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Controlled Thermonuclear Processes

SOME PROPERTIES OF A STEADY STATE HIGH-ENERGY [redacted] INJECTION DEVICE (DCX)

A. Simon
M. Rankin

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A. Simon and M. Rankin

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ABSTRACT

DCX is an experimental Sherwood device utilizing high-energy molecular ion injection and trapping. It is shown that, if the input current of trapped deuterons exceeds a critical amount, there will occur a "burnout" of most of the neutral particles in the system. If this burnout does occur, the input ions will degrade only slightly in energy before becoming disorganized in direction and forming a plasma. Some possible perturbing mechanisms are considered. Impurities are shown to have little effect on the temperature, although their presence decreases the plasma density somewhat. Heat conduction to the walls and to the arc is estimated as well as the effect of cold electrons. It appears that in the absence of plasma instabilities, the final temperature, assuming an input energy of 300 kev, can be as high as 280 kev or as low as 75 kev. A plasma density of 10^{12} or greater may be achievable with a 1 ma input.

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I. INTRODUCTION

DCX is the name of the device which is being built at the Oak Ridge National Laboratory to exploit the molecular injection and trapping techniques developed by John Luce.[1] The essential feature of the method is the injection of a D_2^+ molecular ion across a magnetic field and the subsequent dissociation of this ion into a D^+ and a D^0 or into two D^+ ions and an electron. In either case the resulting D^+ has half the momentum of the original molecule and hence half the Larmor radius in the magnetic field. Thus, if breakup occurs in the outer regions of the orbit of the molecular ion, the resultant D^+ is trapped and does not return to strike the injector. The scheme is sketched in Fig. 1.1.

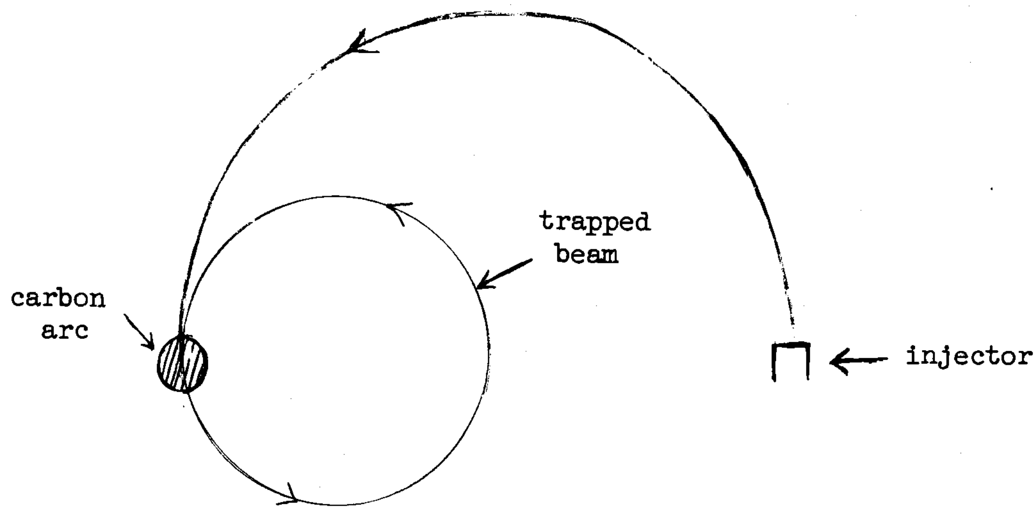

Fig. 1.1. Luce Injection Scheme

The success of this injection scheme is due to two advances made by Luce. The first was the development of high-current sources of molecular ions. The second was the discovery of the High-Current Carbon Arc[2] (HCCA) which can break up molecular ions with good efficiency (over 50% at 20 kev; about 10%

1. J. S. Luce, Molecular Ion Source, CF-55-11-160 (Nov., 1955).
2. J. S. Luce, Molecular Ion Breakup; Preliminary Note, CF-56-7-119 (July, 1956).

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at 600 kev). This composit injection scheme will be referred to as a Luce-type Injection System.

DCX combines a Luce Injection System with a containing geometry of the mirror type. This is the most convenient geometry to use, although not the only possible one. For example, it is perfectly possible to inject into a pinch or a Stellarator. A sketch of DCX is shown in Fig. 1.2 and a picture of the device in its current construction phase is shown in Fig. 1.3. The present plans are to inject about 1 ma of D_2^+ ions at 600 kev by using the cascade accelerator which had been in use at the High Voltage Laboratory of ORNL.

DCX differs in three fundamental respects from the other Sherwood devices. First of all, it makes use of the Luce Injection Scheme. Secondly, it is a completely DC device. The injection, as well as the magnetic field and the HCCA, are all steady state. Finally, DCX grows a plasma by <u>working down</u> in energy rather than by working up.

The calculations in the subsequent sections are concerned with the properties which a device such as DCX will have. One question is the temperature at which the plasma is formed. This is investigated in Section II. Neutral particles are damaging to the system because of their propensity to charge exchange with the hot ions. It is found that there is a critical point at which the input ions "burn out" the neutrals. This is calculated in Section III. Some additional effects which may be important are discussed in Section IV.

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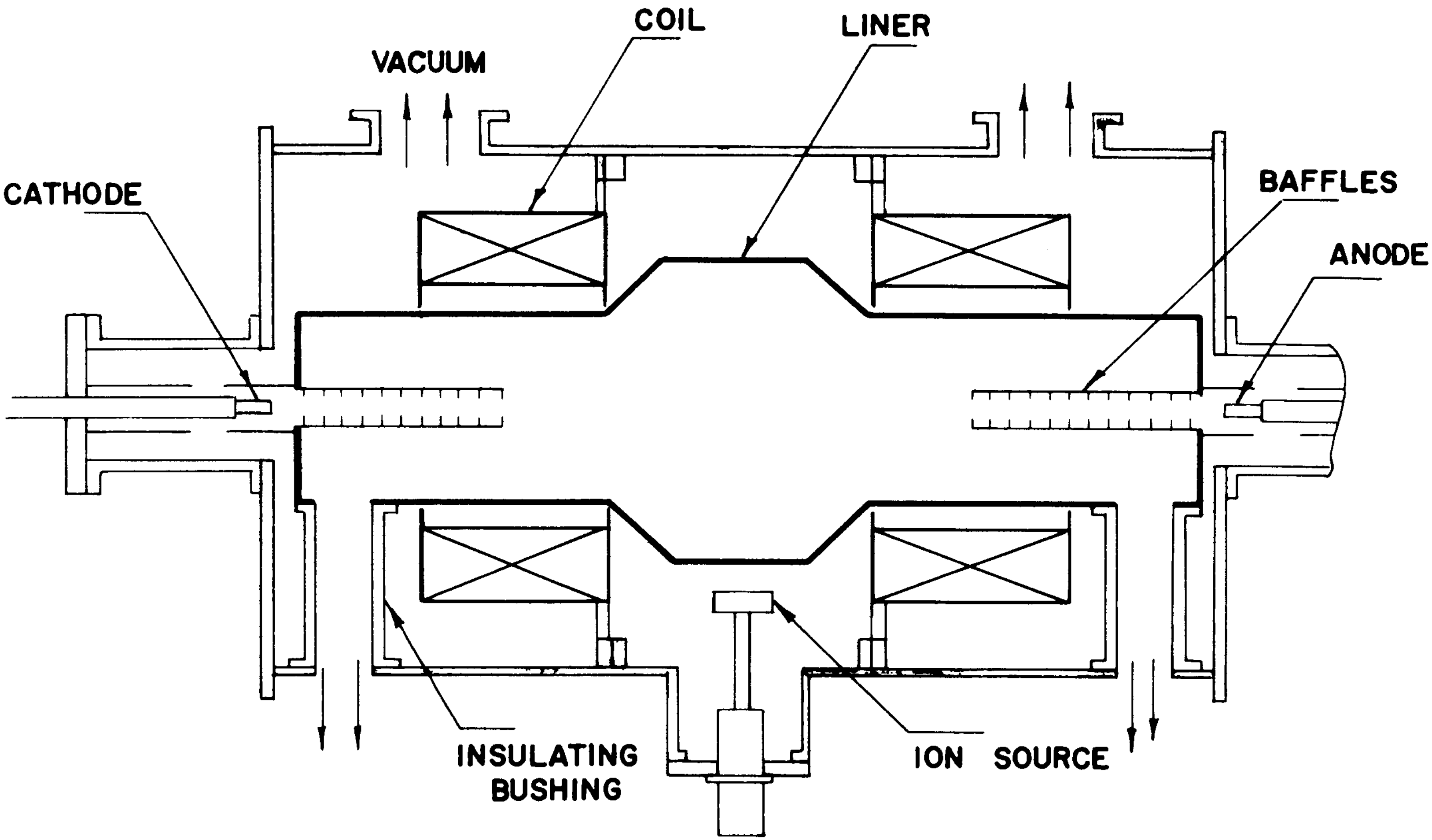

DCX

Fig. 1.2.

