Summary of UCRL Pyrotron (Mirror Machine) Program*

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Under the sponsorship of the Atomic Energy Commission, work has been going forward at the University of California Radiation Laboratory since 1952 to investigate the application of the so-called " magnetic mirror " effect to the creation and confinement of a high temperature plasma. By the middle of 1953 several specific ways by which this principle could be applied to the problem had been conceived and analyzed and were integrated into a proposed approach which has come to be dubbed "The Mirror Machine".[1] Study of the various aspects of the physics of the Mirror Machine has been the responsibility of a Laboratory experimental group (called the "Pyrotron" Group) under the scientific direction of the author. During the intervening years of effort, experiments have been performed which demonstrate the confinement properties of the Mirror Machine geometry and confirm several of its basic principles of operation. There remain, however, many basic quantitative and practical questions to be answered before the possibility of producing self-sustained fusion reactions in a Mirror Machine could be properly assessed. Nevertheless, the experimental and theoretical investigations to date have amply demonstrated the usefulness of the mirror principle in the experimental study of magnetically confined plasmas. This report presents some of the theory of operation of the Mirror Machine, and summarizes the experimental work which has been carried out.

PRINCIPLE OF THE MAGNETIC MIRROR

The modus operandi of the Mirror Machine is to create, heat and control a high temperature plasma by means of externally generated magnetic fields. The magnetic mirror principle is an essential element, not only in the confinement, but in the various manipulations which are performed in order to create and to heat the plasma.

Confinement

The magnetic mirror principle is an old one in the realm of charged particle dynamics. It is encountered for example, in the reflection of charged cosmic ray particles by the earth's magnetic field. As here to be understood, the magnetic mirror effect arises whenever a charged particle moves into a region of magnetic field where the strength of the field increases in a direction parallel to the local direction of the field lines, i.e., wherever the lines of force converge toward each other. Such regions of converging field lines tend to reflect charged particles, that is, they are " magnetic mirrors ". The basic confinement geometry of the Mirror Machine thus is formed by a cage of magnetic field lines lying between two mirrors, so that configuration of magnetic lines resembles a two-ended wine bottle, with the ends of the bottle defining the mirror regions. This is illustrated in Fig. 1, which also shows schematically the location of the external coils which produce the confining fields. The central, uniform field, region can in principle be of arbitrary length, as dictated by experimental convenience or other considerations. For various reasons, it has been found highly desirable to maintain axial symmetry in the fields, although the general principle of particle confinement by mirrors does not require this.

The confinement of a plasma between magnetic mirrors can be understood in terms of an individual particle picture. The conditions which determine the binding of individual particles between magnetic mirrors can be obtained through the use of certain adiabatic invariants applying generally to the motion of charged particles in a magnetic field.

The first of these invariants is the magnetic moment, μ, associated with the rotational component of motion of a charged particle as it carries out its helical motion in the magnetic field.[2] The assumption that μ is an absolute constant of the motion is not strictly valid, but, as later noted, it represents a very good approximation in nearly all cases of practical interest in the Mirror Machine.

The magnitude of μ is given by the expression

$$\mu = W_\perp/H = \tfrac{1}{2}mv_\perp{}^2/H \text{ ergs/gauss} \qquad (1)$$

which states that the ratio of rotational energy to magnetic field remains a constant at any point along the helical trajectory of the charged particle. In this case the magnetic field is to be evaluated at the line of force on which the guiding center of the particle is moving.

Now, at the point at which a particle moving toward a magnetic mirror is reflected, its entire energy of

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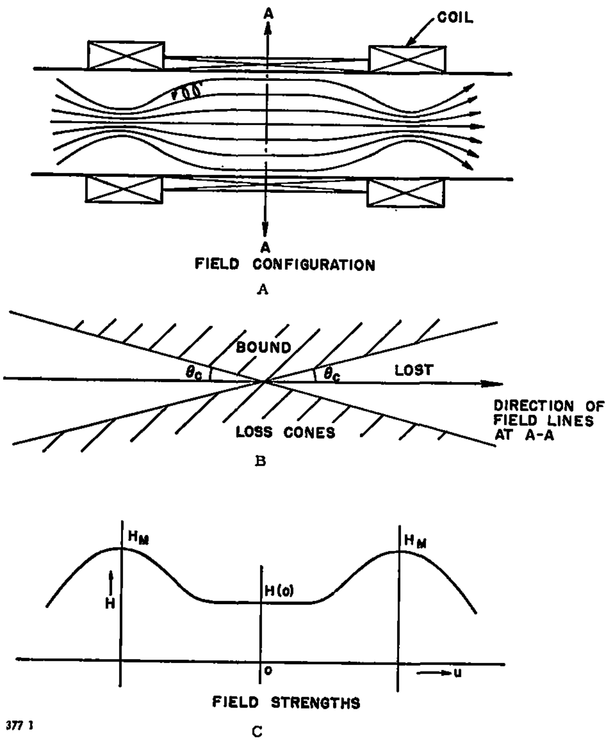

Figure 1. (*a*) Schematic of magnetic field lines and magnetic coils, (*b*) mirror loss cones, (*c*) axial magnetic field variation

motion, W, is in rotation, so that at this point $\mu H = W$. The condition for binding charged particles between two magnetic mirrors of equal strength is therefore simply that for bound particles

$$\mu H_{\mathrm{M}} > W \tag{2}$$

where H_{M} is the strength of the magnetic field at the peak of the mirror. This condition may also be expressed in terms of field strength and energies through use of (1). If H_0 is the lowest value of the magnetic field between the mirrors, and H_{M} is the peak value at the mirror (both being evaluated on the same flux surface) then (2) becomes

$$W/W_{\perp}(0) < R_{\mathrm{M}} \tag{3}$$

where $R_{\mathrm{M}} = H_{\mathrm{M}}/H_0$ (the "mirror ratio") and $W_{\perp}(0)$ is the value of W at the point where H takes on the value H_0.

It is to be noted that the condition that particles be bound does not depend on their mass, charge, absolute energy, or spatial position, nor on the absolute strength or detailed configuration of the magnetic field. Instead, it depends only on the ratios of energy components and magnetic field strengths. Such an insensitivity to the details of particle types or orbits is what is needed to permit the achievement of a confined plasma; i.e., a gas composed of charged particles of different types, charges and energies. The simplicity of the binding conditions reflects the insensitivity to detailed motion required to accomplish this.

Further insight into the nature of confinement of a plasma by mirrors can be obtained by manipulation of the reflection condition. By differentiation, holding the total particle energy constant, it can be shown that a particle moving along a magnetic line of force (or flux surface) into a magnetic mirror always experiences a retarding force which is parallel to the local direction of the magnetic field and is given by the expression[3]

$$F_u = \mu \frac{\partial H}{\partial u} \text{ dynes,} \tag{4}$$

where u is the axial distance from the plane of symmetry.

This force, which is the same as that expected on a classical magnetic dipole moving in a magnetic field gradient, represents the reflecting force of the mirror. Integrated up to the peak of the mirrors, (4) yields again the binding condition (3).

Since μ has been assumed constant, (4) may also be written in the form

$$F_u = -\nabla_u(\mu H) \tag{5}$$

This shows that the quantity μH acts as a potential so that the region between two magnetic mirrors of equal strength lies in a potential well between two potential maxima of height μH_{max}.

Loss Cones

It is evident, either from (2), (3) or (5), that it is not possible to confine a plasma which is isotropic in its velocity conditions—one in which all instantaneous spatial directions of motion are allowed—between two magnetic mirrors: confinement of an isotropic plasma is only possible to contemplate in special cases where multiple mirrors might be employed. This limitation can be understood in terms of the concept of *loss cones*. The pitch angle, θ, of the helical motion of particles moving along a line of force is transformed in accordance with a well-known relationship.[4]

$$\sin \theta(u) = [R(u)]^{\frac{1}{2}} \sin \theta(0) \tag{6}$$

where the angle $\theta(u)$ is measured with respect to the local direction of the magnetic field. $R(u)$ is the mirror ratio, evaluated at u, $R(u) \equiv H(u)/H(0)$.

Expression (6) bears a resemblance to Snell's Law of classical optics, which relates refraction angles within optically dense media. Here $\sqrt{R}$ is analogous to the index of refraction of Snell's Law. As in the optical case, total internal reflection can occur for those angles larger than a critical angle, θ_c, found by setting $\sin \theta$ equal to its maximum value of 1. Thus

$$\sin \theta_c = R_{\mathrm{M}}^{-\frac{1}{2}}. \tag{7}$$

This relation defines the loss cones for particles bound between magnetic mirrors, illustrated in Fig. 1. All particles with pitch angles lying outside the loss cones are bound, while all with pitch angles within the loss cone will be lost upon their first encounter with either mirror (for equal mirror strengths). It should be emphasized that the concept of the mirror loss cone pertains to the velocity space of the trapped particles and has nothing to do with the spatial dimensions of the confining fields.

Although the binding of particles between magnetic mirrors can be accomplished with fields which are not axially symmetric, there are substantial advantages to the adoption of axial symmetry. One of these advantages arises from the fact that all " magnetic bottles " involve magnetic fields with gradients or curvature of the magnetic field lines in the confinement zone, the existence of which gives rise to systematic drifts of the confined particles across the magnetic lines of force.[5] If the particle orbit diameters are small, compared to the dimensional scale of the field gradients or field curvature, these drifts will be slow compared to the particle velocities themselves. If directed across the field, however, they would still be too rapid to be tolerated and would effectively destroy the confinement. Furthermore, drifts of this type are oppositely directed for electrons and ions and may thus give rise to charge separation and electric fields within the plasma. These electric fields then may induce a general drift of the plasma across the field to the walls. However, if the magnetic field is axially symmetric, as for example in the mirror field configuration of Fig. 1, the particle drifts will also be axially symmetric, leading only to a rotational drift of the plasma particles around the axis of symmetry, positive ions and electrons drifting in opposite directions. However, this will not result in a tendency for charge separation to occur, since each flow closes on itself.

Another consequence of the use of axial symmetry is that even though the confined particles may be reflected back and forth between the mirrors a very large number of times, this fact will not lead to a progressive " walking " across the field. In fact, it is possible to show that all particles trapped between the mirrors are also bound to a high order of approximation to the flux surfaces on which they move and may not move outward or inward to another flux tube (apart from the normal slow diffusion effects arising from interparticle collisions).

Once bound, there is no tendency for particles to escape the confining fields, within the assumptions made to this point. However, in predicting the conditions for confinement of a *plasma* by means of conditions applying to the individual particles of the plasma, one makes the tacit assumption that cooperative effects will not act in such a way as to destroy the confinement. Such cooperative effects can modify the confinement through static or time-varying electric fields arising from charge separation, or through diamagnetic effects which change the local strength of the confining fields themselves. However, if the confining magnetic fields are axially symmetric, and if the presence of the plasma does not destroy this symmetry then, as has already been explained, charge separation effects cannot give rise to systematic drifts across the field. Similarly, in such a circumstance the diamagnetic effect of the plasma can only lead to an axially symmetric depression of the confining fields in the central regions of the confinement zone, but will leave the fields at the mirrors essentially unaltered (since the density falls nearly to zero at the peak of the mirrors, where particles are escaping). Symmetric diamagnetic effects therefore tend to increase the mirror ratios above the vacuum field value. Of course, there will exist a critical value of β, the ratio of plasma pressure to magnetic pressure, above which stable confinement is not possible. This critical relative pressure will be dependent on various parameters of the system, such as: the mirror ratio; the shape, symmetry and aspect ratio of the fields; and the plasma boundary conditions. Although the precise conditions for stability of plasmas confined by magnetic mirrors are not at this time sufficiently well understood theoretically to predict them with confidence, there is now agreement that it should be possible to confine plasmas with a substantial value of β between magnetic mirrors.[6] This conclusion is borne out by the experiments here reported, which indicate stable confinement. It should be emphasized, however, that, encouraging as this may be, neither the theoretical predictions nor the experimental results are yet sufficiently advanced to guarantee that plasmas of the size, temperature and pressure necessary to produce self-sustaining fusion reactions in a Mirror Machine would be stable. As in all other known " magnetic bottles " the ultimate role of plasma instabilities has not yet been determined in the Mirror Machine.

LOSS PROCESSES

Non-Adiabatic Effects

Although it has been shown that trapping conditions based on adiabatic invariants predict that a plasma might, in principle, be confined within a Mirror Machine for indefinitely long periods of time, it is clear that mechanisms will exist for the escape of particles, in spite of the trapping.

