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LOS ALAMOS ████████ of the ████████ NEW MEXICO
University of California

Review Of Controlled Thermonuclear Research
At Los Alamos
1965

APPROVED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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LOS ALAMOS SCIENTIFIC LABORATORY
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University of California

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Review Of Controlled Thermonuclear Research
At Los Alamos
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ABSTRACT

The past history, present status, and future plans of the Los Alamos Scientific Laboratory Sherwood program are discussed. A case is presented for pulsed high-density high- β plasmas as a promising route to power producing thermonuclear reactions. A proposal for a closed toroidal theta-pinch experiment (Scyllac) is given. Preliminary plans are also given for a closed flute-stable system - the Caulked Cusp.

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I. A REVIEW OF LOS ALAMOS FUSION RESEARCH

J. L. Tuck

A. INTRODUCTION

In this review, I present a case for pulsed, high-density, high- β plasmas as one route to power producing thermonuclear reactions. The testimony given before the Joint Committee on Atomic Energy, in March 1964, on Los Alamos Sherwood activity is given in part as an appendix.

The review starts with a recapitulation of the characteristics of a power-producing thermonuclear reaction. These are well-known but so far beyond present achievements as to tend to be lost to sight. We then discuss obstacles to the achievement of a power-producing thermonuclear reaction - the immediate obstacle being of course, instabilities of many types, hydromagnetic, electrostatic, micro, universal, (and many more yet to be discovered) which limit the duration of plasma confinement. Lying in wait beyond the instability obstacle, there are other obstacles not yet encountered in full strength, e.g., magnetic radiation, radiation damage to material of the reactor, plasma contamination, etc. These later obstacles are probably very real - but not so completely dominating to the design as the first one.

Briefly, my case for pulsed dense plasma is statistical:

- (1) A confined plasma has a vast spectrum of instabilities, not all of which will be eliminable. By striving for reactors with the shortest possible plasma duration τ , one decreases the chance of being struck down by an instability.

- (2) The one process contributing to a thermonuclear reactor is binary, and consequently increasing with the square of the density; while of the several processes subtracting, some are binary, some are not. Hence increasing the density tends to maximize the ratio gain/loss.

I try to identify two likely breakthrough points in the τ (or n) spectrum, one with a τ as short as the strength of materials will reasonably allow (about 1 to 20 msec), and another, which bypasses the strength of materials difficulty altogether by using a z pinch, but which may have to live with the fast hydromagnetic kink instability and so be forced to very short times (0.1 to 10 μ sec) and therefore heroic extremes of pulse power.

Reviewing next the thermonuclear plasma achievements at Los Alamos, we have achieved:

- (1) The first controlled thermonuclear reaction.

- (2) The strongest controlled thermonuclear reaction, in the sense of having the largest $n\tau$ (density $\times$ time)

- 2×10^{11} ion cm^{-3} sec for a confined plasma at thermonuclear temperature, in the world. In an unconfirmed thermonuclear reaction, we have an even larger $n\tau$ of 2×10^{12} .

So it seems that the pulsed dense-plasma philosophy has justified itself.

From our present position, attractive avenues for further advance are opening up in ways we would not have foreseen two or three years ago. Down the main line of the θ pinch, it now appears that advance to within 1/10 of the $n\tau$ required for a reactor is feasible. Looking much further ahead, calculations indicate that a power-producing reactor from the θ -pinch version of the pulsed high-density approach is by no means to be ruled out.

The Los Alamos controlled thermonuclear research program over the last decade has been characterized by a certain reluctance to

build big or grow large, with the result that our activities have consumed no more than one-tenth of the gross Atomic Energy Commission controlled thermonuclear research budget. Nevertheless we have not been impeded (until this last year) by shortage of funds (in fact we have in most years underspent our budget estimates). But to exploit the good position we believe ourselves to be in and to explore the avenues we see, can no longer be done so cheaply. An appreciable increase in staff and expenditure will be required, possibly by as much as 50%.

B. REACTOR PLASMA PROPERTIES

The Ideal Ignition Temperature is the first central quantity one encounters in describing a power-producing thermonuclear reaction. First put forward by Fermi in his lectures on Thermonuclear Reactions in Los Alamos in 1944, it is the lowest temperature at which the thermonuclear energy production rate exceeds the bremsstrahlung loss rate. Since both are binary processes, the Ideal Ignition Temperature is independent of density. Complications follow when one decomposes the thermonuclear energy into locally deposited (charged particle) and remotely deposited (neutron). Clearly, for a reactor we had better be far above the Ideal Ignition Temperature which is 40 keV for d-d, 5 keV for d-t.

The Lawson criterion comes from the basic requirement that the net thermonuclear energy yield of a plasma must at least repay the energy cost of preparing and maintaining the plasma. The criterion turns out to be the product $n\tau$, density $\times$ time.

This is derived by equating the total energy recoverable from a plasma, which has been burning thermonuclearly for a time τ , via a heat engine of efficiency ϵ , with the energy it took to create the plasma.

We have

$$\epsilon [3nkT + \frac{1}{4} n^2 \langle \sigma v \rangle \tau + \text{magnetic rad.} \times \tau + \text{bremsstrahlung} \times \tau + \text{any other losses}] = (3nkT + \text{magnetic rad.} \times \tau + \text{bremsstrahlung} \times \tau + \text{other loss.})$$

Leaving aside magnetic radiation and other losses and assuming that $T \gg IIT$ so that bremsstrahlung can be neglected, this simplifies to

$$n\tau = \frac{(1 - \epsilon) 12 nkT}{Q \langle \sigma v \rangle}.$$

Using $\epsilon = \frac{1}{3}$, we get the values given in Fig. 1. We see a minimum for $d-t$ at about $n\tau = 6 \cdot 10^{13}$ ion cm^{-3} sec, $T = 24$ keV, and much higher values for $d-d$, $n\tau > 10^{15}$, $T = 60 - 100$ keV.

Now clearly this is not a firm value - we have left out many factors, and it may be very hard to get an ϵ of $\frac{1}{3}$ in real life with neutron heating of superconductors, etc.; e.g., in the worked-out example of a power producing reactor given in Chap. XII by Ribe et al; the $n\tau$ breakeven point turns out to be nearly ten times higher than Lawson's in one case, but equal to it in another case when the superconductor is placed out of reach of the neutrons. However the Lawson criterion lies squarely athwart the path to a reactor, and nobody will get there without doing at least as well as this. So it is a valid lower limit and a point to strive for. Once this point is settled, we are at liberty to look at the properties of the thermonuclear plasmas it prescribes.

At any given temperature, the number of collisions is a function of $n\tau$. So we can compute the number of ion-ion collisions and $d-t$ reacting collisions that occur in a Lawson criterion plasma as a function of T . The curve labeled 90° collision (Fig. 1) gives the $n\tau$ for a 90° ion deflection, including distant small interactions. The ratio of the ordinates of the curves, gives the number of ion-ion 90° deflections per lifetime as a function of temperature. We see the average ion makes twelve 90° deflections in its lifetime at the optimum 24 keV temperature in DT and four at 200 keV. So such plasmas must spend most of their time randomized in velocity and direction and must be

Fig. 1. The Lawson criterion for net energy production in a thermonuclear plasma and the $n\tau$ for 90° ion deflections in the plasma.

without orderly bundles of orbits. For d-d, the number of collisions is an order of magnitude higher. These collision numbers are instructive in another sense; they show how scattering dominates over reactions.

Since n and τ are reciprocally related, it is interesting to examine the τ at which the confining pressure $p = B^2/8\pi$ becomes too high to be supported statically by the strength of materials. There is no absolute mathematical limit on this (autofrettage, etc.), but practically one encounters logarithmically increasing engineering difficulty, once the extrusion pressure of stiff solids is approached. So a reasonable upper limit for p is about 100,000 psi - which would be exerted by a 25-keV electron and ion temperature plasma of density 10^{17} ion/cm³, which corresponds ($n\tau = 10^{14}$) to a τ of 1 msec (Fig. 2). So τ less than this must be ruled out for reactors in which the magnetic confining field of the plasma tends to burst the coils of the machine. Not all systems do; force free coils experience only volume compression forces; self-pinch plasma (z pinches) hardly press on the walls at all. These exceptions provide ways of circumventing the strength of material limit we shall discuss later.

The region far to the long-time (left-hand side) of the τ diagram is greatly to be preferred both from the engineering point of view of working pressures, and also from that of having a smoother flow of power. Thus a steady-state plasma maintained by particles fed in and bled out with sojourn time τ of several seconds would be ideal. This region has been the target for most of the Atomic Energy Commission supported controlled thermonuclear research laboratories - to the extent that it has absorbed three-fourths to nine-tenths of the expenditures to date. It is at this point that we at Los Alamos diverge from them.

In order to explain why we prefer the difficult regions marked A and B in Fig. 2, we first glance at the final state of a plasma confinement system. A static magnetic bottle with plasma relaxes to a uniform plasma resting on and in temperature equilibrium with a wall, with the magnetic field at its vacuum value. This is the state of

Fig. 2. Difficulty of making a thermonuclear reactor.

maximum entropy, and minimum free energy. In parenthesis, the plasma need not rest on a wall if it experiences force describable by a potential, e.g., electric or gravitational fields - so that, surprisingly enough a z pinch could exist permanently in vacuo, in presence of diffusion, (instabilities permitting).¹

Thus in general, a magnetically confined plasma is not in equilibrium; furthermore it is an exceedingly complex system with of order n^2 modes by which it may relax. A catalogue of already classified types of waves in it would fill several pages. We can gain some sense of what will happen in the future on this problem by looking at the past history of controlled fusion research.

At first, theory was of the simplest, i.e., infinite conductivity hydromagnetics. The measures to inhibit hydromagnetic instability, such as magnetic shear, incorporated in magnetic bottles of those days were easily evaded by real plasma which executes maneuvers prohibited by infinite conductivity hydromagnetics. The addition of finite conductivity to the theory was able to explain, e.g., by tearing, buckling modes, some of the new effects. It then became clear that even with finite plasma conductivity, hydromagnetic stability could still be got by going back to the first principles, cf. Rosenbluth and Longmire (1957)² in the form of bottles with magnetic walls everywhere convex to the plasma. Topologically, this forces one to open-ended systems, and at first approach, to systems with magnetic field zeros (cusped geometries and picket fences) (Fig. 3). These are far from out of the running these days - but the nonadiabaticity of field zeros is hard to work with, and these systems find fusion reactor application solely in the pulsed high-density region. More refined application and rereading of the literature revealed geometries with everywhere convex curvatures which, while still open-ended, have no zeros. These are the currently highly topical nonzero absolute minimum bottles (magnetic dimples, wells, hybrid traps, minimum B). So these systems can be both adiabatic and flute stable. Experimentally in some cases, a large ~ 100 - to 100 -fold

EVOLUTION OF FLUTE STABLE SYSTEMS

Fig. 3. Evolution of flute-stable systems.

increase in confinement time results from their use (Joffe), but only to bring to light (this result is not confirmed) another slower instability.

The next improvement (still mentioned in the original Rosenbluth-Longmire paper of 1957), is the possibility of closing off the open ends of flute-stable, convex-walled bottles by very strong concave fields. Since the criterion for amount of instability $\delta \int dl/B$ (or V'') for a particle sampling all regions on a closed line round the system has B in the denominator, it should be possible to more than compensate the flute-inducing drift in the unstable, strong- B , concave part by the stabilizing drift in the stable, lower- B one. Actually the first such system was the caulked cusp, proposed by the writer and Longmire in 1957, and this idea has now become highly topical with Helixions, Multipoles, toroidal strings of Andreoletti systems (Furth and Rosenbluth),³ negative V'' machines, and several more shown in Fig. 3. They should be greatly superior to open low- β systems since they have no mirror losses. The sampling procedure introduces a risk, however, so that the merit of closed, flute-stable systems will be related to the closeness of intercommunications of the good and bad regions. This is the reason for preferring the caulked cusp to the helixion at Los Alamos.

It seems that there are several measures that can be taken against hydromagnetic instability - in addition to shaping the magnetic field. Experimentally and as predicted theoretically, finite Larmor radius (high ion temperature) seems to have a stabilizing effect, essentially by smearing out the space charge which drives the flutes. On the whole, it seems that the outlook for hydromagnetic stability in systems with closed-averaged $\int dl/B$ increasing, backed up by finite Larmor radius stabilization is quite good.

Turning to the electrostatic (or micro) instability problem, let us consider the state and development of a confined plasma meant to produce power:

- (1) The plasma ion and electron temperatures T_i and T_e will probably be different depending on the mode of generation of the plasma.
- (2) The distributions of ion and electron energies need not be Maxwellian at birth.
- (3) Plasma density falls from n to 0 in moving from plasma to field.
- (4) Field rises by a factor of $1/\beta$ in moving from plasma to field.
- (5) Since the plasma is confined, currents of oppositely directed electrons and ions flow in the transition region.
- (6) In a steady state device, there must be some point where the stream of diffusion to the wall is intercepted and disposed of. So plasma must flow along lines to the disposal point.
- (7) If the bottle has a region where magnetic lines leave the system (magnetic mirror), the ions and electrons may have different loss rates, so that the plasma acquires a net electric charge.
- (8) Such an electric charge would be expected to set the plasma into rotation in systems with cylindrical symmetry.
- (9) The turning points of ions and electrons at the magnetic mirror may be different, causing compensating electric fields parallel to magnetic lines to develop.
- (10) In the plasma we have a large selection of possible waves including Alfvén, ion cyclotron, electron acoustic, and ion acoustic modes, moving in various directions.
- (11) Some of these can be expected to form standing waves with the plasma dimensions, i.e., cavity resonances. This means greater wave amplitudes with increased effects from nonlinearity.
- (12) The great range of plasma density and magnetic field variation from center to wall maximizes the possibility of coincidence between wave singularities and resonances of different wave species.

- (13) Electrons in the sheath radiate at harmonics of the electron cyclotron frequency in a direction normal to the magnetic field. If the electrons are hot, the radiation (and absorption) can be strong, such that the mean free path of the radiation is short and the radiation is black body at the harmonics. This may alter the electron temperature in the sheath, creating a temperature gradient. The outgoing radiation will be reflected at the wall, entering the plasma at some other point with a direction not perpendicular to the magnetic field. The possibility of stimulated emission, by the radiation of otherwise nonradiating electrons exists. Resonances should occur with reflecting walls producing standing electron cyclotron waves.