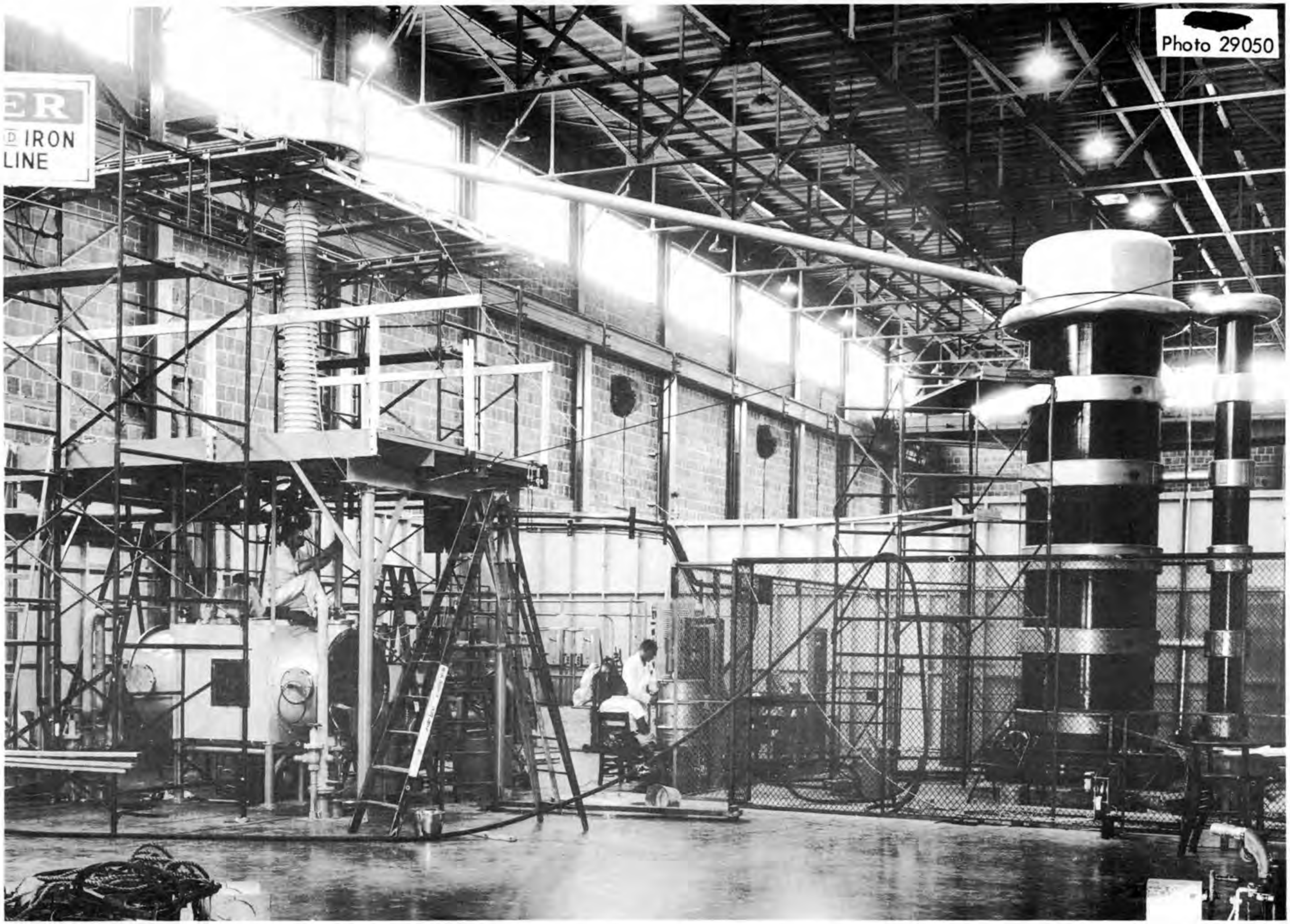

Fig. 1.3. DCX Under Construction.

II. THE IDEAL DCX

In the first version of DCX the trapped beam of D^+ ions will be injected at a steady rate at an energy of 300 kev. In steady state, there will be a "plasma" of cooler ions and electrons below the beam energy which immediately begins to degrade the beam energy by the usual energy loss processes. The cross section for this energy loss is somewhat larger than that for coulomb deflection. Hence, the beam tends to retain its original uniformity in direction and slowly spirals down in Larmor radius as the energy decreases. However, as the energy of the degraded particles approaches that of the "plasma" particles, the energy transfer cross section drops below that for coulomb deflection and the beam is then randomized in direction and goes into the plasma. The exact calculation of this behavior is a formidable task. Instead, an idealized model will be used to determine the approximate temperature of the "plasma."

In this model the injected particles are assumed to stay organized in their motion until they enter the plasma. After entering the plasma, ions are lost through the mirrors in the usual fashion. Impurities and neutral particles are assumed absent. Energy is fed to both the ions and electrons in the plasma by the ions which are slowing down. The electrons lose energy by bremsstrahlung. A schematic diagram of the model is shown in Fig. 2.1.

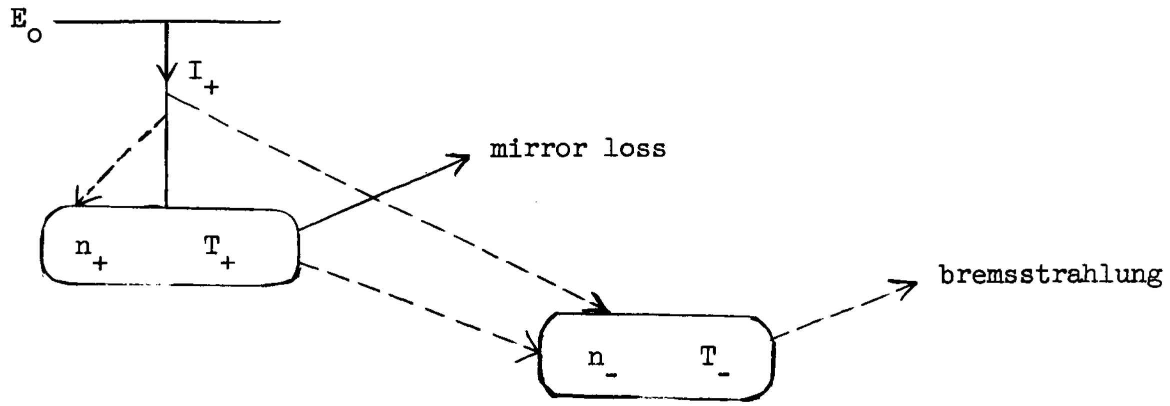

Fig. 2.1. The Ideal DCX

The dotted lines denote the direction of transfer of energy, while the solid lines denote particle paths. Note that no influx or outgo of electrons is assumed. Instead, the electron density is determined by the requirement of space charge neutrality. The electrons are cooler than the ions by virtue of their bremsstrahlung losses.

There are four unknowns to be determined once the input particle current I_+ and input energy E_o are specified. These are the ion and electron densities in the plasma n_+ and n_-, and the temperatures of the plasmas T_+ and T_-. These may be determined by the four equations resulting from the requirements of energy balance, ion conservation, and space-charge neutrality.

Energy Balance in the Ion Cloud

Let $N(E)dE$ denote the number of ions in the organized beam between energy E and $E + dE$. The rate at which energy is being fed into the ion cloud by the organized beam is then

$$P_{in} = \int_{E_+}^{E_o} N(E) \left.\frac{dE}{dt}\right|_+ dE \qquad (2.1)$$

where E_+ ($= \frac{3}{2}$ kT_+) is the average energy of an ion in the plasma and $\left.\frac{dE}{dt}\right|_+$ denotes the rate of loss of energy by an ion of energy E to a plasma at temperature T_+.

In steady state the energy flux of particles in the organized beam must be a constant and equal to the input particle rate. Hence

$$N(E) \frac{dE}{dt} = I_+ \qquad (2.2)$$

where $\frac{dE}{dt}$ represents the rate of loss of energy by the ions in the organized beam to all sources (i.e., both electrons and ions). Thus, Eq. (2.1) becomes

$$P_{in} = I_+ \int_{E_+}^{E_o} \frac{\left.\frac{dE}{dt}\right|_+}{\frac{dE}{dt}} dE = I_+ \int_{E_+}^{E_o} \frac{\left.\frac{dE}{dt}\right|_+}{\left.\frac{dE}{dt}\right|_+ + \left.\frac{dE}{dt}\right|_-} dE \qquad (2.3)$$

A general expression for the energy loss rate by coulomb collision from a particle of mass M to a Maxwell-Boltzmann distribution of target particles of mass m has been given by Chandrasekhar.[3] The result is

$$\frac{dE}{dt} = - \frac{M}{2} \frac{A_D}{\omega} \left[2x^2 \left(1 + \frac{M}{m} \right) G(x) - \phi(x) \right] \qquad (2.4)$$

where ω is the velocity of the particle of mass M and ℓ is defined as:

$$\ell^2 = \frac{m}{2kT} \qquad (2.5)$$

Here T is the temperature of the target particles. The quantity $x = \ell\omega$ and

$$\phi(x) = \frac{2}{\sqrt{\pi}} \int_o^x e^{-y^2} dy$$

and

$$G(x) = \frac{\phi(x) - x\phi'(x)}{2x^2} \qquad (2.6)$$

Finally,

$$A_D = 8\pi n \left(\frac{zZe^2}{M} \right)^2 \ln \Lambda \qquad (2.7)$$

where the density and charge of the target particles are denoted by n and z respectively, and Z is the incident particle's charge. The logarithm

