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Title
SHEEP PINCH DEVICES

Permalink
https://escholarship.org/uc/item/368263wp

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Publication Date
1958-03-01
Radiation Laboratory

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Each person who receives this document must sign the cover sheet in the space below.
It is predicted theoretically\(^1\) that a current-carrying plasma sheet of infinite extent possesses positive stability for some perturbation modes and at least neutral stability for others. Consequently three types of sheet-like discharges are being studied at Berkeley. The first of these, which has been given the name "Triax", consists of a cylindrical plasma sleeve contained between two coaxial conducting cylinders as shown in Fig. 1. A theoretical analysis of the stability of the cylindrical sheet plasma\(^1\) predicts the existence of a "sausage-mode" instability which is, however, expected to grow more slowly than in the case of the unstabilized linear pinch (by the ratio of the radial dimensions). The second pinch device employs a disk-shaped discharge with radial current guided between flat metal plates, this configuration being identical to that of the flat hydromagnetic capacitor\(^2\) without external magnetic field. A significant feature of these configurations is the absence of a plasma edge, i.e. there are no regions of sharply curved magnetic field lines anywhere in these discharges. The importance of this fact for stability is not yet fully investigated theoretically. As a third configuration, a rectangular, flat pinch tube has been constructed, and the behavior of a flat plasma sheet with edges is being studied experimentally.

An obvious disadvantage of the sheet-like plasma is the relatively smaller compression ratio that is obtainable at a given current as compared to an unstabilized pinch. This is, however, also characteristic of pinches stabilized by longitudinal magnetic fields. The principal advantage of the Triax pinch over the stabilized linear pinch is the absence of magnetic field lines intersecting metal electrodes. It has been shown theoretically\(^3\) and experimentally\(^4\) that the heat transfer to the electrodes in the Triax pinch is negligible. This shows linear Triax tubes with metal electrodes to be exceedingly interesting as devices for containing hot plasmas, even if their dimensions are very modest.

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II. PRINCIPAL EQUIPMENT AND TECHNIQUES

We have used tubes of 1 meter and 50 cm length, the diameter of the outer return conductor being about 10 cm. This size is determined by the available quartz tubing, which is used both as insulator and vacuum jacket. Larger sizes are being planned. The inner conductor has been of 5-, 2.5-, and 1.25-cm diameter. In earlier work at low power levels, Pyrex insulators instead of quartz were used. Other materials are being contemplated, and one tube with exposed metal walls is under construction.

The 1-μf, 30-kv capacitors used can supply peak currents of 30,000 amperes each. Low-level runs employ 45 of these capacitors in parallel, while for high-power levels a bank of 100 μf is used. For other purposes, such as starting current and switch triggering, smaller groups of from 4 to 24 capacitors have been used. All connections and leads consist of RG 8/U or RG 9/U coaxial cables.

Switching has previously been accomplished by means of pressurized spark gaps filled with air and fired by a sudden release of pressure or, if programmed switching is desired, triggered by a shock wave from an auxiliary, small spark gap incorporated in the switch assembly. Recently a triggered, low-pressure, high-level switch has been developed.

The gas, usually 99.7%-pure deuterium, flows continuously through the system to avoid accumulation of volatile impurities, and pressures of from 50 to 1000 microns have been used.

III. DIAGNOSTIC EQUIPMENT AND TECHNIQUES

The voltage across the tube and the total current through the tube are measured by means of a voltage divider and a flux loop in one of the connecting cables. These signals are displayed on an oscilloscope and photographed.

Spectroscopic observations, both with and without time resolution, have been made and give some information as to the impurities present, time of appearance of impurity and deuterium lines, and the profiles of deuterium lines broadened by the Stark effect. The profiles were obtained by firing successive shots at different settings of a 0.5-meter grating monochromator. Under low-level conditions, there was sufficient intensity and reproducibility to yield very satisfactory profiles.

