can be made grossly stable, but that small-scale instabilities persist, especially in the tubular region of maximum current density.

To investigate further these small-scale instabilities of the "stabilized pinch," we are using a 12-in.-i.d. linear pinch tube with a 3-in.-o.d. insulated center rod. By controlling a current along this rod, as well as a current along external conducting straps, and a third current in an external $\underline{H_z}$ coil, it is possible to create many grossly stable pinch configurations. The small-scale stability of the tubular region of maximum current density can thus be studied for a wide range of internal and external magnetic field vectors.

The magnetic field distribution in each discharge is obtained by a string of 10 magnetic pick-up loops. The distribution of plasma density is determined by modulating the inner or outer wall current and measuring the radial velocity of the resultant compressional Alfvén waves.

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* Paper to be presented by this author.

In one experiment, an initial $\underline{H_z}$ is entrapped in plasma by preionization, and then pushed radially outward from the rod by a rising $\underline{H_\theta}$. The resultant field distribution, in which $\underline{H_\theta}$ everywhere falls more rapidly than $1/\underline{r}$, should have absolute hydromagnetic stability. The persistence of small-scale instabilities, as observed by the magnetic probes, in this "inverse stabilized pinch" suggests that the basic trouble is nonhydromagnetic.

It is also found that, when the magnetic field approximates a vacuum field distribution, perfectly smooth and reproducible probe signals can be obtained. The absolute plasma current densities at which near-vacuum field distributions have been found stable are larger than current densities at which the "stabilized pinch" and "inverse stabilized pinch" distributions have been found unstable.

1. Introduction

The conventional "stabilized pinch" is afflicted by small-scale instabilities that are evident from many observations,[1] for instance, from the erratic and irreproducible behavior of magnetic probe traces. These instabilities have been attributed variously to electron current phenomena, such as the two-stream instability, and to purely hydromagnetic phenomena, such as interchange instabilities, arising from the imperfect fulfillment of the rather narrow theoretical stability conditions.

In order to examine this question, we have recently constructed a linear pinch tube with a rigid, insulated center conductor† (Fig. 1). This device is designed to create tubular quasi-static pinches of arbitrary inner and outer magnetic field boundary values. A wide variety of these pinches enjoy gross hydromagnetic stability. Kaufman and Newcomb[4] have prepared an analysis of the general case, and Rosenbluth has shown very simply from the energy principle that the particular set of distributions satisfying $dH_\theta/dr < -1/r^2$, $H_\theta > 0$ are stable against all hydromagnetic modes. The latter result is of special interest, since there is no difficulty in creating a pinch configuration where H_θ drops everywhere more rapidly than $1/r$, and then noting whether it is indeed completely stable.

2. Experimental Results on the Linear Hard-Core Pinch

In order to establish the pinch configuration of Fig. 2, an initial H_z is created by an external coil, then the gas is preionized by Bank 9 (Fig. 1), and finally Bank 1 is discharged to give a current flowing along the center conductor and returning through the plasma. (Inductances e and d are left disconnected.) The initial H_z is entrapped in the plasma and pushed outward quasi-statically by the rising H_θ. The axial current density in the plasma is unidirectional, so the H_θ distribution necessarily drops more rapidly than $1/r$.

†Similar discharge tubes, designed to produce tubular dynamic pinches have been studied by Anderson et al., ref. 2,3.

The magnetic probe traces of Fig. 3 illustrate the pinching — or rather, the un-pinching — process, and demonstrate that small-scale instabilities are still present. A fixed, radially oriented glass probe is used, containing 10 magnetic pick-up loops, feeding through a set of RC integrators (350 μsec) into 10 oscilloscope inputs. No attempt was made to obtain highly accurate "plasma pressure" distributions by the method of balancing magnetic field pressure gradients, but the magnitude of the plasma pressure has been demonstrated to be rather low (cf. Fig. 2) under a wide variety of conditions.

The small-scale instabilities (erratic and irreproducible excursions of magnetic field signal) have been observed over an initial gas pressure range of 10 to 1000 μD_2, and found to diminish at the higher densities. They are also attenuated if argon or air is used in place of deuterium.

