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TOKAMAK HEATING AND CURRENT MAINTENANCE WITH INTENSE PULSED ION--ETC(U)
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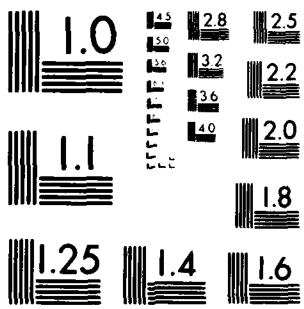

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This paper examines tokamak heating with intense pulsed ion beams. It finds that plasma can be heated to ignition or to Q (approximately) 1 and depending on the injection scheme, the current can be maintained or even generated by the beam.

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CONTENTS

TOKAMAK HEATING AND CURRENT MAINTENANCE WITH INTENSE PULSED ION BEAMS

I. Introduction

This paper examines the possibility of using intense pulsed ion beams to heat a tokamak plasma and maintain its current. In order to maintain the current, the beam must travel nearly parallel to the main toroidal field. There are several obstacles which must be overcome to realize this scheme. First, the ion beam must be produced; second, it must be injected into the toroidal chamber; and third, it must deposit its energy in the plasma. There is now a great deal of experience in producing intense pulsed ion beams, but the problems of injection and deposition are much more difficult.[1]

The deposition of ion beam energy in the center of a tokamak plasma during its steady state operation appears to be extremely difficult. However, the crucial fact is that there are several injection schemes which are viable just as the plasma is initialized. These involve injecting the ion beam into a partially formed plasma. Then when the beam is trapped, one forms the remaining plasma. This means either building up the density by fast gas puffing and/or building up the current in the conventional way after the beam is injected. For a beam energy of 1 megavolt, any gas puff must be fully ionized in much less than about 100 milliseconds in order to prevent beam degradation by charge exchange. This does not seen to be a significant obstacle. The key point then is that the beam can only be injected once and cannot be used as an external power source in the conventional sense. However, since the beam pulse duration is much less than tokamak pulse duration, it can only be used

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as energy injection, not power injection. If ignition is not achieved, the tokamak plasma will heat up and then decay. Then the usual sort of steady state operation is not possible; it is a 'transient tokamak'. However, as we will see, ignition does appear to be achievable with this scheme.

There are now several sources of intense pulsed ion beams and the technology is still advancing very rapidly. For instance reflex tetrodes produce roughly 1 Mev, 250 kA beams of 50-60 nsec duration with efficiency of about 55%. Magnetically insulated diodes can produce 2 Mev, 400 kA beams of 85 nsec duration with 80% efficiency.[2] The high efficiencies make these beams extremely attractive sources for heating plasmas. By contrast the efficiency of the 120 KV neutral beams to be used on TFTR is less than 20%.

We now discuss the injection schemes. The ion beam source is located either in a guide tube which connects up to the sidewall of the tokamak or else can be inside the tokamak itself, right near the liner, if the vacuum is sufficient for diode operation. If a guide tube is used, there is a longitudinal field in it which curves and merges with the main field of the tokamak. For all schemes, the guide tube is nearly parallel to the main magnetic field in the tokamak. (For a magnetically insulated diode, care must be taken since the field in the guide tube is perpendicular to the field in the diode.) If the vacuum requirements for the diode and tokamak are different, a foil transparent to the beam can be placed either where the guide tube connects to the tokamak or else anywhere in the guide tube. If it is inconvenient to insert such a guide tube through the magnetic field coils, another possibility is to place the diode right in the tokamak itself, most likely in the shadow of the limiter or outside the diverter. Of course, the vacuum requirements on the tokamak and diode might well be different. If this be the case, a separate container, or pouch could be constructed for the diode. This would be a metal chamber, except that just in front of the cathode would be a foil, so that the ion beam could exit the separate chamber and enter the tokamak. In front of the foil would be some sort of gate valve attached to the metal container. This valve would be open when the beam is fired, but would be closed between shots so that the foil could be replaced without exposing the tokamak vacuum system to any external environment. After the beam leaves the cathode (and/or foil), it is neutralized by dragging along an equal number of electrons along with it. There appear to be three injection schemes which we discuss separately.

For the first, the guide tube connects to the outside of the tokamak. In the tokamak itself a small volume plasma, surrounded by a vacuum, is localized in the center of the toroidal vacuum chamber. This plasma has nearly the full density and current of the ultimate plasma, but perhaps one quarter or one third of its volume. When the beam enters the tokamak chamber from the guide tube, it does not follow the field lines, but proceeds along its initial trajectory. It does this by setting up an electric field, giving just the appropriate E x B drift to keep the beam on its initial trajectory. The theory of this process has long been known[3] and experiments on moving laser produced plasma blobs into multiple field configurations have generally confirmed it. The essential criterion for cross field propagation is $(\omega_{pb}/\Omega_{cb})^2 \gg 1$ where ω_{pb} is the beam ion plasma frequency and Ω_{cb} is the beam ion cyclotron frequency. Recently it was realized that this same theory applies to the motion of a charge neutralized intense pulsed ion beam across a magnetic field in a vacuum.[1] Preliminary experiments with intense pulsed ion beams have confirmed this. Wessel et al[4] have shown that even if $\omega^2_{pi}/\Omega^2_{ci}$ is as small as 3, the beam propagates four larmor radii across a 6 KG field with an efficiency which varies from shot to shot between 30% to 70%. Another preliminary experiment by Kapetanakos and Golden[5] has demonstrated that an ion beam with V = 500 KeV and current $I = 5 \times 10^2$ Amps ($\omega^2_{pi}/\Omega^2_{ci} = 30$) propagates across a 10 KG field with more than 50% efficiency. However, in this latter experiment it was not clear whether the polarization drift or other space charge effects are responsible for the transmission.

A crucial feature of the ion beam tokamak heating scheme in Ref. 1 was reliance on this cross field E x B drift to get the beam to the edge of the tokamak plasma. The problem in Ref. 1 was, however, that the plasma short circuits the polarization electric field. Then getting the beam across the plasma required an enormously intense beam. However, if the plasma is just a small volume target plasma in the center of the toroidal vacuum chamber, this plasma can short circuit the polarization electric field, and the beam will be trapped right where we want it. Since the beam is injected nearly tangential to the main tokamak field, the beam will circulate around the torus near the edge of this target plasma. Then gas is puffed in to form a full volume plasma with the beam trapped near the center.

Since the density is large, the resistivity is classical and flux is frozen in on the time scale of beam injection. Thus the beam does not create the current. The current must be externally generated either before the beam is injected or partly before and partly after. However once the current is at its final value, the transformer is turned off. The current in this full volume plasma is now carried by the beam. Thus while an external source is needed to generate the current, once the beam is trapped in the plasma, the beam carries the current and the external current drive transformer is turned off. This represents a very considerable savings. For instance in PLT, the Ohmic heating transformer puts out about 0.5 Megawatts for about half a second in its steady state phase or about 250 KJ of energy. This external power from the Ohmic heating is no longer required in our scheme, because it is taken over by the beam. Thus an ion beam heated tokamak requires no Ohmic heating after the plasma has been initialized, and in this way represents a simplification of tokamak design.

The second injection scheme invokes the decay of the return current. Imagine that the toroidal chamber is filled with a low density ($n_p \gtrsim n_b$), low temperature plasma which carries no current. The guide tube now connects to the top most part of the tokamak and the beam is injected nearly tangential to the toroidal magnetic field. The beam enters both charge and current neutralized, so it feels only the effect of the external fields, namely the toroidal magnetic field and also the vertical field if one is present. Hence the beam drifts vertically downward in the torus.

Since the background plasma density is very low, the electron return current velocity is quite high, so anomalous resistivity may be present. As the beam drifts downward, the return current rapidly decays away. The idea then is for the return current to decay sufficiently that when the beam passes through the center of the toroidal chamber, enough current is generated to confine the beam and stop its downward drift. Ideally, once the beam is trapped, the return current will continue to decay until the full tokamak current is built up. Our calculations show this may be possible in some tokamaks and some injection configurations. If on the other hand, the return current decays sufficiently to confine the beam, but not enough to generate the desired current, it may be that some external current drive could be used once the beam is trapped. However, even if an external source is needed to complete the current generation initially, it is still not needed to maintain the current thereafter.

This injection scheme seems to be the one invoked by Mohri et al,[6,7] and Benford et al[8] for the analogous problem of injection of an electron beam into a torus. In either case, as the beam drifts down, it slowly digs a hole for itself; when the beam has drifted to the center of the toroidal chamber, the hole is deep enough to trap the beam.

The third injection scheme involves injection into a full volume, full density plasma which carries no current. The beam is injected at the top of the tokamak, like the previous scheme. However since the plasma density is high, the resistance is classical and no plasma current is generated. Thus the beam drifts vertically downward. As the beam passes through the center, a stabilizing vertical field is pulsed on so that the beam orbits are now trapped. This is rather analogous to trapping a plasma or beam in a mirror by gating one of the mirror coils. Once the beam is trapped, the current is built up in the tokamak in the conventional way. However once the desired current is reached, the transformer is turned off and the current is maintained by the beam.

All three of these injection schemes have certain advantages. In the first, the plasma initially never contacts the wall so probably fewer impurities will enter. Also if the vacuum outside the target plasma is sufficiently good, the diode can be placed right in the tokamak and there will be no need for foils or guide tubes. The second injection scheme has the great advantage that it generates all or part of the tokamak current. Thus at worst the transformer volt seconds needed to generate the current is reduced. At best, the transformer can be eliminated all together. The third injection scheme has the advantage that the initial plasma is fully ionized at full density, so fast gas puffing is not required.

For any injection scheme, it is obviously desirable that the beam fit just around the torus. That is the beam pulse time should be $2\pi R/V_b$. For the configurations we consider this turns out to be 200 to 300 nano-seconds. This is somewhat longer than most ion diode pulse times.

However, a) there is reason to believe that magnetically insulated diodes can be developed with microsecond pulses, b) one can use more than 1 injection port, and c) one can use a trailing voltage pulse on the diode so the beam disperses spatially either in the guide tube or in the tokamak. For instance a 280 nsec beam can be composed of four 70 nsec beams injected 90^{o} apart on the major radius. Thus the required pulse times do not appear to be a significant obstacle to the scheme we propose.

Once the beam is in the system, the next problem is its coupling to the plasma. Clearly one wants the slowing down time of the beam to be comparable to or less than the energy containment time of the plasma. We assume classical slowing down of the beam. However to realistically model the plasma heating, one needs good models for the energy containment time. A large variety of tokamak experiments indicate that the ion losses are neo-classical, and we assume this also. The electron losses are anomalous however, and there seems to be no generally accepted theory on how they scale. Fortunately, many tokamak experiments seem to indicate that the electron energy confinement time τ_e scales as the density times the radius squared.[9] We assume this parametric dependence of τ_e in our calculations. We emphasize, however, that our results are only valid if this scaling law still holds in the unchartered regions of parameter space which we examine.

Our calculations do indeed show that a tokamak energized with an intense pulsed ion beam can achieve breakeven and ignition. In fact the difference bewteen what is required for breakeven and what is required for ignition is generally only about a factor of two in the relevant parameters (i.e. beam energy, toroidal field, etc.). Our calculations show several specific advantages of intense pulsed ion beams over many other heating schemes in addition to the high efficiency of beam production. First of all in approaching breakeven, there are beam-plasma reactions as well as plasma-plasma reactions. This is similar to the 'wet wood burner' approach for neutral beam heated plasmas.[10] Secondly, while most of the beam energy is deposited in electrons, its last bit of energy is deposited directly in the ions. This leads to a quick boost in ion temperature, which in some cases can lead directly to ignition. Thirdly, the beam current can be greater than the total current. This leads not only to greater heating by the beam, but also to Ohmic heating by the return current. Thus really tremendous amounts of power can be deposited in the plasma.

In Section II we derive the equations for the self consistent beam and plasma response and show that they conserve total energy. In Section III we present calculations of beam heating of a variety of tokamaks ranging from small research tokamaks to large reactors. Section IV reviews the problem of equilibrium and stability of intense pulsed beams in plasmas. Section V discusses injection into a low density full volume plasma, Section VI discusses injection into a small volume full density plasma, and Section VII discusses trapping with a pulsed stabilizing field in a full density, full volume plasma which carries no current. Finally Section VIII discusses small scale experiments that can be done to test some of the concepts developed in this paper. In addition to experiments on beam injection itself, there are also experiments one can do to study high beta tokamaks.