The magnetic-field distribution inside the discharge tube was determined by means of conventional probe techniques. For convenience of assembly the probe was introduced through the grounded end electrode, and was enclosed in a quartz tube extending to the mid-point of the Triax discharge. No evidence was found that this arrangement affected the discharge measurably.

Two large liquid-scintillator tanks were used to detect neutrons from the discharge, one being operated close to and one several meters from the Triax. Both the initial proton-recoil pulse and the individual neutron-capture pulses were recorded. The over-all detection efficiency was 5% when the detector was close to the discharge tube.
Various other auxiliary tests have been performed from time to time. An electrostatic probe was used to determine whether an electrode sheath existed (none could be found) and to estimate the resistive voltage drop along the center of the plasma.

Several floating electrodes were introduced into the path of the discharge to determine the effect of electrodes on the voltage across the tube and on the neutron production. Subdivision of the pinch by these floating electrodes had little effect on the behavior of the pinch.

Some measurements were made on the heat delivered per discharge to an end electrode, using a fast responding thermocouple. These measurements verified roughly the theoretical predictions as to the low heat transfer.

IV. TRIAX PINCH MEASUREMENTS

In general, the measurements fell into two main subdivisions according to the value of $\chi$, the ratio of maximum magnetic pressure to initial gas pressure. In the low-power work, for which well-behaved performance was observed without preionization only when the initial pressure was above 200 microns, $\chi$ was always less than $5 \times 10^4$. In high-power work ($\chi > 10^5$), when the initial pressure was relatively low and particularly when higher currents were used, a starting current was required for satisfactory results.

A. Low-Level Observations ($\chi < 5 \times 10^4$)

Typical oscillograms of various signals obtained with a Triax are shown in Fig. 2. This tube, with Pyrex walls and a 5-cm-diam inner conductor, was filled to 475 microns initial pressure; a 45-$\mu$F bank of condensers charged to 20 kv was discharged through it. Each trace in Fig. 2 consists of three superimposed traces from three separate discharges to show the reproducibility from shot to shot.

The first trace (Fig. 2a) shows the tube voltage. The oscillations are due to variations in the plasma thickness, because the total current is changing only slowly. At the time of a pinch (maximum compression), the inductance and its negative second time-derivative are a maximum and the voltage is decreasing at its maximum rate. Eight rebounds from the pinch are discernible in Fig. 2a. The oscillations are smoothly damped and show no signs of instability. The time to reach the first pinch agrees well with the value calculated under the assumption that all the gas is swept into the plasma sheet.

The second signal (Fig. 2b) is a measure of $dI/dt$, and of course shows oscillations that are nearly the mirror image of the voltage oscillations. The time integral of this signal is proportional to the total discharge current, and is shown in Fig. 2c. The lack of structure indicates that the total inductance of the circuit is not greatly affected by the oscillations inside the pinch tube.

The value of the voltage across the tube when $dI/dt = 0$ is a measure of the resistive drop because at this time $dL/dt$ is small. Under the assumption that the current flows in a channel about 5 mm wide (cf. Fig. 4b), an electron temperature can be calculated by use of the conductivity-temperature relation
given by Spitzer. In this particular low-level case, this temperature is about 15 ev.

Figure 2d was obtained from a flat loop wedged between the outer conductor and the outer Pyrex insulator. This signal shows the rate of change of current density flowing along the outer conductor. Comparison of Fig. 2d with Fig. 2b shows that the local current density on the outer conductor is not proportional to the total current. If cylindrical symmetry is assumed, this is presumably due chiefly to a mode of oscillation in which the radial position of the plasma rather than the thickness varies. Such oscillation is expected whenever the plasma sheet is not formed initially in its equilibrium position.

Note also that the frequency of the slower radial mode (seen only in Fig. 2d) is not as reproducible from shot to shot as that of the thickness mode, indicating that these radial oscillations tend to get out of phase as time goes on. Simple theoretical considerations predict a different dependence of the two frequencies on variations in experimental conditions such as initial pressure. The lower damping of the radial mode is also in accord with theory.