In normal operation, Bank 1 is a 1000-μf source. In the case of the distribution of Figs. 2 and 3, Bank 1 was charged to 6 KV. When 8 KV is used and the magnitude of initial H_z is scaled appropriately, a very similar configuration results, but the instabilities become even more prominent. Likewise, when the bank voltage is decreased to 2 KV, the instabilities become much less prominent, but are still visible.

The composition and spatial distribution of a pinched plasma can be investigated directly, by measuring the velocity of radially moving Alfvén waves, generated by modulating the current along the center rod of the pinch tube. In the case of magnetic field distributions similar to that of Fig. 2, the signal reaches probes 1, 2, 3, and 4 almost immediately, but is increasingly delayed in reaching probes that are located at larger radii. These results are readily intelligible in terms of the Alfvén velocity $\underline{v} = (\underline{H}^2/4\pi\rho)^{1/2}$. Near the inner probes 1, 2, 3, and 4, the total magnetic field $|\underline{H}|$ is highest and the particle mass density ρ is lowest, the plasma having been swept outward by the "unpinching" process. The simple Alfvén velocity is not strictly applicable, because in the present case magnetic field and density inhomogeneities are not small over an Alfvén wave length, and because the geometry is not plane, but cylindrically divergent. Nonetheless, it is found that wave transit times measured experimentally on deuterium and argon at 50 to 400 μ initial gas pressure, agree within ±30% with the simple expectation.

In a hard-core tube, it is possible to have both $\underline{H_\theta}$ and $\underline{H_z}$ vacuum fields. As a result, a continuum of hydromagnetically stable configuration can be created, varying from the pure vacuum field to the high plasma current configuration of Fig. 2. It is found experimentally that, when a large vacuum $\underline{H_\theta}$ field (e.g. 15 000 gauss) is superimposed on a pinch involving nonvacuum magnetic field variations of a few thousand gauss, a marked stabilization results.

Configurations of this near-vacuum field type still give smooth and reproducible probe traces at local plasma current densities as high as 0.8 kiloampere/cm^2, whereas instabilities are evident in configurations of the type of Fig. 2 at maximum local plasma current densities of 0.5 kiloampere/cm^2.

In order to separate the effect of high axial and azimuthal current densities, various more complex pinch configurations have been studied. The distribution of Fig. 4 was obtained by first discharging Bank 3 (with 1000 μf at 4 KV) through inductance b taken large compared to the pinch inductance, and inductance d set at zero, thus creating an initial $\underline{H_\theta}$ field. An initial $\underline{H_z}$ field was also established by discharging Bank 6 (200 000 μf, 200 V) through inductance c taken large compared to the inductance of the $\underline{H_z}$ coil. Next Bank 8 (4 μf, 17 KV) was used for preionization, and finally Bank 5 (450 μf, 15 KV) was discharged into the $\underline{H_z}$ coil, in such a way as to generate an $\underline{H_z}$ of polarity opposite to the initial $\underline{H_z}$. As a result, $\underline{H_z}$ passes through zero inside the plasma (e.g. at 70 μsec) and a maximum local azimuthal current density of 1.4 kilo amperes/cm^2 results. It is also interesting to note that $\underline{H_\theta}$ is only very slightly modified in the vicinity of the zero in $\underline{H_z}$, so that little axial current flows and an appreciable plasma pressure must exist. Nevertheless the magnetic probe traces are smooth and reproducible.

This result suggests that the difficulty with configurations of the type of Fig. 2 is not so much the presence of high current density, as the pressure of high axial current density. To test this hypothesis further, we have created quasi-static pinch configurations where $\underline{H_\theta}$ has a zero inside the plasma, $\underline{H_z}$ being somewhat peaked there. Such configurations are found to be highly unstable (as, of course, are all variations of the conventional "stabilized pinch" that have been studied in our tube). The close association of high axial, rather than high azimuthal, current densities with instability is consistent with hydromagnetic theory. For instance, it is easy to show that a zero of $\underline{H_z}$ enhances hydromagnetic stability, while a zero in $\underline{H_\theta}$ diminishes it. Another possible interpretation of the data is that the axial component of the current density, which flows out of the tube electrodes, is subject to an instability-generating modulation by arc-spots or sheaths. Such local disturbances could lead to undesirable geometrical inhomogeneities, as well as to electrostatic phenomena propagated by a modulated electron stream.

