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**UNIVERSITY OF CALIFORNIA
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**SOME ASPECTS OF HIGH TEMPERATURE PLASMA RESEARCH
WITH THE MIRROR MACHINE***

R. F. Post

January 20, 1960

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SOME ASPECTS OF HIGH TEMPERATURE PLASMA RESEARCH
WITH THE MIRROR MACHINE

R. F. Post
Lawrence Radiation Laboratory
University of California
Livermore, California

The major present effort of the Livermore Mirror Machine group is directed toward study of plasma stability and confinement in mirror geometries. Work already reported by our group⁽¹⁾⁽²⁾⁽³⁾⁽⁴⁾ has qualitatively verified the confinement of a plasma and has documented many of the features of operation of the Mirror Machine, such as trapping of a plasma, and heating it by adiabatic magnetic compression. Even so, much remains to be done before a meaningful assessment of the approach can be made.

1. Plasma Injection Studies (Being performed by F. Coensgen, with assistance of W. Nexsen, W. Cummins and A. Sherman)

Since further advances are dependent on a major improvement in injection techniques, much of our effort is being devoted to this problem. One approach has been further to study the problem of generating plasma bursts of highly directed ion energy, and investigating the trapping of such streams into axially symmetric fields. Here the problem is to find conditions under which a substantial portion of the directed ion energy is transformed into rotational energy around the magnetic lines of the field into which the burst is trapped, and to insure that this energy is large compared to the mean electron energies.

Fig. 1 shows experimentally measured D^+ energy spectra emitted from our loaded Ti plasma sources⁽⁵⁾. The mean energy of the ions is indicated in the legend, together with some parameters of the gun assembly and the total number of ions collected by the detector. The total number of ions emitted in a typical burst is greater than 10^{17} . Although these data were taken in a field of 200 gauss, the energy spectra do not seem to be particularly sensitive to the field value in which the source is operated.

Using sources of this kind, Coengsen and his co-workers have studied the angular distribution of trapped D^+ ions as a function of trapping field, for various field configurations, the simplest of which was a uniform field, as shown in Fig. 2. For this case, the angular distributions of ions found are shown in Fig. 3. It was found that substantially more particle energy appears in the form of rotational particle energy using a 1000 gauss trapping field than at lower fields. At 1000 gauss a substantial fraction of the trapped ions possess rotational energies in excess of 100 ev, an order of magnitude greater than the estimated mean electron energies. Thus one of our objectives in studying plasma injection as mentioned above seems to have been reached. In these studies, a magnetic mirror field, halfway down the trapping chamber, was used in conjunction with a mass-spectrographic particle detector (at the far end) to measure the particle angle and energy distributions.

2. The ALICE Experiment (C. C. Damm, R. F. Post and A. Futch)

Another approach to the problem of injection and the creation of a plasma with a high temperature ion component is ALICE (for Adiabatic Low-energy Injection and Capture Experiment), for which we are now making preparations. The idea, which is basically an old one in the field, is to create the plasma by the ionization of a beam of fast atoms as they traverse the confinement chamber. Our approach to this problem is somewhat different from earlier ones,⁽⁶⁾ however, in that we have concluded

that there are substantial advantages to be gained by using relatively low ion energies - 10 to 20 kev - at least in the initial phases of such experimentation. We have reached this conclusion despite the fact that most charge exchange cross-sections reach their maximum value in this general energy range. The design of ALICE was preceded by a study of the scaling laws of the plasma build up, taking into account the requirement of adiabaticity (small orbit size relative to field gradient distances). These same scaling laws have shown us that high magnetic fields should be very advantageous, if all machine dimensions are scaled accordingly.

A schematic layout of the proposed ALICE experiment is shown in Fig. 4. Our experimental work to date has concentrated on the problems of ion source and vacuum technology, both of which, as will be seen, are crucial to the success of the experiment. Fig. 5 shows a view of the disassembled parts of the ion source, which is of conventional type. Up to 0.8 amperes of ion beam are collected 90° from the exit slit. The problem of extraction of the ion beam through the fringing field of the source magnets has not yet been explored, however,