One might first of all question the validity of the assumption of constant magnetic moment, since trapping depends critically on this assumption. It is clear that this assumption cannot be exactly satisfied in actual magnetic fields, where particle orbits are not infinitesimal compared to the dimensions of the confining magnetic field.

It can be seen from first principles, as for example shown by Alfvén[2] that the magnetic moment will be very nearly a constant in situations where the magnetic field varies by only a small amount in the course of a single rotation period of the particle. It might also be suspected, in the light of the analogy between this problem and the general theory of non-adiabatic effects of classical mechanics, that the deviations from adiabaticity should rapidly diminish as the relative orbit size is reduced. Kruskal[7] has shown that the convergence is indeed rapid but his results are not readily applicable to the Mirror Machine. Using numerical methods, however, it has been shown[8]: (*a*) that the fluctuations in magnetic moment associated with non-adiabatic effects are of importance only for relatively large orbits, (*b*) that these fluctuations seem to be cyclic in nature, rather than cumulative, and (*c*) that they diminish approximately exponentially with the reciprocal of the particle orbit size, so that it should always be possible to scale an experiment in such a way as to make non-adiabatic orbit effects negligible. The results may be roughly summarized by noting that, for the typical orbits which were considered, the maximum amplitude of the fractional changes in the magnetic moment, which occurred after successive periods of back-and-forth motion of trapped particles, could be well represented by an expression of the form

$$|\delta\mu/\mu| = ae^{-b/\nu} \tag{8}$$

where $\nu = 2\pi\mathscr{R}/L$, i.e., the mean circumference of the particle orbit divided by the distance between the mirrors. The mirror fields were represented by the function $H_z = H_0\ [1+\alpha \cos uI(\rho)]$ plus the appropriate curl-free function for H_r. Here, in dimensionless form, $u = 2\pi z/L$ and $\rho = 2\pi r/L$. With $\alpha = 0.25$, typical values of the constants a and b were in the range $4 < a < 6$, $1.5 < b < 2$, for various radial positions of the orbits. From these values it can be seen that provided $\nu < 0.2$, the variations in μ are totally negligible, so that the adiabatic orbit approximation is well satisfied. For example, if $L = 100$ cm then all orbits with mean radii less than about 3 cm can be considered to behave adiabatically. This imposes restrictions on the minimum values of magnetic fields which can be used, or on the minimum size of the confinement zones, but it is clear that, as the scale of the apparatus is increased, the assumption of orbital adiabaticity becomes increasingly well satisfied.

Collision Losses

Even under conditions where the adiabatic invariants establish effective trapping of particles, there still remains a simple and direct mechanism for the loss of particles from a mirror machine. This is, of course, the mechanism of interparticle collisions, the mechanism which limits the confinement time of any stable, magnetically confined plasma. Collisions can induce changes in either the magnetic moment or energy of a trapped particle, and thus can cause its velocity vector to enter the escape cone. The dominant collision cross section in a totally ionized plasma is the Coulomb cross section, which varies inversely with the square of the relative energy of the colliding particles. Thus the rate of losses (if dominated by collisions) can be reduced by increasing the kinetic temperature of the plasma. The basic rate of these loss processes may be estimated by consideration of the "relaxation" time of energetic particles in a plasma, as calculated by Chandrasekhar or by Spitzer. In this case, the relevant quantity is the mean rate of dispersion in pitch angle of a particle as a result of collisions, since, if a given trapped particle is scattered through a large angle in velocity space, the probability is large that it will have been scattered into the escape cone and thus lost. As is usual in a plasma, distant collisions (within a Debye sphere) play a greater role than single scattering events. The time for the growth of the angular dispersion in this (multiple) scattering process for a particle of given energy is governed by the relation

$$\bar{\theta}^2 = t/t_D \tag{9}$$

where

$$t_D = \frac{M^2v^3}{\pi ne^4\ \mathscr{H}(x)\log\Lambda}, \tag{10}$$

M and v are the mass and velocity of the scattered particle, $x^2 = W/kT = \frac{1}{2}Mv^2/kT$ and $\log \Lambda$ has the usual value[5] of about 20. $\mathscr{H}(x)$ is a slowly varying function of x and is approximately equal to 0.5 for typical values.

In terms of deuteron energies in kev,

$$t_D = 2.6\times10^{10}W^{\frac{3}{2}}/n \text{ seconds.} \tag{11}$$

For $\bar{\theta}^2 = 1$, the scattering time becomes equal to t. Thus t_D represents a rough estimate of the confinement time of ions in a Mirror Machine. It is clear that the confinement time will also depend on the mirror ratio R, but detailed calculations show that for large values of this ratio, the confinement varies only slowly with R.

Some numerical values are of interest in this connection. Suppose $W = 0.01$ kev, and $n = 10^{14}$, a mean particle energy and density which might be achieved in a simple discharge plasma. In this case $t_D = 0.26$ μsec. This means that the confinement of low temperature plasmas by simple mirrors will be of very short duration, unless means for rapid heating are provided, which would extend the confinement time. On the other hand, for $W = 150$ kev, the same particle density would give $t_D = 0.5$ sec, which is long enough to provide adequate confinement for experimental studies and is within a factor of about 20 of the mean reaction time of a tritium-deuteron plasma at a corresponding temperature. Since the energy released in a single nuclear reaction would be about 100 times the mean energy of the plasma particles, it can be seen that the possibility exists for producing an energetically self-sustaining reaction, with a modest margin of energy profit, in this case about 4 to 1.

The problem of end losses may be more precisely formulated by noting that these losses arise from binary collision processes, so that it should be possible at all times to write the loss rate in the form

$$\dot{n} = -n^2\langle\sigma v\rangle_s f(R) \tag{12}$$

where $\langle\sigma v\rangle_s$ represents a scattering rate parameter and $f(R)$ measures the effective fractional escape cone of the mirrors for diffusing particles. If $\langle\sigma v\rangle_s$ remains approximately constant during the decay, then integration of the equation shows that a given initial density will decay with time as

$$n = n_0\tau/(t+\tau) \tag{13}$$

where

$$\tau = [n_0\langle\sigma v\rangle_s f(R)]^{-1}. \tag{14}$$

The relaxation time approximation consists of setting $f(R) = 1$—i.e., ignoring the dependence on mirror ratio, thereby overestimating the loss rate—and, at the same time, approximating the true value of $n_0\langle\sigma v\rangle_S$ by $1/t_D$, which tends to underestimate the loss rate. Thus, in this approximation, the transient decay of the plasma in a Mirror Machine is given by

$$n = n_0 t_D/(t+t_D). \qquad (15)$$

In this approximation, t_D represents the time for one-half of the original plasma to escape through the mirrors. Now, the instantaneous rate of nuclear reactions which could occur in the plasma is proportional to n^2. Integrating n^2 from (15) over all time, it is found that the total number of reactions which will occur is the same as that calculated by assuming that the density has the constant value n_0 for time t_D and then immediately drops to zero; i.e., number of reactions is proportional to $n_0^2 t_D$.

Actually, although they correctly portray the basic physical processes involved in end losses, estimates of confinement time based on simple relaxation considerations are likely to be in error by factors of two or more. To obtain accurate values of the confinement time more sophisticated methods are required. Judd, McDonald and Rosenbluth,[9] and others,[8] have applied the Fokker-Planck equation to this problem and have derived results which should be much closer to the true situation, even though it was necessary to introduce simplifying approximations in their calculations. They find that calculations based on the simple relaxation considerations tend to overestimate the confinement times. They are also able to calculate explicitly the otherwise intuitive result that the mean energy of the escaping group of particles is always substantially less than the mean energy of the remaining particles, a circumstance which arises because low energy particles are more rapidly scattered than high energy ones.

The most detailed results in these end loss calculations have been obtained by numerical integration. However, before these results were obtained, D. Judd, W. McDonald, and M. Rosenbluth derived an approximate analytic solution which, in many cases, differs only slightly from the more accurate numerical calculations. Their results can be expressed by two equations which describe the dominant mode of decay of an eigenvalue equation for the diffusion of particles in the velocity space of the Mirror Machine.

The first equation, that for the density, is:

$$\dot{n} = -n^2[\tfrac{4}{3}\pi(e^4/m^2)\langle v^{-1}\rangle\langle v^{-2}\rangle \log \Lambda]\lambda(R), \qquad (16)$$

where the angle brackets denote averages over the particle distribution and $\log \Lambda$ is the screening factor.[5] The eigenvalue $\lambda(R)$ is closely approximated by the expression $\lambda(R) = 1/\log_{10}(R)$, showing that the confinement time varies linearly with the mirror ratio, at small mirror ratios, but that it varies more slowly at large values of R. We see immediately from the form of the equation that one can define a scattering time as in Eq. (14):

$$\tau_\lambda = \{[\tfrac{4}{3}\pi(n_0 e^4/m^2 v_0^3)\log \Lambda][v_0^3\langle v^{-1}\rangle\langle v^{-2}\rangle]\lambda(R)\}^{-1}. \qquad (17)$$

The term in the first bracket is almost identical with that for the relaxation time of a particle with the mean velocity v_0. The velocity averages give rise to small departures from the simple relaxation values but, as noted, the corrections are usually not large.

In a similar way, an equation can be written for the rate of energy transport through the mirror by particle escape. The basic rate for this is, of course, simply given by the value of $\dot{n}\bar{W}_S$; but $\bar{W}_S$, the mean energy of escaping particles, as noted, is not the same as the mean energy of the remaining particles. They find, for the rate of energy loss:

$$\dot{n}\bar{W}_S = -n^2[\tfrac{2}{3}\pi(e^4/m)\langle v^{-1}\rangle \log \Lambda]\lambda(R). \qquad (18)$$

Since the value of $\langle v^{-1}\rangle$ is not particularly sensitive to the velocity distribution, one may calculate this for a Maxwellian distribution without committing excessive error.

The mean energy of the escaping ions, $\bar{W}_S$, may be evaluated from the equations. Dividing (18) by (16), $\bar{W}_S$ is seen to be $\tfrac{1}{2}m\langle v^{-2}\rangle^{-1}$. Approximating the actual distribution by a Maxwellian, $\bar{W}_S$ turns out to be $\tfrac{1}{2}kT$, or $\tfrac{1}{3}$ of the Maxwellian mean energy. This is roughly the same value as was obtained by the more accurate numerical calculations.

As far as eventual practical applications are concerned, the over-all result of the detailed end loss calculations is to show that although a power balance can in principle be obtained, both with the DT and DD reactions, by operation at sufficiently high temperatures, the margin is less favorable than the rough calculations indicated. Thus, any contemplated application of the Mirror Machine to the generation of power would doubtless require care in minimizing or effectively recovering the energy carried from the confinement zone by escaping particles. Some possible ways by which this might be accomplished will be discussed in sections to follow. Other methods to reduce end losses through magnetic mirrors have been suggested and are under study. One of these, involving a rotation of the plasma to "enhance" the mirror effect, is under study at this Laboratory and at the Los Alamos Scientific Laboratory.

In the present Mirror Machine program, scattering losses impose a condition on the experimental use of simple mirror systems for the heating and confinement of plasmas. This condition is that operations such as injection and heating must be carried out in times shorter than the scattering times. These requirements can be readily met, however, in most circumstances so that end losses do not present an appreciable barrier to the studies.

Ambipolar Effects

Since the scattering rate for electrons is more rapid than for ions of the same energy, the intrinsic end loss rate for electrons and ions will be markedly different. In an isolated plasma this situation will not persist, since a difference in escape rates will inevitably result in establishing a plasma potential which equalizes the rate. In ordinary discharge plasmas, where this effect also appears, this " ambipolar " loss rate is always dominated by the *slower* species of the plasma. This situation seems to apply also to plasmas confined in the Mirror Machine. Although many different cases are possible, not all of which are understood, the role of ambipolar effects seems mainly to be to introduce a (usually) small correction to the end loss rate as calculated from ion-ion collisions. For example, in the important case where the electron temperature is small compared with the ion temperature, Kaufman[10] has shown that ambipolar phenomena establish a positive plasma potential which, in effect, changes the mirror ratio for the ions to a somewhat smaller value given by the expression

$$R_{\text{eff}} = R[1+\gamma(T_e/T_i)]^{-1}, \tag{19}$$

where γ is a constant of order unity. For cases of practical interest, the resulting correction to the ion loss rates is small. However, the precise role of ambipolar diffusion effects and the electric potentials to which they give rise is not well understood, especially with regard to plasma stability, and must, therefore, be labeled as part of the unfinished business of the Mirror Machine program.