II. The Equations for Beam and Plasma

In this section we write out the equations for the self consistent response of the beam, plasma and poloidal (θ) magnetic field, assuming that the beam has been injected into the plasma. The zero dimensional equations for the (z component of the) beam velocity V_z, electron temperature T_e and ion temperature T_i are

$$n_b M_b \frac{dV_b}{dt} = - n_b M_b (V_b - V_e) \nu_b + n_b eE - n_b M_b V_b \nu_{bi} \tag{1}$$

$$\frac{3}{2} n_e \frac{dT_e}{dt} = n_b M_b \nu_b (V_b - V_e) V_b - E\, n_e e V_e - n_e \nu_{eq} (T_e - T_i) - \frac{3}{2} \frac{n_e T_e}{\tau_e} + P_\alpha - P_r \tag{2}$$

$$\frac{3}{2} n_i \frac{\partial T_i}{\partial t} = n_e \nu_{eq} (T_e - T_i) + n_b M_b \nu_{bi} V_b^2 - \frac{3}{2} \frac{n_i T_i}{\tau_i} \tag{3}$$

where n_b, n_e and n_i are beam, electron, and ion number density. Since n_e and n_i are at the center of the discharge, they are to be regarded as maximum, rather than average densities. Also, V_e is the electron streaming velocity in the z direction. The quantities τ_e and τ_i are the electron and ion energy confinement times. The electron confinement time is taken to have the generally agreed upon scaling[9]

$$\tau_e = 1.5 \times 10^{-18} n_e r_o^2 \tag{4}$$

where r_o is the radius of the plasma current channel. The numerical factor is taken to agree with recent PLT experiments.[11] The ion confinement time is taken to be given by neoclassical scaling

$$\tau_i = r_o^2 / 2K_{ci} \tag{5}$$

where

$$K_{ci} = \frac{0.68}{1 + 0.36\nu_i^*} \cdot \frac{Z_{ef} n \rho_{i\theta}^2}{\tau_i} \left(\frac{r}{R}\right)^{1/2} + \frac{Z_{ef} \rho_i n}{\tau_i} \left(1 + 1.6 \frac{r^2 B^2}{R^2 B_\theta^2}\right) \tag{6}$$

as given by Rutherford and Düchs.[12] Here

$$\tau_i(\text{sec}) = 2.09 \times 10^7 \; T_i^{3/2}(\text{ev}) \; \mu^{1/2}/n\lambda \tag{7}$$

and

$$\nu_i^* = Z_{ef} \; R^{3/2} \; B/\tau_i r^{1/2} \; B_\theta (T_i(\text{ergs})/M)^{1/2} \tag{8}$$

where all units are Gaussian, but the units for T are specified. μ is the ratio of ion to proton mass and λ is the Coulomb logrythm. The collision frequencies are the beam electron slowing down, and electron-ion equilibration and beam-ion slowing down collision frequencies, given by

$$\nu_b = \begin{cases} 1.7 \times 10^{-4} \; n_e \; \lambda \; \mu_b^{1/2} / E_b^{3/2} \; (\text{ev}) \\ 1.6 \times 10^{-9} \; n_e \; \lambda / \mu_b T_e^{3/2} (\text{ev}), \end{cases} \tag{9}$$

whichever is smaller. Above E_b is the beam energy in ev. Also

$$\nu_{bi} = 9 \times 10^{-8} \; Z_{ef} n_e \; \lambda \left(1 + \mu_b/\mu\right) \Big/ \mu_b^{1/2} \; E_b^{3/2}(\text{ev}) \tag{10}$$

$$\nu_{eq} = 3 \times 10^{-9} \; Z_{ef} n_e \; \lambda / \mu T_e^{3/2} \; (\text{ev}) \tag{11}$$

The beam ion heating is small compared to the beam electron heating until the beam loses most of its energy. However the last bit of beam energy is deposited into the ions. The electric field is gotten from the z component of the electron momentum equation

$$E = -\frac{m\nu}{e} V_e - \frac{n_b M \nu_b}{n_e} (V_e - V_b) \tag{12}$$

where ν is electron-ion momentum exchange collision frequency. The quantities P_α and P_R are respectively the α particle heating of electrons (α particle energy is assumed deposited directly in the electrons) and radiation loss due to free bremstrahlung from the center of the plasma. Generally this latter term is not important, but it can be important for high Z_{ef} and/or high density. We use

$$P_r = 1.6 \times 10^{-32} Z_{ef} n_e^2 T_e^{1/2}(\text{ev}) \text{ Watts/cm}^3. \tag{13}$$

The next thing to consider is the equation for the poloidal magnetic field. This is given by

$$\frac{\partial B_\theta}{\partial t} = - c \nabla \times E\Big|_\theta = -c \frac{\partial E_z}{\partial r} . \tag{14}$$

Equation (14) above is inconvenient to work with because it has a strong r dependence. In this paper we work only with quantities independent of r. Therefore some sort of spatial integral of Eq. (14) must be taken. We take a spatial integral which conserves total energy. Taking the dot product of Eq. (14) with $B_\theta/4\pi$, we find

$$\frac{\partial}{\partial t} \frac{B_\theta^2}{8\pi} = - \frac{c}{4\pi} B_\theta \cdot \nabla \times E = - \nabla \frac{cE \times B_\theta i_\theta}{4\pi} - \underline{E} \cdot \underline{J} \tag{15}$$

The first term on the right hand side of Eq. (15) is the divergence of the electromagnetic energy flux; the second term denotes an energy exchange between electromagnetic fields and the fluid. The quantity J is the total current

$$J = n_b eV_b - n_e eV_e. \tag{16}$$

Now let us assume that current density is uniform from $r = 0$ to $r = r_o$ and is zero for $r_o < r < a$ where a is the liner radius. Then integrating both sides of Eq. (15) from 0 to a, we find that an equation for B_θ is

$$\frac{d}{dt}\left(\frac{1}{2} + 2\ell n\left(\frac{a}{r_o}\right)\right)\frac{B_\theta^2}{8\pi} = - E(n_b eV_b - n_e eV_e) - \left.\frac{crE_z B_\theta}{2}\right|_{r = a}$$

where B_θ is the poloidal field at $r = r_o$. The $\left.\frac{crE_z B_\theta}{2}\right|_{r = a}$ term on the right hand side is the power input and current drive from the external circuit. Here we assume that once the beam-plasma system in initialized, there is no power input or current drive from anything except the beam, so that this term is taken equal to zero. Thus the equation for B_θ is

$$\frac{d}{dt}\left(\frac{1}{2} + 2\ell n\left(\frac{a}{\bar{r}_o}\right)\right)\frac{B_\theta^2}{8\pi} = - E(n_b eV_b - n_e eV_e). \tag{17}$$

The one remaining quantity to solve for is the electron drift velocity V_e, This follows from Maxwell's equation $\underline{\nabla} \times \underline{B} = \frac{4\pi \underline{J}}{c}$, or

$$V_e = \frac{-cB_\theta}{2\pi r_o n_e} + \frac{n_b}{n_e} V_b. \tag{18}$$

Equations (1-3), (12), (17) and (18) form a set of equations for the time dependence of the beam- plasma-poloidal field system. It is a simple matter to show that the system conserves energy, or

$$\frac{d}{dt}\mathcal{E} = -\frac{3}{2}\left(\frac{n_e T_e}{\tau_e} + \frac{n_i T_i}{\tau_i}\right) + P_\alpha - P_r \tag{19}$$

where $\mathcal{E}$ is the total thermal energy of the electrons plus ions plus the poloidal field energy plus the beam energy. We emphasize once more that in this paper, we assume that after the beam is shot in, there is no external power or current drive input either from the external circuit or from any other source. Thus, unless ignition is attained, the plasma will at first heat up and then decay, or it will be transient in nature.

III. Calculations of the Dynamics of Tokamak Plasmas

In this section we solve Eqs. (1-3), (12), (17), and (18) numerically for several tokamaks covering a wide range from small research tokamaks to large reactors. In all cases we take $\frac{r_o B}{R B_z} = q \geqslant 1$. We first consider Versator, a small research tokamak with $r_o = 7.5$ cm, a = 15 cm, R = 45 cm and B = 10 KG. A beam with voltage and current of 3×10^5 V and 6×10^4 A is shot in and the total plasma current is taken as equal to the 60kA beam current. Assuming the pulse duration is the time for a beam ion to go around the torus, the beam time and energy are $\tau = 3 \times 10^{-7}$ sec and $E = 6 \times 10^3$ Joules. At t = 0, the electron temperature is 100 ev and the ion temperature is 50 ev. Fig. 1a shows the time dependence of T_e, T_i, I and $V_b/V_b(t = 0)$ (I is the total current) for a proton beam shot into a hydrogen plasma with density 2×10^{13}. Even with such a modest energy beam, there is a large amount of electron and ion heating. Figure 1b shows the dependence of maximum electron temperature, maximum ion temperature and lifetime on initial plasma density. The advantage of higher density is apparent.

Next we have performed a series of calculations for PLT, with $r_o = 20$, a = 40, R = 140 cm. We consider two cases each a proton beam into a hydrogen plasma. The first is a beam V = 2.1 Mev, I = 500 Amps (440 KJ) and a magnetic field of 40 KG, and the second is a beam of 5.24 Mev, I = 690 KA (1 Meg J) and a magnetic field of 55 KG. In each case, the initial beam current is the total current and $T_e(0) = 1$ Kev and $T_i(0) = 500$ eV. In Figs. 2a and 3a are shown the time dependence of total current, electron and ion temperature and relative beam velocity as a function of time for the 2 beams for plasma densities of 10^{14} and 2×10^{14}. Notice that the current decay time is much longer than beam decay time. The reason is that as the plasma heats up, the resistivity decreases so that the current remains frozen in for long times. It is interesting to note that even though the beam transmits forward momentum to the electrons they end up going backwards. Of course, the reason is the inductance of the system. When the electrons try to accelerate forward, an inductive electric builds up and drives them back.

Since all of the energy is deposited at the initiation of the discharge, the plasma heats up and then decays. Thus, if ignition is not achieved, the plasma is not steady state, but is transient in nature. Notice that somewhat after the maximum temperature is reached, there is a long slow decay, followed by an abrupt termination at the end. The reason for the abrupt termination is that when the temperature decreases sufficiently, three things happen which interact to cause a sudden finish. First, the ion energy collision frequency increases with decreasing temperature raising the neoclassical ion thermal conduction; second the resistivity increases so the current decreases more rapidly, lowering Ohmic heating; and thirdly, lowering the current B_θ, further increasing the ion neoclassical thermal conduction.

In Figures 2b and 3b are shown the maximum electron and ion temperature and discharge lifetime for the two beams as a function of density. Also shown are the Q's for a tritium beam shot into a DT plasma. Here Q is defined as the fusion energy, from both beam plasma and plasma-plasma reactions divided by the initial beam energy plus the initial poloidal field energy plus the initial plasma energy. The α particle energy is assumed to be deposited directly in the electrons, and the reaction rates are those given in the NRL plasma formulary.[13] Notice that temperatures maximize at a particular density. This results from the competition between the electron energy confinement time increasing with density, and the larger number of particles sharing the beam energy.

In the remainder of this section, we examine only thermonuclear type plasmas. Our first study is for Alcator C, with r = 10, a = 20, R - 60 cm. We examine whether $Q \leq 1$ can be achieved without pushing either the beam or the tokamak particularly hard. We examine plasma densities between 10^{14} and 10^{15} and magnetic fields between 60 KG < B < 90 KG. These seem to be rather routine operating parameters for Alcator C. The total current is chosen to insure that q = 1, that is $I = 6 \times 10^5$ (B/75 KG) Amps and the voltage is 2.1 Mev. As we will see, one thing which helps to increase Q is to use a beam current larger than the total current, so that there is some current cancellation initially.

Our first calculation attempted to optimize Q with respect to beam and plasma composition. The result was that Q optimizes for a tritium beam shot into a plasma which is one quarter tritium and three quarters deuterium. Figure 4 is a plot of Q as a function of density for three different amounts of current cancellation. In the lower curve, the initial beam current is the total current; in the middle curve, the initial beam current is 1.5 times the total current; and in the top curve it is double. For the top curve, where B = 75 KG, the initial beam energy is 780 KJ. It turns out that Q depends very weakly on B, but depends strongly on plasma density and net beam current.

A plasma having $Q \lesssim 1$ is not of interest as a pure fusion reactor, but it might be of interest as a fission fusion hybrid.[14] It may be that something like Alcator C could be used to study this process on a small scale. It is particularly interesting that in this case, neither the beam or the tokamak is being pushed particularly hard, so there is room to scale up both if for some reason our calculations are overly optimistic.

We now turn to an examination of thermonuclear burn, also in Alcator C. Here we take $n = 10^{15}$ and consider a 5 Mev, 1.5 Meg Amp beam with no current cancellation (beam energy of 1.5 MJ) and a magnetic field of 160 KG. The time dependence of electron temperature, ion temperature, relative beam velocity is shown in Fig. 5. Our calculations also show ignition is also achievable if $Z_{ef} = 3$, but not if $Z_{ef} = 5$. Note that before the beam slows down completely, it deposits the last bit of its energy into the ions, and this additional ion heating is what leads directly to ignition. The high magnetic field required for ignition is of course a disadvantage. The next thing is to see whether by pushing harder on the beam, we can relax the conditions on the tokamak. We consider $n = 10^{15}$, $V = 2.1 \times 10^{6}$, but now a net current of I = 10 B Amps (so q = 1) and vary the magnetic field but also vary the beam current. Fig. 6 shows the region in parameter space where ignition occurs. If the initial beam current is double the total current, a burning plasma can be produced with fields as small as 100 KG. Thus in a tokamak like Alcator C, it appears as if ignition can be produced over a wide range of beam and plasma parameters.

A final series of calculations concerns large volume, low density reactors. We examine a T beam injected into a DT plasma. The size of the system is roughly like TFTR, r = 50 cm, a = 100 cm, R = 250 cm, B = 50 KG and $n = 2 \times 10^{14}$ or 4×10^{14}. The beam voltage is taken as 5 Mev and the total plasma current is 2.5 MAmps. If the beam current is just equal to the plasma current, it does not appear possible to reach ignition. However, if the beam current is partially canceled by plasma current ignition is achievable. For instance, we find that a beam current of about 7.5 MAmps is sufficient to reach ignition for either density. We note also, that the initial beam energy density in this case, is about one fifth of its value for the corresponding case of ignition in Alcator C at a field of 100 KG.

IV. Review of Equilibrium and Stability of Intense Beams in Plasmas

This section reviews both theory and experiment concerning equilibrium and stability of toroidal plasmas containing intense beams. The equilibrium for a charge neutralized beam in a plasma carrying no net current has been worked out by Ott and Sudan.[15] They assume the beam distribution function is proportional to $\delta(H-\bar{H})\delta(P_\phi - \bar{P}_\phi)$ where H is the Hamiltonian, P_ϕ is the canonical angular momentum in the toroidal direction, and then they calculate the self consistent current profile. First they calculate the equilibrium for a straight beam, and find that the current density is nearly uniform if $I \lesssim \frac{1}{3} I_A$, as it is in all cases we have studied. Here, I is the current, and I_A is the Alfven-Lawson current, which is about $3 \times 10^7 \mu_b \, {}^{V_b}\!/_c$ Amps. If this straight equilibrium is bent into a high aspect ratio torus, the resulting ring feels an additional outward force from the centrifugal force and also from the self forces of the beam.

