A Summary of the Berkeley and Livermore Pinch Programs

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The containment of a plasma by a magnetic field can take either of two rather distinct forms. In one case the plasma causes only a small perturbation in a static vacuum magnetic field. In the other case currents flowing within the plasma may be said to generate or bound the magnetic field, thus creating configurations that are radically different from the vacuum field configurations. The pinch program is concerned with phenomena of the latter kind.

Since pinch-type devices are not limited to vacuum magnetic fields, a much greater degree of freedom exists in designing useful configurations. For instance, plasma stability is often improved to a marked extent by sharply defined or even oscillatory spatial magnetic field distributions, which are hard to achieve in a vacuum. It is almost redundant to point out that pinch-type configurations are suited to the containment of plasma energy densities that are comparable to the energy density of the containing magnetic field. This is an important feature in the economics of any potential thermonuclear reactor.

Because pinch magnetic fields are dependent on plasma current, they must disappear as the pinched plasma escapes from containment by instability mechanisms or by diffusion. At low plasma temperatures the plasma diffusion rate is rapid. Consequently the containment times thus far achieved even in stable plasma configurations have been short, meaning some tens of microseconds in devices of 10-cm size. In order to progress toward practical thermonuclear devices, the principal objective must be to prolong containment times by improving the electrical conductivity of the plasma. Those pinch configurations which are grossly unstable are, of course, unsuitable for practical thermonuclear work. Therefore our purely dynamic experiments are conducted only to study basic shock heating and instability mechanisms.

As the plasma escapes from containment, and the pinch magnetic field collapses, the plasma acquires something like the energy density of the magnetic field. In the ideal sense this corresponds to heating, but from a more realistic standpoint it has the more disastrous consequence of loss of containment. Apparently part of this energy is lost in the form of high-energy particles striking the wall and part in the form of impurity radiation. Neutron emission has been observed in most of the experiments, but the relevance of small neutron yields to bulk plasma temperature is not obvious. Therefore our basic evaluation of progress in pinch-type experiments is the reduction of the dissipation rate of the magnetic fields. This is because dissipation destroys containment, and containment is the most fundamental goal of the magnetic bottle. If you have long-time containment, you can achieve high temperature by heating at your leisure, but if you have heating with no containment, then you have neither containment nor high temperature.

My present pessimistic viewpoint is that most of the pinch devices that depend upon high current density within the plasma are beset with an enhanced dissipation rate which is disastrous to pinch containment. This dissipation is derived either from an electron plasma current instability (analogous to the wriggling of a fire hose with high-velocity water flowing through it) or from hydromagnetic turbulence. Both have been predicted in theory and observed in experiment.

STABILIZED PINCH
(Ferguson and Furth)

One of the principal efforts is directed towards understanding and utilizing the stabilized pinch effect for the containment of a thermonuclear plasma (Fig. 1). Stability can be achieved by entrapment of an axial magnetic field $H_z$ in the pinch column, provided a number of secondary conditions are met. The pinch radius must be kept larger than one-fifth the radius of the return-conductor shell, and the plasma pressure must be low compared to $H_z^2/8\pi$. The region containing the hot plasma and the $H_z$ field must be sharply bounded from that containing the pinch field $H_p$.

These theoretical stability criteria of Rosenbluth have been tested in linear pinch experiments. Under improper conditions, in particular for substantial $H_z$ appearing in the external $H_p$ field region, the helical instability mode was induced. The magnetic field behavior in time and space was studied by means of

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Figure 1. The formation of the stabilized-pinch magnetic field configuration

magnetic probes. The occurrence of instabilities was observed synchronously with probes and with optical equipment. The sign of the helical instability was shown to depend on the direction that \( H_z \) has in the \( H_e \) field region. The interdiffusion of the \( H_z \) and \( H_\theta \) regions was found to proceed at a rate derived from pressure balance analysis of the magnetic probe data. These results correspond closely to calculated equilibrium temperatures for plasma in thermal contact with cold electrodes. The region external to the pinch proper (the \( H_\theta \) field region) was found to contain not a vacuum but a pressureless plasma of good conductivity. It follows that sharpness of boundary between the \( H_z \) and \( H_\theta \) field regions is contingent on rapid diminution of \( H_z \) flux external to the pinch as the plasma pulls away from the tube wall. This can be accomplished electrically by introducing a cancelling \( H_z \) flux external to the pinch as the plasma pulls away from the tube wall. \( H_z \) distributions which oscillate in space have also been established by oscillating \( H_z \) at the tube wall in the time during pinch compression.

