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ENERGY RECOVERY FROM A SPACE-CHARGE NEUTRALIZED  
POSITIVE ION BEAM BY MEANS OF  
MAGNETIC ELECTRON SUPPRESSION

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## ABSTRACT

The charge-exchange neutralization efficiency of positive ion based neutral beams used in plasma heating applications decreases as the beam energy increases. Direct energy recovery from the charged particles can be accomplished by electrostatically decelerating the positive ions; the problem is to effect this without accelerating the space-charge neutralizing electrons residing in the beam.

Prior work with both electrostatic and magnetic electron suppression is reviewed. A finite difference ion optics code which solves the nonlinear Vlasov-Poisson equation is adapted to energy recovery application and used to analyze the transverse magnetic field electron suppression experiments carried out at Oak Ridge National Laboratory between 1980 and 1982. Three numerical models are discussed and evaluated. The double plasma model, which assumes an equilibrium Boltzmann distribution of electrons at both the neutralizer potential and the ion collector potential, most successfully duplicates the experimental results with beams in the 40 keV, 10 A range. It is used to analyze the effects of the magnetic field strength, the ion "boost" energy, and the ion beam current density on the ion collection efficiency.

Conclusions of the study are: (1) the electron leakage current scales as  $B^{-1}$ , necessitating magnetic suppression fields in excess of 0.1 tesla; (2) the neutralizer geometry should provide an electrostatic field to counteract the magnetic force on the ions; (3) fractional energy beam ions should be confined to the neutralizer interior; (4) the neutral line density in the recovery region should be less than  $3 \times 10^{-3}$  torr-cm.

Recovery efficiency decreases with increasing beam current density; a net recovery efficiency of 30% (ion collection efficiency of 75%) at 5 mA/cm<sup>2</sup> falls to

zero at  $10 \text{ mA/cm}^2$  for a 40 keV beam. New designs are presented and analyzed; an ion collection efficiency of close to 90% is predicted for an 80 keV  $\text{D}^+$  ion beam with an ion current density of  $50 \text{ mA/cm}^2$ .

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## 1. INTRODUCTION

### A. NEUTRAL BEAM HEATING OF PLASMAS

One of the problems confronting the development of a fusion energy reactor using magnetic confinement of the plasma is the necessity of heating the plasma to temperatures which will allow self-sustaining fusion reactions to be achieved. One method of plasma heating is to inject high energy neutralized particles across the confining magnetic field; these neutral particles are ionized by the plasma and become confined, imparting their energy to the plasma via Coulomb interactions. This technique was successfully demonstrated during the 1970s on such devices as CLEO,<sup>1</sup> ATC,<sup>2</sup> ORMAK,<sup>3</sup> TFR,<sup>4</sup> 2XIIB,<sup>5</sup> DITE,<sup>6</sup> T-11,<sup>7</sup> PLT,<sup>8</sup> JFT-II,<sup>9</sup> ISX-B,<sup>10</sup> PDX,<sup>11</sup> and others. These heating systems had particle energies in the range of 20 to 50 keV, with pulse durations of 20 to 500 milliseconds. Present-day experiments are physically larger with longer pulse lengths and confinement times. Experiments such as TFTR<sup>12</sup> at Princeton Plasma Physics Laboratory (PPPL), Doublet III-D<sup>13</sup> at General Atomic (GA), JET<sup>14</sup> at Culham, and JT-60<sup>15</sup> in Japan are using neutral beam heating systems of 80 to 160 keV for one to ten seconds.

Other applications for high power, high energy neutral beam injectors for fusion energy research are in the area of magnetic mirrors. In addition to heating, neutral beams are used on such tandem mirror experiments as TMX<sup>16</sup> and the future MFTF-B<sup>17</sup> to establish and maintain electrostatic thermal barriers as end-plugs by charge-exchange pumping. MFTF-B envisions using 80 keV beams with 30 second pulse lengths.

High power neutral beams are formed by electrostatically accelerating positive ions, which are subsequently neutralized by passing the ion beam through a gas.

A fraction of the ion beam will capture electrons from the gas, thus forming the neutral beam.

The effect of increasing the pulse length of a neutral beam is to increase the thermal stresses on the system. Many beamline components have long thermal time constants and rely on thermal inertia and low duty cycles to dissipate high power densities. The pulse length for advanced neutral beam systems has increased to the point that beamline components must dissipate their thermal loads in the steady state. One such beamline component that is stretching the limits of present cooling technology is the ion dump, to which the unneutralized portion of the beam is magnetically deflected.

The effect of increasing the beam energy may exacerbate the ion dump problem even more drastically than increasing the pulse length. Not only does the power density increase directly with the energy per particle, but the unneutralized fraction of the beam increases even faster. The equilibrium neutralization fraction for a positive ion beam decreases rapidly with energy; while a 50 keV  $H^+$  beam is 50% neutralized, a 100 keV beam is only 20% neutralized. The unneutralized portion of the beam is both a source of gross system inefficiency and a severe thermal dissipation problem. The higher energies of present beams dictate larger deflection magnets, longer distances for power density attenuation, and physically larger ion dumps. This lengthens the beam line, increasing the cost and decreasing the power transmission to the plasma target. This situation provided an impetus for recovering the energy residing in the unneutralized portion of the beam. Such an energy recovery system would eliminate the ion dump thermal dissipation problem, improve the system efficiency, and possibly reduce the beam line length and capital cost of power supplies.

The Office of Fusion Energy in the Department of Energy (DOE) supported two energy recovery research programs in the 1970s: an electrostatic electron suppression experiment at Lawrence Livermore National Laboratory (LLNL) and a magnetic electron suppression experiment at Oak Ridge National Laboratory (ORNL). However, the success of radiofrequency heating of plasmas at the ion cyclotron frequency on PLT<sup>18</sup> and other devices in the early 1980s made this the preferred heating scenario for future confinement experiments. Accordingly, funding was withdrawn from neutral beam energy recovery research before this thesis project was complete. Emphasis was thereafter shifted from energy recovery experiments to the development of a computer model which could be used to develop the 80 keV energy recovery device which was to be the endpoint of this research.

This thesis will discuss the problem of energy recovery from a space-charge neutralized ion beam in this section and present the basic theory of operation of magnetic electron suppression in Section 2. The details of the numerical analysis used to model the problem are covered in Section 3. Section 4 describes the apparatus and techniques used in the experiments operated from 1980 to 1982; these experiments are analyzed and used to validate the computer model in Section 5. Finally, an 80 keV energy recovery design is presented in Section 6, and its performance is evaluated by the computer model developed in Section 3.

## B. THE ENERGY RECOVERY PROBLEM

The goal of an energy recovery device is to reduce the energy invested in the unneutralized portion of the energetic particle beam. The most obvious method of accomplishing this is to decelerate the positively charged particles by the application

of an electrostatic field. This has been accomplished successfully on many devices that use electron beams for their operation. The problem with neutral beams is the presence of two oppositely charged species; the positive ion beam is space-charge neutralized by electrons. The decelerating electric field for the ions would accelerate the electrons, causing impractically large power drains. Hence, suppression of the ubiquitous electrons is crucial to any energy recovery scheme. Two suppression methods, electrostatic and magnetic, will be briefly discussed.

### B.1 Electrostatic Electron Suppression

Electrostatic suppression is the removal of electrons from the beam by electric fields; the resulting ion beam is then decelerated. Methods may be separated into immersed grids and circumferential field penetration. One of the first applications of immersed grids was in the pioneering isotope separator experiments of Oliphant and Yates<sup>19</sup> in 1938; the technique was later employed in uranium isotope enrichment experiments at the Y-12 plant in Oak Ridge.<sup>20</sup> It was employed to overcome the difficulties in magnetically separating full energy U-235 ions from U-238 ions that had lost part of their energy through collisions. Magnetic separation could be enhanced by decelerating the uranium ion beam to about 40 eV; only ions that had lost less than this energy would be collected. The principal difficulty of this technique was the short lifetime of the wire grid that was placed in the path of the beam and biased so as to decelerate the ions. Grid erosion is a common failing of immersed grid concepts; this enrichment method was subsequently abandoned.

Bender, Barr, and Moir extended their experience with direct converters for magnetic mirror exhaust to neutral beam energy recovery with the Immersed Grid Converter.<sup>21,22</sup> This basically consisted of three grids immersed in the ion beam

that reversed the accel/decel process that had accelerated the ion beam. Like all immersed grid concepts, it could operate at relatively high gas pressures. However, direct beam interception by the grids caused thermal stresses and thermionic electron emission, which impaired the recovery efficiency.

A novel approach employing circumferential field penetration, developed by Fumelli and co-workers at F.A.R., was dubbed the Long Electron Suppressor.<sup>23-25</sup> The potential barrier for electrons is formed by a highly transparent, negative grid surrounding the beam just after the gas neutralizer cell. Although the sheath width imposed by the neutralizer plasma is smaller than the suppressor grid diameter, ions in the sheath are deflected outwards through the grid, decreasing the sheath density and hence widening the sheath and deflecting more ions. If the suppressor is sufficiently long, the sheath will eventually penetrate to the axis, stopping electrons. Since most of the ions are deflected out of the suppressor, they can be decelerated and collected outside the beam region with plates biased close to the potential of the ion source. While no grids are directly exposed to the beam, this system adds to the length of the beam line and has problems associated with secondary electrons created at the suppressor grid and power loading on this grid.

Another circumferential field penetration device is the Space-Charge Controlled Beam Direct Converter, investigated at Livermore by Barr, Moir, Hamilton, et al.<sup>26-28</sup> In this device a suppressor ring maintained at high negative potential surrounds the beam and suppresses free electrons. Space-charge forces then expand the beam and the positive ions are collected on a series of electrodes held at high positive potential (close to the potential of the ion source). A second suppressor ring located downstream from the collector electrodes prevents electrons from entering the expansion/collection region from the downstream side. The last reported results obtained with a 100 keV, 1.7 A hydrogen beam had an initial

recovery efficiency of  $65\% \pm 7\%$ , falling to 50% at the end of the 600 millisecond pulse due to gas pressure increases. The gas pressure must be kept very low since electrons produced in the collection volume are accelerated to the collection electrodes. Positive ions produced in the volume that are accelerated to the suppressor electrode produce secondary electrons, which are in turn accelerated to the collector. Charge exchange that occurs after beam blowup but before collection is yet another loss mechanism that is pressure dependent, as is beam blowup itself. The recovery region also lengthens the beamline by a considerable amount.

In summary, problems associated with the electrostatic suppression systems so far proposed are electrostatic field penetration, grid interception, and pumping requirements. Inadequate field penetration can be solved only by reducing beam dimensions, increasing suppression voltage, or lengthening the suppressor. Grid interception leads to problems with thermal loading and secondary electron emission. Stringent pumping requirements are necessary to enhance space-charge expansion and reduce volume losses. While many of these problems are intrinsic to energy recovery devices, it will be seen that magnetic electron suppression has clear advantages with regard to field penetration.

## B.2 Magnetic Electron Suppression

The use of a transverse magnetic field to inhibit the motion of electrons while manipulating positively charged ions with electric fields had early application in the field of ion thruster research. One such device is the Hall Current Accelerator, developed for space propulsion and reported on in 1962.<sup>29</sup> It uses a longitudinal electric field to accelerate ions through a quasi-neutral plasma. Backstreaming electrons are inhibited by a radial magnetic field. The regime in which it operates

is characterized by electron gyroradii and Debye lengths which are much smaller than the accelerating column, whereas the ion gyroradii and electron mean-free-path lengths are much longer. Since the plasma in the accelerating region is approximately charge neutral, the thrust density is not limited by space-charge effects. The major loss mechanism is energy and momentum transfer to the walls.

Meyer designed an ion accelerator, termed the Space-Charge Sheath Electric Thruster,<sup>30,31</sup> which used a principle similar to that of the Hall Accelerator, but without the wall losses. It is similar to the Hall Current thruster in that ions are accelerated by an axial electric field, and electrons are inhibited by a radial magnetic field. However, the ions are accelerated not in the plasma interior but across a space-charge sheath with dimensions comparable to the electron gyroradius. The anode is a surface ionizer held at positive potential; the virtual cathode is a grounded electron emitter. Although the ion current extracted from this thruster is limited to the Child-Langmuir level, the sheath dimensions are small enough to allow high current densities. Electron leakage was fairly high with this device; in a 1970 test, the smallest electron drain current (loss current) obtained was 43% of the accelerated ion current.

Magnetic electron blocking has also been exploited by Humphries and others to develop magnetically insulated diodes for high energy, high current proton pulses.<sup>32</sup> These diodes are similar in concept to Meyer's ion thruster, using magnetic fields that are transverse to the acceleration electric field to inhibit backstreaming electrons, while the presence of the electron cloud allows the ion extraction current to exceed the Child-Langmuir space-charge limit. These diodes generally employ cylindrical geometries and extract thousands of amperes at hundreds of kilovolts for very short pulse lengths. Hence, much of the work in the

field is concerned with relativistic electron sheaths, self-induced magnetic fields, and closed electron current paths over non-steady-state time scales.

Sudan and Lovelace<sup>33</sup> and Forrester<sup>34</sup> developed non-relativistic models for parallel plate diodes of infinite extent that seem applicable to the deceleration of a space-charge neutralized ion beam. Sudan and Lovelace speculated on possible two-stream instabilities within the electron sheath, either between ions and electrons or between counter-streaming electrons. Forrester reasoned that a minimum electron current density was needed for sheath stability, which could only be supplied by external sources in a finite parallel plate geometry. This viewpoint was later modified somewhat in the face of apparently conflicting experimental evidence.<sup>35</sup>

### C. ENERGY RECOVERY EXPERIMENTS AT ORNL

In 1978, Stirling, Haselton, and Kim modified a PLT beamline in order to test an energy recovery concept employing a transverse magnetic field to block electron leakage.<sup>36</sup> The influence of magnetic fields on beam space-charge neutralization had previously been reported by Morgan and Kelley in 1961.<sup>37</sup>

In this PLT configuration, the ion source was elevated to a maximum of 800 V above ground by a boost voltage power supply. The neutralizer cell was maintained at the negative acceleration potential and was extended into the pole gap of the former ion deflection magnet. Typical beam parameters were 10 A of extracted current at 22 kV for 40 millisecond pulse lengths.  $\mathbf{E} \times \mathbf{B}$  drifting electrons that escaped the gas cell were collected on a concentric electrode biased a few hundred volts positive with respect to the neutralizer. Any ground surface near the

neutralizer could serve as a full energy ion collector, provided the ion trajectories were appropriate.

Initial experiments were limited by available power supplies, yielding small currents that were difficult to measure accurately. Estimated recovery efficiencies ranged from 20% to 80% of the available full energy ion current. Molecular hydrogen ions, accelerated to full extraction energy, dissociate in the neutralizer into atomic particles with insufficient energy to leave the gas cell and are thereby unavailable for recovery. The diagnostics were quite crude during this period; inability to distinguish between increases in recovery current and decreases in electron loss current led to some erroneous conclusions regarding the parametric effects of the boost voltage and magnetic field strength. The main outcome of these experiments was the demonstration that electron leakage can be controlled at these energies and current densities by a transverse magnetic field and the realization that fractional energy ions needed to be constrained to the neutralizer interior.

The success of the ORNL experiments encouraged investigators at LLNL to modify the electrostatic direct converter experiment in order to compare magnetic electron suppression with electrostatic. The geometry was not optimized for magnetic suppression; the ion source was maintained at high positive potential, a transverse magnetic field was applied across a grounded aperture, and the first electron suppressor was replaced with an electron collector. The ion recovery efficiency was only 40% at beam turn-on and dropped to 23% by the end of a 300 millisecond pulse.<sup>28</sup>

Experiments at ORNL continued with the "loose-coupled" geometry of Stirling and Kim<sup>38</sup> in 1978 and the "close-coupled" geometry of Stirling and Dagenhart<sup>39</sup> in 1979. The terms "loose" and "close" referred to the proximity of a ground

potential surface to the end of the neutralizer. The author of this thesis became involved when the necessity of accurate current diagnostics became increasingly apparent, and he became chief investigator of the close-coupled experiment in 1980. The close-coupled experiment was repaired after extensive damage from frozen waterlines and operated again in 1981. A new apparatus was designed and fabricated during this period and operated in 1982 until funding withdrawal forced a premature termination. The experimental data presented in this thesis were obtained during the 1980 to 1982 operating period.

In 1980 Whealton and Wooten<sup>40</sup> modified a finite-difference optics code in order to calculate the ion trajectories arising from a simplified energy recovery model. It solved a coupled Vlasov-Poisson equation with an equilibrium electron plasma at ground potential in an infinite slot (2D) geometry for a thin magnetic field at the end of the neutralizer. In the zero magnetic field region of the neutralizer, the conditions imposed were either that the potential was a constant or that the net charge density was zero. In 1981, Whealton, McGaffey, and Wooten<sup>41</sup> attempted to expand the complexity of the model by laying the groundwork for solving a Vlasov equation for electrons as well as ions. This investigator took over this development when the thesis direction changed from experimental to theoretical. The numerical models used in this problem are discussed in detail in Section 3.

Energy recovery appears to be an idea whose time has come and gone. Radio-frequency (RF) heating has supplanted neutral beam heating as the preferred auxiliary heating technique on envisioned experiments for the remainder of this century. Although RF heating has not yet achieved the power levels of neutral beams, near-term experiments should offer points of comparison. RF heating has many perceived advantages over neutral beams, among which are simplicity,

accessibility, and resistance to neutron damage. Negative ion sources, although still in their infancy, are being developed for applications demanding high energy neutral beams. Negative ions are neutralized by electron stripping, the cross sections for which remain relatively high into the MeV energy range. It is believed that the Japanese have not abandoned energy recovery research, although published results are lacking. The French plan to operate their Long Electron Suppressor on the Tore Supra beam lines with the ion collection surfaces slightly more negative than the neutralizer potential.<sup>42</sup> The device has been redubbed the Electrostatic Beam Dump since no attempt is made to recover the ion energy; in fact, the system efficiency decreases slightly with its use.<sup>43</sup> Its purpose is to remove the ions from the neutralized beam by space-charge blowup rather than by magnetic deflection. The U.S. fusion program is content with the efficiencies of present-day neutral beams.

#### D. UNITS

Standard International (SI) or MKSA (meter, kilogram, second, ampere) units are used throughout this thesis. Notable exceptions are listed below; these units conform to accepted usage in the field.

1. The centimeter (cm) is frequently used for distance ( $1 \text{ cm} = 10^{-2} \text{ meter}$ ).
2. The gauss (G) is used to denote magnetic flux density ( $1 \text{ G} = 10^{-4} \text{ tesla}$ ). The terms magnetic field, magnetic field strength, and magnetic field intensity are often used interchangeably for magnetic flux density.
3. The torr (mm Hg @0°C) is used to denote vacuum pressures ( $1 \text{ torr} = 7.5 \times 10^{-3} \text{ pascals}$ ).

## 2. PRINCIPLES OF OPERATION

### A. NEUTRAL BEAM OPERATION

#### A.1 Normal Mode Operation

Figure 2.1 shows the power supply configuration used by a positive ion neutral beam system in the normal mode of operation. Positive ions are created in the ion source, which is maintained at a high positive potential with respect to ground by the acceleration (accel) supply. The power supplies used to produce the source plasma float at the accel potential, and their primary power is provided by a high voltage isolation transformer.

The accelerator consists of three grids arranged in an accel/decel configuration. Positive ions are electrostatically accelerated across the first or accel gap and are slightly decelerated across the second or decel gap. The accel gap is often separated into two gaps for beam energies of 80 keV or greater. The decel gap prevents electrons from the gas cell neutralizer from being accelerated back toward the ion source. The decel potential is provided by a separate supply referenced to ground; this supply is typically sized to provide about 10% of the accel supply current at about 10% of the accel voltage.

The positive ions traverse a gas-filled tube called the neutralizer, where they are neutralized by charge-exchange reactions with the background gas. The line density in the neutralizer is maintained at a high enough value to achieve equilibrium between the neutralization and ionization processes. The fraction of the ion beam that is neutralized is a decreasing function of particle energy.

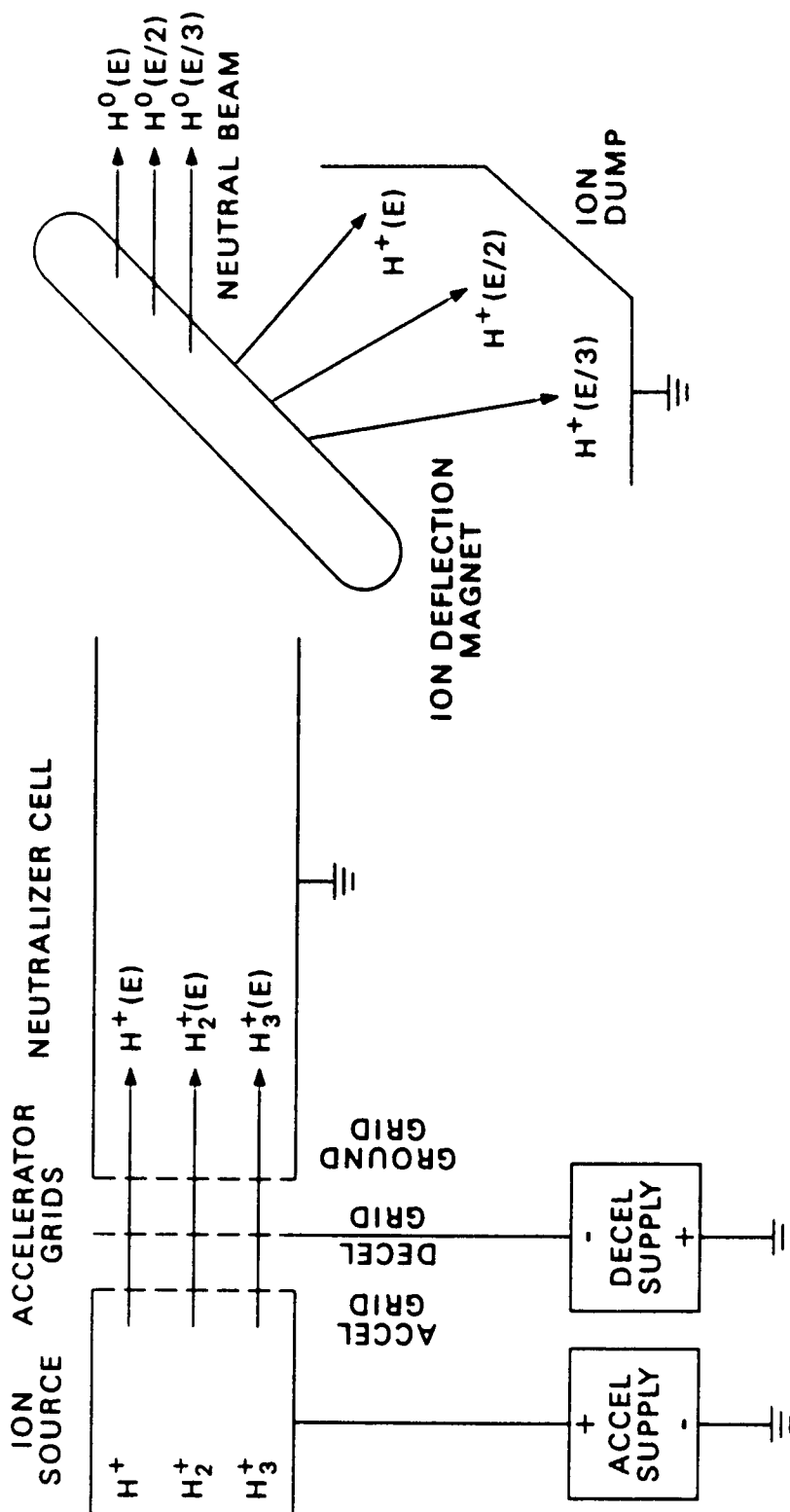


Fig. 2.1. Power supply configuration for normal operation of a neutral beam injector. The deflection magnet downstream of the neutralizer cell bends the unneutralized beam particles onto water-cooled ion dumps.

The charged fraction of the beam is swept onto water-cooled ion dumps by a deflection magnet positioned after the neutralizer. This removes the charged particles before they encounter the magnetic fields of the plasma confinement device. These magnetic fields deflect beam ions onto the walls of the drift tube, causing wall heating, outgassing, and gas pressure increases.

## A.2 Energy Recovery Operation

The basic idea of an energy recovery device is to reclaim the energy residing in the unneutralized portion of the ion beam. This is accomplished by electrostatically decelerating these ions and collecting them on surfaces whose potential is close to the ion source potential. Since it is difficult to collect ions at their birth potential (i.e., with no energy loss), the ions are given a slight excess velocity to enable them to reach the collection surface. This is accomplished by elevating the ion source slightly above ground and collecting these ions at ground potential. The difference between the ion source potential and ground is called the boost potential. This boost potential constitutes an energy loss, so it is desirable to operate at as low a boost voltage as is compatible with efficient ion collection.

Electrons created in the neutralizer are constrained from accelerating to ground by a transverse magnetic field that is applied across the end of the neutralizer. Electrons that do enter the retarding sheath region find themselves in the presence of a transverse magnetic field and an inwardly directed axial electric field. They drift vertically due to  $\mathbf{E} \times \mathbf{B}$  effects and are collected on an electron collector which surrounds the neutralizer and is biased positively with respect to it. Again, since this represents a loss mechanism, the electron collector voltage with respect to the neutralizer is held at as low a value as is consonant with

efficient electron collection. Figure 2.2 shows the neutralizer, electron collector, and electron suppression magnet for a typical energy recovery geometry.

Figure 2.3 shows two power supply configurations for energy recovery operation; both configurations provide identical potential variations along the beam line. In energy recovery operation, the beam is formed by the same accel/decel method as in the normal mode. However, the neutralizer is now maintained at a negative voltage with respect to ground and the ion source is near ground potential.

Power supply configuration I may be preferable to configuration II from a system design standpoint. The decel and electron collector supplies and the isolation transformer needed to power them are identical in both configurations. The total power to be provided by the accel and boost supplies is the same for both configurations, although distributed differently.

In configuration I, the boost supply provides the total beam current while the accel supply provides the neutralization current and neutralizer loss current. The two supplies share the beam power since both contribute to the total acceleration voltage.

In configuration II, the boost supply provides only the ion recovery current, while the accel supply again provides the neutralization and loss currents. The power requirements are more easily separated in this configuration: the boost supply provides the power to collect the full energy ions, while the accel supply provides all the neutral beam power, as well as the neutralizer losses.