In our scaling and parametric studies of the ALICE experiment, we have utilized a simple build up equation, modified to include some effects which are particularly important at low energies. We have assumed injection of fast atoms into a highly evacuated chamber containing a low density "break up" plasma in addition to a residual gas background. This equation, for the change with time of trapped ion density, is:

$$\begin{aligned} \dot{n} = & \frac{I_0 L}{V} \left[n_0 \sigma_{oi} + n_{eo} \frac{\langle \sigma v \rangle_{io}}{v} + n_i (\sigma_i + \sigma_{io}(A)) \right] \\ & + n \left[\frac{I_0 L}{V} (\sigma_i + \frac{\langle \sigma v \rangle_i}{v}) - n_0 \sigma_{io}(n) \right] \\ & - n^2 \langle \sigma v \rangle_c \end{aligned} \quad (1)$$

i.e. $\dot{n} = a + bn + cn^2$

Here:

- n - number of trapped fast ions/cm³.
- n_o - number of background neutral gas atoms (or molecules)/cm³,
here assumed constant during initial build up.
- n_{eo} - electron density of background plasma present at $t = 0$.
- n_i - ion density of background plasma present at $t = 0$.
- I_o - injected "current" of fast neutral atoms (or molecular
ions, if equation used for DCX or OGRA type experiments).
- L - effective breakup path length of incoming beam.
- V - effective volume into which trapping is taking place and
over which particles are spread by precession effects, etc.
- v - velocity of injected particles.
- σ_{01} - breakup cross-section for a fast injected particle on the
background neutral gas particles.
- $\sigma_{10}(A)$ - charge exchange cross-section for a fast ion on a neutral
atom of the same atomic species (or vice-versa).
- $\sigma_{10}(M)$ - charge exchange cross-section for a fast ion on a molecule
of the background gas.
- σ_1 - ionization cross-section for a fast injected particle on
a trapped ion.
- $\langle \sigma v \rangle_{10}$ - ionization rate parameter for ionization by electrons of
the breakup or "background" plasma.
- $\langle \sigma v \rangle_1$ - ionization rate parameter for electrons of the trapped
plasma.
- $\langle \sigma v \rangle_c$ - effective collision rate parameter for loss of trapped
ions by scattering into the escape cone.

Some critical conditions can be derived immediately from (1). The condition for exponential build up is that $b > 0$, i.e. that the neutral background pressure is less than a critical pressure n_{oc} ;

$$n_o < n_{oc} = \frac{I_o L}{V} \left\{ \frac{\sigma_i + \frac{\langle \sigma v \rangle_{i_o}}{v}}{\sigma_{i_o}(M)} \right\} \text{ cm}^{-3} \quad (2)$$

The form of (1) shows that the initial build up is approximately linear with time, at a rate which is given by

$$\dot{n} = \left(\frac{I_o L}{V} \right)^2 \left\{ \frac{[\sigma_i + \frac{\langle \sigma v \rangle_{e_o}}{v}] \sigma_{o_i}}{\sigma_{i_o}(M) v} \right\} \cdot \left[\frac{n_o}{n_{oc}} \right] \quad (3)$$

if no breakup plasma is used. If a breakup plasma is used, with $n_i = n_{eo} \gg n_o$,

$$\dot{n} = \frac{I_o L}{V} n_i \left[\frac{\langle \sigma v \rangle_{e_o}}{v} + \sigma_i + \sigma_{i_o}(A) \right] \quad (4)$$

At low energies, the charge exchange trapping term, $\sigma_{i_o}(A)$ is usually much larger than the other two terms. Therefore, in this case, the trapped density will rise approximately linearly with time from 0 to n_e in a total time which is approximately

$$t_L = \frac{V}{I_o L \sigma_{i_o}(A)} \quad \text{Sec.} \quad (5)$$

When exponential build up is achieved, so that $bn \gg a$, but still $bn \ll cn^2$, $n \sim e^{-t/t_E}$ where

$$t_E = \frac{V}{I_0 L} \frac{1}{(\sigma_i + \frac{\langle \sigma v \rangle_e}{v})} \cdot \frac{1}{(1 - \frac{n_0}{n_{oc}})} = \frac{1}{b} \text{ sec.} \quad (6)$$

When the limiting density is reached ($\dot{n} = 0$), $|bn| \gg a$, $b > 0$) the final density is determined by the equation

$$n_f = \left(\frac{I_0 L}{V} \right) \frac{(\sigma_i + \frac{\langle \sigma v \rangle_e}{v})}{\langle \sigma v \rangle_e} \cdot \left(1 - \frac{n_0}{n_{oc}} \right) \text{ cm}^{-3} \quad (7)$$