To achieve higher temperatures and so impede resistive interdiffusion of the \( H_z \) and \( H_\theta \) field regions, experiments are now being conducted in toroidal geometry (Fig. 2). The pinch current is generated by induction, and the drainage of heat into electrodes is eliminated. Preliminary experiments performed at low power level have allowed approximate reproduction of linear pinch results. As \( H_z \) flux expands by diffusion into the \( H_\theta \) field region, its energy content is diminished and the plasma is heated correspondingly. A pinch surface layer several diffusion depths thick is theoretically given a third of the characteristic temperature \( T_\phi = H_z^2/8\pi nk \), provided radiative losses are small. How much of the pinch can be heated depends on the diffusion depth tolerable from the stability point of view. In actual experiments with a Gamma torus, with a \( 10^4 \) joule, 30 kev, 300 ka bank (Fig. 3) and a ceramic toroidal pinch of 10 cm minor diameter (Fig. 4), we have found little evidence that the plasma temperature exceeds that attained in the linear pinch work. The electrical conductivity corresponds to about 10 ev, even though more than 5000 ev per particle is dissipated resistively in the first quarter-cycle of the current. Neutron yields corresponding to about 300 to 500 ev ion temperature are observed, but these appear to be due to nonthermonuclear mechanisms of ion acceleration. We observe very great sensitivity of neutron yields to the steepness of the trapped \( H_z \)

Figure 2. The toroidal stabilized-pinch configuration
distribution in the pinch. Plasma heat-loss rates of the observed magnitude are hard to explain except by heavy element impurity radiation, or by some equally disastrous mechanism. During the first quarter-cycle time of our toroidal pinch we have excluded by time-resolved vacuum ultraviolet measurements the possibility of impurity radiation loss. We have discovered instead a catastrophic loss of runaway 3 to 5 kev electrons. The flux of runaway electrons striking the wall, as measured by the soft X-ray flux, is comparable in magnitude to the pinch current of 250 ka. The implication of the non-adiabatic behavior of these electrons, namely that they move freely across the magnetic lines of force of the pinch, is that they represent a disastrous energy-loss mechanism. We suspect either a current-induced instability or hydromagnetic instability that drives plasma turbulence, resulting in the nonadiabatic electron behavior.

It seems likely that the high electrical resistivities that have been observed should be explained in terms of this effect, rather than in terms of a very low electron temperature. If so, one cannot anticipate an improvement at higher power levels and consequently the so-called stabilized pinch may turn out to be unsuitable as a useful magnetic bottle.

**Sheet Pinch Devices**

(Anderson, Baker, Kunkel and Pyle)

A pinch can be stabilized by means other than the entrapment of an axial magnetic field. It is predicted theoretically that a current-carrying plasma sheet of infinite extent possesses positive stability for some perturbation modes and at least neutral stability for others. This stability is approached in sheet pinch devices of modest size. Both the flat sheet and the cylindrical, edgeless configuration (the latter having been given the name "Triax") are being studied. The Triax pinch device is shown in Fig. 5.

An obvious disadvantage of the sheet-like plasma is the relatively small compression ratio that is obtainable at a given current, as compared to an unstabilized filamentary pinch. This feature is, however, also characteristic of ordinary 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. Experiments with thermocouples in the electrodes and variation of effective tube length by means of inserted floating "dummy" electrodes indeed both point to low heat transfer to the electrodes, in agreement with theoretical predictions.

Determination of the current density distribution as a function of time, using magnetic probes in low power level discharges ($T \approx 10$ ev, starting density 400-1000 $\mu$ of $D_2$, mean compression factor 5, peak current $\approx 6 \times 10^5$ amp, total energy supply $\approx 10^4$ joules, 50 $\mu$f, 20 kv), clearly shows well-reproducible, repeated oscillations of the plasma sheet thickness (Fig. 6). These results are in full agreement with inductance calculations made from the tube voltage. Under suitable conditions, up to ten oscillations can be...
discerned (lasting for about 3 μsec) and there is no sign of hydromagnetic instability. In fact, time-resolved spectroscopic observations in the visible part of the spectrum indicate full ionization of deuterium after the second pinch and low recombination until the second current reversal. The observed resistance of the plasma is in agreement with that calculated using the temperature and the mean compression deduced from probe measurements.

In the attempts to obtain a temperature sufficiently high for thermonuclear reactions, lower initial gas densities (down to 75 μ of D2) and higher currents (up to I_{max} ≈ 1.5 × 10^6 amp) are being used. In this case slow starter currents of about 4 × 10^4 amp peak and about 10 μsec duration are needed to ionize the gas fully and preheat it, presumably to above 10-ev temperature, without causing appreciable compression. Sudden pinching of this plasma by the main discharge current is capable of producing several hundred ev temperature after thermalization. Again, several bounces of the plasma sheet thickness are observed, smaller and more rapid now than at low level. After these bounces a burst of neutrons (of the order of 10^4 to 10^5 per discharge) lasting for a few tenths of a μsec is detected. A thermonuclear explanation would require an ion temperature of 300–400 ev. Simultaneously a “bump” in the tube voltage, 2–3 kv high, is seen indicating a distinct temporary increase in tube impedance. The exact cause of this increase in tube impedance has not yet been ascertained and hence the nature of the neutron production is still uncertain. Direct acceleration of deuterons along the plasma seems to be ruled out because subdivision by insertion of the dummy electrodes did not appreciably reduce the neutron production. Emission of visible impurity light, predominantly from silicon ions, sets in during or shortly after the voltage bump. The observed resistance of the discharge points to an electron temperature of probably not more than 50 ev, yet ten times this energy per particle is introduced and so again we are beset with a dissipation rate that is not yet understood.

