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RECENT DEVELOPMENTS IN CONTROLLED THERMONUCLEAR FUSION RESEARCH

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INTRODUCTION

Controlled thermonuclear research was initiated at the University of California, Lawrence Radiation Laboratory, early in 1952. After a review of various magnetic field configurations for confinement of a hot plasma, active investigation of magnetic mirror fields was initiated at the Livermore site. About a year later experimental studies of pinch discharges were started at the Berkeley site and soon afterwards also at Livermore. Finally, in 1955 the Astron concept was added to the program. This latter device involves the use of very high currents of relativistic electrons circulating in a magnetic field to modify the vacuum field and provide a system of closed lines of force for confining a plasma. In addition to these rather specific approaches to controlled fusion a variety of fundamental studies of the transmission of microwaves through plasma, the generation and propagation of torsional Alfvén waves and other basic plasma phenomena of general interest have also been carried out.

1. MAGNETIC MIRROR PROGRAM

a. General Aspects of Magnetic Mirror Confinement[1]

The particles of a hot plasma confined by a magnetic field spiral along the magnetic lines of force. The motion of the particles is characterized by the fact that the magnetic moment of each particle in the absence of collisions is a constant of the motion, provided that the change in magnetic field intensity during one revolution of the particle in its spiral motion is not too great. The total kinetic energy of a particle may be represented as $W = W_\perp + W_\parallel$, where $W_\perp = 1/2\ mv_\perp^2$ and $W_\parallel = 1/2\ mv_\parallel^2$, in which $v_\perp$ is the component of velocity perpendicular to the magnetic field and $v_\parallel$ is that parallel with the field. The magnetic moment

$$\mu = \frac{W_\perp}{H} = \frac{1/2\ mv_\perp^2}{H}$$

is therefore an approximate invariant, and the total kinetic energy W is an exact invariant of the motion. The angle θ between the velocity of the particle and the magnetic field at any point is given by

$$\sin^2 \theta = \frac{v_\perp^2}{v_\perp^2 + v_\parallel^2} = \frac{W_\perp}{W_\perp + W_\parallel} .$$

As a particle approaches a region of increasing field intensity, $W_\perp$ increases as H increases until $W_\parallel$ becomes zero, at which point the motion of the particle is instantaneously in a plane perpendicular to the magnetic field. The axial motion of the particle is then reversed, and the particle is reflected from the region of strong magnetic field, hence the expression "magnetic mirror".

In 1952 R. F. Post[1] and his colleagues began theoretical and experimental research into the confinement of plasma by the use of magnetic mirrors. The magnetic mirror confining field is axially symmetric and consists of a central region of relatively low field intensity between two regions of high field intensity (the magnetic mirrors) at each end. The field is produced by co-axial coils in which the magnetomotive force is concentrated near the ends. If H_o is the magnetic field intensity at the midpoint and H_m the maximum value near the ends, then the mirror ratio $R = H_m/H_o > W/H_m$ for a particle to be confined by reflection at the mirrors. This condition defines the critical pitch angle, θ_c

$$\sin \theta_c = \frac{1}{R^{1/2}} = \left(\frac{H_o}{H_m}\right)^{1/2}$$

such that all particles with pitch angle less than θ_c relative to the magnetic field at the median plane will escape through the ends, while those with pitch angle greater than θ_c will be trapped between the mirrors. If the particles in the plasma are randomly oriented and the mirror ratio $R = 2$, then about 0.3 of the particles are lost immediately and the remainder are trapped.

If the orbit size of the particle is not small, a significant change in the magnetic field occurs in one rotation of the particle, and the assumption that the magnetic moment is a constant of the motion may no longer be valid. Analytical treatment of this case is difficult, but the problem has been investigated[2] by numerical methods. A field shape represented by

$$H_z = H_o \left[1 + \alpha \cos \frac{2\pi z}{L} I(r)\right]$$

was assumed, and particle orbits were traced during many reflections until the cumulative errors of the electronic computer became significant. The conclusions are that the average fractional change in the magnetic moment for each reflection can best be represented by an expression of the form

$$\frac{\Delta\mu}{\mu} = \alpha \exp - \frac{bL}{2\pi R}$$

where L is the distance between the magnetic mirror peaks and $2\pi R$ is the mean circumference of the circular trace of the orbit in the median plane. Thus, if the characteristic length of the machine is sufficiently large compared with the orbit dimension, the deviations in the magnetic moment are negligible and the particles behave adiabatically. Since for the shape of field chosen for these calculations, $\alpha \simeq 5$ and $b \simeq 2$, depending somewhat on the radial position of the orbits, it follows that the motion is essentially adiabatic if $2\pi R/L < 0.2$ and possibly for even larger orbits. Certain classes of particle which fail to meet this criterion are nevertheless found to be trapped indefinitely, because the magnetic moment changes cyclically over such a narrow range that the particle is still trapped. Those for which the magnetic moment changes without any apparent limit eventually fall into the escape cone with $\theta < \theta_c$ and are lost out the mirror.