And so on; the list could be continued.

We now can expect to find in this plasma: unequal T_e , T_i , non-Maxwellian distributions $v_{||} \neq v_{\perp}$, temperature gradients, currents along magnetic lines, density gradients, flows along magnetic lines, centrifugal forces, etc., every one of which have been shown to drive one or another growing wave already classified in current plasma theory. Current plasma theory usually has to be linearized though nature is nonlinear. Nonlinear finite-amplitude theory with second-order effects such as interactions between different model systems is mostly in the future.

I conclude therefore that:

- (1) A great number of kinds of instability are possible in a confined plasma.
- (2) Theory is quite incomplete.
- (3) Plasma theory should be heard with attention when it predicts an instability.
- (4) Plasma theory should be treated with reserve if it predicts stability for any particular combination of plasma parameters n , T_e , T_i , f , etc.

Nevertheless, although vast numbers of instabilities seem possible, there seem to be excellent chances that some whole classes of wave instabilities can be stabilized - for example, finite Larmor radius may again be effective in smearing out wave disturbances. But more than this, it seems very likely to me that the net bad effect of instability-enhanced motion across the magnetic confining field may be diminished by dynamic methods, e.g., alternating and rotating magnetic fields - for these can have a continual restoring and reshaping effect on a magnetic boundary, and can even reverse the direction of the flow of diffusion. Dynamic confinement methods should therefore be an important item for laboratories aiming at steady-state confinement. However for the next few years, it seems very unlikely that all or even a large fraction of possible instabilities will be stabilizable.

So I conclude that the safest approach must be a statistical one - the most likely route to a reactor is that least likely to encounter a killing instability. Now clearly, if instabilities were predominantly favored by large n , there would be a systematic clustering of instabilities to the small- τ , large- n end of the spectrum, leaving the large- τ , steady-state end clear, and my argument for pulsed reactors would be invalidated. This is certainly not the case with hydromagnetic instabilities or Alfvén waves which are largely independent of n . The electrostatic and wave instabilities are too numerous and varied to generalize. There will doubtless be some instabilities among them which are favored at high n , but not all.

We next observe that if we have an irreducible residue of instabilities which produce a randomly distributed set of effective loss times $\tau_1 \dots \tau_n$, then each τ_k cancels out all plasma-confinement systems with τ greater than τ_k . Thus the largest possible confinement time for a reactor must be the shortest τ in the distribution.

Hence the reactor least likely to be killed by an instability is that requiring the smallest effective confinement time.

Once this important point is accepted, the optimum breakthrough

points to get to a reactor are those with the smallest τ s: i.e., Region A in Fig. 2, as close to the strength of materials limit $\tau \sim 1$ msec as seems engineeringly practicable, and Region B in the microsecond region for z pinches, limited only to keeping the energy release from being too explosive and the electromagnetic pulse power requirements too extreme.

Another argument in favor of the pulsed dense-plasma approach to fusion power is as follows: In spite of all the instabilities and radiative loss processes, we know that a power producing fusion reaction has been made. It is, appropriately, a pulsed high-density plasma device whose parameter stands a little off the right-hand end of Fig. 2. By backing off from those dread parameters to the minimum extent consistent with safety, one at least stands in the vicinity of a region having a known positive energy balance.

The foregoing arguments for a pulsed high-density approach to thermonuclear power are not meant to imply that it is the only one. It merely seems to be the easiest.

The fusion power situation can, it seems to me, be thought to have distinct analogy with that which occurred in the development of the internal combustion engine. There the problem is how to maximize the upper temperature of the Carnot cycle, without destroying one's engineering materials. The reciprocating internal combustion engine is the crude pulsed solution to that problem, analogous to the pulsed thermonuclear reactor. The far more elegant, smoothly-running gas turbine would then be the analogue of the steady-state low- β , thermonuclear reactor.

C. PAST HISTORY AND PRESENT STATUS OF THE
LOS ALAMOS SCIENTIFIC LABORATORY PROGRAM

1. The Scylla Theta-Pinch Experiment

The original concept of this experiment in 1957-1958 was to heat a preionized plasma in two stages, first to a few eV by a strong radial shock produced by an E_θ field from a rising B_z (axial) magnetic field, and secondly by adiabatic compression by the rising B_z field to kilovolt temperatures. The first experiments were done with short ~ 10 -cm-long coils of 7-cm diameter shaped to produce magnetic mirrors, with magnetic fields rising to 50 kG in times of about 1.25 μ sec.

The device produced neutrons from the start, though only on the second half-cycle of the oscillating magnetic field. It was soon found that these neutrons were produced from a small ellipsoidal region at the center of the coil, and that these neutrons were quite different in energy distribution from the so-called "phony" neutrons that had been widely obtained from z pinches, undoubtedly produced by instability mechanisms and not thermonuclear. The extent and number of interlocking and differing diagnostic experiments that have been made on the Scylla plasmas over the last 8 years are rarely realized. The list in the main article on Scylla in this report should be read. Elaborate diagnostic experiments showed that the plasma depended for its high temperature on annihilation of the reversed magnetic field left over from the previous half-cycle; that the reversed magnetic field played some more fundamental role than being merely a residue from the previous half-cycle was first shown by Kolb at the Naval Research Laboratory.⁴

A hypothesis for the reversed-field heating mechanism may be of interest. After the magnetic field reversal, an intense current sheath sweeps inward, driving a shock. This heats the plasma enough to trap inside the magnetic field left over from the previous half-cycle. The magnetic compression proceeds, but an internal magnetic-dipole field

reversed in sign with respect to an external field is highly unstable with respect to flipping over the internal dipole. So this occurs. A rigid ring would continue to turn, end over end, the initial configurational energy periodically becoming all kinetic. A nonrigid plasma can never recover its original configuration, so a fluctuating, at every point increasingly tangled configuration results, the thermal energy still being divided equally on the average between configurational and kinetic. The tangling or knotting increases to the point where motion becomes indistinguishable from thermal. After this, the compression by the external field proceeds to pressure balance.

There are now many θ pinches throughout the world. They differ greatly in their construction and phenomena. In some, the reversed magnetic field persists, and some produce hollow plasmas with the reversed magnetic field down the axis. It has been shown that axial compression contributes heating in some of them, and some show breakup into plasma rings, twin rotating filaments, etc. The plasma in some Scylla models develops into a single rotating filament with exponentially growing drift to the wall, i.e., an instability. Scylla has a higher effective voltage than most θ pinches, and, in accordance with the initial philosophy of shock heating, makes more neutrons and is hotter. The Scylla plasma is not unique, however. There exists one θ pinch,⁵ that at General Electric (Schenectady), which followed the Scylla prescriptions quite closely and duplicated the Scylla results and extended them. The General Electric group discovered that by resorting to very strong preionization in the presence of a low-bias magnetic field and at lower pressures, operation could be obtained without reversed magnetic field heating. The Los Alamos Scylla IV adopted this technique - which amounts to achievement of the original concept of the experiment - with great improvements in impurity content, temperature, and, especially, stability.

By 1960, evidence for a thermonuclear (but not Maxwellized) origin for the Scylla neutrons (10^7 to 10^8 or more per shot) had piled up to a point where it must be regarded as confirmed. It would be churlish to deny the part that luck played in this achievement of the first laboratory thermonuclear reaction. Without the reversed-field heating which was not part of the original design, the experiment would not have developed thermonuclear temperatures as it then was, and might have been abandoned.

The properties of the Scylla plasma are discussed more fully later in this paper. I shall content myself with certain special questions which might arise. The Scylla thermonuclear reaction is quite strong (100 W for 3 μ sec) but:

- (a) Is it really a confined plasma?
- (b) Could it be grossly unstable but last too brief a time to show it?

The present low-density-regime Scylla IV plasma has the following properties:

T_e (Maxwellized) - 300 eV
 T_i (largely monoenergetic) - 8 keV
 τ to half-neutron yield - 3 μ sec
 n - 3×10^{16} ion cm^{-3}
Volume - 50 cc
Total neutron yield - 5×10^8 per pulse
Neutron rate - 1.7×10^{14}
Configuration ellipsoid - 0.63-cm minor dia, 80-cm major dia
Number of 90° ion-ion collisions per ion per pulse - ~ 1
Plasma pressure - 324 atmospheres
Magnetic field (external) - 90,000 G
Magnetic field (internal) - very small
Path length per ion per pulse - 870 cm
Impurity content - $< 0.1\%$
Gross thermonuclear power during the pulse - 95 W

The plasma presents a picture of a field-free region, with ions executing straight line-paths and being reflected from the magnetic walls, the motion being predominantly radial. A radially directed ion makes 1400 reflections from the wall in its lifetime - which is surely a characteristic of a confined plasma. In connection with the second question: In such hot plasma, flute-growth velocity can be very high - approximately 50 cm/ μ sec. Although the observed confinement lasts perhaps five flute-instability e-folding times, no flutes are seen. Nevertheless when the conditions are changed significantly to lower temperatures and a shorter coil, in the same magnetic cycle time, major wall losses occur and strong flutes develop. The higher temperatures and longer length effects on stability are both indications that some finite Larmor radius stabilization is being obtained.

Since the ion energy distribution in the Scylla plasma is more isoenergetic than Maxwellian, it is appropriate to discuss what is meant by the terms temperature and thermonuclear. Taking the electron temperature to be zero and outside the discussion: The energy density of a plasma of n ions/cm³ having a Maxwell distribution at temperature τ (in eV) is $3/2 \epsilon \tau$ ($\epsilon = 1.6 \times 10^{-12}$ erg/eV). The energy density of a plasma of n ions/cm³ all having the same energy W (eV) is $n \epsilon W$. Hence a Maxwellized plasma of temperature T is adiabatic with an isoenergetic plasma of energy $W_{\text{erg}} = 3 T/2$. The problem we are attacking is the preparation and confinement of plasma of high average ion energy. If nuclear reactions are formed by collisions between average members of the distribution, I define such reactions as thermonuclear. Nevertheless as discussed on page 18, for a plasma to be power producing, $n \tau$ will be large enough for appreciable Maxwellization to have occurred. It is a curious fact that for a given energy density, the isoenergetic plasma gives the lowest possible thermonuclear rate at all temperatures for d-d. The relaxation of an isoenergetic plasma therefore increases the thermonuclear yield. Nonthermonuclear reactions are those generated by a minority of ions in nonequilibrium with a majority, i.e., a beam of high-energy particles circulating in a cold plasma. Such a plasma relaxes to diminish the yield.

In the earlier high-pressure regime, $T_i \sim 2.0$ keV, a wave of plasma impurities can be seen (from the Mach-Zehnder figures) to form at the wall and move inward. One of the most encouraging features of the low-pressure regime is the absence of such wall effects (Fig. 4).

Two hypotheses, which as yet we cannot distinguish, can be proposed to explain this: (a) The high-pressure regime has more impurities and radiates more (about 40 times classical bremsstrahlung). This radiation may heat the wall and evaporate it. (b) The low-pressure regime shows no radial diffusion whatever, whereas the high-pressure regime diffuses somewhat. We may then have sufficient Bohm diffusion by microinstability in the latter, similarly to heat the wall. Absolute measurements of the bremsstrahlung rate from the low-pressure Scylla plasma now show that the bremsstrahlung rate is only twice classical. This is a very low value indeed. Radiation from earlier Scylla plasmas has been as much as 200 times classical, and, in the rare cases that such absolute measurements have been obtained from laboratory plasmas elsewhere, the observed bremsstrahlung rate has been similarly larger than theory. This low radiation rate has important consequences for the future extension of the Scylla machine to longer times and closed systems. Until now, the influx of wall impurities in the high-pressure regime had made it seem pointless to attempt longer confinement by going to a closed-geometry Scylla.

2. Plasma Guns, Plasma Injection, and Trapping Studies

The hydromagnetic coaxial plasma gun developed in this Laboratory provides a directed burst of dense plasma (10^{17} to 10^{18} ions total) with energy adjustable from 2 to 10 keV. The operation of the gun is considerably embarrassed by a later emission of slower, cooler plasma. This gun, now in wide use around the world, makes enough hot plasma that, once it is injected and captured into a static magnetic bottle, significant plasma physics experiments can be made. The operation of the gun is not clearly understood. It does not function by the simple-minded sweeping out of plasma by a $j \times B$ current magnetic-field piston. The energies observed

Fig. 4. Compressed plasma of the Los Alamos Scylla IV θ pinch as shown by Mach-Zehnder interferogram at $\lambda = 6943 \text{ \AA}$. This is near peak compression in the new low pressure, higher temperature regime without reverse magnetic field heating. P (initial) = 15 m-torr D_2 . B applied = 90 kGauss. Time = 1.6 μsec . Plasma mean length = 70 cm. 1 fringe = $3 \cdot 10^{17}$ electron/cm². Mean ion energy (calc) = 7.3 keV (equivalent to 4.9 keV ion temperature for Maxwelllized ion energies). Electron temperature = 300 eV. Mean neutron yield = 6×10^8 per discharge. Note absence of wall impurities.

are many times too high for that. Probably some terminal acceleration process is involved. The plasma slug from the gun exerts dynamic pressures of $\frac{1}{2} \rho n m \bar{V}^2$, large enough to deform multi-kilogauss magnetic fields. Much interesting work is being done on the conduction of this gun plasma down magnetic ducts. A first requirement for effective application of these gun plasmas is to be able to control them magnetically, i.e., stop them, steer them round corners, and so on. It is a surprising thing, after nearly fifteen years of plasma research throughout the world, that no one has succeeded in steering a slug of hot plasma round a 90° curve with more than 10 to 20% efficiency. In the laboratory, such plasmas act in ways that would not be predicted. This is because actual situations turn out to be more complicated than can reasonably be foreseen. Certain very interesting trapping possibilities exist by virtue of the polarization charges which develop when gun plasmas cross magnetic fields. For example a gun plasma is directed across a magnetic field, lines of which are continuous, but reversed in direction from, magnetic lines traversed earlier by the plasma. When the fast plasma penetrating the field reaches this region, a large current of polarization electrons can travel along the magnetic lines between the two regions to cancel the polarization, thus halting the plasma automatically. This was one of the rare cases when observations on polarization and conduction led to a purposeful change in the magnetic field configuration - which functioned in the way predicted.

It may be noteworthy that the 1964 United States exchange delegation on their tour of the USSR fusion installations, reported a large increase in Soviet work with plasma guns, ducts, and trapping, very much along the lines of that at Los Alamos.