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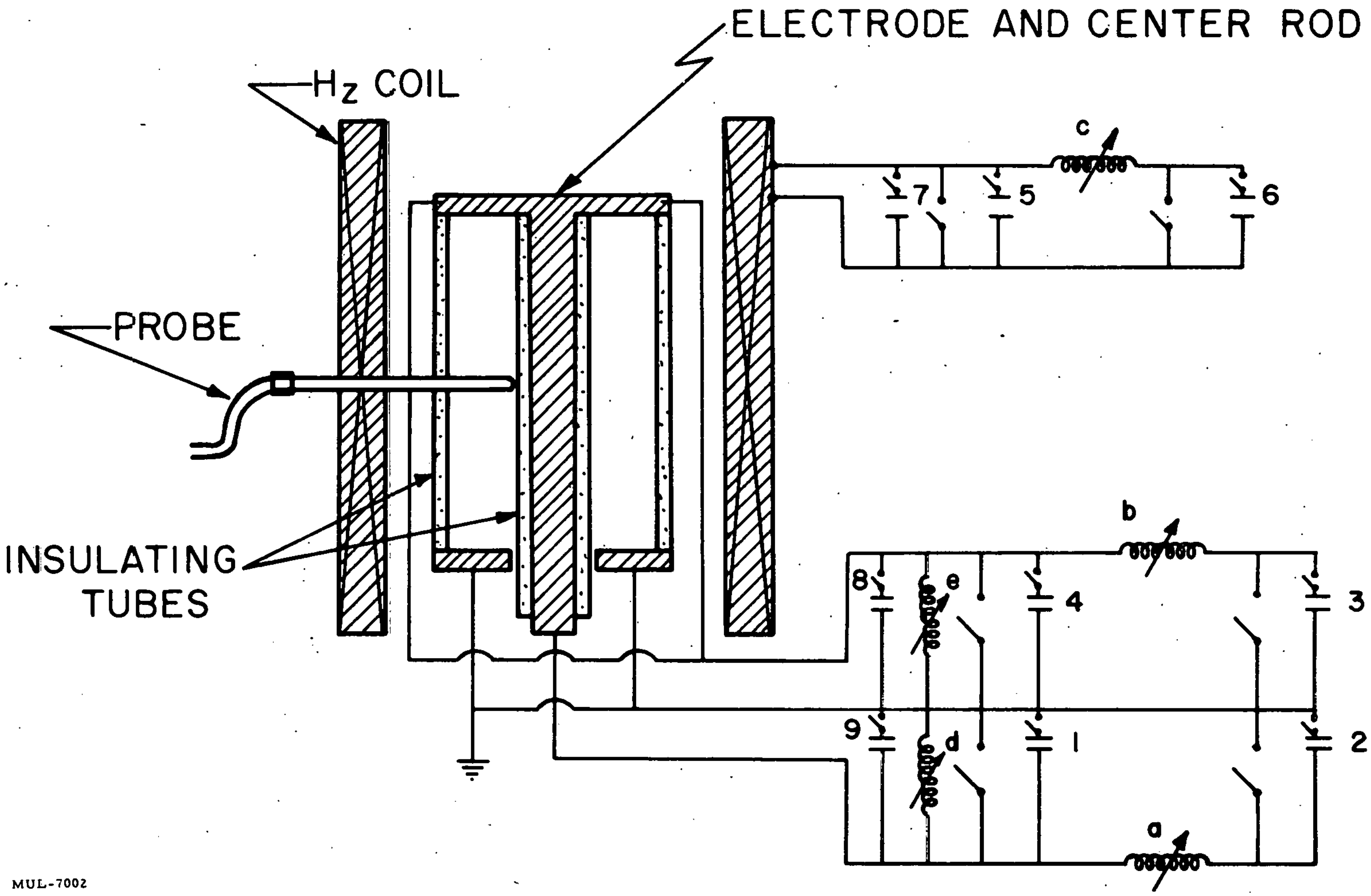

Fig. 1. Hard-core pinch tube, with 12-in. outer fused quartz tube and 3-in. inner Pyrex tube. The electrodes are made of 1/8-in. stainless steel, and the inter-electrode distance is 18 in.