Ott and Sudan consider two different configurations. The first is where the ring is confined by a vertical field B_{zo}. A single particle has larmor radius R_o. If the minor radius of the ring is r_o, they find that for $I/I_A \ll 1$,

$$R = R_o \left\{ 1 + \frac{I}{I_A} \left[\ell n \frac{8R}{r_o} - \frac{5}{4} + \frac{5}{12} \frac{I}{I_A} \right] \right\} \tag{20}$$

For instance if ${}^{I}\!/_{I_A} = 0.1$, the major radius is about 30% larger than the single particle larmor radius. Thus while the self fields of the beam exert a significant outward force; equilibrium still does exist and is not very different from what one expects intuitively. The other configuration they consider has the beam surrounded by a perfectly conducting toroidal wall. Here image currents in the wall can balance the outward centrifugal force even in the absence of a vertical field. To demonstrate this consider a line current inside a conducting cylinder of radius a. If a line current I is displaced Δ from the center of cylinder, the image current provide a restoring force per unit length of $2I^2\Delta/(a^2 - \Delta^2)c^2$. In addition there is the force from the vertical field. Balancing both these forces against the centrifugal force, we find the outward displacement is

$$\frac{\Delta}{a} = \left(1 + \left(\frac{\omega_{pi}^2 r_o^2 R^1}{4c^2 a}\right)^2\right)^{1/2} - \frac{1}{4}\frac{\omega_{pi}^2 r_o^2 R^1}{ac^2} \qquad (21)$$

where $R^1 = {}^{RR_o}\!/_{R_o} - R$, R being the major radius of the torus and R_o the larmor radius in the vertical field. As in the case when the ring is confined only by a vertical field, the self fields give rise to an additional outward field. The total outward displacement is calculated self consistently correct to lowest order in ${}^{r_o}\!/R$ in Ref. 15. Toroidal equilibria have also been calculated if the background plasma carries current and has non zero pressure.[16] To summarize, Vlasov equilibria exist for the sorts of plasmas we have considered in the previous two sections. These $I \lesssim \frac{1}{3} I_A$ so the equilibria are not greatly distorted by the beam self forces.

We now turn to the question of the stability of the beam plasma system.[17-25] Of course this is an extremely complex matter; the MHD stability of the toroidal plasma alone generally requires an involved numerical analysis. This paper does little more than scratch the surface. One useful result derived by Lovelace[18] for a large aspect ratio torus is that if the tokamak plasma has no equilibrium current or pressure, the MHD stability of the beam plasma system follows from the MHD stability of the plasma itself if one makes the replacement $p \rightarrow \frac{1}{2} n_b M V_b^2$. Thus one has the Kruskal-Shafranov stability condition. Also one has a simple analog to the Suydam stability condition which is

$$\frac{1}{4}\frac{d\,\ell n q}{d\,\ell n r} + r\frac{d}{dr}\ \beta_t - \frac{r^2}{R^2q^2}\,\beta_t > 0 \tag{22}$$

where $\beta_t = 4\pi n_b M V_b^2/B_z^2$ and $q = \frac{rB_z(r)}{RB_\theta(r)}$. Lovelace also finds a sufficient stability condition for kink modes with $m = 1,\ 0 < n^2 << (R/a)^2$ to be

$$\frac{d}{dr}\,\beta_t + \frac{2r}{R^2}\,(1 - 1/q^2) > 0 \tag{23}$$

Another useful result, derived by Finn,[22] also for large aspect ratio tori, is that the beam plasma system is stable if $q > 1$, except that there may be bands of instability around $\omega_{ci} \sim nV_b/R$. However for an ion beam in a tokamak, very large n's are required for resonance, that is $n \sim 50$. These n's are so large that it is unlikely that the theory used by Finn is valid.[26] Nevertheless, both his theory and Lovelace's point to the general result that the beam plasma system will probably be MHD stable to kink modes if $q \geqslant 1$.

Another possible MHD instability is the ballooning mode. If Lovelace's result, $p \to 1/2\, n_b M V_b^2$ holds in a torus, as well as a straight cylinder, ballooning modes can be driven by the beam energy density, just as they are driven by pressure in ideal MHD. This could be a significant problem because the beam energies we deal with are not that small compared to the magnetic energy. For instance in the example of Versator in the last section, the local β_t is about 15% and the average β_t is about 4% if B = 13 KG. For Alcator C with V_b = 5 MeV, I = 1.5 MA, the local β_t is about 10% while the average β is about 2.5%. In this respect it is useful to know that conventional tokamak plasma equilibria, which are stable to low m number ballooning modes, can be found[27] and which have an average β_t of 12%. Thus it seems that the beam plasma systems which we have considered may well be stable to ballooning modes. Also stable tokamak plasmas with average β of 2.5% have been produced experimentally.

Let us now discuss briefly a relevant experiment.[28] Intense electron beams have been produced in a controlled manner in Ormak by lowering the density to produce runaway discharges. The energy of the beam electron is several MeV, the total current is about 10^5 Amps, and the confined beam energy is more than 2 KJ. These beams are stably confined in Ormak for 35 msec or longer. The actual decay time is about 100 msec, but there are a series of steps in the current decrease, which shortens the time to 35 msec. These steps presumably result from some instability. Thus in Ormak, an intense relativistic electron beam can be confined for times relevant to the scheme considered here.

V. Beam Injection Into a Full Volume Low Density Plasma

The first injection scheme which we discuss is injection into a full volume low density ($n_p \gtrsim n_b$) plasma. Initially the plasma carries no current and has low temperature (in our calculations we assume initial temperatures of $T_e = 10$ ev, $T_i = 5$ ev). The beam is injected nearly parallel to the main toroidal field through an opening at the top or bottom of the torus. Because of the presence of the plasma, the beam is charge and current neutralized so the ions feel no self forces, but only the forces from the externally applied toroidal and vertical field. Hence each ion orbit goes principally around the torus, but has a small vertical drift

$$V_D = V_b \left(\frac{B_{zo}}{B} + \frac{V_b}{R_o \Omega} \right) \tag{24}$$

where R_o is the major radius at injection and Ω is the ion cyclotron frequency in the toroidal field. Let us assume without loss of generality that if $B_{zo} = 0$, the drift is downward.

To prevent the beam from just drifting in the top and out the bottom, the return current must decay sufficiently just as the beam passes through the center of the toroidal chamber, or on a time of order

$$\tau = \frac{a}{V_D} \; . \tag{25}$$

This is the reason for a low initial density; if the density is high, the return current drift velocity will be small and the resistivity will be classical.

Let us now calculate what current is necessary to stop the beam. Assuming the poloidal field has the form

$$B_\theta = 2B_{\theta o} \frac{\left(\frac{(R - R_o)^2 + Z^2}{r_o^2}\right)^{1/2}}{1 + \frac{(R - R_o)^2 + Z^2}{r_o^2}} \quad , \tag{26}$$

(the factor of 2 is so that the maximum poloidal field is $B_{\theta o}$), one can show either by calculating the drift orbits, or by utilizing the constancy of canonical angular momentum in the toroidal direction, that the ion orbits are confined if

$$\frac{\Omega_{\theta o} R_o}{V + \Omega_{zo} R} > 1, \tag{27}$$

where $\Omega_{\theta o}$ and Ω_{zo} are the ion cyclotron frequencies in the fields $B_{\theta o}$ and B_{zo} respectively. For versator, with a 300 KeV proton beam with the drift velocity 80% canceled out by B_{zo}, we find that the condition for closed ion orbits is $B_{\theta o} > 300$ G. For Alcator C, a 2 Mev Tritium beam with the drift velocity 80% canceled by a vertical field, requires a $B_{\theta o}$ of about 900 G. Thus a condition for beam trapping is that the fields $B_{\theta o}$ reach at least these appropriate values.

The decay time of the return current is determined in part by the background plasma density. The drift velocity is determined by the vertical field B_{zo}. These two quantities can then be adjusted to provide optimum conditions for beam trapping. Since the vertical drift velocity depends on vertical field only through the combination $\left(B_{zo}/B + V_b/R_o\Omega\right)$; and since, as we saw in the last section, the self fields of the beam provide an outward force; it may be beneficial to have $B_{zo}/B < -V_b/R_o\Omega$ and have the ion beam drift upward. Then when it stops, it will be closer to those equilibria discussed in the previous section.

We now discuss the model for the decay of the return current. The idea is that because the electron drift velocity is so large, some plasma instability is excited which gives rise to a rapid decay of this return current. Here we consider only the ion acoustic instability. Not only is this current driven instability the simplest, it also appears to be the only one which can act on a time scale sufficiently fast to stop the beam.

The current driven ion acoustic instability has been studied in many different laboratory experiments, and also in many different particle in cell simulations. The qualitative features of many of these experiments and simulations seem consistent with ion acoustic turbulence with $k\lambda_D \sim 0.5$ being excited to a fluctuating rms potential of about $0.03 < e\phi/T_e < 0.15$. The quasi-linear theory of this instability[29] predicts an anomalous electron-ion collision frequency of

$$\nu_{an} = \frac{\sqrt{2\pi}}{2} (k\lambda_D)\omega_{pe} \left(\frac{e\phi}{T_e}\bigg|_{rms} \right)^2 \sim \frac{\omega_{pe}}{2} \left(\frac{e\phi}{T_e}\bigg|_{rms} \right)^2 . \tag{28}$$

In our calculations we assume that $\nu_{an} = \omega_{pe}/100$ or $\omega_{pe}/1000$ for a plasma whose electron drift velocity V_e is greater than 50% larger than the critical drift velocity V_c for instability. For $V_c < V_e < 1.5\,V_c$, ν_{an} increases linearly with $V_e - V_c$ to its final value. The electron heating, associated with this collision frequency has been observed in particle simulations. Our procedure then is to add ν_{an} to ν in (Eq. (12) whenever ion-acoustic waves are linearly unstable.

The total plasma heating $E \cdot J$ is then greatly enhanced by the anomalous resistance. The next question is how this total heating is partitioned between electrons and ions. As long as the ion acoustic waves are at steady state, one can derive a simple relation between the electron and ion heating rates.

Say that the ion wave transfers momentum from ions to electrons at a rate P. Then it can be shown, from resonant quasi-linear theory, that in the reference frame in which the ions are at rest, energy is transferred from electrons to ions at a rate $(\omega/k)\dot{P}$, where (ω/k) is the phase velocity of the ion acoustic wave. If the electron drift velocity is denoted V_e, then momentum and energy conservation equations for electrons and ions read

$$nm\dot{V}_e = -\dot{P} \qquad \text{(a)}$$

$$nmV_e\dot{V}_e + 3/2\, n\, \dot{T}_e = -\frac{\omega}{k}\dot{P} = -\frac{3}{2}\, n\dot{T}_i \qquad \text{(b)} \qquad (29)$$

From Eqs. (29a and b), it is a simple matter to solve for the ratio of heating rates,

$$\frac{\dot{T}_e}{\dot{T}_i} = \frac{(V_e - \omega/k)}{(\omega/k)} \approx V_e \Big/ \sqrt{T_e/M} \qquad (30)$$

The anomalous heating of the plasma is divided among electrons and ions according to this prescription. The electron heating dominates the ion heating; however, the small amount of ion heating plays a crucial role in the dynamics because the condition for instability depends on T_i/T_e. (By neglecting the anomalous ion heating, we calculate that much larger currents can be generated).

The final thing to do is to determine the instability threshold for the ion acoustic waves. This is actually quite complicated because the ion Landau damping rate depends sensitively on the ion distribution function. We examine two possible situations. First imagine the ion distribution function is Maxwellian. Then the critical drift velocity is given by

$$V_{CM} \approx \sqrt{\frac{T_e}{m}} \left(\sqrt{\frac{m}{M}} + \left(\frac{T_e}{T_i}\right)^{3/2} \exp - \left(\frac{T_e}{2T_i} + 3/2\right)\right). \tag{31a}$$

Another possibility, which is suggested by particle simulations and some theory,[29] is that the ions form a non-thermal tail on the distribution function whose temperature is roughly the electron temperature. Assuming the ion heating goes into producing this non thermal tail, the ratio of the tail to thermal ion density is roughly T_i/T_e. If the ion Landau damping comes from this tail, we find

$$V_{CT} \approx \sqrt{\frac{T_e}{m}} \left(\sqrt{\frac{m}{M}} + {}^{T_i}\!/_{T_e} \exp - 1/2\right) . \tag{31b}$$

Let us emphasize that for this second model, our calculations of ion temperature are unchanged; the non thermal tail feature comes in only in calculating the critical electron drift velocity for instability. As we will see, the ion tail model allows somewhat more current to be generated than do Maxwellian ions, but the difference is not great.

This model for current generation is speculative since it relies on a plasma instability. However we describe the process as accurately as possible, and tie our model to experiments, simulations and nonlinear theories of the current driven ion acoustic instability.

We have done a variety of calculations of current generation, mostly for Versator. In Fig. 7 is shown the time dependence of T_e, T_i, $V_b/V_b(t = 0)$ and B_θ for a 3×10^5 V, 6×10^4 A, 7.5 cm radius beam shot into a plasma with $n = 3 \times 10^{12}$. The anomalous collision frequency is taken as $\omega_{pe}/1000$. If there were no current neutralization at all, B_θ would be 1600 G so somewhat more than one quarter of the total beam current is generated. In Fig. 8 are shown beam currents generated as a function of background density for various models of anomalous resistivity. In all cases studied here, the plasma density is greater than the beam density. Henceforth all calculations we report use the ion tail model with $\nu_{an} = \omega_{pe}/1000$. In Fig. 9 is shown the current generated in Alcator C as a function of density for a 2 Mev, 1.2 MA 8 cm radius beam. Notice that for both devices the current generated is just sufficient to confine the beam at low density, but is not sufficient at high density. Hence it is of interest to look for ways of enhancing the current generation.