3. Plasma Focus Experiment

In 1960 some studies were made on coaxial guns in an effort to understand how they worked and thereby improve them. To determine the angular distribution of the ejected plasma, the d-d neutrons generated when the plasma slug impinged on a distant D_2O ice target were plotted.

This led to the observation that some neutrons were produced at the gun itself. Further exploration and optimization including working with a static deuterium filling, resulted in an apparatus which forms a plasma focus with extraordinary properties.

The focus has a volume of a few cubic millimeters. It generates a burst of neutrons lasting 0.1 to 0.2 μ sec, numbering up to $2 \cdot 10^{10}$. This is a very large number, and since mistakes have been made about neutrons before, the methods of detection and margin of error will be discussed. The yield is not measured by proton recoil in a scintillator, and is therefore not subject to confusion with γ -ray Compton electrons. The yield is measured by the activation of silver in a standardized moderator-counter system. Such a method is not subject to intensity or pile-up errors -- the only errors being:

- (a) reflection of neutrons from the environment, and
- (b) error in calibration or malfunction of the scaling equipment.

The environment errors should be small here, possibly 5 to 10%. The moderator-counter system was developed as a neutron detection standard many years ago in the nuclear physics department of the Laboratory and has been adopted and checked widely in laboratories throughout the world. However, in order to make more sure and increase accuracy, a recalibration against a standardized d-d neutron source has been made. We can safely dismiss the possibility that the neutron yield measurement is in gross error.

Knowledge of the nature of the plasma focus is so far quite incomplete. The shape of the plasma focus is known, the electron temperature is known by differential absorber measurements on the bremsstrahlung, and it is known that the neutrons are close to isotropic. A Mach-Zehnder interferometer with great field magnification is being set up which should yield electron line density directly, as was used so effectively for the Scylla IV plasma. The Los Alamos extension of the Ashby-Jephcott He-Ne laser beam is also to be applied. This gives a continuous record of electron density along a very narrow pencil beam.

To produce so large a neutron rate from so small a volume by thermonuclear reaction requires a density of about 10^{19} ion/cm³ and a temperature of about 10 keV, since the duration of the neutron burst exceeds the Maxwellizing time.

The obvious deduction from the experimental arrangement is that a sheath sweeps down the space between the inner and outer coaxial electrodes and contracts into a z pinch when it runs off the end.

However, z pinches (Columbus I - V) were studied extensively at Los Alamos in earlier years - 1953 onwards. Although these devices produced neutrons, it was shown that these neutrons were anisotropic, and, in fact, must have been produced by acceleration in the strong electric fields of M = 0 (neck or pinch-off) instabilities.

The ion temperatures in such z pinches were probably quite low. However, an instability explanation for a yield of 2×10^{10} neutrons from a few cubic mm of plasma is difficult for two reasons:

- (a) The current of 10-keV deuterons required to pass through a cubic mm of deuterium of density 10^{19} is 5×10^8 amperes, which far exceeds the total current flowing in the apparatus ($\sim 10^6$ amperes).
- (b) The neutrons are isotropic.

Another curious inconsistency is that the calculated pinch-off time for an M = 0 instability is much less than the observed 0.2- μ sec neutron emission period. The suspicion is that we have here, for the first time, a hot z pinch, so hot that we are getting some finite Larmor radius stabilization.

If this possible thermonuclear reaction becomes confirmed, which will need much further study, the n τ value of 5×10^{12} becomes the largest known, exceeding the previous Scylla record of 2×10^{11} .

There is a close similarity between the plasma focus and one reported by Filippov et al.⁶ Their neutron yield was less, and ours was reached by a different route (stumbled on in fact). The intensity of the d-d reactions in the few cubic mm of the plasma focus would perhaps best be

appreciated by calculating how long all the plasmas of the world's machines would have to run on deuterium to yield 2×10^{10} neutrons. It is simpler to calculate the running time of one of the largest steady-state machines - OGRA. This is credited with 80,000 liters volume of plasma (of density 10^9 ion/cm³ at mean energy 100 keV). If filled with deuterium, this gives a total yield rate $Y = \frac{1}{2} n^2 \langle \sigma v \rangle V$ of 2×10^8 neutrons/sec. It would take about 100 seconds continuous operation of this large machine to equal the neutrons generated in $\sim 2.5 \times 10^{-7}$ sec from the few cubic mm volume of the plasma focus.

D. A SKETCH OF FUTURE PLANS AND PROBLEMS

Opening up before us are numerous attractive lines of research which as little as a year ago were hidden from view.

1. As we have seen, the Scylla IV plasma is dense and hot. For the present 3- μ sec durations it is also stable, so that it does not cross the compression field to any detectable extent but runs quite rapidly out of the open ends. We need to know how long it would last if the ends were closed. We do not expect it to remain stable for the classical diffusion time, of course, but it becomes practically mandatory to find out what the confinement time for a $\beta = 1$ plasma dense enough and nearly hot enough for a reactor would be.

The problem of a $\beta = 1$ plasma in a torus is that of combatting the outward force on the diamagnetic body - the so-called gross stability - in the magnetic field gradient of a torus. The solution to this force problem, by placing alternating Joffe bars on the outside of the torus is given in Chapter XII. It turns out that the confining system derived by Furth and Rosenbluth can also be applied (with some modification) to compensating the outward drift in a torus while maintaining $\int dl/B$ stability.

The plans for such a closed Scylla (Scyllac) are given. This will require a new building of total floor space comparable with our present total.

2. The ~ 0.6 -cm-dia, 50-cm-long hot plasma ellipsoid of Scylla IV makes a natural starting point for a z pinch.

3. To complicate the situation further, Scylla turns out to have very good reactor possibilities. This is unexpected. It was planned as a plasma physics experiment - just to make a thermonuclearly reacting plasma in the laboratory - with no claims to being a prototype reactor. And it must be admitted, when in the company of enthusiasts disputing whether their machines would make thermonuclear power for \$72.00 or \$85.00 per kilowatt, the chances that the Scylla plasma at 100 watts for 3 μ sec could ever repay the megawatts expended in the compression coil seemed remote. We have examined the feasibility of two examples of pulsed high-density reactors (summarized in the Scylla section), including multiplying blanket, heat transfer, and stresses. It turns out to be more straightforward to make a power-producing reactor than was previously believed. The extrapolation beyond present plasma behavior is far less than "engineering concepts" for thermonuclear reactors have usually had to make.

4. The fast plasmas generated by our hydromagnetic guns make possible fundamental plasma physical studies of the way anisotropic plasmas, plasma winds, etc., react with magnetic walls in a way that it does not seem possible to reach any other way. The gun plasmas are a vital component of the plasma trapping methods (entropy and polarization) for getting gun plasma into magnetic bottles suddenly. If the confinement time of the closed flute-stable bottles at realistic reactor-type densities turns out to be milliseconds - what other method is going to be available for filling them? So a start on a closed flute-stable bottle with walls of magnetic field thick and strong enough to hold gun plasmas seems strongly indicated. The problem is which bottle is safest from the point of view of stability and most economical to build. Our top priority effort over the last 6 months has been on this problem. It seems fairly clear now that safety and economy are incompatible - the helixion⁷ is magnetically more economical than the

multipole. But the magnetic lines joining different regions are long and complicated in the helixion and connect positive and negative curvature regions most directly in the multipole. Plans for a multipolar (multifilar) machine powered by a 10-MJ energy storage systems are advanced but not complete.

5. The concept of a z pinch so strong as to yield a positive thermonuclear power balance before the fast hydromagnetic kink instability can take it apart is an old one. Under the title "Columbus X Concept," it is discussed in my previous review of Los Alamos fusion research for the Atoms for Peace Conference, Geneva, 1958.⁸ The term inertial confinement is sometimes used (wrongly) to mean fast z pinch. A z pinch, in fact, gives some confinement over and above that for a straight implosion, which has the minimum possible confinement. This concept now comes back strongly for the following reasons: (a) Straight z pinches were extensively studied at Los Alamos in the years 1952-1957. Z pinches have a special advantage over all other magnetic confinement systems in one respect - they give more confinement pressure per unit of magnetic energy than any other system, but they are extremely unstable. They provide excellent, though very brief, condensations of plasma (Fig. 5) but such plasmas were never hot - merely cold plasma traversed by a few fast ions. We tried to increase the temperature through increase of contraction velocity by raising the applied voltage. This was ineffective; at high voltages the plasma sheath refuses to detach from the wall which conducts, emitting pressureless impurity plasma. So we gained no knowledge of what a hot z pinch is like. (b) Now however, we can make hot plasmas by other methods - Scylla or hydromagnetic guns. The experiment of taking the long, 8-keV Scylla IV ellipsoid, which floats in vacuo away from all walls, as the starting point for a z pinch looks very attractive. (c) On the theoretical side, the snowplow theory of z pinches, which has been most serviceable for explaining the contraction process, stops off before the interesting

Fig. 5. 50,000-ampere z pinch in argon produced at Los Alamos in 1953.

stage when the pinch has contracted to a radius and is at such a temperature that it is narrower than the snowplow sheath thickness allows. Such a plasma might even be stable to $M = 0$ necking-off modes. So this old problem needs to be taken up again theoretically and with computers. (d) In the early 1950's no methods for measuring the density in z pinches were available; the density was too high to be measured by microwaves, and the laser had not yet been invented. Such pinches are now ideal subjects for our Mach-Zehnder technique, which has worked so well for Scylla. The He-Ne narrow-beam laser should similarly work well. (e) To get power from a Columbus X type reactor calls for very large currents and voltages if the disassembly time is only that given by pinch radius/sound velocity. That the z pinch might be a candidate for finite Larmor radius stabilization is a possibility that had not occurred to me previously. But now we even have evidence that stabilization of some kind may be occurring in the plasma focus - since the duration is otherwise about one hundred times too long. If this should turn out to be true, the currents and voltages for a Columbus X type reactor can become quite reasonable - we can even start thinking of a d-d reactor. In view of the advantage in cross section, it can hardly be doubted that the d-t thermonuclear reactor will come before the d-d. Nevertheless, the multiplying blanket and the associated tritium chemical plant is a monstrous inconvenience. It would surely be worth a great deal in terms of increased input power to be rid of them by going to d-d if at all possible.

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APPENDIX

TESTIMONY OF J. L. TUCK BEFORE JOINT CONGRESSIONAL COMMITTEE ON ATOMIC ENERGY, MARCH 1964^{*}

Dr. Tuck: First, speaking to the question in pursuing Project Sherwood, "Are we flogging a dead horse?". In my opinion fusion power is one of the really noble worthwhile projects of the present time. The world will soon have to depend on nuclear power for this, fusion power is much more acceptable than fission. The reason for this is not because deuterium is more plentiful or cheaper than uranium, the fuel cost is a negligible part of nuclear power cost, the real reason is that fusion is safer, it won't blow up, and it doesn't leave behind long-lived poisonous fission products. Furthermore, though I do not consider this important compared with the above, some considerable time after fusion power is an accepted fact, it logically offers the means for high specific impulse space navigation, by comparison, with which all other methods including fission reactor rockets are lame. The trouble is that the achievement of controlled fusion is a difficult and subtle matter enormously much more so than fission.

But the very magnificence of the goal of Project Sherwood led its followers into trouble. For example, some enthusiasts oversold the

^{*} Hearings before the Joint Committee on Atomic Energy, Congress of the United States, Eighty-Eighth Congress, March 2 and 3, 1964. Part 3, (U. S. Government Printing Office, Washington, 1964) pp 1467-1470.

AEC in the first days of the project on its immediacy so that there was too much money. We Sherwood scientists were inexperienced in this new subject, and truth to tell, naive, and some of us had new laboratories to create. Everything that popped into our heads was built and everyone was hired who could be caught. So there are, let's face it, many highly respected physicists who scowl at the word Sherwood. As I will try to show, this is unjustified, in fact there is nothing wrong with the Sherwood horse, it merely had a wild and misspent youth. Other countries suffered in the same way, the Zeta pinch in England cost \$5 or \$10 million of hard-earned money. It got the same results as our Los Alamos Perhapsatron which cost only \$40,000 and neither were thermonuclear. We don't know about the early Russian mistakes except the time when they believed the early Zeta claims and crash built a duplicate which they called Alpha.

Considering now the LASL participation in fusion. We got into this very early, perhaps the first in the United States. We decided to take the rather down-to-earth approach of trying to make a thermonuclear reaction, something which had never been done before in the laboratory, by whatever means we could and however brief it might be, and not bother too much about reactors. We succeeded at the second attempt in 1958. Our first attempt was the Perhapsatron which used the simple pinch effect for which we were the first in (1951), and seeing that it wasn't going to work, the first out. The pinch effect was prime favorite in those days, and some European laboratories, after arduous work were just getting moving on it, when we dropped it at LASL. It caused a sensation.

All the time we resisted the temptation to build huge machines or hire large staffs. The net result is that we have spent only one-tenth of the total Sherwood costs and are by far the smallest in size of the four AEC laboratories. This sounds very virtuous, but I have now come to realize that it was suicidal. Representative Cannon, chairman of the powerful Appropriations Committee has demanded very reasonably that "some concepts be cut out, you ought to know enough by now to weed out

the unpromising ones" and funds for Sherwood are now being restricted.

How is the AEC to take account of these effects? Two months ago we discussed in Washington the proposal to cut out Los Alamos fusion completely, the logic being that after all it represents the smallest capital investment, and is therefore the most economical way of obeying senatorial instructions. Crazy logic of course, like throwing out the baby with the bath water. It didn't happen but it has frightened us and now the cuts are being parceled out among the four laboratories essentially in the ratio of their size, 4, 4, 2, and 1.

Returning to the IASL story: In 1957 we then turned to the θ -pinch Scylla apparatus which seemed to give a thermonuclear reaction from the very beginning. This machine was exhibited in operation at the Atoms for Peace Conference in Geneva, Switzerland, in 1958 with the clear understanding that it was probably thermonuclear but that that still had to be proved. We have passed through four models of this device and we are now quite certain beyond a shadow of a doubt, that we had then and now have a stronger true but brief thermonuclear reaction. The yardstick which measured progress in this field toward a reactor is $n\tau$, density $\times$ time, and in this respect our small Scylla apparatus stands among the highest in the world. There are now many θ pinches in fusion laboratories, so much so that Academician Artsimovich was moved to say in his summary of controlled thermonuclear research progress at the last international conference in Austria, "Soon no housewife will be without one" but he went on, "but what a feeble thermonuclear reaction, only enough to give one neutron to each inhabitant of Austria. We must do better than that". Well, we have: We now make 1 billion neutrons per shot, enough to give everyone in the world half a neutron apiece. Our thermonuclear conclusions have been confirmed and extended in a scaled-up Scylla-like device which the General Electric Company have built with their own funds. It will be exhibited at the New York World's Fair.