If an appreciable plasma density is built up, then by collision processes ions which are initially trapped are continually being scattered into the

escape cone and lost. The dominant collision cross-section in a fully ionized plasma is the coulomb cross-section, which varies inversely as the square of the relative energy of the colliding particles. Thus the rate of loss by scattering decreases rapidly as the average energy or temperature of the confined plasma is increased. For this reason confinement by a magnetic-mirror field becomes more effective as the temperature of the plasma increases.

In the scattering process the dispersion in the pitch angle due to small-angle scattering is much more significant than the very infrequent large-scale scattering events.(1) The rate of growth of angular dispersion is similar to the displacement in a random-walk problem and can be expressed in the form $\overline{\theta}^2 = t/t_D$; i.e. the square of the average displacement angle is proportional to the time. The constant t_D is the time at which the average dispersion angle is equal to one radian. Since most of the initially confined particles are lost from the escape cone for changes in pitch angle of this order, t_D is essentially the time for one-half the original plasma to escape out the ends by scattering.

Calculations on the scattering-loss time result in the approximate formula

$$t_D = 2.6 \times 10^{10} \frac{W^{3/2}}{n} \text{ seconds}$$

for deuterons, where W is the energy of the particles in kiloelectron-volts and n is the ion density in ions per cubic centimeter. Thus, for a deuteron energy of 0.01 kev and $n = 10^{14}$ ions/cm^3, as may be achieved in a vigorous discharge, $t_D = 0.26$ μsec--a very brief period of confinement. However, if $W = 150$ kev then $t_D = 0.5$ sec, which is a very adequate confinement time for experimental purposes.

b. <u>Adiabatic Magnetic Compression and Heating of a Plasma</u>

The experiments which have been carried out by Post and his group at Livermore are of two types--magnetic compression and heating of an initially

cold plasma, and the injection of energetic particles into a magnetic-mirror field to build up a hot plasma. In the former type of experiments a plasma is injected into a weak magnetic-mirror field and the intensity of the magnetic field then increased by a large factor by discharging a condenser bank through the mirror coils. The original field lines, together with the plasma, are compressed into a slender spindle near the axis of the machine. If the change in field intensity is small during the period of rotation of an ion in the field, the magnetic moment is a constant during the compression, i.e. $\mu = W_\perp/H = \text{const.}$, so that the rotational energy will increase in direct proportion to the magnetic field intensity:

$$W_\perp(t) = W_\perp(0)\,\frac{H(t)}{H(0)}\,.$$

Since by radial compression the rotational energy of the particles is increased, the mirror confinement of the particles is improved.

Experiments on the Table Top[3] machine have demonstrated the expected compression and heating of a plasma by a rising magnetic-mirror field. In this machine the plasma is injected in an initial field intensity of about 40 gauss. The injected plasma contains electrons of average energy of about 10 ev which are held by the low initial field. However, deuterons of energy greater than about 1 ev (about 5 cm radius at 40 gauss) are immediately lost to the walls in this weak field. In 1/2 msec the field is increased to about 40 kG, yielding a compression ratio of about 1000 or more. The coil is then short-circuited, and the field decreases with the L/R time-constant of the coil, which is of the order of several milliseconds. For various starting conditions the energy distribution of electrons scattered out through the mirror at one end was measured at the time of maximum field and found to correspond to a temperature of 10-20 kev. From these results it is clear that the plasma

electrons are heated as expected by magnetic compression. Since only very low energy positive ions are initially confined, positive ion average energy of only about one kev or less is to be expected. Although direct measurement of the positive ion energy distribution has not been accomplished it is clear that the contribution to the plasma energy density is negligible as compared with that of the much more energetic electrons. By bolometer and other measurements on the total energy of the particles escaping through the mirrors during the decay of the plasma, the plasma energy density at its peak value during the field pulse was found to be about 0.08 that of the magnetic field energy density (plasma $\beta = 0.08$). The fact that no evidence for instabilities has been observed during a confinement time at least as long as 10 msec with such a high ratio of plasma energy density to confining field energy is most encouraging.

