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Electron Trapping in High-Current Ion Beam Pipes

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Electron Trapping in High-Current Ion Beam Pipes*

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Abstract

The space charge voltage depression in a drifting heavy ion beam during the final stages of current pulse compression can be hundreds of kilovolts. For example, a 1kA beam of ions at β = v/c = 0.4 would have a beam center-to-edge potential difference of 75kV. With suitable clearance from beam edge to the beam pipe, this amount is typically increased by a factor of 2 to 3 by the (1 + 2 ln(b/a)) term that accounts for the ratio of pipe radius to beam radius. Such high voltages, and resulting high electric fields at the pipe wall, will result in electrons being pulled into the beam pipe. These electrons which are emitted from the grounded beam pipe, will pass through the ion beam at high velocity and then turn around without (usually) striking the wall and continue to pass through the beam on repeated oscillations.

It is possible to control the longitudinal motion of these trapped electrons by suitably varying the pipe size while considering the beam diameter. A segment of the beam pipe that has a larger diameter will result in a potential well that traps the electrons longitudinally. In a constant current scenario in a uniform pipe, the electrons will drift in the direction of the beam. However, the head and especially the tail of the ion beam will have a dramatic effect on the electrons, causing them to be pulled into the ion beam. These complex processes will continue until the ion beam passes through an optical

element such as a beam transport magnet that will effectively block the motion of the electron clouds following the ions.

In this paper, we will show examples of how electrons can be trapped and controlled by varying the conditions determining their emission and confinement. Ray tracing simulations using the EGN2[1] computer code will be used to model the electron trajectories in the presence of a high current heavy ion beam. The self magnetic field of the ion beam, while not sufficient to affect the ions themselves significantly, has a strong influence on the electron orbits.

[1] SLAC Electron Trajectory Program, W.B. Herrmannsfeldt, SLAC-331 (1988)

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Subject Topic: Beam Dynamics

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1. Introduction

In the typical Heavy Ion Fusion accelerator scenario, space-charge dominated beams are transported through a series of focusing elements to the target chamber. Any variation in the space charge, such as might be induced by electrons being pulled into the beams, can affect the beam transport system behavior. If deliberate and predictable, the electrons can reduce the effective space charge of the ion beam, thus relaxing the requirements on the strength of the focusing system. However, if the electrons are emitted in copious amounts from various parts of the beam transport system, they could vary in strength from shot to shot, or even be azimuthally non uniform.

In some previous preliminary discussions, it has frequently been said that the electrons will be pulled through the beam at high velocity, and will be buried in the chamber wall. If that happened, the neutralizing effect of the electrons would be minimized. However, it is immediately obvious that single electrons pulled into the beam in this way, having departed from a grounded pipe, will not have sufficient energy to get back to the pipe wall unless emitted with no transverse or longitudinal velocity relative to the beam axis. Because an intense beam supplies the space charge attraction, the self-magnetic field of the ion beam will cause the electrons to be deflected in the direction of the ion beam velocity. Thus even if the electrons are emitted precisely toward the center of the ion beam, and from a uniform pipe with no longitudinal electric fields, the electrons will still encounter forces that will impart velocity terms such that they cannot get back to the pipe wall. Of course, if large numbers of electrons are emitted, collective effects will change this situation so that some electrons are lost to the wall after spending an indeterminate time in the vicinity of the ion beam. Furthermore, any optical element such as a quadrupole or dipole magnet, will prevent electrons from staying trapped in a moving ion beam. The conclusion seems to be that if electrons are emitted into the ion beam in sufficient quantity, the beam transport system could behave with random perturbative effects.

The well-know expressions for space charge fields and voltages show that heavy ion beams can induce very substantial fields. In this paper, we will demonstrate the trapping phenomena as described above. We will show that a significant amount of neutralization is possible. It is beyond our present capability to sustain this calculation until equilibrium has been reached, if indeed such a condition exists. Various other transient affects associated with the rising beam current are also beyond our present capability to model. However, the fact that on the order of 20%, or more, of the space charge can be neutralized in a beam segment a meter in length does raise questions about how to account for this in Heavy Ion Fusion transport models.