It is surprising to us how little prestige the AEC made out of

this very real achievement of the first laboratory thermonuclear reaction. Here, we had an achievement - not just a promise. No doubt, if the AEC had not had the uncomfortable task of holding the balance among the four competing AEC fusion laboratories, and we had not been so much smaller, it would have been easier for them.

There have been two reviews by outside scientific authorities of the overall Sherwood effort and both times, the Los Alamos work was picked out for favorable comment. The last review of the General Advisory Panel recommended an increase of staff for LASL and we propose, if given the chance, to increase from 50 to 54 people. Our present budget is approximately \$2 million per annum. We are at last beginning to see how to make an intelligent but prudent expansion of our work. This is mainly in the direction of closed pulsed systems called caulked cusps but also involves making longer duration Scyllas.

Our philosophy is to concentrate on pulsed devices for fusion. The reason for this is not that we wouldn't prefer to have a steady running fusion reactor such as the other laboratories concentrate on - but that nature has plenty of surprises in store for us all yet. There are some quite likely ones (instabilities) which could kill steady running fusion reactor concepts dead but still leave pulsed concepts alive. It is safer, therefore, to stay with pulsed concepts and let the steady running, if nature lets us, come later. It is ironic that just when we see how money might at last be spent wisely on fusion, the money that we refused in the early days is no longer available.

I do not know the answer to the problems of growing up. I suspect there will always be some waste associated with vigorous new growth and vitality. Certainly if the U.S. effort hadn't started the way it did, we would now be tremendously behind in the subject vis-a-vis the rest of the world. So in a sense, the United States is indebted to the early superenthusiasts.

But there is still a problem - an organizational one for which I do offer a solution. Clearly - *de minimis non curat lex* - the law

does not occupy itself with trifles - and for you, as representative of the United States, the relative survival of one laboratory versus another is a trifle - what matters is whether the job is done. I think the job will be less well done if Los Alamos gets pinched out.

As for the difficulty of finding the right level at which to support fusion, I propose that we express it in terms of what we spend on fission - some small fraction - say 5 percent and peg it there for awhile. Surely this is logical - both are trying to provide nuclear power but fission is the more advanced.

Mr. Conway: Except they are cutting back on the fission program.

Dr. Tuck: But 5 percent would still leave us in clover. Thank you.

Representative Westland: I was just going to say in response to your de minimis non curat lex that this is a case of res ipsa loquitur.

Dr. McDaniel: Mr. Chairman, I note from the last speaker that there is no absence of enthusiasm for our project.

Representative Westland: I would like to say that as long as you gentlemen can keep your sense of humor as exhibited by Dr. Tuck, things will probably be in pretty good shape in your field. We have the same problem in the job we have.

Dr. McDaniel: I think I would like to call on Dr. Allen Kolb from the Naval Research Laboratory who has a few words to say before we close.

Dr. Kolb: After the last presentation, I more or less changed the direction of what I would like to say. Actually, I share Dr. Tuck's enthusiasm for his Scylla-like machine and it might be interesting just to say that we spend a substantial sum of money in the Navy to establish that what he considers to be a fact is a fact.

Representative Westland: I was wondering if I might interrupt here. Dr. Tuck, was it Scylla that blew up?

Mr. Conway: Some years ago, Dr. Tuck, about 5 years ago, I revisited your laboratory with Senator Hickenlooper, the day after you had some sort of explosion. It was right under Dr. Bradbury's office, as I remember.

Dr. Tuck: Actually I always think it is always nice to have a little change of pace. When we switched the machine on one of the capacitors blew up and caught fire. It made a tremendous flame. So whenever I show the people the thing working, I always show the burst of flame.

Mr. Conway: I think of that in connection with your reference to fusion advantages compared to fission. You didn't wish to imply that the fission reactors that have been built today are in any way dangerous?

Representative Westland: A shaking of the head cannot be picked up by the recorder. I want the record to show that Dr. Tuck shook his head in a manner to indicate a "no" answer.

II. PERSONNEL AND FINANCIAL HISTORY OF THE LOS ALAMOS SHERWOOD PROGRAM

E. L. Kemp

The Sherwood program began at Los Alamos in January 1952 with a group of about five scientists and an annual budget of around \$100,000. In the following 13 years the annual personnel never exceeded 65 people with a maximum annual budget near \$3,000,000. Figures 1 and 2 show, respectively, the personnel and operating expenses for each year. These curves show that the cost per man-year has remained fairly constant near \$40,000 for the last 10 years. The total expense budget at Los Alamos over the whole operation period amounts to approximately \$21,000,000.

In years past it was fairly common for Los Alamos to return some of its appropriation for use by other Sherwood laboratories. However, during the past two fiscal years, the Los Alamos Scientific Laboratory Sherwood staff has increased from 47 to 55 which is the limit permitted by the present Sherwood budget. Dr. N. E. Bradbury, the director of the Los Alamos Scientific Laboratory, has authorized continued expansion of Los Alamos Scientific Laboratory Sherwood personnel to the extent permitted by funds made available in the future. Planned expansion is shown dotted on Fig. 1 in accordance with the increased funding shown dotted on Fig. 2. The cost per man-year is roughly constant at \$40,000.

Fig. 1. Sherwood personnel at Los Alamos Scientific Laboratory, 1951-1965.

Fig. 2. Los Alamos Scientific Laboratory expenditures for Project Sherwood, 1951-1965.

III. HYDROMAGNETIC PLASMA GUN DEVELOPMENT

I. Henins and J. Marshall

An obvious way of charging a thermonuclear reactor is to accelerate a puff of plasma to high velocity, trap it in the containment field of the reactor, and allow the energy of translation to degrade into thermal energy. In principle it should be possible to accelerate a plasma to almost any particle energy by, for example, applying $\vec{j} \times \vec{B}$ forces over a long acceleration path. There are possible advantages in this indirect method of heating a plasma in that: (1) The plasma may be at low temperature while it is accelerated so that boiling of impurities from walls may be reduced. (2) The high-speed plasma can be removed from the region where it is generated, where presumably the pressure is high, to a highly evacuated containment region. (3) Large quantities of plasma can, in principle, be handled, there being very little of the intensity limitation caused by space charge in charged particle beams.

There has been a program for the development of hydromagnetic plasma guns at Los Alamos since 1957. In all of the acceleration methods which have been tried, the plasma has been derived from a burst of gas admitted to an initially evacuated system by a fast mechanical valve. First tried were electrodeless discharges in which the plasma was accelerated by magnetic mirror fields, either simply time varying as in a θ pinch or moving in space as well (a moving magnetic piston). These methods were attractive a priori because, there being no electrodes,

there could be no contamination by electrode material. Such guns have been abandoned here in favor of coaxial guns, but have been developed further elsewhere in the world. Under some conditions they may be preferable, but the yield of fast plasma is so much larger from a coaxial gun of comparable input energy that it has appeared more attractive.

The coaxial gun in its present local form (Fig. 1), generates and accelerates plasma between copper electrodes of 3.18- and 8.25-cm diameter. The electrodes are 50-cm long, and the gas inlet is through an annular slot in the center electrode 20 cm from the muzzle. It is driven by a 30- μ F capacitor bank at 21 kV which is switched by ignitrons so as to provide a source inductance at the gun terminals of about 10nH. A fast valve driven by thermal expansion admits about 1 cm³-atm of deuterium gas through a labyrinth designed to prevent plasma damage to the dry Viton O-ring which seals the inlet plenum. The terminal insulator is a pierced Pyrex disk protected from direct radiation from the discharge by a copper baffle. The end of the central electrode is approximately hemispherical. These perhaps boring details are given to emphasize the fact that a minor change in any of these parameters would probably make a major change in gun behavior. Additional important parameters are the following: delay between gas admission and firing time, steepness of the front of the admitted gas, cleanness of the vacuum, and recent history of the gun such as when it was last fired and with what gas. The present parameters are the result of an extensive series of experiments designed to optimize the cleanness and yield of thermonuclear plasma. Enough parameters are involved here that a systematic search through them is a very difficult job, and the present gun design is certainly not the best possible.

The mechanism of gun operation can be thought of very simply as the $\vec{j} \times \vec{B}$ interaction of a radial plasma current with the $B = 2i/r$ magnetic field of the current along the center electrode which feeds the discharge. In actual fact it is much more complicated than this,

Fig. 1. Plasma gun design with fast thermal expansion valve. (1) Gas inlet. (2) Sixteen REX-4 cables to valve driver capacitor bank. (3) Driver section. (4) One-half-in.-thick glass insulator. (5) Lucite clamping ring. (6) Twenty-four B.I.C.C. Type-20 cables to gun capacitor bank. (7) Sonic line. (8) Outer electrode. (9) Inner electrode. (10) Gas outlet holes (15 holes, 1/8-in. diam). (11) Valve spring. (12) Valve plenum. (13) Teflon bumper washer. (14) Polyethylene insulation. (15) Phenolic insulator. (16) Cooling air inlet. (17) Small holes for air outlet.

involving critical breakdown conditions, motion of a current front along the barrel through the gas filling so as to leave energy stored both in kinetic energy of plasma and magnetic field, and finally utilization of some of this stored energy to produce a jet of fast plasma from the tip of the center electrode. These mechanisms are not thoroughly understood. Given leisure for the job, they would certainly offer rewarding subjects for study.

The fast plasma jet contains about 5×10^{17} deuterons of approximately 10-keV kinetic energy. They appear to be emitted in a hollow cone of something like 10° half-width. This is about 1% of the injected gas. The fast deuterium plasma is followed by a slower plasma (~ 100 eV 10^7 cm/sec) containing most of the rest of the admitted gas. The properties of the plasma have been deduced from a large variety of experiments including calorimetry, diamagnetism, spectroscopy, particle analysis, neutron emission, and others. It is hoped in the future to study further empirically the effects of changes in electrode configuration and other gun parameters. In addition, measurements will be made which it is hoped will shed some light on the important phenomena which appear to produce the fast plasma at the gun muzzle. Hopefully, a better understanding of these phenomena will allow improvement of gun performance. Most of the recent efforts in this program have been directed toward the study and elimination of plasma impurities. During approximately the last year, a serious contamination of the fast plasma with high-speed, multiply-ionized carbon impurities was observed and apparently has been cured by the rigorous exclusion of all sources of oil and grease from the vacuum system and the protection of what organic materials remained from decomposition by the plasma. It is planned during the coming year to study the impurities further by particle analysis in a large, cleanly pumped metal tank. At present the impurities are dominated by secondary plasma ions generated when the fast plasma interacts with the glass walls of the system.

IV. AXIAL INJECTION

I. Henins and J. Marshall

A large part of the experimental work which has been carried out in the hydromagnetic gun program has dealt with injection of gun plasma along magnetic field lines into either magnetic guide fields or containment geometries. Unfortunately, axial injection of containment geometries implies an open geometry, for instance a mirror machine, and the trend at the moment is toward closed geometries. Still, axial guide fields might prove useful between gun and containment region, and at least they provide a means of keeping gun plasma substantially off the walls of a system so that there is some hope of studying primary gun plasma rather than secondary plasma derived from wall evaporation.

A series of experimental programs has been conducted in the past few years including such things as the collision of two gun plasmas impinging on each other from opposite ends of the same guide field, gun injection of one of the Scylla θ pinches, and gun injection of a more-or-less static mirror machine. These programs had a variety of motivations most of which included to some degree the desire to produce a hot plasma suitable for charging a reactor. From them, a great deal has been learned about gun plasmas, of which perhaps the most important single thing is that they are extremely difficult to diagnose reliably. Probes inserted into a high-energy streaming gun plasma are subject to

an enormous rate of deposition of surface energy. This usually results in evaporation of the surface of the probe, generation of a local secondary plasma of high-energy density but relatively low-particle energy, and completely false results. The same thing happens with the slits of a particle analyzer, so that to achieve reliable results one must back off to large distances where the energy flux is low. The net result of the energy flux difficulty is that all diagnostics must be done from outside the plasma or at least with no ordinary material probes. Such measurements tend to average the effects from a reasonably large plasma volume so that the experimenter must be careful not to accept too smooth and simple a picture of what is going on inside.

A brief summary of what appears to be happening in the injection of gun plasma into axial guide fields might be as follows: The generation of the fast plasma is partly in the guide field itself, so that it is impossible to separate the phenomena of plasma acceleration from those of field penetration. Intense electric fields are generated in the region around the injection point, some of these having to do with the different magnetic ballistic properties of the electrons and ions, the ions in general being able to penetrate the field farther, and consequently producing a positive space charge sheath on the outside of the plasma. Inductive effects in the gun, however, are fundamentally responsible for the acceleration of the ions and can do this only through electric fields. This implies an electric field in the direction of ion acceleration so that out in front of the gun there is a high negative potential driven effectively through a very low impedance since an ion current of the order of 10^5 A is accelerated by some 10 kV. Wall effects are extremely important in the penetration of the fast plasma into the field, and under some conditions all the electrons in the plasma that have penetrated the field originate at the wall (Ashby, Culham, 1963). Under some wall conditions, the fast plasma is confined to a relatively smooth cylindrical volume of approximately the same diameter as the outer gun electrode. With the wall pulled back

away from the gun muzzle, the plasma shreds badly on entering the field but appears cleaner in that it does not evaporate large quantities of glass as it does with the glass wall closer around the gun muzzle.

The fast injected plasma is thoroughly mixed with magnetic field although, in general, it has substantial diamagnetism, the particle-energy density close to the muzzle exceeding the field-energy density. The diamagnetic effects up to a meter or so away from the gun are large enough so that plasma effects on the field allow self trapping of the plasma behind a magnetic mirror in a manner apparently similar to Tuck's "Entropy Trapping" proposal. Single particle trapping is well known to be impossible in a d.c. magnetic field. The dynamics of the fast plasma have been studied in guide fields by observation of the diamagnetism of the plasma as it moves along the field and by allowing the plasma to strike various instruments and targets. It is hoped next to apply the Jahoda, Baker, and Hammel modification of the Ashby and Jephcott gas laser interferometer technique to studying the plasma density along a guide field as a function of time and distance.