3. S. Chandrasekhar, Astrophys. J. 97, 255 (1943).

results from the usual cutoff on the maximum impact parameter. This quantity is rather slowly energy dependent and in these calculations it will be taken to be a constant whose value is 20. Hence

$$\ln \Lambda \cong 20 \tag{2.8}$$

Consider the energy loss rate from ions to a cloud of electrons. Unless the electrons are extremely cold ($E_{elec} < \frac{m}{M} E_{ion}$), the electron velocity will be very much larger than that of the ions and the quantity x is very small. Assuming this (the numerical results will justify this), one obtains a simplified expression for the loss rate to electrons. Since

$$\left.\begin{aligned} G(x) &\longrightarrow \frac{2}{3\sqrt{\pi}}\, x \\ \phi(x) &\longrightarrow \frac{2}{\sqrt{\pi}}\, x \end{aligned}\right\} \quad \text{as } x \longrightarrow 0 \tag{2.9}$$

one obtains

$$\left.\frac{dE}{dt}\right|_{-} = - \frac{M}{2} \frac{A_D}{\omega} \frac{2}{\sqrt{\pi}}\, x \left(\frac{2}{3} \frac{M}{m} x^2 - 1 \right)$$

Substituting from Eqs. (2.8) and (2.5),

$$\left.\frac{dE}{dt}\right|_{-} = - \frac{160\sqrt{\pi}\; n_- e^4}{M} \sqrt{\frac{m}{2kT_-}} \left(\frac{M\omega^2}{3kT_-} - 1 \right) \tag{2.10}$$

In the case of energy loss from ions to ions, the more general expression of Eq. (2.4) must be retained.

Returning now to the energy loss to the ion cloud by the organized beam, one can rewrite Eq. (2.3) by substituting from Eqs. (2.4) and (2.10). The result is

$$P_{in} = I_+ \int_{E_+}^{E_o} \frac{n_+ \left[4x^2 G(x) - \phi(x)\right] dE}{n_+ \left[4x^2 G(x) - \phi(x)\right] + n_- \sqrt{\frac{3m}{\pi E_-}} \left(\frac{E}{E_-} - 1\right) \sqrt{\frac{2E}{M}}} \qquad (2.11)$$

where $E_- = \frac{3}{2} kT_-$ and $x \equiv \sqrt{\frac{M\omega^2}{2kT_+}} = \sqrt{\frac{3E}{2E_+}}$

In steady state the power delivered to the ion cloud must equal the energy lost by it to the electron cloud. Assume that all the ions in the cloud are at a single energy $E_+ = \frac{3}{2} kT_+$. The loss rate to the electrons is then, by Eq. (2.10),

$$P_{out} = Vn_+n_- \frac{80\sqrt{3\pi}\, e^4}{M} \sqrt{\frac{m}{E_-}} \left(\frac{E_+}{E_-} - 1\right) \qquad (2.12)$$

where V is the volume of the plasma. More correctly, of course, one should average this over a Maxwell-Boltzmann distribution of the ions. The numerical results are insensitive to this, however, and this correction will be ignored. Upon equating the power delivery and loss, one obtains the first of the four equations:

$$\boxed{\frac{I_+}{V} \int_{E_+}^{E_o} \frac{n_+ \left[4x^2 G(x) - \phi(x)\right] dE}{n_+ \left[4x^2 G(x) - \phi(x)\right] + n_- \sqrt{\frac{6mE}{\pi M E_-}} \left(\frac{E}{E_-} - 1\right)} = n_+n_- \frac{80\sqrt{3\pi}\, e^4}{M} \sqrt{\frac{m}{E_-}} \left(\frac{E_+}{E_-} - 1\right)} \qquad (2.13)$$

where $x^2 = \frac{3}{2} \frac{E}{E_+}$.

Energy Balance in the Electron Cloud

Since all the energy lost by the ions in slowing down ultimately reaches the electrons, the power input to the electrons is simply

$$P_{in} = I_+(E_o - E_+) \tag{2.14}$$

Energy is radiated by bremsstrahlung at the rate

$$P_{out} = V \frac{64}{3\sqrt{3\pi}} \frac{n_+ n_- e^6}{mc^3 \hbar} \cdot \sqrt{\frac{E_-}{m}} \tag{2.15}$$

Hence, the second equation is

$$\boxed{\frac{I_+}{V} (E_o - E_-) = n_+ n_- \frac{64}{3\sqrt{3\pi}} \frac{e^6}{mc^3 \hbar} \sqrt{\frac{E_-}{m}}} \tag{2.16}$$

Ion Conservation

Mirror losses are the result of particle collisions which produce a scattered particle with its velocity vector in the escape cone. An approximate expression for the loss rate is[4]

$$\frac{dn_+}{dt} \cong V \frac{n_+^2}{2} \sigma_c v_+ P \tag{2.17}$$

where σ_c is taken to be the coulomb "cross section" in the plasma for scattering by multiple small angle collisions through 90 deg, v_+ is the r.m.s. ion velocity in the plasma ($= \sqrt{\frac{2E_+}{M}}$) and P is the probability of the velocity lying in the escape cone after a random 90-deg collision. If P is taken to be the ratio of the area in the escape cone to the total area, this is[5]

4. A. Simon, Nine Lectures on Project Sherwood, ORNL-2285, Eq. (6.7) (March, 1957).
5. Ibid, Eq. (6.8).

$$P = 1 - \sqrt{1 - \frac{1}{R}} \qquad (2.18)$$

The 90-deg "cross section" is[6]

$$"\sigma_c" \cong 8\pi \left(\frac{e^2}{Mv^2}\right)^2 \ln\Lambda$$

$$= 2\pi \left(\frac{e^2}{E_+}\right)^2 \ln\Lambda \qquad (2.19)$$

In steady state

$$\boxed{\frac{I_+}{V} = n_+^2 \frac{20\ \pi e^4 v_+ P}{E_+^2}} \qquad (2.20)$$

Charge Neutrality in the Large

The electron density is determined by the condition that the total number of electrons equal the total number of ions, both in the plasma and in the beam slowing down. Hence

$$n_- V = n_+ V + \int_{E_+}^{E_o} N(E)dE$$

or

$$n_- = n_+ + \frac{I_+}{V} \int_{E_+}^{E_o} \frac{dE}{\left.\frac{dE}{dt}\right|_+ + \left.\frac{dE}{dt}\right|_-}$$

6. Ibid, Eq. (2.9).

Substituting from Eqs. (2.4) and (2.10), one has

$$\boxed{n_- = n_+ + \frac{I_+}{V} \frac{M}{80\ \pi e^4} \int_{E_+}^{E_o} \frac{\sqrt{\frac{2E}{M}}\ dE}{n_+\left[4x^2 G(x) - \phi(x)\right] + n_- \sqrt{\frac{6mE}{\pi ME_-}}\left(\frac{E}{E_-} - 1\right)}} \qquad (2.21)$$

where $x^2 = \frac{3}{2}\frac{E}{E_+}$.

The requirement of space charge neutrality in the large merits some discussion. If the input ions remain concentrated in a small region of the device until they become randomized, it would make more sense to require $n_+ = n_-$ in the remainder of the machine. On the other hand, large precessions of the input ions may be expected because of the nonuniformity of the magnetic fields in DCX. Hence, an appreciable fraction of the volume may be filled with a "semi-organized" beam in the process of slowing down. In this case, the requirement of Eq. (2.21) may be more sensible. The numerical results are insensitive to either of these two choices.

<u>Reduction to Two Equations</u>

Upon substituting Eq. (2.20) in Eq. (2.16) one obtains an expression for the ratio n_+/n_- which is independent of input current. Thus

$$\frac{n_+}{n_-} = \frac{16}{15\sqrt{6\pi^3}} \cdot \sqrt{\frac{ME_-}{mE_+}} \cdot \left(\frac{e^2}{\hbar c}\right) \cdot \frac{E_+^2}{mc^2(E_o - E_+)} \frac{1}{P} \qquad (2.22)$$

Note that this ratio represents the fraction of the total ions which are actually in the plasma.

Equations (2.22) and (2.20) may now be substituted in Eqs. (2.13) and (2.21) so as to eliminate all dependence on plasma densities or input current. The resulting equations are:

$$\int_{E_+}^{E_o} \frac{\left[4x^2G(x) - \phi(x)\right] dE}{\left[4x^2G(x) - \phi(x)\right] + \left(\frac{n_-}{n_+}\right) \cdot \sqrt{\frac{6mE}{\pi ME_-}} \left(\frac{E}{E_-} - 1\right)}$$

$$= \frac{n_-}{n_+} \sqrt{\frac{6mE_+}{\pi ME_-}} \left(\frac{E_+}{E_-} - 1\right) \frac{2E_+}{P} \qquad (2.23)$$

and

$$\frac{n_-}{n_+} = 1 + \frac{P}{2(E_+)^{3/2}} \int_{E_+}^{E_o} \frac{\sqrt{E}\ dE}{\left[4x^2G(x) - \phi(x)\right] + \frac{n_-}{n_+} \sqrt{\frac{6mE}{\pi ME_-}} \left(\frac{E}{E_-} - 1\right)} \qquad (2.24)$$

where $x^2 = \frac{3}{2} \frac{E}{E_+}$ and $\frac{n_+}{n_-}$ is defined by Eq. (2.22).