The plasma confined in a magnetic mirror field might be expected to be unstable against the line interchange or flute instability. The time for the development of such an instability should it occur is the time for sound to travel the length of the confined plasma body. Sound speed in the plasma is given by

$$v_s = (\gamma p/\rho)^{1/2} = \left(\frac{5}{3}\ \frac{n_+kT + n_-kT}{n_+m_+ + n_-m_-}\right)^{1/2} .$$

Since for the experiment under discussion $n_+ = n_- = n$, $kT_+ \ll kT_-$ and $m_+ \gg m_-$ then

$$v_s = \left(\frac{5}{3}\ \frac{nkT_-}{nm_+}\right)^{1/2} = \left(\frac{5}{3}\ \frac{\bar{W}_-}{m_+}\right)^{1/2}$$

where $\bar{W}_-$ is the average electron energy. Thus for $\bar{W}_- = 20$ kev $= 3.2 \times 10^{-8}$ ergs and $m_+ = 3.3 \times 10^{-24}$ g (for deuterons)

$$v_s = \left(\frac{5}{3}\ \frac{3.2 \times 10^{-8}}{3.3 \times 10^{-24}}\right)^{1/2} = 1.25 \times 10^{8} \text{ cm/sec}$$

and is independent of the plasma density, n, which was about 5×10^{13} ions/cm^3.

The length of the hot plasma body was about 10 cm. Therefore the transit time for sound over the length of the plasma body was

$$\tau_s = \frac{10}{1.25 \times 10^8} = 0.8 \times 10^{-7} \text{ sec.}$$

The observed containment time $\tau_c \approx 10^{-2}$ sec so that

$$\tau_c = \frac{10^{-2}\tau_s}{0.8 \times 10^{-7}} = 1.25 \times 10^5 \tau_s$$

thus of the order of 10^5 times the expected growth time for interchange instabilities, were they to occur. Whereas this high degree of stability is not understood it is quite encouraging since, if instabilities scale as is now believed, this observation provides some hope that magnetic mirror confinement may be free of instabilities for values of the plasma $\beta = 8\pi nkT/H^2$, which are great enough to permit significant advances toward controlled fusion power.

Another observation of interest carried out in the Table Top compression experiment was the measurement of the radial distribution of the energetic electrons in the plasma as a function of the time.[4] A scintillator probe sensitive to electrons of several kev energy was inserted in the median plane (half way between the mirror coils) of the machine and the counting rate observed as a function of the radius. At radial positions greater than 2.5 cm from the axis essentially no pulse signals were observed. When the probe was at radial distances less than 2.5 cm it interfered with plasma formation and produced a large counting rate. The radius of the hot plasma is therefore about 2.5 cm and very few energetic electrons appear to be lost by radial diffusion.

Multiple-compression experiments are also being carried out. Plasma is injected into an 18-in. diameter chamber in a weak magnetic field. By proper shaping of a sequence of pulsed fields the plasma is compressed and transferred successively into a 9-in. diameter chamber and finally into a 3-in.

diameter chamber, where a very high pulsed field intensity of at least 150 kG can be applied. The advantages of this system are that the plasma is rapidly removed from the region where it was produced, leaving the neutral gas and even the high atomic number ions behind, and that a greater over-all compression is possible.

Using a very cold plasma injected into the first stage, the transfer and compression was carried out as expected.(1) Improvements are now being made in the injection system by which the injected plasma particles will have much greater initial transverse energies.(5,6) By this system it is reasonable to expect that positive ion plasma temperatures of the order of 10 kev and densities of the order of 10^{14} ions/cm^3 can be attained.

c. Energetic Particle Injection

From the inception of the magnetic mirror program a major objective has been the buildup of a plasma by injecting energetic positive ions into the confining volume. However, if a particle is injected into a magnetic field from the outside, it will come back out again unless either the field, the particle energy or the particle charge/mass ratio changes while it is in the field.

Many schemes have been considered for injection and trapping by change of charge state,(7-9) the injection of either energetic neutral beams of particles which are ionized inside the confining volume or of molecular ions such as D_2^+ which are dissociated into atomic ions and trapped. At Livermore, preliminary work has been carried out in preparationfor the injection of energetic neutral and molecular ions. With equipment now in operation at Livermore a D_2^+ beam of 0.3 amp at 100 kev can be injected into an aperture 3 in. in diameter with a divergence angle of about 4 deg. An energetic neutral atomic particle beam corresponding to a beam current of 0.1 amp at 100 kev is also produced by focusing and neutralizing the atomic ion beam from this same equipment. A very intense neutral particle beam at 20 kev is now also under development.

The differential equations describing the buildup of the ion density and the reduction of the neutral density by ion pumping have been set up and solved numerically for a number of cases. The case of particular interest is that in which an intense deuterium arc down the axis of the machine is used as a target for molecular-ion dissociation.(10) The molecular ions are injected into helical orbits so that they pass through the arc many times and are essentially all dissociated before returning to the point of injection. The calculations show that with an input of 0.3 amp of 400 kev D_2^+ ions the atomic ion density should build up to 10^{13} ions/cm^3 and the neutral-particle density should be reduced from an initial value of 2×10^{10} particles/cm^3 (corresponding to a pressure of 5×10^{-7} mm Hg) to something like 4×10^7 particles/cm^3. The expected ratio of ion to neutral density is of the order of 250 000, which is beginning to approach conditions of practical interest. The expectation is that, after the plasma has built up to a density of the order of 3×10^{11} ions/cm^3, the arc can be turned off and the high-temperature plasma then used as a target for molecular-ion dissociation. Work on this very promising method of producing a hot plasma will not be continued at the Lawrence Radiation Laboratory since by mutual agreement high energy molecular ion injection in the U.S.A. will be developed exclusively at the Oak Ridge National Laboratory, at least for the immediate future.