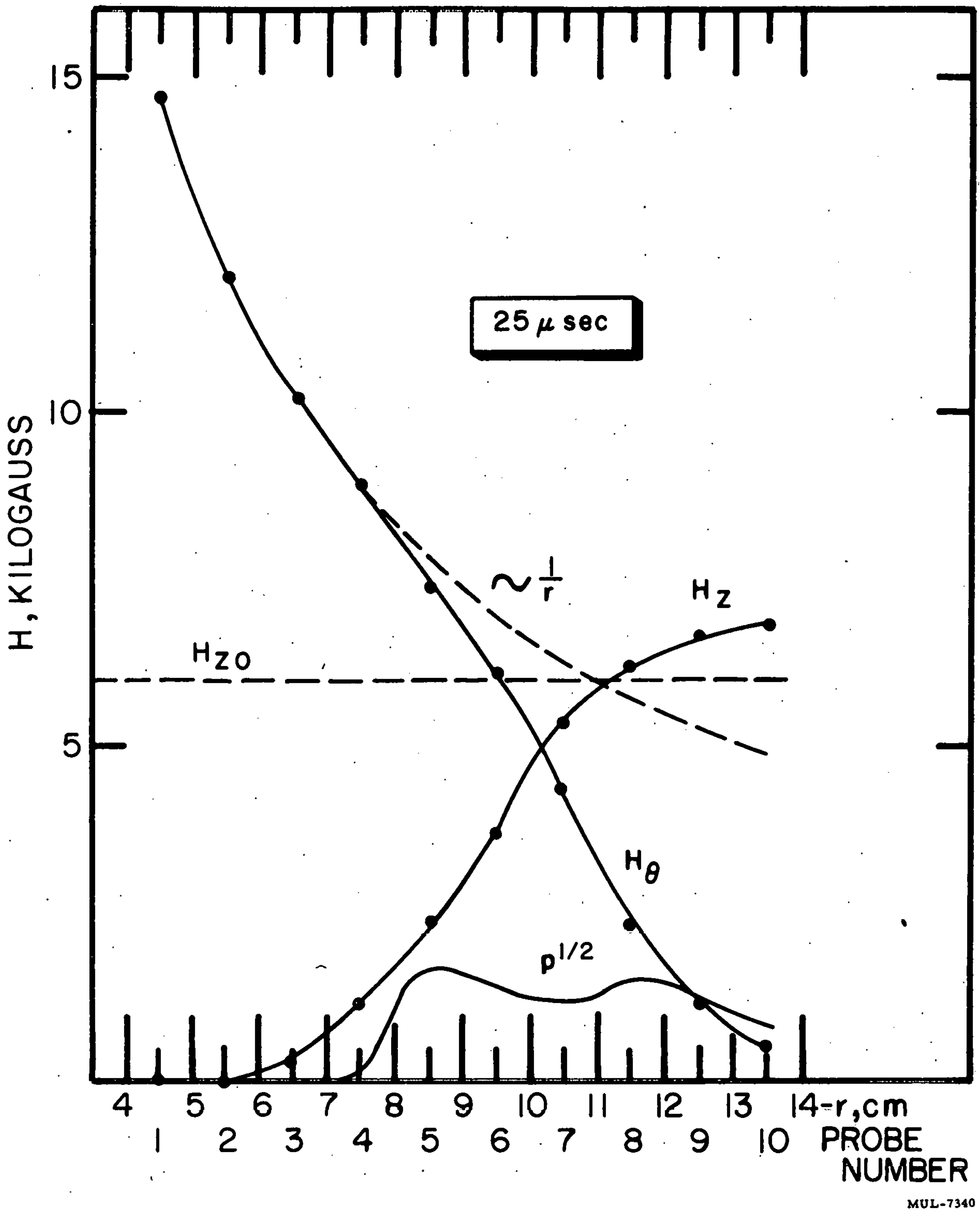

Fig. 2. "Inverse stabilized pinch" distribution, taken at 25 μsec from probe traces of Fig. 3. The square root of the plasma pressure is plotted in units of kilogauss.