Equations (2.23) and (2.24) may be solved numerically for the two plasma energies E_+ ($= 3/2\ kT_+$) and E_- ($= 3/2\ kT_-$). The results then give the ratio of ions in the plasma to all ions directly by use of Eq. (2.22). Finally, the plasma density may be obtained from Eq. (2.20) after the input current is specified.

Numerical Results

For an input energy E_o = 300 kev and a mirror ratio R = 2, the following results were obtained:

$$E_+ \cong 0.944\ E_o \cong 280 \text{ kev}$$

$$E_- \cong 0.71\ E_o = 210 \text{ kev}$$

$$\frac{n_+}{n_-} \cong 0.97.$$

Assuming an input current of 1 milliampere and a volume of 4×10^4 cc, the ion density is

$$n_+ \cong 1.1 \times 10^{13}/\text{cc}$$

Some preliminary calculations at $E_o = 50$ kev yielded values of E_+ which were between E_o and $0.98\ E_o$.

Discussion of Results

The numerical result that the plasma particle energy is close to the input energy is not unexpected. The reason for this is the fact that the energy fed down to the electrons is proportional to $E_o - E_+$. The electrons must lose their energy by bremsstrahlung, which is a very slow $\left(\frac{e^2}{\hbar c}\right)$ process. Hence, equilibrium results at temperatures close to that of the source.

A more unexpected result is the fact that most of the energy loss by the organized ions is to the ion cloud and not to the electrons. This is the reverse of the situation when the electrons and ions are very cold $(< \frac{m}{M}\ E_o)$ compared to the organized ions. For comparable electron and ion temperatures, Eqs. (2.4) and (2.10) show that energy loss to the ions dominates by $\sqrt{M/m}$. This may also be seen from comparison of the two terms in the denominators of Eqs. (2.23) and (2.24). Hence, it is an excellent approximation to neglect this second term. In this case our equations become:

$$\frac{E_o - E_+}{E_+} = \frac{n_-}{n_+}\ \frac{2}{P}\ \sqrt{\frac{6mE_+}{\pi ME_-}}\left(\frac{E_+}{E_-} - 1\right) \qquad (2.25)$$

$$\frac{n_-}{n_+} = 1 + \frac{P}{2(E_+)^{3/2}} \int_{E_+}^{E} \frac{\sqrt{E}\ dE}{4x^2G(x) - \phi(x)} \qquad (2.26)$$

The solution of these simplified equations gives numerical results which are very close to the previous values.

Note that 97% of the ions are in the plasma and that only 3% are in the process of slowing down. This result also means that the characteristic slowing down time is only 3% of the characteristic mirror loss time.

One final remark should be made about the ion density quoted in the numerical results. The high value of this quantity is due to the high plasma temperature and hence low mirror losses. The resultant β of the plasma ($\beta = \frac{nkT}{H^2/8\pi}$) would be greater than unity in the DCX now being built since the center-plane field is about 8Kg. Needless to say, one would be delighted to find that this phenomenon is the only one limiting the plasma buildup.

III. NEUTRAL BURNOUT

Any realistic device, particularly at startup, will have large numbers of neutral particles in it. These neutral particles will remove hot ions from the system because of the charge exchange process. In this process, a hot ion strikes a neutral and picks up an electron becoming a fast neutral. This neutral is lost to the system while the cold ion left behind is itself readily lost through the mirrors. The cross section for charge exchange is a steeply decreasing function of the ion velocity above about 30 kev ($\sim 1/v^8$). However, even at 300 kev it has a value of about 3×10^{-18} cm^2 which is very much larger than the coulomb cross sections involved in energy loss and particle deflection. Hence, if any appreciable number of neutrals remain in the system, they will remove the hot ions by charge exchange, and few, if any, ions will survive to form a plasma.

On the other hand, every charge exchange destroys a neutral. Furthermore, the ionization caused by the fast ion will remove many more neutrals by this means, since the ionization cross section is more than 20 times as large as charge exchange at 300 kev. It seems reasonable that there will be a critical point for the input current, at which point the ions "burnout" the neutrals as fast as they are flooding into the plasma. Once this point is passed, the ions get ahead of the neutrals. The plasma builds up, hence burning out additional neutrals, and the system cleans out the neutrals in short order. Another way of saying this is that it is hard to see how any neutrals can survive in any appreciable plasma at 300 kev or so.

This conjecture may be investigated numerically. Consider the rate of buildup of ion density n_+ in the plasma. The time-dependent equations are:

$$\frac{dn_+}{dt} = \frac{I_+}{V} - \frac{n_+^2}{2} \sigma_c vP - n_+ n_o \sigma_{cx} v \qquad (3.1)$$

$$\frac{dn_o}{dt} = \frac{Nv_o}{4} \frac{S}{V} - \frac{n_o v_o}{4} \frac{S}{V} - n_o n_+ (\sigma_i + \sigma_{cx}) v \qquad (3.2)$$

The first term on the right of Eq. (3.1) represents the constant source input, with V being the plasma volume. The second term takes account of mirror losses, while the last term represents loss of fast ions by charge exchange.

The neutral density n_o also varies in time as given by Eq. (3.2). It is assumed here that the plasma has a surface area S and that there is constant streaming of neutrals into the plasma from the external manifold through the surface S. If the constant density of neutrals in the manifold is denoted by N, there will be a steady kinetic streaming into the plasma at a rate of $Nv_o/4$ particles per unit area, where v_o is the thermal velocity of the neutrals. Similarly, the neutrals in the plasma may stream out as given by the second term in the right of Eq. (3.2). Finally, the effects of neutral burnout by ionization and charge exchange are represented by the last term on the right.

The results of Section II have shown that the ions do not lose much of their energy while slowing down into the plasma. Hence, it is a good approximation to assume all cross sections and velocities to be constant in Eqs. (3.1) and (3.2) at some value close to the source energy. The resulting equations may then be solved quite readily on an analogue computer. Most of the numerical results to be described below were obtained assuming an energy of 250 kev for the coefficients in Eqs. (3.1) and (3.2). There is one run at the energy $E_+ = 280$ kev found in Section II.

The numerical results were found to be in agreement with a qualitative criterion for the critical current which could be guessed in advance. On the basis of the previous discussion, one might expect the critical current to occur at the point where the neutrals are being "burned out" just as fast as they are coming in. Now the number of neutrals destroyed by a fast ion before it itself is lost is clearly $(\sigma_i + \sigma_{cx})/\sigma_{cx}$. Hence, the critical input current should be

$$I_{crit} = \frac{\sigma_{cx}}{\sigma_i + \sigma_{cx}} I_o \qquad (3.3)$$

where I_o is the total current of neutrals streaming into the plasma. The numerical results below have shown that there is indeed a neutral "burnout."

However, the event is not a sudden phenomenon but rather a smooth transition over a narrow range of current. It will be seen, however, that the relationship of Eq. (3.3) gives the current at which most of the neutrals have disappeared and at which the plasma has built up to near full density.

Coefficients

The first version of DCX, which is now being built, has mirror coils with a 17 in. I.D. and a spacing between the inner faces of the coil of 18-1/2 in. (See Fig. 3.1.)

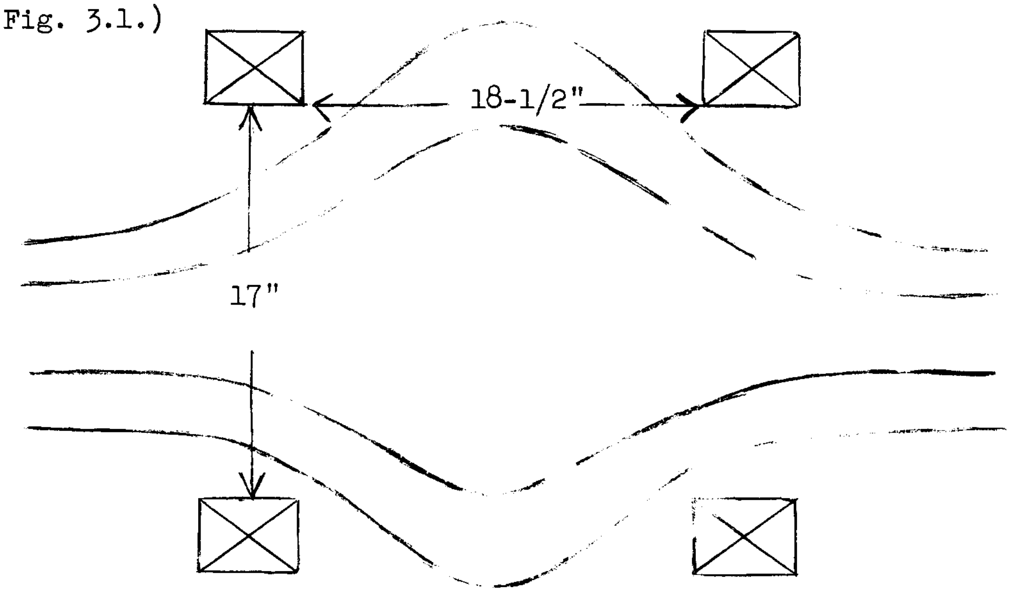

Fig. 3.1. Dimensions of DCX

If one inscribes a cylinder whose rims just touch the inner edge of the coils, the inscribed volume is then