The slow gun plasma which follows the fast is roughly one hundred times as dense and is clearly not desirable as a diluent of the fast plasma in a reactor experiment. It appears to behave hydromagnetically in its interaction with the field, under some conditions (relatively low guide fields) extending as a field-free arm of plasma into the guide field, but then acting as a zero- β , slow, dense, plasma-stream scattering source in the guide field. Measurements of these phenomena are particularly difficult because of the previous passage of high-energy plasma, and it is hoped that laser interferometry will add considerable information.

V. TRANSVERSE INJECTION

D. A. Baker and J. E. Hammel

This program was originally undertaken in an attempt to inject gun plasma into a transverse field, and then to accelerate it to higher-particle energies by the application of an orthogonal electric field, so as to produce an $(\vec{E} \times \vec{B})/B^2$ plasma drift. Difficulty was encountered in the attempt to accelerate the plasma to higher velocities, but a very interesting and potentially useful behavior was found in that the plasma entered the transverse field easily and could be controlled subsequently by allowing self-generated depolarizing currents to be drawn along field lines to conducting surfaces.

The gun plasma, upon encountering the transverse magnetic field, is subject to a $\vec{v} \times \vec{B}$ Lorentz force which polarizes the jet of plasma, leaving space charges on the surfaces parallel to the field. These space charges produce an electric field, normal to the plasma velocity and to the magnetic field, just sufficient to provide an E/B plasma drift speed equal to the initial speed of the gun plasma. The plasma jet continues to drift across the field, probably with a loss of surface plasma from the space charge region, until it hits something or goes out the other side of the field, except when it comes to a set of field lines leading to a conducting surface capable of discharging the polarization charge. When this happens a current flows along the field lines from the electrically-charged surface of the plasma to the depolar-

izing conductor, along the conductor to the field lines leading back to the oppositely charged plasma surface, and then along these field lines to the plasma. Currents of the order of 10^4 A are observed passing through a Rogowsky loop around the depolarizing conductor or around the bundle of field lines between it and the polarized plasma surface. Clearly a current of this magnitude isn't carried in a vacuum but depends on the presence of a plasma for space charge neutralization. The currents which flow can be thought of as neutralizing the space charges which allow the plasma to drift across the field or as applying $\vec{j} \times \vec{B}$ forces to the plasma so as to stop it.

The transverse injection process provides an automatic mechanism for the separation of fast plasma from the slower undesirable plasma following it out of a gun. A separation is possible because of the delay in current buildup in the inductance associated with the depolarization current loop. A burst of plasma which moves past a short depolarization conductor can pass beyond the short-circuited field lines before the current builds up enough to decelerate it appreciably. On the other hand, slower plasma following immediately behind spends a longer time in the short-circuited region and even finds a certain amount of current already built up by the fast plasma.

If plasma is injected across a field which reverses its direction on the other side of a field null, there is an opportunity for the plasma to depolarize itself, since if the plasma is to keep moving the polarization must reverse its direction where the field reverses. If the field lines on one side of the null connect by a reasonably short vacuum path to those on the other side, it becomes possible for the plasma polarization on the exit side to be overwhelmed by currents derived from the polarization of the entering plasma. This stops the plasma in the field-null region and would appear to offer an ideal mechanism for the trapping of gun plasma in bridged cusp-field-null devices. This effect has been observed here and is planned as the method of injection of the caulked cusp machine discussed below.

Ohkawa at General Atomic and Kerst at Wisconsin are using it to inject their toroidal octufilar experiments.

A short linear section model of the Caulked Cusp machine is under construction, with which it is planned to replace the present mirror coil arrangement in the Transverse Injection experiment.

VI. CAULKED CUSP MACHINE

D. A. Baker, J. E. Hammel, I. Henins, E. L. Kemp, L. Mann
J. Marshall, and J. L. Tuck

1. Introduction - Plans are being made at Los Alamos to build a closed-geometry, field-null machine on a scale large enough so that it will be capable of working at high plasma particle energy and energy density. This is a project involving considerable complication and technical difficulty, so that rather strong reasons are necessary for it to be undertaken at all. We feel that there are sufficient reasons, and they are discussed below. We have in addition strong reasons why the project should be carried out in this Laboratory, rather than elsewhere. They are: (1) The motivation is here; (2) The machine is an outgrowth of ideas which were germinated here for the most part; (3) The plasma experiments and technology at present in the Laboratory are suitable for this machine and lead naturally to it; (4) The chances are that if it is not built here, it won't be built anywhere, at any rate, for a long time.

2. Closed-Field Geometry Reactors - In the various injection studies carried out with coaxial guns it has become more and more obvious that if there are field lines leading from the plasma to a wall, plasma will follow the lines and bombard the wall. It is painfully obvious from these experiments, and even more from the Scylla experiments, that if energetic plasma is allowed to hit a wall, large amounts of gas are evolved. The approximate figures for the high-energy plasma yield

from our present coaxial gun (5×10^{17} deuterons at 10 keV) correspond to 800 J of particle energy. The plasma is produced in somewhat less than 1 μ sec, so these figures correspond to an instantaneous power level of about 1000 MW. A power this large absorbed by a solid surface, even over a rather large area, overloads the heat absorption capacity of the surface so that material is evaporated. The wall vapor spoils the vacuum in the system, and that part of it which is ionized by the incident plasma produces a secondary plasma to confuse measurements.

What might appear to be a barely adequate thermonuclear reactor plasma ($n = 10^{15}$ /cm³, $T = 20$ keV) would have an ion power flux of several thousand MW per cm². A very small fraction of this, and of the even larger electron energy flux allowed to scatter out of a containment region along field lines, would produce a flood of gas from any wall. There appears, then, to be a great advantage in the use of field geometries for reactors in which no field lines lead directly from the contained plasma to any material wall.

3. Flute-Stable Closed Geometries - It has been understood for a long time that stability against fluting can be realized in a magnetic containment device by arranging it so that the field lines are convex toward the plasma. This is equivalent to the statement that the magnetic field increases its strength in the outward direction. Unfortunately, field lines which are everywhere convex inward imply cusps which lead lines out from the containment region so that an open geometry results. It is impossible to make a closed-field geometry where the lines are convex inward along their entire lengths, so to attain flute stability in a closed geometry some sort of favorable average must be achieved between flute-stable and flute-unstable regions. A large fraction of the flute-stable containment geometries conceived so far contain one or more regions of minimum field strength, i.e., regions around which the field strength increases in every outward direction. The minima can be of a zero or nonzero nature. Zero and nonzero minima are separately interesting in containment devices, and it is plain that, strong state-

ments by enthusiasts for one or the other notwithstanding, both types of containment deserve investigation.

The type of flute-stable containment device with a field zero inside has a longer history than the type with a nonzero field minimum, simply because the field itself is easier to visualize. Even so, it has not yet had a fair test. The main reason for this is that a field zero implies nonadiabatic containment of individual particles in the very center of the flute-stable containment region. The ions passing near the field zero fail to conserve their orbital magnetic moments, and this has the effect of scattering particles so that their pitch angle changes relative to the field lines in the cusps. Only a few passes close to the field zero are required for most of the particles to leak out. Experiments with nonzero field minimum devices do not suffer from this difficulty, hence the work of Ioffe which has demonstrated an improvement of stability of plasma confinement in an open-field geometry when the field is made to increase in the outward direction.

The experimental difficulty of cusp leakiness induced by non-adiabatic ion scattering near a field null is similar in a way to the scattering difficulty which might be expected in an actual reactor. Ion-ion collisions are the very essence of a reactor, and there are many more Coulomb collisions than collisions leading to a fusion reaction. Consequently an open-geometry reactor will certainly lose a large fraction of its plasma through its mirrors whether or not it is capable of adiabatic containment. In a closed-field geometry, particles scattered out in this way return along the same lines to the machine, and so are not lost. Consequently a field zero does no harm in this case. It appears then that closed-field-geometry machines, if they are possible at all, have strong advantages over open-geometry machines. A machine with a field zero inside requires closed-field geometry from the beginning, but in a sense so does any machine if it is to be investigated under reactor conditions.

It should be noted that high-plasma-density machines are to some extent excluded from the considerations immediately above. Such machines, if of open-field geometry, would certainly leak particles. However, by going to large plasma containment volumes, it might well be possible to make a reactor by offsetting the higher reaction rate against the leak rate.

Considerable attention has been given recently to closed-field-geometry, flute-stable containment systems. Whether or not a geometry is considered flute-stable is usually determined by the $\int dl/B$ criterion. Stability is implied if the line integral decreases as it is taken over closed-field lines farther out from the plasma. Under certain assumptions the integral provides a means of averaging flute motion between the regions of the field having favorable and unfavorable curvature. The assumptions which lead to the $\int dl/B$ criterion are not strictly applicable to a real plasma, so that the worth of any containment geometry will eventually have to be based on experiment. The criterion assumes for instance that the plasma is isotropic in its velocity distribution and remains so after a fluting displacement. The assumption is also made that communication along a field line is rapid enough so that fluting can actually be averaged between good and bad regions. Strictly, the $\int dl/B$ criterion applies to a $\beta = 0$ plasma (pressure so low that the plasma does not distort the containment field). Presumably β will be approximately zero between the plasma and the vacuum wall of the system so that the theory will be partly applicable in this region. The problem of communication along a field line appears to favor short distance along lines between regions of favorable and unfavorable curvature.

Interesting proposals for toroidal flute-stable systems have been made recently by Furth and Rosenbluth, by J. L. Johnson, and by J. B. Taylor. These systems share the properties of having nonzero field minima, if indeed they have any minimum at all, and of closing their field lines around the circumference of the torus, a long distance.

In most cases the field lines do not close until they have passed an indefinite number of times around the torus. It still is not completely clear to everyone in the field over just what limits the $\int dl/B$ should be taken in such systems. It would appear that some valid picture of the shape of a flute in an intermediate stage of growth is required to determine this. Experiments are required, difficult experiments in large and complicated field geometries.

4. Closed-Field Containment Geometries with Field Nulls - The proposal for a flute-stable, closed-field-geometry containment field was first made by Tuck in 1957. Similar proposals were made independently by Braginsky and Kadomtsev in the U.S.S.R. Tuck's proposal, the "Caulked Picket Fence," used a conducting ring or series of rings inside of and coaxial with a pulsed solenoid and opposing by flux conservation the field of the solenoid. A toroidal quadrifilar null is formed inside the ring concentric with it. Two of the leaky field surfaces, leading from the null, bridge the ring and return, so as to bring escaping particles back. The other two pass along the solenoid where they may connect to other ring nulls or, if the solenoid is bent into a torus, they can return to the other side of the same null. This would effectively stop all leaks along lines. The "Caulked Picket Fence" diagram reproduced here from Glasstone and Lovberg is for a case where the ring current is larger than would be induced in a perfect conductor. This would imply a more complicated magnetic history than simple pulsing on of the solenoid current.

Also the field in the diagram could not be generated with uniform current density in the solenoid.

Experimental work is needed to establish whether configurations of this sort are capable of containing a reactor plasma. Actual work has been done and is still in progress under Kerst at Wisconsin and Ohkawa at General Atomic on what they call toroidal octupoles. The properties of these systems are similar to the Caulked Picket Fence except that the field lines are normal to the toroidal direction. The programs of these workers are quite similar in that both groups are studying machines with cusp lines bridged over four internal conducting rings. The rings are in the corners of a toroidal outer vessel of approximately square cross section and are driven inductively by currents in the wall of the outer vessel. These currents originate in a capacitor bank, and both Kerst and Ohkawa use rather modest stored energies. This of course simplifies the engineering of the machines, but it limits the particle energies which can be contained. As a result, the plasma energies are quite low and this, by reducing the energy with which the plasma

can bombard a surface, makes it possible to hang the ring conductors on supports. In addition, because of reduced charge exchange cross sections accompanying the low plasma temperatures as well as smaller particle velocities, the vacuum requirements are quite modest. On the other hand, because of the low plasma energies, there are a number of important diagnostic techniques which cannot be applied.

5. Caulked Cusp Machine - We are planning to build here a caulked field-null machine capable of working at high plasma particle energy and plasma energy density. This machine would involve a large step in technical difficulty beyond those mentioned in the previous paragraph. The extra difficulty is owing to our conviction that experiments at high plasma energies, energies as nearly thermonuclear as possible, are required. This means that bulky, heavy apparatus will be required and that large amounts of magnetic field energy will have to be stored and transferred. The scale of the experiment is one which we are reasonably well equipped to handle because of our years of experience with large energy storage. It would be considerably more difficult for a small isolated group such as can normally be formed in laboratories on less than the National Laboratory level.

The reasons for going to large plasma energy are mostly based on past experience which has taught us that in this field almost any experiment will involve new and unexpected phenomena. To investigate the behavior of reactor plasmas, experiments must be performed with plasmas as nearly like reactor plasmas as possible. With large plasma energy a different set of experimental phenomena is found from that at low energy. Certainly if fusion reactors ever exist they will involve large plasma energies, and there is good reason for experimenters to keep their feet wet in this particular puddle. Another reason is that the larger variety of diagnostic techniques accompanying high plasma energy will make interpretation of injection and containment experiments easier. With a machine designed for high energy it is always possible to turn down the field and the plasma energy to study it at low energy.

The reverse, however, is not true.

There exist in this Laboratory techniques and fields of experimentation which apply naturally to a machine of this kind. They include plasma guns and a well established experimental program involving the injection of gun plasma across magnetic fields. These programs have been discussed above and need no further description here. There is, however, a pertinent point having to do with the importance of their being here rather than elsewhere. A priori, it should make no difference whether a technique exists in one's own laboratory or elsewhere. One should be able to take over a technique lock, stock, and barrel from somewhere else and apply it. In practice this has turned out to be untrue for many techniques, and especially for coaxial plasma guns. Even the copying of a coaxial gun by another experimenter across the hall in the same building leads to different behavior. The reasons have to do with the improvements which every physicist or engineer finds himself morally compelled to make in a machine which he is trying to copy, and with the large number of parameters significant to the operation of a coaxial gun. Frequently the same experimenter with the same coaxial gun finds that he has tuned it up so as to produce different results.