Configuration II is a bit more complex than configuration I since both supplies are no longer referenced to ground. It requires an additional isolation transformer for the accel supply as well as a telemetry system to control it from ground potential. Both configurations were tested during the course of the experiments;

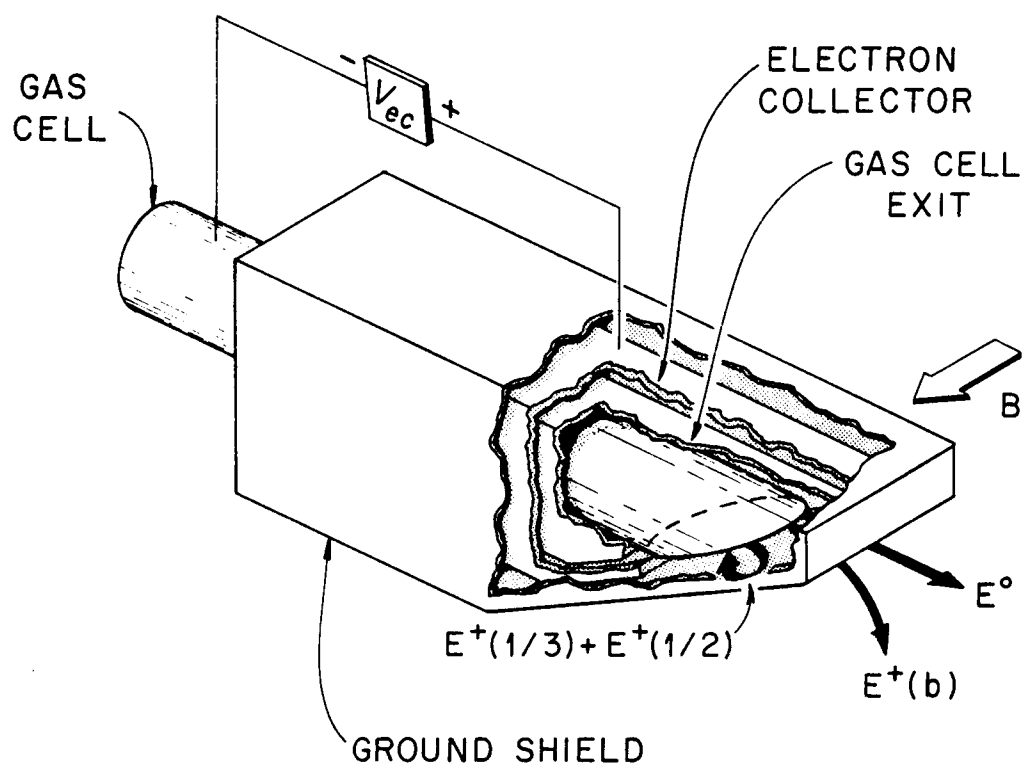
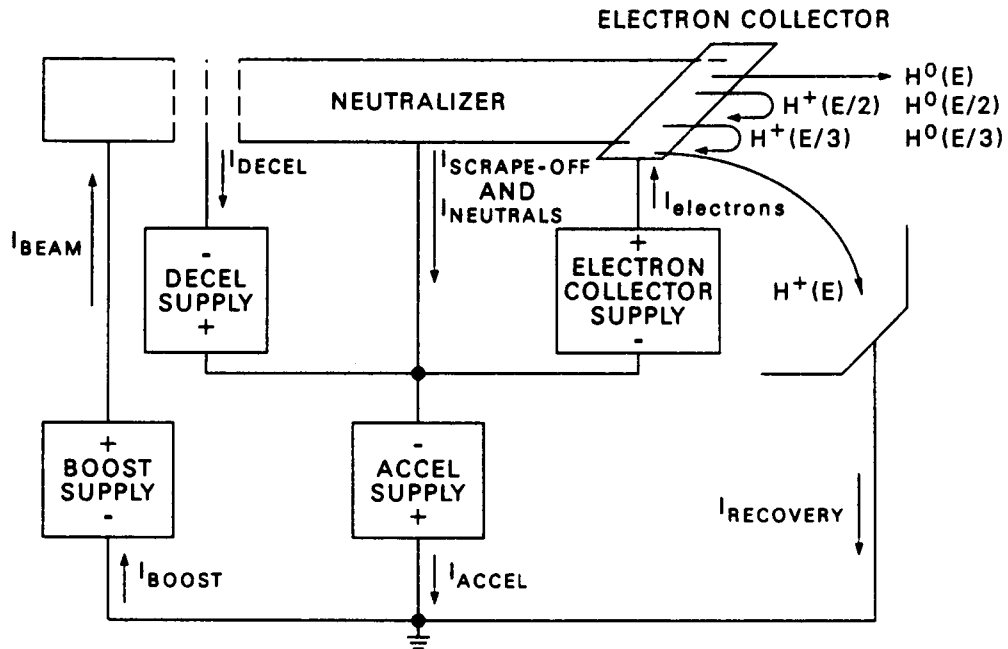
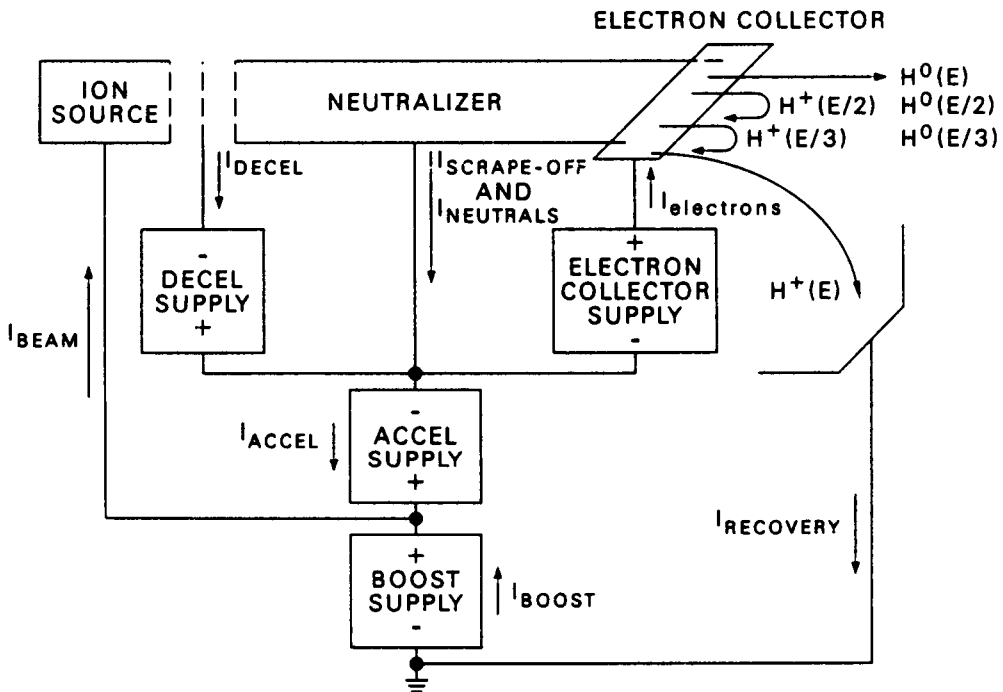


Fig. 2.2. Representative energy recovery device using magnetic electron suppression.



(a) POWER SUPPLY CONFIGURATION I



(b) POWER SUPPLY CONFIGURATION II

Fig. 2.3. Alternative power supply configurations for energy recovery operation.

the availability of existing equipment and diagnostic considerations favored configuration II. This is discussed more fully in Section 4.

## B. BEAM DISSOCIATION AND NEUTRALIZATION

The hydrogen plasma produced in the ion source is composed of three species of positive ions,  $H^+$ ,  $H_2^+$ , and  $H_3^+$ . These ions are extracted in the same ratios as obtain in the source and acquire the full energy of the acceleration potential. Upon entering the neutralizing gas cell, these energetic ions interact with the background gas in a variety of atomic processes. Kim and Haselton<sup>44</sup> have solved the rate equations analytically; results for a 40 keV hydrogen beam (80 keV deuterium beam) are shown in Figure 2.4. It should be noted that for neutralizer line densities above  $2 \times 10^{16} \text{ cm}^{-2}$ , the negative ion and molecular components become negligible and complete dissociation of the beam can be assumed. Since this is the regime in which neutral beams are designed to operate, the analysis can be simplified accordingly.

Complete dissociation of the molecular ions that are accelerated to energy  $E$  yields fractional energy beam components:

$$H_2^+(E) \rightarrow H^+(E/2) + H^0(E/2) , \quad (2.1)$$

$$H_3^+(E) \rightarrow H^+(E/3) + 2H^0(E/3) . \quad (2.2)$$

The fraction of ions and neutrals at each energy can be calculated from the rate equations

$$\frac{dn^+}{dx} = N_0[-n^+\sigma_{10}(E) + n^0\sigma_{01}(E)] , \quad (2.3)$$

$$\frac{dn^0}{dx} = N_0[+n^+\sigma_{10}(E) - n^0\sigma_{01}(E)] , \quad (2.4)$$

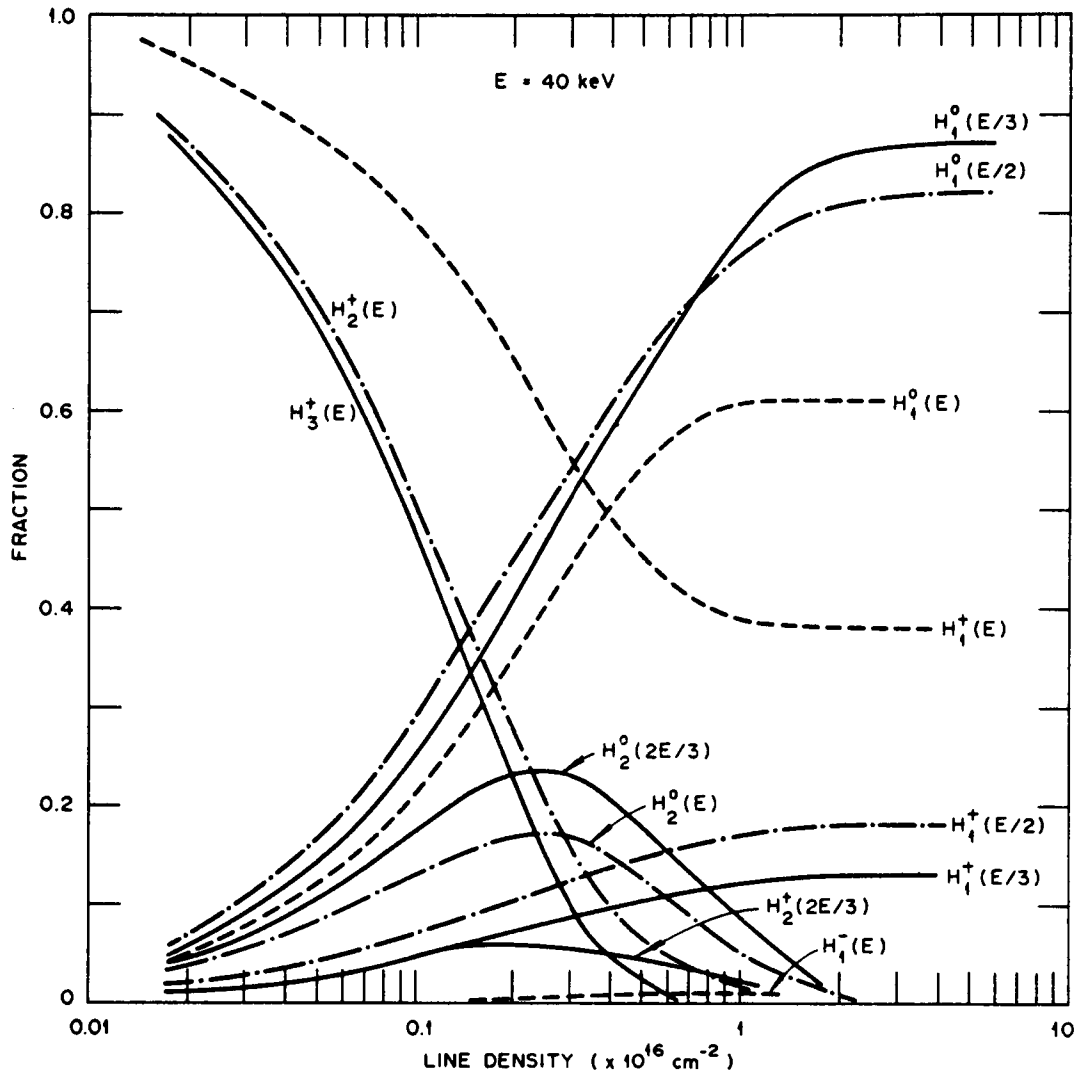
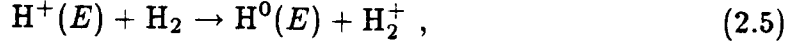
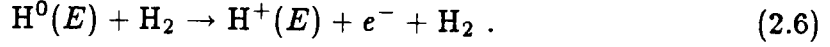


Fig. 2.4. Variation of fractional powers carried by particle species as a function of the downstream line density of  $H_2$  ( $D_2$ ) for a 40 keV hydrogen (80 keV deuterium) beam.

where  $n^+$  is the fast ion density,  $n^0$  is the fast neutral density,  $N_0$  is the background gas density,  $\sigma_{10}(E)$  is the electron capture cross section,



and  $\sigma_{01}(E)$  is the electron stripping cross section,



The ion and neutral beam density solutions can be expressed as a function of the line density  $\pi$ :

$$n^+(\pi) = n^+(0) \left\{ \left( \frac{\sigma_{01}}{\sigma_{01} + \sigma_{10}} \right) + \left( \frac{\sigma_{10}}{\sigma_{01} + \sigma_{10}} \right) \exp[-(\sigma_{01} + \sigma_{10})\pi] \right\} , \quad (2.7)$$

$$n^0(\pi) = n^+(0) \left\{ \left( \frac{\sigma_{10}}{\sigma_{01} + \sigma_{10}} \right) - \left( \frac{\sigma_{10}}{\sigma_{01} + \sigma_{10}} \right) \exp[-(\sigma_{01} + \sigma_{10})\pi] \right\} , \quad (2.8)$$

$$\pi = \int_0^L N_0(x) dx . \quad (2.9)$$

As the line density  $\pi$  is increased, the ion and neutral densities approach

$$n^+(\infty) = \left[ \frac{\sigma_{01}(E)}{\sigma_{01}(E) + \sigma_{10}(E)} \right] n^+(0) = f_{1\infty}(E) n^+(0) , \quad (2.10)$$

$$n^0(\infty) = \left[ \frac{\sigma_{10}(E)}{\sigma_{01}(E) + \sigma_{10}(E)} \right] n^+(0) = f_{0\infty}(E) n^+(0) , \quad (2.11)$$

where  $n^+(0)$  is the initial beam ion density, and  $f_{1\infty}(E)$  and  $f_{0\infty}(E)$  are defined as the ionization and neutralization equilibrium fractions. The values of the curves at the far right of Figure 2.4 correspond to the ionization and neutralization equilibrium fractions for each of the three energies present in the beam.

## C. LOSS MECHANISMS

### C.1 Electron Leakage Current

The neutralizer gas cell contains a plasma that is produced by the beam interactions with the background gas. This plasma is the source of free electrons which provide space-charge neutralization of the ion beam to prevent electrostatic blowup. The plasma density is more than an order of magnitude greater than the beam density and the space potential is near the neutralizer potential. In the case of energy recovery, this plasma is also the source of electrons which can be accelerated to ground, thereby draining power from the system.

The plasma density in the neutralizer depends on the production rate cross section  $\sigma_{ei}$ , the neutral density  $n_0$ , the beam energy  $V_b$ , the electron temperature  $T_e$ , and the beam half-width  $d$ . Dunn and Self<sup>45</sup> derive a scaling law that relates the electron density  $n_e$  to the beam particle density  $n_b$ ,

$$\frac{n_e}{n_b} = \frac{\sigma_{ei} n_0 d (V_b)^{1/2}}{0.344 (k T_e / e)^{1/2}} . \quad (2.12)$$

For the 36 kV, 10 A beam that is analyzed in detail in Chapter V, the calculated plasma density is 28 times the beam particle density ( $n_e \simeq 3 \times 10^9 \text{ cm}^{-3}$ ). This assumes a local pressure of  $6 \times 10^{-4}$  torr and an electron temperature of 8 eV.<sup>46,47</sup> Burrell et al.<sup>46</sup> measured plasma densities in excess of  $10^{11} \text{ cm}^{-3}$  near the extraction grids for a 100 kV, 7.8 A beam, and report an  $n_e/n_b$  ratio of about 30. Guethlein and Kunkel<sup>47</sup> measured a plasma density in the neutralizer of 1 to  $10 \times 10^{10} \text{ cm}^{-3}$  for gas pressures in the  $10^{-3}$  torr region. A plasma in contact with the ground surfaces of the vacuum vessel will also form by the same mechanisms that produce the neutralizer plasma; the space potential is near the system ground.

A double sheath separating the neutralizer plasma from the ground or target plasma forms at the end of the neutralizer cell. Electrons from the neutralizer plasma that reach the virtual cathode boundary are accelerated toward the virtual anode. For a sufficiently high magnetic field, these electrons possess gyroradii smaller than the sheath dimensions and drift in the  $\mathbf{E} \times \mathbf{B}$  direction.

In the case of a rectangular geometry such as in Figure 2.5, the upward electron drift tends to accumulate negative charge at the top of the device, which causes a vertical polarization field  $\mathbf{E}_p$  to appear. In other geometries a vertical electric field component may exist as part of the Poisson equation solution. The effect of the vertical electric field crossed with the applied magnetic field is to transport electrons out of the top of the neutralizer. This leakage current is inversely proportional to the magnetic field strength and can be collected by a positively biased electrode positioned over the end of the neutralizer.

Electrons can also be transported across the field lines by collisional diffusion and by turbulence resulting from sheath instabilities. The leakage current seen in experiments will be shown to be inversely proportional to  $B$ .

## C.2 Volume Processes

Magnetic suppression of electrons creates a sheath at the end of the neutralizer whose dimensions are determined by the beam current density, neutral background density, and the position of ground surfaces. Strong electric fields exist in this recovery volume, and any electric charges created in this region will be swept out, thereby draining power from the system.

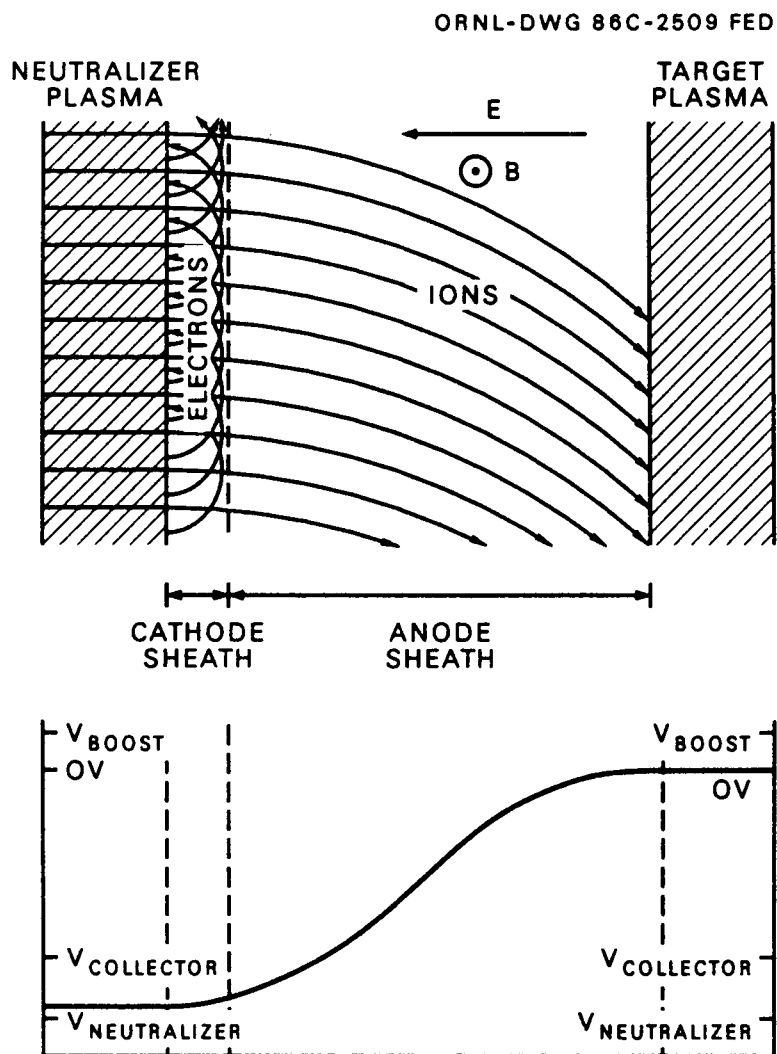
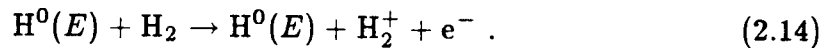
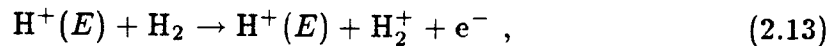


Fig. 2.5. Schematic of the double sheath which separates the neutralizer plasma from the target plasma.

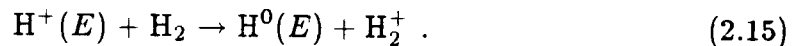
Volume ionization occurs when energetic beam particles ionize the background gas, creating ion-electron pairs,



Ionization near the cathode sheath will create electrons whose birth potential is more negative than the collector potential. These electrons will become trapped on equipotential surfaces and, in the absence of collisions or instabilities, will drift toward the upper electron collector. The ions will be collected on the negative neutralizer.

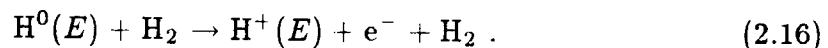
Electrons created at potentials more positive than the collector potential must eventually go to ground surfaces. If the field line on which they are created intersects a ground surface, the electric field will accelerate them along this path to ground. Otherwise they will drift toward the top ground plate. The ions will strike either the electron collector or the neutralizer.

A second volume process that adds losses to the system is charge exchange of beam ions with the background gas,



When this occurs in the recovery region, the slow ion will be accelerated back to the neutralizer. The fast neutral will continue in a straight line and most probably will depart the beam envelope. The energy of this neutral thus does not contribute to delivered beam power, and its energy cannot be recovered.

A third volume process is stripping of the beam neutrals by the background gas,



This loss mechanism is present in all neutral beams and is referred to as reionization loss. This effect is accounted for in the transmission efficiency  $\eta_T$  for the neutral beam in the normal mode and is therefore not included as an energy recovery loss.

The cross sections for volume ionization by energetic electrons are more than an order of magnitude below those for energetic ions and neutrals. This ionization process becomes a concern only when the total electron path length becomes very large. P.I.G. (Penning Ionization Gauge<sup>48,49</sup>) discharges occur when electrons are constrained to magnetic field lines and oscillate between two negative potential surfaces. Such a process could occur only in the neutralizer; care was taken in the design of the electrodes to prevent P.I.G. discharges.

Volume losses are discussed and quantitative effects are estimated in Section 5.

### C.3 Secondary Electron Emission

Secondary electrons are emitted when energetic ions strike the collector and neutralizer surfaces with energies greater than  $2\phi$ , where  $\phi$  is the work function of the surface. The secondary emission coefficient (number of electrons emitted per incident ion) is a function of the incident particle energy, the incident angle, and the surface condition.

(a) The secondary emission coefficient for normally incident  $H^+$  on clean Cu is approximately unity, varying from 0.78 at 10 keV to 1.23 at 40 keV.<sup>50</sup>

(b) The secondary emission coefficient increases as the angle of incidence decreases. The coefficient  $\gamma$  varies with the angle of impact  $\theta$  between the incoming

direction and the surface normal in the manner<sup>51</sup>

$$\gamma(\theta) = \frac{\gamma(\theta = 0)}{\cos \theta} . \quad (2.17)$$

The computer calculations indicate that ions strike the negative potential surfaces of the neutralizer and collector at shallow angles with respect to the surface, enhancing the emission of electrons.

(c) The secondary emission coefficient is dependent on the cleanliness of the emitting surface and appears to increase when the surface is covered with gas. The secondary emission coefficient for 10 keV H<sup>+</sup> ions on a degassed Cu surface is 0.7, while the same ions yield a coefficient of 2.0 to 2.6 for an uncleaned Cu surface.<sup>51</sup>

Secondary electrons emitted from the lower neutralizer should contribute to the cathode sheath electron flow and drift to the electron collector. Electrons emitted from the collector, particularly the exterior of the collector side plates, will be accelerated along magnetic field lines to ground surfaces. Electrons emitted from ground surfaces will be collected on ground surfaces with no energy loss.

#### D. DEFINITIONS OF EFFICIENCY

There are many efficiency terms that are used to describe neutral beam and energy recovery systems, each with its own justification and application. These will be defined in this section.

The *ion current collection efficiency*, or simply ion collection efficiency, is the measure of how well the energy recovery device collects the full energy ions that emerge from the neutralizer,

$$\eta_{ic} = \frac{\text{ion current collected}}{\text{available ion current}} = \frac{I_{ion}}{\eta_N f_{1\infty}(E_0) \eta_1 I_0} . \quad (2.18)$$

Here  $\eta_N$  is the neutralizer transmission efficiency, which is a function of beam optics;  $\eta_1$  is the fraction of atomic ions in the source plasma ( $\eta_2$  and  $\eta_3$  are the

fractions for the molecular ions  $H_2^+$  and  $H_3^+$ ); and  $I_0$  is the total beam current extracted from the ion source. The denominator merely represents the full energy ion current emerging from the neutralizer. The fractional energy ions are not available for recovery, since they do not possess sufficient energy to reach a ground surface.

The ion collection efficiency is a function of boost voltage; the higher the boost voltage, the more easily ions can be collected on ground surfaces. The *ion power recovery efficiency* reflects the power expended by the boost supply in order to collect ions,

$$\eta_{ip} = \frac{\text{power recovered from ions}}{\text{power residing in ions}} = \frac{I_{ion}(V_0 - V_{boost})}{\eta_N f_{1\infty}(E_0) \eta_1 V_0 I_0} . \quad (2.19)$$

Here use can be made of the definition of ion collection efficiency and the dimensionless parameter  $\mu$ , defined as the ratio of the boost voltage to the beam acceleration voltage,

$$\eta_{ip} = \eta_{ic}(1 - \mu) . \quad (2.20)$$

The *net current recovery efficiency* takes the electron losses into account; the difference between the ion collection current and the electron loss current is the net recovery current,

$$\eta_c = \frac{\text{net recovery current}}{\text{available ion current}} = \eta_{ic} - \frac{I_{loss}}{\eta_N f_{1\infty}(E_0) \eta_1 I_0} . \quad (2.21)$$

The *net power recovery efficiency* is defined in an analogous fashion,

$$\eta_p = \frac{\text{net power recovered}}{\text{power residing in ions}} = \eta_c(1 - \mu) . \quad (2.22)$$

The *system efficiency* for a neutral beam is liberally defined as the ratio of the neutral power delivered to the plasma to the electrical power expended. This definition is based on the assumption that all the delivered neutral power is utilized. A more strict definition would recognize that in some applications, such

as barrier pumping in tandem mirrors and some tokamak heating scenarios, only the full energy neutral component is useful and the fractional energy components may be harmful. This discussion will use the more liberal definition, which can be expressed as

$$\eta_{\text{sys}} = \eta_T [\eta_1 f_{0\infty}(E) + \eta_2 f_{0\infty}(E/2) + \eta_3 f_{0\infty}(E/3)] . \quad (2.23)$$

Here  $\eta_T$  is the total system transmission efficiency, which takes into account all the beam losses between the accelerator and the target plasma. Neglected in this definition of system efficiency are the power used to generate the ion source plasma and the power expended by the decel supply (typically a few percent of the accel power).

The purpose of energy recovery is to reduce the electrical power spent to deliver neutral power to the plasma. The reduction in total electrical power is the power recovered from the full energy ion population. The system efficiency with energy recovery can be expressed in terms of the normal mode system efficiency:

$$\eta_{\text{sys}}^* = \frac{\eta_{\text{sys}}}{1 - \eta_c(1 - \mu)\eta_N\eta_1 f_{1\infty}(E)} . \quad (2.24)$$

The potential improvement in system efficiency with energy recovery is dependent not only on the net power recovery efficiency but also on such beam parameters as neutralizer transmission efficiency and atomic ion fraction.

The latest generation of positive ion sources is characterized by high atomic ion fractions and low divergence beam optics. Figure 2.6 shows the system efficiency as a function of beam energy for a state-of-the-art positive ion source with an atomic fraction ( $\eta_1$ ) of 90%, a neutralizer transmission efficiency ( $\eta_N$ ) of 98%, and an overall system transmission efficiency ( $\eta_T$ ) of 85%.<sup>52</sup> The parameter of variation between the family of curves in Figure 2.6 is the net power collection efficiency ( $\eta_p$ ). A power collection efficiency of 0% corresponds to normal mode

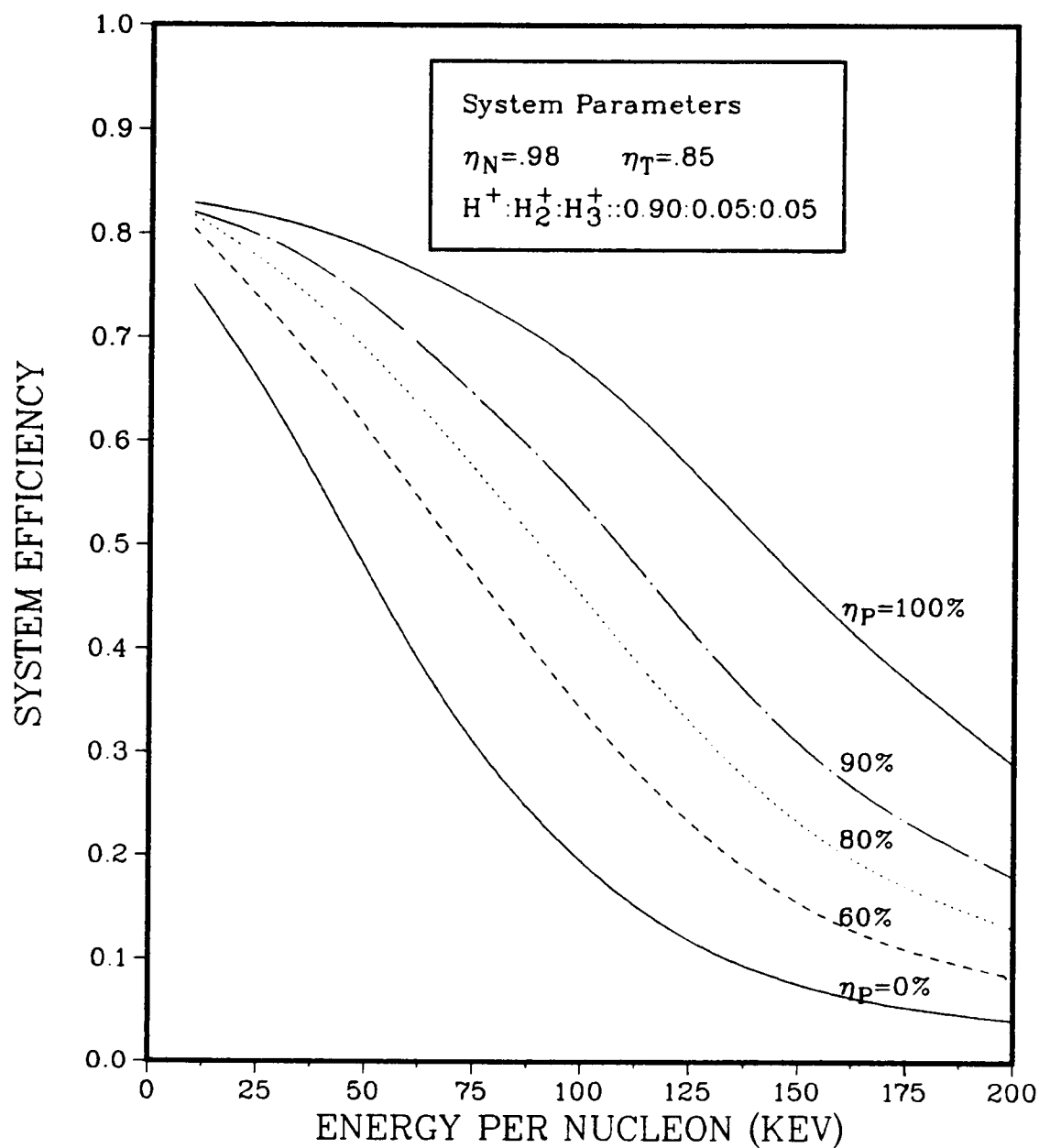


Fig. 2.6. Overall system efficiency vs. beam energy as a function of net power recovery efficiency.

operation while a power collection efficiency of 100% represents the theoretical maximum. This maximum would be very difficult to achieve in practice, as it implies that all the full energy ions can be collected at their birth potential and that the electron loss currents can be reduced to zero. It can be seen in Figure 2.6 that for beam energies greater than about 175 keV per nucleon, the unrecoverable energy residing in the fractional energy ions exceeds the neutral power delivered to the target.