$$V_{cyl} = \frac{\pi(17)^2}{4} (18.5)(2.54)^3$$

$$= 6.9 \times 10^4 \text{ cm}^3$$

Since only part of this volume will be occupied by the plasma, the parameter V was taken to be

$$V \cong 4 \times 10^4 \text{ cm}^3$$

Assume further that the plasma has a semi-spherical shape with a typical radius of about 8 in. In that case

$$\frac{S}{V} \cong \frac{3}{r} = \frac{3}{8(2.54)} \cong 0.15 \text{ cm}^{-1}$$

and thus

$$S \cong 6 \times 10^3 \text{ cm}^2$$

The thermal velocity of the neutrals was chosen to be that of a deuterium molecule at 300°K. Thus

$$v_o = 1.9 \times 10^5 \text{ cm/sec}$$

and the density of the neutrals in the manifold N is given by the manifold pressure. A mirror ratio of 2 was chosen throughout.

The coulomb "cross section" was chosen as in Eq. (2.19) to be

$$\sigma_c = 40\pi \left(\frac{e^2}{E_+}\right)^2$$

while the ionization cross section at 250 kev was computed from the formula[7]

$$\sigma_i = .285 \frac{2\pi e^4}{|E_o| \, mv_+^2} \ln\left(\frac{2mv_+^2}{0.048 \, |E_o|}\right)$$

$$= 1.0 \times 10^{-16} \text{ at } 250 \text{ kev}$$

with $|E_o| = 16$ ev. Finally, the charge exchange cross section was taken from the measured values of Stier and Barnett[8] for H^+ in hydrogen gas

7. H. Bethe and J. Ashkin, Part II, Experimental Nuclear Physics, John Wiley and Sons, New York (1953).
8. P. M. Stier and C. F. Barnett, Phys. Rev. 103, 896 (1956).

assuming that the deuteron cross section is the same at the same relative velocity. This is 5.5×10^{-18} at 250 kev.

Numerical Results

Equations (3.1) and (3.2) may be put in a more convenient form by defining the dimensionless quantities

$$n_o' = \frac{n_o}{N} \tag{3.4}$$

$$n_+' = \frac{n_+}{\sqrt{\dfrac{2I_+}{\sigma_{cx} vPV}}} \tag{3.5}$$

Note that the initial values of n_o' and n_+' are 1 and 0 respectively before the beam is turned on, and that if all the neutrals are burned out, n_+' rises to its maximum theoretical value of unity. In terms of these variables, dropping the primes one has

$$\frac{dn_+}{dt} = A(1 - n_+^2) - Bn_+n_o \tag{3.6}$$

$$\frac{dn_o}{dt} = C(1 - n_o) - Dn_+n_o \tag{3.7}$$

where

$$A = \left(\frac{I_+\sigma_c vP}{2V}\right)^{1/2} \tag{3.8}$$

$$B = N\sigma_{cx}v \tag{3.9}$$

$$C = \frac{v_oS}{4V} \tag{3.10}$$

$$D = \left(\frac{2I_+}{\sigma_c vPV}\right)^{1/2} (\sigma_i + \sigma_{cx})v \tag{3.11}$$

Some typical analogue computer runs are shown in Figs. 3.2 through 3.5. The first two figures are a case for which the critical current is below the critical point. It is seen that the neutral density falls only slightly and that the ions do not build up appreciably in time. The last two figures illustrate a case well beyond the critical current. The neutral density falls rapidly in a time of the order of 50 milliseconds to 10% of its original value and the ion density climbs almost linearly to close to its optimum value.

Focussing attention now on the equilibrium results, these are shown in Fig. 3.6. These results show that the critical current varies linearly with the pressure as predicted by Eq. (3.3). The arrows indicate the currents predicted by Eq. (3.3) for each of the three pressures. Note the steep rise in equilibrium ion density with increasing current.

Discussion of Results

The first version of DCX, which is being built, may be expected to operate at a vacuum of about 10^{-6} mm. For this case, Fig. 3.6 indicates that the critical current is about 80 ma. Since this first device will only furnish about 1 ma, it would seem that neutral burnout will not occur.

This conclusion may be unduly pessimistic, however. At least one of the assumptions made in the calculation may be pessimistic by a factor of 10^3 or greater. This is the assumption concerning the rate of neutral influx into the plasma. At a pressure of 10^{-6} mm, $N \cong 3 \times 10^{10}$ and since $v_o = 1.9 \times 10^5$, the input flux is 6×10^{15} cm^{-2} sec^{-1}. On the other hand, P. R. Bell has pointed out the limiting influx of neutrals is not from the manifold, but from emission by the walls. The Princeton Sherwood Group has listed some typical experimental values for the outgassing rate from a clean wall (with no baking). These are[9]

$$F = 2.13 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$F = .96 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$F = .53 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$$

9. W. R. Farber et al., A Conceptual Design of the Model C Stellerator, NYO-7309, p. 48 (1956).

[redacted]

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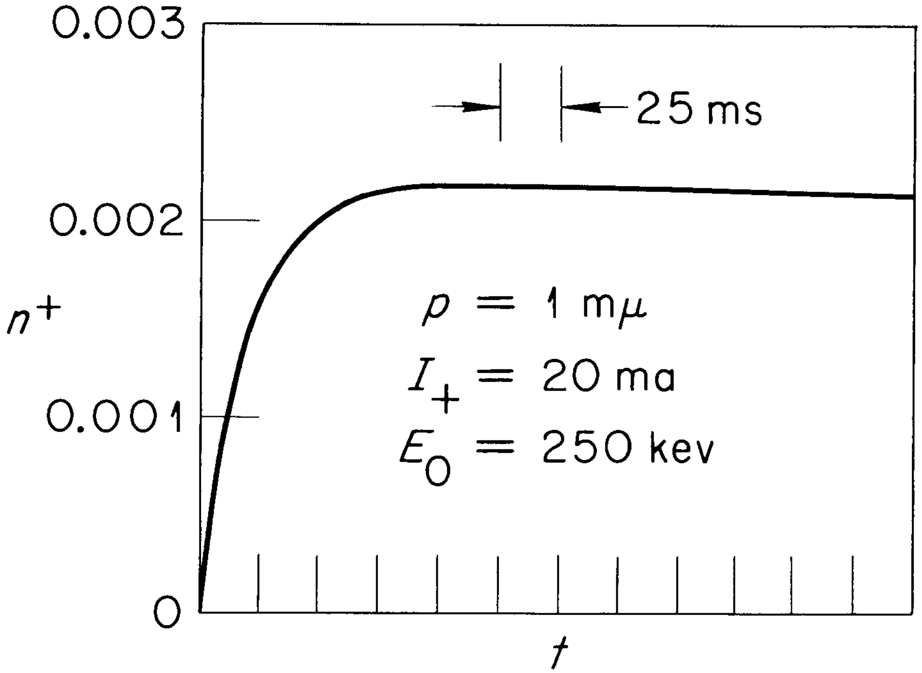

Fig. 3.2.

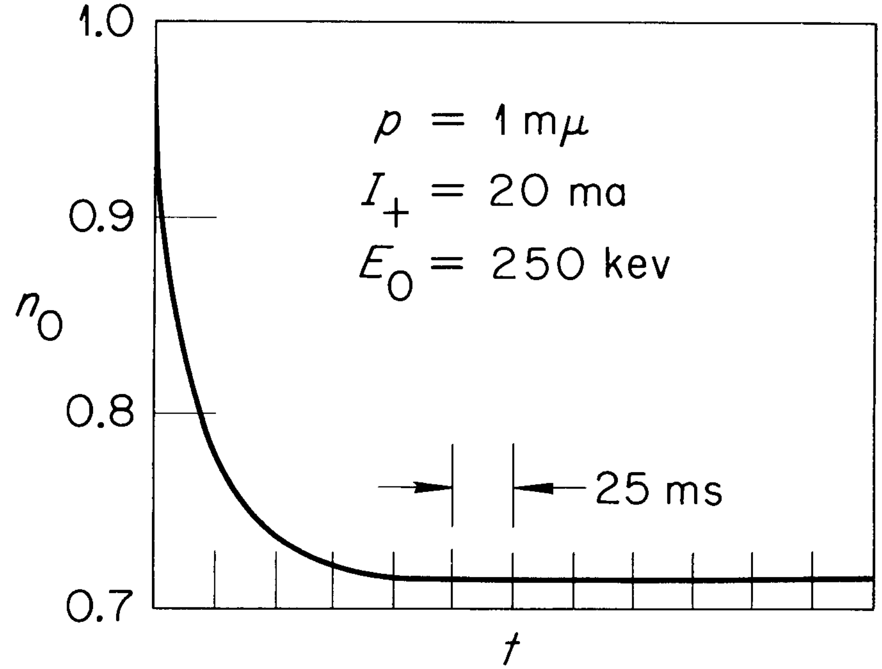

Fig. 3.3.