One possible approach to increasing the current generation is a smaller beam radius so as to decrease the magnetic diffusion time through the beam and increase the electron return current drift velocity. The same calculations were redone for Versator assuming a beam radius of 5 cm. The unshielded poloidal field is now 2400 G. The poloidal field generated is shown as a function of density in Fig. 10. Notice that at minimum background density, nearly half of the beam current can be generated. Also shown is the time at which the poloidal field reaches 300 G (the field needed to confine the beam). This time is a weakly increasing function of density.

Another way to increase the current generation is to use a spatially structured beam. For instance say that the beam for Versator is not the solid beam with r = 7.5 cm of Fig. 11a, but four solid beams of half the radius as shown in Fig. 11b. The return current efficiently diffuses out of each beam so four current elements are formed. Then they attract each other and join into a single beam. Because of the complicated spatial structure, we cannot quantitatively analyze this problem. However a calculation of the decay of the return current for r = 3.75 and I = 15 KA should give a qualitative picture. The poloidal field generated for the 4 beams (i.e. the unshielded field is 1.6 KG) is shown in Fig. 12 as a function of density. Notice that more than half the unshielded current is generated. Also shown is the time for the poloidal field to reach 300 G.

We now turn to a discussion of the current generation experiment on Spac V done by Mohri et al.[6] In his experiment, a 500 KV, 80 KA 2-3 cm radius electron beam shot into a plasma with density $n = 5 \times 10^{13}$ generated a 28 KA current in 500 nsec. We have calculated the anomalous current generation for Mohri's parameters. Although we consider an ion beam and the experiment was done with an electron beam, this should not make very much difference because the physics is dominated almost entirely by the decay of the return current which in turn does not depend on what the beam is. For instance, Fig. 7 shows that the beam only responds slightly to the field generation. We calculate that for a 2 cm radius beam, a current of 20.7 KA is generated in about 500 nsec; whereas for a 3 cm radius beam, a current of 11.6 KA is generated also in a time of 500 nsec. The time scales seem to be in reasonable agreement with Mohri's experiment, but the total current generated, is somewhat less than what he measures. One possible explanation for the discrepancy is that Mohri uses a plasma anode, which apparently forces the return current to flow in the plasma just outside the beam. It may be that it is easier for the return current to diffuse through this low temperature plasma.

A possible way to simulate this effect in an intense pulsed ion beam is to use a very small radius beam, so that the return current does not have to diffuse very far to get out of the beam. We have performed a calculation on Versator with a 1.6 cm radius beam with a background plasma density of 10^{13}. In this case, a current of 36 KA is generated in 300 nsec. Of course the net current generated depends on how the return current diffuses through the rest of the plasma outside the beam.

To summarize, tokamak current can be generated by the ion beam by taking advantage of the anomalous decay of the return current. It seems certain that sufficient current can be generated to at least stop the beam near the center of the toroidal chamber. Generating sufficient current to power the tokamak plasma is more difficult, but appears to be possible, at least for small volume devices. If the current generated is sufficient to stop the beam, but is less than the required tokamak current, the additional current could be built up with an external transformer. We reemphasize that this transformer would be needed only to generate the current, not to Ohmically heat the plasma. Finally, the model used for calculating the decay of the return current seems to be in qualitative agreement with the measurements on Spac V.

VI. Injection Into A Full Density, Low Volume Plasma

This section deals with the second injection scheme, the injection of the ion beam into a spatially localized plasma in the center of the tokamak. The idea is that the beam (which charge neutralizes by dragging an equal number of electrons off the cathode) propagates across the vacuum region by setting up a polarization drift. Then the E x B drift velocity of the beam will be nearly equal to its original velocity as long as $(\omega_{pb}/\Omega_{cb})^2 >> 1$ where ω_{pb} and Ω_{cb} are respectively the plasma and cyclotron frequency of the beam ions.

One possibility is that the diode is placed in a long guide tube which joins the sidewall of the tokamak. The field lines in the guide tube curve and merge with the main field lines in the tokamak near the joint. When the beam comes to this region of curved field lines, it sets up a polarization drift which keeps it moving straight through the vacuum region. Also the diode may be placed in the tokamak, either directly, or in a separate chamber as discussed in the introduction. In either case, the beam moves across the vacuum and strikes the target plasma. When it does so, it propagates nearly parallel to the field. This target plasma has high electrical conductivity so that it will short out the polarization electric field. The beam will then be trapped in the plasma, which will serve as a channel to guide the beam around the torus. Since the beam does not carry any net electrical current on injection, the target plasma must carry the necessary current before the beam is shot in. Thus the initial plasma temperature will be fairly high. Also, since we assume it to be full density, the electron drift velocity will be low. Hence it is likely that the resistivity will be classical and the poloidal field will only change on the relatively slow classical diffusion time scale. Therefore, the beam does not generate net current as it did in the previous section. However, it does maintain the existing current. Since the beam is shot in parallel to the current from the outer side of the plasma, the drift orbits can carry the beam ions a significant distance into the center of the plasma. For instance if the poloidal field is as given in Eq. (26), with $B_{\theta o}$ = 3 KG and a 1 Mev proton beam in PLT, the displacement of the beam from the magnetic surface is about 5 to 10 cm. This should help trap the beam in the target plasma and move the average position of the beam ion further from the liner.

There are several principle limitations on this method. First, even under ideal conditions the distance the beam can propagate is limited by electron expansion along the field lines.[1] As shown in Ref. 1, the distance the beam can propagate across the field is limited to roughly

$$d \lesssim \left(\omega_{pb} / \Omega_{cb} \right) b \qquad (32a)$$

where b is the beam radius. Expressing this in terms of beam parameters, this is

$$d(cm) \lesssim 1.7 \times 10^5 \mu_b^{3/4} \ I^{1/2}/V^{1/4} \ BZ^{1/2}) \qquad (32b)$$

where I is the diode current in amps, V is the beam voltage in volts, and B is the magnetic field in Gauss. For the beams and tokamaks discussed in Section III, d is longer than the distance from the outer wall to the center.

The second limitation is that the polarization electric field does not somehow short circuit (and thereby stop the beam) between the diode and target plasma. For instance if the front end of the beam meets the curved field while the rear is in electrical contact with the cathode, the polarization field might short circuit on the cathode. Of course the guide tube can be sufficiently long to prevent this. Also the magnetic field lines in the tokamak are at different potentials when the beam passes through. Thus these field lines cannot intersect a conductor. Another potential problem is that because of the initial target plasma current, the field lines form magnetic surfaces. Hence a single field line passes through the entire beam. However, the length of time it would take to short circuit the polarization field along the field lines is very long. For instance at the q = 3 surface, an electron has to travel 3 times around the torus before it can short circuit the field. Even if it goes at the speed of light, the beam just has time to propagate across. If the electron travels at the speed of a beam ion, there should be no problem at all.

Thirdly, there are large electrostatic fields in the vacuum region. The voltage drop across the beam, due to the polarization field is

$$U(\text{volts}) = bvB \sin\theta \qquad (33)$$

where b is the beam radius in meters, v is the beam velocity in meters/sec, B is the magnetic field in Webers/m^2 and θ is the angle between the field and beam velocity. For the large beams we have been considering, with $\theta \sim 0.1$, we find typically a voltage drop of 1 Mev and an electric field of 10^5V/cm. For a beam in a small tokamak like versator, the voltages and fields are much less. In any case, the vacuum vessel must be engineered to withstand this. In summary, the problem of electrostatic isolation of the beam in the vacuum region looks like an important problem to solve in designing an experiment.

We now briefly discuss several ways in which the plasma can be initially localized at the center of the vacuum chamber. One approach is electron-cyclotron breakdown as discussed by Peng et al.[30] Here millimeter wave power is injected into the tokamak and it causes breakdown at the point of resonant toroidal field. A plasma sheet is produced and the electrons drift upward because of the gradient in toroidal field. Thus there is an upward electron current through the plasma sheet and a return current through the conducting vacuum chamber. Once this plasma is formed, the main toroidal current is turned on and a current channel should form in the center of the vacuum chamber. Another scheme, which utilizes electron cyclotron breakdown, but does not allow plasma to ever contact the wall is as follows. Millimeter wave power from one or several gyrotrons is focused onto one or several spots producing globules of plasma on these spots. The electrons expand along the field and produce a thin ring of plasma going around the torus. Of course this plasma is unconfined and will expand along the major radius. Before it can expand however, a current is induced in it to create a confined plasma. The current must be induced slowly enough not to ionize the surrounding gas, but quickly enough that the plasma remains confined in the center and does not spread out to the limiter.

A recent NRL-Oakridge experiment[31] has confirmed that the ISX-B plasma can be pre-ionized with 80 KW of power from a 35 GC gyrotron. For about the first half millisecond the plasma is well localized at the center of the toroidal vacuum chamber. After this half millisecond or so, the gyrotron would be turned off and the current would be turned on.

Another possible way to form the initial target plasma is to use vaporization of a DT pellet with a high power laser. Such laser pellet schemes have been discussed previously in the context of refueling stellarators and tokamaks. Here a pellet or pellets are dropped into the vacuum chamber and when they reach the desired location they are ionized by the laser. The plasmas expand principally along the field lines and eventually will join up to form a single plasma ring around the torus. When this happens, the current is turned on, as in the previous scheme, to form a confined plasma in the middle of the toroidal chamber.

Compression of the toroidal field is another way to produce a full density spatially localized plasma. If the toroidal field is compressed by a factor C, the plasma radius also shrinks by this same factor. During compression the plasma pulls away from the limiter to form a ring in the center of the conducting chamber. This process was demonstrated in Tunan-2 tokamak, where upon compression of the toroidal field from 3.2 to 11.5 KG in 120 μsec, the plasma density at the limiter dropped until it was less than 0.005 times the central density.[32] Of course in a confinement time, the outer regions fill in again. Nevertheless the several milliseconds it takes for this should be plenty of time to shoot in the beam. Another possibility is to use vertical field compression as on ATC.[33] Here the major radius is compressed by a factor C and the minor radius by $\sqrt{C}$. Once the plasma is compressed, the beam can be fired in as with toroidal field compression. The usual disadvantage of compression, namely the reduction in plasma volume does not apply here. The purpose of compression is not to heat the plasma, but only to draw it in from the walls so the beam can be fired in. Once the beam is in, there is no reason for the plasma not to diffuse outward.

If the plasma edge is defined by a poloidal diverter rather than a material limiter, it is possible that a spatially limited plasma can be formed by varying the current in the diverter coil. Imagine that at early time the current in the diverter coil is high, so that the separatrix is near the center of the vacuum chamber. Then in a time small compared to a confinement time, the diverter current is reduced and the plasma slowly diffuses outward. The beam can be fired into the target plasma at any time before its minor radius expands significantly.

As a final scheme for producing the target plasma, we consider an analogous mechanical scheme. Imagine that the limiter has moving parts like a shutter. Initially the limiter radius is small and it defined the radius of a localized plasma. At some time, the shutter is 'snapped' and the limiter suddenly expands to a larger radius. Before the plasma expands out to this larger radius, the beam can be fired in. Of course the resistivity of the limiter material must be sufficiently large that 1) the power deposited in it by decay or eddy currents is manageable, and 2) the toroidal field can diffuse through the limiter material during the time which it snaps outward.

To summarize, we note that since there are so many possible ways of producing this target plasma, and since some have been either partially or completely verified experimentally, the production of this plasma probably is not a great obstacle to tokamak plasma heating with intense pulsed ion beams.

VII. Beam Trapping with a Pulsed Stabilizing Field

The third injection scheme involves injection into a full volume, full density low temperature ($T \lesssim 1ev$) plasma which carries no current. The initial injection is as described in Section V. The ion beam comes in on the top. Because there is charge and current neuturality, the beam drifts downward in only the externally imposed fields. Since the density of the background plasma is high, there is no anomalous resistivity, that is no net current generation. Imagine that in addition to the toroidal field, there is a uniform vertical field which cancels out 90% of the downward centrifugal drift. For instance in PLT, with a 40 KG toroidal field, a 1 Mev proton beam and a 1 KG vertical field, the downward drift velocity in the combined toroidal and vertical fields would be about 3.5×10^6 cm/sec, so that the time to drift from the injector to the center of the toroidal vacuum chamber would be something over 10μ sec. As the beam approaches the center, a stabilizing field would be pulsed on in a time of order of this 10μ sec. For instance this stabilizing field might be a betatron field

$$B_z = B_{zo}\left(\frac{R_o}{R}\right)^n \quad \text{(a)}$$

$$B_R = -\frac{n}{R} z B_{zo}\left(\frac{R_o}{R}\right)^n \quad \text{(b)} \qquad (34)$$

where R is the major radius. As long as $0 < n < 1$, the equilibrium ion drift orbits are ellipses (for $n = 1/2$ it is a circle) and the frequency of the orbit motion in the poloidal plane is

$$\omega = V_b \frac{B_{zo}}{B_o R_o} (n(1-n))^{1/2} \tag{35}$$

where B_o is the toroidal field at $R = R_o$.

Thus extra coils are needed in the liner, coils which can pulse a field from say $B_z = 0.9\ B_{zo}$ to the field given in Eq. (34) in perhaps 10μ sec. This then will stabilize the beam near the center of the toroidal chamber. Since this is a very small change in vertical field, there is very little compression of the background plasma; after an initial slight compression, the background plasma will undoubtedly relax back and contact the walls. However the plasma is not in equilibrium since its current is opposite to the beam current. Thus the plasma will exist in some complicated flow pattern, but of course no net charge or current will be created. Therefore after the stabilizing field is pulsed on, the configuration is that the beam is in a stable orbit confined near the center of the tokamak and there is no net current. The idea now is to pulse on the main tokamak current and form a conventional tokamak plasma with the beam confined in its center.