6. Machine Design - A machine with large plasma energy density is not easy to build in the octufire configuration. The reason is that the octufire in its simple form is not in mechanical equilibrium. A magnetic force drives each of the rings toward the field zero in the torus. The radial component of this force can be supported by tensile or compressive strength of the ring (Fig. 1), but the only way of supporting the axial component of the force is directly with support rods. At large particle energy, and therefore large magnetic field, or large dimensions, or both, the forces are larger; and with large plasma energy densities the support rods are intolerable. One can dream of systems with shaped walls so that the rings would be supported axially by the field itself, but these appear more complicated than

Fig. 1. Toroidal octufile configuration.

would be desirable for a start.

A toroidal quadrupolar machine has the advantage of mechanical equilibrium, in the absence of gravity at least, although it has the disadvantage of smaller $\int dl/B$ stability than the octupole. It is shown in principle in Fig. 2 with floating conducting rings carrying current in one toroidal direction, the current inductively driven by an oppositely directed primary current in the outer torus. Mechanical forces are a bursting hoop stress in the inner ring and a compressive hoop stress in the outer. A field of this type can be shown always to have some region near the separatrix (the field surface which connects to the null) inside of which $\int dl/B$ stability is formally achieved. This follows since the favorable portion of the line integral, the part in the region where the lines are concave inward, can be made overwhelmingly large by integrating along a line close to the field null so that the denominator contains a small value of B . A flute-stable machine with a field of this shape can always be constructed in principle by scaling the field and/or the linear dimensions so that particles of the desired energy can be contained inside the calculated last stable line of the field. In principle, the containment field could be achieved by scaling either the field strength or the linear size of the machine. In practice there is usually some maximum field strength which can be allowed, either because of mechanical strength, enhanced loss of flux through soaking into conductors, or plasma injection considerations.

7. Field Computation - A computing machine field computation effort is in progress with the object of arriving at a field shape capable of presumably flute-stable plasma confinement of 10-keV deuteron plasmas with the minimum practicable field energy. A workable machine code for this purpose to calculate shapes, strengths, and the appropriate integrals of toroidal bridged quadrupolar fields has been adapted from the octupole relaxation code of R. A. Dory developed for Kerst at Wisconsin. Examples of fields computed here by this code are given in Figs. 3 and 4 .

Fig. 2. Toroidal quadrupole configuration.

Fig. 3. Dory code field plot (Example 1).

DORY CODE FIELD LINES
PROBLEM NUMBER 3211

NUMBER OF ITERATIONS 1029

II

Fig. 4. Dory code field plot (Example 2).

Other computation methods are in various stages of development, particularly by Ralph Lewis and Emory Stovall of this Laboratory. The effort will continue until a satisfactory field is worked out. It is assumed from the meager experimental information available that five deuteron gyro radii of containment field should be provided between the separatrix and any material wall. For 10-keV deuterons this amounts to 10^5 -G cm. The method at present is first to assume a set of boundary flux surfaces. These might be thought of as the surfaces of two perfectly conducting, coplanar, coaxial floating rings inside of a perfectly conducting doughnut. A solution of Laplace's equation is now found by the computer code where the net flux passing between the rings is zero, and both the rings and the doughnut are flux surfaces of the field. The strength of the computed field is next scaled to have a maximum value in the injection region of 10 kG or a maximum in the bridge regions of 50 kG. The linear dimensions of the machine are then scaled to provide the assumed 10^5 -G cm containment blanket in the outer bridge (the weakest point). An approximation, based on the observed fact that the shapes of the field lines depend very little on changes of the toroidal aspect ratio of the field, is used to adjust the size of the hole in the doughnut so that the necessary flux can be passed through it in a ferromagnetic core. The laminated iron core is necessary in order to drive the rings inductively without excessive lost energy and stray field in the primary circuit. Figure 5 shows the closest approach to a reasonable field shape calculated so far. This particular field is still unsatisfactory in that it has excessive strengths at the corners of the rings, and that there is a mirror region in the bridge fields inside the separatrix. Some increase of field energy will almost certainly be required to rectify these shortcomings, but since the energy in this case within the stable containment region is a little less than 5 MJ, it is reasonably certain that the stored energy required to generate the field of the actual machine can be made less than 10 MJ.

Fig. 5. Present least-energy quadrupole field.

There has not as yet been found any orderly way of attacking this problem because of the practically infinite number of parameters involved in arbitrary boundary shapes. After a formally satisfactory field is found it has to be inspected carefully to determine whether this actual field can be generated and held without ruinous distortion using actual materials of finite conductivity. One of the major problems is the soaking of fields into conductors. This involves solution of the transient skin effect, and this should rightly be done for the particular surface shapes and field shapes finally employed. During the search this is not practical of course, but a working understanding of the effects involved has been attempted by solving for the soakage in a coaxial geometry with a hollow cylindrical inner conductor. The field is assumed to rise sinusoidally for a quarter-period and then to be perfectly crowbarred. With a 10-msec quarter-period, the effective skin depth in copper at room temperature is about one cm. This means that a large amount of flux can soak into the ring surface at high field regions and thus become unavailable for containment. There are various conceivable tricks for minimizing these effects, some of them even less practicable than others. The reason why they have to be considered at all is that the amount of energy required to be stored (in a capacitor bank presumably) is larger than has ever been transferred from one capacitor bank before.

8. Levitation - The inner rings of the machine will have to be capable of being levitated during the interesting experimental time of a shot. This has been done before, by Colgate and Furth, for instance, in the Levitron hard-core toroidal-pinch machine, but in this machine the problem is harder in that larger weights, longer pin pulling distances, and probably longer levitation times are required. Plans at present are to drive the entire doughnut into a free-fall trajectory with cams, pull the ring supports pneumatically through bellows, allow the entire assembly to fall freely with no ring supports for from 10 to 30 msec, reinsert the supports, and decelerate with cams. A model

levitation machine is in detailed design for testing.

9. Liner and Coil Structure - The machine will have a resistive metal liner so as to avoid a number of very serious problems which would exist if there were a metallic liner with a feed gap. These problems center around the electric fields and consequent crossed-field plasma drifts which would be found around such a feed point. The difficulty could, in principle, be avoided with an insulating liner, but a ceramic or glass liner of this size and form appears impracticable. The liner can be formed out of pie sections of thin stainless steel of about the size of truck fenders, welded together, and with a hand-smoothed gasket surface inside and outside in the median plane. The metal liner will be backed up and supported against atmospheric pressure by a fiberglass, epoxy-resin, and copper-coil structure made up of a large number of subcoil units having equal numbers of turns, as nearly as possible equal in resistance, and a distribution of current conductors calculated so as to bound the field in the doughnut (Fig. 6). The subcoil units will be connected in parallel to an extent which it is hoped will allow redistribution of current in case of imperfect centering of the rings, so as to provide sufficient mechanical stability. This problem has not yet been seriously investigated, but certainly it must be before construction starts. The problem, of course, is that a pair of rings such as the floating conductors, carrying currents in the same direction and isolated from other conductors, would be expected to be subject to a pinch instability, the two rings approaching one another on one side of the axis and separating on the other. A perfectly conducting outer wall would be expected to reduce this instability by providing image currents which would repel a ring if it approached the wall closely. Unfortunately the outer wall cannot be considered to be perfectly conducting on the scale of this experiment, particularly since the resistive liner enforces a long field-rise time to prevent excessive energy loss in the short circuited resistive turn which it represents in the electrical circuit. The skin-effect field soaking to be expected

Fig. 6. Conceptual toroidal quadrupole machine (Cut away).

on this time scale (~ 10 -msec rise time) could represent a serious distortion of the field with time, since more flux would be expected to soak in in high field regions than in low. This distortion can be largely eliminated by the use of a wound coil of many relatively small conductors. For various electrotechnical reasons, 10 kV is a reasonable voltage for the energy storage device for this machine. Ten kV and 10-msec rise implies a reasonably large number of turns in the coil (something like 25 to 50).

10. Vacuum System - All of these magnetic and mechanical problems have to be solved under clean vacuum conditions. Appreciable amounts of hydrocarbons on the walls have been observed to interfere with gun operation, and if any reasonable containment time is to be achieved the vacuum will have to be a rather good one. It is planned to pump the system primarily by a combination of ion pumping and titanium sublimation. The vacuum problem is alleviated in a negative sort of way by the likelihood that the high-energy deuterons will combine with wall oxygen to produce lightly bound wall water. This problem is rather hard to lick at the moment, and the total pressure will probably be no better than about 10^{-8} -torr.

11. Injection Port - At the injection position there must be a hole in the doughnut and in the current winding outside the doughnut. Since in most places the current conductors will be laid as close as possible to the last stable flux surface so as to conserve field energy, this poses a considerable difficulty in field distortion, particularly as the injection hole will probably have to be a rather large one. A way of getting around this problem appears to be offered by the arrangement sketched in Fig. 7. Using this trick of bulging the doughnut in one place and filling the bulge with an extension of the same field, the winding can be pulled back far enough from the field so that local perturbations such as spreading the wires apart to pass around an injection hole won't seriously distort the containment field.

It is most likely that some sort of guide field will be placed

WIRES LAID ON
FLUX SURFACES
NORMAL TO FIELD

WIRE DENSITY
PROPORTIONAL
TO FIELD

Fig. 7. Field extension in injection region.

between the gun muzzle and the containment field. Whatever this is, it need not last as long as the containment field and therefore can be isolated from the containment field region by metal flux guiding surfaces. The guide field region will probably have to be experimented with after the containment field is constructed and in operation. A massive metal flange will provide both magnetic isolation and a convenient attachment point.

12. Laminated Iron Core - The desired field in the Caulked Cusp machine will all be in the space between the coil windings and the floating rings. However, the coil by itself also produces a field which threads through the hole in the doughnut, and makes a dipole field at large distances. These two fields can be considered as being produced by parallel inductive circuits, one on the inside surface of the coil, and one on the outside. The outside circuit is parasitic in the sense that it produces a field unwanted in the machine. An iron core, threaded through the hole in the doughnut and returning on the outside (Fig. 8), can be considered as increasing the inductance of the outer parasitic inductor without affecting the inner one. With no iron core, the two inductances, in this case, would each be of the order of 1 μ H. Approximately half of the energy fed to the machine terminals would appear in the parasitic field. With an iron core, the parasitic energy can be made negligible. Of course the core must not be allowed to saturate.

In the pulse approximation the resistance of either of the floating rings can be considered to be zero. Thus, during a pulse, the flux threading the inner ring cannot change. Containment field has to be generated, however, in the inner bridge, and this produces a flux change through the inner ring. The iron core then must be capable of handling this flux without saturating. The amount of flux change which can be carried by an iron core in a pulse can be doubled by back-biasing the core so that its flux is reversed during the pulse. Since this can make the hole in the doughnut smaller, the perimeter can be reduced and less flux is required. In principle, then the amount of iron required

Fig. 8. Conceptual toroidal quadrupole machine. Cables, levitation details, and experimental ports are left out for simplicity.

for the core can be reduced by more than a factor of two by back-biasing.

In practice back-biasing introduces difficulties. Since the flux is reversed in the relatively short field rise time of a shot, a large voltage is induced in the bias winding, and this must not be allowed to drive current through the bias supply, both because of the large overload which it would produce there and because of interference with machine operation. The standard method of handling this difficulty is a choke in the bias supply line. The choke, however, is a monster, and fortunately one is not necessary in this machine since the bias current can be transferred from the winding to the floating rings just before a shot by simply opening the bias circuit (first with a resistor-capacitor combination across the switch to reduce arcing). There is still possibility of an accident however, if, for instance, the capacitor bank driving the machine should fire prematurely while the bias supply is still connected. Prefires of this kind are quite probable with capacitor banks and may be even more probable with a very large bank. It should be possible to protect the system while the bank is being charged by short circuiting the machine terminals with a mechanical switch, the switch to be opened just before current is transferred to the rings from the bias winding. A fault in the short interval remaining could be handled by explosively triggered dielectric switching, which is likely to be unpleasant and require rebuilding the switch, but which can prevent much worse damage. The long L/R time constant of the rings on the core, (~ 100 sec) which makes possible the transfer of current from the bias winding to the rings, also makes impossible fast pulse biasing of the core. If it were possible, pulse biasing would be convenient because then the bias field would be forced to be parallel to the core laminations, a condition which does not necessarily apply to a d.c. field. Only the component of the bias field parallel to the laminations can be reversed during a pulse. With a rectangular assembly of the iron core in elevation and cross section, it is possible to make sure that the bias field is parallel to the laminations, provided

the laminations lie in planes parallel to the plane of the assembly, and provided the bias winding is applied to the surface of the core in exactly the right pattern. The pattern, incidentally, is different for different values of the bias. With a nonrectangular cross section of the core, as for instance, if an attempt is made to fill the non-rectangular hole in the doughnut completely with iron, perfect parallelism of bias field with laminations is possible only with a toroidal core and bias winding. This is likely to be more expensive than a rectangular assembly and to have other practical difficulties, so it is not planned at present.

The core will be made of ordinary 60-cycle laminations of silicon steel. Theoretically this may not be the optimum material in this application, but for economy and reliability it is usually important to allow industry to fabricate things in their accustomed way.

13. Energy Storage and Switching - The large amount of stored energy required for the Caulked Cusp machine is a major cause of worry. To our knowledge, no one has yet operated a capacitor bank at this level of energy storage. Capacitor banks which nominally approach this size exist, as for example, the Zeus bank here at Los Alamos, which is rated at 6 MJ. On the other hand the Zeus bank has never been connected all in parallel to the same load, and it is a rare capacitor bank which is operated at full voltage more than occasionally. The reason for all this diffidence is that the probability of electrical failures goes up proportionally to the number of components employed and that for a large bank an electrical failure can be most spectacular.

Capacitor banks, however, are well established in our local technology, and in principle we know how to safeguard against the worst accidents by more-or-less elaborate systems designed to dump bank energy in a safe place in case of a fault. Certainly our first experiments with this machine will be driven by capacitor energy storage from banks of a size covered by our experience.