Density Variations for a Below Critical Current.

[redacted]
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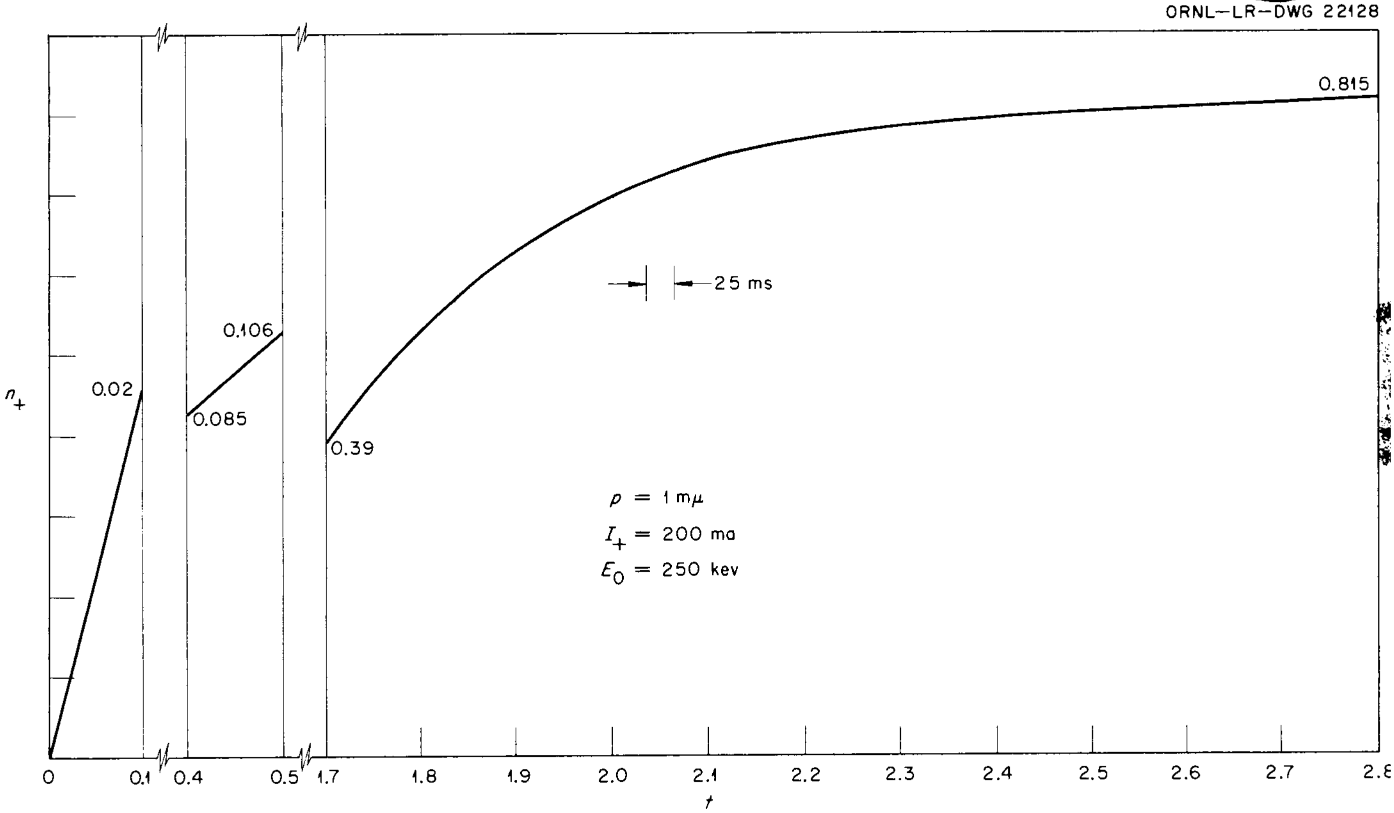

Fig. 3.4

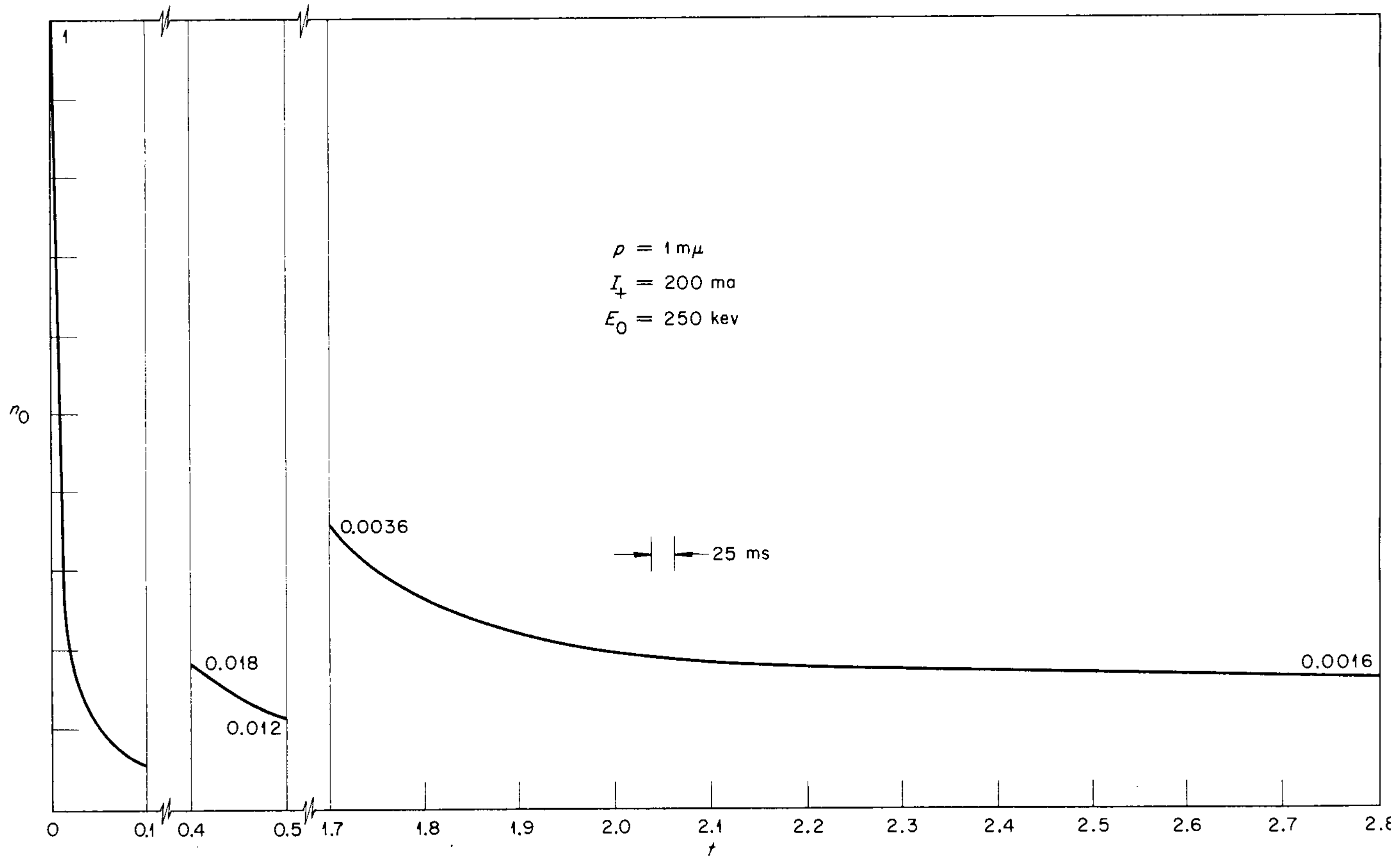

Fig. 3.5

Density Variations for an Above Critical Current.