VIII. Suggestions for Small Scale Experiments

While the injection schemes discussed in Sections V-VII may be somewhat uncertain, it is very useful to know that they can be tested on small scale experiments in either linear or toroidal geometry. This section discusses several such experiments. First of all one could do additional experiments like those of Wessel et al[4] and Kapetanakos and Golden,[5] the purpose being to see how well the beam propagates across a magnetic field in a vacuum. Principally it would be interesting to see if the transmission efficiency, for lengths relevant to this scheme (about 5-10 beam larmor radii) could be increased to near unity by increasing ω_{pb}/Ω_{cb}. The proper configuration is no longer beam injection perpendicular to B, but rather beam injection nearly parallel to B. This may be easier because much smaller electric fields are now required to drift the beam across the magnetic field.

Another related experiment is shown schematically in Fig. 13. Here the beam is injected nearly parallel to the magnetic field into a cylindrical chamber which has a plasma localized in the center of it. According to the theory presented here, when the beam collides with this plasma, the polarization field should short circuit and the beam's cross field motion should stop. That is the plasma should form a channel for the beam. A very interesting experiment then would be to measure, and attempt to optimize, the efficiency of beam propagation from the diode to a detector far down the second cylindrical chamber. Of course either of these experiments could be performed on a tokamak also. However the latter would require a spacially localized plasma in the center of the toroidal vacuum chamber.

It is also possible to do experiments on current generation in linear geometry. Imagine a diode in a vacuum in a guide tube. The diode produces a charge neutralized intense pulsed ion beam which propagates down the guide tube. A short way down, the beam comes to a foil which separates the vacuum from a low density plasma. The idea then is to study the decay of the return current to see how much current can be generated at which plasma densities, how long it takes to generate the current, what current driven instabilities are excited, etc. This sort of experiment could give important information as to the background plasma density and vertical field needed to trap an ion beam in a toroidal chamber.

This type of experiment could also be done relatively easily in toroidal geometry, since there is no requirement for an initially localized plasma in the tokamak. The idea would be to have the beam enter at the top of the tokamak, drift down, generate current, and stop at the center, as discussed in Section V. In order to keep the beam away from the conducting walls on entering the tokamak, it should be possible to induce an initial sudden displacement of the beam with a sharp pulsed field ripple right near the opening. A verital ripple would give the beam a sideways displacement, or a horizontal ripple would give it a downward displacement. Thus one could do experiments relevant to injection by current generation in either linear or toroidal geometry.

Both of the injection schemes which capitalize on the downward (or upward) drift of the ion beam rely on the fact that the beam is charge neutralized. Since $\omega_{pb}^2/\Omega_{cb}^2 >> 1$, electrostatic forces would dominate the magnetic forces if there were no charge neutralization. (In fact the injection into a full density low volume plasma exploits this.) This charge neutralization could also be tested on a simple experiment in linear geometry. Imagine a diode in vacuum in straight magnetized guide tube as shown in Fig. 14. A little way down the tube, a foil separates a region of low temperature plasma whose density can be varied. In the plasma region the guide tube bends through for instance a 180° or 270° turn. There might or might not be a vertical field.

The idea then is to have a detector on the other side of the bend to see if the intense beam follows the single particle drift orbit. Specifically one would be interesting to see what the density requirement on the background plasma is for shorting out all electric fields.

Finally let us note that injection of an ion beam into a tokamak gives an ideal way to study the β limitation of a tokamak. According to Lovelace,[18] the energy density of the ion beam is interchangeable with plasma pressure in MHD stability theory. Since the injection time of the ion beam is small compared to any MHD instability, the plasma 'pressure' and magnetic pressure can be continuously varied by changing the beam energy and toroidal field. Thus one can experimentally study a type of high beta tokamak, and particularly, can examine the conditions for the onset of MHD ballooning instabilities.

IX. Conclusions

We find that tokamak heating and current maintenance with intense pulsed ion beams is an extremely interesting area for future experimental and theoretical studies. Our calculations indicate that one shot from an ion beam at the initiation of the discharge can be sufficient to reach ignition in either small volume or large volume tokamaks. Since ion beams are inherently very efficient, and they allow the elimination of the entire steady state Ohmic heating circuit, they could most likely give rise to very economical reactor designs. Finally there are several interesting small scale physics experiments which can be performed to test the concepts developed in this paper.

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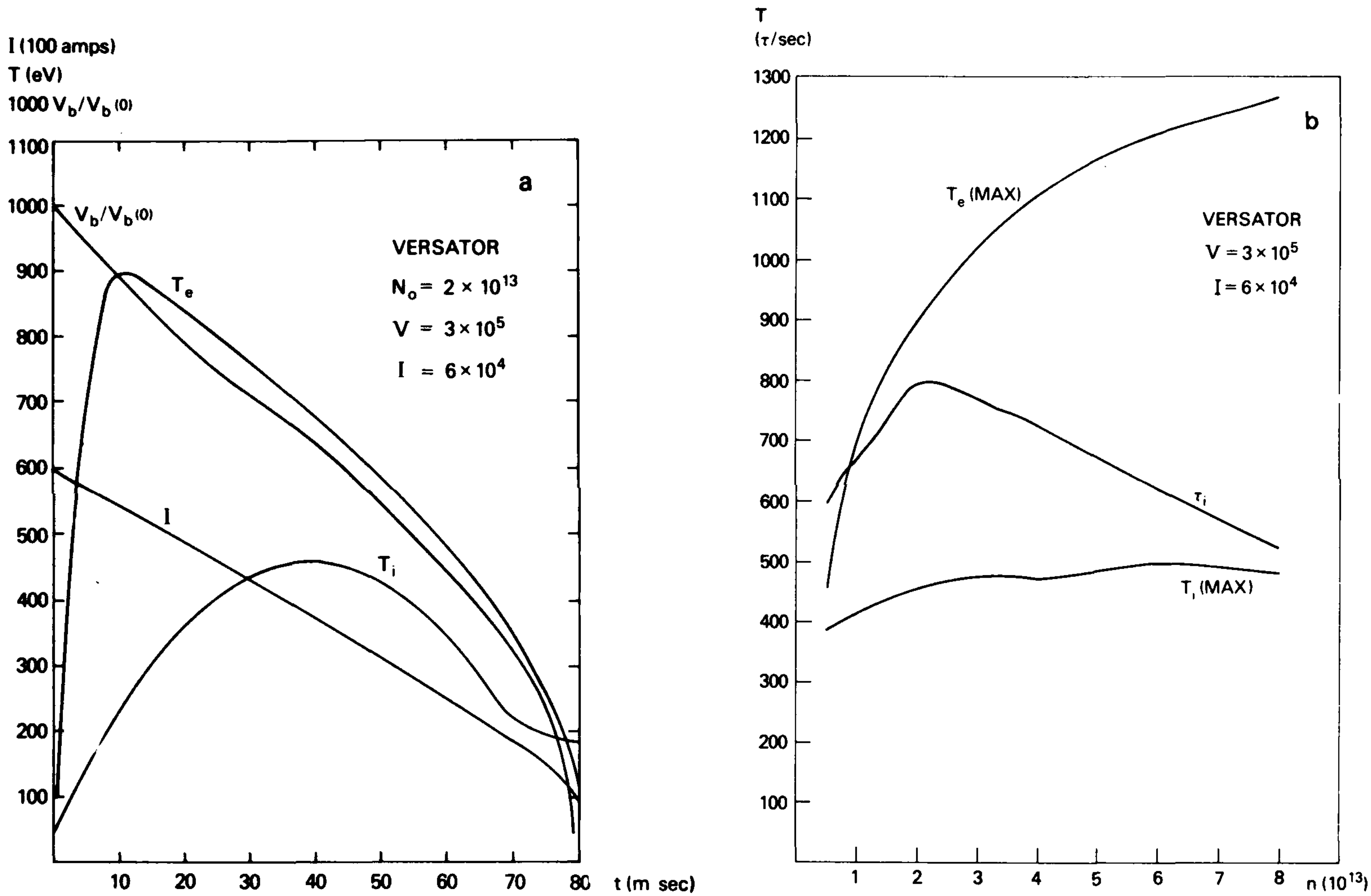

Fig. 1 - a) The time dependence of T_e, T_i, current and relative beam velocity for versator, b) Maximum electron and ion temperature and plasma lifetime as a function of density

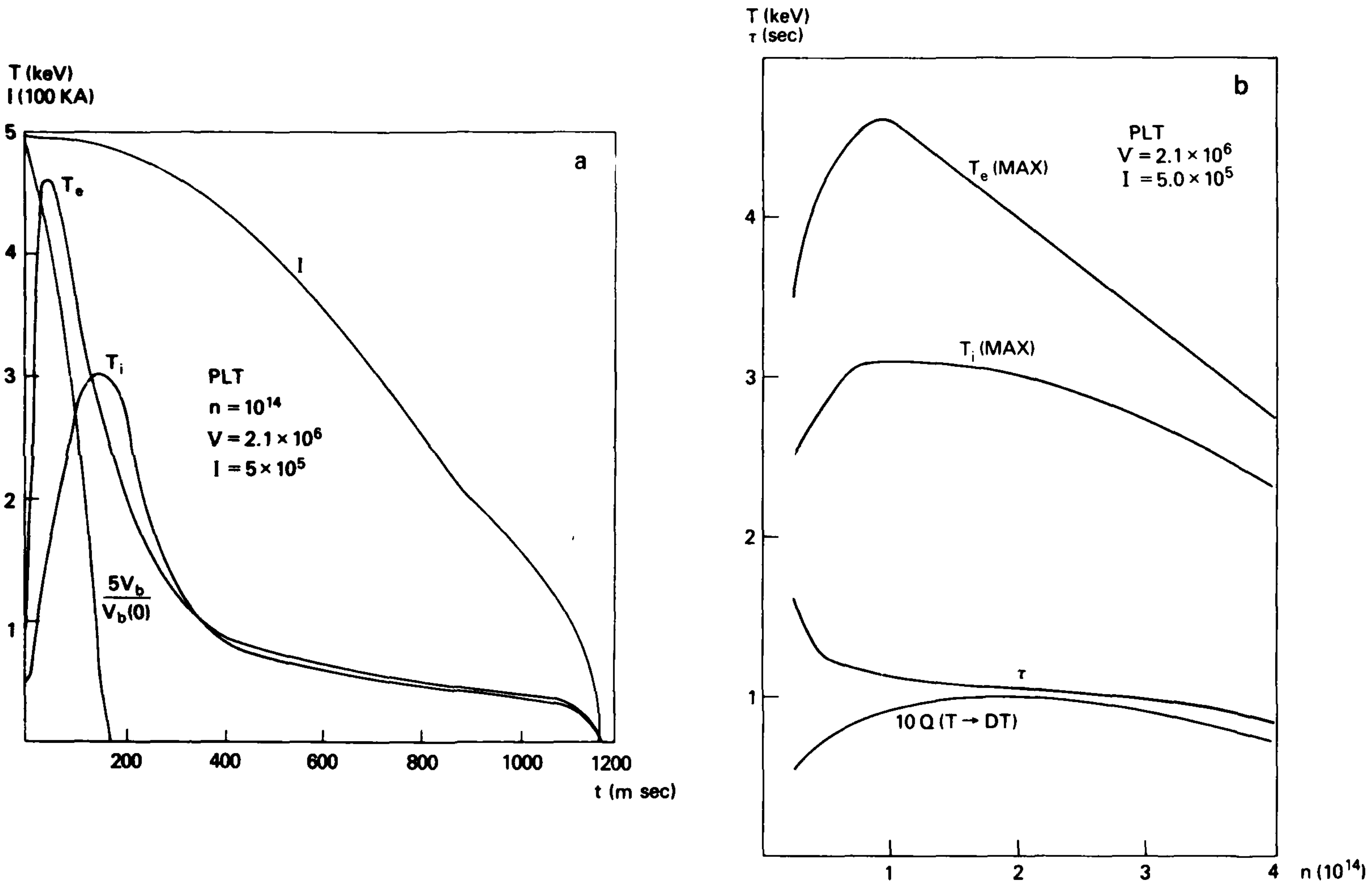

Fig. 2 - a) Time dependence of T_e, T_i, current and relative beam velocity for PLT, b) Maximum electron and ion temperature, plasma lifetime and Q as a function of density