Confinement of Impurities

In the study of magnetically confined plasmas, and in their eventual practical utilization, contamination of the plasma by unwanted impurities presents a serious problem. Since the plasma particle densities which are of present and future interest are about 10^{14}–10^{15} cm^{-3}, the presence of impurities to the extent of even a small fraction of a microgram per liter represents a sizeable amount of contamination, percentage-wise. Impurities usually originate from adsorbed layers on the chamber walls, the release of even a small fraction of an atomic monolayer corresponding to a large degree of contamination.

Impurities of high atomic number greatly increase the radiation losses from the plasma. At temperatures of a few million degrees the radiation loss mechanism is principally from electron-excited optical transitions of incompletely stripped impurity ions. In this case, the intrinsic radiation rates per impurity ion can be as high as one million times the radiation rate of a hydrogen ion. At thermonuclear temperatures, the stripping becomes more nearly complete, so that the radiation rate from impurities becomes less intense, finally approaching the bremsstrahlung value, Z^2 times the loss rate for hydrogen. But even in this case, because of the relatively narrow margin between the thermonuclear power production and the radiation loss rates from even a perfectly pure hydrogenic plasma, the concentration of high-Z impurities must be kept to a minimum. The actual level of impurities in any magnetically confined plasma will be determined by a competition between their rate of influx and the degree to which they are confined by the magnetic fields.

In the light of these facts, it is important to note that in the Mirror Machine, the confinement of impurity ions should be much poorer than for energetic hydrogen ions. Thus there tends to exist a natural "purification" mechanism discriminating against the presence of impurities in the plasma.

This happy circumstance arises from three general causes. First, the scattering rate for stripped high-Z ions is more rapid than for hydrogen ions of the same energy. Second, impurity ions originating from the walls will always have much lower energies than the mean energy of the confined ions. This will increase their loss rate by scattering. Third, in the "normal" high temperature confinement condition in the Mirror Machine, where ion energies are much greater than the electron temperature, the sign of the plasma potential should be positive, so that low energy positive ions cannot be bound at all, but will be actively expelled. These circumstances could be of an importance equal to that of adequate confinement in the eventual problems of establishing a power balance from fusion reactions.

BASIC OPERATIONS

In order to create, heat and confine a hot plasma in any magnetic bottle a series of operations is always required. In the Mirror Machine a somewhat different philosophy of these operations has been adopted from that used in most other approaches, for example, those utilizing the pinch effect. In those approaches, one starts with a chamber filled with neutral gas and then attempts to ionize the gas, heat and confine the resulting plasma. By contrast, in the Mirror Machine a highly evacuated chamber is employed, into the center of which a relatively energetic *plasma* is injected, trapped and subsequently further heated. Since the Mirror Machine possesses "open" ends through which the plasma can be introduced by means of external sources, injection methods can be employed which are not possible in systems of toroidal topology.

By using the magnetic mirror effect in various ways, it is possible to perform several basic operations on a plasma. These are employed in the Mirror Machine to create, heat, control and study the plasma. In addition to simple confinement the following operations are used.

1. Radial compression—adiabatic compression of the plasma performed by uniformly increasing the strength of the confining fields.
2. Axial compression—adiabatic compression performed by causing the mirrors to move closer together.
3. Transfer or axial acceleration—pushing the plasma axially from one confinement region to another by moving the mirrors.
4. "Valve" action—controlling the direction of diffusion of the plasma by weakening or strengthening one mirror relative to the other.

In the experimental study of these operations most of the emphasis has been placed on achieving conditions where the assumption of adiabaticity is valid and where collision losses and ambipolar effects are minimized by control of the heating cycle. This operational regime is a relatively simple one to understand, is readily analyzed theoretically, and presents some substantial practical advantages.

The primary method of heating used in the Mirror Machine is adiabatic compression; i.e., the heating occurs when the confining magnetic fields are changed at a rate which is relatively slow compared with the periods of rotation of the plasma ions.

The adiabatic magnetic heating of a plasma can be understood either from an individual particle viewpoint, or from general thermodynamic principles. Consider, first, the behavior of trapped particles in a confining field which is increasing with time. In such a field, the energy of each trapped particle will increase, simply because of the constancy of the magnetic moment, $\mu = W_\perp/H$ = constant (Eq. (1)). Thus, rotational energy will increase in direct proportion to the magnetic field:

$$W_\perp(t) = W_\perp(0)H(t)/H(0) \equiv W_\perp(0)\alpha. \quad (20)$$

At the same time it can be shown that adiabatic magnetic heating of this type proceeds so that the flux through each elementary orbit remains constant and also so that the guiding centre of each particle remains on the same flux tube of the increasing magnetic field, i.e., the plasma is uniformly compressed toward the magnetic axis of the confining field.[11]

This leads to an increase in the plasma density as well as an increase in its mean energy. This is the *radial* compression listed above. Since energy is imparted to the rotational component of particle motion, this type of heating leads to more effective binding of the particles.

Axial compression, accomplished by mechanically or electrically moving the mirror fields toward each other, results in the same type of heating as discussed by Fermi in his theory of the origin of cosmic rays.[4] Axial compression leads to an increase in the parallel energy component of each trapped particle by an amount proportional to the *square* of the compression factor. If the mirrors are separated by a distance $L(t)$ then

$$W_\parallel(t) = W_\parallel(0)[L(0)/L(t)]^2 \equiv W_\parallel(0)\kappa^2. \quad (21)$$

In this case the heating leads to poorer trapping, so that it can only be used to a limited extent.

The increase in density which results from these two compression processes is given by the product of the radial and axial compression factors. The radial compression is determined by the constant flux condition, which implies that the radius of the plasma will vary as $H^{-\frac{1}{2}}$ and its area therefore as H^{-1}. The total compression is then given by

$$\frac{n(t)}{n(0)} = \frac{H(0, t)}{H(0, 0)}\kappa = \alpha\kappa.$$

Both types of adiabatic compression heating can be related to simple thermodynamic gas laws. In radial compression, the gas behaves as a two-dimensional gas, since there are two degrees of freedom associated with rotational energy. For this case, the gas constant, γ, has the value 2 and the heating varies linearly with the density $T_\perp \sim n^{\gamma-1} \sim n$. In the case of axial compression, there is only one degree of freedom (motion along the lines of force) so that $\gamma = (2+f)/f = 3$ and $T_\parallel \sim n^2$. If collisions become important during the compression heating, all three degrees of freedom will be coupled and the heating will proceed as in an ordinary gas; $T \sim n$.

Compression

Magnetic compression processes, as used in the operation of the Mirror Machine, can be calculated by the use of a single integral which incorporates all of the adiabatic assumptions. The adiabatic invariants which apply to the motion of trapped particles of the plasma moving between the mirrors are (1) the magnetic moment, $\mu = W_\perp/H$ and (2) the action integral of the particle momentum along magnetic lines of force, taken over a period of the bound motion along a line of force, i.e., $\oint p_\parallel du = A$. The constancy of A is dependent on the assumption that the magnetic field shall change only by a small relative amount during the time of one period, a condition which is usually satisfied in the experiments. When this is true, the total energy of each particle is also slowly varying so that the angle transformation relationship, Eq. (6), applies to the motion.

All three of the above conditions can be combined in a single equation which predicts the essential character of the compression process.[12] Since we are not interested in the detailed motion of each particle, but only in the salient features of its motion, it is convenient in this equation to represent the orbit of each trapped particle solely by the location of its end point or "high water mark" in the confining mirror fields. The subsequent fate of the plasma can then be predicted by following the evolution of these end points. The equation derived is:

$$[H(0)]^{\frac{1}{2}} \int_{u_1}^{u_2} [R_m - R(u)]^{\frac{1}{2}}\, du = S = \text{constant} \quad (22)$$

where u_1 and u_2 are the extreme values of u reached by the particle, and $R(u)$ is the function, $H(u)/H(0)$; i.e., the field strength at any point u, relative to its value at $u = 0$, where the field has its weakest value. R_m is the value of $R(u)$ at u_1 or u_2 (i.e., at the high water marks). The value of the constant S is to be chosen from the initial conditions.

Equation (22) may also be written in other forms which are sometimes more convenient to use. Written as an integral over the variable R, it becomes

$$[H(0)]^{\frac{1}{2}} \int_{R_m(1)}^{R_m(2)} (R_m - R)^{\frac{1}{2}} \frac{du}{dR}\, dR = S, \quad (23)$$

where $du/dR = (dR/du)^{-1}$ expressed as a function of R. Here, of course, $R_m(1)$ and $R_m(2)$ have the same numerical value. When the confining fields have a plane of symmetry at $u = 0$ the lower limit of (22) may be taken as zero, and the upper limit as u_m, with corresponding limits 1 and R_m for Eq. (23).

By use of the compression equation, the motion of the end points, u_m or R_m can be determined. Combining this motion with the constant flux condition, the transformation of the radial distribution can also be obtained. To show that this last statement is true, it is necessary to demonstrate that, in the adiabatic, collision-free limit here assumed, there is no " mixing " of the distribution from one flux surface to another, even after many reflections have occurred. This can be shown using the compression equations. Consider the possible orbits which a particle of given fixed magnetic moment, μ, energy W, and action integral A can execute in the field. These orbits will be describable by the compression equation. Now we may evidently write (23) in the form

$$\int_{H_m(1)}^{H_m(2)} (H_m - H)^{\frac{1}{2}}\left(\frac{du}{dH}\right)dH = S. \quad (24)$$

Consider two possible orbits (a) and (b) for the above particle, characterized by integrals S_a and S_b respectively. Only du/dH may differ between the two orbits. Therefore, we may subtract integral S_a from S_b to arrive at a condition which these derivatives must satisfy. This condition is, since $S_a = S_b$,

$$\int_{H_m(1)}^{H_m(2)} (H_m - H)^{\frac{1}{2}}\left(\frac{du}{dH}\bigg|_a - \frac{du}{dH}\bigg|_b\right)dH = 0. \quad (25)$$

If the field system is axially symmetric, then this equation can be satisfied only for those orbits for which the value $(du/dH)|_a$ and $(du/dH)|_b$ are the same at every point along u, i.e., on the surface of flux tubes. Thus, in this case, the particles are constrained to move on flux surfaces so that mixing does not occur, as was to be proved. But even if the magnetic field is only approximately axially symmetric, then, as pointed out by Teller,[13] Eq. (25) still defines a set of separate closed surfaces on which the particles are constrained to move. These surfaces are generated from any initial given orbit by finding adjacent orbits along flux lines for which (25) is satisfied.

It is evident that, if the magnetic field changes adiabatically, (25) is still valid quasi-statically, so that the motion of the particle orbits is still constrained to lie on fixed but slowly collapsing flux tubes of the system. This allows the prediction of radial compression effects by use of the compression equation. Thus each initial end point of an orbit say $[u_m(0), r(0)]$ will be transformed to a new point, $[u_m(t), r(t)]$ such that

$$\left[\int_0^{r(0)} 2\pi r H_z dr\right]_{u_m(0)} = \left[\int_0^{r(t)} 2\pi r H_z dr\right]_{u_m(t)}. \quad (26)$$

To be used with the compression equations is the relationship giving the particle energy as a function of time. From the constancy of μ it follows immediately that the final kinetic energy of any particle is related to its initial energy by the equation

$$W(t) = W(0)\left[\frac{R_m(t)}{R_m(0)}\right]\left[\frac{H(0, t)}{H(0, 0)}\right]. \quad (27)$$

It is important to note that, under the assumptions made, particle energies do not appear in the integrals (22) or (23), so that if the trapped particle density is represented by its distribution in u_1, u_2 or R_m, this distribution transforms in time in accordance with these equations, independent of the energy distribution. The transformation of the energy distribution which results from the compression can then be found by using (27) together with the results from the compression equation.

When the external applied magnetic field is substantially altered by the pressure of the plasma, it is necessary to use self-consistent field values in computing the compression, found by iteration of the solutions to the compression equation, or by other means. For many purposes, however, this difficult procedure would not seem to be necessary, since its omission does not lead to large errors.

Radial Compression

The heating and the increase in density resulting from a simple radial compression can be found from the compression equations above, if the shape of the confining field is known.