2. Space-Charge Fields

The radial electric field from a round ion beam is given by[2]:

$$E_r = I*(1 - f)/(2\pi\varepsilon_o \beta c r), \qquad \text{for } r \geq a, \ (a = \text{beam radius}),$$

where E_r is the radial electric field due to the ion beam current I at the radius r, f is the fraction of neutralization, and βc is the ion beam velocity. To determine the fraction of neutralization, we will compare the electric field (at $r = a$) with and without the introduction of electrons from the pipe walls.

When the field is integrated to the pipe wall, at radius b, the voltage profile is:

$V(r) = V_s(1-f)(1 + 2ln(b/a) - (r/a)^2)$, for $r \leq a$, and

$V(r) = V_s(1-f)(2\,ln(b/r))$, for $r > a$, where we follow Reiser[2] in defining

$V_s = I/4\pi\varepsilon_0\beta c \approx 30\, I/\beta$.

Figure 1 shows the voltage profile of an unneutralized, uniform beam with a=14mm in a 50mm radius pipe for a 1000A heavy ion beam with β=0.4 (4 GeV for mass A=50) ion beam. Other typical beam profiles (e.g., semi Gaussian), do not differ greatly from this voltage profile. For the purposes of this study we will stay with uniform beams.

Figure 2 shows an EGN2[1] plot of the ion beam in a pipe section 1000 mesh units long. Although this problem scales to any unit, for the purposes of evaluating surface fields, we will assume a 1mm mesh unit. Thus we have a pipe section that has a taper from 25 mm to 50 mm and back again to 25 mm. As noted earlier, this creates a potential well due to the space charge that traps electrons longitudinally.

3. Neutralization Simulations

A fairly extensive series of simulations of electrons entering the ion beam from various points along the beam pipe showed how trapping can occur. Emission from the high-field corner of the beginning of the taper, at the upstream end, is the most likely case for 'stable' neutralization, i.e., stable in the sense that the electrons go at least the full length of the section and many are reflected at least once. Because of the periodic nature of the electron orbits, there seem certain to be collective phenomena that result in unstable orbits for the electrons. In Figure 3 we show the first pass of electrons emitted from the upstream corner. Electrons emitted from the other end of the pipe are retarded by the self magnetic field of the ion beams, and generally do not propagate very far if at all.

The orbits in Figure 3 were arbitrarily stopped in order to illustrate their characteristics. In Figure 4, the electrons are allowed to remain in the pipe for a significant time. Note that space charge is being iteratively relaxed in order to achieve a semblance of equilibrium. Injection is not space charge limited because, by definition, that would cancel all the field on the emitting surface. The amount of current being injected was determined empirically to be close to that which could be successfully simulated.

Figure 5 shows the voltage profile for both the initial beam and the neutralized beam. The neutralization fraction is about 24% based on the field at the edge of the beam in the center of the beam pipe. In the example shown in Fig. 4, about 550 A of electrons are injected into the 1000 A ion beam. Neutralization at 24%, is thus almost 50% efficient in the effect of the electrons. This is a higher "efficiency" than we might have expected.

4. Conclusions

The conditions used in these examples are not extreme for a heavy ion fusion beam as it approaches full compression and is transported into the target chamber. Depending on the number of beam lines, the currents can be an order of magnitude higher before the longitudinal compression process has been completed and the beams enter the chamber. Beam pipes will not be much larger than the 10 cm diameter example used here or else magnets will be too large and too expensive. It is certainly clear that tapers must be made very carefully and every effort must be made to eliminate corners that can result in field enhancement. In this example of a 1 kA beam of mass A=50 ions at 4 GeV, the surface field on the uniform middle of the beam pipe is more than 3kV/mm when there is no neutralization. This field is doubled in the smaller 25 mm radius pipe segment and is up to 10 kV/mm near the beginning of the radial taper. This is well into the region when vacuum discharge becomes a concern.[3]