However, for a field energy of 10 MJ, or for conceivably larger energies to come in the future, it may be that an alternate energy storage scheme may be better. One can think of a number of ways of storing energy which might become more convenient than capacitor banks at large energy levels. The method among these which looks most attractive for the requirements of a machine of this kind is inductive energy storage. In principle, one simply charges a storage inductor by building a large current up in it from a d.c. source, and then opens a switch in series, forcing the current to transfer into the desired load. Unfortunately it is notoriously difficult to open a switch in series with an inductor because of the arc which forms across the switch contacts. In the simple system just described it can be shown that, in driving an inductive load such as we will have here, only one-fourth of the energy initially stored can be transferred to the load inductor. Half of the energy goes into the arc across the switch contacts, and the remaining quarter is still in the storage inductor. The arc can be replaced by a resistor capable of dissipating this amount of energy less spectacularly. Electrolytic resistors are cheap and eminently suitable. But, still, a 40-MJ inductor, if it is to be charged by a reasonable power supply, is a large piece of hardware. Its L/R time constant, if it is to be charged by a 2-MW supply, must be at least 40 sec, and more than 100 tons of copper would be required. In addition to this, a switch would be required to open something like a quarter of a million amperes at 10 kV. It is quite possible that a switch of this sort could be developed. There have been several ideas here as to how it could be done, but this looks like a separate research project in its own right, and we are short of personnel.

Several ingenious methods have been suggested elsewhere for making inductive energy storage practicable. Notable is the work of H. C. Early and collaborators at Michigan and the suggestions of Furth and of Simon and Bronner of Princeton. For various reasons we consider these solutions to be unsuitable for our application.

One method for transferring inductively stored energy, however, which has been considered to some extent by Carruthers and Smart of the British Atomic Energy Authority, appears simple enough so that it might be applied here, and to offer a chance that it might markedly increase the reliability of the system. This is to connect a large capacitor bank across the switch so as to keep the voltage near zero as the switch is opened. Switch 2 would be closed just before Switch 1

is opened to connect the load to the supply. For a 10-MJ energy transfer the main capacitor C_1 would have to be capable of storing somewhat less than 5 MJ on a pulse basis. C_2 would be a small capacitor capable of absorbing the inductively stored energy in the generator circuit. The normal cabling of a 5-MJ bank has so many leads in parallel that the inductance would be negligible in a case like this. The time history of the energy transfer assuming L_1 and L_2 equal would be as follows:

At the half-way time, the current in each inductor is half the initial current in the storage inductor. Thus each inductor contains one-fourth of the energy, and therefore the capacitor contains one-half.

This energy transfer scheme has been studied in some detail recently and it looks sufficiently promising that an attempt is being made to develop the necessary mechanical interruptor switching. In addition a mechanical clamp switch will be needed to back up ignitron clamps.

14. Diagnostics - The purpose of the Caulked Cusp experiment is to investigate the possibility of using field geometries of this general sort, or sharing certain properties with it, for the containment of a thermonuclear reactor plasma. It is somewhat unlikely, of course, that the machine itself as it is projected will be satisfactory as a long time plasma container and that it will be possible to inject plasma satisfactorily exactly as planned. Accordingly, the entire exercise becomes purposeless unless plasma behavior in both the injection and containment phases can be studied in detail. Experience in Sherwood has been that diagnostics are mostly developed on the experiment itself and are not planned in advance. Frequently, the diagnostics planned in advance are not useful for some unforeseen reason. It is highly important to provide access to the machine for any diagnostic technique which might be thought to be applicable. Certainly some diagnostic methods not yet thought of will be applicable through the same ports and others will not.

Unfortunately the large amount of field energy required for the experiment forces the design toward a tight fit between the field excitation windings and the containment region. Otherwise it would be possible to leave gaps between coils for ad lib. diagnostic ports to be added later. As it is, a large number of small ports will have to be incorporated in the original coil design. Most diagnostics in use at the present time can be done through rather small holes. For those that require large holes, the bulge around the injection azimuth and a similar one on the other side of the machine should provide reasonable access.

Diagnostics will be aimed at: (1) understanding the injection process including the initial penetration of gun plasma and trapping in the machine, (2) spreading of plasma around the machine, (3) containment and loss of plasma and of plasma energy. Methods of diagnostics will include whatever is applicable of methods used in the past plus useful future developments. A partial list of methods previously used in the laboratory which are likely to be useful in this experiment follows:

1. Optical
 - a) Infrared laser interferometry
 - b) Visible and uv spectroscopy
 - c) Visible photography
 - d) Microwave interferometry
2. Magnetic
 - a) Probes
 - b) Diamagnetic pickup coils outside containment region
3. Electrostatic
 - a) Probes
 - b) Capacitive pickup
4. Particles
 - a) d-d neutrons
 - b) d-d protons and tritons
5. Thermal
 - a) Calorimetry on targets
 - b) Energy loss through radiation and particle flux

In addition there are many more diagnostic techniques which don't look particularly useful to begin with but which may turn out to be possible or useful later. There are also techniques in use elsewhere which have not been used as yet in this laboratory. Particularly important is the observation of charge exchange neutrals. Molecular beam probes may also be useful.

VII. DENSE PLASMA FOCUS EXPERIMENT

J. W. Mather, A. E. Schofield, and A. H. Williams

The creation of a dense deuterium plasma focus or foci beyond the end of the inner electrode of a coaxial electrode geometry is an outgrowth of the hydromagnetic gun work¹ performed in 1960. Since then, this dynamical mode has been studied in more detail; the results are in publication.² These results resemble those reported by Petrov³ and Filippov⁴ using a metal-wall pinch tube apparatus.

In this work it is shown that the current sheath is established at the breech in a quasi-stable configuration which progresses toward the end of the center electrode owing to the $\vec{j} \times \vec{B}$ force. The sheath moves through a uniform gas distribution of pressures ~ 2 to 4 torr. At the end of the center electrode, most of the condenser energy is stored behind the sheath and, as the sheath leaves the end of the electrode, this energy is rapidly converted into plasma energy by the pinch effect forces which produce the dense plasma focus. The focusing action of the current sheath is not an unnatural phenomenon. It is a well-known theorem that an unconstrained current circuit will move in such a way as to maximize its inductance -- in this case the final current position is on axis. A schematic of the electrode geometry is shown in Fig. 1. The plasma produced in this manner has many interesting properties.

Soft x-ray pinhole images of the dense plasma shown in Fig. 2 were taken in a perpendicular direction to the discharge axis in the region

Fig. 1. Schematic of the discharge apparatus showing approximately the shape of the current sheath during the formative stages of the plasma focus.

Soft X Ray - Positive Voltage

Al Abs. 3.14 mg/cm²

Cu

W

a

c

b

d

Pinhole Diameters

Neutrons

a - 0.9 mm

0.6×10^{10}

b - 0.45 mm

1.0×10^{10}

c - 0.625 mm

0.5×10^{10}

d - 0.625 mm

1.4×10^{10}

Fig. 2. Pinhole images of the dense plasma foci in the light of soft x rays for a copper (a,b) and tungsten (c,d) electrode for several neutron yields and pinhole sizes. The face of the 5-cm-diam center electrode is ~2.5 cm to the left of center in each photograph.

of the end of the electrode for various pinhole diameters and for similar neutron yields ($\sim 10^{10}$ /burst). Copper and tungsten center electrodes were used as indicated. Such measurements show that the volume of plasma is extremely small (1 to 5 mm³) and approximately centered on axis at 1.5 to 2 cm in front of the electrode. The blackening of the x-ray film increases with neutron production.

A dual soft x-ray spectrometer is utilized to record the ratio of soft x-ray intensity from the dense plasma through separate channels of different absorber material or thickness. Such measurement, assuming the plasma emits pure deuterium bremsstrahlung, yields the electron temperature as a function of time. Figure 3 shows a typical example of the time correlation between the neutron production rate (dN/dt) and the electron temperature (T_e). Relative to the beginning of the neutron pulse, $T_e \sim 0.5$ keV occurs in ~ 0.2 μ sec and rises rapidly to ~ 7 keV in an additional 0.2 μ sec. An electron temperature $T_e \geq 5$ keV lasts for ~ 0.3 μ sec. Neutron production peaks at ~ 0.2 μ sec and then falls to approximately one-half value at ~ 0.45 μ sec, during which time the electron temperature continues to rise. These observations show that the electron temperature lags the neutron rate and suggest that the mechanism responsible for the neutrons may be associated with an electromagnetic compression mechanism (pinch effect). For the Z-pinch-type mechanism, the ions are preferentially heated by the collapsing current sheath and the cold electrons are heated then by collisional impacts with hot ions: A collision of a hot ion $W_i > kT_e$ with a cold electron distribution exponentially damps the energy of a fast ion with a time constant⁵ $\tau_{ie} \sim \frac{1.1 \times 10^{12}}{n} [T_e(\text{keV})]^{3/2}$ so that the ion approaches asymptotically to the energy of $3/2 kT_e$; n is the particle density. Thus it seems that the electron temperature would be determined by a balance between the rate of bremsstrahlung radiation and the rate of collisional energy transfer from the ion.

Neutron production depends to first order on the energy of the condenser bank. The largest yields observed are 2×10^{10} /burst, for a

Fig. 3. A simultaneous measurement of neutron production (dN/dt) and electron temperature (T_e) as a function of time. Actually the ratio of soft x-ray transmission through two different absorption channels (6.25 and 3.14 mg/cm² of Al), with the assumption of pure deuterium bremsstrahlung, gives T_e .

burst time of ~ 0.2 to $0.3 \mu\text{sec}$. Neutron production from the dense plasma appears to be spatially isotropic. Measurements of the yield ratio, upstream to downstream of the plasma focus, give $\sim 1 \pm 5\%$. The uncertainty of $\sim 5\%$ leads to a center of mass (c.m.) velocity of $< 2 \times 10^7 \text{ cm/sec}$. This is found to be the case for either a positive- or negative-center electrode. The uncertainty of $\sim 5\%$ is more than likely due to statistics, since such a calculated c.m. velocity would lead to a smearing of the x-ray pinhole photographs and also to the time-dependent soft x-ray signals. Neither is observed.

Magnetic probe analyses of the dynamics of the current sheath show good agreement with the "snowplow" "M" theory, especially for that portion of the sheath near the surface of the center electrode. Furthermore, small axial magnetic fields in the region of the plasma focus are compressed by the symmetrical collapse of the current sheath as it leaves the end of the center electrode. This latter measurement is difficult to refute since neutron yields were measured as the axial probe sampled the compressed field. When the probe was eventually placed at the focus, the probe was destroyed and neutron yield was absent.

An analysis of the rate of change of current (di/dt) and the voltage at the breech (V) shows that the inductance of the discharge increases approximately linearly between the breech and end of the center electrode; then as the current collapses, a large change in inductance is observed to occur in $\sim 0.1 \mu\text{sec}$. The inductance subsequently continues to increase in a less rapid manner. This analysis is made for a particular discharge and strongly shows that a majority of the current participates in the dense plasma formation and that no subsidiary breakdown occurs in the accelerator section. Reading from top to bottom in Fig. 4 are oscilloscope traces (sweep speed $0.5 \mu\text{sec/cm}$) of (1) the total current and (2) breech voltage. The third and fourth trace are di/dt and breech voltage, respectively, for a separate discharge. The large inductive change occurs near peak current. Similar conclusions were obtained from magnetic probe measurements in the annulus along the

Fig. 4. Oscilloscope traces, reading from top to bottom, show a simultaneous measurement of total current and breech voltage and also di/dt and breech voltage for a separate discharge. Sweep speed $0.5 \mu\text{sec/cm}$. An analysis of the third and fourth trace leads to the inductance $L_D(t)$ of the discharge.

length of the accelerator.

If it is assumed that the plasma is collision-dominated and, further, that a least-deuteron temperature $T_i \sim 5$ keV is due only to the sheath implosion and not increased by any subsequent adiabatic compression, one would calculate a particle density of $\sim 2 \times 10^{19}/\text{cc}$ on the assumption that neutron production is due to a high-temperature, collision-dominated plasma. A time duration of $0.25 \mu\text{sec}$, volume of $\sim 1 \text{ mm}^3$, and a neutron yield of $\sim 10^{10}/\text{burst}$ were used in the above calculation. These data lead to a product of particle density times time $n\tau \sim 5 \times 10^{12}$. For the maximum neutron yield of $2 \times 10^{10}/\text{burst}$, either deuteron temperatures in excess of 5 keV or slightly larger densities are sufficient to account for the neutron yield. In any case, it is not difficult to obtain internal consistency with a thermonuclear neutron yield calculation. A further check on the internal consistency can be made using the Bennett pinch relation, i.e., $I^2 = 200 \pi r^2 nkT$. For $T_e \approx T_i = 5$ keV, $r = 0.05$ cm, a current of $I \sim 7 \times 10^5$ A is required in order for the plasma pressure to be balanced by the magnetic pressure. At 20 kV, peak current is $\sim 8 \times 10^5$ A.

One may ask, can these neutrons be caused by an acceleration process. We dispel immediately the process of an $m = 0$ "necking-off" instability first proposed for the Columbus pinches, with the following comments: (1) it is shown experimentally that the reversal of the center electrode voltage does not affect the isotropy of the neutron distribution and (2) to obtain a neutron yield of $\sim 4 \times 10^{16}/\text{sec}$ would require at least 10^8 A of deuteron current at an energy of 10 keV striking a target of 5×10^{18} deuterons/ cm^2 . Only 8×10^5 A of electron current are available in the experiment.

To test the hypothesis of a collision-dominated thermal plasma, it is planned to perform a deuterium-tritium experiment. Since the $\langle \sigma v \rangle_{DT}$ cross section at temperatures of ~ 5 keV is $\sim 100 \times \langle \sigma v \rangle_{DD}$, neutron yields for a 50% mixture of D-T would be some 50 times larger. Since it is next to impossible to measure the ion temperature, a comparison between

D-D and D-T would be extremely useful. There is also a second reason for the D-T experiment, namely, to test another hypothesis that the larger Larmor radius of the tritium ion will increase the plasma lifetime according to the finite orbit stabilization theory. It appears to date that no satisfactory theory, including the hydromagnetic instability theory, can account for the long lifetime of the plasma focus. However, it appears that the finite orbit theory is a good contender, and a simple calculation shows that the plasma with properties mentioned previously is stable. It is in this connection that the use of tritium may enhance the lifetime and give possibly the first test of the finite orbit stabilization theory in dense plasmas.

Our immediate objective in the plasma focus experiment is to measure the plasma electron density by the well-known Schlieren and interferometric technique. The Schlieren technique detects deviations of parallel light due to refractivity gradients in the plasma; in the limit of small deviations $\epsilon \cong L/n \nabla n$, where L is the path length and ∇n is the refractivity gradient averaged along the light path. For an electron gas $n - 1 = -4.46 \times 10^{-14} \lambda^2 N_e$ where λ is the wavelength of light and N_e the electron density. The Schlieren technique is suitable for detecting rapid density changes; however, the interpretation in terms of electron density depends on plasma shape. The Mach-Zehnder interferometer will eventually replace the Schlieren technique and yield a less ambiguous electron density.