In some cases the strength of field in the central region can be represented by a parabolic distribution, i.e., by the function $R(u) = 1 + (u/\lambda)^2$. Inserting this into the compression equation one finds that, in addition to radial compression, even with the mirrors held stationary, an axial compression occurs in accordance with the relationship

$$[H(0)]\ (R_m - 1)^2 = \text{constant};$$

i.e., $H(0)u_m^4$ = constant, so that for the axial compression factor one obtains

$$\kappa = \frac{u_m(0)}{u_m(t)} = \left[\frac{H(0, t)}{H(0, 0)}\right]^{\frac{1}{4}} = \alpha^{\frac{1}{4}}. \quad (28)$$

This results in a uniform axial compression of the entire trapped plasma. In those cases where very large compression factors are used, the extra increase in density which results is substantial. Combining the radial compression with the axial compression factor above, the density is seen to vary as

$$n(t) = n(0)\alpha\kappa = n(0)\alpha^{\frac{5}{4}}. \quad (29)$$

Taking an example from some of the experiments, if $\alpha = 10^3$, then the axial compression amounts to about a factor of six, a very noticeable effect.

Combined Radial and Axial Compression

Although the trapping is always improved by a simple radial compression, the trapping may be made less effective, when both radial and axial compression are employed, unless certain restrictions are observed. The effect of a combined radial and axial compression can be predicted from the compression equations (22) or (23) by allowing $R(u)$ to be a function of the time. Consider the case where the behavior of $R(u)$ is representable by a simple scaling of the axial coordinates of the field. This represents, approximately, a practical situation in which the mirror ratios are left fixed, but the mirrors are moved together as a function of time.

To represent this situation, let $R(u)$ be given by the function $g(u/\lambda)$ where λ changes with time (λ decreasing corresponds to axial compression, λ increasing corresponds to expansion); then, if $g^{-1}(R)$ is the function inverse to $g(u/\lambda)$, so that $\lambda g^{-1}(R) = u$, then $du/dR = \lambda d(g^{-1})/dR$. In this case, $g^{-1}(R)$ is not, of course, a function of the time, but is constant during the compression. Thus, (23) becomes

$$\lambda[H(0)]^{\frac{1}{2}} \int_{R_{\mathrm{m}}(1)}^{R_{\mathrm{m}}(2)} (R_{\mathrm{m}} - R)^{\frac{1}{2}} \left(\frac{dg^{-1}}{dR}\right) dR = S, \quad (30)$$

but now the integrand is no longer an explicit function of the time.

The condition that all plasma particles remain at least as tightly bound after the compression as before, is simply that R_{m} does not increase for any particle. From (30) this is seen to be possible only if $\lambda[H(0)]^{\frac{1}{2}}$ is constant, or at least does not decrease with time, i.e.,

$$\lambda^2(t)H(0, t) \geqslant \lambda^2(0)H(0, 0) \quad (31)$$

or,

$$\kappa^2 \leqslant \alpha, \quad (32)$$

since $\lambda(0)/\lambda(t) = \kappa$, the axial compression factor. If the mirror ratio is also a function of time, then, in simple cases, this condition takes the form

$$\kappa^2 \leqslant \alpha[R(t) - 1]/[R(0) - 1]. \quad (33)$$

The case, $\lambda^2 H =$ constant, is interesting because it represents a uniform compression of the plasma in all three dimensions. For this case, since the values of R_{m} remain constant for all trapped particles, the energy of each of the particles, as given by Eq. (27), is simply proportional to α. However, the volume of the plasma varies as $(\alpha\kappa)^{-1}$ and therefore as $\alpha^{-\frac{3}{2}}$. Thus, the mean particle energy varies inversely with (volume)$^{\frac{2}{3}}$, i.e., $\bar{W} \sim n^{\frac{2}{3}}$. This is the same as the law of adiabatic heating of an ideal gas, as derived from thermodynamic considerations. Although this correspondence with the classical result might also have been foreseen from Liouville's equation, it is interesting to see it emerge from the equations of a magnetically confined plasma.

If only an axial compression is carried out, with $H(0)$ remaining constant, the compression equation (30) shows that the particles must climb higher on the mirrors, so that the actual amount of axial compression of the plasma which occurs will be less than the geometrical compression ratio. For example, if the strength of confining fields varies parabolically, so that $R(u) = 1 + (u/\lambda)^2$, then it is found that $\lambda(R_{\mathrm{m}} - 1) =$ constant, so that for every particle, $u_{\mathrm{m}} \sim \lambda^{\frac{1}{2}}$. Although the compression is uniform, it proceeds only as $\lambda^{\frac{1}{2}}$ rather than linearly with the geometric compression.

Competing Effects

Collisions

When properly scheduled, magnetic compression results in improved trapping of the plasma, and the ordering effect of the compression acts in opposition to the disordering effect of collisions. Since the effect of heating the plasma is to reduce the mutual Coulomb collision cross section of the heated particles, it is clear that it should be possible to carry out the compression at such a rate that it continues to overcome the collision losses throughout the cycle and thus inhibits the onset of losses through the mirrors. The condition for this to occur can be estimated from the relaxation time considerations already discussed. It is required that, during the compression, the gain of perpendicular (rotational) energy shall exceed the gain of parallel energy (kinetic energy of motion in the direction of the field lines). Taking as an example the simple case of radial compression, from (20) the gain of rotational energy is obtainable from $W_\perp(t) = W_\perp(0)\alpha(t)$, Eq. (20).

On the other hand, the mean instantaneous rate of change of parallel energy of the ions, owing to collisions, will be given approximately by the expression:

$$\langle dW_\parallel/dt \rangle = \tfrac{1}{3}\langle dW/dt \rangle = \tfrac{1}{3}W/t_{\mathrm{D}}.$$

Now from (11), $t_{\mathrm{D}} = AW^{\frac{3}{2}}/n$ sec, where $A = 2.6 \times 10^{10}$ for deuteron energies expressed in kev. If compression heating dominates over dispersion due to collisions, throughout the compression, then we obtain $W_\perp \gg W_\parallel$, so that we may set $W_\perp \approx W$. If the duration of the heating operation is equal to t, then we require that $W_\perp \gg \bar{W}_\parallel$, for all times less than t. This requires, therefore, from the relations above, that

$$\alpha W(0) \gg \frac{n(0)}{3A[W(0)]^{\frac{1}{2}}} \int_0^t [\alpha(t')]^{\frac{1}{2}} dt'. \quad (34)$$

If H increases linearly with time, so that $\alpha(t') = 1 + t'/\tau$, then (34) becomes (dropping the zeroes in $n(0)$, etc.)

$$\frac{2}{9}\frac{n\tau}{A}\frac{1}{W^{\frac{3}{2}}}\left[\alpha^{\frac{1}{2}} - \frac{1}{\alpha}\right] \ll 1. \quad (35)$$

If the compression factor, α, is large, then this can be expressed as a simple condition on the time within which the compression must be accomplished to avoid excessive scattering losses. This condition is

$$t_\alpha < \frac{9}{2}\frac{AW^{\frac{3}{2}}\alpha^{\frac{1}{2}}}{n} \text{ seconds.} \quad (36)$$

It is apparent that if the particle energy is low it is more difficult to satisfy this condition. For this reason, even when it is satisfied for most of the constituent particles of an initial distribution, the lowest energy particles of the distribution are still likely to be lost.

To illustrate a case which might typically be encountered in an experiment, suppose that $\bar{W}_\perp \approx \bar{W} = 0.1$ kev and the initial density, n, is 10^{12} cm^{-3}. If it is desired to compress by a factor of 100, so that the

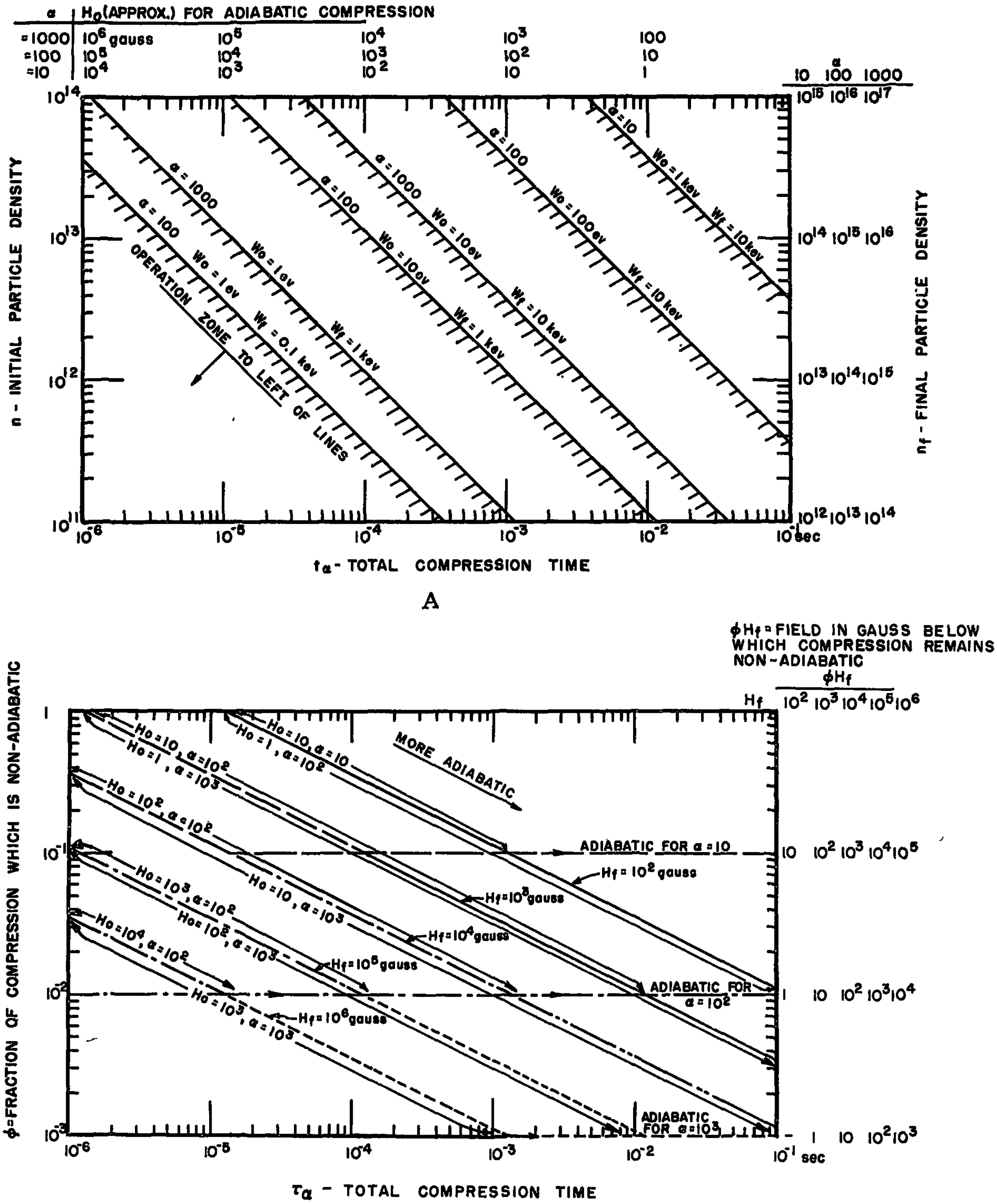

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Figure 2. (*a*) Allowed operation zones for adiabatic magnetic compression to suppress collisional effects; (*b*) deviations from adiabaticity, fraction of compression pulse during which ions are not compressed adiabatically

final mean energy becomes 10 kev and the final density 10^{14}, then (36) shows that the compression time must be less than about 0.04 sec. This is not an unduly restrictive requirement. Raising the initial energy allows even slower compression rates to be used.

Figure 2(*a*) illustrates the condition imposed by Eq. (36) for various values of compression rates and initial energy. To satisfy the condition, compression times must be shorter than the values given by the boundary lines. The final particle densities reached are shown along the right margin, for various values of α_{max}. If the condition of adiabaticity, i.e.,

$$\tau_H = \left[\frac{1}{H}\frac{dH}{dt}\right]^{-1} > \tau_g = \frac{2\pi Mc}{eH}$$

(the gyromagnetic period), is to be satisfied throughout the compression, then the initial magnetic field for this to be true can be specified for each total compression time. These values of initial field, H_0, are indicated along the upper margin of the plot. It can be seen that this condition could not conceivably be satisfied for the shortest compression times and largest compression ratios indicated. It is worth noting, however, because of the dependence of τ_g on mass, that the adiabatic condition is likely to be well satisfied at all times for electrons, even when it may not be satisfied for ions.

However, in many cases of practical interest, the compression will depart from adiabaticity only for a short time at its very beginning. In this case the heating and compression may not deviate significantly from the adiabatic values. Because the gyromagnetic period, τ_g, rapidly diminishes, as the field starts to increase, while the doubling period of the field, τ_H, increases; the ratio of these two quantities rapidly increases with time. This ratio is given by the expression

$$\chi = \tau_H/\tau_g = eH^2/2\pi Mc\dot{H}, \tag{37}$$

where $\chi \gg 1$ corresponds to the adiabatic limit.