None of the efficiencies defined in this section take the electron collector supply into account. It is anticipated that, with a strong magnetic suppression field to reduce leakage current and a low collector bias, this term can be reduced to negligible values.

### 3. NUMERICAL MODELING

The numerical code used in modeling the energy recovery device is a variation of the ORNL ion optics code, originally developed by Jaeger and Whitson<sup>53</sup> and extensively modified and improved by Whealton and co-workers.<sup>54</sup> The code has been described in great detail in the literature; its basic operation will be described here before considering the modifications necessary for the energy recovery problem.

#### A. ORNL ION OPTICS CODE

The ORNL ion optics code is a finite-difference code that solves a coupled Vlasov-Poisson system of equations,

$$\nabla^2 u = \exp(-u) - \int f_i d\mathbf{v} , \quad (3.1)$$

$$\mathbf{v} \cdot \nabla f_i + \frac{d\mathbf{v}}{dt} \cdot \nabla_v f_i = 0 . \quad (3.2)$$

Poisson's equation (3.1) describes the electrostatic potential arising from an ion distribution function  $f_i$ , a Boltzmann distribution of electrons, and applied potentials at the boundaries. Vlasov's equation (3.2) describes the phase-space occupation of the ions under the influence of an electrostatic potential distribution. Note that these equations are coupled through the scaled electrostatic potential  $u$  and the ion distribution function  $f_i$  and that they are nonlinear in nature. We will first consider the Poisson equation.

### A.1 Electrostatic Potentials: Solution of the Poisson Equation

Poisson's equation in MKS units can be expressed as

$$\nabla^2 \Phi = \frac{\rho}{\epsilon_0} = \frac{e}{\epsilon_0} \left\{ n_i - n_{e0} \exp \left[ \frac{-e(\Phi_0 - \Phi)}{kT_e} \right] \right\} \quad (3.3)$$

where

$\epsilon_0$  = permittivity of free space

$e$  = electronic charge

$k$  = Boltzmann's constant

$\Phi_0$  = electrostatic potential at center of source plasma

$n_{e0}$  = electron density at center of the source plasma.

This equation is simplified by scaling the potential by the electron temperature  $T_e$  and scaling the axial distance  $z$  and the vertical distance  $r$  by the Debye length  $\lambda_D$ :

$$u = \frac{e(\Phi_0 - \Phi)}{kT_e} , \quad (3.4)$$

$$x = z/\lambda_D , \quad (3.5)$$

$$y = r/\lambda_D , \quad (3.6)$$

$$\lambda_D = \left( \frac{\epsilon_0 k T_e}{n_{e0} e^2} \right)^{1/2} . \quad (3.7)$$

Equation (3.3) can now be expressed in scaled coordinates as

$$\nabla^2 u = \frac{-n_i}{n_{e0}} + \exp(-u) . \quad (3.8)$$

We further require that  $n_{e0} = n_{i0} = 1$  at the emitting surface. This is equivalent to requiring space-charge neutralization at the center of the plasma.

We have assumed a Boltzmann distribution of electron densities

$$n_e = n_{e0} \exp \left[ \frac{-e(\Phi_0 - \Phi)}{kT_e} \right] \quad (3.9)$$

in equation (3.3); this electron charge term is effective primarily where  $\Phi \simeq \Phi_0$  ( $u \simeq 0$ ), that is, in the center of the ion source plasma.

The finite-difference code replaces the partial derivatives in the Laplace operator with the usual three-point central difference quotients,

$$u_x \simeq \frac{u(x+h, y) - u(x-h, y)}{2h} \quad (3.10)$$

$$u_{xx} \simeq \frac{u(x+h, y) + u(x-h, y) - 2u(x, y)}{h^2} \quad (3.11)$$

The code allows for irregular boundaries, using linear interpolation to scale contributions from neighboring points. In general, following the numbering scheme in Figure 3.1,

$$u_0 = \left( \frac{h_2}{h_1 + h_2} \right) u_1 + \left( \frac{h_1}{h_1 + h_2} \right) u_2 \quad (3.12)$$

$$u_1 = u(x_0 + h_1, y_0) = u_0 + h_1 u_x + \frac{h_1^2}{2} u_{xx} + \dots \quad (3.13)$$

$$u_3 = u(x_0 - h_3, y_0) = u_0 - h_3 u_x + \frac{h_3^2}{2} u_{xx} + \dots \quad (3.14)$$

We can eliminate  $u_x$  and solve for  $u_{xx}$  to get:

$$u_{xx} = \frac{2[h_3 u_1 + h_1 u_3 - (h_1 + h_3) u_0]}{h_1 h_3 (h_1 + h_3)} + \dots \quad (3.15)$$

Similarly for  $u_{yy}$ ,

$$u_{yy} = \frac{2[h_4 u_2 + h_2 u_4 - (h_2 + h_4) u_0]}{h_2 h_4 (h_2 + h_4)} + \dots \quad (3.16)$$

Equation (3.1) can now be expressed as

$$u_{xx} + u_{yy} = C_1 u_1 + C_2 u_2 + C_3 u_3 + C_4 u_4 - C_0 u_0 = -\rho_i \quad (3.17)$$

and solved for  $u_0$ ,

$$u_0 = k_1 u_1 + k_2 u_2 + k_3 u_3 + k_4 u_4 + k_5 \rho_i \quad (3.18)$$

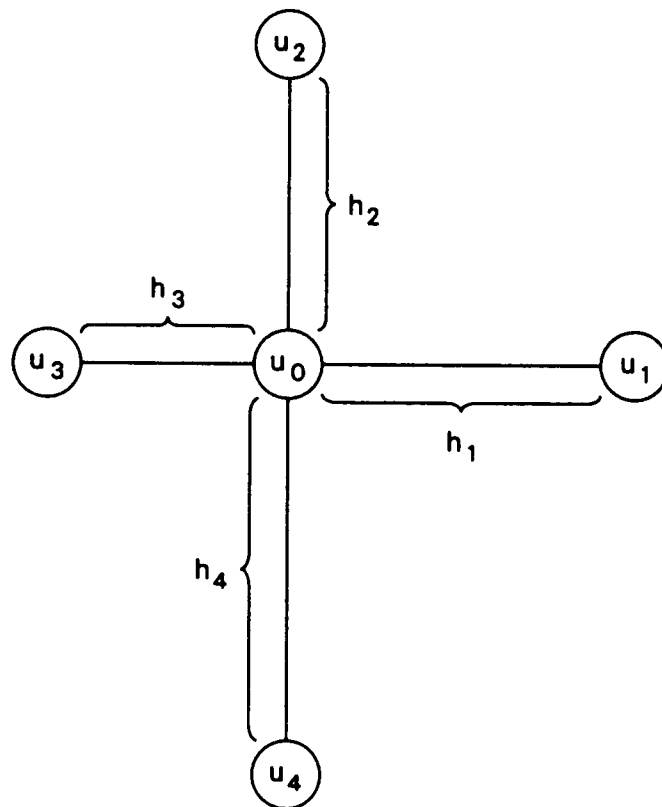


Fig. 3.1. General case of the numbering scheme for the finite difference mesh.  
 Away from irregular boundaries, the mesh intervals  $h_i$  reduce to unity.

The coefficients  $k_1, k_2, k_3, k_4$ , and  $k_5$  are determined by the mesh intervals  $h_1, h_2, h_3$ , and  $h_4$ . For a mesh cell with regular boundaries,  $h_1 = h_2 = h_3 = h_4 = 1$ , so that (3.18) reduces to

$$u_0 = \frac{1}{4}u_1 + \frac{1}{4}u_2 + \frac{1}{4}u_3 + \frac{1}{4}u_4 - \frac{1}{4}\rho_i. \quad (3.19)$$

The parameter  $\rho_i$  is the positive ion charge density, derived from the solution to the Vlasov equation; the nonlinear electron term is not yet considered.

The initial solution sets  $\rho_i$  to zero; this corresponds to the Laplace problem  $\nabla^2 u = 0$ . The mesh generator of Hornsby<sup>55</sup> demands a simply connected closed surface; either Neumann or Dirichlet boundary conditions are specified on all surfaces. Surfaces that are conducting electrodes use Dirichlet boundary conditions ( $u = \text{constant}$ ); other surfaces represent free-space boundaries and require Neumann conditions ( $\partial u / \partial n = E_\perp = 0$ ). The former condition fixes electrode potentials while the latter forces the electric field to be parallel to the surface. Neumann surfaces are generally the gaps between electrodes at different potentials; the geometry is usually configured so that these surfaces are removed from regions of interest.

The solution  $u_0$  of the algebraic equation (3.18) is iterated by a Gauss-Seidel method, whereby  $u_0$  is calculated from two neighboring values of  $u$  of the same order of iteration, and two values of the previous order of iteration:

$$u_0^{(n)} = k_1 u_1^{(n-1)} + k_2 u_2^{(n-1)} + k_3 u_3^{(n)} + k_4 u_4^{(n)} \quad (3.20)$$

The Gauss-Seidel method offers slightly higher rates of convergence than the explicit Jacobi method:

$$u_0^{(n)} = k_1 u_1^{(n-1)} + k_2 u_2^{(n-1)} + k_3 u_3^{(n-1)} + k_4 u_4^{(n-1)}. \quad (3.21)$$

It also saves on memory requirements since the  $n$ th iteration can immediately overwrite the  $(n-1)$ th iteration.

After the Laplace equation is solved for the potential in the absence of space charge,  $u$  can then be inserted into the Vlasov equation to compute the resulting positive ion trajectories. By a technique that will be discussed shortly, the space charge arising from these positive ions,  $\rho_i$ , is next calculated, and the cycle begins again with iterating the solution to equation (3.18).

The code uses a simultaneous convergence scheme to solve the nonlinear Poisson equation, whereby the nonlinear potential is estimated and used in the next linear potential approximation. Suppose  $u_0^{(n)}$  is the  $n$ th Gauss-Seidel iteration of  $u_0$ , obtained from

$$u_0^{(n)} = k_1 u_1^{(n-1)} + k_2 u_2^{(n-1)} + k_3 u_3^{(n)} + k_4 u_4^{(n)} + k_5 \rho_i . \quad (3.22)$$

At this point in the calculation,  $u_0^{(n)}$  may be referred to as a linear potential, since it is the solution to the "linear" equation

$$\nabla^2 u = \rho_i , \quad (3.23)$$

where  $\rho_i$  is the normalized ion space-charge term arising from the solution to the Vlasov equation. Although  $\rho_i$  is dependent on  $u$  through the Vlasov equation, (3.23) may be considered linear since  $\rho_i$  is a constant throughout the Gauss-Seidel iteration cycle.

The nonlinear electron term,  $\exp(-u)$ , which arises from the assumed Boltzmann distribution of electrons, modifies this linear solution; the resulting  $u$  is obtained via a Newton method.

As shown earlier, the Laplace operator may be represented by a finite difference operator

$$\begin{aligned} \nabla^2 u_0 &= C_1 u_1 + C_2 u_2 + C_3 u_3 + C_4 u_4 - C_0 u_0 \\ &= k_0 u_0 - k_0 g , \end{aligned} \quad (3.24)$$

where the coefficients  $C_i = f(h_1, h_2, h_3, h_4)$ ,  $k_0 = -C_0$ , and  $g = (C_1 u_1 + C_2 u_2 + C_3 u_3 + C_4 u_4)/C_0$ . The linear solution  $u_{00}$  for the potential at node 0 is

$$u_{00} = \left( \frac{k_0 g - \rho_i}{k_0} \right) . \quad (3.25)$$

Similarly, the solution  $u_0$  at node 0 of the nonlinear equation

$$\nabla^2 u + \rho_i - \exp(-u) = 0 \quad (3.26)$$

is

$$u_0 = \left( \frac{k_0 g - \rho_i}{k_0} \right) + \frac{\exp(-u_0)}{k_0} = u_{00} + \frac{\exp(-u_0)}{k_0} , \quad (3.27)$$

$$f(u_0) = u_0 - \exp(-u_0)/k_0 - u_{00} = 0 \quad (3.28)$$

We estimate the solution to this nonlinear equation by iterating with Newton's method:

$$u_0^{(m+1)} = u_0^{(m)} - \frac{f(u_0^{(m)})}{f'(u_0^{(m)})} \quad (3.29)$$

$$f'(u_0) = \frac{\partial f(u_0)}{\partial u_0} = 1 + \frac{\exp(-u_0)}{k_0} \quad (3.30)$$

$$u_0^{(m+1)} = \frac{(u_0^{(m)} + 1)\exp(-u_0^{(m)}) + k_0 u_{00}}{k_0 + \exp(-u_0^{(m)})} \quad (3.31)$$

Using the linear potential solution  $u_{00}$  as the initial guess, the potential  $u_0$  is computed to sufficient accuracy in a few iterations. The simultaneous convergence scheme does not demand that the residue between Newton iterations become vanishingly small before using the estimate in the next Gauss-Seidel iteration. Before returning to the Gauss-Seidel loop, successive over-relaxation (SOR) is used to further speed convergence:

$$u_0^{(n)} = \beta u_0^{(n)} + (1 - \beta) u_0^{(n-1)} , \quad (3.32)$$

where  $u_0^{(n)}$  is the potential just derived from the Newton method, and  $u_0^{(n-1)}$  is the potential from the previous Gauss-Seidel iteration. A value of  $\beta$  between 1 and 2 yields much faster convergence than a  $\beta$  of unity; a typical value is  $\beta = 1.75$ .

The Poisson loop, comprising the Gauss-Seidel iterations, the Newton iterations, and the SOR iteration, is repeated for a specified number of times (on the order of 100), at which point the potential is considered solved for the given ion distribution. The next step is to again solve the Vlasov equation with the new potential distribution.

## A.2 Ion Trajectories: Solution to the Vlasov Equation

The ion trajectories in the ion optics code arise from the solution to the Vlasov equation

$$\mathbf{v} \cdot \nabla f_i + \frac{\mathbf{F}}{m_i} \cdot \nabla_v f_i = 0 , \quad (3.2)$$

where  $\mathbf{F}$  is the electrostatic Coulomb force

$$\mathbf{F} = q\mathbf{E} = -q\nabla\Phi . \quad (3.33)$$

$\Phi$  is related to the solution  $u$  of the Poisson equation (3.8) through the scaling relationship (3.4).

Whealton implemented an expeditious technique to solving this Vlasov equation by directly solving the equations of motion for a specified initial ion distribution function.<sup>56</sup> In each cell defined by the Poisson mesh points, a constant electric field vector is calculated from the potentials at the nodes. It follows from the assumption of a constant acceleration that the ion motion within the cell can be described by a parabola,

$$\mathbf{v} = \mathbf{v}_0 + \mathbf{a}t , \quad (3.34)$$

$$\mathbf{r} = \mathbf{r}_0 + \mathbf{v}_0 t + \frac{1}{2} \mathbf{a} t^2 . \quad (3.35)$$

The code treats the time  $t$  as a dependent variable, with the axial distance  $x$  being the independent variable. Since this code was originally developed to model ion accelerators, ion motion is expected to be primarily in the  $x$ -direction, and the velocity component  $v_x$  increases with increasing  $x$ .

From the above equations of motion, a particle with velocity  $v_{x0}$  at  $x_0$  will acquire a velocity  $v_x$  at point  $x$

$$v_x = [v_{x0}^2 + 2a_x(x - x_0)]^{1/2} . \quad (3.36)$$

Normally  $(x - x_0)$  is equal to the size of a Poisson cell in the  $x$ -direction. If the acceleration  $a_x$  is small, the time taken to cross the cell is calculated as

$$t = |(x - x_0)/v_x| ; \quad (3.37)$$

otherwise

$$t = |(v_x - v_{x0})/a_x| . \quad (3.38)$$

This time  $t$  is then used to calculate the new velocity and coordinate in the  $y$ -direction:

$$v_y = v_{y0} + a_y t \quad (3.39)$$

$$y = y_0 + v_{y0} t + \frac{1}{2} a_y t^2 . \quad (3.40)$$

Should  $y$  or  $v_y$  change too drastically over the mesh cell, the cell is subdivided into  $N$  intervals and a parabolic trajectory is calculated over each subinterval. This method of orbit refining only when necessary leads to very smooth trajectories without increasing the number of nodes over which the entire Vlasov-Poisson system is solved.

Whealton and co-workers extended this treatment of ion motion to consider particles which reverse their direction. Since the time for a particle to move from

$x_0$  to  $x$  is given by

$$t = \frac{-v_{x0} \pm [v_{x0}^2 + 2a_x(x - x_0)]^{1/2}}{a_x}, \quad (3.41)$$

then  $v_{x0}^2 \leq -2a_x(x - x_0)$  can be used as a criterion for orbit reversal. In such a case,  $x$  would be decremented rather than incremented as the particle reversed direction; orbit refinement is always carried out when a particle turns around. This feature of reverse ion movement was essential in extending the code to energy recovery problems, since in energy recovery the ions are being decelerated rather than accelerated.

Ion orbits are terminated when they leave the device, when they impinge on an electrode surface, or when the number of coordinate points describing the trajectory exceeds a specified limit. Charge is deposited on the Poisson mesh in a straightforward manner as the trajectory is traced. Each ion trajectory has a current density ( $j_i$ ) and velocity (ion temperature) at the emission surface ( $v_{i0}$ ) associated with it as initial conditions. The initial space charge can be expressed as

$$\rho_{i0} = \frac{j_i}{v_{i0}}; \quad (3.42)$$

and all space charge is scaled to this value as the particle velocity changes:

$$\rho_i = \left( \frac{v_i}{v_{i0}} \right) \rho_{i0}. \quad (3.43)$$

The charge is apportioned to the Poisson mesh points in a linear interpolation based on the distances of the nodes to the trajectory.

Numerical damping is added to the scheme by under-relaxing  $\rho_i$  based on the value of  $\rho_i$  from the last major iteration:

$$\rho_i^{(k)} = \alpha \rho_i^{(k)} + (1 - \alpha) \rho_i^{(k-1)}. \quad (3.44)$$

Once all the ion trajectories are finished and their charge deposited, one major iteration is complete. The next major iteration starts with inputting the new

charge deposition into the Poisson equation and solving for the new potential. Figure 3.2 shows the iteration scheme in flowchart form.

## B. MODIFICATIONS FOR THE ENERGY RECOVERY PROBLEM

### B.1 The Single Vlasov Model

The ion optics code just described was used in initial studies of the ion energy recovery problem at ORNL; it is referred to as the single Vlasov code since only the ion Vlasov equation is solved. Modifications to treat the ion energy recovery problem were minimal and were concerned primarily with specifying the conditions within the neutralizer and including the blocking magnetic field.<sup>40,57</sup> The Coulomb force (3.33) is replaced by the full Lorentz force:

$$\mathbf{F} = q(-\nabla\Phi + \mathbf{v} \times \mathbf{B}) . \quad (3.45)$$

In these initial computations, the energy recovery device was divided into three regions, as shown in Figure 3.3. In region I, the neutralizer, the magnetic field is specified as zero and the neutralizer plasma is represented by requiring either  $\rho = 0$  or  $\Phi = \text{constant}$ . The first condition forces space-charge neutrality of the plasma; the fields are determined by the neutralizer boundary conditions and are similar to the vacuum fields. The alternative condition assumes that the plasma potential in the neutralizer will remain close to the potential of the boundary surrounding it, due to the electrical conductivity of the plasma along magnetic field lines.

Region II is a narrow strip where the magnetic field is a nonzero constant. All the magnetic effects on the ion trajectories occur in this region.

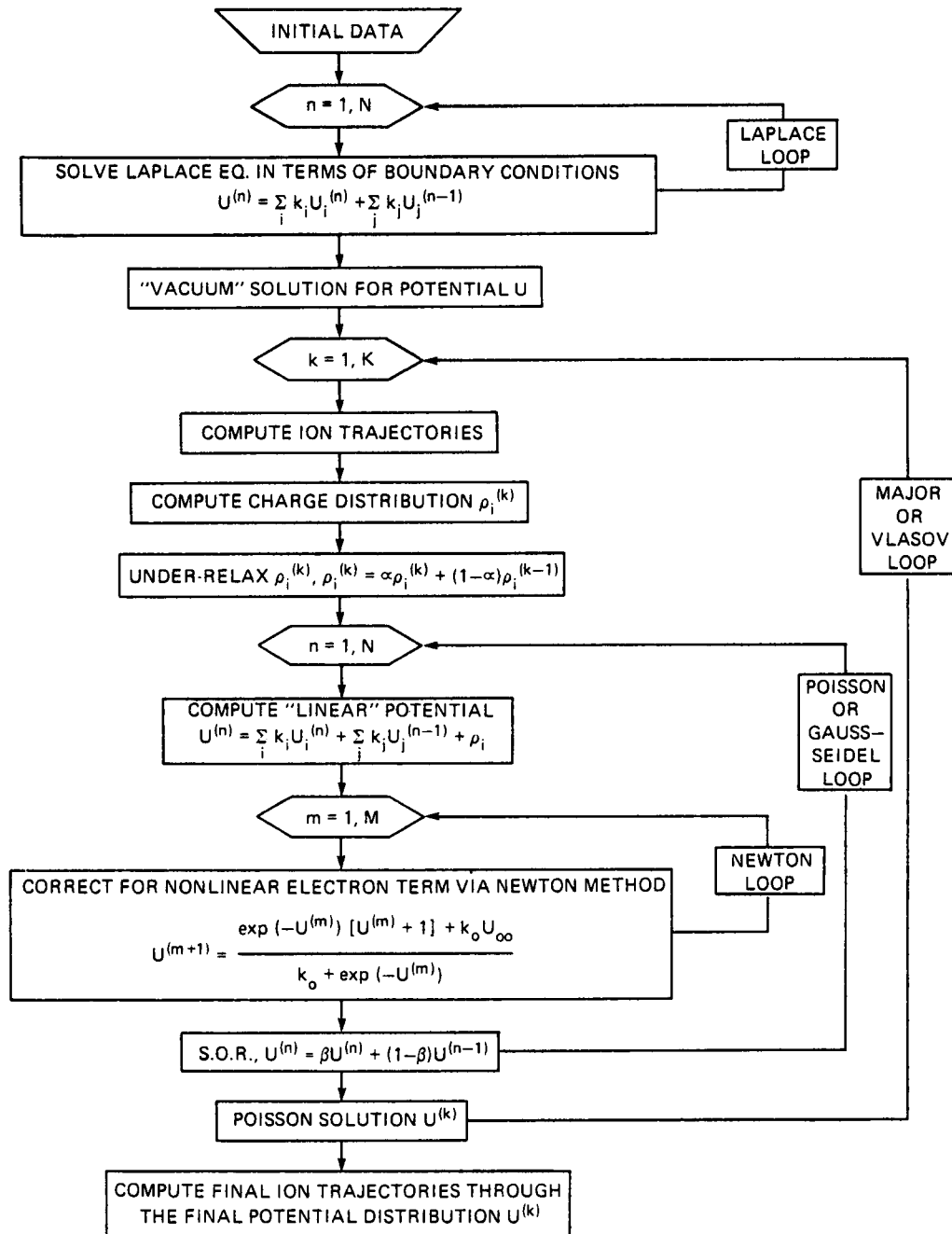


Fig. 3.2. Flowchart for Poisson-Vlasov computations.

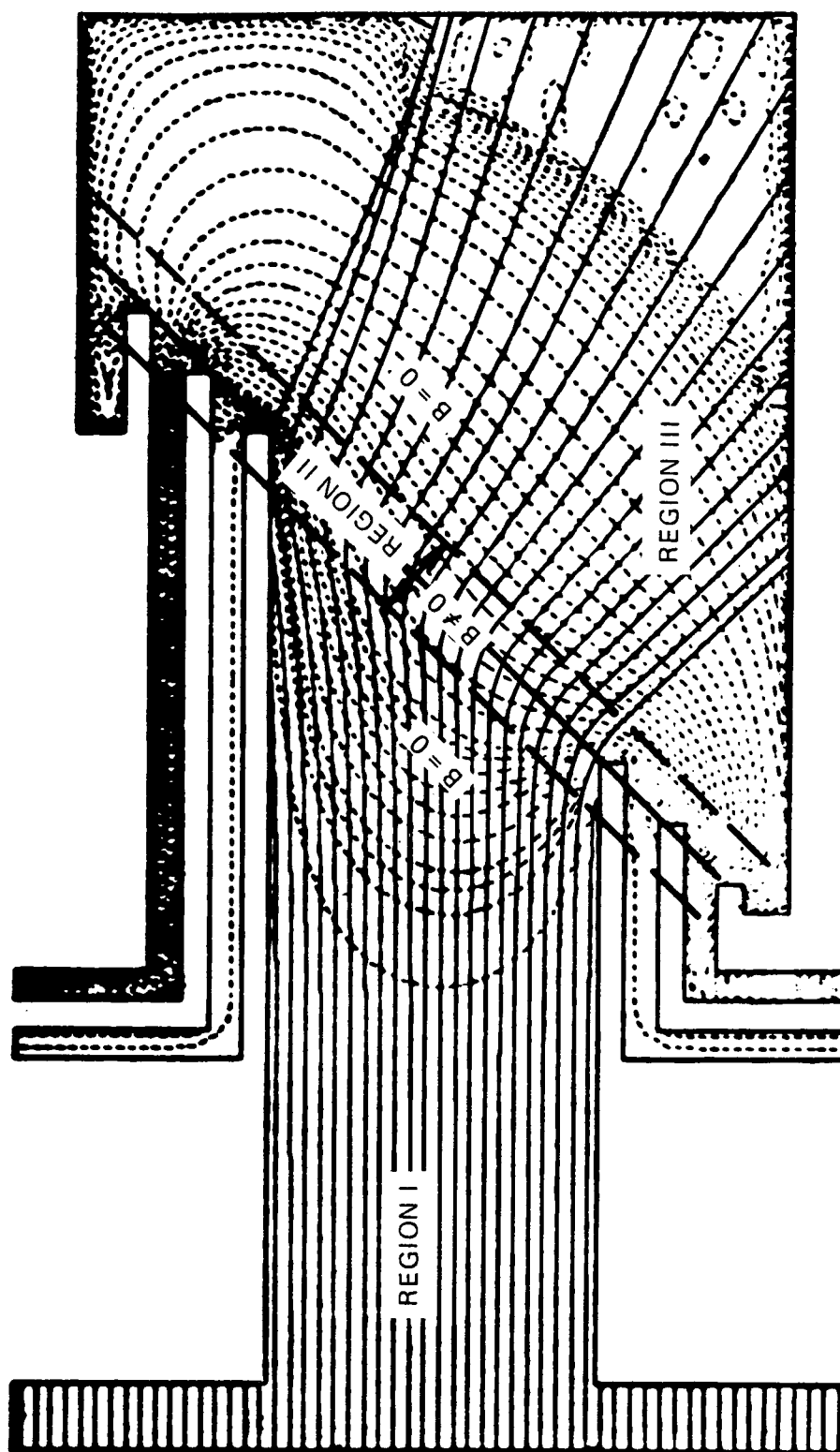


Fig. 3.3. Single Vlasov model for energy recovery. The magnetic field is constant in Region II and zero elsewhere. The dotted contours are equipotential surfaces.

Region III is the target plasma region, and it assumes a plasma in intimate contact with the surrounding ground surfaces. This target plasma is created by the neutral beam ionizing the background gas. This electron plasma is represented by the Boltzmann term in equation (3.1) and is solved for in the same manner as previously described.

The electrostatic potential  $\Phi$  is still scaled by

$$u = \frac{e(\Phi_0 - \Phi)}{kT_e}, \quad (3.4)$$

where  $\Phi_0 = 0$ . The effect of choosing such a  $\Phi_0$  is that  $u = 0$  at ground surfaces, where the term  $\exp(-u)$  has an effect. The large negative potential of the neutralizer scales to a  $u > 0$ , where the ground electron plasma has no effect.

The electron term in the Poisson equation keeps the space potential  $\Phi$  from becoming too positive with respect to ground. As the positive ions are decelerated, the effective space charge becomes large, causing the potential to rise above ground ( $u$  becomes negative). The  $\exp(-u)$  term then becomes correspondingly large as well, reducing the space potential excursion to within a few  $kT_e/e$  of ground potential.

This model was used to evaluate the slanted neutralizer and magnet geometry, which was operated between 1978 and 1981, and was instrumental in the design of a rectangular neutralizer with vertical magnet, which was operated in 1982. The code was successful in determining the field strength, position, and orientation of the blocking magnet in order to optimize the full energy ion collection, as well as qualitatively studying the effects of boost voltage variation.<sup>58</sup> Its main shortcomings were the unrealistic, discontinuous magnetic field distribution, the arbitrary position of the virtual cathode of the neutralizer, and the absence of electrons and fractional energy ions. These considerations prompted the development of a double Vlasov code which treated electrons exactly.

## B.2 The Double Vlasov Model

The double Vlasov code was developed in order to trace electron trajectories as well as ion trajectories in an effort to study the electron losses that were plaguing the experiment. It was also hoped that by replacing the constraints  $\rho = 0$  or  $\Phi = \text{constant}$  in the neutralizer with charge-depositing electrons, more realistic sheath boundaries could be achieved.