The differential equation (1) admits of a general solution, in terms of the dimensionless variables $\alpha = n/n_f$, $\tau = t/t_0$ and $\gamma = |2ac/b^2|$ (for $b > 0$) as,

$$\frac{n}{n_f} = \alpha = \frac{1 - e^{-\tau}}{1 + \left[\frac{\sqrt{1+2\gamma} + 1}{\sqrt{1+2\gamma} - 1} \right] e^{-\tau}} \approx \frac{1 - e^{-\tau}}{1 + (\gamma/2) e^{-\tau}}, \quad (8)$$

Since $\gamma \ll 1$ in many cases.

$$\text{Here } t_0 = \frac{1}{b\sqrt{1 - \frac{4ac}{b^2}}} = \frac{1}{b\sqrt{1 - 2\gamma}} \approx \frac{1}{b} = t_E \quad (9)$$

For $b < 0$ (no exponential build up),

$$\frac{n}{n_f} = \alpha = \frac{1 - e^{-\tau}}{1 + \left[\frac{\sqrt{1+2\tau} - 1}{\sqrt{1+2\tau} + 1} \right] e^{-\tau}} \approx 1 - e^{-\tau} \quad (10)$$

$$t_o \approx \frac{V}{I_o L} \left(\frac{1}{(\sigma_i + \frac{\langle \sigma_r \rangle_e}{r})} \right) \left(\frac{1}{\left(\frac{n_o}{n_{oc}} - 1 \right)} \right) \quad \text{sec.} \quad (11)$$

and

$$n_f = \left| \frac{b}{2c} \right| \left[\sqrt{1+2\tau} - 1 \right] \approx \left| \frac{a}{b} \right| \text{ cm}^{-3} \quad (12)$$

From equation (8) it can be determined that the final density is only approached after a time equal to 5 to 10 times t_o , in the case of an exponential build up, but (10) shows that when $b < 0$ the limiting density is approached much more rapidly. However, the final density reached when $b > 0$ will generally be much larger than that for $b < 0$.

If we now consider the scaling of the parameters n_{on} , t_o and n_f with size of the proposed machine and strength of the magnetic field, new insight into the physical implications of these solutions will emerge. Consider now the scaling laws which apply to a machine such as ALICE if the adiabatic parameter is held constant, i.e., if, for a given configuration of mirror coils, the ratio of orbit diameter to field gradient lengths is held fixed. This will imply, of course, that for each particle energy or magnetic field strength considered, the size of the basic machine must

change. However, it is clear that this represents a scaling relationship which is appropriate in designing a new experiment, where considerations of feasibility and cost are important, and dimensions have not yet been fixed.

We choose for the definition of the adiabatic parameter, $\epsilon = 2\pi\bar{\rho}/L_0$, i.e., it is the mean ion orbit circumference divided by the length L_0 , between the mirrors. The other scaling parameters needed, from equation (1) are that $L = 2\bar{R}$, i.e., the breakup path length for the injected fast atoms is equal to the mean plasma diameter. We then write that the plasma volume to be filled is $V = \pi\bar{R}^2 L_0 \eta$, i.e., it is the total available volume between the mirrors, diminished by a factor $\eta < 1$ to account for the detailed spatial distribution of the plasma. We also write $\bar{\rho} = \lambda \bar{R}$, $\lambda < 1$, i.e., the mean orbit radius is a fraction λ of the plasma radius. Current scaling effects in the ion source are approximately taken into account by scaling in terms of $P_0 = I_0 W_{ev}$, i.e., injected current times particle energy, since many ion source systems and structures suffer from power handling rather than current limitations. It is also assumed of necessity that the cross-section of the injected beam is always less than the diameter of the plasma column.