If evaluated for a linearly rising field, and for M = the mass of a deuteron, this becomes

$$\chi = \frac{0.8\times 10^3 H_0 t_\alpha[\alpha(t)]^2}{(\alpha_{max}-1)}. \tag{38}$$

Figure 2(*b*) shows the fraction of the total magnetic compression during which the adiabatic assumption fails to be satisfied, i.e., the value of $H/(\alpha_{max}H_0) = \alpha(t)/\alpha_{max}$ at which χ rises to unity for various values of α_{max}, t_α and H_0. When this fraction is small, the adiabatic result will be approached.

The general effect of compressing at too slow a rate is to retain the most energetic components of the particle distribution, while losing the lower energy groups before the compression is completed. This tends, therefore, to "upgrade" the energy distribution to a somewhat higher mean energy than would have been expected, albeit at a lower density than predicted by the simple compression equation.

If axial compression as well as radial compression is included, the compression time requirement becomes somewhat more restrictive, because of the increased density and because of the change in parallel energy which accompanies axial compression.

Ambipolar Diffusion

Ambipolar diffusion effects must also play a role in the compression of a plasma. However, as has already been indicated, this role seems to be a secondary one in the experiments conducted to date, not interfering appreciably with the observed heating effects. More sophisticated experimental work will, however, have to be done to determine the precise influence of ambipolar diffusion on the plasma history. The exact way in which the ambipolar effects will appear will depend on questions of the relative initial ion and electron mean energies. For example, when the initial ion energies are higher than the electron energies, the energy of these electrons can be expected to lag increasingly behind the ion mean energy, since the collision effects will cause the heating energy to be shared among all degrees of freedom of these electrons, so that their heating rate will tend to be dependent on the $\frac{2}{3}$ power of the compression, rather than the first power.[12] On the other hand, those electrons which start with energies sufficiently above the ion energies will be heated at the same rate as the ions and so will remain at a higher energy than the ions throughout the compression. The ratio of electron and ion energies at which the scattering times become comparable can be estimated from the relaxation time, Eq. (10). From this equation it can be seen that

$$W_e/W_i = (M/m)^{\frac{1}{3}} \approx 15,$$

if evaluated for M = mass of a deuteron.

Radiation from Impurities

It has already been noted that, especially at relatively low plasma temperatures, radiation from impurities can represent a potent mechanism for loss of energy from the plasma through the agency of electronic excitation of incompletely stripped impurity ions. The rate of this radiation loss is thus proportional to the product of the electron particle density and the particle density of the impurity ions. But in many cases the impurity density is roughly a constant fraction, q, of the plasma ion density itself, so that the radiation rate varies as qn_e^2. The absolute rate of impurity radiation per unit volume is then representable by an expression of the form (for each type of ion)[14]:

$$p_r = qn_e^2 T_e^{-\frac{1}{2}} f(h\nu/kT). \tag{39}$$

On the other hand, the rate of energy input to the plasma depends *linearly* on the electron density and the rate of rise of the magnetic field. For example, in the collision-free limit for a simple radial compression, Eq. (20) gives for the energy gain:

$$p_h = n_e dH/dt. \tag{40}$$

In order to heat the plasma it is obviously necessary to put in energy from the magnetic compression at a rate more rapid than the radiation rate. Since the energy input rate varies linearly with density, whereas the radiation varies as the square of the density for any given rate of increase of the field, there exists an initial density above which the temperature will not increase, the energy from compression being dissipated by radiation. However, since the density can be arbitrarily set by controlling the injection, it is always possible to find a low enough initial density which leads to heating. Fortunately, it has been found possible to control the impurity levels to the point where radiation imposes no more stringent a limitation on the initial density than does the requirement of collision losses discussed previously: in the experiments, electron heating occurs essentially as predicted by the compression equations. If the electrons were not heated, but were maintained at a low temperature by radiation losses, the ion energies would also tend to be quickly damped by collision cooling.

Adiabatic Expansion—Energy Recovery

Before leaving the subject of adiabatic compression, it is important to note that, under the assumptions made, all of the operations discussed are reversible: i.e., the same equations apply to a magnetic expansion of the plasma, carried out by appropriate manipulation of the confining fields. In this case, the roles of radial and axial decompression, in their competition with collision effects, are just reversed from the case of compression. Axial decompression leads to improved confinement of the remaining plasma whereas radial decompression leads to poorer trapping. An appropriate combination of the two operations is therefore indicated. In an adiabatic expansion the energy of the plasma will decrease, corresponding to a transfer of energy back to the confining fields, and (usually) an accompanying flow of electrical energy out of the system.[1] This fact offers a possible avenue to the direct electrical recovery of plasma internal energy, either that associated with charged reaction products or unreacted plasma. In the Mirror Machine, efficient recovery of the kinetic energy of escaping particles, which might be accomplished by adiabatic expansion, could be a very important means of improving the power balance. It enables one to visualize a continuously operating "plasma engine" which would utilize the compression and expansion operations, which have been described above, to create, heat, confine and recover energy from a reacting plasma. The feasibility of such a machine has, of course, not yet been proved.

INJECTION

One of the most difficult technical problems of the Mirror Machine program has been the problem of injection. Because of the nature of plasma confinement by magnetic mirrors, it is not often satisfactory to create the plasma by ionizing a cold gas inside the confinement volume. Instead, other methods have been employed which involve the injection of plasma or of streams of energetic particles. The "open ended" topology of the Mirror Machine allows one to employ some unusual methods for injection.

The dilemma which is faced in all injection problems is the essential impossibility of trapping charged particles within a static magnetic field under conservative conditions; i.e., in order to inject, *something* must change. Various methods for injecting into a Mirror Machine have been proposed[15] and several of them are under study. They employ one or more of the following effects: (*a*) *time-varying fields*, (*b*) *collision or cooperative-particle interactions* and (*c*) *change of charge state of the injected particles*.

Time-Varying Fields

In the first category lie several of the methods which have been applied in the program to date. In early experiments,[16] beams of energetic particles were captured between the mirrors by injecting them through regions where they were subjected to radio-frequency fields. These fields produce an irreversible energy gain which leads to trapping. This method has not been actively pursued because of problems of field penetration but it remains a potentially interesting process.

External Injection

Another method which has been successfully exploited might be called "external adiabatic trapping". In this method a plasma is captured by injecting it through the mirrors into a rapidly rising magnetic field.[17] This method is similar to that employed in a betatron to accomplish injection. It can be understood qualitatively from the binding equations (2) or (3). Suppose a plasma is injected through a mirror from outside the confinement zone. Then none of its ions will be initially bound. For these ions, an inequality which is the inverse of the binding condition will apply, i.e.,

$$W > \mu H_M. \tag{41}$$

If, however, during the transit of the plasma through the confinement zone, the strength of the magnetic field is increased sufficiently, then because of the constancy of μ, the mirror field strength H_M may increase sufficiently to reverse the inequality so that many of the plasma ions are captured. This can be accomplished either by strengthening the entire field, or simply by changing the field at the mirrors.

The condition that particles should be captured under these conditions has been worked out.[1] It shows, as might be expected, that injection can be accomplished only as long as the magnetic field changes by a sufficient fractional amount during one transit of the particles. If the injected ions of the plasma flow over the top of the first mirror, making a small helix angle, ϵ, with respect to the plane of the Mirror ($\epsilon = \frac{1}{2}\pi - \theta$, where θ is the pitch angle) then injection can be accomplished as long as

$$\frac{dH}{dt} \geqslant H\left(\frac{R}{R-1}\right)^{\frac{1}{2}} \frac{\epsilon^2}{(L/v_0)} \tag{42}$$

where L is the separation between the mirrors (assumed large compared to length of the mirror regions), v_0 is the velocity of the injected ions, and R is the mirror ratio. If the field is assumed to rise linearly with time, then the maximum acceptance time over which injection can be accomplished will be given by

$$\tau = \frac{L}{v_0}\left(\frac{R-1}{R}\right)^{\frac{1}{2}} \frac{1}{\epsilon^2}, \tag{43}$$

When only the mirrors are strengthened, rather than the entire field, a similar expression is found. Also, if the far mirror is made much larger than the near mirror, the acceptance time is doubled.

It can be seen that this injection mechanism is most effective for particles entering with small angles, ϵ. Thus, if a stream of plasma with a wide range of helix angles is injected through the mirrors, then the injection condition will continue to be satisfied longest for the smallest angles ϵ.

Internal Injection

Injection can also be accomplished by sources located partially *within* the confinement volume. Here the problem is one of preventing the plasma particles from returning and hitting the source. One of the methods studied has been the use of compact ion sources located just inside the confinement volume, emitting energetic ions in a direction perpendicular to the local direction of the field lines. The great advantage of using such sources is that the plasma is initially created with a very high ion energy—many kilovolts—thus over-leaping most of the heating problems. There are serious problems, however, in reducing the method to practice. As injected, the ions miss the source after their first turn, because of the field gradient in which they move. From the force equation (4) it can easily be shown that, in the adiabatic approximation, an ion injected at right angles to a field gradient advances in one turn by a distance

$$\Delta u = \pi\rho^2/\lambda \tag{44}$$

where ρ is the mean radius of curvature of the particle in the field and λ is a characteristic distance associated with the field gradient, defined by

$$\frac{1}{\lambda} \equiv -\frac{1}{H}\frac{\partial H}{\partial u}, \tag{45}$$

and not to be confused with the eigenvalue, $\lambda(R)$, used earlier.

Having missed the source on the first turn, the ions may then travel to the far end of the confinement region, where they are reflected (since they were "born" inside the mirrors). While moving along the field lines, the ions will precess slowly around the axis of the machine, because of their finite orbit size. It is possible to arrange conditions so that this precession, though necessarily small at each reflection, since the ions are nearly adiabatic (small orbits), can still be large enough to cause the ions to miss the source on their first return. If this is the case, then they may continue to be reflected back and forth in the volume until they have precessed completely around the axis. This might take, typically, 50 to 100 traversals. At this time they would be likely to hit the source and be lost, thus limiting the injection and confinement time to about the period of precession around the axis, too short a time to be of much interest. If, however, the magnetic field is increased while this is going on, then by the time each ion has precessed around to a position where it might hit the source, the axial compression which occurs in the increasing field may prevent it from returning to the source position, so that it becomes trapped. In this way the time over which injection can be accomplished may be substantially extended over that of a single precession period. Injection will cease either (*a*) when, because of the increasing field, the orbits become too small to miss the source, on the first turn, because of the ρ^2 dependence of (44), or (*b*) when they are not sufficiently compressed axially to miss the source. The most efficient use of the injection time occurs when conditions (*a*) and (*b*) fail simultaneously.

The amount of axial compression which occurs when the field is increased can be calculated readily from the compression equation (22). Assuming that the mirrors are alike, this may be written as

$$H^{\frac{1}{2}}J = S$$

where

$$J = \int_0^{u_m} [R_m - R]^{\frac{1}{2}} du.$$

On differentiating, we obtain

$$H^{\frac{1}{2}}\, dJ + \tfrac{1}{2}JH^{\frac{1}{2}} = dS = 0;$$

but

$$dJ = \left(\frac{\partial J}{\partial u_m}\right)du_m + \left(\frac{\partial J}{\partial t}\right)dt.$$

Hence, if $\partial J/\partial t = 0$ (field *shape* does not change with time), we find that

$$|\delta u_m| = \frac{1}{\tau}\left[\frac{J}{2}\left(\frac{\partial J}{\partial u_m}\right)^{-1}\right]\delta t \equiv \lambda_J\frac{\delta t}{\tau_H}, \tag{46}$$

where λ_J is the characteristic distance given by the expression in brackets and $\tau_H \equiv H/(dH/dt)$ represents the instantaneous doubling time of the field as it increases. If the field increases linearly with time, τ_H is simply the time in seconds subsequent to the initiation of the field rise. In the equations, δu_m represents the distance which the end point of motion of the particle progresses during time δt, if δt corresponds to one of the times of return of the particle to the first mirror.