An alternative approach, that of relatively low-energy neutral-particle injection,(11) is being actively pursued at the Livermore site. This is the ALICE experiment in which a very intense beam (300 to 500 ma) of hydrogen ions at 15 to 20 kev will be focused into a nearly parallel beam of cross section about 3 x 5 cm and passed through a tenuous neutralizing target. At the energy adopted for this development about 95% of the incident ions will be neutralized. The resulting energetic neutral atomic beam will be directed across the trapping

region of a magnetic mirror machine with a central field intensity of about 50 kG. The main part of the beam will cross the trapping volume and go out the other side into a "burial chamber", where a high gettering speed will be maintained by periodic vacuum evaporation of well outgassed molybdenum. A small fraction of the energetic neutral particles will encounter either residual gas molecules in the trapping volume or a low-density background plasma, experience a charge-exchange event and become trapped as an energetic ion. By this process a hot plasma will be built up in about one second. To ensure that not more than a small fraction of the trapped energetic ions are lost by a subsequent charge-exchange event on a residual gas molecule the neutral gas density must be kept very low--in the range 1 to 5 x 10^{-9} mm Hg. Means of sealing large flanges with metallic gaskets(12) and maintaining very large pumping speeds down to pressures less than 10^{-9} mm Hg(13) have been developed. An ion source capable of producing 500 ma of hydrogen or deuterium ions is in operation.(14) Beam collimation and neutralization are yet to be accomplished before an effective test of the ALICE plasma buildup principle can be carried out. When this is eventually done, a plasma of about the same positive ion energy and density as that in the multiple-compression experiment should result, but the plasma volume (~50 cm^3) will be larger and the containment time (~1 sec) much longer than in the multiple-compression experiment. If both multiple-compression and the ALICE experiments are successful, the next step in the mirror machine program would most likely be a combination of these two systems. Meanwhile both devices give promise of producing hot and dense plasma for experimental study.

2. THE ASTRON PROGRAM

a. Role of Relativistic Electrons in the Astron

Christofilos has proposed a novel method of heating and confining a plasma

utilizing very high energy electrons.[15] In the Astron device it is proposed to use intense circulating currents of very high energy electrons (1) to modify the vacuum field to form a closed pattern of magnetic lines of force for confining a plasma, (2) to create a plasma by ionizing neutral gas, and (3) to heat the resulting plasma by collision processes to the desired reaction temperature. The main chamber of the Astron is to consist of a cylindrical chamber with an axial magnetic field produced by external windings somewhat concentrated at the ends to provide magnetic mirrors. Within this chamber a cylindrical layer of highly relativistic electrons moving helically in the field and being reflected from the mirrors at the ends is to be built up in circulating current. When the population of the electron layer per cm of axial length reaches the value $N_o = \gamma/r_e$, where γ is the relativistic mass of the electrons in restmass units and r_e is the classical electron radius, the magnetic field at the center due to the circulating electrons is about equal and opposite to the vacuum field, and the resultant field inside the layer is approximately zero. If the number of electrons per unit length in the layer is increased above N_o the field inside will be reversed relative to that outside the electron layer. When this occurs the magnetic lines of force form a closed pattern providing a flattened toroidal trapping region within which a plasma may be confined.

When the desired field configuration is attained neutral gas is to be admitted and ionized to form a plasma, which is then heated up by collisions with the energetic electrons. As the plasma energy density increases the ampere-turns in the external field windings will have to be increased to compensate for the diamagnetism of the plasma and maintain the appropriate field intensity at the outside edge of the electron layer. By continually feeding in high-energy electrons the system is to be brought to and maintained in a steady state at any desired plasma density and temperature.

b. High-Current, High-Energy Electron Beam Injection System

In order to attain the conditions required for the Astron an efficient system for injecting very high currents of energetic electrons has been designed and some elements have been tested. The first requirement is an electron gun of unprecedented beam output and quality.[16] The present gun is superficially similar to those used in high-power klystrons with the added feature of a special field configuration which ensures that the random angle of the output beam electrons will be very small. In the present gun the beam output is 60 amp at 600 kev with a random angle of less than 1/5 degree and a pulse time of 0.15 μsec. The high voltage is produced by an iron-core pulse transformer of special design. A modification of the present gun to provide for a somewhat larger cathode is now being built which should produce a beam of about 200 amp at 600 kev for pulse periods of 0.1 μsec.