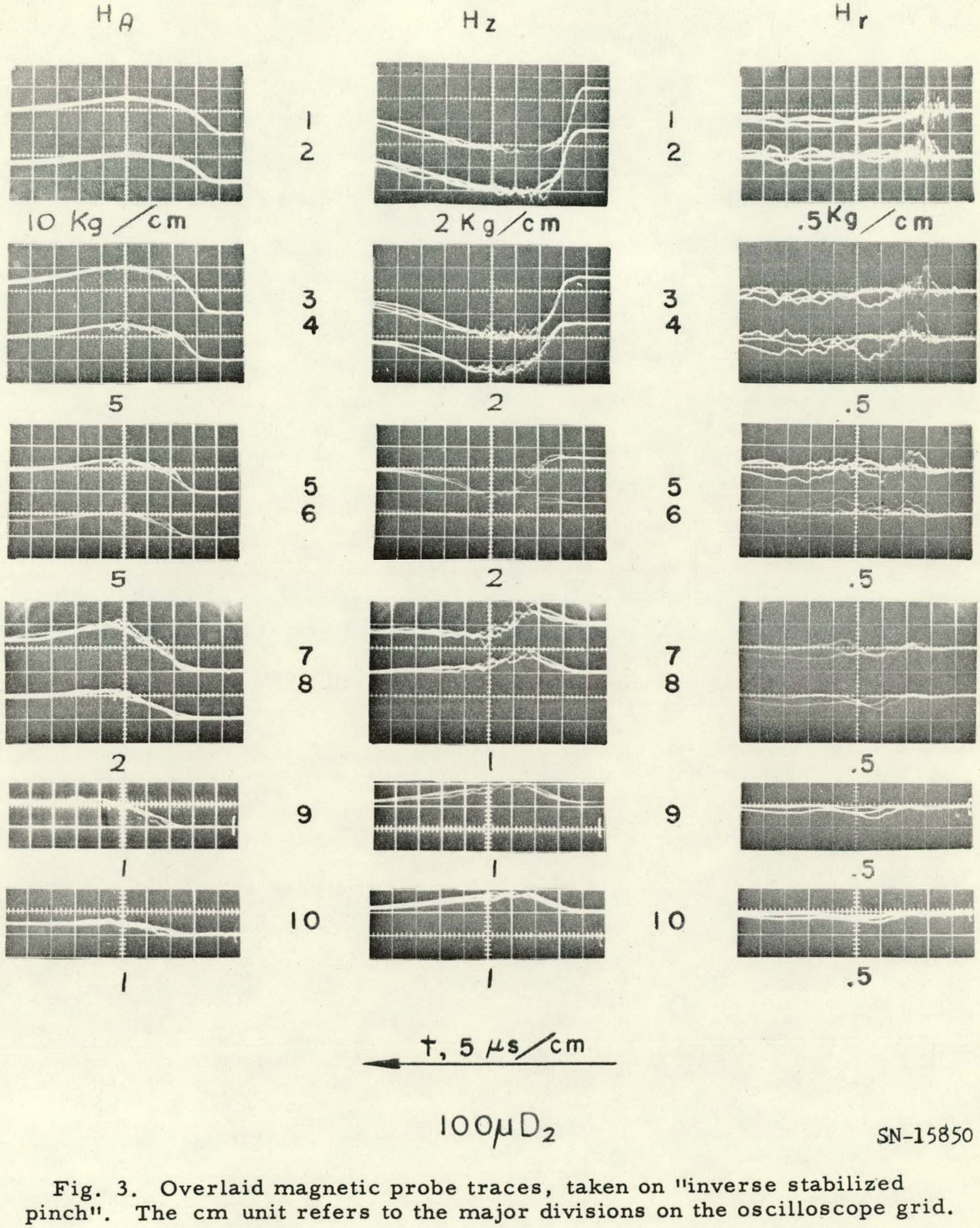

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Fig. 3. Overlaid magnetic probe traces, taken on "inverse stabilized pinch". The cm unit refers to the major divisions on the oscilloscope grid.