[redacted]

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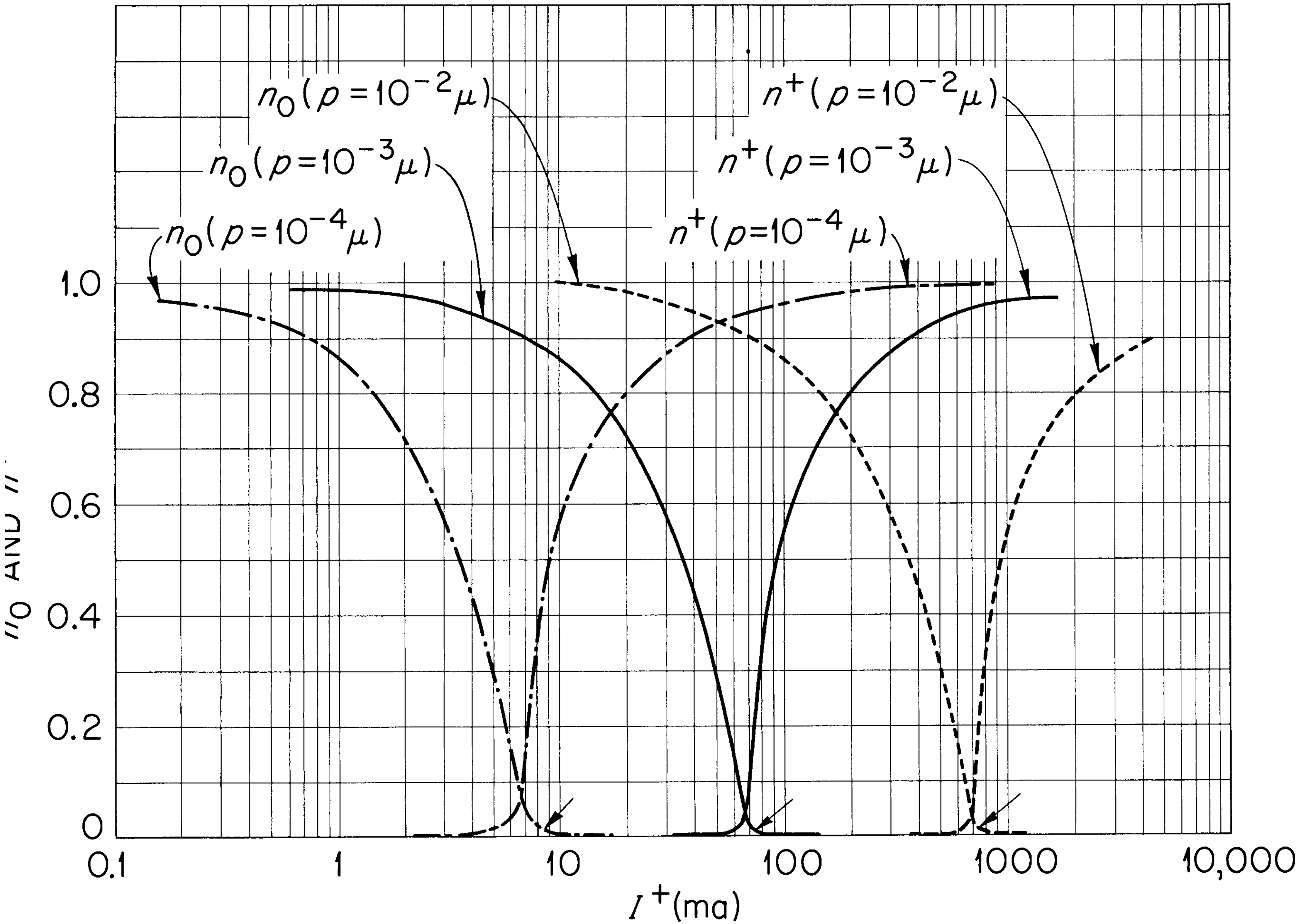

Fig. 3.6. Steady State Densities for 250-kev D^+.

Hence, even though the effective wall area is somewhat larger than the plasma surface, it may be that the neutral influx has been taken too large by a factor of 10^3 or larger. If this is true, the critical current would be reduced by the same factor. Another unknown factor is the influence of the carbon arc itself on burnout. Preliminary evidence indicates that the arc acts as an ion pump. A final point is that it may be necessary to go well above the critical current in order to bring the neutral density down to the point where charge exchange is small compared to plasma formation ($\sigma_{cx}/\sigma_{coul} \cong 10^5$ at 250 kev). It should be noted that plans are well under way for the construction of a 1 ampere 600 kev supply.

<u>Asymptotic Relations</u>

One check on the analogue results is obtained by solving the steady state equations for the case of currents which are well above the critical point. In that case

$$n_+ = 1 - \epsilon$$

Keeping terms of first order in ϵ only in Eqs. (3.6) and (3.7) one finds

$$\epsilon = \frac{\frac{C}{D}\;\frac{B}{A}}{2 + 2\frac{C}{D} + \frac{C}{D}\;\frac{B}{A}} \rightarrow \frac{1}{2}\;\frac{Nv_oS}{4I_+}\left(\frac{\sigma_{cx}}{\sigma_i + \sigma_{cx}}\right)$$

and

$$n_o = \frac{2\frac{C}{D}}{2 + 2\frac{C}{D} + \frac{C}{D}\;\frac{B}{A}} \rightarrow \frac{v_oS}{4(\sigma_i + \sigma_{cx})}\sqrt{\frac{\sigma_cP}{2I_+vV}}$$

IV. ADDITIONAL EFFECTS

Impurities

The presence of the carbon arc will undoubtedly contribute large numbers of carbon ions to the plasma. It is often stated (rather loosely) that the presence of impurities in a plasma will increase the bremsstrahlung power loss by the factor z^3. This argument may be fallacious in the case of a steady state mirror machine.

Owing to the fact that mirror loss is due to coulomb collisions, the more general form for the ion conservation equation in steady state for a mirror machine is

$$\frac{I_+}{V} = \frac{(\overline{z^2}n_+)^2}{2} \sigma_c vP \tag{4.1}$$

where $\overline{z^2}$ is the average z^2 in the plasma and n_+ is the total ion density. All ion species are assumed to be at the same temperature and the coulomb cross section with $z = 1$ is denoted by σ_c. The difference in velocities of the ion species is neglected here and a common velocity is denoted by v. The essential point is that with a constant source term, the product $\overline{z^2}n_+$ remains constant in a mirror machine.

On the other hand, the power radiated in bremsstrahlung varies as:

$$P_{brems} \sim \overline{z^2}n_+n_- \tag{4.2}$$

Hence, since $\overline{z^2}n_+$ stays constant, it is clear that the power radiated in bremsstrahlung rises no faster than z as impurities are added to a mirror machine.

For example, suppose that the plasma in DCX should contain 10% carbon ions. Since $z = 6$, we have $\overline{z^2} = 4.5$ and $\bar{z} = 1.5$. Thus the bremsstrahlung rate is increased by 1.5 and the ion density is decreased by the factor 4.5. This increased bremsstrahlung has a minor effect on the plasma temperature. Since the energy fed to the electrons goes out as bremsstrahlung, one must increase $E_o - E_+$ over its value for $\bar{z} = 1$ by a factor of about 1.5. Previously (see Section II) we had $E_o - E_+ \cong 0.06\ E_o$. Hence, we now require $E_o - E_+ \cong 0.1\ E_o$ or $E_+ = 0.9\ E_o$ which is still an exceedingly hot plasma.

Heat Transfer to Arc

The arc itself, of course, represents a serious sink for heat, not only through excitation radiation but through the presence of cool ions and electrons in the interior. On the other hand, it may be no worse in this respect than the walls of DCX since these are only one Larmor radius from the plasma. The calculation in the next section considers the effect of heat transfer to the walls and shows that even under the most severe assumptions, the resulting plasma temperature is still high.

The arc may be even less troublesome than a wall since it represents a "wall" at a rather high temperature ($\cong$ 100 volts). In any event, if the arc holds down the full development of the plasma temperature, it may be possible to shut off the arc and continue feeding ions by using the breakup due to the plasma already existant.

Heat Transfer to the Walls

Up to this point, energy loss from the system has been assumed to occur by means of bremsstrahlung. Of course, heat transfer by the usual thermal conduction means does also occur and may be quite important, particularly since the walls may be as close as one Larmor radius away. The power loss from a system per unit volume due to thermal conduction is

$$P_{cond} = - K \frac{d^2T}{dx^2} \qquad (4.3)$$

where K is the thermal conduction coefficient in a magnetic field. Now

$$K = \frac{nk\lambda v}{2(\omega \tau)^2} \qquad (4.4)$$

where n is the ion density, k is Boltzmann's constant, λ is the ion mean free path for collision, v is the ion velocity, ω is the ion cyclotron frequency and $\tau = \lambda/v$ is the mean free time between ion collisions. Assuming a parabolic temperature distribution one has

$$\frac{d^2T}{dx^2} \cong - \frac{2(T_c - T_o)}{\ell^2} \qquad (4.5)$$

where T_c is the temperature in the center of plasma, T_o is the wall temperature and ℓ the distance between these two points. The combined expression for the power loss by conduction becomes:

$$P_{cond} \cong \frac{nk\lambda v}{(\omega\tau)^2} \frac{(T_c - T_o)}{\ell^2} \tag{4.6}$$

$$= \frac{nkv^3}{\omega^2\lambda} \frac{T_c - T_o}{\ell^2}$$

$$= n^2 \frac{\sigma kv^3}{\omega^2} \frac{T_c - T_o}{\ell^2}$$

where σ is the collision cross section. Now ℓ should be chosen to be about one Larmor radius. Hence

$$\ell = r_o = \frac{v}{\omega}$$

$$P_{cond} \cong n^2\sigma vkT_c$$

neglecting T_o compared to T_c.