In order to reverse the field inside the layer it is necessary for the electron energy to be well into the relativistic range. Although at 2 Mev field reversal may be marginally feasible, the accelerator which has been designed for the Astron model tests will accelerate the beam from the new gun to 5 Mev. To avoid degrading the beam quality, acceleration will be accomplished by a pulsed dc field rather than by high frequency. The accelerator will consist of an assembly of pulse transformers with the accelerating column inside the iron core structure. As in the pulse transformer gun, the electron beam becomes the secondary for a number of simultaneously energized primary windings of a pulse transformer system. The injector is designed for at output of 200 amp of electrons at 5 Mev with pulse length of about 0.1 μsec and repetition rate of 60 pulses/second.

The electron beam is to be injected through a magnetically shielded tube tangentially into the field in an extension at one end of the Astron trapping

chamber. This extension will consist of two concentric cylinders in the annulus between which the electrons will spiral along the field at a radius equal to about 3/3 the radius of the trapping chamber. Because of the small pitch angle of the sprial and the short duration of the beam pulses, the electrons will form short cylinders of circulating current moving coaxially along the annulus of the extension.

Over the length of the extension, the field coils will be so arranged that the field intensity will decrease slowly as the electrons approal the trapping chamber.(17) If no other provision were made the cylindrical bunches of electrons would experience an increase in axial velocity in passing from a region of higher to a region of lower vector potential, would be reflected from the magnetic mirror at the far end of the trapping region and return to strike the injector tube. To prevent this loss from occurring it is necessary to absorbe energy from the axial component of the motion as the electron bunches slide down the magnetic vector potential. This is to be accomplished by mounting between the outer wall of the injection annulus and the electron orbits an array of circular resistors. As the short bunches of electrons pass through the resistors they induce dissipative currents in the resistors which remove energy from the axial motion of the bunches. In this manner the electrons lose energy so that they cannot return to the point of injection but are trapped between the magnetic potential ramp at the injection end and the magnetic mirror on the far end of the trapping region. Although the electrons already trapped experience some energy gain from the field energy brought in by each subsequent bunch of electrons, calculations indicate that a magnetic potential well of the order of 20 per cent is sufficient to ensure trapping enough electrons in the layer to reverse the magnetic field.

c. Reversal of the Magnetic Field by Rotating Electrons

Whether reversal of the magnetic field by high currents of relativistic electrons is feasible has been examined by Lewi Tonks in a sequence of calculations.(18) Since the electrons in the layer will be slowed down by residual gas even in the absence of plasma, the equilibrium energy distribution consists of all energies from the initial injection value down to a cut-off value at which the electrons are lost. Space charge neutralization by ionization of the residual gas is assumed. Neglecting for the present the angular scattering of the electrons but including the energy loss, a self-consistent solution for the electron orbits and the modified magnetic field has been obtained. By determining the self-consistent configuration starting with a very small population in the electron layer and increasing the population, conditions have been found which result in a steady reduction and eventual reversal of the field.

Whether the electron layer will be stable under conditions of a reversed field cannot be determined by calculations of the kind described above. For this reason the primary goal of the experimental program is to explore the stability of the electron layer with parameters so chosen that reversal of the field should be feasible, assuming instabilities do not develop. If the layer with reversed field proves to be stable then the layer with plasma should also be stable, at least up to some as yet undetermined value of the plasma energy density.

d. Present Status of the Astron Development

The major accomplishment in the Astron development has been the design, construction and operation of the first model electron gun. The beam from the present gun has been introduced through a magnetically shielded tube tangentially into a cylindrical vacuum tank with an approximate axial magnetic field. The beam pulse is reflected from a weak magnetic mirror and then trapped by

energizing a pulsed coil which again reflects the electrons before they can return to the point of injection. Rotating electrons so trapped between mirrors have been retained for periods up to several seconds.[19] Experiments of this kind will be continued in order to measure and improve the efficiency of the injection process. The present energy of the electrons is too small to permit the trapping of a sequence of beam pulses for building up an appreciable layer density.

Construction of the improved gun to provide a beam current of 200 amp and the induction accelerator described above to increase the energy to 5 Mev should be completed in two years or less. With these facilities it will be possible to determine whether the electron layer with reversed field is stable, and, if so, to build up a hot plasma to whatever energy density is permitted by stability limitations.

3. THE PINCH PROGRAM

a. Linear and Toroidal Pinch Configurations

Wherever the problem of controlled fusion has been considered, the pinch effect has come to mind as the most promising first step toward both heating and confining a plasma. The simple linear pinch, such as that of Baker [20] and colleagues at the Berkeley site of the Lawrence Radiation Laboratory, was found to be so unstable against instability breakup that the column of plasma compressed by the self field of the plasma current could be confined for only about a microsecond. Such a discharge in deuterium can nevertheless produce fusion neutrons in quantities up to 10^9 neutrons/pulse. However, these neutrons are known to be due, not to thermonuclear processes, but to the acceleration of deuterons in the plasma by inductive effects associated with the instability breakup of the plasma.[21] Because of the very brief confinement time there seems to be no possibility that the simple linear pinch can provide a favorable balance of power.