The equations to be solved in the double Vlasov code are:

$$\nabla^2 \Phi = q \int f_i d\mathbf{v}_i - q \int f_e d\mathbf{v}_e , \quad (3.46)$$

$$\mathbf{v}_i \cdot \nabla_r f_i + \frac{e}{m_i} (\mathbf{v}_i \times \mathbf{B} - \nabla \Phi) \cdot \nabla_v f_i = 0 , \quad (3.47)$$

$$\mathbf{v}_e \cdot \nabla_r f_e + \frac{e}{m_e} (\mathbf{v}_e \times \mathbf{B} - \nabla \Phi) \cdot \nabla_v f_e = 0 , \quad (3.48)$$

$$\mathbf{v}_e \cdot \nabla_r f_e = 0 , \quad \text{where } \mathbf{v}_e = \frac{-\nabla \Phi \times \mathbf{B}}{B^2} . \quad (3.49)$$

The Poisson equation (3.46) now has an electron term that arises from the solution to the electron Vlasov equation, (3.48) or (3.49). The charge deposition from the electron trajectories is made in an analogous manner to the charge deposition from the positive ions. The main difference in the calculation of electron trajectories is the inclusion of guiding center motion, equation (3.49), in addition to exact electron motion, equation (3.48).

At each step in the electron trajectory, the gyroradius is calculated from the local value of the magnetic field and the electron's kinetic energy. Kinetic energy is used to distinguish between an electron's kinetic velocity and its guiding center drift velocity,

$$r_g = \frac{m_e v_e}{eB} = \frac{(2m_e E)^{1/2}}{eB} , \quad (3.50)$$

where  $E$  is the kinetic energy of the electron. Should the gyroradius exceed the dimensions of a Poisson cell, the exact equations of motion are solved as in the

case for ions. If the gyroradius is less than the Poisson cell dimension, guiding center drift motion is employed. The equations of motion become

$$a_y = a_x = 0 , \quad (3.51)$$

$$v_x = v_{Dx} = \frac{E_y}{B} , \quad (3.52)$$

$$t = \frac{|x - x_0|}{|v_{Dx}|} , \quad (3.53)$$

$$v_y = v_{Dy} = \frac{-E_x}{B} , \quad (3.54)$$

$$y = y_0 + v_{Dy}t . \quad (3.55)$$

Here  $E_y$  and  $E_x$  are the components of the electric field.

Charge deposition in guiding center is based on the trajectory drift velocity. The particle does not gain any kinetic energy while in drift motion, and the kinetic energy it had when it entered drift motion is used to calculate subsequent gyroradii. When the particle reaches a region of magnetic field where its gyroradius again exceeds the cell dimensions, its kinetic velocity vector is restored and it again follows the exact equations of motion.

A more realistic magnetic field distribution was also employed in this model. The field of the magnet employed in the ORNL experiments was measured at the midplane of the pole gap, both along and perpendicular to the principal axis; the results are shown in Figure 3.4. This distribution was modeled by assuming a constant field strength in the direction parallel to the principal axis and a Gaussian distribution in the direction perpendicular to it. The function

$$B = B_0 \exp \left( \frac{-s^2}{a^2} \right) , \quad (3.56)$$

where  $s$  is the perpendicular distance to the axis and  $a$  is an e-folding length equal to 0.167 m, described the midplane field pattern quite accurately.

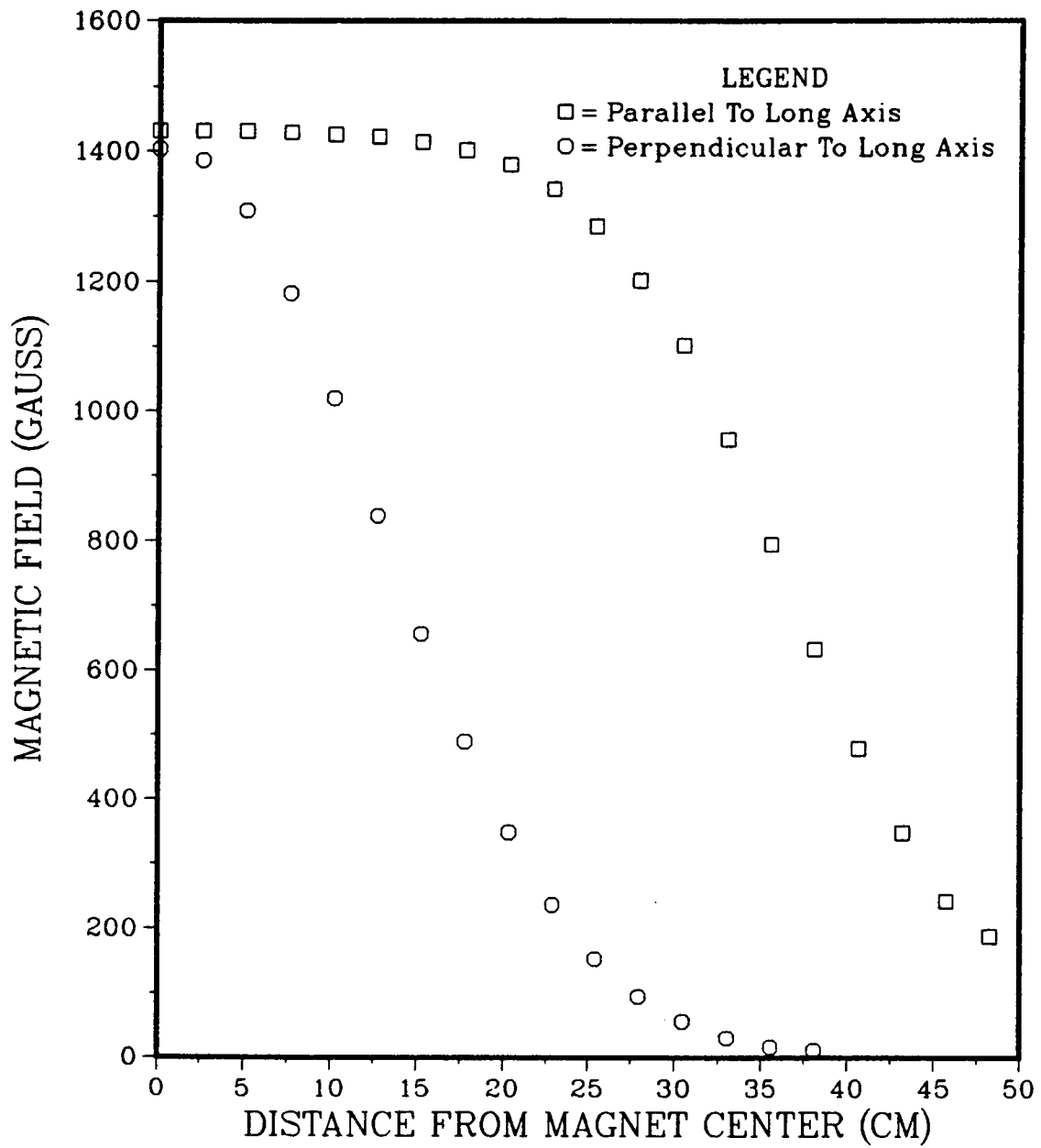


Fig. 3.4. Magnetic field distribution at the midplane of the pole gap. Measurements are made both parallel and perpendicular to the long poleface axis.

The double Vlasov model was successful in duplicating experimental measurements only at current densities on the order of  $1 \text{ mA/cm}^2$ . Figures 3.5 and 3.6 show the numerical results for  $j_i = 1 \text{ mA/cm}^2$  and  $10 \text{ mA/cm}^2$ , respectively. Both cases have a beam energy of 40 keV, a boost voltage of 5 kV, and an electron collector bias of +5 kV with respect to the neutralizer. In the high current density case, the potential hill in the neutralizer causes complete beam blowup, a result that was not observed in the experiment.

At the emission surface, the boundary condition for space-charge neutrality ( $\rho = 0$ ) demands that the electrons be traveling at the same velocity as the ions. Therefore, their initial energy differs by the ion to electron mass ratio  $m_i/m_e = 1836$ ; a 40 keV ion is thus neutralized by a 22 eV electron.

These electrons traveling with the ion beam cannot provide space-charge neutralization throughout the neutralizer interior. As the ions are decelerated, depositing more positive charge, the electrons are accelerated, thus depositing less electrical charge. This charge imbalance creates a positive potential well, which decelerates the ions and accelerates the electrons even more during the next Vlasov iteration. At high current densities this positive potential well becomes higher on each iteration and continues to move toward the emission surface.

The problem with the model is that neutralizing electrons do not travel with the ion beam but rather are continually generated by the interaction of the beam with the neutral gas and the metallic walls of the neutralizer. The double plasma model, to be discussed next, is an effort to describe this effect in a manner susceptible to efficient numerical solution.

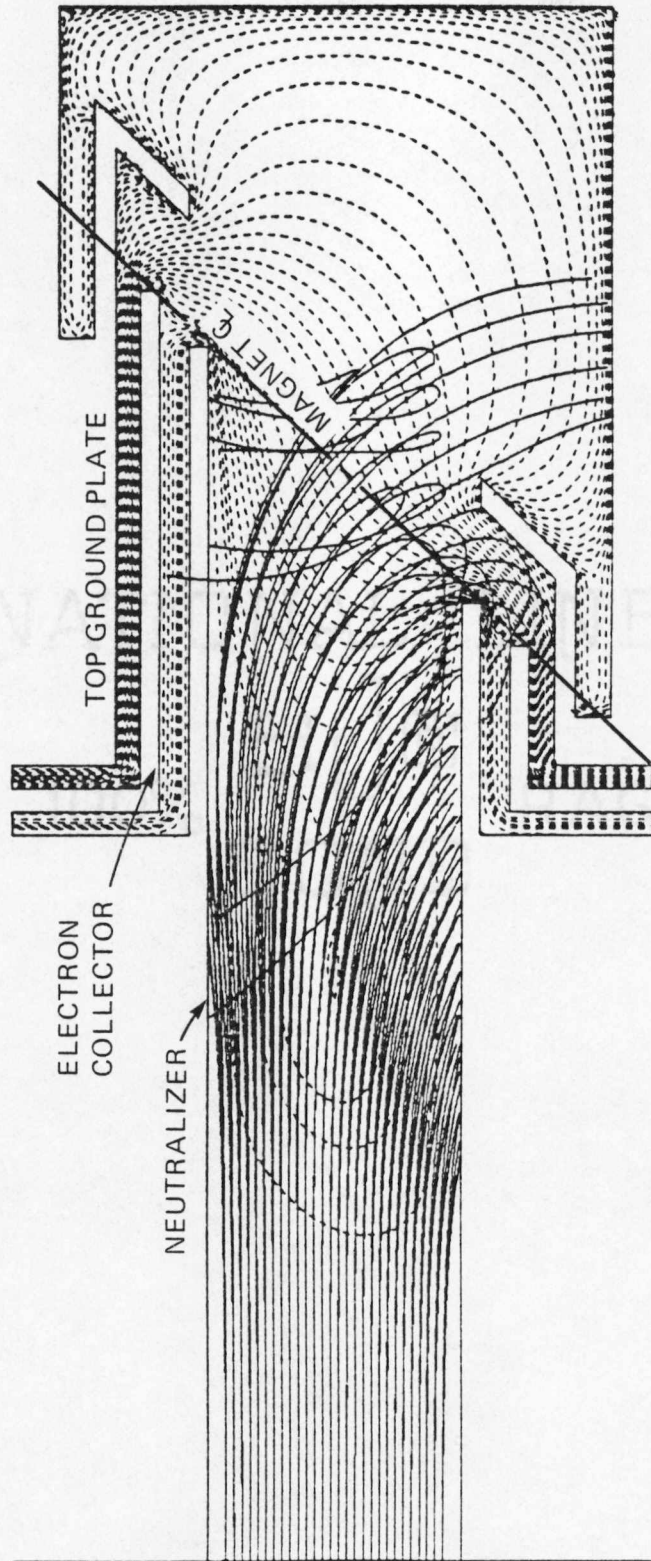
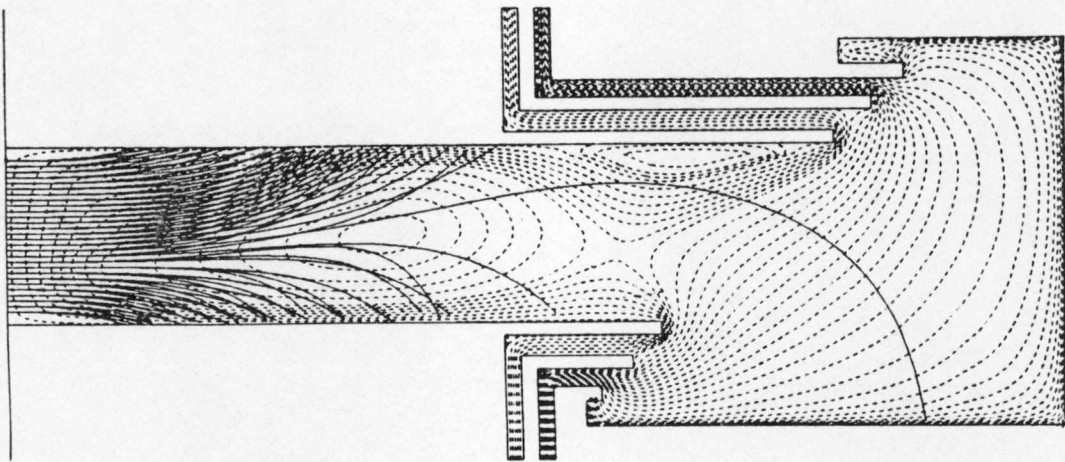
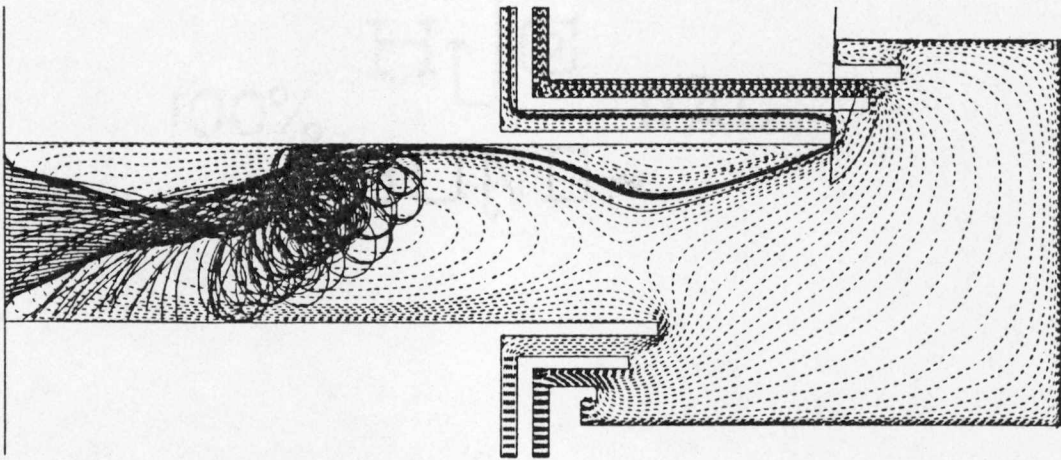


Fig. 3.5. Example of double Vlasov results for  $J^+ = 1 \text{ mA/cm}^2$ . Note that the fractional energy ions do not reach ground surfaces.



(a) ION TRAJECTORIES



(b) ELECTRON TRAJECTORIES

Fig. 3.6. Example of double Vlasov results for  $J^+ = 10 \text{ mA/cm}^2$ . The upper figure [a] shows the ion trajectories while [b] shows the electron trajectories. A potential well has formed in the neutralizer which tends to disperse the ions and trap the electrons.

### B.3 The Double Plasma Model

The double plasma model assumes that two plasmas exist in the device, each with a Boltzmann distribution of electrons. The first is the target or ground plasma, which fills the vacuum tank and has a space potential close to ground. The second is the neutralizer plasma that fills the gas cell; its space potential is assumed to be close to the neutralizer potential. Each plasma may be considered a source of electrons which prevents the local potential from becoming too positive with respect to the nearby conducting boundaries. A double sheath forms between these two plasmas, and it is across this sheath that the ions are decelerated.

The ground plasma is represented by the nonlinear electron term in

$$\nabla^2 u = \exp(-u) - \rho_i \quad (3.8)$$

as discussed in Section 3.A.1: the  $\exp(-u)$  term is incorporated into the linear potential solution via the Newton method,

$$u^{(m+1)} = \frac{[\exp(-u^{(m)})](u^{(m)} + 1) + k_0 u_{00}}{k_0 + \exp(-u^{(m)})} \quad (3.31)$$

At first sight it would appear that the neutralizer electrons could be modeled in an analogous manner, with a Boltzmann distribution of electrons centered about the neutralizer potential as the nonlinear term

$$\nabla^2 u = \exp(u - u_0) - \rho_i, \quad (3.57)$$

where  $u_0$  is the neutralizer potential. However, this yields the following form for the Newton method:

$$u^{(m+1)} = \frac{[\exp(u^{(m)} - u_0)](1 - u^{(m)}) + k_0 u_{00}}{k_0 - \exp(u^{(m)} - u_0)} \quad (3.58)$$

Away from irregular boundaries,  $h_1 = h_2 = h_3 = h_4 = 1$  and thus  $k_0 = 1$ . It can be seen immediately that this places a pole in the denominator at  $u^{(m)} = u_0$ ,

thus leading to numerical instability. In addition, the nonlinear term only becomes effective for  $u \simeq u_0$ . Even a slight excess of positive charge in the neutralizer will yield a linear solution  $u \ll u_0$ , rendering the electron term useless in restoring the potential toward  $u_0$ .

A more desirable model for the neutralizer plasma would be one that tends to drive the linear solution of  $u$  toward a value more positive than  $u_0$ , thus allowing the  $\exp(u - u_0)$  term to relax the potential back toward  $u_0$ . Ideally, the linear charge term should be proportional to the ion current density, since the plasma density in the neutralizer is directly proportional to the total beam flux density (ions plus neutrals). The equation to be solved in the neutralizer is thus

$$\nabla^2 u = \rho_e - \exp(u - u_0) . \quad (3.59)$$

The first term is an electron term equal to the ion density in the neutralizer, while the second term is a compensating Boltzmann distribution of ions that keeps  $u$  from becoming more positive than the surrounding neutralizer.

Again, the equation is solved in two steps, with the quasi-linear equation

$$\nabla^2 u = \rho_e \quad (3.60)$$

being solved by the Gauss-Seidel iteration method and the nonlinear solution being estimated by a Newton method:

$$u^{(m+1)} = \frac{(u^{(m)} - 1)\exp(u^{(m)} - u_0) + k_0 u_{00}}{k_0 + \exp(u^{(m)} - u_0)} . \quad (3.61)$$

This method is completely stable and provides a sheath solution that becomes stationary after a suitable number of iterations.

#### B.4 Fractional Energy Ions

The code assumes that the accelerated ion beam has been completely dissociated and neutralized by the time it reaches the emission surface; thus the energy spectrum of ions and neutrals is calculated from initial data before the Vlasov-Poisson equations are considered. The ratio of ion species in the ion source may be represented by

$$\text{H}^+ : \text{H}_2^+ : \text{H}_3^+ :: \eta_1 : \eta_2 : \eta_3 \quad (3.62)$$

where  $\eta_1 + \eta_2 + \eta_3 = 1$ . Dissociation of the molecular ions after they acquire the full acceleration energy  $E$  yields fractional energy ions:

$$\text{H}_2^+(E) \rightarrow 2\text{H}^+(E/2) \quad (3.63)$$

$$\text{H}_3^+(E) \rightarrow 3\text{H}^+(E/3) \quad (3.64)$$

We further assume a neutral line density in the neutralizer that allows for equilibrium neutralization fractions to be realized. If  $f_{1\infty}(E)$  represents the ionization equilibrium fraction for protons of energy  $E$  in  $\text{H}_2$ , then

$$j^+(E) = \eta_1 f_{1\infty}(E) I / A \quad (3.65)$$

$$j^+(E/2) = \eta_2 f_{1\infty}(E/2) I / A \quad (3.66)$$

$$j^+(E/3) = \eta_3 f_{1\infty}(E/3) I / A \quad (3.67)$$

where  $I$  is the total extracted beam current,  $A$  is the beam cross-section area, and  $j^+$  is the current density associated with each ion energy.

The input parameters are the ion species ratio in the source ( $\eta_1, \eta_2, \eta_3$ ), the ionization equilibrium fraction for each of the three ion energies [ $f_{1\infty}(E), f_{1\infty}(E/2), f_{1\infty}(E/3)$ ], and the full energy ion current density [ $j^+(E)$ ].

Equal numbers of ion trajectories are traced for each energy ion; the fractional energy ion trajectories have their current density per trajectory apportioned according to the current densities  $j^+(E/2)$  and  $j^+(E/3)$ , where

$$j^+(E/2) = \frac{\eta_2 f_{1\infty}(E/2) j^+(E)}{\eta_1 f_{1\infty}(E)} \quad (3.68)$$

$$j^+(E/3) = \frac{\eta_3 f_{1\infty}(E/3) j^+(E)}{\eta_1 f_{1\infty}(E)} . \quad (3.69)$$

The charges from these trajectories are deposited in the usual manner; the trajectories for all three energies are completed before the next Poisson solution is undertaken.

#### B.5 Volume Scattering and Secondary Electron Emission

The solution for the electrostatic potential and ion trajectories is considered complete after a specified number of major iterations. Convergence of the solution is periodically checked by increasing the number of major (Vlasov) and/or minor (Poisson) iterations and observing the solution. If no change has occurred by increasing the number of iterations, then the computation is considered converged. Typically 100 to 200 minor iterations and 10 to 20 major iterations yield converged solutions; the CPU time on a DEC PDP-10 is on the order of an hour for a finite-difference grid using a few thousand points.

The effects of the beam interacting with the background gas and impinging on electrode surfaces are studied after the solution for the electrostatic potential and ion trajectories is complete. A Monte Carlo routine is used to model the ionization and charge-exchange events caused by the energetic beam particles (both ions and neutrals) passing through the background gas. Ions are again traced through the device, describing the same trajectories as in the final iteration; these ions are

referred to as primary ions. For every incremental step  $dx$  in the axial direction, the probability for a scattering event occurring in that interval is calculated. The probability for an ionization event is

$$p_{\text{ion}} = 1 - \exp[-n_0\sigma_{\text{ion}}(E)dx] , \quad (3.70)$$

and for a charge-exchange event,

$$p_{\text{ce}} = 1 - \exp[-n_0\sigma_{\text{ce}}(E)dx] . \quad (3.71)$$

The cross sections for ionization ( $\sigma_{\text{ion}}$ ) and charge exchange ( $\sigma_{\text{ce}}$ ) are computed by a table look-up scheme based on the primary ion energy ( $E$ ); the cross-section values are obtained from Barnett et al.<sup>59</sup> The neutral density ( $n_0$ ) is calculated from the local gas pressure ( $p$ ) and gas temperature ( $T$ ) by

$$n_0(\text{m}^{-3}) = \frac{133.322(\text{pascals/torr})p(\text{torr})}{1.3805 \times 10^{-23}(\text{J/K})T(\text{K})} . \quad (3.72)$$

The pressure  $p$  is specified at two axial points in the device and the local pressure is linearly extrapolated.

The Monte Carlo algorithm checks first for charge exchange and then for ionization. If  $r \leq p_{\text{ce}}$ , where  $r$  is a randomly generated number between 0 and 1, then a charge-exchange event has occurred. If  $p_{\text{ce}} < r \leq (p_{\text{ce}} + p_{\text{ion}})$ , then an ionization event has occurred. Note that this algorithm becomes weighted in favor of charge exchange should the neutral density  $n_0$  ever be large enough that the scattering probabilities approach 0.5 over the distance  $dx$ . In such a case,  $dx$  is decreased via the orbit refinement technique discussed in Section 3.A.2.

When an ionization event occurs, the primary ion's trajectory information is stored and a new secondary ion trajectory is traced until it leaves the device. The secondary ion starts from rest at the point of creation. A secondary electron trajectory is also traced from this point; once these secondary trajectories are

complete, the primary ion continues on its path, capable of causing more scattering events.

In the event of an ion-neutral charge exchange, the primary ion retains its velocity vector at the point of collision but not its charge; it becomes a neutral that follows straight line motion unaffected by electric and magnetic fields. A secondary ion is then started from rest at the point of impact.

Scattering events from the neutral particles in the beam are also included. The number of primary neutral trajectories traced is equal to the number of primary ions traced; however, the neutral flux density per trajectory ( $\Gamma_0$ ) is adjusted according to the ionization equilibrium fractions, source ion species ratio, and the full energy ion current density per trajectory,

$$\Gamma_0(E) = \left( \frac{1 - f_{1\infty}(E)}{f_{1\infty}(E)} \right) j^+(E) , \quad (3.73)$$

$$\Gamma_0(E/2) = \left( \frac{\eta_2}{\eta_1} \right) \left( \frac{1 - f_{1\infty}(E/2)}{f_{1\infty}(E)} \right) j^+(E) , \quad (3.74)$$

$$\Gamma_0(E/3) = \left( \frac{\eta_3}{\eta_1} \right) \left( \frac{1 - f_{1\infty}(E/3)}{f_{1\infty}(E)} \right) j^+(E) . \quad (3.75)$$

Ionization events from a primary neutral are handled in the same manner as those from a primary ion. For a neutral-ion charge-exchange event, the primary neutral retains its velocity vector and is assigned an ion current density equal to the neutral flux density; it continues its trajectory as an ion. The neutral created at rest is not affected by the fields and is not treated.

Finally, primary ions that terminate their trajectories on electrode surfaces generate secondary electrons which are then traced from rest. The secondary electron trajectories are assigned the same current density as the primary ions which created them; this is equivalent to a secondary emission coefficient of unity.

Since these particles arising from volume ionization, charge exchange, and secondary electron production are generated after the Vlasov-Poisson iterations

are complete, their trajectories do not affect the electric fields or the primary ion trajectories. The current density per trajectory is retained merely for statistical purposes. The type of particle, the impact surface, the current density per trajectory, and impact energy are noted for each trajectory, allowing information about the net current and power to each component in the device to be computed.

## 4. EXPERIMENTAL APPARATUS

### A. DESCRIPTION OF THE GENERIC EXPERIMENT

Three sequences of energy recovery experiments were performed on the West Beamline of the ORNL Medium Energy Test Facility (METF-W) between 1980 and 1982. The experiment of 1980 used the energy recovery hardware previously designed and operated by Stirling and Dagenhart; the experiment of 1981 used a new power supply configuration and improved diagnostics. A new neutralizer/electron collector/magnet geometry was fabricated and tested in 1982; the design was based on the theoretical work of Whealton and Wooten, and the experiment used the equipment and methods developed in 1981. This section discusses the evolution of the experimental method and the factors common to all experiments. Each experiment will then be characterized separately and differences will be detailed.

#### A.1 The Medium Energy Test Facility

The Medium Energy Test Facility (METF) was constructed in 1976 for the development of the 40 kV, 60 A neutral beam systems used to heat the Princeton Large Torus (PLT) experiment.<sup>60,61</sup> The METF comprises two beamlines which share a common target tank; the energy recovery experiments were carried out on the west beamline. A photograph of the METF-W beamline and a drawing detailing the main components of a PLT beamline are shown in Figures 4.1 and 4.2. The METF-W beamline consists of a vacuum tank for the neutralizer and electron

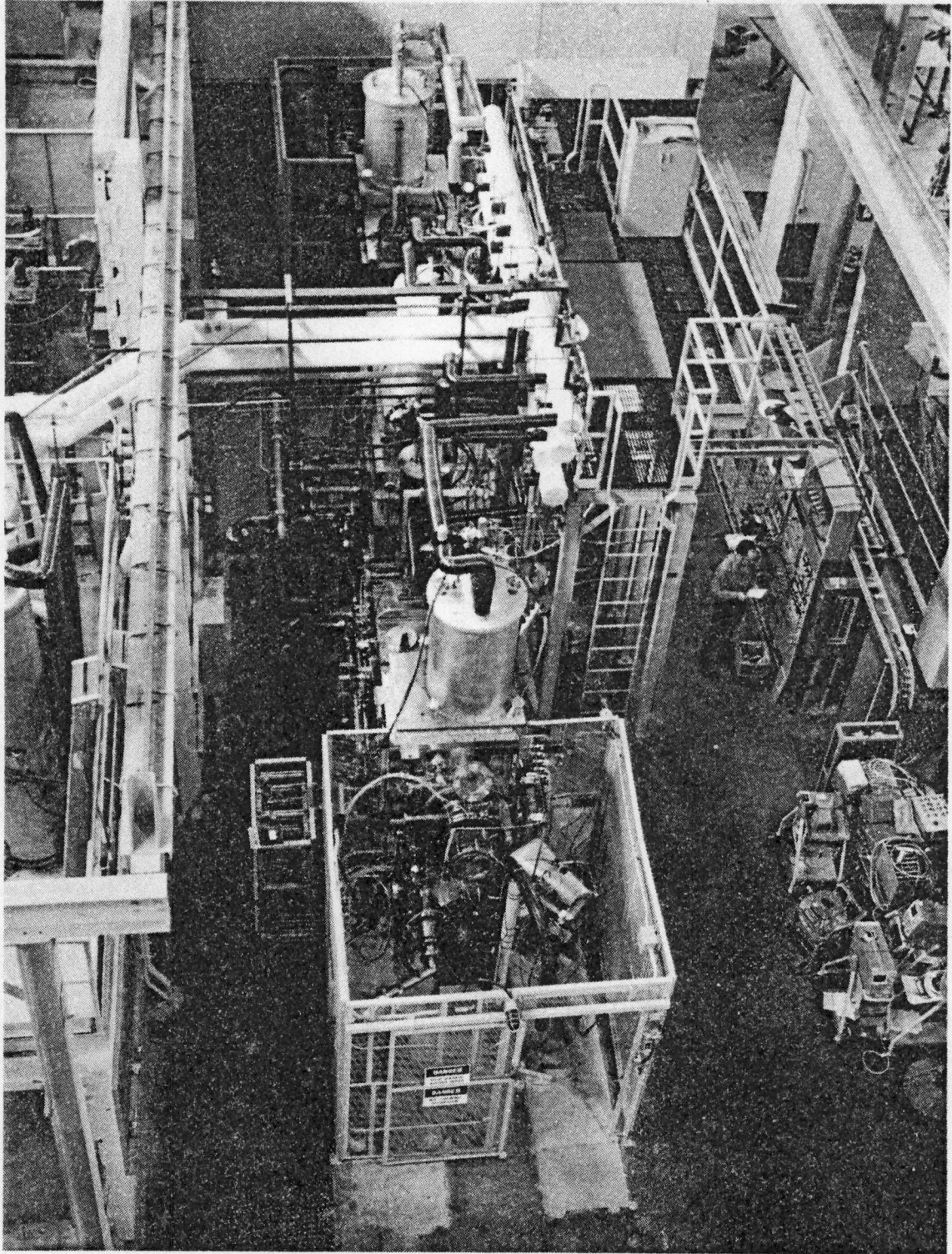


Fig. 4.1. Overhead view of the Medium Energy Test Facility (METF) west beam line.