This expression is to be compared with the bremsstrahlung loss rate given in Eq. (2.15) (divided by V). Using the value of σ given in Eq. (2.19) with $\ln\Lambda = 20$ and with $kT_c \cong 2/3\ E_+$, one has

$$\frac{P_{cond}}{P_{brems}} \cong 39 \frac{mc^2}{\sqrt{E_- E_+}}$$

which has the value 80 for the case of $E_+ = 280$ kev and $E_- = 210$ kev as was found above.

This very large ratio of conduction loss to bremsstrahlung may be quite spurious. It is very unrealistic to assume a smooth parabolic variation of temperature with radius when the wall is so close. This is particularly true in the case of a plasma consisting of very hot particles. The tendency for these particles upon striking a wall is to plow into the interior with a small probability of return to the exterior with reduced energy. Recent results on deuterium sputtering,[10] for example, show that the sputtering rate falls rapidly with increasing energy. This implies that there will not be a large number of cooler particles near the wall and that the plasma temperature stays fairly uniform until very close to the wall (if a "temperature" can be defined in that region at all!).

Perhaps the most important argument of all is to consider what effect the most pessimistic assumptions about heat conduction have on the temperature in DCX. Consider the following set of assumptions. Every ion within a Larmor radius of the wall transfers some fraction of its energy E_+ to the wall per collision. Now the number of collisions per unit volume is

$$N_c \cong \frac{n_+^2 \sigma_c}{2} v,$$

and hence the total number of collisions per second within a Larmor radius of the wall is

$$N = \frac{n_+^2 \sigma_c}{2} v r_o S$$

where r_o is the Larmor radius and S the wall surface area. If the fraction of energy transferred is denoted by E_+/f where f is greater than or equal to unity, the total energy transfer to the walls is

$$E_{out} = \frac{n_+^2}{2} \sigma_c v r_o S \frac{E_+}{f}$$

10. O. C. Yonts, private communication.

In steady state, this must equal the energy input to the gas, which is $I_+(E_o - E_+)$. Hence

$$I_+(E_o - E_+) = \frac{n_+^2}{2} \sigma_c v r_o S \frac{E_+}{f}$$

On the other hand, by particle conservation

$$\frac{I_+}{V} = \frac{n_+^2}{2} \sigma_c v P$$

Hence

$$E_o - E_+ = \frac{r_o S}{V} \frac{E_+}{Pf}$$

or

$$E_+ = \frac{E_o}{1 + \frac{r_o S}{V} \frac{1}{Pf}}$$

Now the mirror escape probability is 0.3 for a mirror ratio of 2. In addition, $r_o S/V$ is of the order of unity in DCX for the input ions. Finally, choose f to have its most unfavorable value, unity. In this case

$$E_+ \cong \frac{E_o}{4}$$

$$= 75 \text{ kev}$$

This result, although still constituting a plasma temperature of great interest, is undoubtedly extremely pessimistic. For one thing, the particle density, and hence the heat transfer rate ($\sim n^2$), should be reduced near the walls. A second point is that as the plasma temperature drops, the ratio $r_o S/V$ becomes smaller than unity since the Larmor radius shrinks. Finally, it is unrealistic to assume loss of the entire energy of the particle to the wall upon collision. These considerations make it seem more likely that the effect of conduction to the walls is to reduce the temperature to something like $E_o/2$ or so. A more accurate value can be obtained by repeating the self-consistent temperature calculations of Section II, using the heat conduction formula of Eq. (4.6) in place of the bremsstrahlung losses. This is now being done. It is clear, however, by the qualitative considerations above, that the result will be in excess of $E_o/4$. In addition, this calculation will still have the uncertainties regarding the value of n near the wall and the temperature profile.

Perhaps the most striking feature of these results is the fact that the most pessimistic assumptions still result in temperatures which are of extreme interest to Project Sherwood. This is a direct result of working down in energy.

Particle Diffusion to the Walls

Ions and electrons will reach the walls by means of coulomb collisions which deflect their orbits through appreciable angles. Since this is the very same mechanism which produces a leakage through the mirrors, it seems clear that this loss rate must be of the same order as mirror losses. This is particularly so in one case, since for a mirror ratio of 2 the escape probability P is so high (= 0.3). Hence, diffusion to the walls should not decrease the plasma densities by any appreciable amount over the value calculated by simple mirror loss.

Effect of Cold Electrons

One sure way to depress the temperature of the plasma is to have large numbers of cold electrons around together with a continuous influx and outgo of cold electrons. The cross section for energy transfer to cold electrons can be very much larger than for all other processes. On the other hand, if the total influx of cold electrons is of the order of magnitude of the hot ion particle current, this does not represent a serious energy drain from the system. For example, if one cold electron enters per hot ion, then even if it stays in the system long enough to come to equilibrium with the ions, the resultant energy per particle is still $E_o/2$, which is 150 kev. More likely, since cold particles are preferentially lost through the mirrors, it only drains part of this energy before departing.

Where will these electrons come from? One possible source is the arc itself. In this case the electrons are not very cold ($\cong$ 100 volts or greater) and do not play a very dominant role in the ion's energy degradation. In addition, these electrons are localized in the region of the arc. In this sense, they play the role of a rather warm "wall" and should have a much smaller effect on the temperature than the actual walls themselves. There will be little tendency for the electrons to drift far into the plasma owing to their small Larmor radius ($\cong$ .05 mm) and preferential loss through the mirrors.

A second source of cold electrons is those resulting from the ionization of the D_2^+. Thus, $D_2^+ \longrightarrow D^+ + D^+ + e$. It is clear that this source represents no more than one electron for every two deuterons trapped. Furthermore, these electrons are also localized in the immediate vicinity of the arc.

A third source is the electrons resulting from ionization of the neutral particles at the critical current point. These could constitute about 20 electrons per hot ion injected (since $\sigma_i \cong 20\ \sigma_{cx}$ at 250 kev). However, above this current this ratio would fall off. Even a ratio of 20 to 1 would not be completely disastrous, since at equilibrium $E_+ = E_o/20 = 15$ kev. However, considerations of preferential mirror loss, failure to come to equilibrium, and higher injection currents make this less of a worry.

A fourth source of electrons is those resulting from wall bombardment. Since the number of ions striking the wall are less than or equal to the input hot ion rate in steady state and since the secondary electron production is of the order of unity,[11] this does not represent a large influx of electrons. Besides the electrons again are localized near the walls.

Another possible source of electrons is those which ride in on the input beam. There seems to be no quantitative data on this score, although it is hard to see how this rate could exceed the ion rate.

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11. H. S. W. Massey and E. H. S. Burhop, <u>Electronic and Ionic Impact Phenomena</u>, p. 549, Oxford (1952).

In summary, large numbers of cold electrons could severely decrease the temperature in DCX. It seems difficult to see how such large inputs could be obtained unless one deliberately set out to produce them. Nevertheless, the possibility exists. In this case, one possible countermove would be to inject large numbers of hot electrons into the plasma so as to make the plasma negative and thus inhibit the influx of other electrons. DCX is being built with this possibility in mind, and it will be possible to inject electrons through the mirrors if this should seem necessary.

Most of the considerations above will apply as well to cold ions which could result from neutral ionization and wall bombardment.

V. SUMMARY

It appears that if the input current of trapped deuterons to DCX exceeds a critical amount there will occur a "burnout" of most of the neutral particles in the system. This critical current is linearly dependent on the neutral pressure in the system and might be as high as 80 ma at a pressure of 10^{-6} mm or as small as a factor of 10^{3} or greater below this value. The large variation in these predictions is due to the unknown action of the arc as an ion pump and to uncertainties in the magnitude of the neutral influx to the plasma.

If appreciable burnout should occur, and if bremsstrahlung is the chief mechanism of energy loss from the system, the input ions will degrade only slightly in energy before becoming disorganized in direction and forming a plasma. For an input energy of 300 kev, the ions would form a plasma at 280 kev. At this energy, the plasma density with a 1 ma input current could be as high as 10^{13} per cc. Direct thermal conduction to the walls may represent a more serious energy drain from the system than does bremsstrahlung. Nevertheless, calculations of a highly pessimistic nature still yield ion temperatures no lower than 75 kev. More likely, this mechanism might drop the temperature to 150 kev or so.

Considerations of other possible perturbing mechanisms indicate that impurities should not seriously decrease the temperature, although the density will be decreased somewhat. The arc itself may have no worse an effect on the temperature in DCX than the walls. In any event, if the arc does retard the full development of the plasma temperature, it can be turned off and the breakup accomplished by the residual plasma. Cold electrons are also a possible source of temperature degradation. No large sources of cold electrons are present and those which have been considered are not very much larger in particle input than the input ion current. At worse, even if the energy is fully shared with these cold electrons, the resultant temperature would still be of the order of 15 kev or greater.

Of course, plasma instabilities could effectively stop the entire development of a hot plasma. These seem quite difficult to predict with any certainty at the present stage of the theory for a device such as DCX. In a sense, of course, this is one of the reasons for building DCX.

The very favorable temperature estimates which have been cited above are a direct result of working down in energy. It is hard to see how a device such as DCX can end up at an uninteresting temperature, from the Sherwood viewpoint. Of course, even if DCX should perform as well as hoped for, it will be very far from a device which yields more power than is put into it. Achievement of this goal will require a considerably larger device. These points will be discussed in a later report.