Scaling of the dense plasma focus is being undertaken with the view of increasing the available condenser energy from 18 kJ to 0.25 MJ. The neutron data, to date, show an approximate linear relationship with energy. If this relationship continues, neutron yields $>10^{11}$ /burst can be expected for the D-D reaction. An increase in the final plasma density is also expected since larger initial gas densities are required at higher energies in order to meet the experimental condition that the current sheath arrive at the breech end of a given electrode structure at peak current time. It is a curious fact that the maximum average

current sheath velocity in the annulus between two coaxial cylindrical electrodes is limited to values $\leq 1.5 \times 10^7$ cm/sec. Thus larger $\vec{j} \times \vec{B}$ forces, due to the larger currents must be offset by larger initial gas densities.

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VIII. CAULKED STUFFED NONZERO ABSOLUTE MINIMUM B (NZAM) EXPERIMENT

L. C. Burkhardt, H. J. Karr, and J. N. DiMarco

The caulked stuffed nonzero absolute minimum B geometry encompasses a superposition of three magnetic fields: (1) a dc axial field provided by coils external to the vacuum tank, (2) a pulsed B_θ field, generated by current conductors through the axial stuffer tube, and (3) the field due to an azimuthal current conductor suspended in the midplane of the device providing closed magnetic field lines about this coil. A schematic of the geometry is shown in Fig. 1, and a typical field plot is shown in Fig. 2. The combined fields produce a minimum B region encircling the stuffer current conductor. Part of the minimum B region is closed on itself through a bridged region between the wall of the vacuum tank (acting like a flux conserver) and the azimuthal conductor. The remainder of the minimum B region is connected by open field lines (in the sense that field lines intersect the wall at a distance from the NZAM region); however, large mirror fields will be encountered by the escaping plasma from the NZAM region. The lines of constant B form closed nested surfaces about the minimum region. The construction of this device is nearly completed. The method currently under study for filling the minimum B region with plasma entails the $\vec{E} \times \vec{B}/B^2$ rotational heating technique in which a radial electric field is impressed between the central stuffer current conductor and the azimuthal current conductor. This electric field, crossed into the axial magnetic field

Fig. 1. Caulked stuffed cusp geometry.

Fig. 2. Mark III caulked stuffed picket fence.

$\vec{E} \times \vec{B}/B^2$, produces an azimuthal drift of the plasma (ions and electrons), $v_o = E_r/B_z$. This technique of heating, rather than plasma injection into the minimum region, creates a hot plasma within the confining field region. The main objective of this experiment is to study the confinement of a hot plasma in a minimum B field geometry and answer questions as to (1) the stability of the plasma in the unfavorable B curvature region of the bridge, (2) the axial drift of the plasma away from the minimum B region during the heating pulse, (3) the effect of the large mirror field region on confinement, and (4) electric drift along B lines (during the heating phase).

The spatial extent of the minimum B region, on the basis of a preliminary field plot, is a region $\sim 75 \times 50$ cm in cross section which encircles the stuffer current conductor. This problem is currently being coded to determine lines of magnetic force and contours of constant $|B|$.

The plasma will be examined using the following diagnostics: (1) plasma density will be measured using the He-Ne laser densitometer, (2) neutral particle detectors will sample the energetic hot ions through charge exchange using a gas exchange cell and magnetic and electrostatic analyzers, (3) spectroscopy, using the Doppler shift of the D_β or He^{II} (used as a trace element) lines will detect the rotational velocity, (4) electrostatic and magnetic probes will be used to measure the extent of the plasma during the heating stage. These measurements will be correlated with other parameters such as applied voltage, field magnitude, and injected gas pressure. Once the plasma is put into rotation, the radial electric field is removed. At this time, most of the energy is in Larmor energy and the question of stability and confinement can be assessed.

A high-vacuum tank (14,000 liter) has been placed into operation. A vacuum of 3×10^{-10} torr has been reached using cryogenic, sublimation, and VacIon pumping. External field coils will provide a dc magnetic field of ~ 12 kg over several meters in length. The caulking field coil

is completed, and, in conjunction with the dc field and the stuffer conductor, will provide a minimum B (NZAM) magnetic field system.

The objective set forth in the above depends, by and large, on the generation of a hot plasma. Experimental work has been and is currently proceeding to study the generation of a hot plasma using the $\vec{E} \times \vec{B}$ rotational heating technique. At present this heating is studied in ordinary mirror-field geometry by applying a radial electric field between a cylindrical conductor and the stuffer current conductor. Gas is injected through a series of radial ports located in the stuffer conductor.

The main results to date show that a plasma is indeed set into rotation. Doppler shift measurements of the He^{II} line in this case correspond to v_{θ} velocities of $\sim 2.2 \times 10^7$ cm/sec. The results at times of 8 and 15 μsec are shown in Fig. 3. For deuterons, this would correspond to a rotational energy of ~ 500 eV. As expected, the results are very sensitive to the applied radial electric field, gas pressure, and the axial magnetic field. Wall contamination is a major problem. A change in wall material from aluminum to copper is planned. Plasma density measurements using a laser densitometer are in progress.

Fig. 3

Fig. 3. Rotating plasma doppler shift.

IX. BEAM-PLASMA EXPERIMENT

J. McLeod

The object of the beam-plasma experiment is rapid generation of a high-density plasma with a high ion temperature inside a magnetic trap bypassing a very large electron current parallel to the magnetic field lines through a pre-existing neutral gas. This approach is an alternative to injecting a plasma from outside the trap. Reports in the Russian literature¹⁻³ indicate that it is possible to generate high ion temperatures if the electron beam density is sufficiently high. The beam currents used in these Russian experiments are far higher than any current which could be realized by a space-charge-limited electron gun at the low voltages used. The electron currents quoted range up to 40 A at 2 kV which would require a perveance of 500 micropervs if Child's law applied. This is 100 times larger than the perveance of the best vacuum diode. Increasing the accelerating voltage to draw more current is not acceptable since this increases the electron beam velocity which must match the phase velocity of some wave in the plasma if an interaction is to occur.

The Russian workers have reported the production of a plasma with an ion temperature of about 1 keV, an ion density of $7.5 \times 10^{10} \text{ cm}^{-3}$, and a volume of $7.5 \times 10^3 \text{ cm}^3$ which was generated by an electron beam of 12 A at 1100 V. Note that the plasma ion energy is about equal to the beam electron energy. The plasma density seems to have been limited by

the beam current, but it is not clear why a larger beam current was not used. It seems likely that it may have been limited by the capacity of the pumps to handle the continuous gas flow. We hope to overcome this difficulty by using a pulsed gas feed. It is also not clear why the accelerating potential was not raised above 1100 V. It may be that the violent spontaneous interaction on which their experiment depended becomes weaker as the electron beam velocity is increased. If so, we hope that we may be able to overcome this by premodulating the electron beam current at the natural frequency of this weakened interaction so that the power coupled to the plasma ions would still be sufficient to beat them. The frequency required would be of the order of megacycles.

The experimental apparatus consists of a 30-cm-diam stainless steel high-vacuum vessel ~2 m long. Axial field coils can be positioned to obtain a reasonably uniform axial magnetic field along the tube. The electron gun components are being installed. The first experiments will entail the study of the properties of the electron gun with reference to current magnitude, spatial extent, and beam divergence.

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IX. "SLINGSHOT" ACCELERATOR

J. W. Mather and E. E. Wittman

A new type of plasma accelerator proposed by J. W. Mather and J. A. Phillips has been constructed. In principle, it should allow one to produce a relatively clean plasma and also eject this plasma into a magnetic confinement system. This accelerator consists of two concentric drive coils which produce, in essence, a quadrupolar magnetic field in the annular region between the inner and outer single-turn coils and a second coil located adjacent to the drive coils at one end. The purpose of the second coil is to generate a magnetic field that will unbalance the axial magnetic field and thus produce an axial thrust on the plasma. With this coil arrangement, closed field lines will be obtained that encircle the two drive coils and the ejection coil to form a magnetic field "slingshot" configuration. The experimental arrangement encompasses three main parts, (1) the generation of a plasma ring discharge in the annulus similar to a toroidal pinch discharge, (2) the ejection of the plasma ring current by the field imbalance due to the ejection coil, and (3) the radial compression or focusing of the ejected plasma ring by shaping the outer drive coil. It is expected that the main attributes of this type of accelerator are (1) a cleaner plasma than that obtained from coaxial guns, (2) large axial velocities, and (3) higher plasma densities than can be obtained from theta-pinch guns (conical or straight).

A small "slingshot" accelerator is now being studied which consists of a 12.5-cm inner and 27.5-cm outer diameter coil system with a length of 7.5 cm. A 45- μ F, 20-kV capacitor bank produces peak currents of ~ 450 kA with a rise time of 3.0 μ sec. Preliminary measurements show that (1) a magnetic field zero exists approximately centered in the annulus region between the drive coils before a plasma is generated and (2) with argon or helium gas filling, a plasma ring discharge is observed to collapse in radius to the equilibrium radius. From end-on integrated light photographs, the plasma ring appears centrally located and grossly stable. For helium pressures of ~ 0.1 torr, the ring discharge is observed to exhibit irregularities which suggest an $m = 0$ (necking-off) instability. At higher pressures, the plasma ring becomes more stable. Generally, the boundary of the ring discharge appears more stable on the inner side and less so on the outer periphery. Time-dependent light photographs and magnetic field distributions will be obtained to determine if trapped magnetic fields are present. Trapped fields will inhibit the ejection of the plasma ring. The ejection coil will consist of a 17.5-cm-diameter single-turn coil located at one end. The rise time of the ejection field will be ~ 0.1 to 0.3 μ sec.

XI. PULSED FIELD CALCULATIONS

H. R. Lewis, Jr., and E. J. Stovall, Jr.

In order to design an experiment like the caulked, stuffed cusp experiment [a nonzero absolute minimum field (NZAM) configuration] or the toroidal, caulked cusp experiment properly, it is necessary to determine the shape and dimensions of the apparatus, as well as electrical operating conditions, such that the desired magnetic field configuration is achieved within the experimental volume, and such that it is feasible to obtain and operate the apparatus. With the caulked, stuffed cusp experiment, it is also required to provide an appropriate electric field for the $\vec{E} \times \vec{B}$ heating phase. The magnetic field in the caulked, stuffed cusp experiment consists of two parts: a component whose period is long compared with the time required for field to penetrate the metal walls of the apparatus, plus a component whose period is shorter than the time required for much penetration. It is a useful approximation to consider the first component to be static and to consider the second component not to penetrate the walls of the apparatus at all. Likewise, it is useful to consider the magnetic field in the toroidal, caulked cusp experiment not to penetrate the walls of the apparatus at all. Computation of static magnetic fields presents no difficulty if the current sources are known. On the other hand, if the magnetic field does not penetrate the metal walls which bound the experimental volume, then eddy currents are induced in the walls and those eddy currents render computation of the

magnetic field appreciably more difficult. In the two experiments being considered, there is nearly complete symmetry about an axis. In that case, computation of a magnetic field which does not penetrate the metal walls can be reduced to solving a boundary value problem for the so-called stream function, $\psi = rA_\theta$, where r is distance from the axis of symmetry and A_θ is the azimuthal component of the vector potential; the other components of the vector potential are zero. The equation satisfied by ψ within the experimental volume is

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial z^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = 0,$$

where z is distance along the axis of symmetry. The boundary conditions are that ψ assume constant values on the metal walls. This equation is very similar to the equation for the electrostatic scalar potential, φ , in such a geometry. That equation is

$$\frac{\partial^2 \varphi}{\partial r^2} + \frac{\partial^2 \varphi}{\partial z^2} + \frac{1}{r} \frac{\partial \varphi}{\partial r} = 0,$$

and the boundary conditions are that φ assume constant values of the metal boundaries. Thus, the fast-vacuum magnetic fields in the two experiments, as well as the electric field for the $\vec{E} \times \vec{B}$ heating can be approximated by solving

$$\frac{\partial^2 f}{\partial r^2} + \frac{\partial^2 f}{\partial z^2} + c \frac{1}{r} \frac{\partial f}{\partial r} = 0,$$

where $f = \psi$ if $c = -1$, and $f = \varphi$ if $c = +1$.

The usual method of solving this equation is to approximate the equation by a difference equation which is then solved by standard relaxation techniques over a mesh of points. This procedure has been applied to the toroidal, caulked cusp geometry. However, there are two basic objections to this method which are related to the rather arbitrary

shapes of boundaries being considered here and to the fact that the region over which the equation is to be solved is not simply connected. The first objection is the very slow rate of convergence of the standard relaxation techniques when applied to these geometries, a fact which renders obtaining a solution very costly even with high-speed computers. The second objection to the usual difference approximation is the necessity of determining the extent to which the results obtained fail to satisfy the original differential equation. This difficulty is always present if a difference approximation is used, although it can be considerably reduced if irregular meshes can be introduced.

Two new approaches for obtaining numerical solutions of the differential equation have been devised. One of these is a method of solving the difference equation over a possible irregular mesh, which does not involve repeated iterations. This method shows promise of being an advantageous technique in using the difference approximation with complex boundaries.

The second new method of solving the differential equation does not involve a difference approximation. With this method, an exact analytic solution of the differential equation is obtained in the region of interest, and this exact solution is made to approximate the boundaries. This approach has the advantage that the results obtained always represent a physical situation -- because an exact solution of Maxwell's equations is achieved -- and that electric and magnetic fields can be obtained by exact differentiation of the potentials. Furthermore, it has been demonstrated by application to the caulked, stuffed cusp and toroidal, caulked cusp geometries that the boundaries can be satisfactorily approximated, and that the computing time involved for a given trial is short. It is necessary to use some intuition when applying this method. However, with experience, a small number of trials can suffice to obtain a satisfactory fit to the boundaries. A computer code is now available for determining contours of constant field intensity and $\int dl/B$ along field lines.

XII. SCYLLA THETA-PINCH EXPERIMENTS - STATUS, PLANS, AND PROPOSAL
FOR A CLOSED TOROIDAL THETA PINCH (SCYLLAC) (LA-3289-MS)

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