Experiments to stabilize a pinch discharge by imposing an axial magnetic field on the tube before initiating the pinch were first carried out by Baker and colleagues in Berkeley.[22] The axial flux is locked into the highly conducting plasma of the discharge and is compressed together with the plasma by the azimuthal field generated by the discharge current. Colgate, Ferguson and Furth later carried out extensive experiments at Livermore for both a linear and a toroidal "magnetically stabilized" pinch.[23] Magnetic probe measurements on the linear magnetically stabilized pinch yielded results crudely in agreement with the expectations of the Rosenbluth theory.[24] However, since in the linear pinch the plasma is in good thermal contact with the end electrodes it was not surprising that the plasma temperature was never very high (about 30 ev) so that the electrical conductivity of the plasma was low. Rapid interdiffusion of axial and azimuthal fields are expected under these conditions, and the plasma boundary layer of mixed fields was always broader than would be expected for high plasma temperature.

The next logical step was to eliminate the end electrodes by converting the magnetically stabilized pinch to a toroidal form and producing the discharge voltage around the torus by induction.[25] With no electrodes in contact with the plasma the toroidal magnetically stabilized pinch was thought to have the possibility of creating such a high plasma temperature (and therefore high electrical conductivity) that the interpenetration of axial and azimuthal fields would be very slow. If this were true a long confinement time of the hot plasma was anticipated. Magnetic probe and plasma conductivity measurements, however, clearly showed that the plasma boundary layer of mixed fields was unexpectedly broad and the plasma temperature produced in the magnetically stabilized toroidal pinch was much lower (about 20 ev) than had been expected. Since many thousands of joules of energy are poured into the plasma from the

condenser bank during the discharge the plasma temperature should have reached several thousand electron-volts. A search was made for the energy loss mechanisms, and the major loss was found to be due to the ejection of electrons (in the energy range 1.5 to 5 kev) which strike the wall and produce soft x-rays. The belief is that in the plasma boundary layer, in which the pinch current flows, runaway electrons are produced, are accelerated along the spiral lines of force in this region and excite cross modes of electrical oscillation. The non-adiabatic effects of these oscillations may be responsible for the loss of the runaway electrons which appear to account for most of the power input into the discharge.

A recent development at Livermore by Colgate and Furth in an effort to understand the processes which occur in the plasma boundary layer is the "hard core" pinch.[26] In this device the pinch tube has a central copper conductor (surrounded by a cylindrical quartz tube) which carries the full discharge return current. Since the plasma is outside the central conductor, it is pushed outward from the center by the azimuthal field in the inverse of the normal magnetically stabilized pinch. Because the curvature of the plasma boundary layer is away from the plasma, the configuration according to hydromagnetic theory should be stable. Experimental results obtained with multiple magnetic probes performed on the linear hard core pinch have shown that some configurations which are hydromagnetically stable in theory are nevertheless unstable.

Magnetic fluctuations are observed to be quite different at the cathode and anode ends of the tube--the fluctuations near the cathode being smaller in amplitude but extending up into the high frequency range, whereas fluctuations at the anode are larger in amplitude but made up of only the lower frequency oscillations. The fluctuations have been explored along the length of the discharge with the conclusion that the higher frequency oscillations are

progressively damped out in the plasma, whereas the lower frequency oscillations are progressively amplified. It appears that electrons leaving the cathode are modulated, perhaps due to sheath oscillations, and subsequently interact with the plasma producing the observed results.

The vacuum field of the hard core pinch, in which the axial field is independent of r and the azimuthal field falls off as $1/r$, exhibits the quality of shear in the sense that the pitch of the resultant field lines changes with radius. The property of shear in the confining field contributes to the stability of the system, as in the Stellarator. It is found that, in addition to the unstable configurations mentioned above, stable configurations are also found when the field with plasma does not depart to radically from the vacuum field; i.e. when the plasma β is small. These stable configurations are of particular interest and significance.

The linear hard core pinch has the same limitation in attainable temperature as the linear magnetically stabilized pinch due to thermal contact of the plasma with end electrodes. In order to permit the attainment of high temperatures, the hard core pinch is now being built in a toroidal form in which the central conductor becomes a ring. It is proposed to hold the ring in place by magnetic levitation resulting from currents induced in the ring; thus the new device is called the Levitron. The objective will be to determine whether stable configurations discovered in the linear hard core pinch are stable in the toroidal form and whether severe energy losses due to runaway electrons will again occur as in the case of the magnetically stabilized pinch.