The above definitions, taken together with the relationships between H_p and particle energy, are sufficient to define the desired scaling laws. For example, the value of the critical neutral density n_{oc} (eq. 2) is given by

$$n_{oc} = 3.5 \times 10^2 (A^{1/2}) P_0 \bar{H}^2 \left\{ W^{-\frac{5}{2}} \left[\frac{\sigma_i + \frac{\langle \sigma \rangle}{v}}{\sigma_{io}(M)} \right] \right\} \left\{ \frac{\epsilon \lambda}{\eta} \right\} \text{ cm}^{-3} \quad (13)$$

Here A is the atomic weight of the injected atom, P_0 is the injected beam power in kilowatts, W is the injected particle energy in kev, and $\bar{H}$ is the mean confining magnetic field in gauss. The most striking dependences of this scaling law are those on magnetic field and particle energy. The effect of the $W^{-5/2}$ term is to weight the lower injection energies, entirely overcoming the opposite variation with energy of the cross-section ratios in the square brackets. In Fig. (6) equation (13) is plotted as a function of W for various values of $P_0 \bar{H}^2$, with $A = 2$ (deuterons) and $\left[\frac{e\lambda}{\eta} \right]$ being set equal to 1. The background gas is assumed to be hydrogen. Calculation of more realistic values of the geometrical parameters indicate that they lead to somewhat larger values of $\left[\frac{e\lambda}{\eta} \right]$ than assumed so that the curves generally will indicate too low a value of n_{oc} by as much as a factor 10. Also, at low ion energies inherent limitations in ion source technology will no doubt step in and cut-off the curves. However, as is clear from eq. (13), Fig. (6) shows that high magnetic fields and low injection energies are favored.

The curves also show that, restricting consideration to energies between 10 Kev and 100 Kev, quite low absolute initial neutral pressures are generally required for feasible values of $P_0 \bar{H}^2$.

If the particle energy is held fixed, the scaling with magnetic field can be displayed as a plot of n_{oc} vs. magnetic field. In Fig. 7 such plots are given, for various values of injected current, and an energy of 10 Kev.

Another parameter which is important in the design of a machine is the theoretical build up exponentiation time, t_0 . It may be important to keep t_0 as small as possible to minimize wall loading or other practical problems of the machine. The scaling laws for this quantity can be derived in the same way as for n_{oc} , yielding the result

$$t_0 = 6.3 \times 10^{-11} \frac{1}{P_0 \bar{H}^2} \left\{ W^2 \left[\sigma_i + \frac{\langle \sigma \nu \rangle_i}{v} \right]^{-1} \right\} \left\{ \frac{\eta}{\epsilon \lambda} \left(1 - \frac{n_0}{n_{xc}} \right)^{-1} \right\} \text{ sec.} \quad (14)$$

In Fig. (8) equation (14) is plotted, with the parameters $\left[\frac{\eta}{e\lambda} \cdot (1 - n_o/n_{oc})^{-1} \right]$ set equal to 1, thus somewhat underestimating actual values of t_o . It is clear that at high energies or with low magnetic fields the build up times may become very long. In Fig. (9) t_o is presented as a function of magnetic field, for $W = 10$ Kev, and for various injected currents.

If, as one certainly hopes, build up of the plasma could proceed to steady-state, the final density reached, n_f , becomes of interest. The scaling law for n_f is,

$$n_f = 5.8 \times 10^{20} (A^{1/2}) P_o \bar{H}^2 \left\{ W^{-1/2} \left[\sigma_i + \frac{\langle \sigma v \rangle_i}{v} \right] \right\} \cdot \left\{ \frac{\epsilon \lambda}{\gamma} \left(1 - \frac{n_o}{n_{oc}} \right) \right\} \text{ cm}^{-3} \quad (15)$$

This result, which is only weakly dependent on particle energy, however, shows strikingly the advantage of using high magnetic fields. This is illustrated by Fig. (10) which shows n_f plotted as a function of $\bar{H}$.

Finally, the scaling of $\beta_{max} = \left[n_f \bar{w} / (H^2 / 8\pi) \right]$ can be determined. It turns out to be not strongly dependent on energy, and not at all on magnetic field.

$$\beta_{max} = 3.3 \times 10^{13} P_o \left\{ W^{-1/2} \left[\sigma_i + \frac{\langle \sigma v \rangle_i}{v} \right] \right\} \cdot \left\{ \frac{\epsilon \lambda}{\gamma} \left(1 - \frac{n_o}{n_{oc}} \right) \right\} \quad (16)$$

Returning now to Fig. (4) the schematic layout of the ALICE experiment, one can perhaps understand the design philosophy which we have employed somewhat more clearly. Relatively low particle energies and high operating magnetic field (50,000 gauss central field) have been chosen in a definite attempt to take advantage of the scaling laws observed above. Despite these optimizations, however, the required critical pressure will still be very low (about 2×10^{-9} mm Hg) even at injected currents of several tenths of one ampere, so that considerable effort on both the source and the vacuum problems will be required. However, it is equally clear that successful achievement of an exponential build-up and attainment of the limiting density would represent a significant milestone, albeit one which can only be achieved if a high degree of plasma stability can be maintained throughout the build up cycle. At this time, this latter question is completely open.