In simple cases, for example where the mirrors are widely separated, $\lambda_J = \lambda$ so that (46) reduces to the simple expression,

$$|\delta u_m| = \lambda\delta t/\tau_H \tag{47}$$

where λ is defined as in Eq. (45). If the angle of emission of the ions with respect to the normal to the field lines is not exactly zero, but is $\pm\epsilon$ then (47) and (44) become

$$|\delta u_m| = \lambda[(\delta t/\tau_H) - \epsilon^2] \tag{48}$$

$$|\Delta u_m| = \pi^2\rho^2/\lambda \pm 2\pi\rho\epsilon. \tag{49}$$

In order for injection to be accomplished, both δu_m and Δu_m must simultaneously be larger than Δz, the length of the source in the direction of the magnetic field. The maximum injection time available may be estimated by setting $\epsilon = 0$ and $\delta u_m = \Delta u_m \geqslant \Delta z$ and solving for τ_{max}:

$$\tau_{max} = (\lambda/\pi\rho)^2\delta t. \tag{50}$$

Here δt is the total transit time in one precession period, which might be many times the one-way transit time of the ion between the mirrors. Thus, for typical values of λ and ρ which are compatible with the condition $\Delta u_m \geqslant \Delta z$, τ_{max} can be of the order of a thousand times the single transit time, so that theoretical injection times of about a millisecond correspond to confinement volumes of average dimensions. More detailed calculations have been made which, however, do not materially change the expected times.

Despite the extended injection times which can be achieved, the method of internal injection with conventional ion sources has serious drawbacks. First, even if it functioned exactly in accordance with theory, the density which could be achieved with current densities as limited by known ion source technology is small, so that a substantial degree of compression would have to be used, subsequent to the injection phase, in order to raise the density to a high enough value. Second, there are serious problems in achieving space-charge neutralization of the injected beams early in their history, so that the trapping can proceed. These problems are now being studied experimentally.[18] However, in addition to the use of conventional ion sources, there is reason to believe that plasma injectors being studied in other parts of the program can be adapted for use in this high energy injection approach, with substantial advantages in the way of achievable densities.

Traveling Mirror Injection

To conclude the discussion of injection into time-varying fields, mention should be made of the use of traveling mirrors to accomplish injection. If a plasma source is immersed in a moving mirror confinement zone, a capture process similar to the one mentioned in the previous discussions can occur. This process has been observed experimentally.[19]

In this case, the velocity of translation and the shape of the moving mirror field can be chosen to maximize the injection time. Just as in the case of internal adiabatic injection, if necessary, this time can, in principle, be made much larger than the precession time.

Capture by Collision or Cooperative Particle Interactions

Collision effects can lead to capture of a plasma as well as to losses. This effect has been successfully exploited in some of the experiments. For example, if a relatively dense, low temperature plasma is suddenly discharged into a mirror confinement chamber then there is an appreciable probability that some of the plasma will be captured by mutual collision effects within the volume. The rest of the plasma will then escape through the second mirror, leaving behind a trapped component. Since the capture arises from nonconservative processes, there is no requirement that the magnetic field be changed to accomplish this injection, but the confinement time will necessarily be limited if heating is not employed.

The approximate conditions for collision capture can be established from relaxation time considerations. If the helix angle of particles crossing the mirrors is ϵ, then particles will tend to be captured which approximately satisfy the condition[15]

$$\epsilon^2 \leqslant 2.5\times 10^{-18} Ln/\bar{W}^2 \tag{51}$$

where L is the distance between mirrors, $\bar{W}$ is the mean particle energy in kilovolts and n is the plasma ion density. It is clear that this condition strongly favors small helix angles and low particle energies.

Another method which involves cooperative phenomena to effect injection has been successfully demonstrated and studied qualitatively. This is the method of injecting plasma streams across the confinement volume and causing them to intersect in the center of the confinement volume. It is well known, from astrophysical theory and other evidence, that a stream of plasma can move across a magnetic field, sustained in an evacuated region, by the process of setting up a state of charge separation on opposing surfaces of the stream. This is the same mechanism as that which occurs in a flute instability,[20] for example, where it enables the transport of certain unstable plasma configurations across a magnetic field. Such effects have been reported in the literature.[21]

When such streams enter a conducting medium, for example another plasma disposed along the magnetic field lines, they can no longer freely cross the field and will tend to mix with the other plasma. This is the clue to the injection mechanism. This process has been qualitatively demonstrated in some of the experiments to be reported, but the potentialities of the method have not been fully explored.

In principle, any cooperative mechanism such as collision and polarization effects, just described, or plasma diamagnetic effects, can lead to capture of at least a part of an injected plasma. The utilization of cooperative processes seems to represent a very promising attack on the problem of injection.

Change of Charge State

Another method by which energetic particles can be trapped in a magnetic confinement volume is by change of charge state. For example, beams of energetic neutral atoms can be produced by established techniques. Such beams can freely penetrate a magnetic confinement volume, and would normally pass completely through it. If, however, a mechanism exists which will ionize a part of all of the atoms of the beam as it passes through the chambers, the ions and electrons thus produced could be trapped. One of the main difficulties of the method is the establishment of an effective breakup mechanism. G. Gibson, W. Lamb and E. Lauer[22] are studying the possibility of using a very low residual neutral gas pressure as a means for ionizing very energetic atoms, so that a high energy plasma would slowly accumulate in a dc magnetic confinement zone. Their method is potentially applicable to any steady-state magnetic bottle. Another method, which might be especially applicable to the Mirror Machine, would be to use the plasma created by one of the injection processes already described to provide efficient breakup for neutral beams of somewhat lower energies than those considered by Lauer *et al.*

Molecular ions can also be used in the same way to accomplish injection. Studies at Oak Ridge National Laboratory are now being carried forward using an unusual arc breakup mechanism discovered by Luce.[23] In this method, capture of energetic molecular ions results when they are broken up into their constituent atomic ions, because of the sudden change of radius of curvature of the orbits in the field. The potentialities and difficulties of this method have not been fully explored, but intensive work is being carried out at Oak Ridge to generate a high temperature plasma by these methods. Although Luce's method is, in principle, applicable to any dc magnetic bottle, the present experiments are being done in magnetic mirror geometry.

SUMMARY OF EXPERIMENTAL RESULTS

The experimental study of the confinement of plasma by magnetic mirrors began on a small scale in early 1952. Preliminary experiments conducted by Post and Steller[24] with transient plasmas produced by rf excitation within dc magnetic mirror fields showed qualitatively that confinement was possible. This was followed up by the experiments of Ford[16] and others on rf trapping of a plasma. In 1953, a serious effort was undertaken to investigate compression heating of the plasma. In the early experiments of Coensgen in 1953 and 1954,[25] plasma produced by means of an electromagnetic shock tube was magnetically compressed by pulsed mirror fields which rose to peak values of about 200,000 gauss in a period of a hundred microseconds or so. Time-resolved pictures of the compression process were obtained and showed that the plasma was being stably compressed. It was soon realized, however, that the magnetic field technology then developed did not allow effective use of the magnetic compression process with the high densities being used. Recently, the Los Alamos group[26] and Kolb[27] at NRL have performed similar experiments, but with greatly improved energy storage and pulsed field technology and have obtained more striking results. The early experiments of Coensgen, however, pointed out the basic feasibility of the magnetic compression process and provided encouragement for continuation of the research.

Because of a realization that, under the conditions then achievable, the compression process would function more effectively with less dense, more highly ionized plasmas, a search was made for improved methods of injection. This led to the development, by Ford and Coensgen, of early forms of the occluded gas source, a source in which a burst of ionized hydrogen was released by an electrical discharge on the surface of a "hydride" of titanium. Using this source, it was soon possible to show that substantial heating was occurring and that the plasma was being confined for periods of the order of a millisecond, in rough agreement with the expected diffusion loss rates. In the experiments of Coensgen, escaping energetic radiation and particles were observed that gave direct proof of the heating. Confinement was established both by the analysis of the escaping radiation and by direct measurement with microwave interferometric techniques.[25]

Theoretical calculations based on certain hydromagnetic models were being made at about this time. These seemed to indicate that plasmas in Mirror Machines should exhibit hydromagnetic instabilities and, under the conditions of the experiments then being conducted, might be expected to be lost in a very few microseconds. The fact that plasmas were demonstrably being confined, for periods perhaps a thousand times as long as the theoretical instability times, led to the realization that the model used in the early calculations did not correspond closely enough to the real situation. Since that time, it has been realized that stability may be influenced by: (*a*) the finite nature of an actual plasma in a Mirror Machine, as opposed to the infinite periodic plasma of the early theory; (*b*) the existence of conductors or quasi-conductors at the ends of the machine; (*c*) the nonisotropic nature of the plasma pressure; (*d*) the non-zero size of the particle orbits and, perhaps, (*e*) the existence of ambipolar effects. Although there is general agreement that these factors may explain the observed stability, and calculations have been performed[6] (with simplifying assumptions) which predict stable confinement, the problem is so complicated that no wholly satisfactory theoretical treatment has yet been made.

DC Mirror Machine "Cucumber"

In 1954, an experiment of another type was also tried, specifically aimed at the problem of stability and diffusion across a magnetic field. It was desirable for many reasons to obtain a situation in which the particle pressure constituted as large a fraction as possible of the magnetic pressure. Aside from the obvious method of pushing the temperature and density up, one way to accomplish this is to reduce the magnetic pressure to the lowest practicable value, so that a low temperature, low density plasma might suffice. Thus a dc Mirror Machine, called "Cucumber", was built, with a large-diameter central chamber (eventually 18 in.) and very low confining fields (as low as 20 gauss). The machine was "capped" with strong mirror coils (6000 gauss) so that very large mirror ratios could be achieved. In Cucumber the process of collision trapping, described in the previous section, operated very effectively, so that it was possible to trap a substantial fraction of an injected low energy plasma by this process alone. Stable and long time confinement of the plasma was observed, under conditions where the plasma pressure was estimated to be several percent of the (low) magnetic pressure. These experiments helped qualitatively to confirm the stability picture and to show the influence of high mirror ratios in reducing end losses. They also showed that, under the conditions of the experiment at least, there seemed to be no anomalously large rate of transverse diffusion of the plasma across the magnetic field. An example of the confinement data taken in this machine is shown in Fig. 3. The traces represent signals received on a very thin wire probe. The plasma source was pulsed in all cases, but in only one case were all the confining fields turned on.

Recent Experiments

The recent experimental work in the Mirror Machine program has concentrated on the objectives of (1) studying the heating and confinement process in detail with relatively simple injection techniques, (2) increasing the total usable compression factors to reach higher temperatures and longer confinement times and (3) exploration of new high energy injection methods.

High Compression

The most fruitful experiments to date have been the so-called "high-compression" or "plasma injection" experiments, in which a burst of relatively low energy plasma is injected into an evacuated chamber immersed in an initial weak magnetic mirror field. The field is then rapidly increased to a high final value (in a few hundred microseconds) compressing and heating the plasma in the manner already described. Results of these experiments are being reported[17, 28] so that a brief summary only will be given here.

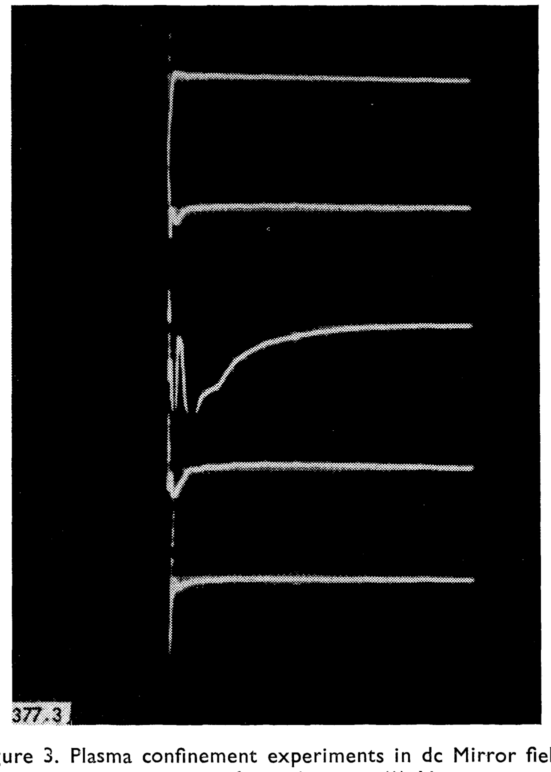

Figure 3. Plasma confinement experiments in dc Mirror fields. Traces represent, starting from the top: (1) Mirror at source position off. (2) Mirror at far end off. (3) All fields on. (4) Mirror fields on central field off. (5) Central field on, Mirror fields off. Tr ce time is 8 msec

Figure 4 shows one of the devices with which these experiments have been performed. The machine shown has been used to perform plasma injection studies in which the plasma bursts were trapped and strongly compressed.