It is not clear if this phenomenon is a limiting factor in high current beam transport, but it is certainly a factor that must be taken into account. One can speculate on ways in which neutralization from the walls of the beam pipe can be used to relax the focusing requirements. At the very least, to do this one needs to devise ways in which the injected current can be controlled. In particular, if the injected current is allowed to be random, then it will not be azimuthally symmetric. It is possible, though not at all clear, that this could cause beam deflections.

References

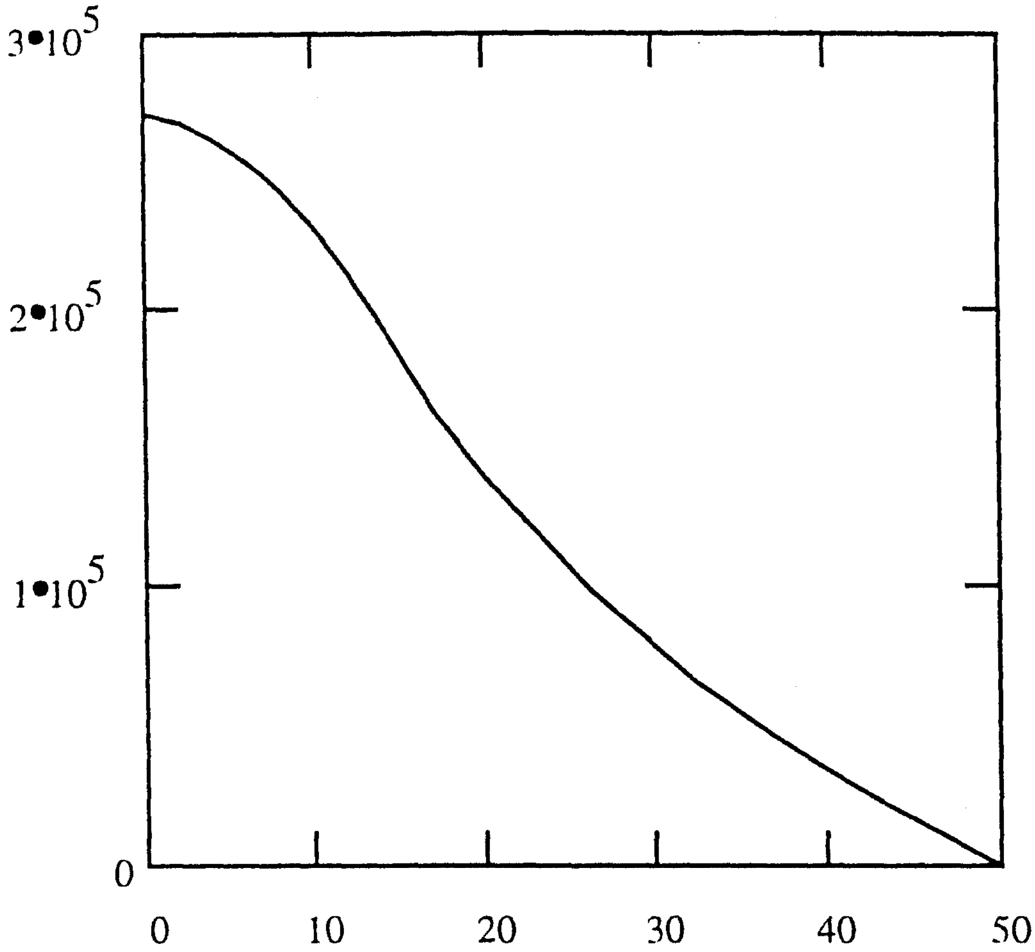
[1] SLAC Electron Trajectory Program, W.B. Herrmannsfeldt, SLAC-331 (1988).