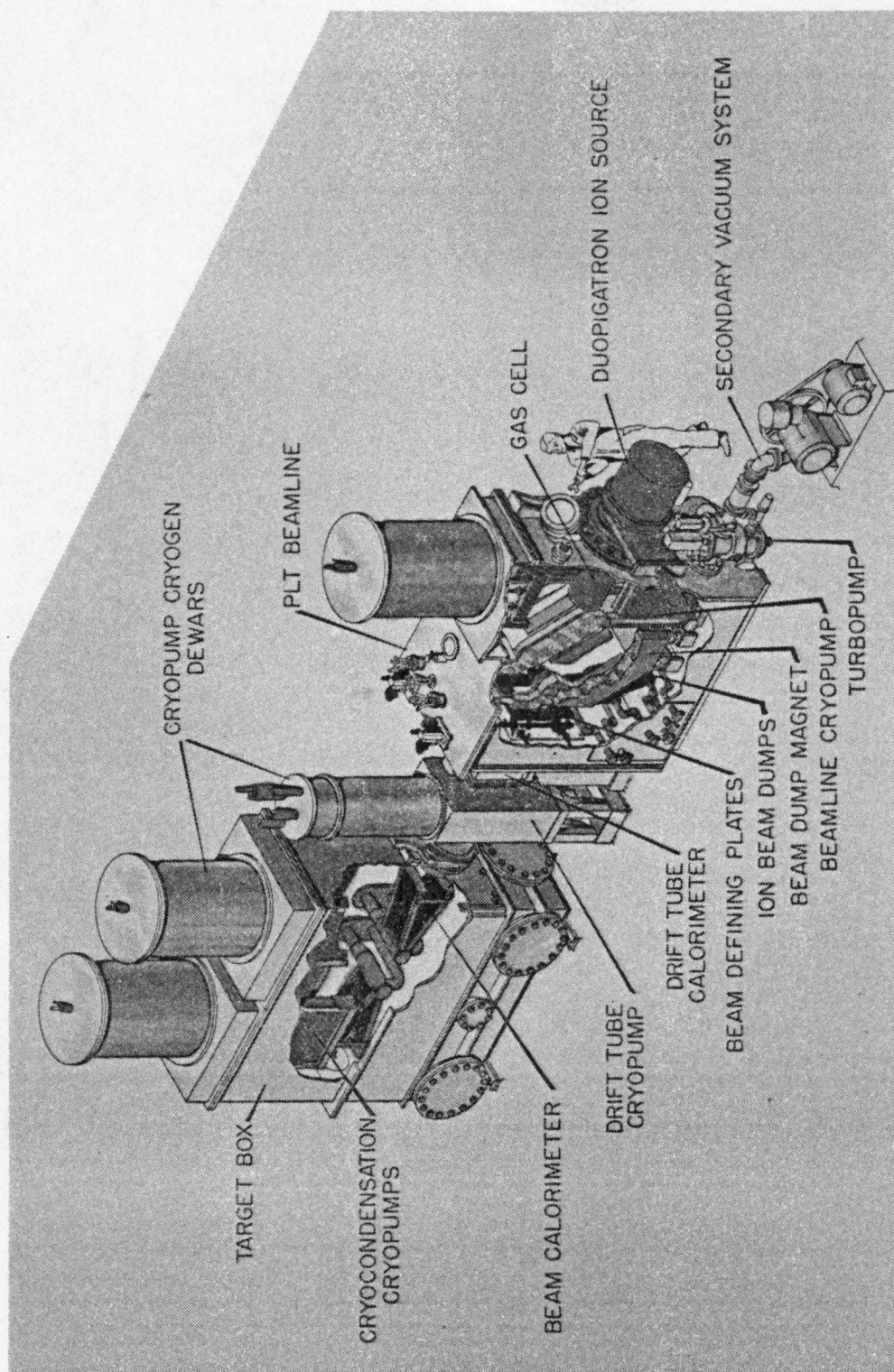


Fig. 4.2. Sketch of principal components of a PLT beam line.

blocking magnet, a vacuum tank for the beam target, and a drift tube and isolation valve between the two tanks. Each tank is pumped by a cryocondensation pump consisting of two liquid helium (LHe) cooled panels maintained at a temperature of 4.2 K onto which the hydrogen gas condenses. These panels are thermally protected from energetic particles by 120° chevron baffles which are placed in front of them; these baffles are maintained at 77 K by liquid nitrogen (LN<sub>2</sub>) cooling. Each cryopump has a total inlet area of 2.5 m<sup>2</sup> and has a pumping speed of 200,000 L/s. The west beamline cryopump panels straddle the neutralizer. The target tank cryopump was frequently not filled with LHe but maintained at 77 K in order to condense moisture from the background. This did not affect the pressure in the energy recovery region, as the large volume of the target tank provided ballast pumping over the short pulse lengths of the experiment. It was an economy measure not to fill the target tank pump with LHe, as the pumps consume 3-5 liters per hour. The background pressure in the west beamline was typically about  $8 \times 10^{-6}$  torr.

The two tanks can be decoupled by a 12 inch (30 cm) diameter isolation valve. The drift tube between the west tank and the isolation valve contains an uninstrumented beam target that can be moved into the beam. This allows operation even when the target chamber is up to atmosphere. For normal beam operation, where the gas cell neutralizer is at ground potential, there is also an isolation valve between the ion source and the tank; this isolation valve forms the upper part of the neutralizer. The valve was removed for energy recovery operation, since the neutralizer is maintained at high negative potentials and must extend from the ion source accelerator to the electron blocking magnet. Lack of a source isolation valve meant that the cryopumps had to be warmed up before

the ion source could be brought up to atmosphere. The total turnaround time for system repairs (warmup and cooldown) was about three days.

The METF data acquisition system uses a PDP-11/34 computer and is capable of monitoring up to 32 calorimetry channels (10 ms/data point), 22 "fast" channels (2 ms/data point) for electrical signals, and 16 gas pressure channels. The calorimetry data, representing power deposited on system components, are simultaneously displayed on a color CRT at the test stand and printed on a Versatec printer in the METF computer room. All information collected and reduced by the PDP-11/34 was transmitted to the FED PDP-10 either in real time or after storage on a disk. One disk could hold several hours worth of experimental data. Once in the PDP-10, the data could be further analyzed and/or transferred to magnetic tape for archival purposes. The CRT display, printer, storage disk, and PDP-10 link could be activated independently of one another.

## A.2 Power Supplies and Biasing Networks

The experiment that was operated in 1980 used the power supply connection referred to as configuration I in Section 2; Figure 2.3 (p. 16) shows the idealized connection. In actuality, separate decel and electron collector power supplies were not available, nor was the isolation transformer needed to provide primary power at elevated negative voltages. Instead, the decel, accel, and electron collector voltages were developed across a resistive voltage divider by the accel supply; a more detailed circuit is shown in Figure 4.3.

The accel supply is a 60 kV, 60 A dc power supply which feeds two parallel Eimac X-2062J tetrodes that act as a modulator. The drive pulse to the modulator is removed whenever the accel current exceeds a set point, turning off the high

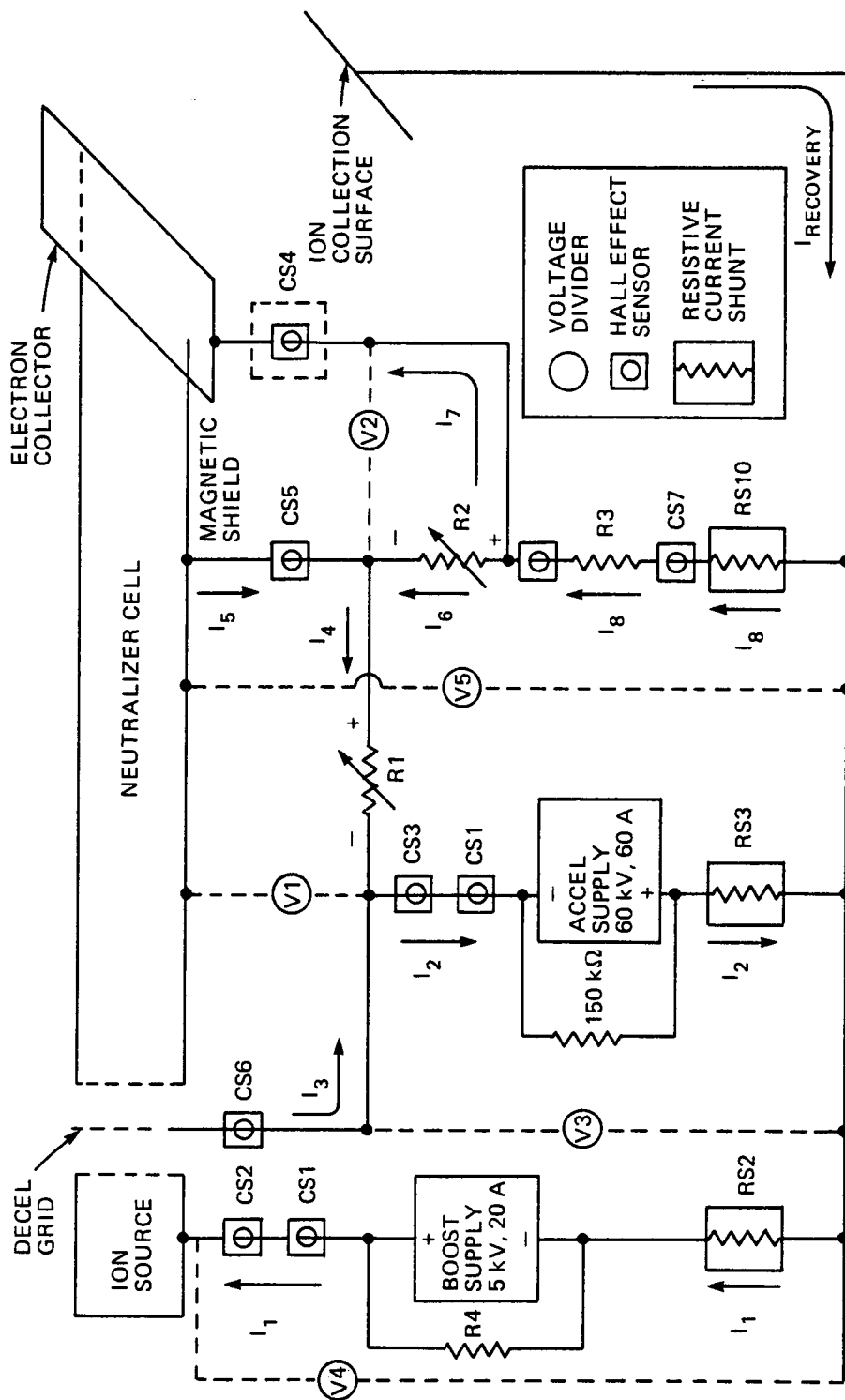


Fig. 4.3. Detailed circuit of power supply configuration I.

voltage in 100  $\mu$ s. This protects against damage from high voltage breakdowns and arcs in the ion accelerator and energy recovery equipment.

The accel and boost supplies are pulsed on before the ion source arc is struck in order to establish the proper operating potentials. Before the beam is turned on by the ion source arc,  $I_1 = I_3 = I_5 = I_7 = 0$  and  $I_2 = I_4 = I_6 = I_8 = I_{\text{accel}}$ . The decel, beam, and electron collector voltages in the absence of beam are thus

$$V_{\text{decel}} = \left( \frac{R_1}{R_1 + R_2 + R_3} \right) V_{\text{accel}} , \quad (4.1)$$

$$V_{\text{beam}} = V_{\text{boost}} + \left( \frac{R_2 + R_3}{R_1 + R_2 + R_3} \right) V_{\text{accel}} , \quad (4.2)$$

$$V_{\text{elec coll}} = \left( \frac{R_2}{R_1 + R_2 + R_3} \right) V_{\text{accel}} . \quad (4.3)$$

Typical values for the resistors in the voltage divider were  $R_1 = 60$  to  $150 \Omega$  (1.5 kW),  $R_2 = 600$  to  $1900 \Omega$  (1.0 kW), and  $R_3 = 10 \text{ k}\Omega$  (2.0 kW). The values quoted for power dissipation are for average powers; typical operation is at a 1–2% duty cycle with forced-air convection cooling. The resistance values of  $R_1$  and  $R_2$  are adjusted to provide the desired decel and electron collector voltages for a given accel supply voltage. When the beam is turned on,  $I_4$  is increased by the addition of the ion neutralization and scrape-off current  $I_5$ , which in turn increases the decel voltage. Hence  $R_1$  is adjusted to provide a pre-beam decel voltage that is high enough to suppress backstreaming electrons ( $V_{\text{decel}} \geq 500 \text{ V}$ ), yet low enough when the beam is on to avoid breakdowns in the decel gap ( $V_{\text{decel}} \leq 4 \text{ kV}$ ).

The electron collector voltage is determined by current  $I_6$ , which is heavily dependent on the electron collector current  $I_7$ . The higher the electron current collected, the lower will be the electron collector voltage. As will be seen in

Section 5, the electron current collected is strongly influenced by the value of the magnetic field. At low magnetic fields, the electron current is high and the electron collector voltage decreases. At high magnetic fields,  $I_7$  can reverse its polarity (collecting positive ions), causing the bias voltage to exceed its pre-beam value.

The advantages of connecting the power supplies as in configuration I are threefold:

- a) It simplifies the routing of high voltage cables and implementation of personnel safety systems, since all power supplies are referenced to the building ground.
- b) It enables all the power supply currents to be read at ground potential.
- c) It allows a wide range of boost voltage control, since this voltage is independent of the electron loss current.

However, the disadvantages of this configuration are considerable:

- a) The boost supply limits the beam current and/or boost voltage. A beam current of 14 A while maintaining a 5 kV boost potential was the practical limit from this supply.
- b) Changing the boost potential changes the beam energy; the accel voltage must then be changed in order to compensate. Changing the accel voltage changes the decel and electron collector voltages as well.
- c) It is difficult to measure the net ion recovery current accurately. This recovery current is calculated as  $I_{\text{rec}} = I_1 + I_8 - I_2$ , using the polarity conventions of Figure 4.3. As will be discussed later, small errors in the measurement of each current lead to large errors in the recovery current calculation.

In 1981 and 1982 the power supply connection labeled configuration II in Figure 2.3 (p. 16) was employed. In this configuration, the accel supply is biased above

ground by the boost supply. The actual circuit diagram for the 1982 experiment is shown in Figure 4.4.

The advantages of the configuration II power supply connection are:

- a) The boost supply provides only the ion recovery current, not the total beam current. This allows higher beam current operation.
- b) The beam energy is determined by the accel supply; the boost voltage can be varied without changing the energy of the beam or its optical properties.
- c) The ion recovery current is measured at ground potential as the boost supply current. This simplifies the measurement and provides increased accuracy in determining the net recovery current.

There are some disadvantages associated with the configuration II power supply connection:

- a) Referencing the accel supply to the boost potential introduced potential safety problems which needed to be addressed. All cabling common to the positive terminal of the accel supply was insulated from ground for the full boost potential. A varistor string and spark gaps were added to keep the boost voltage below 6 kV. A ground switch was added for personnel safety.
- b) Currents that were previously measured at ground potential are located at elevated potentials.
- c) It becomes impossible to maintain a small boost voltage when operating under conditions which yield large net loss currents.

A negative net recovery current occurs when the electron loss current exceeds the ion collection current. This net loss current cannot pass through the boost supply because of its polarity; a bypass resistor is provided for this purpose. Moreover, a current limiting resistor is placed at the positive terminal of the boost supply to protect it from a current overload should either sparkgap fire. Control of the

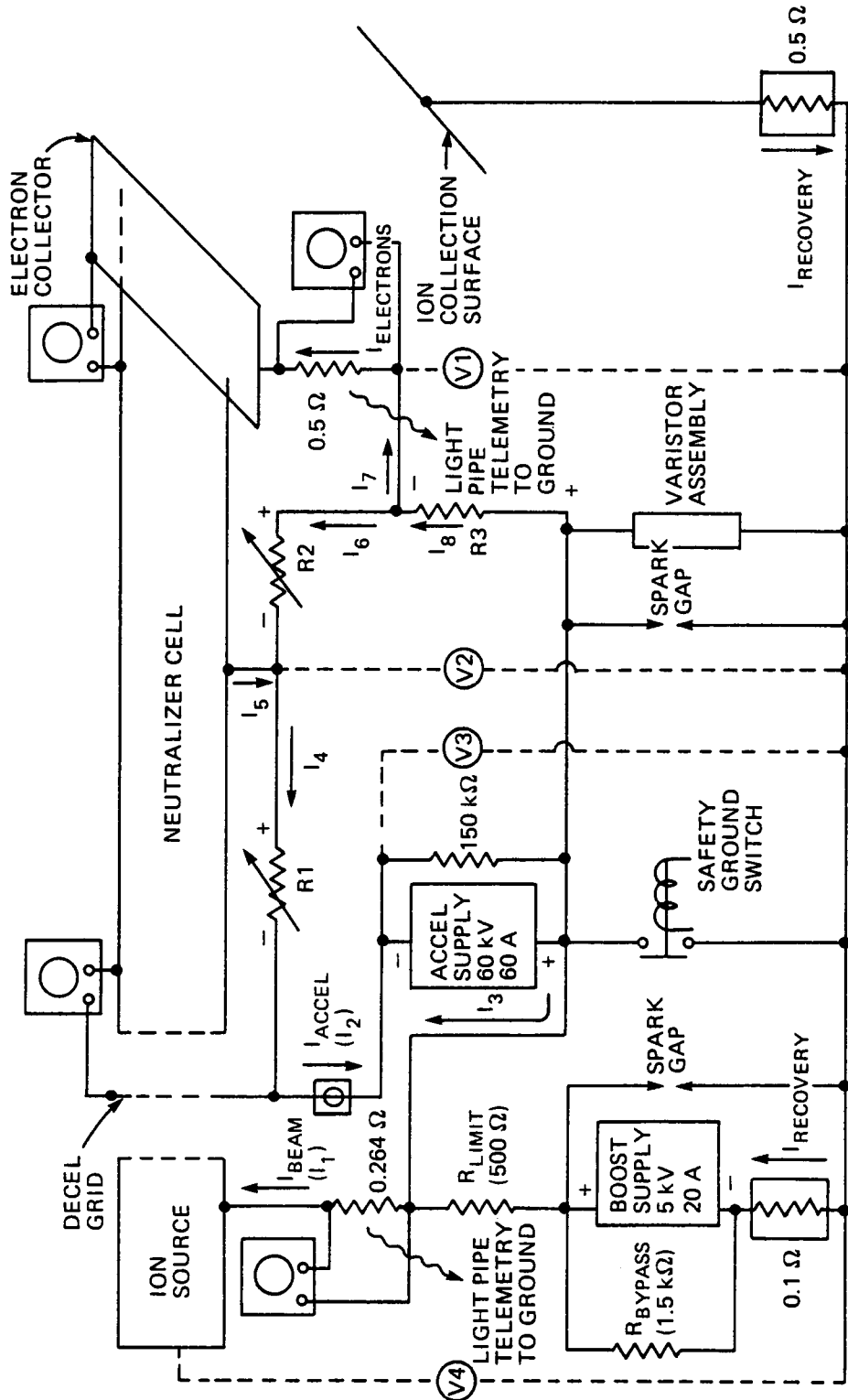


Fig. 4.4. Detailed circuit of power supply configuration II.

boost voltage is lost when  $-I_{\text{rec}}(R_{\text{bypass}} + R_{\text{limit}}) > V_{\text{boost}}$ . The net loss current increases as the boost voltage is lowered since the ion collection current decreases; this made it difficult to operate at low boost voltages, since the loss current would increase the boost potential. The lower limit of the bypass resistor is determined by its power dissipation rating,  $(\max V_{\text{boost}})^2/R_{\text{bypass}}$ . The lower limit for the current limiting resistor is determined by the current rating of the boost supply,  $(\max V_{\text{boost}})/R_{\text{limit}} \leq 20$  A. The bypass resistor was decreased from 2.5 k $\Omega$  to 1.5 k $\Omega$  during the course of the experiments, and the current limiting resistor was later reduced from 500  $\Omega$  to 250  $\Omega$ .

### A.3 Current Measurements

Many of the currents of interest in the energy recovery experiment occurred at potentials far removed from ground. The telemetry problem of transferring these data across a high voltage interface was compounded by the high levels of rf noise emitted by the experiment, particularly at low magnetic fields and high beam powers.

Initial experiments used commercially available current sensors that operate on the Hall effect principle. The current sensor is at ground potential and surrounds the insulated cable carrying the current to be measured. The magnetic field generated by the cable current interacts with the Hall effect element to produce a voltage proportional to the cable current. RG-19 cables were used to provide the necessary voltage insulation; the smallest diameter current sensor that would accommodate such a large cable was one designed for 250 A full-scale measurements. Since many of the currents of interest were less than an ampere, the operating point was in a nonlinear region near zero and the signal was almost lost in the noise. Biasing

the operating point to a more linear region by passing a dc current through each sensor was unsuccessful. The principal problem associated with using these Hall effect sensors was their susceptibility to electrical noise. After electrostatic and soft iron shielding proved ineffective, tests determined that the noise carried on the currents themselves was responsible for the erroneous readings. At low magnetic field values the noise on the electron collector current could be more than  $\pm 100\%$  of the signal value, causing errors in measurement and even reversing the apparent polarity of the signal. Although these sensors continued to be used where the currents were large and relatively quiet (i.e., the accel supply current), elsewhere they were replaced by optical telemetry.

In the optical telemetry system, the voltage developed across a current shunt resistor is transformed by a voltage-to-frequency (V/F) convertor which modulates an LED; the signal is then transmitted to ground via a light pipe where it is restored to an analog value by a phototransistor and F/V convertor. The high voltage side of the telemetry system was self-contained and battery operated. The system was partially successful; it worked well for the beam current, which was also visually monitored on a floating oscilloscope referenced to the boost potential for comparison with the telemetry signal. The electron collector current was often too noisy for this system to handle; it could also reverse polarity, while the telemetry system was designed for unipolar signals. Biasing it to accept bipolar signals would put an unacceptably large drain on the batteries in the absence of signal. Each optical channel could operate for 8 to 10 hours before recharging the batteries when running the experiment on a 1% duty cycle. Ultimately, the electron collector current was filtered with a four-pole 2 kHz low-pass filter and observed on a floating oscilloscope referenced to the neutralizer potential. Its time-varying signal was not recorded by the data acquisition system.

In 1981 selected ground surfaces (front magnet liner, rear magnet liner, top ground plate, bottom ground plate, front ground plate, and ion dump) were isolated from the vacuum tank (system ground) with thin strips of Mylar insulation. In 1982 the north and south magnet pole faces were added to this list. Each surface was connected to the tank ground by a  $0.5 \Omega$  resistor, enabling the net current striking each ground surface to be recorded.

It was remarked earlier in this chapter that the net recovery current was difficult to measure accurately while using the power supply connection of configuration I. The net recovery current is calculated as

$$I_{\text{rec}} = I_1 + I_8 - I_2 = I_{\text{beam}} + I_{\text{bias}} - I_{\text{accel}} , \quad (4.4)$$

using the numbering system of Figure 4.3 (p. 63) and the equivalent nomenclature. The Hall effect sensors CS2, CS7, and CS3 were used to measure each respective current separately. This technique was later refined by passing all three cables through the same sensor (CS1) in such a manner that the three currents would algebraically add to yield the net recovery current. The former method suffered from using three separate sensors that refused to stay accurately calibrated ( $\leq 1\%$ ), while the latter method gave a net signal that was typically less than  $0.1\%$  of the sensor design value and hence in the nonlinear region.

The most accurate method of calculating the net recovery current in configuration I was to measure  $I_1$ ,  $I_2$ , and  $I_8$  with resistive current shunts located at ground potential (RS2, RS3, RS10); the recovery current was calculated by the data acquisition computer. Accuracy is still rather poor with this technique, as a  $1\%$  error in the current readings can lead to as much as a  $50\%$  error in the

net recovery current calculation. For example, in 1980 the following values were recorded for a 43 kV, 14 A beam:

$$\begin{aligned} I_{\text{rec}} &= I_{\text{boost}} (I_1) + I_{\text{bias}} (I_8) - I_{\text{accel}} (I_2) \\ &= 14.57 \text{ A} + 10.00 \text{ A} - 23.57 \text{ A} = 1.00 \text{ A} . \end{aligned}$$

However, 1% changes in the current measurements can yield a net recovery current as low as

$$I_{\text{rec}} = 14.42 \text{ A} + 9.90 \text{ A} - 23.81 \text{ A} = 0.51 \text{ A}$$

or as high as

$$I_{\text{rec}} = 14.72 \text{ A} + 10.10 \text{ A} - 23.33 \text{ A} = 1.49 \text{ A} .$$

This problem was alleviated by using the power supply connection of configuration II, wherein the net recovery current is a single measurement made by a current shunt at ground potential.

#### A.4 Diagnostics and Data Acquisition

The principal diagnostic in the energy recovery experiment is the calorimetry system, whereby the power loading on each water-cooled component in the experiment is measured. The power is calculated by using  $\Delta T$  thermopiles to measure the temperature difference between the inlet and outlet cooling water and turbine flowmeters to measure the water flow. The  $\Delta T$  signals, amplified and digitized by a NEFF 620 amplifier/multiplexer, are sampled every 10 ms by the data acquisition system. The product of the water temperature rise and the water flow is integrated over the interval between pulses (10 or 20 seconds) to obtain an absolute energy measurement. Each calorimetry channel was calibrated by using a 3 kW dc heater to input a known power into each circuit; 6 months later the 12 most important

channels were rechecked. Four channels were within  $\pm 1\%$ , four were within  $\pm 2\%$ , and the remaining four were within  $\pm 5\%$ . Some systematic errors can be caused by the change of  $\Delta T$  sensitivity to changes in water flow, or by changes in the flowmeter constant (pulses/gal-s<sup>-1</sup>) due to turbine bearing wear; these errors are thought to be small. Of more concern are drift in the amplifier channels for the  $\Delta T$  signals and the apparent heating or cooling of components with abrupt changes in the inlet water temperature. Although the water temperature changes as much as 7°C during an operating period, the rate of change is low. Amplifier drift was compensated for by introducing a relatively large positive dc offset to each  $\Delta T$  channel and subtracting an adjustable offset during data analysis. Baseline offsets are adjusted before the start of each experimental run by the software in order to produce zero power loading on each component. Another source of error was electrical noise pickup from the experiment; this noise was present only during the first 1% of the integration period. The largest source of calorimetry error by far is due to difficulty in achieving a series of identical beam pulses.

The calorimetric analysis calculates the energy deposited in the cooling water from the onset of one beam pulse to the onset of the next pulse. It divides this energy by the beam pulse length as measured from the actual beam current pulse duration. At least five successive beam pulses are needed to bring most of the components to thermal equilibrium; hence, some of the thermal energy measured over the interval between pulses was deposited by previous pulses. A high voltage breakdown produces a short pulse, which deposits less energy. The calculated power for that pulse will be erroneously high, since the energy deposited by previous pulses will still be present and it will be divided by a short pulse length. A full pulse length on the succeeding pulse will yield an erroneously low calculated power, since the preceding pulse did not deposit much energy, and the full pulse

length is used to calculate the power. For each calorimetric data point, five pulses are used to bring the components to equilibrium, and the average of the next ten pulses is used as the power loading; the standard deviation is considered the error in the measurement. When the experiment is operated in the normal mode, approximately 87% of the  $I \times V$  power from the supplies is accounted for by the calorimetry system. This figure is reduced to 80% for energy recovery operation.

It is obvious from this discussion that the power loading on each component is an average value. Most of the currents and voltages vary during a pulse, some quite considerably. Average currents and voltages, calculated by integrating the signals over the pulse, are used when making comparisons with calorimetric data. When comparing electrical signals with other electrical signals, all values are taken at the same instant in the beam pulse.

The ion species ratio in the source is an important parameter in the calculations for the ion recovery efficiency, as this determines the full energy ion current. In the slanted geometry experiments of 1980 and 1981, magnetic momentum analysis was performed on the beam with the ion deflection magnet while operating in the normal mode. The beam is swept across a calorimetric sensor in the ion dump to obtain the power associated with each energy component. The assumption of an equilibrium gas cell allows the species ratio in the ion source to be calculated. The neutralizer/magnet configuration for the 1982 experiment did not allow this measurement to be performed. Instead, the species ratio in the ion source was measured at another test stand before the source was transferred to METF-W.