These high compression experiments have shown that an initial plasma burst filling the confinement volume with a hydrogen plasma to a density of 10^{11} to 10^{12} cm^{-3} can be stably compressed to a final density of $\sim 10^{14}$ cm^{-3} by using very large magnetic compression ratios. The compression times used were in the general range of 200 to 500 microseconds. The magnetic compression factors used ranged to 1000 to 1 or even more. The diameter of the compressed plasma column was determined in some of the experiments by means of fine wire probes, and by study of the radial

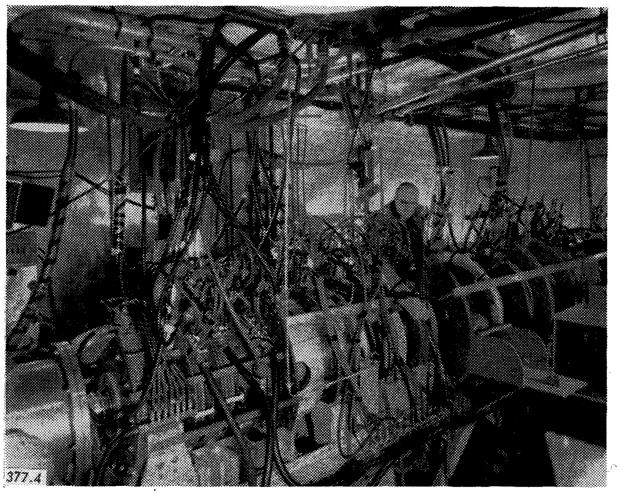

Figure 4. Mirror machine used in plasma injection and transfer studies (F. H. Coensgen[17])

distribution of escaping electrons. It was found that the radial compression of the plasma followed the predicted behavior with acceptable accuracy. Axial compression effects were also observed, in rough agreement with the predictions of the compression equations.

Particle Emission

The effective confinement time of the plasma was deduced by analysis of escaping particle fluxes through the mirror and by other means, and was found typically to be characterized by half-value times of the order of a millisecond, with energetic components of the plasma being observed to remain as long as 20 milliseconds. In some of the experiments, involving very large compression factors, the electron energy distribution of escaping electrons was measured by absorber techniques, over a range of about 3 kev to 120 kev. Figure 5 shows an oscilloscope trace of the escaping electron flux as measured by a collimated scintillator. The sweep time is 5 milliseconds. By

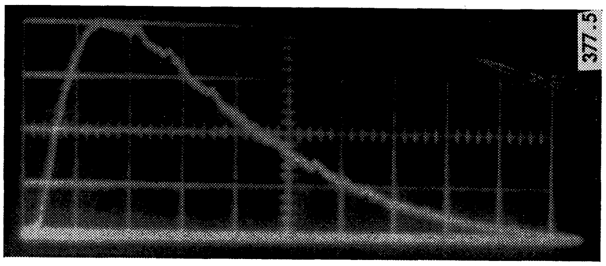

Figure 5. Flux of escaping electrons as measured by scintillation crystal located on magnetic axis, 5 cm outside mirror peak, $\frac{1}{4}$-in. collimator. Sweep time is 5 msec; compression time, 0.5 msec

weighting the observed distributions to take account of the influence of particle energy on the escaping particle fluxes, it was possible to fit the distribution to a Maxwellian distribution corresponding to electron temperatures between 10 and 20 kev. These high electron temperatures were confirmed by the use of microwave radiometry, which also served to establish a lower limit on the plasma density and to yield information on the axial compression which had occurred.

As might have been expected, the peak of the flux of escaping electrons occurs almost simultaneously with the peak of the plasma compression. This is in contrast to the time of X-ray emission, as shown in Fig. 6 and discussed below. Although the curves in Figs. 5 and 6 are generally similar, Fig. 5 does show some small periodic fluctuations for which the explanation is not entirely clear.

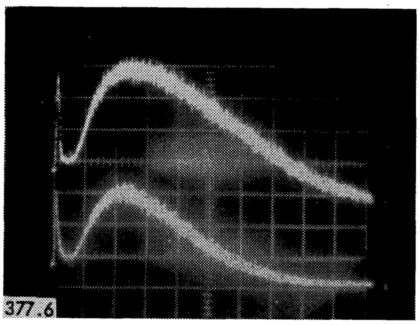

Figure 6. High energy X-ray flux at midplane. Compression time is 0.5 msec; magnetic field decay time to 1/e, ~ 20 msec; central field, 40,000 gauss; compression factor, ~ 1000 :1 ; sweep time, 10 msec

It was realized that, in the experiments where the highest compressions (lowest initial fields) were used, the ion mean energies could not have been as high as the indicated electron temperatures. In these experiments, it was not at that time possible to measure the ion energies directly. These could be inferred, however, from the confinement data and from the initial conditions, and are believed to have been about 1 kev. In separate experiments, where the conditions were more favorable for measurement, compression heating of ions was observed, with final energies as high as 2 to 3 kev being observed. The small volume of plasma used in all of these experiments, together with the relatively slow time scale of the compressions precluded the possibility of appreciable numbers of neutrons being observed.

In these high compression experiments, as normally carried out, there seem to be no gross plasma instabilities. Measurement of the total energy content of the plasma by scintillator and calorimetric techniques leads one to infer that the plasma pressure at the end of the compression cycle was in some cases about 8 percent of the applied magnetic pressure. This is still not a sufficiently high value, nor was it obtained under sufficiently general circumstances to conclude that large volumes of a plasma at useful temperature and pressures could be stably confined in a Mirror Machine.

X-ray Emission

Although the behavior of the major part of the plasma was, on the whole, explicable in terms of the concepts of compression heating and simple collision losses, there remain some interesting effects to be explained. An example of one of these is the fact that it is possible to detect the radial escape of a small fraction of the most energetic electrons of the plasma by the X rays which they produce at the chamber wall in the middle of the machine. This escape rate, though slow, seems too rapid to be explained in terms of ordinary scattering because of the high energies of the escaping electrons. At the midplane of the machine the flux tubes have their largest diameter, so that trapped electrons which are drifting radially will contact the chamber wall first at this point.

In the experiments, a collimated and filtered X-ray signal was detected by a scintillation crystal located at the midplane of the machine. This crystal responded only to X-ray quanta with energies above about 100

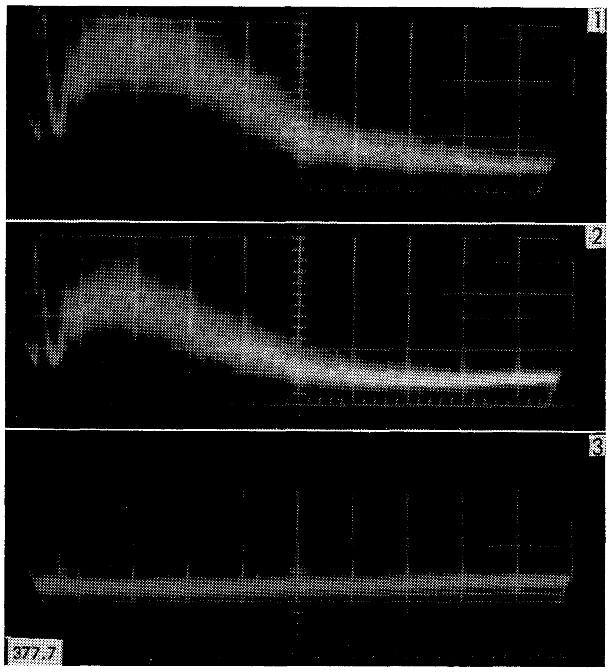

Figure 7. Quenching of electron thermal radiation by introduction of impurity gas (argon). Starting at the top: (1) no argon—base pressure = 5×10^{-7} mm Hg; (2) argon density, $\sim 2\times10^{11}$ cm^{-3}; and (3) argon density, $\sim 10^{12}$ cm^{-3}

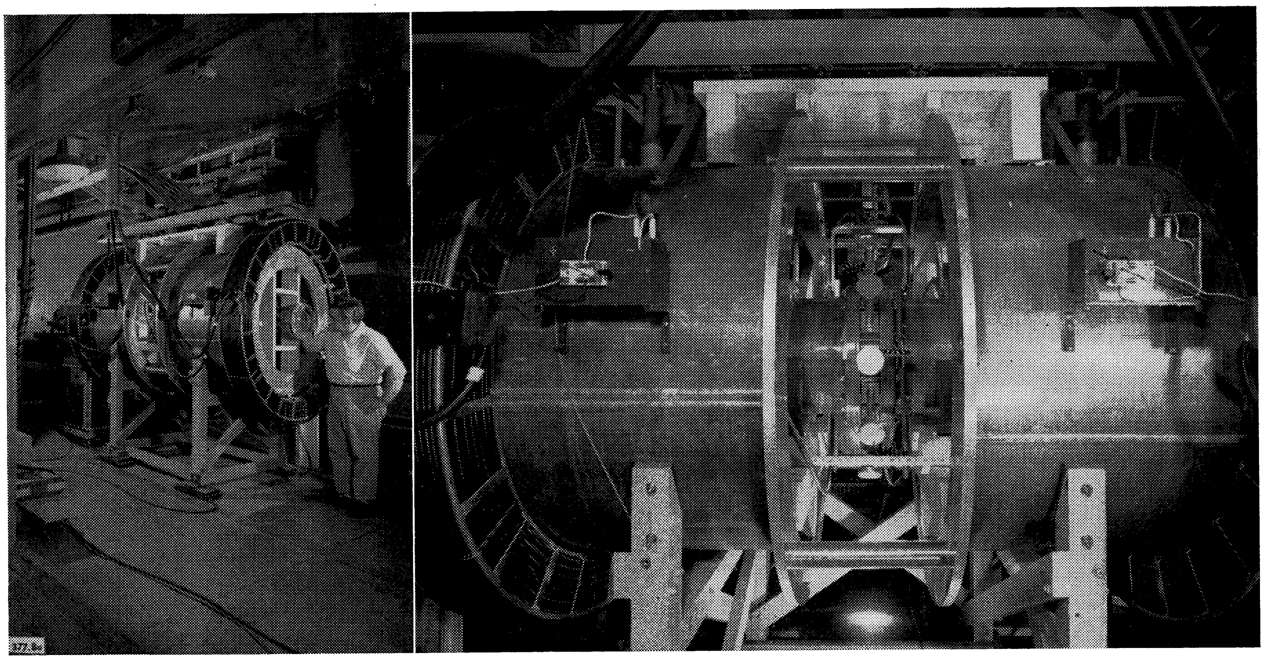

Figure 8. Mirror machine used for radial injection studies

kev. Examples of the signals observed are shown in Fig. 6. The sweep time used was 10 msec. Apart from an initial transient (mostly of electrical origin) it can be seen that the signals are small for a time of the order of a millisecond and reach their maxima at about 2 to 3 msec after the start of the compression cycle. The compressing magnetic field, however, rose to its maximum amplitude of about 40,000 gauss (in the center of the machine) in 0.5 msec then decayed exponentially with a time constant of about 20 msec. Thus, the maximum X-ray signal was received much later than the time of maximum compression. This is evidence of a slow outward radial motion of an energetic component of the heated electrons. Part of this radial motion, and the subsequent decay of the amplitude of the observed signal, can be identified with the decay and consequent slow radial expansion of the confining field. But there remains a slow drift which is not easily explained in this way. Now, in 3 msec, a 100-kv electron will have traveled about 6×10^7 cm, and will have executed some 3×10^8 revolutions in the confining field. In the experiments, the radial distance between the chamber wall and the surface of the compressed plasma is about 7 cm. One can therefore estimate that the radial drift velocity of 100 kev electrons could have a maximum value of about 2.5×10^3 cm/sec. Although this inferred radial drift velocity is very small compared to the electron velocity itself it is still too large to explain by ordinary scattering, both since the Coulomb scattering cross section of 100-kev electrons is very small (about 6×10^{-23} cm^2 on hydrogen) and because multiple scattering would provide a very strong selective mechanism against any particle reaching the wall prior to being scattered into the escape cone. On the other hand, a quite small electric field, fluctuating at a frequency comparable to or slower than the electron gyromagnetic frequency, could induce a randomly directed crossed electric and magnetic field drift which would cause the observed radial transport. Such a drift would not be expected to interfere appreciably with the normal mirror binding of the energetic electrons. Since it is known that the number of electrons reaching the wall is small compared to the total number, and that the plasma density outside the compressed column is much smaller than in the column it appears that the mechanism causing the transport operates primarily in this region, and not in the main body of the plasma. It is tempting, therefore, to ascribe the transport to fluctuation phenomena associated with the low density of this exterior plasma.