The interpretations given here have been checked by detailed magnetic-probe studies and also by spectroscopic observations, to be discussed later.

Magnetic-Probe Studies. Probe studies in the low-power Triax pinch have shown fairly good reproducibility up to about 2.5 μsec, depending on various factors such as gas pressure and voltage. Figure 3 shows a three-dimensional view of the current density as a function of both radial position and time, extending over the first 1.5 μsec of the discharge. The nature of the pinch and the existence of a rather large current penetration is apparent from this figure. The width at half-maximum of the current channel at the time of the first pinch is apparently 1/4 of the original thickness before breakdown. The oscillations in thickness are more easily seen in Fig. 4b where the width of the current channel (determined by the positions of half-maximum current-density values) is plotted against time. This width is closely correlated with the effective inductance in the discharge, and comparison with the observed tube voltage bears out the interpretation given above. A pressure-balance calculation using the measured mean compression together with the assumption that the plasma has the same temperature everywhere leads to estimated temperatures of about 4 ev at the time of the first pinch and 15 ev at the current peak.

Spectroscopic Study. Spectrograms (without time resolution) of a low-energy Triax showed a line spectrum with no continuum. The principal impurities were silicon and oxygen from the insulators, carbon from gaskets, and copper from electrodes, as expected. A time-resolved profile of the deuterium line D_3 was obtained with a monochromator and photoelectric detector. In Fig. 4 the top trace is the tube voltage against time, the second curve shows the thickness of the plasma sheet as deduced from magnetic-probe measurements described earlier, and the third and fourth traces are typical of a large number of curves of light intensity vs time taken at various wavelengths in the neighborhood of λ4860 (the latter being the wavelength of the center of the profile of D_3). The fourth trace shows that the profile of D_3 is very much broadened by inter-atomic Stark effect at the times of the first and second pinches. An application of the Holtzmark theory to the profile at the time of the first pinch (0.8 μsec)
indicates that while the density of ions is not uniform throughout the plasma there is a layer in which the density reaches some thirteen times the density of atoms in the gas before the discharge begins. This result is in reasonable agreement with the conclusions from the probe studies. By the time of the third pinch, the deuterium atoms in the dense parts of the plasma have become completely ionized and cease to radiate. The remaining light, visible in the trace at \( \lambda 4860 \) at 1.5 \( \mu \text{sec} \) and later, must come from neutral atoms at or near the walls where the density is low, as shown by the narrow profile at these late times.

Figure 5 shows at slower sweep speed the voltage, current, and intensity of the line \( D_\beta, \lambda 4860 \). The burst of light at the time of the first zero in the current indicates that at this time the plasma spreads to the walls and thereafter again forms into a pinched sheet as the current builds up. After the second zero, the current remains at too low a value to hold the plasma away from the wall, and there follows a prolonged emission of \( D_\beta \) because of recombination at the walls.

B. The Triax Pinch at High Level (\( \chi > 10^5 \))

Operating a Triax tube at high level and a pressure of approximately 100 microns leads to well-behaved pinches only when the main discharge is preceded by a low-energy starter discharge which ionizes and preheats the gas. This predischARGE is estimated to give the plasma a temperature of about 15 volts, the current being such that the magnetic pressure approximately balances the particle pressure against the walls.

Because of the contamination problems with Pyrex, quartz insulators were used in these high-level runs. Switching apparatus was developed which allowed firing the starter current (16 \( \mu \text{f} \) charged to 20 kv, producing 40,000 amp peak in 12 \( \mu \text{sec} \)) for a predetermined length of time and then firing the main current. Normal operation of the tube shows no impurities introduced by the starter current. The effect of the starter current on pinch formation at 140-\( \mu \) pressure in a 50-cm tube having inner and outer conductor radii of 5 and 10 cm, respectively, is shown in Fig. 6. The upper trace (taken without starter) does not show the marked pinch dynamics, while the next (with starter) shows good pinches. Fig. 6c shows the current trace with a proton-recoil signal from the neutron detector superimposed on the current. Peak current was about \( 1.3 \times 10^6 \) amp, and \( 2 \times 10^4 \) neutrons/pulse were observed. Note the time coincidence of neutron production with the pronounced bump on the voltage curve, which is preceded by a series of pinch oscillations of decreasing amplitude. Such a bump is of course suggestive of instabilities. Several arguments, described below, militate against interpretation of this voltage bump in terms of presently known instabilities, but a determined search for such instabilities is continuing. Furthermore, the thermonuclear origin of the neutrons has not been ruled out.