Both ion sources had atomic ion fractions of about 80% when measured by magnetic momentum analysis; this measurement technique usually yields results that are about 5% higher than Doppler shift spectroscopy and about 10% higher than SIMS analysis of beam implanted silicon crystals.<sup>62</sup>

## B. SLANTED MAGNET/NEUTRALIZER GEOMETRY

### B.1 Ion Source

The ion source used in the energy recovery experiments of 1980 and 1981 was a modified PLT prototype.<sup>63</sup> This prototype used a 20 cm diameter extraction grid rather than the 22 cm diameter grid ultimately used in the PLT production sources. The extraction area was reduced to an 18 cm diameter by a tantalum mask for the 1980 experiments; it was further reduced to 16.3 cm diameter in 1981. The purpose of this reduction in beam cross section was to lower the power being deposited on the neutralizer. A 29 A beam was extracted at 48 kV from this source in 1981 while operating in the normal mode; such parameters could not be achieved in the energy recovery mode. The ion species ratio in the source was  $H^+ : H_2^+ : H_3^+ :: 0.81 : 0.10 : 0.09$  as measured by magnetic momentum analysis. Optimum beam optics occurred at  $2.8 \mu\text{perv}$  ( $A \times V^{-1.5} \times 10^{-6}$ ) which corresponds to 22 A at 40 kV; the power transmission to the beam target was 50.5% at this value of perveance. Ion beams follow Child-Langmuir scaling as a consequence of dimensional analysis;<sup>64</sup> the beam optics depend only on the beam perveance and remain constant for constant  $IV^{-1.5}$ .

### B.2 Energy Recovery Apparatus

The neutralizer and electron collector are maintained at a high negative potential and must fit within the 28 cm pole gap of a grounded magnet. To prevent electrical breakdowns, the circular cross-section neutralizer is reduced from a 22 cm diameter near the ion source to a 15 cm diameter over the last 70 cm of length.

The total length is 180 cm, as compared to a typical PLT beamline neutralizer length of 100 cm. The neutralizer diameter constriction and excessive length are responsible for the poor power transmission; half the beam power is deposited on the neutralizer even at optimum perveance.

Figure 4.5 shows the components of the energy recovery system. The 22 cm to 15 cm reducer section is at the far left, followed by the final neutralizer section. This end section is divided into nine separate cooling circuits for diagnostic purposes. There is a total of 12 neutralizer cooling circuits monitored by the calorimetry system. The end of the neutralizer is slanted at an angle of  $55^\circ$  to the vertical. A rectangular cap is positioned around the end of the neutralizer to match to the rectangular geometry of the electron collector and suppression magnet. This is the uncooled copper shell with the elliptical aperture in the center of Figure 4.5; all source, neutralizer, and electron collector components are fabricated from copper.

The electron collector is rectangular in cross section and surrounds the end of the neutralizer with about 1 cm of clearance. It has water cooling on the top and bottom only, and is the second component from the right in Figure 4.5. The final component in Figure 4.5 is the ground plate assembly, which surrounds the electron collector. The top, bottom, and front sections have separate water cooling circuits; in 1981 each was electrically isolated in order to measure the net current collected by each. The open sides are closed by the magnet pole pieces and liners when the apparatus is in place.

The electron suppression magnet is the ion deflection magnet designed for the PLT beamlines. Its immobility is responsible for the long neutralizers used in these experiments. Figure 4.6 shows the magnet in its test frame; water-cooled liners were added to the front and rear of the pole pieces to protect the magnet

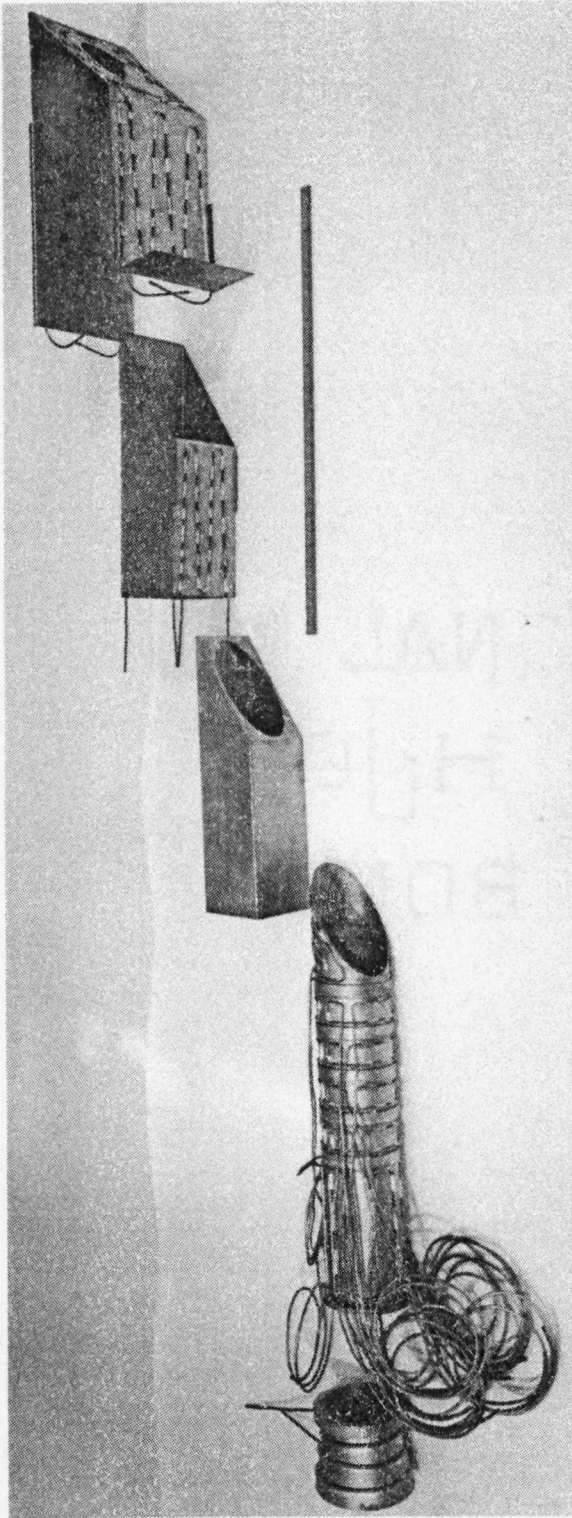


Fig. 4.5. Components of the slanted neutralizer energy recovery device. At the left is the cylindrical neutralizer end with multiple cooling circuits, followed by a rectangular neutralizer shell, the electron collector, and the grounded ion collection surfaces.

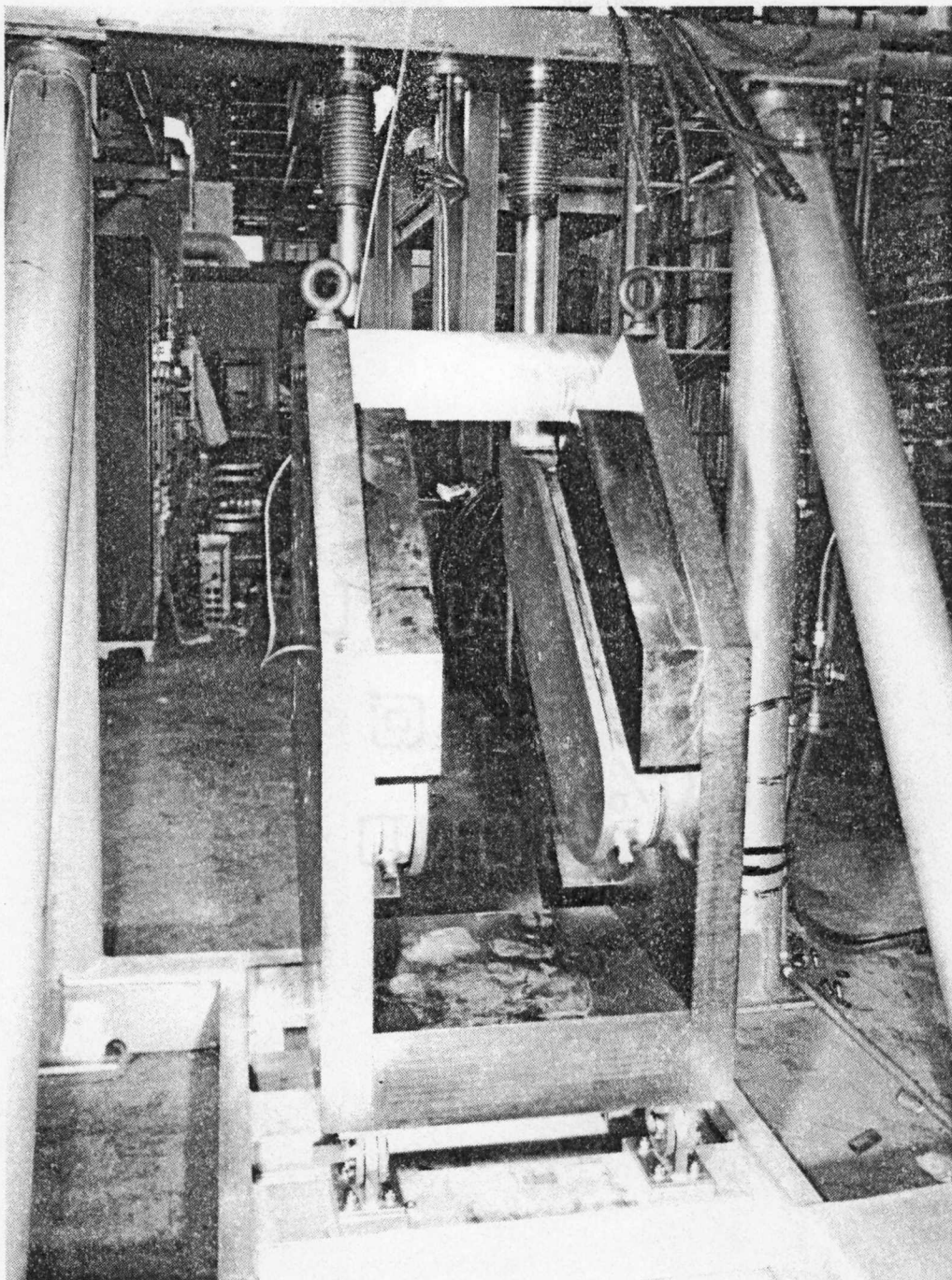


Fig. 4.6. The electron suppression magnet in its test frame.

frame from energetic particles during the energy recovery experiments. The pole pieces are about 80 cm long by 30 cm wide with a 28 cm gap. The peak magnetic field strength in gauss is 3.5 times the magnet current in amperes. The field distribution at the midplane is Gaussian along the short dimension (Figure 4.7). The pole pieces and the front and rear liners were isolated from ground in 1981, but the mica and Mylar insulation on the pole pieces failed almost immediately.

The calorimetry system for this experiment monitored 32 cooling channels for diagnostic purposes; the locations and labels are shown in Figure 4.8. The copper cooling lines for the neutralizer were brought out of the vacuum tank through an epoxy insulator just above the ion source. The electron collector water lines used a similar epoxy feedthrough located in the same area. The high voltage was applied to the neutralizer and electron collector by connecting to these water lines. Figure 4.9 shows the principal system components installed in the METF-W vacuum tank.

The 1980 experiment was terminated by a pump failure in the facility demineralized water system. Cessation of flow caused the water to freeze due to the proximity of the cryopumps. The resulting leaks from the expansion were repaired for the 1981 experiment, but the work-hardened copper remained susceptible to leaks if excessive mechanical stress was applied. The voltage holding capabilities were never regained, and the later experiments operated at lower parameters.

## C. VERTICAL MAGNET/RECTANGULAR NEUTRALIZER GEOMETRY

### C.1 Ion Source

A number of ion sources were tried on the 1982 experiment before a workable combination of components was achieved. The lack of a source isolation valve

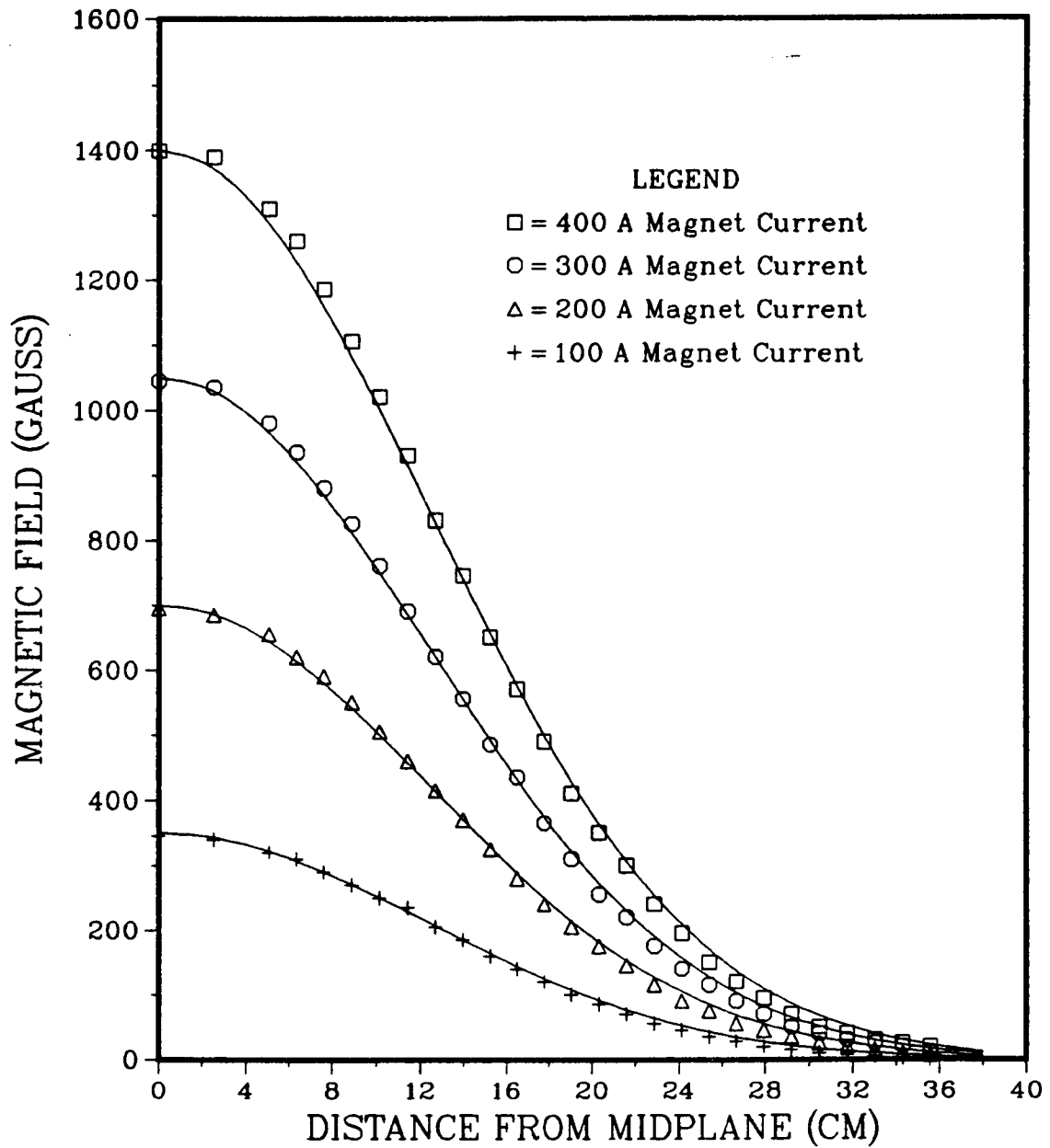


Fig. 4.7. Midgap field strength perpendicular to the long poleface axis as a function of magnet current. Points are measured values while lines are the function  $B \text{ (gauss)} = 3.5 \times I \text{ (A)} \exp\{-[x \text{ (cm)} / 17]^2\}$ .

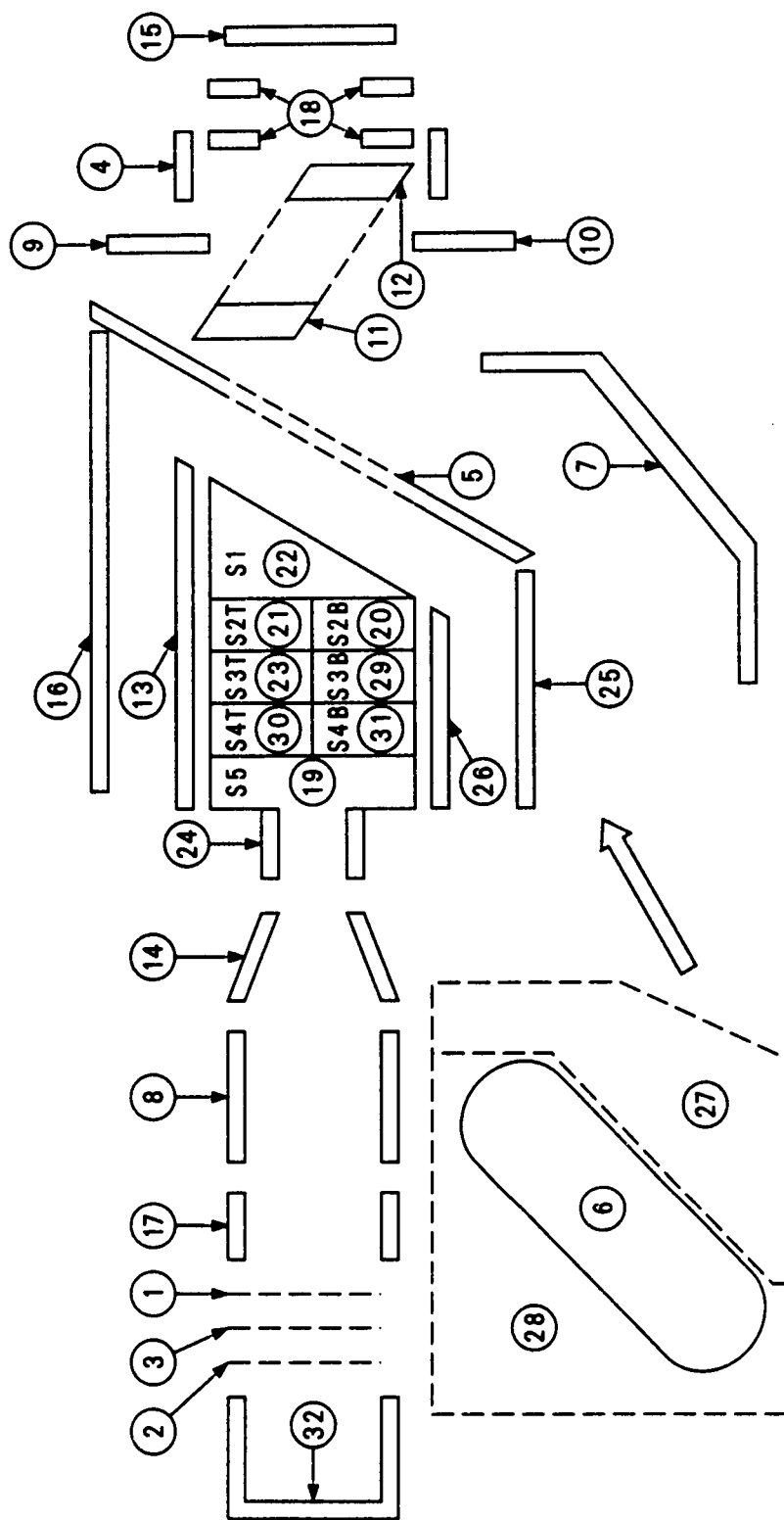


Fig. 4.8. Components of the slanted neutralizer experiment calorimetry system.

| Calorimetry<br>Channel | Beamline Component             |    |
|------------------------|--------------------------------|----|
| 1                      | "Ground" Grid                  | 17 |
| 2                      | Plasma Grid                    | 18 |
| 3                      | Decel Grid                     | 19 |
| 4                      | Drift Tube Liner               | 20 |
| 5                      | Front Ground Plate             | 21 |
| 6                      | Magnet Polefaces (No. and So.) | 22 |
| 7                      | Ion Dumps                      | 23 |
| 8                      | 22 cm Neutralizer Section      | 24 |
| 9                      | Top Defining Plate             | 25 |
| 10                     | Bottom Defining Plate          | 26 |
| 11                     | North Defining Plate           | 27 |
| 12                     | South Defining Plate           | 28 |
| 13                     | Top Electron Collector         | 29 |
| 14                     | Tapered Neutralizer Section    | 30 |
| 15                     | Torus Target                   | 31 |
| 16                     | Top Ground Plate               | 32 |
|                        | Auxiliary Neutralizer          |    |
|                        | Beam Apertures                 |    |
|                        | Neutralizer Section 5          |    |
|                        | Neutralizer Section 2 Bottom   |    |
|                        | Neutralizer Section 2 Top      |    |
|                        | Neutralizer Section 1          |    |
|                        | Neutralizer Section 3 Top      |    |
|                        | 15 cm Neutralizer Section      |    |
|                        | Bottom Ground Electrode        |    |
|                        | Bottom Electron Collector      |    |
|                        | Front Magnet Liner             |    |
|                        | Rear Magnet Liner              |    |
|                        | Neutralizer Section 3 Bottom   |    |
|                        | Neutralizer Section 4 Top      |    |
|                        | Neutralizer Section 4 Bottom   |    |
|                        | Backstreaming Electron Plate   |    |

Figure 4.8 (continued)

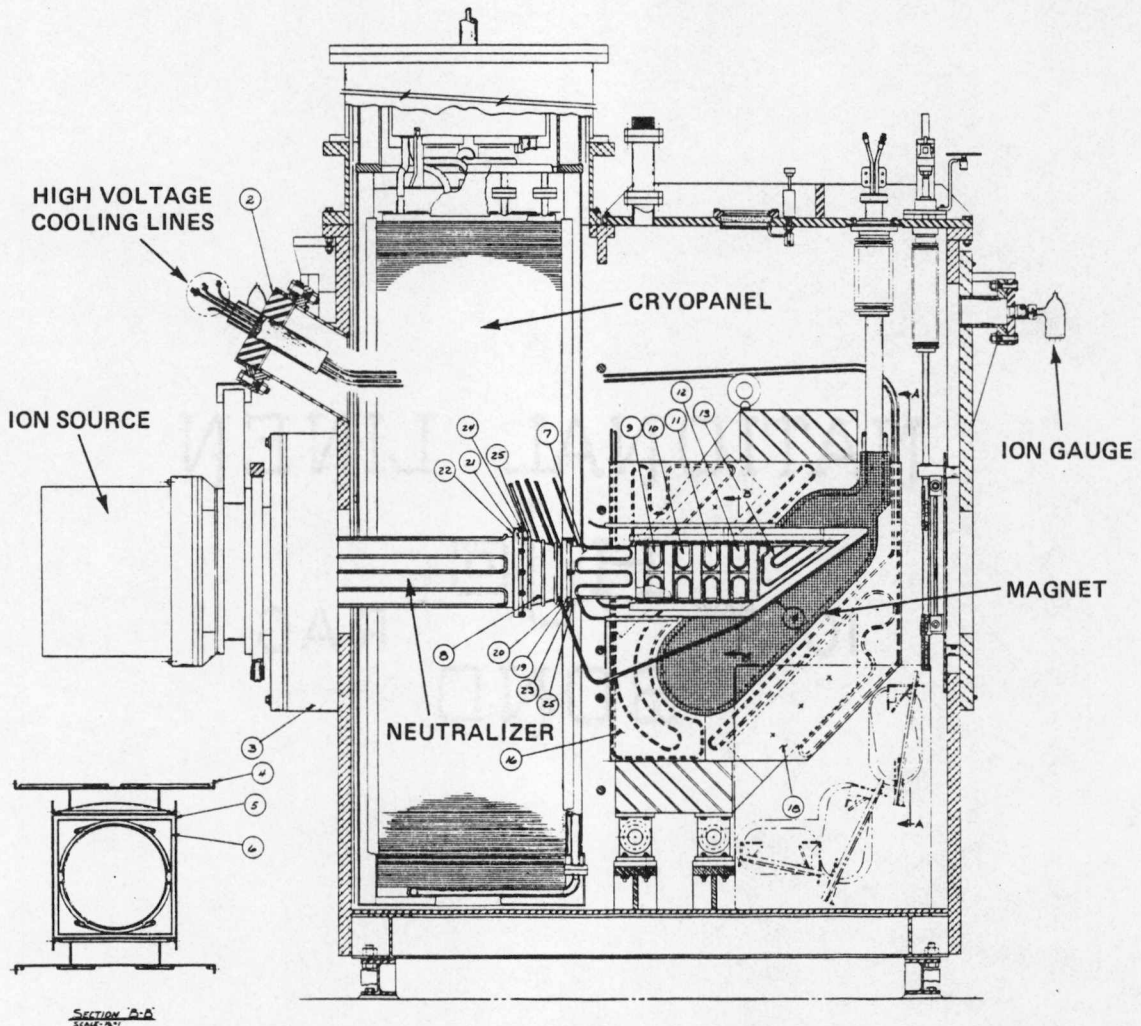


Fig. 4.9. Slanted neutralizer experiment as installed in the METF-W.

in this cryopumped system meant lengthy warmup and cooldown cycles for any source component modification. The same set of grids was used throughout this exercise; a three grid, accel/decel arrangement with a 0.75 cm accel gap (optimized for 50 kV/25 A operation) was employed.

The first plasma generator used was from the standard PDX ion source; this source has delivered 100 A beams at 50 kV using a 30 cm diameter extraction grid.<sup>65</sup> Operation with a new accelerator and neutralizer was plagued with difficulties. A reliable arc would not strike until the tank pressure was above  $2 \times 10^{-4}$  torr. In an effort to decrease the gas throughput needed to operate the source, the standard 4-hole intermediate electrode was replaced with an experimental 2-hole intermediate electrode and its companion first anode. Operation was again difficult; improper gas pressures were suspected. A pressure gauge was installed in the second anode chamber, where the pressure without an arc was  $3 \times 10^{-2}$  torr. This is quite high, while the pressure in the filament chamber was only about  $7 \times 10^{-2}$  torr, which is quite low. The longer than ordinary neutralizer has a gas conductance calculated to be in the 1500 to 2500 L/s range while the total conductance of the accelerator is around 1200 L/s. These relatively low conductances contributed to the poor pressure distributions in the ion source.

The APIS half-scale ion source<sup>66</sup> became available during this period and replaced the PDX plasma generator. It has a  $25 \times 35$  cm cross section and is designed to operate with the  $10 \times 25$  cm accelerator used in this experiment. It operated at substantially lower tank pressures than the PDX ion source ( $5 \times 10^{-5}$  torr), although operation was erratic at even lower pressures. The source was used to generate the data that are presented and analyzed in Section 5.

## C.2 Energy Recovery Apparatus

The energy recovery apparatus was redesigned to alleviate the voltage feedthrough problems of the previous experiments and also to provide more flexibility in accommodating alternative designs. The neutralizer cross section is  $10.5 \times 26$  cm, with the long dimension oriented vertically. The main neutralizer is 140 cm long and constitutes one water-cooled circuit. The end piece of the neutralizer is 7.5 cm long and contains four water-cooled circuits, one for each side. It is designed to support the electron collector assembly. Two extension pieces were fabricated to be inserted between the main neutralizer section and the end piece. One is 15 cm long and contains one cooling circuit; the other is 7.5 cm long and contains four water cooling circuits. This allowed the length of the neutralizer to be either 147.5, 155, 162.5, or 170 cm long. Time constraints did not allow the neutralizer length to be varied; the 15 cm spacer was used for all experiments, giving a neutralizer length of 162.5 cm. The neutralizer projected 7.5 cm into the pole gap, or halfway to the center.

The electron collector was modified during the operation of the experiment. The original electron collector had two side plates and a top plate, each of which was electrically, thermally, and mechanically isolated from the others. Each component had an individual water circuit and was made of copper. The electron collector sides were flush with the end of the neutralizer, while the top extended 1 cm past the neutralizer. The original design called for 1 cm spacing between the electron collector plates and the adjacent neutralizer surfaces. This was extended to 2 cm when it became apparent upon assembly that water line misrouting had reduced the voltage holding gap between the collector and neutralizer to perilously low values. This same water line misplacement resulted in abandoning half

of the concentric metallic shields designed to protect insulator surfaces from being coated with copper from line-of-sight sputtering. Each collector component was supported from the neutralizer via four insulator posts.

The side electron collector plates were 7.5 cm wide. The top electron collector plate had a flat section that was 8.5 cm deep (including the 1 cm by which it extended past the neutralizer). The overhang was intended to facilitate the collection of electrons which escaped the neutralizer. The top collector plate extended an additional 8.5 cm back toward the ion source; this section had a gabled "roof" in order to provide a transverse component to the electrostatic field by which electrons  $\mathbf{E} \times \mathbf{B}$  drifting in the gap between the neutralizer and top collector plate could be collected off-axis.

The ground plates were similar to the configuration used in the previous experiment. The top and bottom ground plates were situated above and below the neutralizer and extended downstream past it. They were mounted on rails for ease of movement, in order to accommodate the variable length neutralizer as well as to ascertain the effect of ground plate position with respect to the neutralizer. The supporting guide rails were affixed to the magnet liners by insulated posts. No front ground plate was employed in this geometry. It was reasoned that this plate was not necessary to establish a ground potential surface and thus fix the deceleration sheath dimensions—the anode sheath would be fixed by the target plasma created by beam interactions with the background gas. Its absence would allow increased pumping and decreased pressure in the recovery region. The importance of the front ground plate as an ion collection surface was not recognized.