[2] Martin Reiser, Theory and Design of Charged Particle Beams, Wiley Series in Beam Physics and Accelerator Technology, Ed. Mel Month, (John Wiley & Sons, 1994)

[3] Stanley Humpries, Jr., Principles of Charged Particle Acceleration, (John Wiley & Sons, New York, 1986)

Figure Captions

1. Voltage profile due to space charge of a 1kA heavy ion beam, mass A=50, 4 GeV, in a 50 mm radius beam pipe.
2. Uniform beam simulated by the ray tracing program EGN2 for the beam of Fig. 1 in a pipe with constricted ends resulting in a region in which electrons can be longitudinally confined. The parallel horizontal lines are ion trajectories and the curved lines show equipotential surfaces.
3. Typical paths made by the emitted electrons during their first pass through the beam pipe. Ion paths are stopped by a virtual beam-stopping electrode.
4. Electron orbits in the pipe when they are allowed to remain for a significant number of cycles. The neutralization fraction, found from the radial field at the edge of the ion beam, is about 23% from an injected current of 550A from the left hand corner of the beam pipe.
5. Voltage profile for the case in Fig. 4 showing about 23% space charge neutralization.



Radial Position, b=50, a=14

Fig. 1

Fig 2

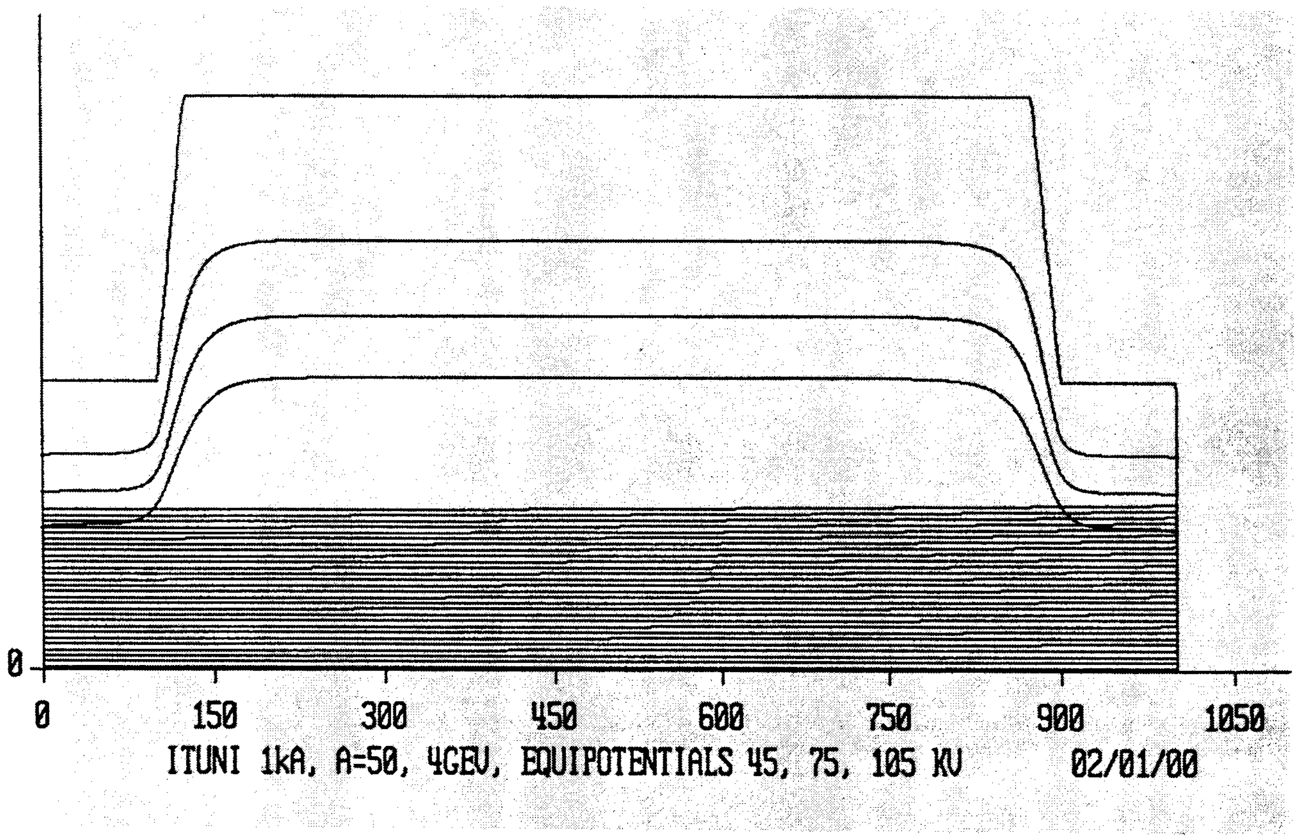
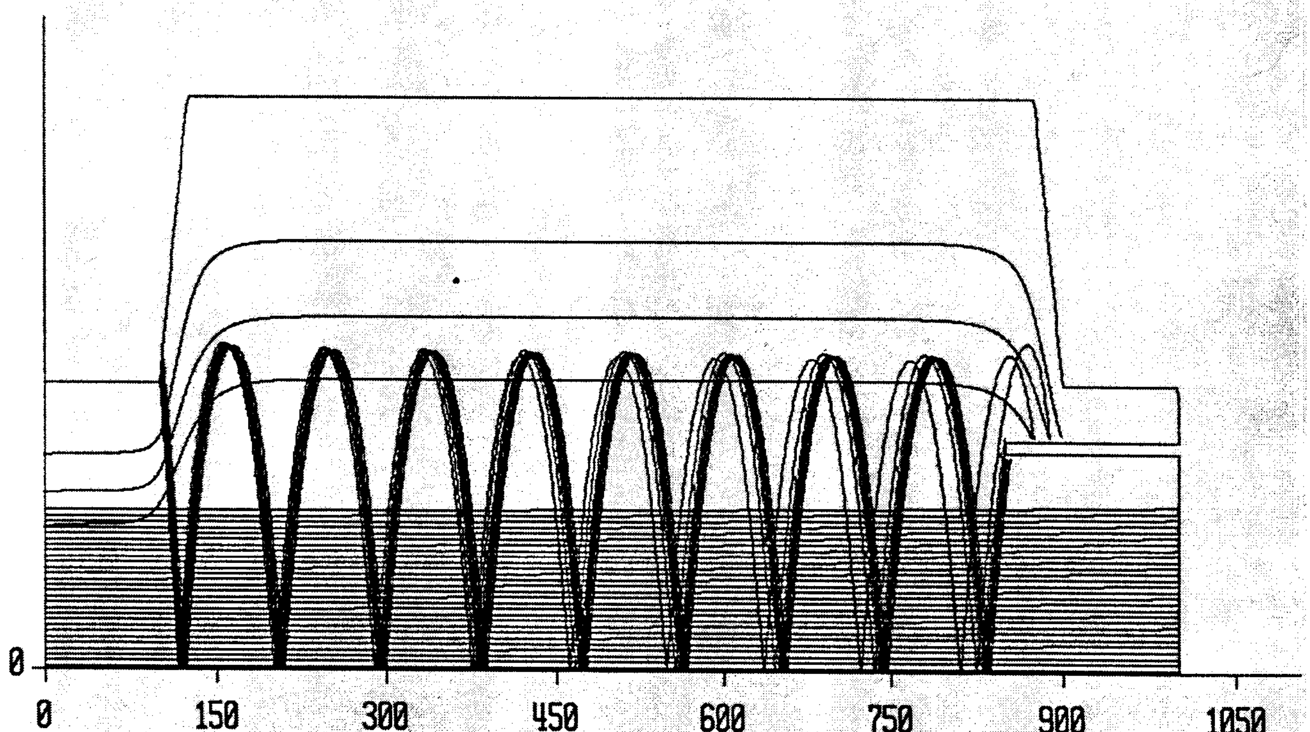