**HOMOPOLAR**
(Anderson, Baker, Bratenahl, Furth and Kunkel)

Long-time containment of a plasma is usually associated with quasi-static configurations where the plasma is at rest in the laboratory frame. However, containment of a long-lived thermonuclear plasma can theoretically be achieved in systems in which the plasma is in rapid rotation.

Of the many interesting rotational plasma configurations, the homopolar geometry has thus far received most attention (Fig. 7). Here a radial current and an axial magnetic field are used to set plasma into azimuthal drift motion. A transient radial current flows during the acceleration stage, and this can serve incidentally to pinch the plasma axially away from insulating end plates. The axial magnetic field employed in practice has been of the mirror machine type. The centrifugal force associated with plasma rotation tends to hold the ions away from the axis, and there-
fore traps them in the region of bulging field. Thus axial containment is achieved at first by the azimuthal pinch field and later by the centrifugal trapping effect. Rotational kinetic energy can be converted to plasma heating by viscosity or turbulent mixing, and so a measurement of the rotational decay time determines the containment achieved.

The experimental program to date has been directed exclusively to documenting the physics of rotating plasma using primarily argon. Plasma angular momentum has been measured unambiguously as a function of time, by short-circuiting the machine at various stages of its cycle and observing the charge drawn out. Ion kinetic energies above 500 ev in argon and 50 ev in deuterium have thus been demonstrated. Doppler-shift measurements indicate, if anything, still larger energies. The presence of very high centrifugal plasma pressure has been shown by the deformation of the starting magnetic field. For 5-µsec plasma-acceleration times, substantial plasma rotation has been observed up to 200 µsec later. Several large homopolars, having thermonuclear potentialities, have been completed (Fig. 8). An important incidental use of the homopolar machine is as a fast-discharge capacitor. Dielectric constants of $10^6$ to $10^7$ have been produced with ease, and output-current rates of rise of $5 \times 10^{11}$ amp/sec have been generated.

**SHOCK HEATING AND THE SCREW DYNAMIC PINCH**

(Furth and Wright)

In shock heating a body of plasma the basic procedure is to apply a high magnetic pressure that rises in a time short compared to the transit time of an Alfvén wave across a plasma dimension. A large fraction of the energy put into a shock may produce irreversible heating, and this large and sudden heating is the useful objective. The theory of a magnetohydrodynamic shock in the limit of no particle collisions predicts that in weak shocks (velocity less than twice the Alfvén speed) all the irreversible energy must appear as ion heating, whereas very strong shocks may serve only to heat the electrons.
One very critical test of the division of energy between ions and electrons in a shock is the observation of a thermonuclear yield. For this and other obvious reasons we are attempting to observe a transient but provable thermonuclear neutron yield from a partially stabilized dynamic pinch (Fig. 9).

It is well known that the standard dynamic pinch is subject to sausage (or \( m = 0 \)) instabilities which grow nonlinearly and effect the rapid self-destruction of this pinch configuration. The study of thermonuclear reactions in the dynamic pinch is made doubly difficult because the copious nonthermonuclear yield from \( m = 0 \) instability mechanisms masks the true yield, and also because the rapid deterioration of the pinch geometry prevents further heating by adiabatic compression following the hydrodynamic stage. If the \( m = 0 \) instability is inhibited by the use of an axial magnetic field, then the helical (or \( m = 1 \)) mode dominates, but the time scale of instability growth to destruction is extended. A disadvantage of included axial magnetic field is that it weakens the hydrodynamic ion interaction and serves to energize the plasma electrons instead. For this reason, as well as for reasons of optimizing plasma versus magnetic field energy content, the stabilizing axial field is applied to the pinch column in the form of an encasing sheath. The feasibility of this “screw-dynamic pinch” configuration was deduced from stabilized pinch experiments proving the space outside the pinch column to be not vacuum but conductive pressureless plasma. The configuration is generated simply by imparting a slight helical pitch to the pinch tube return conductor. The resultant field distributions have been derived analytically and verified experimentally in some detail. For high compressions, the magnetic energy storage in the screw-dynamic pinch approaches that in the standard dynamic pinch, or half that of the dynamic pinch with 50% internal stabilizing field pressure. Preliminary experiments conducted with a 15,000 joule, 70 kv, 250 ka supply have shown the expected hydrodynamics and instability pattern. Neutron pulses of about \( 10^5 \) were recorded coincident with the \( m = 1 \) instability and correlated in magnitude with the violence of this instability rather than the applied voltage. The neutron yield was unaffected by the presence of substantial fractions of helium, but could be totally suppressed at 300 microns starting pressure. The mechanism of production is not understood, but it is thought that Fermi-type acceleration of fast deuterons rather than bulk heating of the plasma might account for the yield observed. A bank of \( 10^6 \) joule energy storage and 300 kv is being applied to the study of a larger screw-dynamic device (Figs. 10 and 11).