After initiating experiments on magnetic stabilization of the pinch, the Berkeley group sought configurations for stable confinement not dependent upon magnetic stabilization. One such configuration is the sheet pinch.[27] An infinite sheet of plasma centrally located between two infinite conducting

planes has neutral stability. Two approximations to the infinite sheet pinch have been under investigation for the past two years. These are the Tubular Pinch (or Triax) and the plane sheet pinch of limited width. Of these two the Tubular Pinch has received much the greater effort.

In the Tubular Pinch the gas is enclosed in an annular space between two cylinders. When the gas is ionized and the pulsed voltage applied between the lower ring electrode and the top electrode, the high plasma current produces azimuthal fields inside and outside of the plasma which compress the plasma into a cylindrical sheet. A number of hydrodynamic bounces can be seen on the voltage trace, and the configuration appears to be stable unless the current exceeds about 1 Ma. The Tubular Pinch produces about 10^6 neutrons per pulse, which do not show evidence for appreciable deuteron acceleration in the plasma. However, the resistance of the plasma is too high to permit the assumption that the plasma reaches a sufficiently high temperature to produce thermonuclear neutrons. Recent experiments[28] looking lengthwise along the plasma with a streak camera have revealed that when the plasma current is very high the plasma does not remain centered in the annulus between the two return conductors, but is thrown toward and strikes the inner wall after about 3 μsec. This effect appears to be due to the lack of balance in the inductances between the inner and outer return conductors, respectively, and the plasma. A modification of the Tubular Pinch has recently been constructed which permits increasing the inductance of the outer conductor and so balance the forces on the plasma. With this correction made it is hoped the plasma sheet can be kept away from the walls and consequently reach significantly higher temperature. It should be pointed out that in the Tubular Pinch configuration the magnetic fields are everywhere orthogonal to the plasma current so that thermal conductivity to the end electrodes should be smaller by several orders of magnitude than that existing

in the magnetically stabilized pinch. The long confinement time and anticipated higher temperature of the Tubular Pinch would seem to offer at least the possibility of making interesting measurements on the behavior of high temperature plasma.

b. The Homopolar Rotating Plasma Device

Another plasma confinement scheme developed at Berkeley is the Homopolar device[29] in which the plasma is created in crossed electric and magnetic fields and experiences rotation from the resulting torque. In this device a flat sheet pinch is produced by a radial flow of current from an outer ring electrode to a central electrode. A magnetic field is produced which is generally orthogonal to the current so that the plasma thus created experiences a torque and is set into rotation to velocities up to about 5×10^6 cm/sec. Parameters can be adjusted so that the current pulse from the condenser bank is critically damped. After cessation of radial current flow the sheet plasma continues to rotate and to maintain a voltage across the terminals for periods of several hundred microseconds. This is an extreme case of rotational confinement which may prove very useful for a period during which shock heating is applied to raise the temperature of the plasma. Although the energy stored in the plasma is very large (of the order of 10 kJ), the rotational motion is relatively coherent, whereas the random motion corresponding to the temperature is probably not in excess of 50 ev. If it is to be useful as a thermonuclear device, some means of adding random energy or convertingsome of the energy of coherent motion must be found The Homopolar device, moreover, has unusual properties as an energy-storage circuit element.[30] After the plasma has been set into rotational motion, maintaining a voltage across its terminals, as in the case of a Faraday-disc generator, energy can be extracted from the device by connecting a low-impedance load across the terminals.

Recent experiments on the Homopolar device show that when the outer electrode is an anode the current density during the steady-state phase shows a remarkable band structure in which rather equally spaced arcs run around the machine at the drift velocity of the plasma.[31] The character of these localized regions of contact between the plasma and the anode are still under study, but the explanation for this striking phenomenon is not yet clear.

4. PLASMA WAVES AND OSCILLATIONS

a. Interaction of Plasma with Microwaves

The response of a plasma to high frequency electromagnetic waves provides a useful diagnostic method which has been developed to an advanced state by Wharton at Livermore.[32] In the event that the collision frequency is small compared with electron plasma frequency given by $\omega_p = (4\pi n_e e^2/m)^{1/2}$ radians/sec, the electromagnetic wave is propagated through the plasma with an effective dielectric constant equal to

$$K = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{4\pi n_e e^2}{m\omega^2}$$

where ω is the angular frequency of the electromagnetic wave, e and m are the charge and mass of the electron, and n_e is the electron density. Numerically the plasma frequency is then $f_p = 9 \times 10^3\ n_e^{1/2}$. Specifically, for a microwave of wavelength equal to 8 mm, the frequency is 3.75×10^{10} cycles/sec and would correspond to a plasma density of $n_e = 1.7 \times 10^{13}$ electrons/cm^3. Thus plasma densities characteristic of many plasma physics experiments are such that the plasma frequency is in the range of microwaves for which sources, wave guides, horns and other circuit components are available.