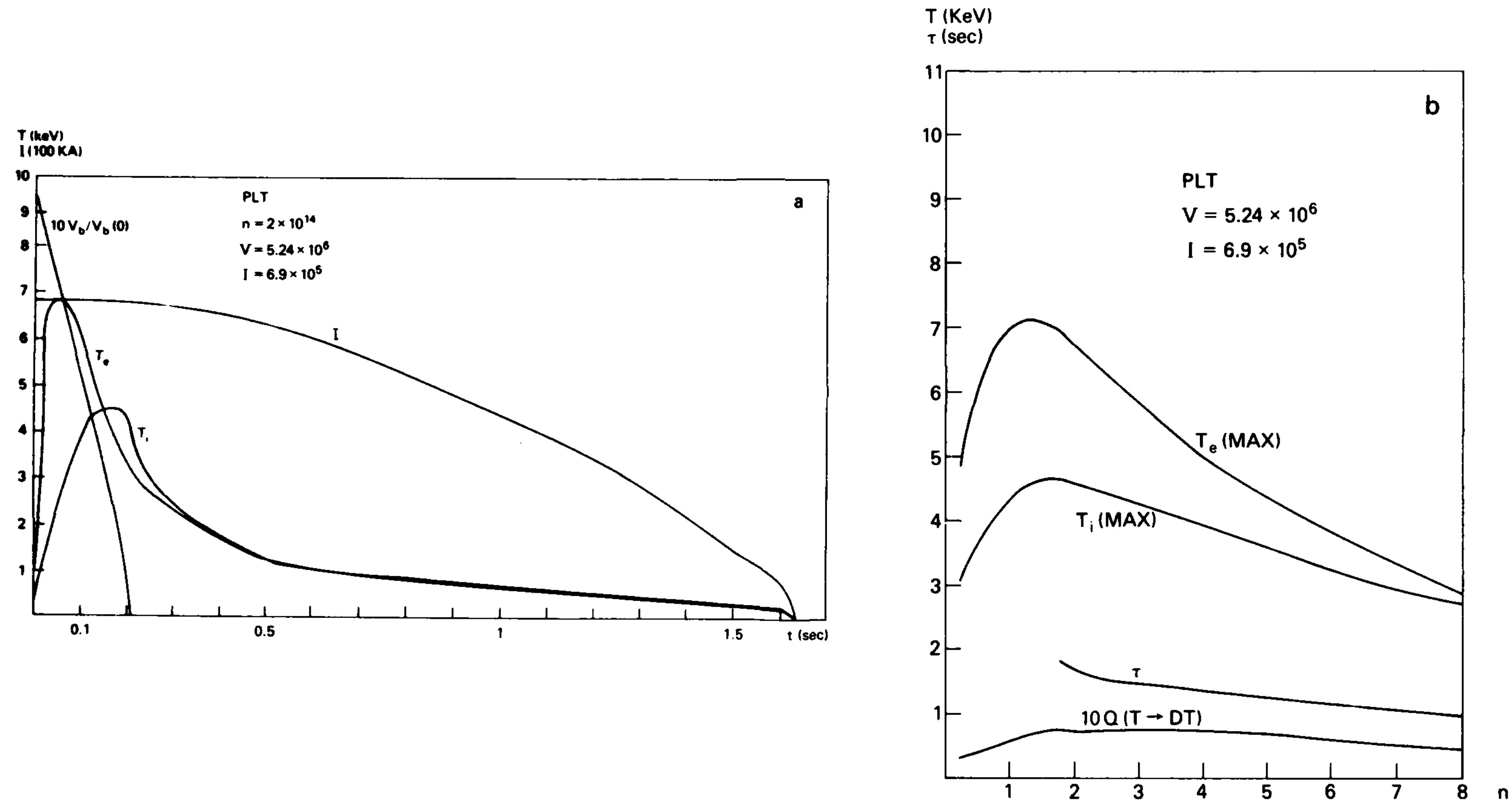

Fig. 3 - Same as Fig. 2 for PLT with a more energetic beam

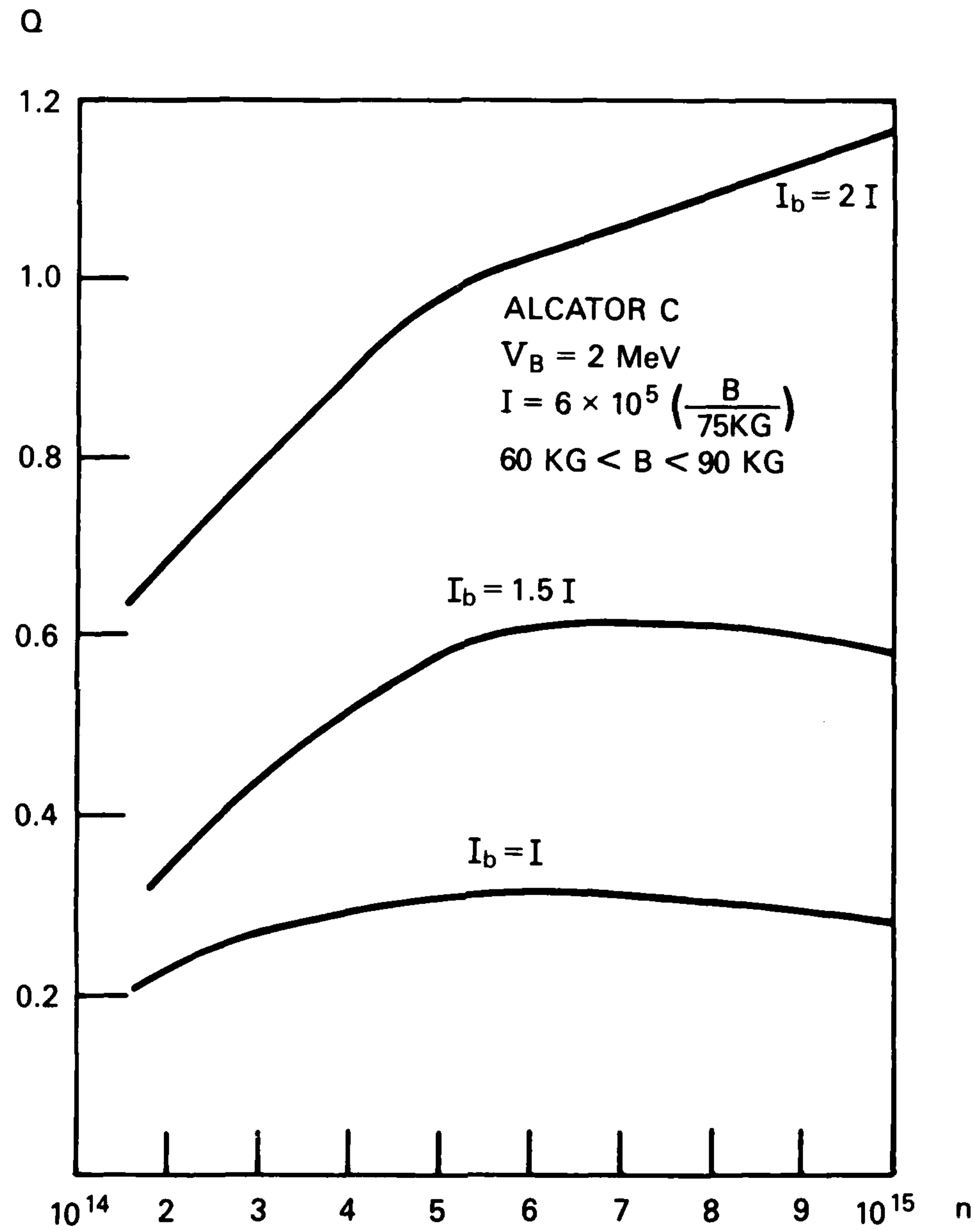

Fig. 4 - Q as a function of density and beam current to total current for Alcator C

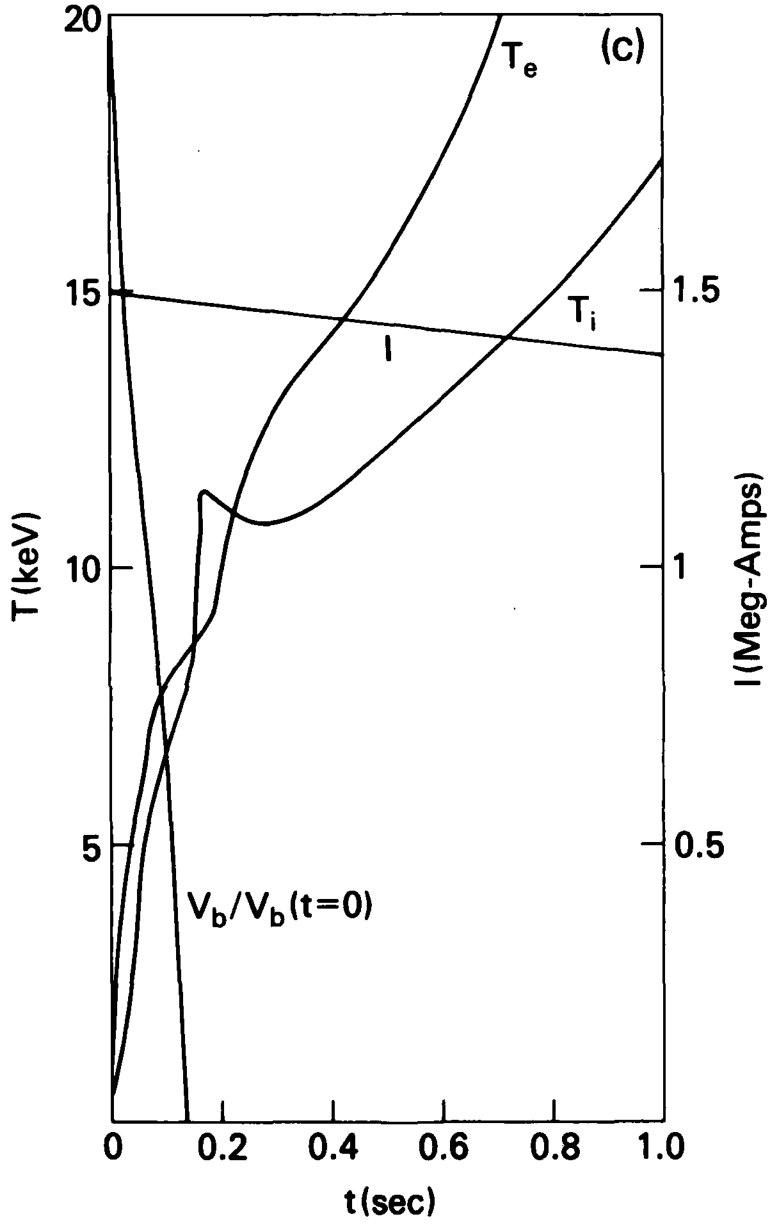

Fig. 5 - Electron and ion temperature, current and relative beam velocity for a ignited DT plasma in Alcator C