In the ALICE calculation presented here, some of the spatial effects in the build up have been ignored, as well as the role of the trapped plasma in "pumping" the background gas. For design purposes we have made what we feel is a conservative assumption, namely that all pumping is to be accomplished by means other than plasma ionization. Further calculations are being made to explore the implications of these assumptions and to generalize the results presented here.

3. Radial Density Distribution and Diffusion of Confined Plasma (R. E. Ellis and R. F. Post)

Some of the measurements of the properties of a adiabatically compressed and confined plasma have been reported⁽¹⁾⁽²⁾. These measurements have shown that the plasma thus produced has a very high electron temperature and appears to be stably confined. A further proof of its inherent stability would be to determine the rate of diffusion of the confined plasma across the magnetic field, during the confinement. From theoretical expressions such as those derived by Spitzer⁽⁷⁾ one can calculate that at the very high electron temperatures (25 Kev) and high magnetic fields ($> 10^4$ gauss)

which we achieve in our experiments radial diffusion should proceed at a very slow rate, i.e., about 0.4 cm/sec, for the plasma conditions which have been measured. Thus the main mechanism of plasma losses out of the confining field should be by the process of mirror losses, proceeding with essentially no accompanying radial diffusion. This circumstance therefore poses a severe test for the stability of the confined plasma.

We have performed experiments which give a measure of the radial distribution of the confined plasma as a function of time after peak compression. These measurements were accomplished by the use of an array of scintillation photometers (scintillator plus photocell) placed just outside one of the mirrors. The schematic arrangement of the apparatus is shown in Fig. (11). With a magnetic compression time of 0.5 ms and a field decay time constant of about 10 milliseconds, signals similar to those shown in Fig. (12) were received in the scintillator photometers (sweep time 5 milliseconds). When analyzed for their radial dependence, curves such as those of Fig. (13) resulted. If these data are normalized to the same central height and corrected for the slight expansion of the magnetic flux surfaces which occurs as the confining field slowly decays, curves of the kind shown in Fig. (14) result. An analysis of these data shows that little, if any, radial diffusion of the plasma occurs during the time of observation, although the statistical accuracy of the data does not permit comparison with the theoretical result to better than order of magnitude. Nevertheless it is clear that transport of the plasma across the magnetic field proceeds very slowly during the confinement. Comparison with the so-called "Bohm" diffusion formula, which might be expected to apply in the presence of plasma oscillations or turbulence, shows that our measured rate is some 10^5 times smaller.

Since the plasma confined in these experiments evidently represents an example of stable confinement, we are continuing to study its properties and to determine whether it is only a special case (arising perhaps because of the disparity between electron and ion temperatures), or whether it gives some promise for stable plasma confinement under more general circumstances, such as those referred to in the first part of this paper.

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D^+ ENERGY SPECTRA FROM AN
OCCLUDED GAS PLASMA SOURCE
 $H_z = 198$ GAUSS

Fig. 1. D^+ energy spectrum from Ti plasma sources.

MUL-6454

MUL-7201

Fig. 2. Schematic arrangement of equipment for plasma injection studies.

MUL-7233

Fig. 3. Angular distribution function for trapped D^+ ions as a function of trapping magnetic fields.

MUL-7203

ALICE

Fig. 4. Schematic layout of ALICE.

Fig. 5. ALICE ion source.

Fig. 6. Critical neutral pressure as a function of injected particle energy.

Fig. 7. Critical neutral pressure as a function of confining magnetic field (under appropriate scaling).

Fig. 8. Breakup exponentiation time as a function of injected particle energy.

Fig. 9. Breakup exponentiation time as a function of confining magnetic field.

Fig. 10. Steady-state density of trapped ions as a function of confining magnetic field.

Fig. 11. Schematic arrangement of apparatus for density and temperature measurement of adiabatically compressed plasma.

Fig. 12. Typical oscilloscope trace of scattering from scintillator photometer of type used to determine radial density distribution.

Fig. 13. Experimentally determined radial distributions of escaping fast electrons.

Fig. 14. Normalized radial distribution of fast electron flux.

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