(a) If the neutrons are assumed to be thermonuclear, their number is consistent with the temperatures possible from known heating mechanisms in the tube (resistive heating, shock heating, and adiabatic compression, which could have produced a temperature of about 300 volts). This consistency was lacking in the much larger yields from the linear pinch.
(b) Neutron production has been shown to be roughly uniform throughout the length of the tube, thus ruling out some proposed nonthermonuclear processes for neutron production. The low neutron production precludes the measurement of neutron energy by nuclear-emulsion techniques, as was done with the simple dynamic pinch, but a high-pressure cloud chamber is being readied which may make this measurement possible.

(c) With regard to the voltage bump as an instability, it must be remembered that in the linear pinch the voltage disturbance at the time of neutron production is a series of wild transients of more than 100 kv amplitude which even reversed polarity. The behavior in the Triax is not of this character.

(d) Neutron production by runaway deuterons traveling longitudinally through the plasma was ruled out by the insertion of several annular electrodes. Supported by friction between the insulating tubes and floated electrically, these electrodes had no effect on voltage, current, or neutron production. This experiment also seemed to rule out sheath formation at electrodes and apparently verified the prediction that the heat transfer to the electrodes was too small to cool the plasma appreciably.

(e) Addition of a longitudinal magnetic field of 200 gauss shifts the neutron production to a later time, but does not seem to affect the number of neutrons appreciably.

(f) Because instabilities in the Triax might be expected to be enhanced if the wall separation were increased, another tube having an inner conductor of 2.5-cm diameter was constructed. The high-level characteristics of this tube are shown in Fig. 7. The voltage bump is not appreciably larger than in Fig. 6.

Various characteristics of the tube mentioned under (f) above are shown in Fig. 7, taken at 75-micron initial pressure and with the main bank of 100 µf charged to 20 kv. Starter current was used as before. The new voltage curve (Fig. 7a) is considerably different from that in Fig. 6b and is interpreted as being due to a superposition of the two modes of oscillation of the plasma mentioned previously.

The neutron yield for this tube, shown in Fig. 7b superimposed on the current trace, was higher than for the previous tube, i.e. $2 \times 10^5$ per pulse. The production begins near the end of the bump on the voltage curve.

The last three traces in Fig. 7 show the behavior of the light emitted from the tube. The most interesting feature is the sudden appearance of impurities, represented by $\mathrm{Si}^{++} (\lambda 4552)$ just at the end of the neutron production.

Experiments with streaking cameras are underway and radiation in the vacuum ultraviolet will be studied, in an effort to understand more fully the mechanism of the Triax discharge. These experiments, coupled with a determination of neutron energies, will help to establish whether the neutron production is compatible with a thermonuclear process.
REFERENCES

1. Smith, L., University of California Radiation Laboratory, Berkeley, private communication.


Fig. 1. Schematic cross section of the Triax pinch tube.

Fig. 2. Typical oscillograms obtained from the low-level Triax pinch.

Fig. 3. A three-dimensional view of current density as function of radial position and time in low-level Triax pinch.
Fig. 6. Triax voltage without and with 40 kiloamp starter current, and neutron signal superimposed upon total current at high level. (Inner conductor, 5 cm diam.)

Fig. 7. Triax voltage with starter current, neutron signal superimposed upon total current and light intensities at high level. (Inner conductor, 2.5 cm diam.)