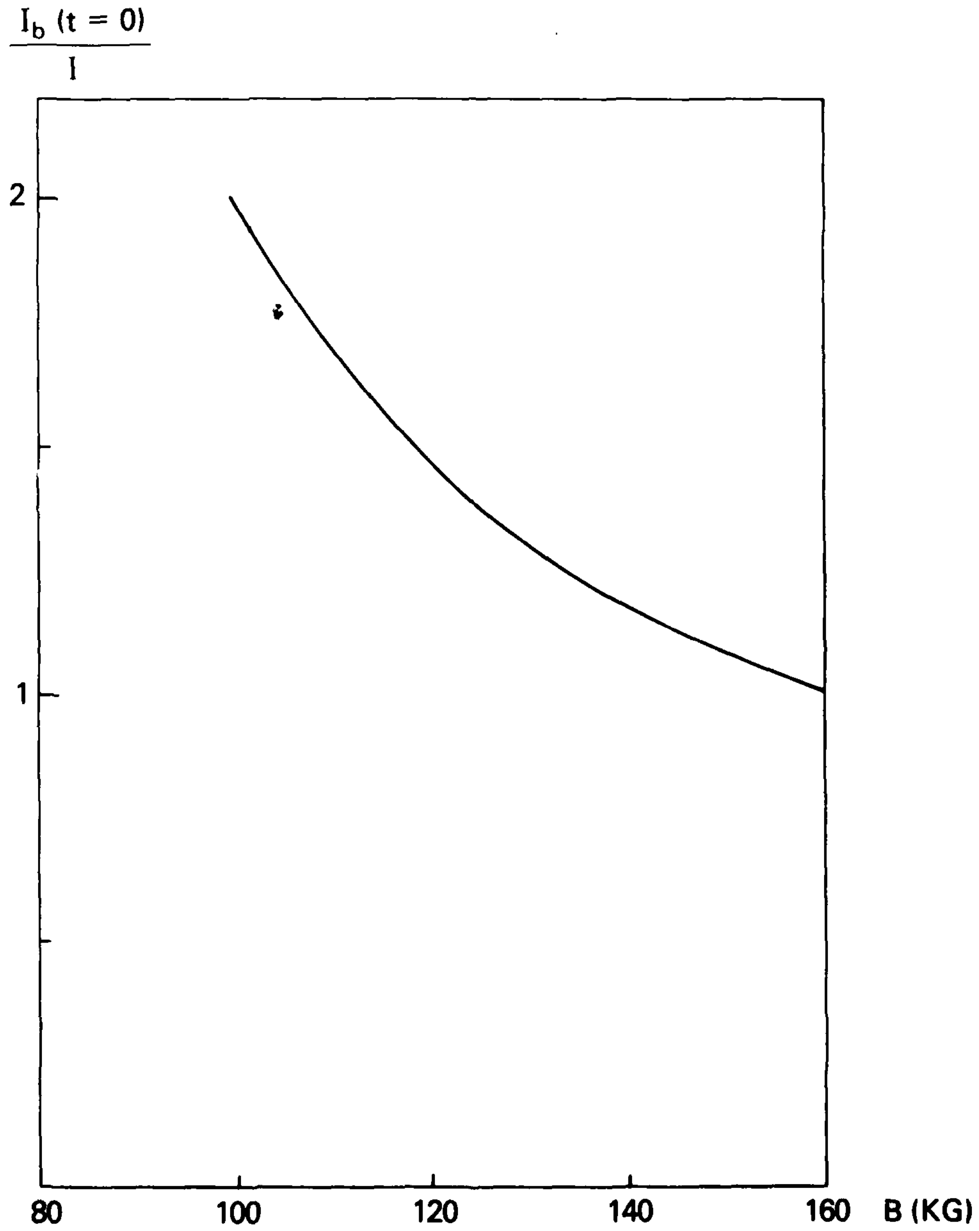

Fig. 6 - Requirements for ignition in Alcator C in B and I_b/I parameter space

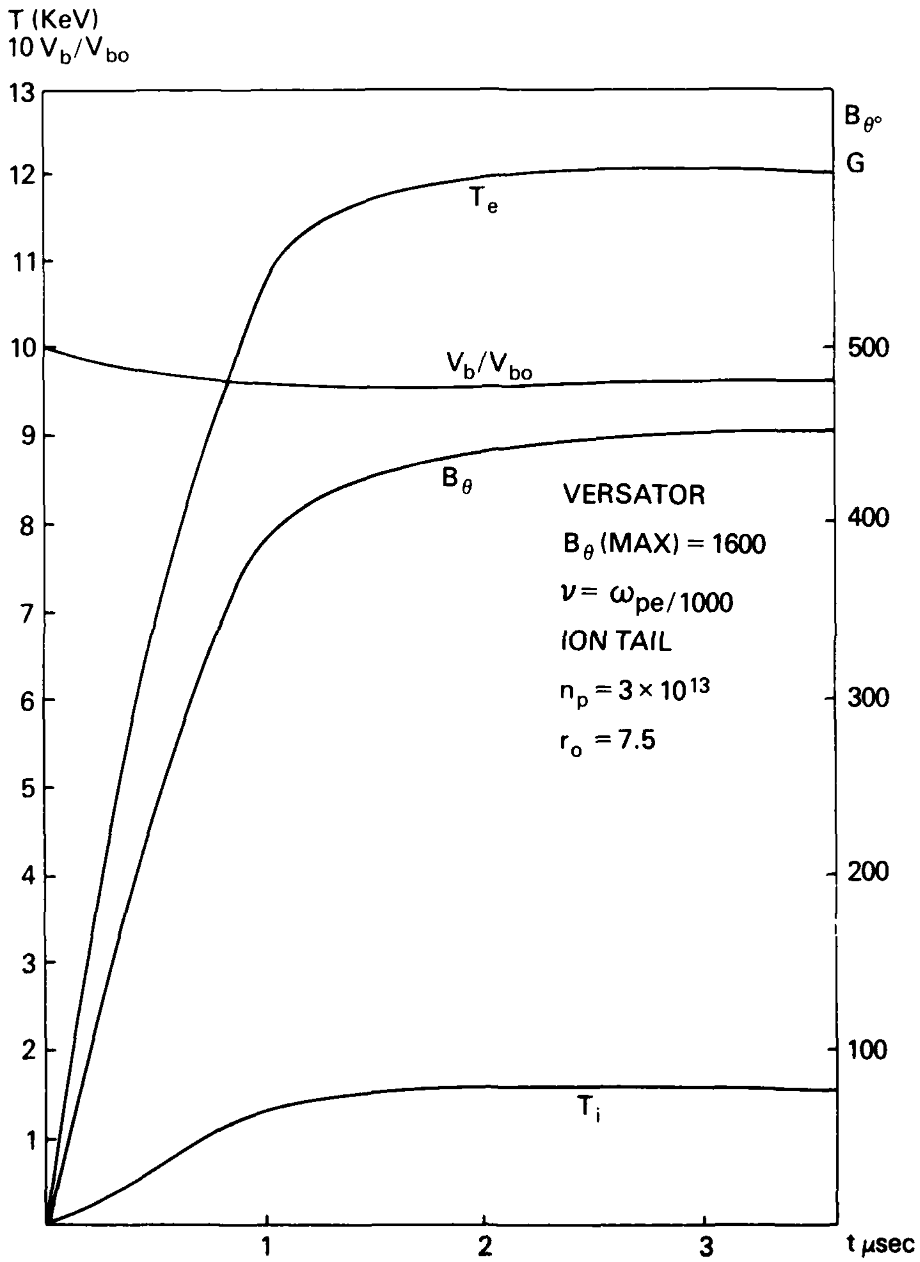

Fig. 7 - Electron and ion temperature, poloidal field and relative beam velocity for current generation in versator.

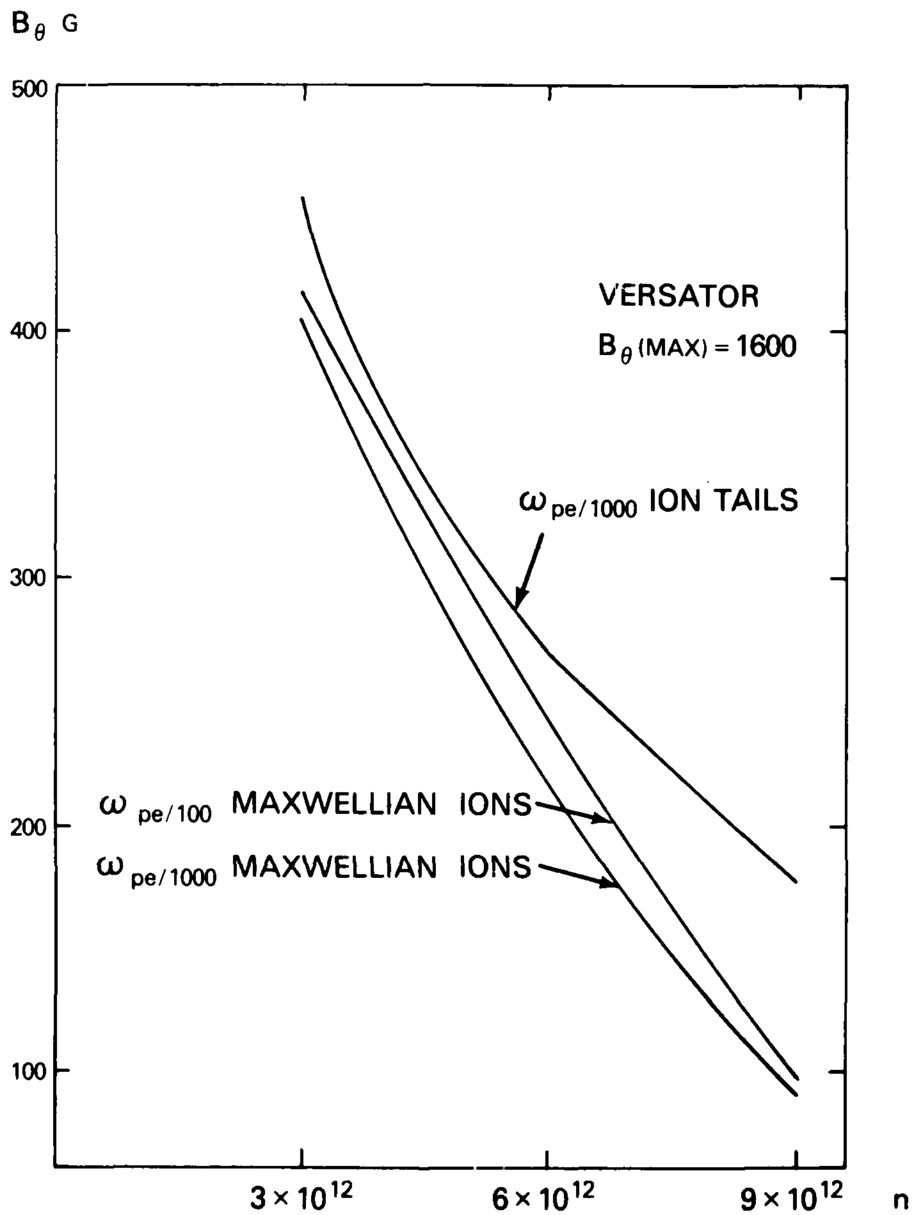

Fig. 8 - Comparison of current generation with different models of anomalous resistivity in versator.

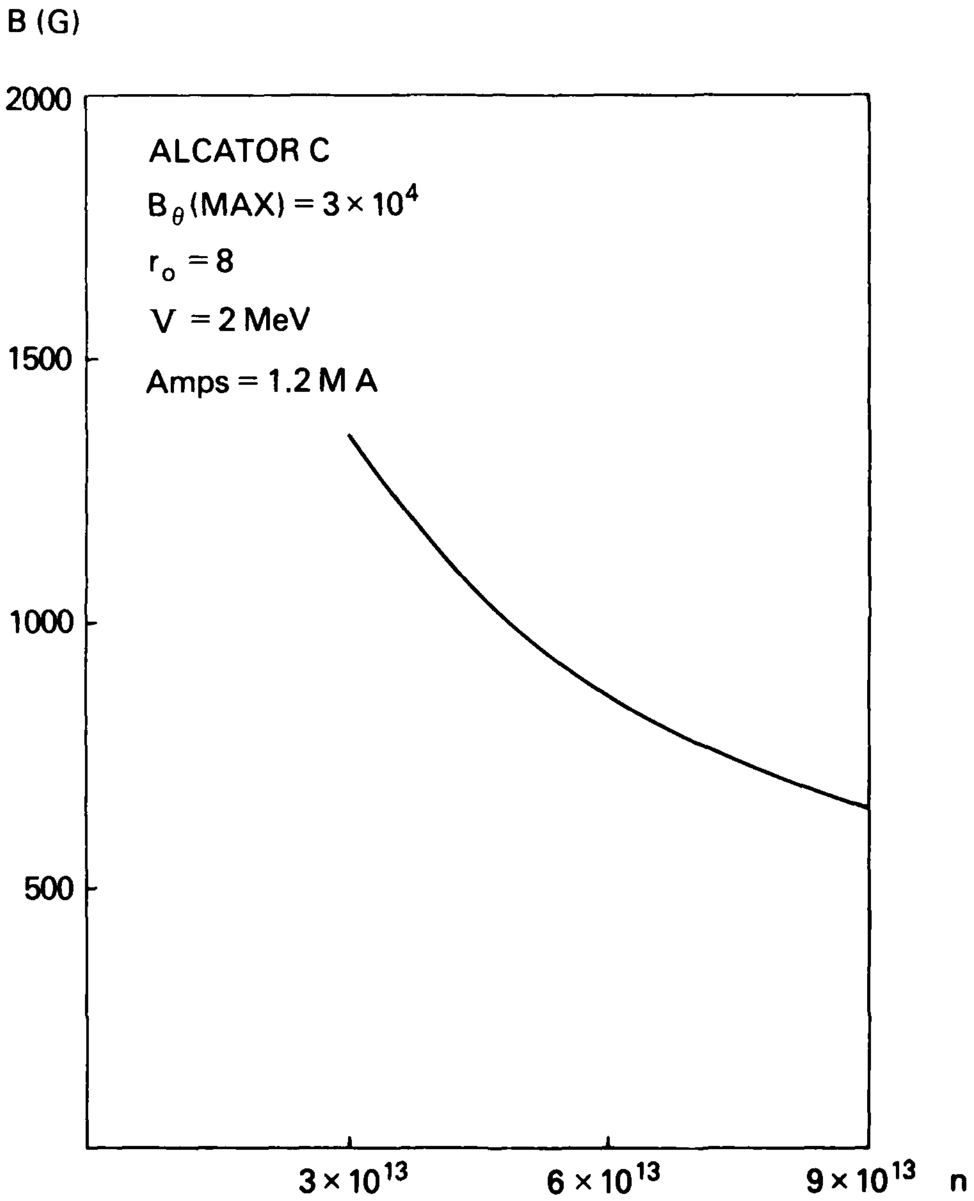

Fig. 9 - Current generation as a function of density in Alcator C.

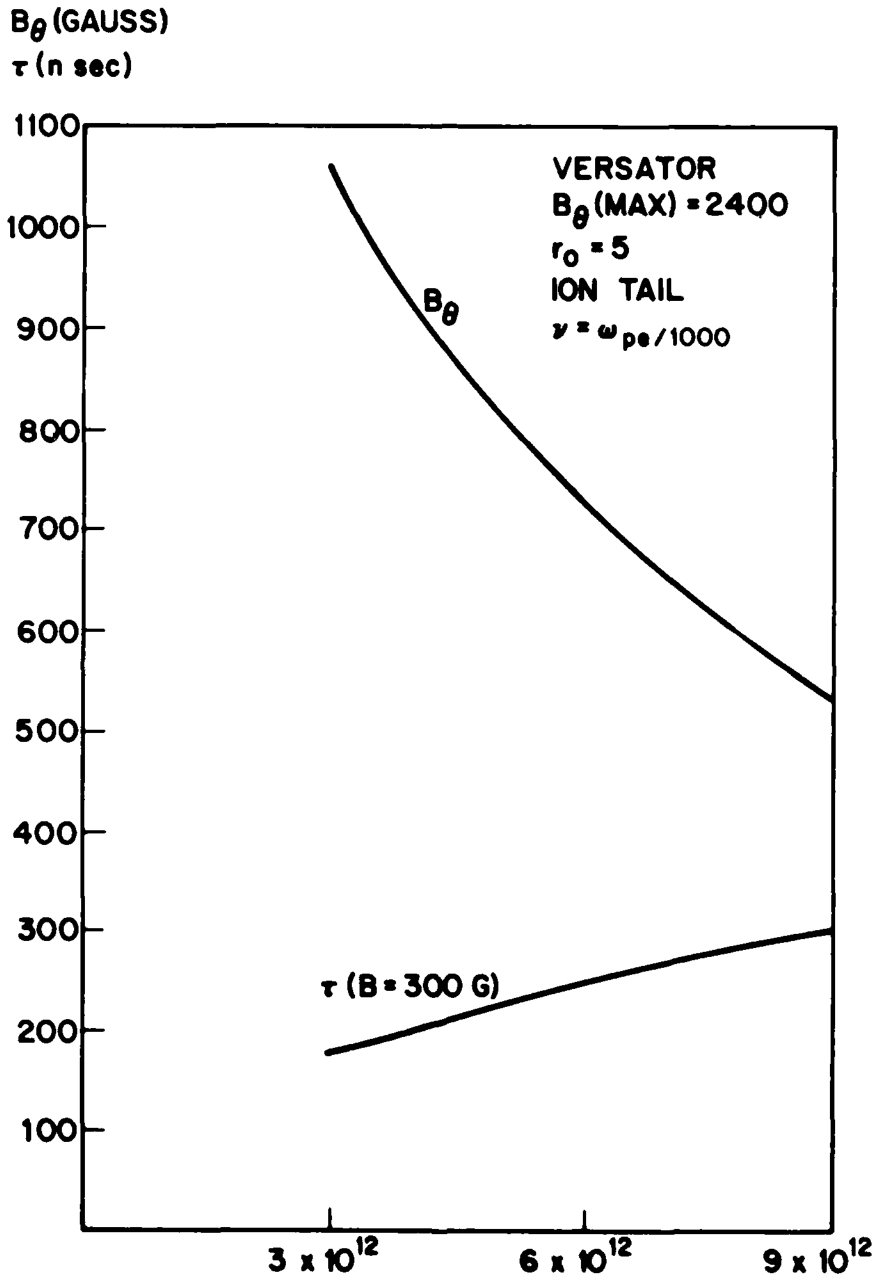

Fig. 10 - Current generation as a function of density in Versator for a 5 cm beam radius.