Microwaves directed into a plasma body are transmitted with a phase shift

$$\beta = \frac{\omega}{c}\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2} = \frac{\omega}{c} K^{1/2}$$

when the microwave frequency is greater than the plasma frequency, but are

absorbed and reflected strongly when the plasma frequency exceeds the microwave frequency. The condition $\omega = \omega_p$ is referred to as the cut-off frequency. These effects are somewhat broadened if the frequency of the electromagnetic wave is comparable with either the collision frequency in the plasma or the electron gyrofrequency in the magnetic field. However, for most cases of interest the cut-off frequency and phase shift are quite sharply defined so that measurements of plasma density can be made.

Based upon the above phenomena, Wharton has developed a microwave interferometer in which the phase shift per wavelength through the plasma can be accurately determined. In addition, observation of phase shift or cut-off for several different microwave frequencies gives very good information on the maximum electron density in the plasma as well as some information of the distribution in density along the microwave beam path.

b. Generation and Propagation of Torsional (Alfvén) Waves

Wilcox and Baker have studied the generation and propagation of torsional Alfvén waves in a highly ionized plasma column.(33) The experimental arrangement was derived from the homopolar device described above. A column of plasma is produced by discharging a small condenser bank through the gas in a cylindrical chamber within which there is a nearly uniform axial magnetic field of intensity up to about 16 kG. By discharging a sharply rising voltage pulse between a short central electrode at one end of the chamber and the chamber wall, an $\bar{E} \times \bar{H}$ torsional force is applied to the plasma column at one end. A corresponding voltage pulse is then detected between the central electrode on the far end and the chamber wall after a brief delay.

The velocity of propagation of an Alfvén wave is given by $V_A = B/(4\pi\rho)^{1/2}$ cm/sec. By plotting the observed velocity against the magnetic field intensity from about 7 to 16 kG, a straight line is obtained. However, instead of

extrapolating to zero intercept, the experimental curve has an appreciable non-zero intercept, the cause of which is not known. At B = 10 kG the measured value of $V_A = 2.8 \times 10^7$ cm/sec, which yields $\rho = 1.0 \times 10^{-8}$ g/cm^3 or 6.1×10^{15} protons/cm^3. The hydrogen pressure before the discharge was regulated to 100 μ Hg, corresponding to 7.1×10^{15} protons/cm^3.

By measuring the magnetic field fluctuations associated with the wave, the energy transfer from the external circuit to the wave was found to be 43%. This relatively high efficiency is important to the next step which will involve input from a high frequency oscillator and a non-uniform axial magnetic field of the mirror machine type. Waves initiated at the end of the chamber will propagate into a region of diminishing field intensity and reach a point where the Alfvén wave frequency equals the ion cyclotron frequency, at which point the wave should be absorbed and the plasma at the center of the mirror machine heated.

Somewhat related experiments on torsional Alfvén waves have been carried out by Chambers and Furth at Livermore.[34] In their experiments the plasma is a hollow reflux or Penning[35] type of discharge. By applying a radio frequency field radially through the plasma near one of the ring electrodes at one end, axially propagating Alfvén waves are generated in the plasma. As the magnetic field is changed the location of the point at which the ion cyclotron resonance is satisfied is observed to move from a point near one end to the central region between the magnetic mirrors. Magnetic pickup loops are used as probes for detecting the high frequency fields associated with the resonance. As is also expected, when the field is everywhere above the ion cyclotron resonance point the wave is transmitted along the entire length of the hollow plasma and is detected at the far end of the machine. When resonence occurs anywhere over the length of the machine the wave is observed to be completely absorbed and no signal is observed near the electrode at the far end. Although the energy

fed into the plasma in this experiment is very small, it appears that the "magnetic beach" type of plasma heating as predicted by Stix[36] has been observed.

5. CONCLUDING REMARKS

In the above discussion of controlled thermonuclear research at the University of California Lawrence Radiation Laboratory technological developments have been omitted and the descriptions of experiments have been very brief. However, the main lines of endeavor toward the production and confinement of a very hot plasma have been outlined and the status and plans of each of the projects briefly described.

A question which might be fairly asked is, "What are the prospects for success from such a diverse program?" The answer to the question depends, of course, upon the kind of success one is seeking. The probability of any one component of the program leading directly toward the controlled release of fusion power may be small. However, the knowledge of plasma physics being gained and the technology being developed certainly contribute to the eventual attainment of controlled fusion power. Moreover, the justification for intense research on high temperature plasma is by no means limited to the single goal of controlled fusion power. Other practical objectives that may very well be realized are magnetohydrodynamic power generation, plasma thermocouple energy conversion, plasma propulsion and energy generation for interplanetary vehicles, sources of very intense microwaves and many other thoroughly worthwhile goals.

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