0
0
150
300
450
600
750
900
1050
ITUNI 1kA, A=50, 4GEV, EQUIPOTENTIALS 45, 75, 105 KV
02/01/00

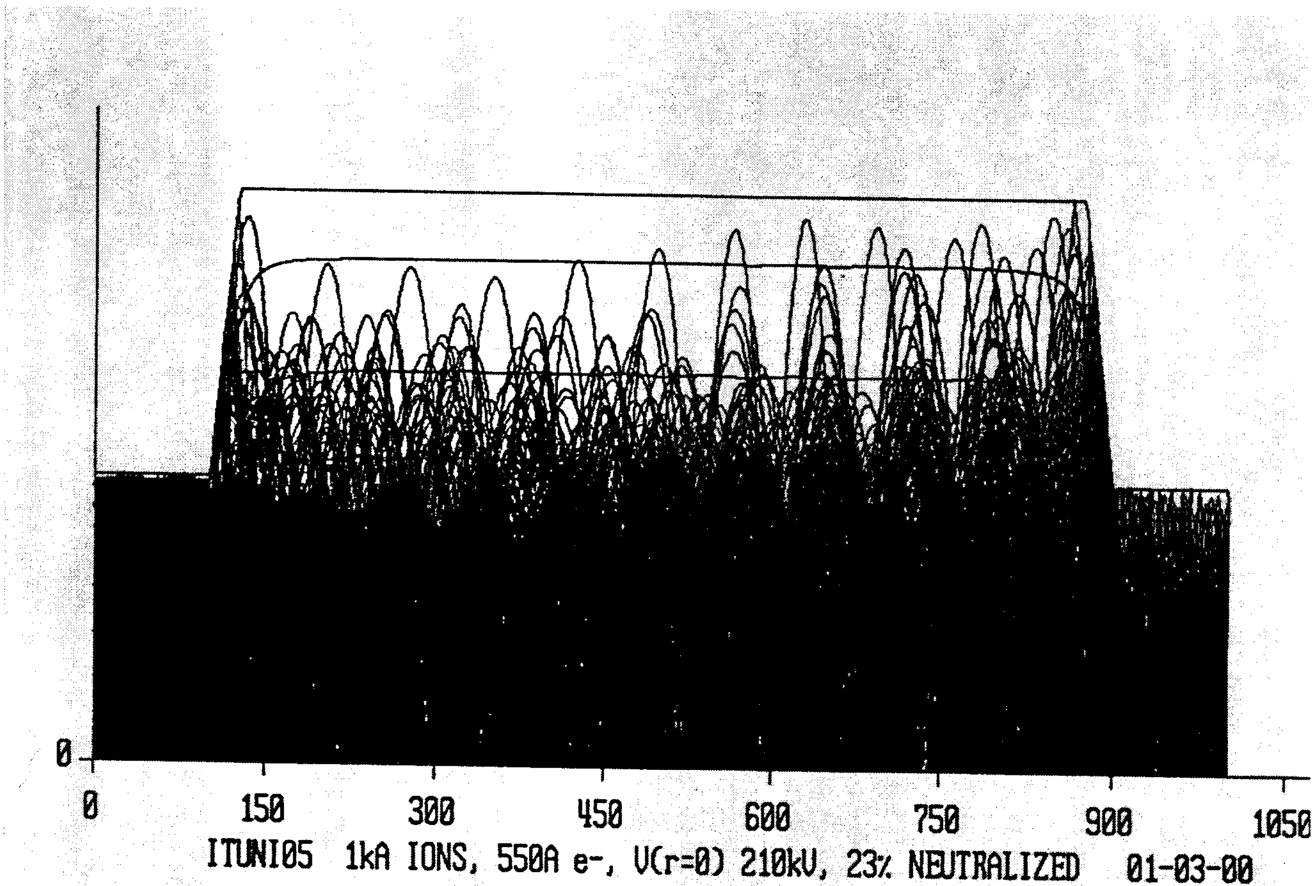
Fig. 2



ITUNI01 Trapping of electrons illustrated with low electron current.