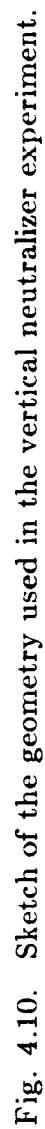
The energy recovery apparatus was modified after initial operation. The electron collector surfaces were extended 3.2 cm past the end of the neutralizer and 1.25 cm below the bottom of the neutralizer. The insulators supporting the top

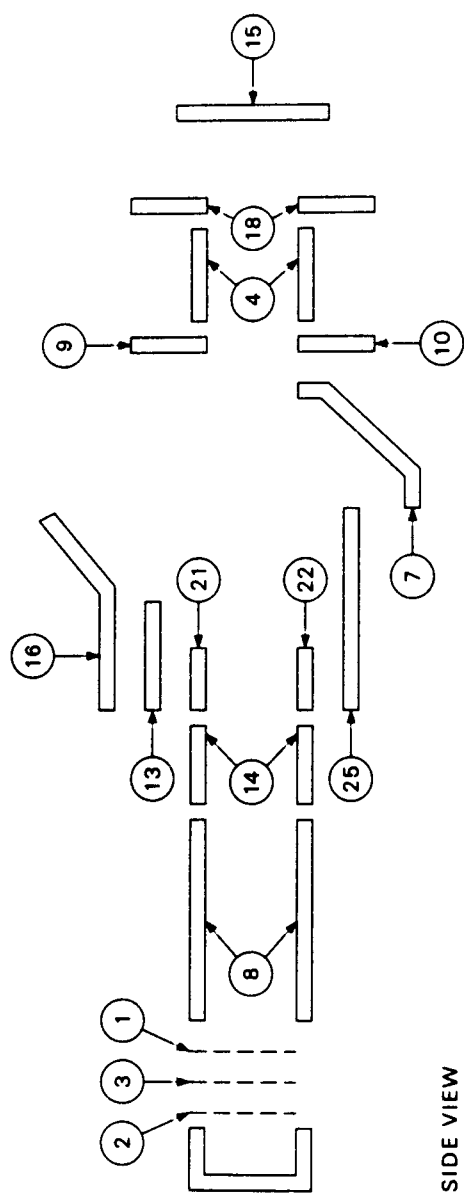
electron collector from the top of the neutralizer were removed because of severe damage from drifting electrons; the top collector was supported from the side collectors. The final end geometry is shown in Figures 4.10 and 4.11; note that the neutralizer was inadvertently displaced toward the south magnet pole face. Later inspection showed that arcing had occurred between the top electron collector and the top ground plate at the south pole face rail (2.5 cm gap).

The suppression magnet was extensively modified in order to orient the long axis of its poles in the vertical direction. A disproportionate amount of the experimental budget was squandered on accomplishing this in a leak-tight manner. New feedthrough flanges eventually had to be fabricated which would allow us to pump on the coils with a mechanical pump (the coils were designed to operate at atmospheric pressure).

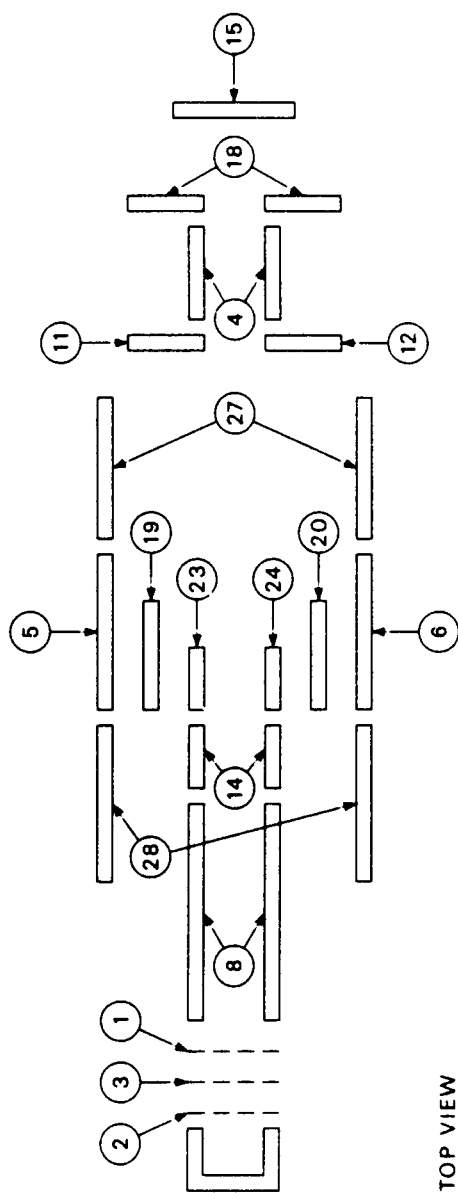
The calorimetry system for this experiment monitored 28 cooling channels; the locations and labels are shown in Figure 4.11. The copper water cooling lines maintained at negative potentials were brought out of the vacuum tank through the epoxy insulator to which the neutralizer was mounted. This enabled the entire neutralizer/collector assembly to be withdrawn from the tank for maintenance without the necessity of entering the vacuum tank to break water connections, as in the previous experiment. The cooling water lines for ground surfaces were brought out through Plexiglas flanges. Figure 4.12 shows the principal energy recovery components installed in the METF-W vacuum tank.

This experiment never operated as reliably as the previous experiment. This was due in part to inability to modify components as experimental results dictated because of programmatic insolvency. However, the principal factor in the poor performance of this experiment is the ion trajectories themselves, as will be demonstrated in the next section.





**SIDE VIEW**



**TOP VIEW**

Fig. 4.11. Components of the vertical neutralizer experiment calorimetry system.

| Calorimetry<br>Channel | Beamline Component             |    |
|------------------------|--------------------------------|----|
| 1                      | "Ground" Grid                  | 15 |
| 2                      | Plasma Grid                    | 16 |
| 3                      | Decel Grid                     | 17 |
| 4                      | Drift Tube Liner               | 18 |
| 5                      | North Magnet Pole Face         | 19 |
| 6                      | South Magnet Pole Face         | 20 |
| 7                      | Ion Dumps                      | 21 |
| 8                      | Main Neutralizer Section       | 22 |
| 9                      | Top Defining Plate             | 23 |
| 10                     | Bottom Defining Plate          | 24 |
| 11                     | North Defining Plate           | 25 |
| 12                     | South Defining Plate           | 26 |
| 13                     | Top Electron Collector         | 27 |
| 14                     | Neutralizer Extension          | 28 |
|                        | Torus Target                   |    |
|                        | Top Ground Plate               |    |
|                        | Spare                          |    |
|                        | Beam Aperture                  |    |
|                        | North Electron Collector       |    |
|                        | South Electron Collector       |    |
|                        | Top Neutralizer End Section    |    |
|                        | Bottom Neutralizer End Section |    |
|                        | North Neutralizer End Section  |    |
|                        | South Neutralizer End Section  |    |
|                        | Bottom Ground Plate            |    |
|                        | Spare                          |    |
|                        | Front Magnet Liner             |    |
|                        | Rear Magnet Liner              |    |

Figure 4.11 (continued)

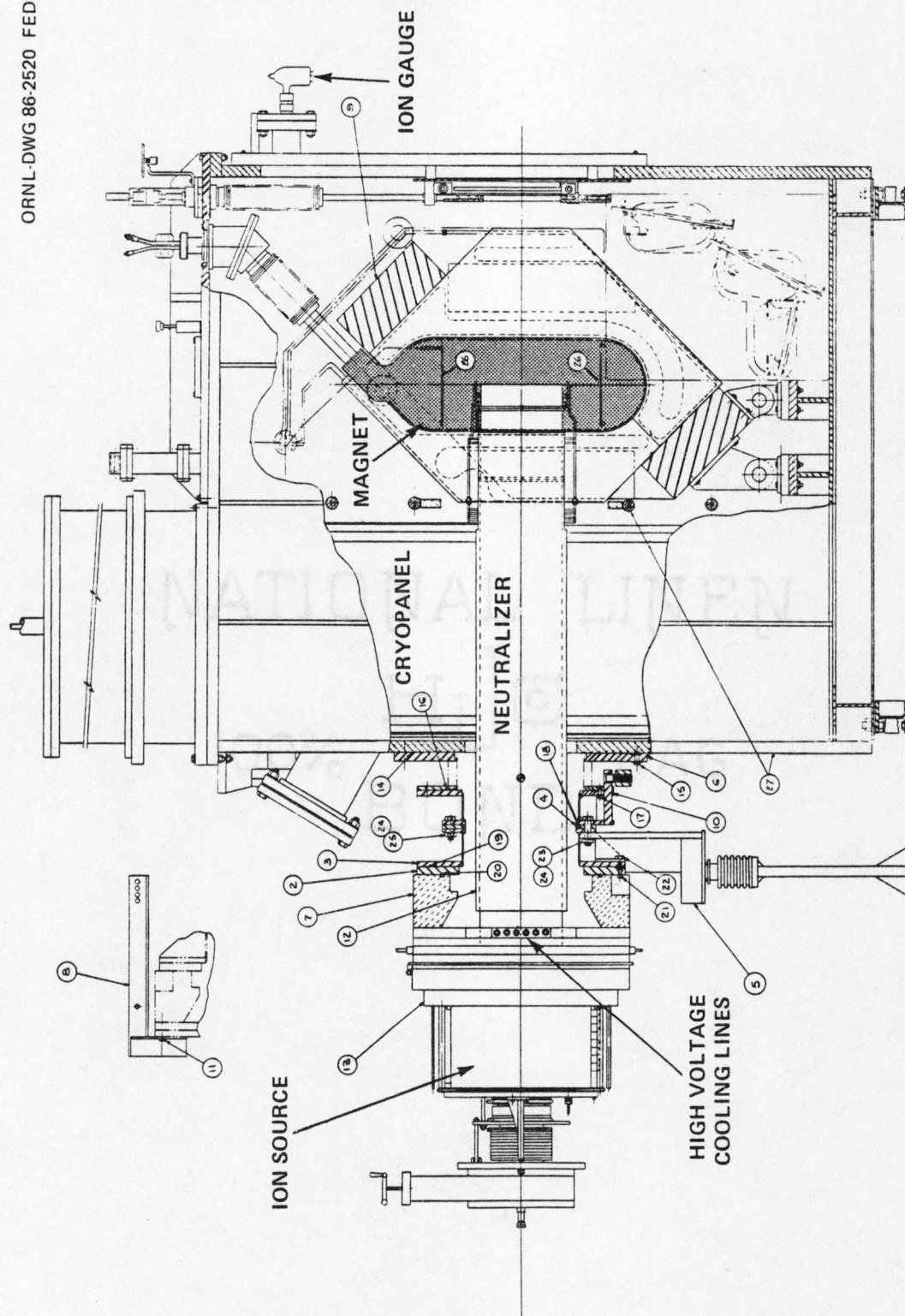


Fig. 4.12. Vertical neutralizer experiment as installed in the METF-W.

## 5. ANALYSIS

### A. SLANTED MAGNET/NEUTRALIZER EXPERIMENT

The slanted magnet/neutralizer experiment described in the previous section was a qualified success. The system sustained damage from a waterline freeze, and subsequent repairs never allowed previously attained parameters to be duplicated. On the other hand, improved diagnostics provided for better understanding of device operation. An attempt will now be made to separate the interdependent experimental parameters in order to understand the effect of each on system performance.

#### A.1 The Effect of the Magnetic Field

The magnetic field in the energy recovery device has a major effect on the net recovery efficiency through its influence on the ion trajectories and electron leakage current. Figure 5.1 indicates how the net current recovery efficiency varies with magnetic field strength for two similar experimental cases. One case shows positive net recovery efficiency for a 40 keV, 10 A beam when the field is between 700 and 1500 G, while a 36 keV, 10 A beam barely reaches breakeven at 1100 G. Both cases employed a boost voltage of 5 kV and an electron collector potential of about 7 kV with respect to the neutralizer. The discrepancy between the two cases is due to the gas pressure in the recovery region; the pressure measured at the ion gauge at the end of the tank is 50% higher in the 36 keV case.

Recovery efficiencies of  $60\% \pm 30\%$  were measured in the 1980 experiments; the large error bars are due to the three current sensor method of calculating the net recovery current. The current recovery efficiency in the 1981 experiments

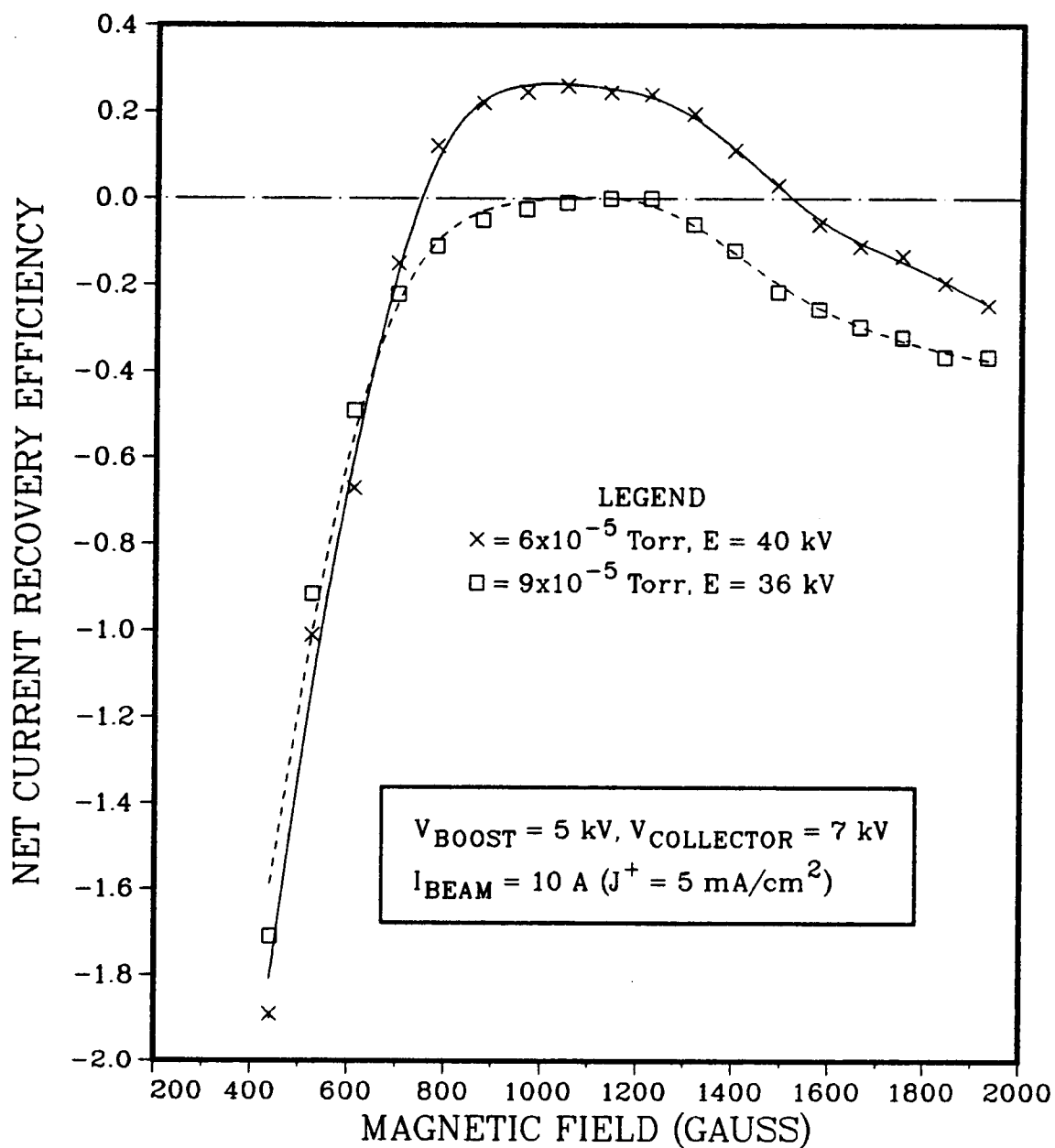


Fig. 5.1. Net current recovery efficiency vs. magnetic field for the slanted neutralizer experiment.

never exceeded 30%. The difference is attributed to improved diagnostics, slightly higher gas pressures, and less reliable system operation after the waterline freeze-up repairs in 1981. Although the 36 keV case never exhibited a positive net recovery efficiency, it will be analyzed in some detail since operation was relatively reliable and repeatable, allowing accurate calorimetric data to be obtained.

The variation of recovery efficiency with magnetic field in Figure 5.1 is quite characteristic of this experiment. The leakage electron current from the neutralizer plasma decreases with increasing magnetic field; it will be shown that it is inversely proportional to field strength. In this slanted neutralizer geometry, the ion collection efficiency peaks when the downward magnetic force on the ions counterbalances the upward electrostatic forces from the deceleration fields. The charge-exchange and volume ionization losses due to increased gas pressure in the recovery region are most evident at field strengths above 700 G.

The power loading on the beam target and auxiliary structures is  $74.5 \pm 0.7$  kW for the 36 keV, 10 A case. The full-energy ion current available for recovery is calculated from

$$I^+(E) = \frac{P_0 \eta_1 (H^+) f_{1\infty}(E)}{V_0 [\eta_1 (H^+) f_{0\infty}(E) + \eta_2 (H_2^+) f_{0\infty}(E/2) + \eta_3 (H_3^+) f_{0\infty}(E/3)]} \quad (5.1)$$

where  $P_0$  is the neutral power emerging from the neutralizer,  $V_0$  is the beam acceleration voltage,  $\eta_1 : \eta_2 : \eta_3$  are the  $H^+ : H_2^+ : H_3^+$  species ratio in the ion source, and  $f_{1\infty}(E)$  and  $f_{0\infty}(E)$  are the ionization and neutralization equilibrium fractions for a beam of energy  $E$  passing through  $H_2$ ;

|                         |                                     |
|-------------------------|-------------------------------------|
| $\eta_1 = .80$          | $f_{0\infty}(36 \text{ keV}) = .67$ |
| $\eta_2 = .10$          | $f_{0\infty}(18 \text{ keV}) = .82$ |
| $\eta_3 = .10$          | $f_{0\infty}(12 \text{ keV}) = .85$ |
| $V_0 = 36 \text{ kV}$   | $f_{1\infty}(36 \text{ keV}) = .33$ |
| $P_0 = 74.5 \text{ kW}$ |                                     |

The available full-energy ion current is calculated to be .78 A, corresponding to a current density of 4.4 mA/cm<sup>2</sup>.

The ion collection current is calculated by the power loading on selected ground surfaces. At a high boost potential of 5 kV and a relatively modest current density of 5 mA/cm<sup>2</sup>, full energy ions will be collected primarily on ground surfaces that are not accessible to energetic electrons, such as the ion dump, far tank wall (defining plates), bottom ground plate, and front ground plate. Neutral particles contribute to the power loading on some of these surfaces, particularly the front ground plate and defining plates. The analysis assumes that power loading from neutrals is independent of the magnetic field. The power loadings are shown in Table I and the ion contributions in Table II; the suppositions used to separate the ion and neutral contributions are discussed below.

1) At high magnetic fields, ions do not reach the far tank wall and thus the defining plate power loading is due entirely to neutral particles. This value is subtracted from the power observed at other fields to obtain the ion contribution. It should be noted from Table I that the power loading on the bottom defining plate at 1840 and 1925 G is abnormally low with very high standard deviations; these values are discarded and the loading at 1750 G is used as the neutral particle power.

2) The power loading on the ion dumps and bottom ground plate is due entirely to ions since these components are inaccessible to neutrals and energetic electrons.

TABLE I  
POWER LOADING ON GROUND SURFACES  
AS A FUNCTION OF MAGNETIC FIELD

| <i>B</i><br>G | Defining Plates |              | Ion<br>Dumps<br>kW | Ground Plates |             |
|---------------|-----------------|--------------|--------------------|---------------|-------------|
|               | Top<br>kW       | Bottom<br>kW |                    | Bottom<br>kW  | Front<br>kW |
| 438           | 3.37 ± .08      | -1.06 ± .07  | -.13 ± .17         | .05 ± .07     | 5.70 ± .12  |
| 525           | 3.46 ± .06      | 6.22 ± .06   | .65 ± .10          | .13 ± .08     | 4.67 ± .10  |
| 613           | 3.48 ± .11      | 6.37 ± .07   | .43 ± .21          | .04 ± .07     | 4.47 ± .09  |
| 700           | 3.29 ± .07      | 6.66 ± .06   | .76 ± .24          | .14 ± .08     | 4.53 ± .11  |
| 788           | 3.15 ± .04      | 6.96 ± .07   | 1.28 ± .24         | .20 ± .07     | 4.44 ± .12  |
| 875           | 3.02 ± .13      | 7.07 ± .08   | 1.13 ± .23         | .05 ± .08     | 4.34 ± .12  |
| 963           | 3.01 ± .06      | 7.19 ± .04   | 1.23 ± .33         | .18 ± .07     | 4.58 ± .13  |
| 1050          | 3.20 ± .09      | 7.23 ± .06   | 1.68 ± .19         | .25 ± .08     | 4.63 ± .10  |
| 1138          | 3.22 ± .12      | 7.01 ± .07   | 1.47 ± .16         | .45 ± .08     | 4.84 ± .10  |
| 1225          | 3.23 ± .07      | 6.85 ± .10   | 1.46 ± .39         | .53 ± .08     | 4.78 ± .14  |
| 1313          | 3.32 ± .13      | 6.63 ± .04   | 1.18 ± .14         | .66 ± .06     | 4.89 ± .12  |
| 1400          | 3.52 ± .05      | 6.61 ± .01   | 1.41 ± .22         | .64 ± .05     | 4.69 ± .11  |
| 1488          | 3.57 ± .17      | 6.45 ± .10   | .64 ± .27          | .55 ± .11     | 4.87 ± .11  |
| 1575          | 3.61 ± .11      | 6.60 ± .08   | 1.38 ± .21         | .67 ± .14     | 5.04 ± .12  |
| 1663          | 3.55 ± .05      | 6.37 ± .06   | 1.01 ± .37         | .30 ± .07     | 4.94 ± .09  |
| 1750          | 3.50 ± .08      | 6.30 ± .08   | .49 ± .26          | .15 ± .13     | 4.92 ± .08  |
| 1838          | 3.35 ± .06      | 5.48 ± .79   | 1.25 ± .18         | .11 ± .12     | 4.92 ± .06  |
| 1925          | 3.20 ± .06      | 2.25 ± .19   | .52 ± .11          | .22 ± .09     | 4.90 ± .17  |

TABLE II  
POWER LOADING ON GROUND SURFACES FROM FULL ENERGY  
IONS AS A FUNCTION OF MAGNETIC FIELD

| <i>B</i><br>G | Defining Plates |              | Ion<br>Dumps<br>kW | Ground Plates |             | Total<br>Power<br>kW |
|---------------|-----------------|--------------|--------------------|---------------|-------------|----------------------|
|               | Top<br>kW       | Bottom<br>kW |                    | Bottom<br>kW  | Front<br>kW |                      |
| 525           | .26 ± .08       | -.08 ± .10   | .65 ± .10          | .13 ± .08     | .23 ± .16   | .93 ± .24            |
| 613           | .28 ± .13       | .07 ± .11    | .43 ± .21          | .04 ± .07     | .13 ± .15   | .67 ± .32            |
| 700           | .09 ± .09       | .37 ± .10    | .76 ± .24          | .14 ± .08     | .19 ± .16   | 1.46 ± .33           |
| 788           | -.05 ± .07      | .66 ± .11    | 1.28 ± .24         | .20 ± .07     | .10 ± .17   | 2.24 ± .33           |
| 875           | -.18 ± .14      | .77 ± .11    | 1.13 ± .23         | .05 ± .08     | .00 ± .17   | 1.95 ± .34           |
| 963           | -.19 ± .08      | .89 ± .09    | 1.23 ± .33         | .18 ± .07     | .24 ± .18   | 2.54 ± .40           |
| 1050          | .00 ± .11       | .93 ± .10    | 1.68 ± .19         | .25 ± .08     | .29 ± .16   | 3.15 ± .30           |
| 1138          | -.08 ± .13      | .71 ± .11    | 1.47 ± .16         | .45 ± .08     | .50 ± .16   | 3.13 ± .30           |
| 1225          | .03 ± .09       | .55 ± .13    | 1.46 ± .39         | .53 ± .08     | .44 ± .18   | 2.98 ± .47           |
| 1313          | .12 ± .14       | .33 ± .09    | 1.18 ± .14         | .66 ± .06     | .55 ± .17   | 2.72 ± .29           |
| 1400          | .32 ± .08       | .31 ± .08    | 1.41 ± .22         | .64 ± .05     | .35 ± .16   | 2.71 ± .30           |
| 1488          | .37 ± .18       | .15 ± .13    | .64 ± .27          | .55 ± .11     | .53 ± .16   | 1.87 ± .40           |
| 1575          | .41 ± .13       | .30 ± .11    | 1.38 ± .21         | .67 ± .14     | .70 ± .17   | 3.05 ± .34           |
| 1663          | .35 ± .08       | .07 ± .10    | 1.01 ± .37         | .30 ± .07     | .60 ± .15   | 1.98 ± .43           |
| 1750          | .30 ± .10       | .00 ± .11    | .49 ± .26          | .15 ± .13     | .58 ± .14   | 1.22 ± .36           |
| 1838          | .15 ± .08       | -.82 ± .79   | 1.25 ± .18         | .11 ± .12     | .58 ± .13   | 1.94 ± .83           |
| 1925          | .00 ± .08       | -4.05 ± .21  | .52 ± .11          | .22 ± .09     | .56 ± .21   | 1.30 ± .34           |

3) The front ground plate power is composed of ions and neutrals. The minimum power loading at 875 G is assumed to be due entirely to neutrals. This approximation has the tendency of underestimating ion collection at most magnetic fields, since the computer code identifies the front ground plate as an ion collection surface at all values of magnetic field.

It should be recognized that some of the power loading on the bottom defining plate, ion dump, and bottom ground plate can be due to neutrals arising from deflected full-energy ions which then charge-exchange with the background gas. Counting these charge-exchange neutrals as ions tends to overestimate the ion collection current. Energetic electrons may contribute to the power loading on the front ground plate at low magnetic field values, again causing the ion collection current to be overestimated. A sudden increase in power loading on the front ground plate as the magnetic field is lowered from 525 to 438 G is exhibited in Table I. Although this could be due to increased ion interception, the loading at 438 G was discarded and an ion collection value was not calculated. The top ground plate becomes an ion collection surface at very low magnetic fields, although the power loading at these values is dominated by neutralizer electrons. Neglecting the top ground plate results in underestimating the collection efficiency at low magnetic fields.

Figure 5.2 compares the ion collection efficiency calculated from the above assumptions with the results from the computer model. The experimental error bars are due only to the standard deviations of the original calorimetric data that propagated through the calculations. The causes for the decrease in ion collection efficiency at the extremes of magnetic field strength can be seen from the computer solutions displayed in Figure 5.3. At low magnetic fields, the upward electrostatic force from the slanted neutralizer dominates the magnetic force, driving the ions into the upper electron collector. At high magnetic fields, many ions are bent to the bottom of the neutralizer before they

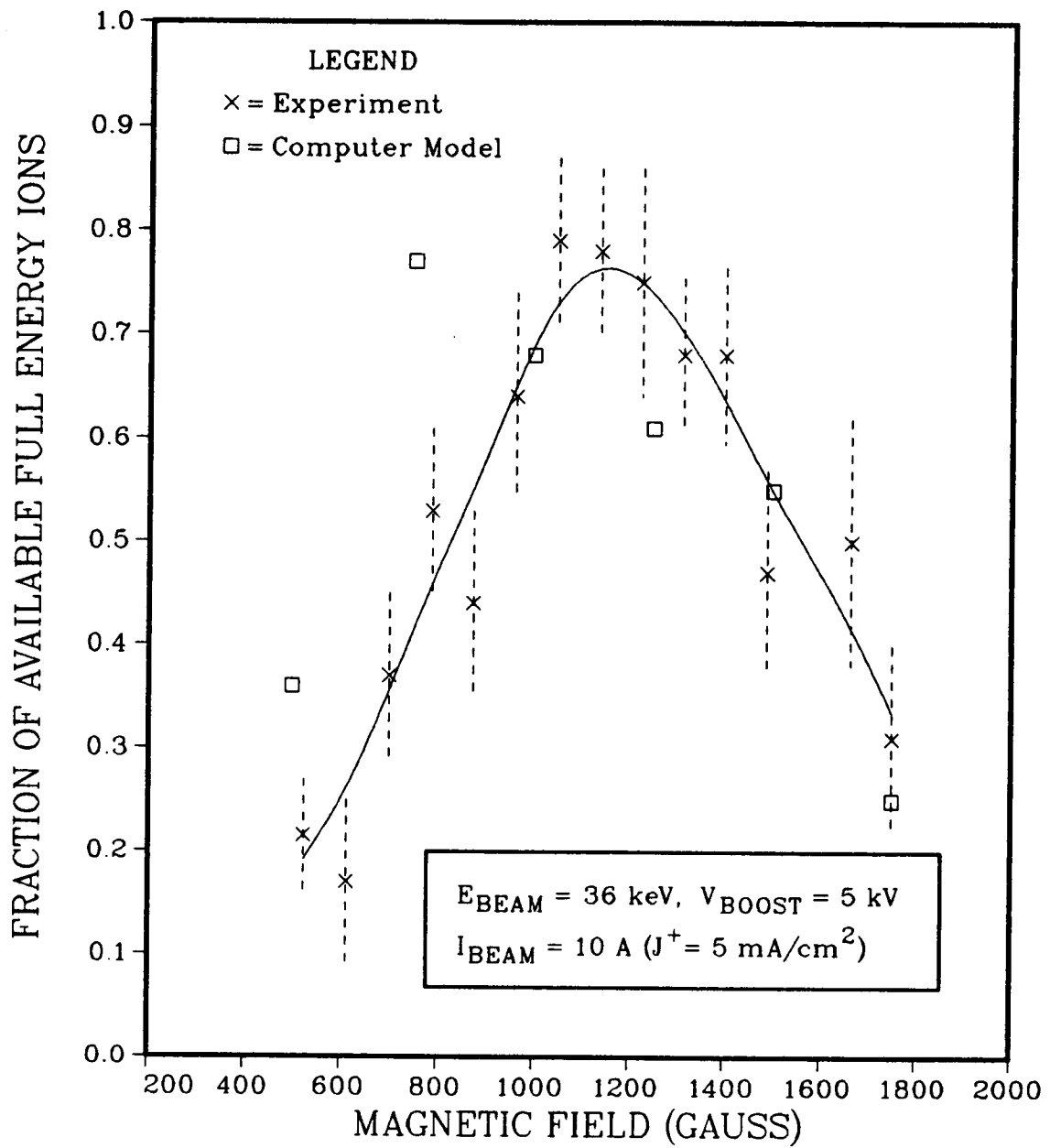


Fig. 5.2. Ion collection efficiency vs. magnetic field for the slanted neutralizer experiment; comparison of computer model to experiment.