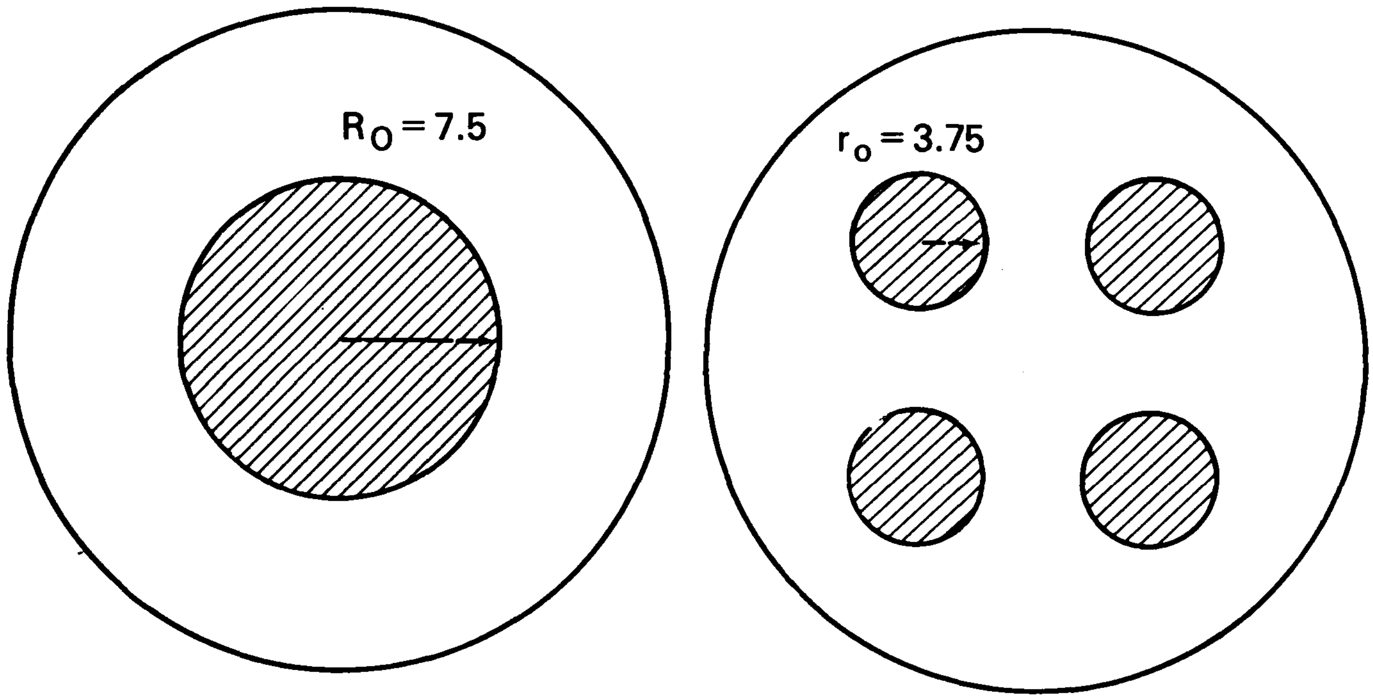

Fig. 11 - Schematic of a spatially structure beam.

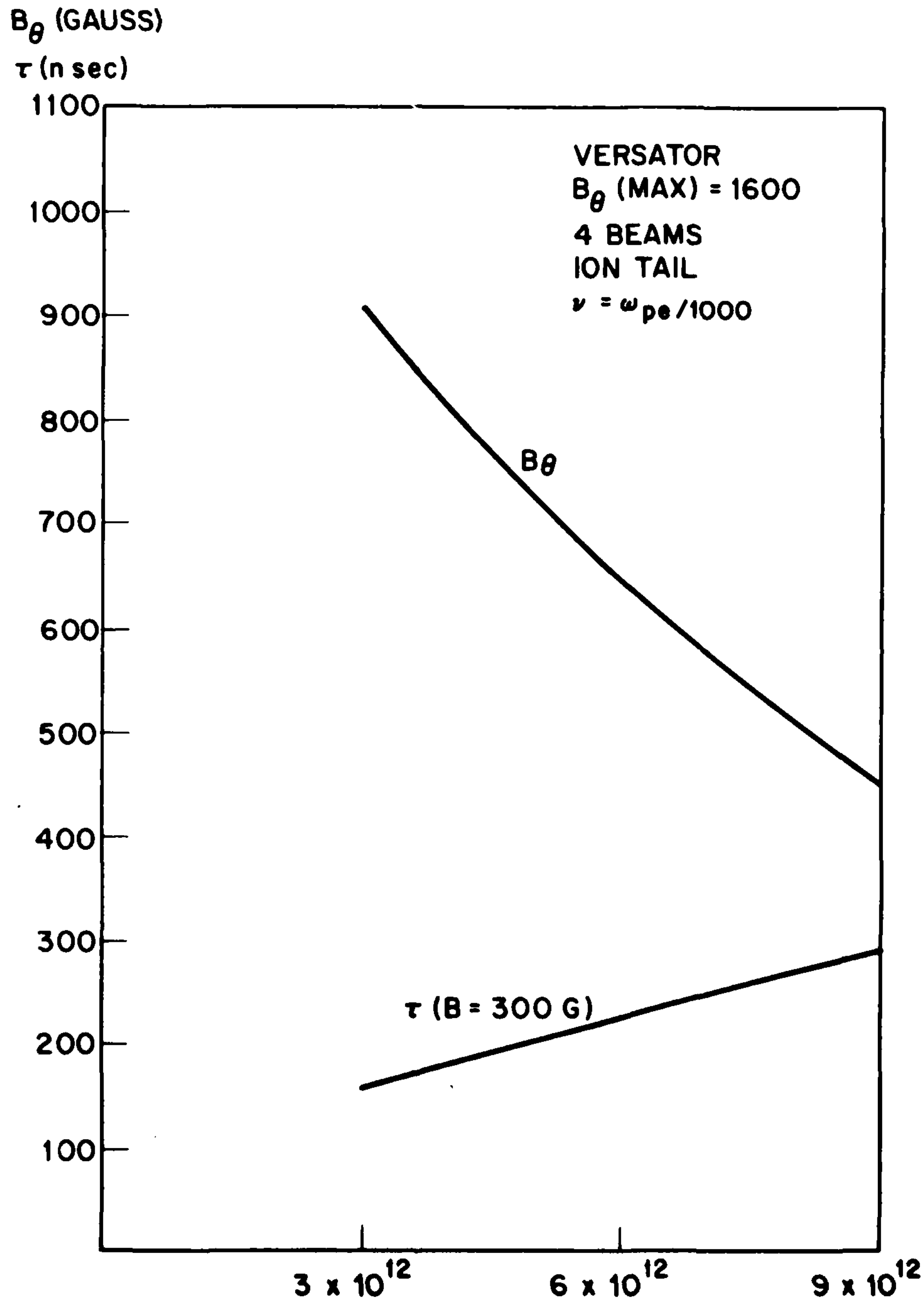

Fig. 12 - Current generation as a function of density for Versator for a structured beam.

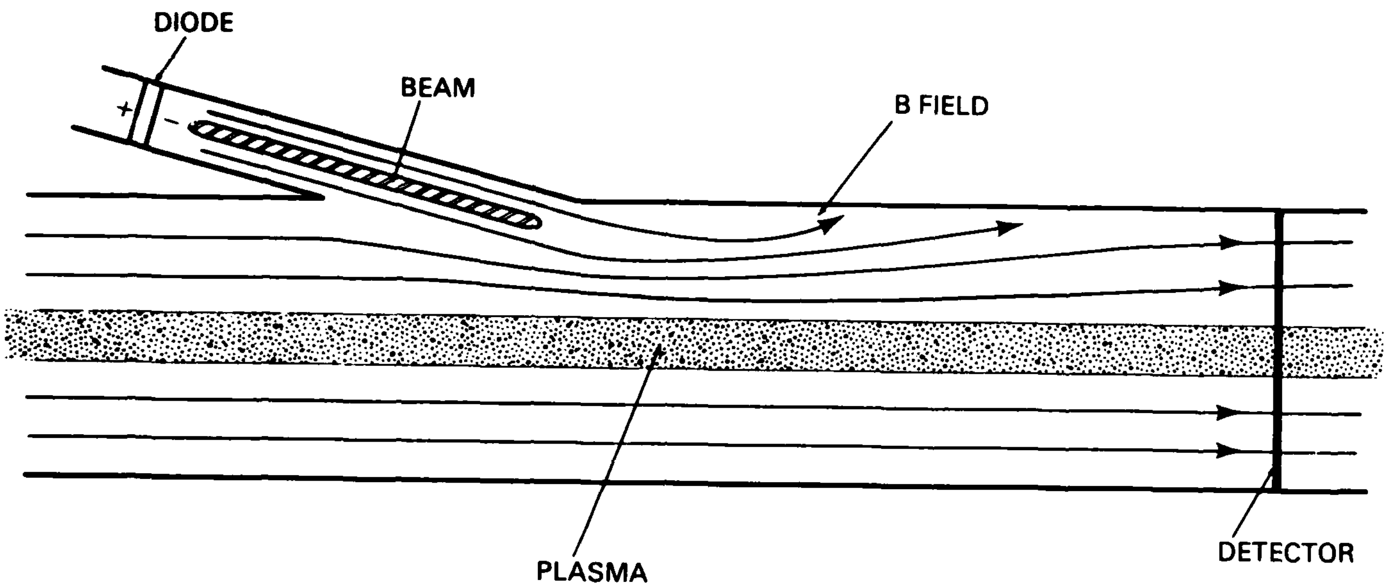

Fig. 13 - Schematic of an experiment to test injection into a full density, low volume plasma in linear geometry.

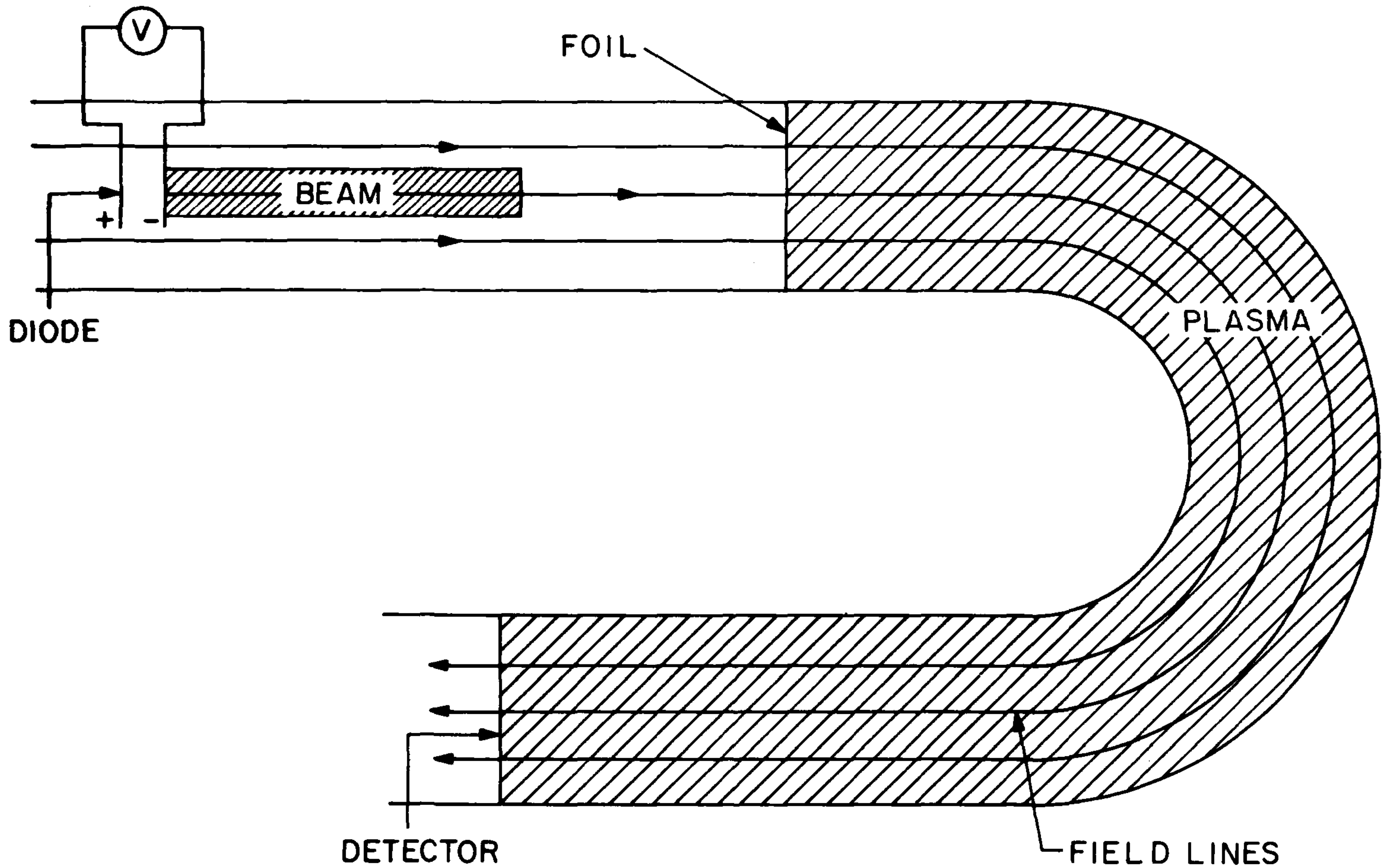

Fig. 14 - Schematic of an experiment to test for space charge neutralization in (topologically) linear geometry.

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