Fig. 3

Fig 1


0
0
150
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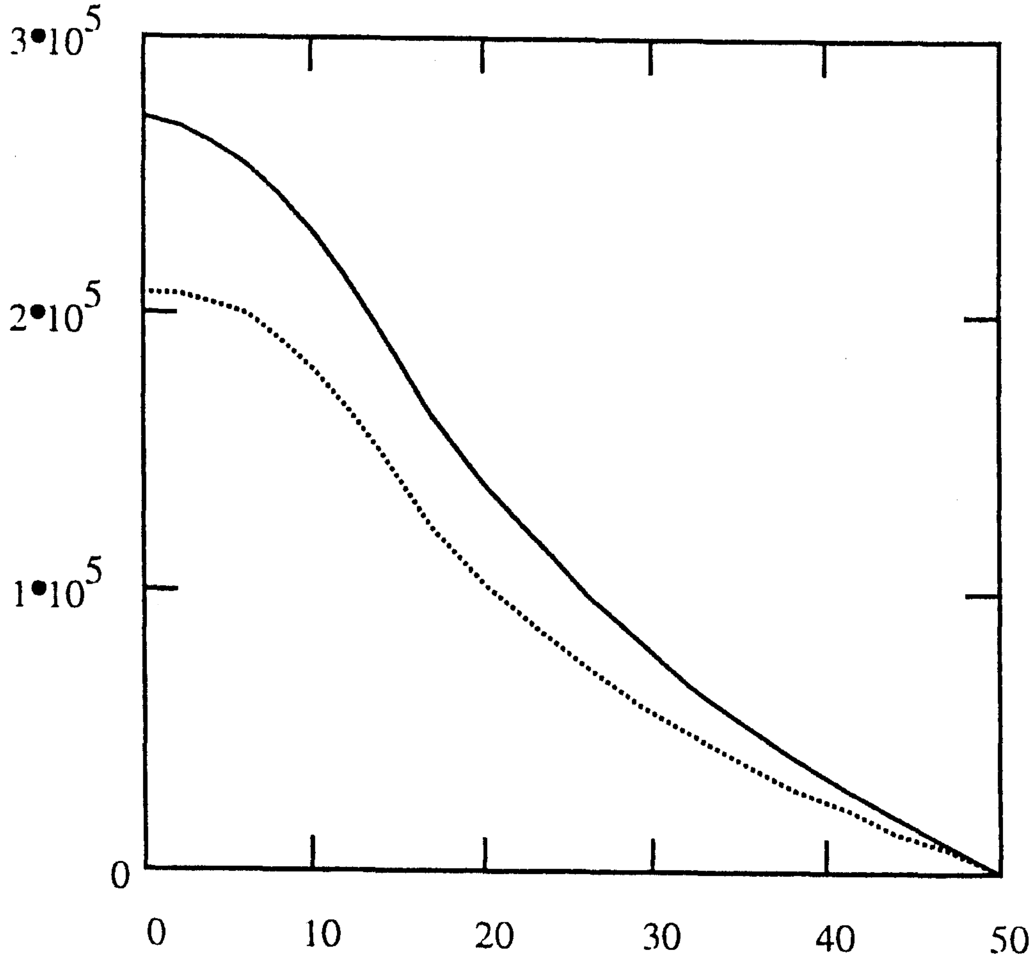
750
900
1050
ITUNI05 1kA IONS, 550A e-, V(r=0) 210kV, 23% NEUTRALIZED 01-03-00

Fig. 4



Radial Position, b=50, a=14

Fig. 5