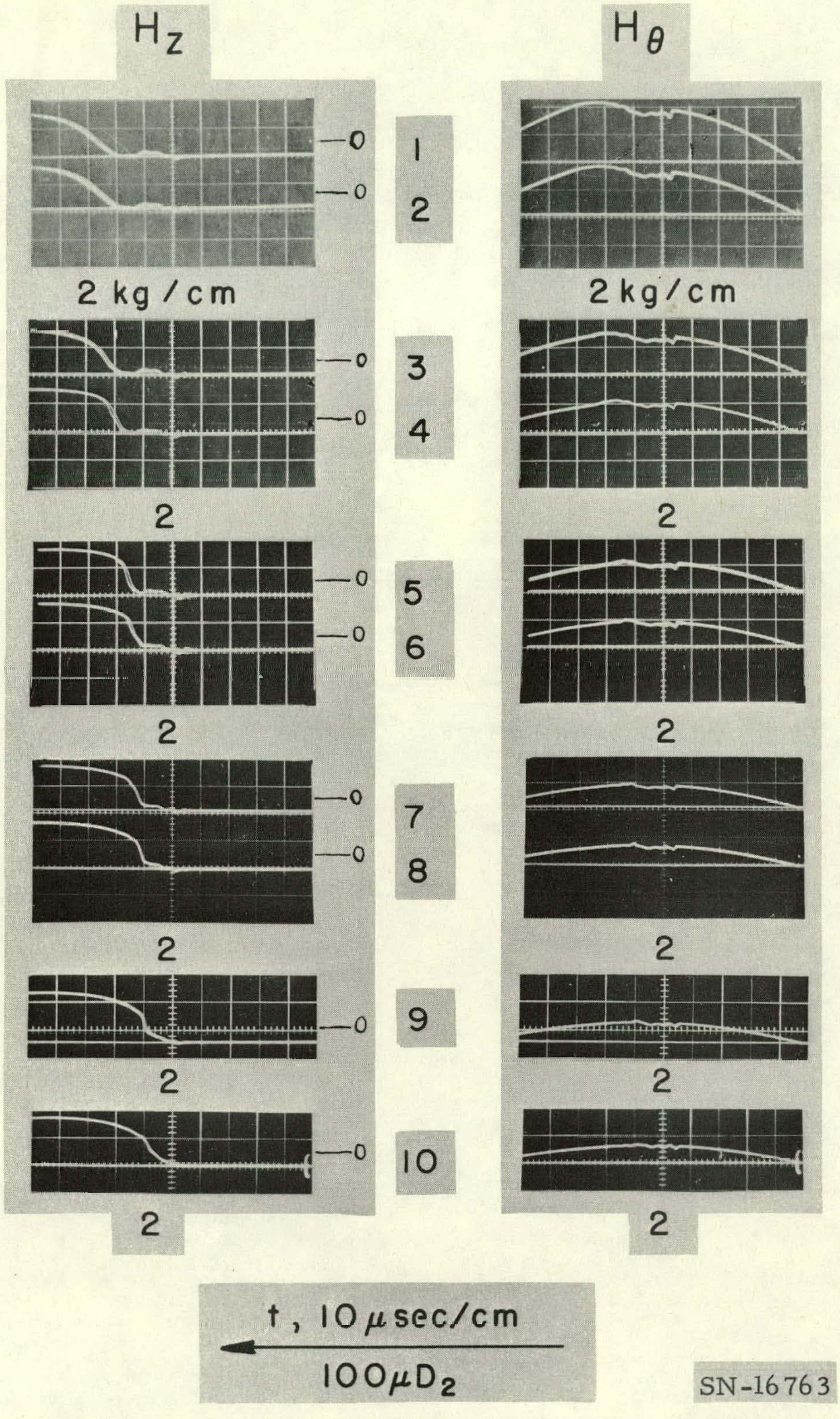

Fig. 4. Overlaid magnetic probe traces, for $\underline{H_z}$ passing through zero inside plasma.