In the high compression experiments it was possible to show that the heating effects were quenched by the introduction of relatively small particle densities of high-Z gases, such as argon. This quenching effect became effective at about the density predicted by the theory of the radiation losses discussed earlier; i.e., at about 3×10^{11} cm^{-3} for a field rising in 0.5 msec. Figure 7 illustrates this quenching effect as measured by an 8-mm microwave radiometer. Shown are traces for three argon pressures. Peak signal is proportional to T_e.

The quenching is noticeable at 2×10^{11} cm^{-3} and is complete at 10^{12}. It is possible to conclude from these measurements that the normal impurity level had been reduced to the point that it did not substantially interfere with the compression heating process.

Low-Energy Injection

Two injection methods were used in these high compression experiments. In the most commonly used method, a low-density, 5- to 10-μsec burst of hydrogen plasma was injected in an axial direction through one of the mirrors from a source located just outside the mirror. Capture of the plasma was accomplished, in the manner described in the previous section, by starting with a weak initial field and rapidly increasing it. Continued increase of the field led to the compression effects which have been described.

In another injection method used, synchronized bursts of plasma were injected across the chamber, aimed toward the axis of the machine. By carefully timing the confining fields with respect to the injected bursts, it was possible to capture much of the plasma at the time the beams intercepted each other in the center of the machine. Figure 8 shows two views of a machine used for studies of radial plasma injection.

High-Energy Injection

Other experiments have been carried out, which are aimed at studying the injection of high energy ion streams into a Mirror Machine.[18] Because of the desirability of extending the time scale of the injection phase, close attention had to be paid to the role of charge exchange processes between trapped ions and the background gas, since such processes represent a powerful loss mechanism in this type of experiment. The apparatus developed for this experiment, shown in Fig. 9, was therefore designed with unusual attention to vacuum problems. A thin-walled stainless steel vacuum chamber was used, with metal gaskets throughout. The entire chamber was baked out at elevated temperatures. With these precautions it was possible to reach base pressures below 10^{-9} mm Hg.

Observations were conducted both with pulsed and with dc fields. Careful studies of ion orbit trajectories were made with collimated sources at ion energies of about 10 kilovolts. These studies confirmed the general picture of the ion behavior in the machine, and demonstrated the precession effects alluded to in the discussion of injection methods. An attempt was then made to increase the current density and to trap a high current density beam. It was then found that serious space-charge "blowup" effects were occurring in the vicinity of the source leading to the loss (by striking the back of the source) of most of the injected beam. Although it was proved that a small fraction of the beam was actually trapped and continued to be reflected back and forth in the machine for several thousand reflections (several milliseconds), insufficient beam was trapped to call the experiment a success. At this time the blowup process is being studied, and methods are under consideration to improve the degree of space-charge neutralization.

CONCLUSION

One might characterize the theoretical and experimental philosophy of the Mirror Machine program to date by a few words: "An attempt to study phenomena in a high temperature plasma by the extrapolation of ideas and methods already established in the field of charged particle dynamics into the realm of plasma dynamics." Thus the attitude has been to set up situations which were clearly and demonstrably workable at sufficiently low particle densities and then proceed to push the density and temperature as far as possible into a regime where the reactions of the particles on the confining fields is no longer negligible. Although such an approach necessarily implies the use of externally generated confining fields, it has much to recommend it. One deliberately picks those situations where symmetry and the method of confinement tend to minimize the possibility of what might be called "uncooperative" phenomena in the confined plasma, and where collision effects play a secondary role throughout the experiment. The advantages gained are: simplicity of understanding, the possibility of starting with very low densities and working up, and the likelihood that simple conservation laws will be adequate to define the essentials of the behavior of the plasma. The price which one pays for this is to introduce new technical problems of a more difficult nature than those encountered in some of the other approaches, for example, the simple linear pinch, and to be confined to working in a regime where the basic time scale is essentially set by a single collision time of the plasma ions. In the long run, although it clearly represents a compromise, this regime might still turn out to be a necessary one for the attainment of fusion power.

Judged in terms of the eventual goal of fusion power, progress thus far in the Mirror Machine program is limited indeed: where *seconds* of confinement time will be needed *milliseconds* have been achieved; where ion mean energies of a *hundred* kilovolts or more would be needed, perhaps a kilovolt has been attained. But judged in terms of the growth of understanding of the basic processes and problems of injection, heating, and confinement, substantial progress has been made. The goals for the future still lie in the direction of understanding these processes and their

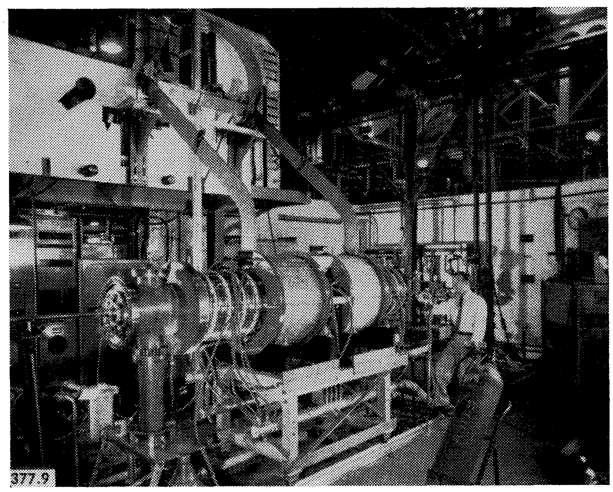

Figure 9. Mirror machine for injection of high energy ions. Entire vacuum chamber may be baked to reach pressure of 10^{-9} mm Hg

limitations more fully. From this understanding an assessment can be made of the future of the Mirror Machine in the quest for fusion power.

ACKNOWLEDGEMENTS

I wish to acknowledge especially the work of several members of the Mirror Machine experimental group: in the high compression experiments, Drs. Ford and Ellis; in the multi-stage compression work, Dr. Coensgen and William Cummins; in the high energy injection studies, Drs. Damm and Eby; and in the development of microwave measurements, Charles Wharton. Throughout the work Dr. Herbert York and Dr. Edward Teller have maintained a constant interest and encouragement.

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Mr. Post presented Paper P/377, above, at the Conference and added the following remarks on recent measurements made with a multi-stage mirror machine.

In order more effectively to use the magnetic compression technique we have constructed a machine which employs three successive stages of magnetic compression. This is accomplished by using magnetic mirrors at each stage both to compress the plasma and to transfer it rapidly along the machine. In this way it is possible to take maximum advantage of the compression process without requiring very large condenser banks. What is more important is that it has been shown experimentally that it is possible to arrange for such a rapid sequence of transfer operations as to leave behind most of the neutral gas and the impurities which may be produced in the injection region. In this way a nearly pure hot hydrogen plasma can be obtained, minimizing charge exchange losses.

Figure 10 shows an outline drawing of the multi-stage machine and also shows the sequence of magnetic field changes which are used in the successive compression and transfer operations. Figure 11 shows a view of the entire machine.

By means of microwave interferometer stations

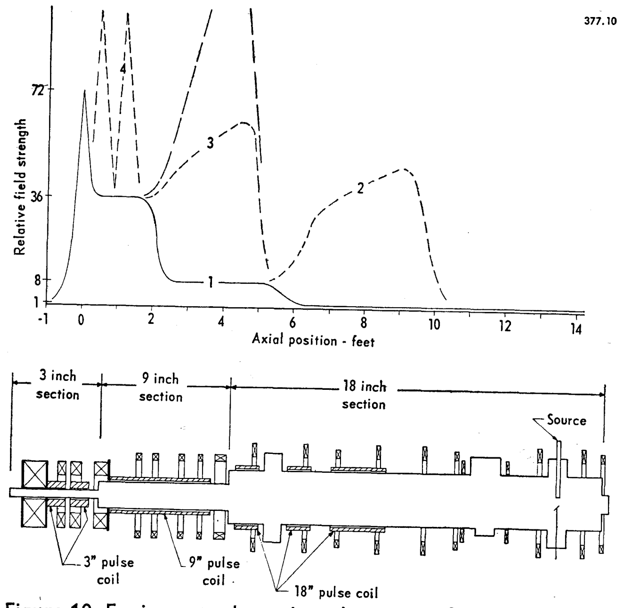

Figure 10. Equipment schematic and magnetic field sequences in multi-stage experiment

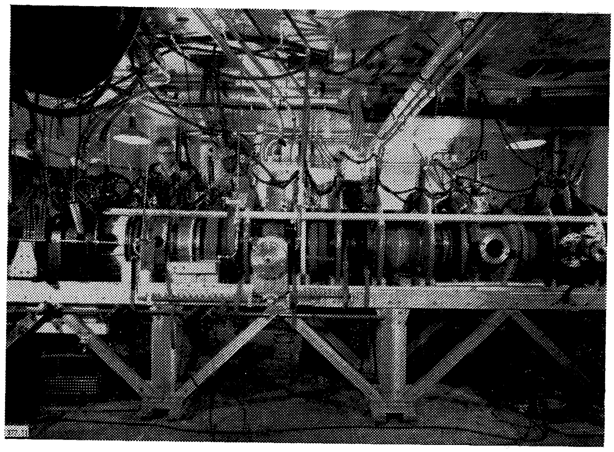

Figure 11. Multi-stage compression and transfer apparatus

which are placed at several points along the machine, it is possible to follow the plasma during its successive compressions, except in the case of the final and most intense compression. It is found that the density increases at each stage in relatively close agreement with theory. This encourages us to believe that these compression and transfer operations do not, as yet, give rise to plasma instability.

Electron heating and confinement effects have also been measured in this machine and have been found to be similar to those observed in the single stage machine. Also, under some circumstances, it has been possible for us to measure the type and the energy distribution of ions escaping from this machine. Figure 12 shows measured energy distributions integrated over the time of the compression pulse. In case (*a*) the plasma burst was injected parallel to the machine axis, so that only a small fraction of the initial ion kinetic energy appeared initially in rotational motion. Even so, the heating produced by two stages of magnetic compression can clearly be seen. Figure 12(*b*) shows a similar analysis taken with sources directed nearly across the magnetic field. In this case, even with a single compression and transfer a pronounced ion heating was observed.

These compression experiments have shown us that we can inject and heat a plasma by carrying it through manipulations by means of magnetic mirrors. We feel that these results are not only helpful to us in learning about plasma heating and confinement, but also have a bearing on the possible future practical use of a mirror machine. This is because the operations of transfer and compression, which are carried out adiabatically, should also in principle be reversible, so that energy could possibly be extracted directly from the plasma in electrical form by performing controlled transfers and radial and longitudinal expansions which are just the inverse of the operations we have demonstrated.

In all these compression experiments, although the ion energies reached were substantial, the plasma volumes were too small to yield any appreciable numbers of neutrons. The equipment is now being modified to permit the confinement of larger plasma volumes at higher final ion energies.

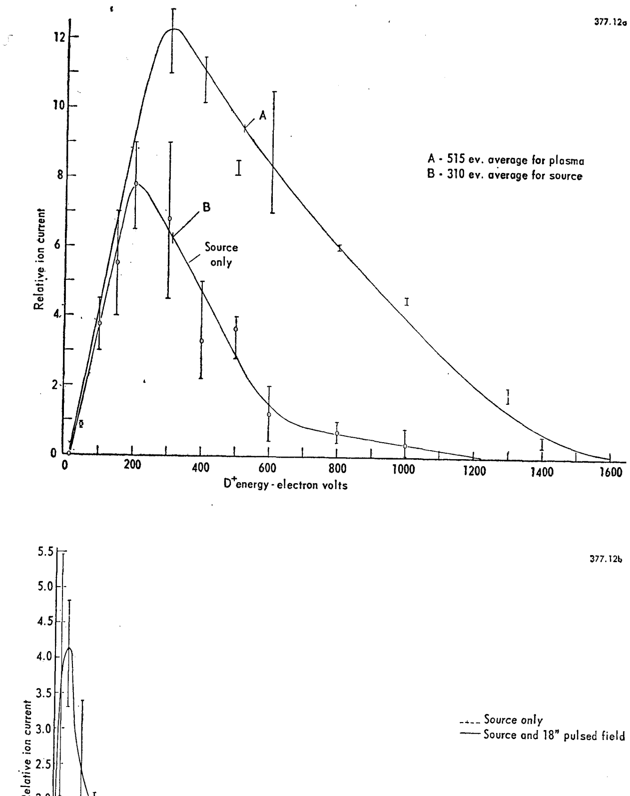

Figure 12. Energy distribution for escaping D^+ ions: (*a*) for longitudinal injection, (*b*) for radial injection