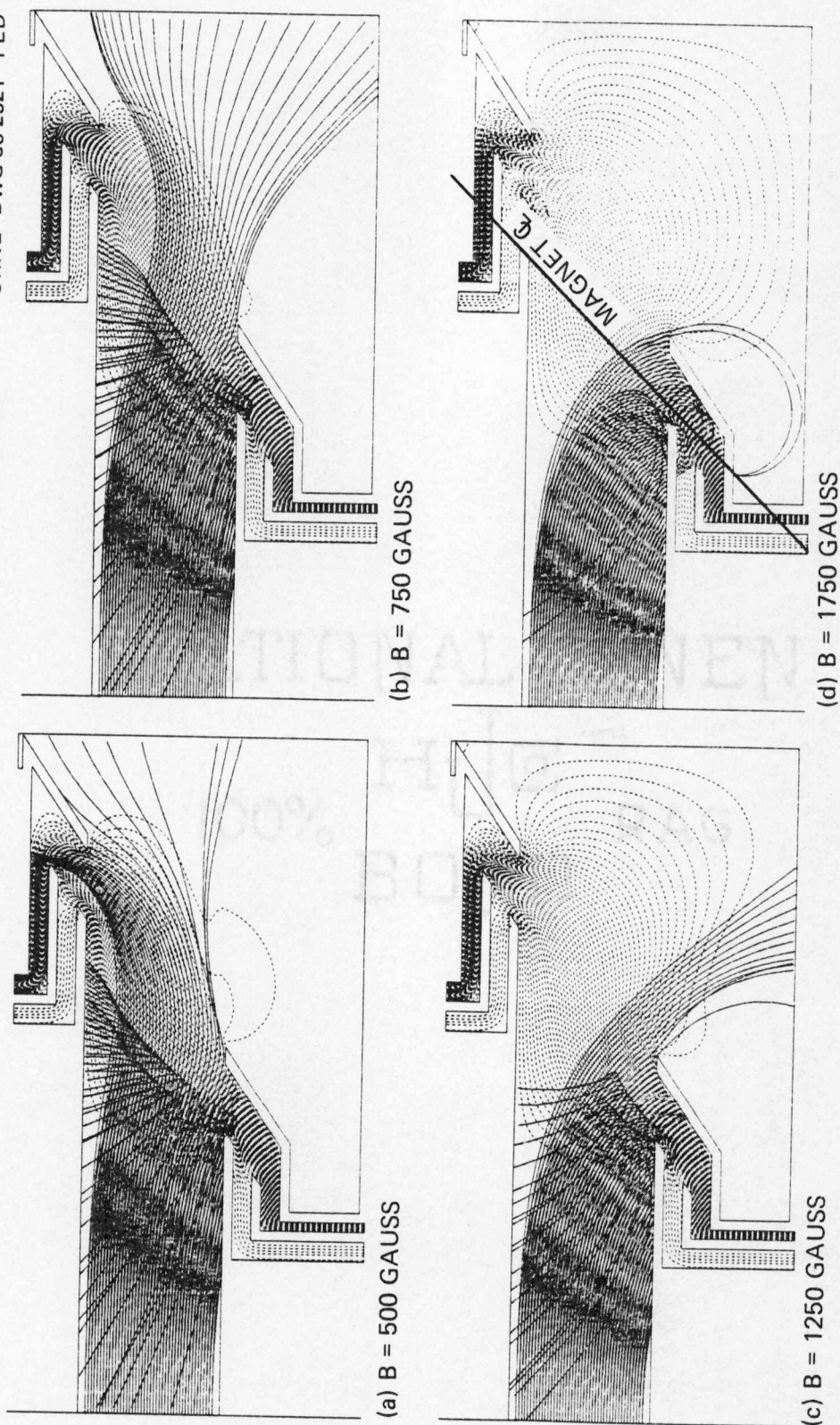


Fig. 5.3. Side view of ion trajectories as a function of magnetic field in the slanted neutralizer geometry.

( $V_{\text{beam}} = 36 \text{ kV}$ ,  $V_{\text{boost}} = 5 \text{ kV}$ ,  $V_{\text{ec}} = 4 \text{ kV}$ ,  $J^+ = 5 \text{ mA/cm}^2$ )

can be recovered; others intercept the lower electron collector plate. The increase in upper electron collector loading at low fields and the increase in lower electron collector loading at high fields is shown in Figure 5.4.

## A.2 The Effect of Electron Collector Bias

The power loading on the bottom electron collector plate is primarily due to interception of beam ions at high magnetic fields. This loading is affected by the bias potential of the collector only to the extent that the energy of the intercepted ions is altered. Figure 5.4 demonstrates the insensitivity of the lower collector power loading to changes in the collector bias potential.

Electrons from the neutralizer plasma become trapped on equipotential surfaces and acquire an  $\mathbf{E} \times \mathbf{B}$  drift velocity that leads them to the upper electron collector. The collector must be biased somewhat positive with respect to the neutralizer in order to collect these electrons. Figure 5.5 shows that when the collector is shorted to the neutralizer ( $V_{ec} = 0$ ), the collector current is positive; this is the result of ion interception and secondary electron emission and obtains even at intermediate values of the magnetic field. Increasing the collector bias to 4 kV increases the electron collection current dramatically; further increase to 7 kV has less of an effect. The electron collector voltage should be kept as low as possible in order to minimize the power drain on the system. A practical consideration for low electron collector voltages is to avoid collector-to-neutralizer breakdowns.

The increase in upper collector power loading in Figure 5.4, when the bias is increased to 4 kV, is due to the collection of electrons from the neutralizer plasma. Figure 5.6 shows that this difference in power loading is inversely proportional to the magnetic field; this  $B^{-1}$  dependence would seem to rule out classical diffusion as the dominant transport mechanism. Classical diffusion across magnetic field lines is proportional to

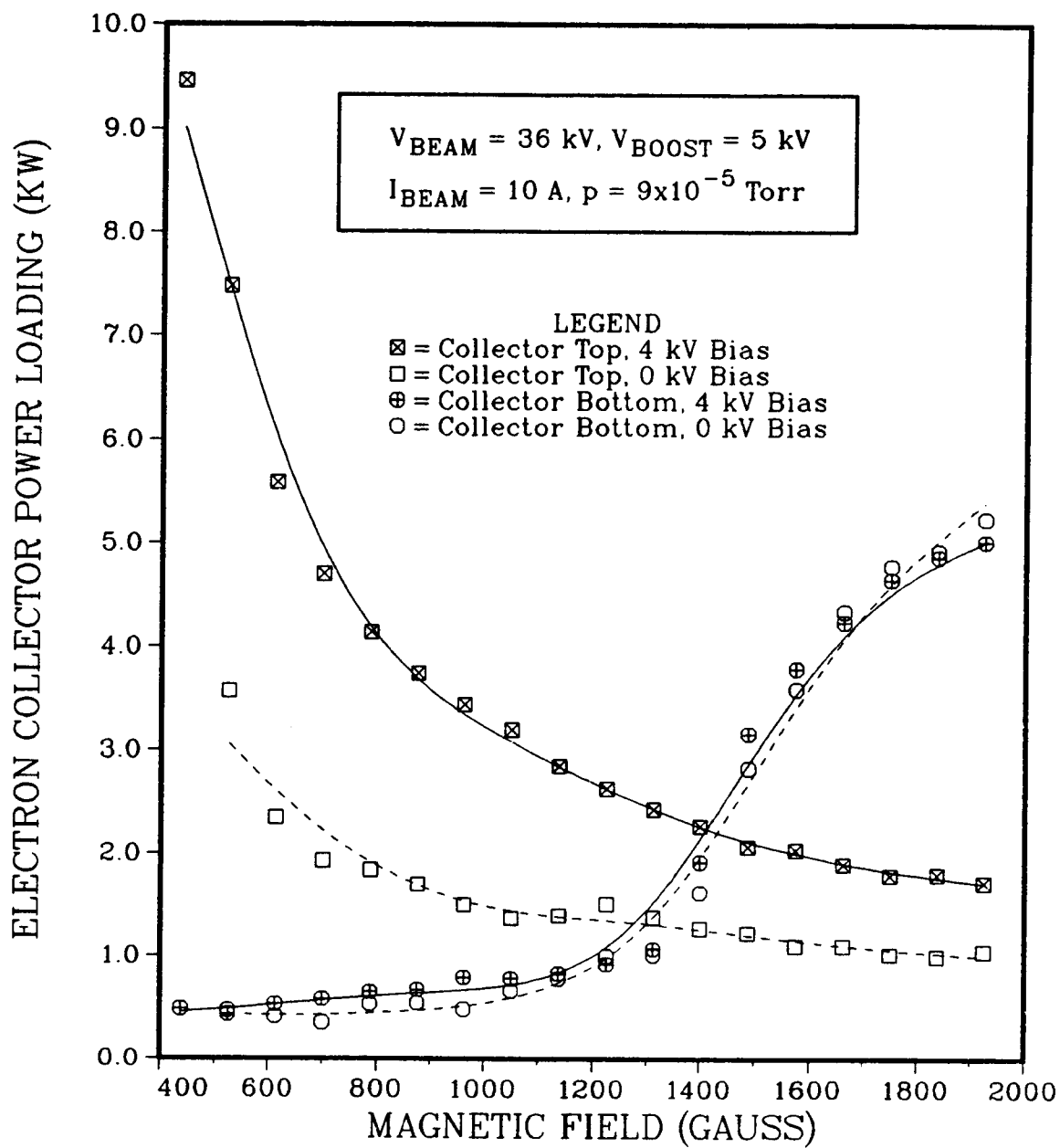


Fig. 5.4. Electron collector power loading vs. magnetic field as a function of collector bias.

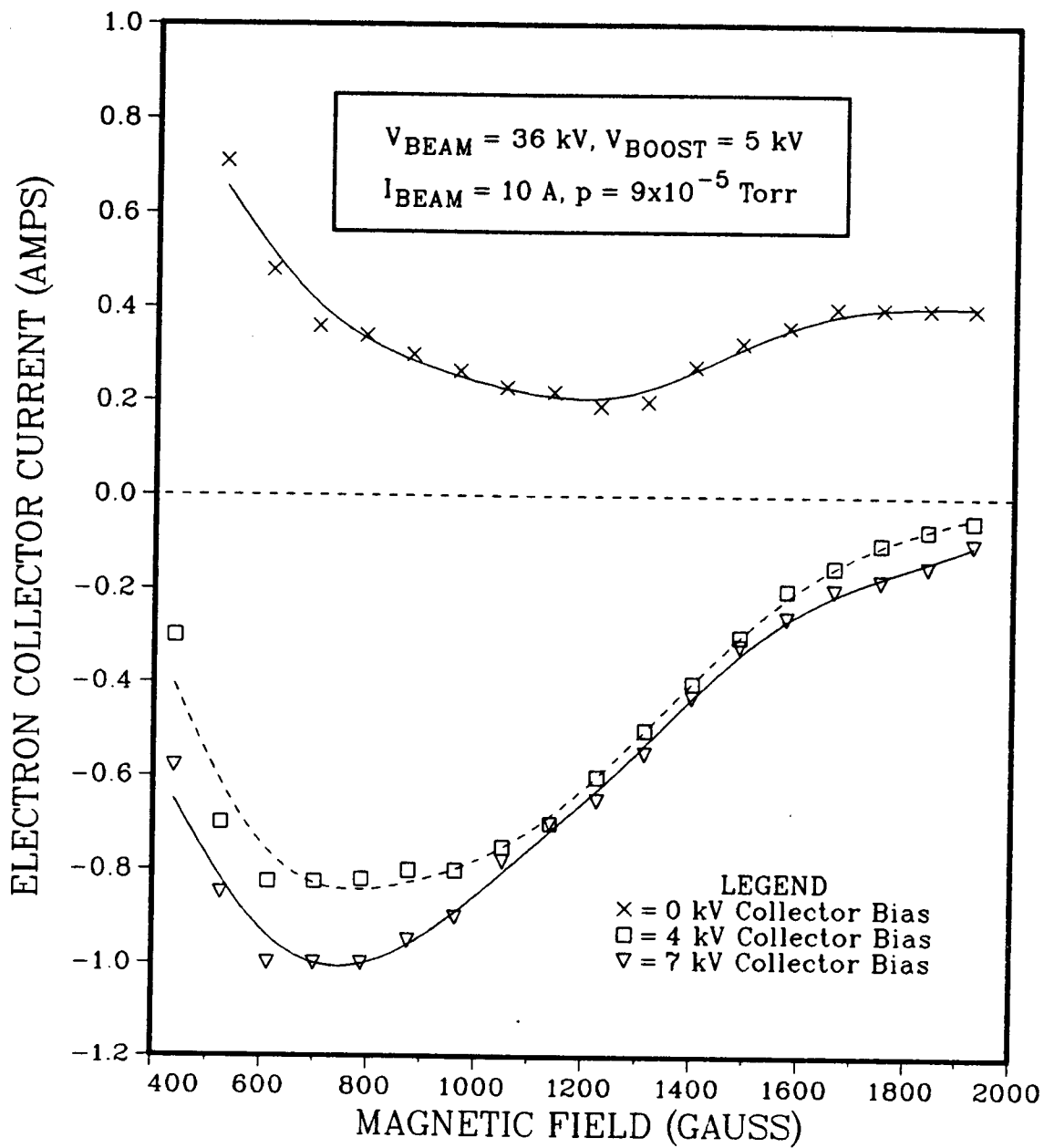


Fig. 5.5. Net current to the electron collector vs. magnetic field as a function of collector bias.

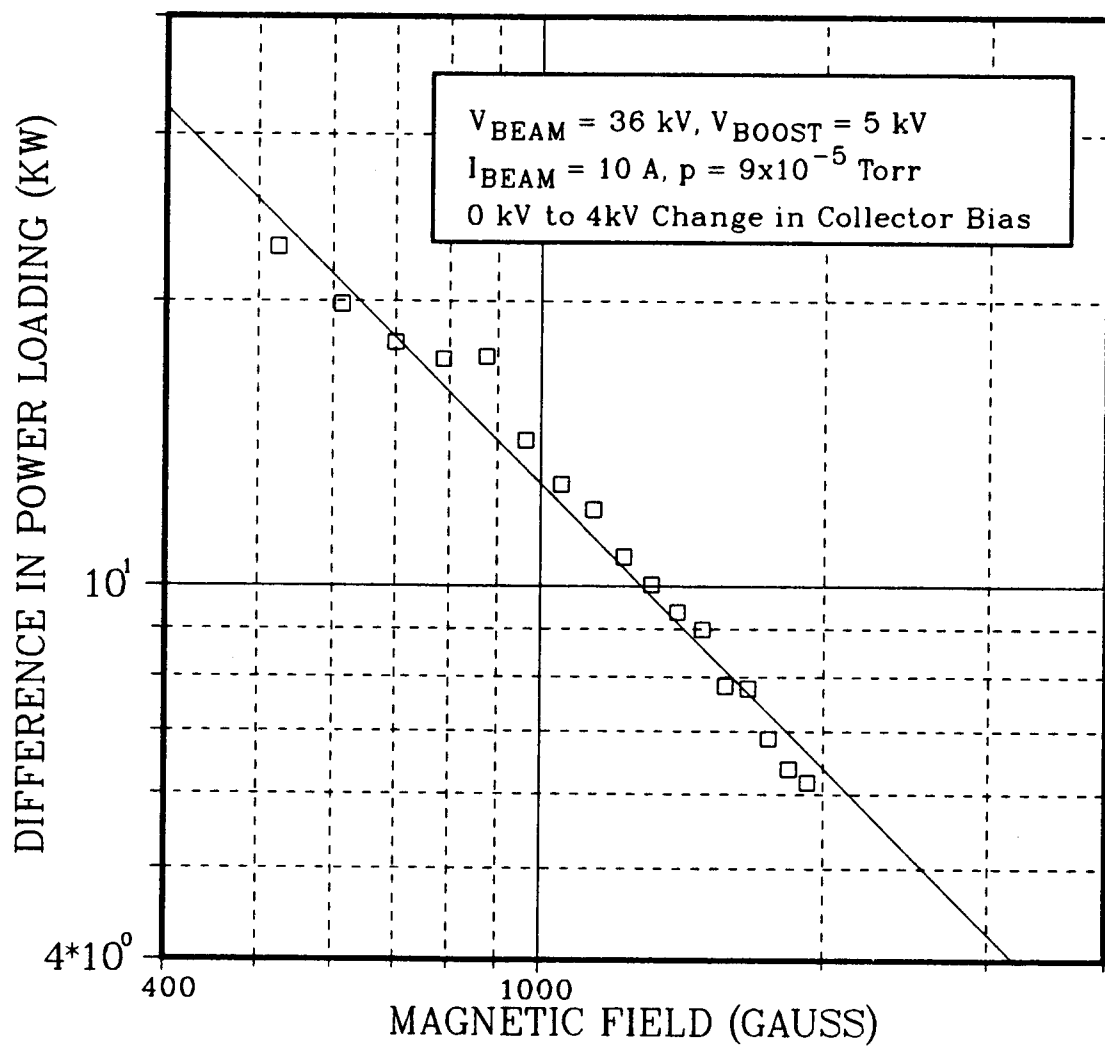


Fig. 5.6. Difference in top ground plate power loading vs. magnetic field as the collector bias is reduced from 4 kV to 0 kV.

$\nu_c^2/\omega_c^2$ , where  $\nu_c$  is the particle collision frequency and  $\omega_c$  is the particle gyrofrequency in the magnetic field. Since  $\omega_c = eB/m$ , the electron current out of the neutralizer would be reduced by  $B^{-2}$  were classical collisional diffusion the dominant transport mechanism.

Sheath fluctuations, microinstabilities, and other collective processes give rise to particle transport that follows  $B^{-1}$  scaling and is referred to as Bohm diffusion; a typical discussion of this phenomenon can be found in Krall and Trivelpiece.<sup>67</sup> In order to compare the leakage current to Bohm diffusion, an effective diffusion coefficient will need to be calculated.

The current density diffusing out of the neutralizer can be expressed as

$$j = eD_{\text{eff}} \left( \frac{\partial n_e}{\partial x} \right) . \quad (5.2)$$

The electron density gradient can be approximated by a characteristic scale length, which is the width of the cathode sheath. This cathode sheath width is on the order of the electron gyroradius  $r_g$ ,<sup>34</sup>

$$j = eD_{\text{eff}} \left( \frac{n_e}{r_g} \right) , \quad (5.3)$$

$$D_{\text{eff}} = \frac{j}{e} \left( \frac{r_g}{n_e} \right) . \quad (5.4)$$

The electron leakage current out of the neutralizer can be calculated by dividing the power loading difference on the top ground plate in Figure 5.6 by the neutralizer potential. At a magnetic field of 1000 G, this leakage current is

$$I = \frac{12.8 \text{ kW}}{36 \text{ kV}} = 0.36 \text{ A} , \quad (5.5)$$

$$j = \frac{I}{A_{\text{neutralizer}}} = \frac{0.36 \text{ A}}{0.0177 \text{ m}^2} = 20.34 \text{ A/m}^2 . \quad (5.6)$$

In Section 2.C.1 (p. 21) the electron density was calculated to be  $3 \times 10^{15} \text{ m}^{-3}$  for a local neutralizer pressure of  $6 \times 10^{-4} \text{ torr}$  and an electron temperature of 8 eV. The gyroradius for an 8 eV electron in a 1000 G field is

$$r_g = \frac{(2m_e k T_e)^{1/2}}{eB} = 9.54 \times 10^{-5} \text{ m} . \quad (5.7)$$

The effective diffusion coefficient can now be calculated from equation (5.4):

$$D_{\text{eff}} = \frac{20.34 \text{ A/m}^2 \times 9.54 \times 10^{-5} \text{ m}}{1.6 \times 10^{-19} \text{ C} \times 3 \times 10^{15} \text{ m}^{-3}} = 4.04 \text{ m}^2/\text{s} . \quad (5.8)$$

The Bohm diffusion coefficient is empirically derived<sup>67</sup> and can be expressed in MKS units as

$$D_{\text{Bohm}} = \left[ \frac{T_e (\text{eV})}{16B(\text{tesla})} \right] \text{ m}^2/\text{s} \quad (5.9)$$

For a magnetic field of 0.1 tesla (1000 G) and an electron temperature of 8 eV, the Bohm diffusion coefficient is  $5.0 \text{ m}^2/\text{s}$ , which is in close agreement with the effective diffusion coefficient of  $4.0 \text{ m}^2/\text{s}$  calculated in equation (5.8).

To the extent that the above approximations used to derive the effective diffusion coefficient are valid, it appears that Bohm diffusion is responsible for transporting electrons across the insulating magnetic field at the end of the neutralizer.

Neutralizer electrons that are not collected deposit their power on the top ground plate. Figure 5.7 shows the decrease in electron current to the top ground plate when positive bias is applied to the collector. The effect of this collector bias on the net current recovery efficiency can be observed in Figure 5.8; a bias of 7 kV was necessary to achieve breakeven.

### A.3 The Effect of Boost Voltage

Energy recovery efficiency increases as the boost voltage is increased, as can be seen in Figure 5.9. The power recovery efficiency is plotted in addition to the current

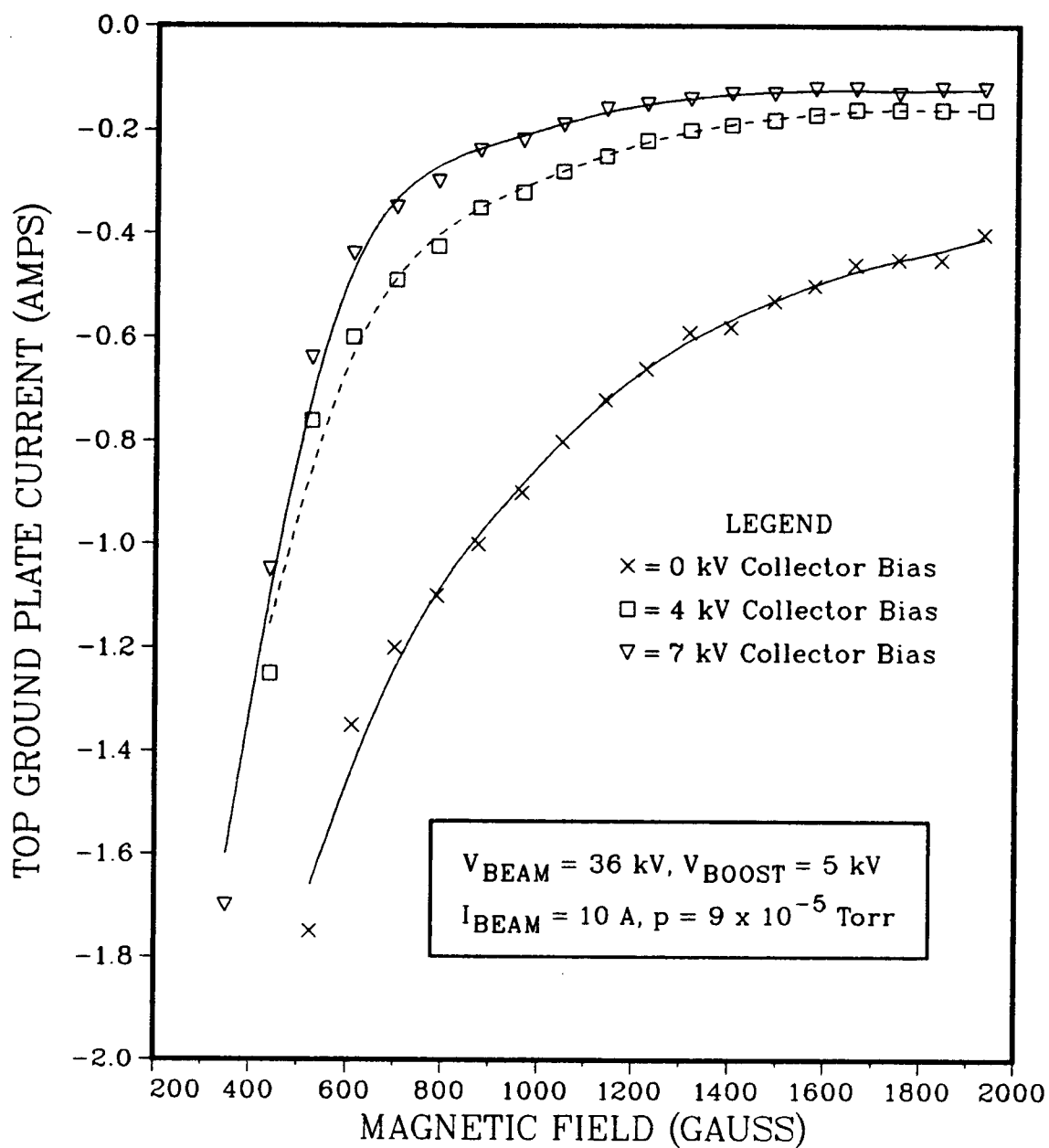


Fig. 5.7. Current to the top ground plate vs. magnetic field as a function of collector bias in the slanted neutralizer experiment.

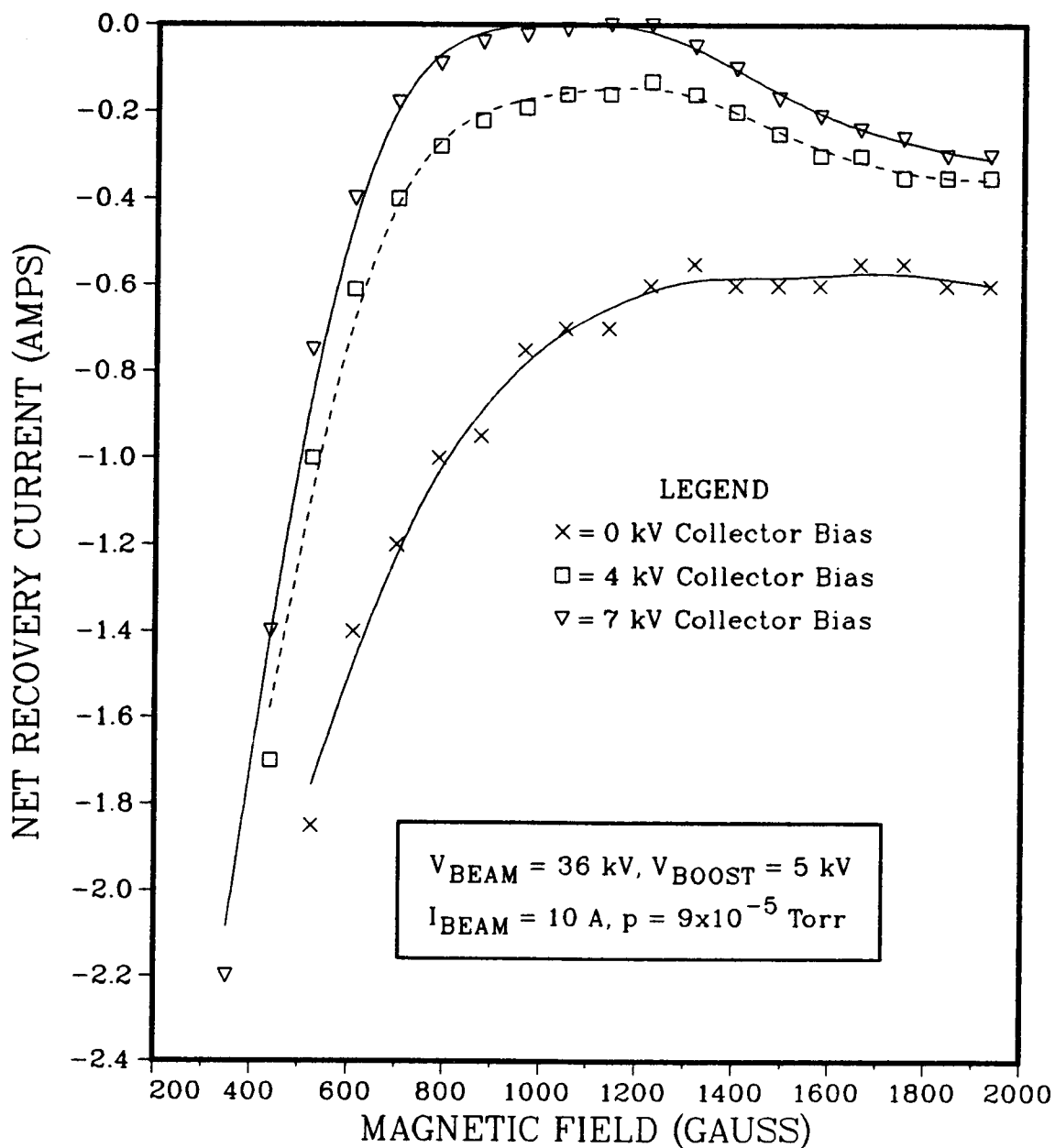


Fig. 5.8. Net recovery current vs. magnetic field as a function of collector bias in the slanted neutralizer experiment.

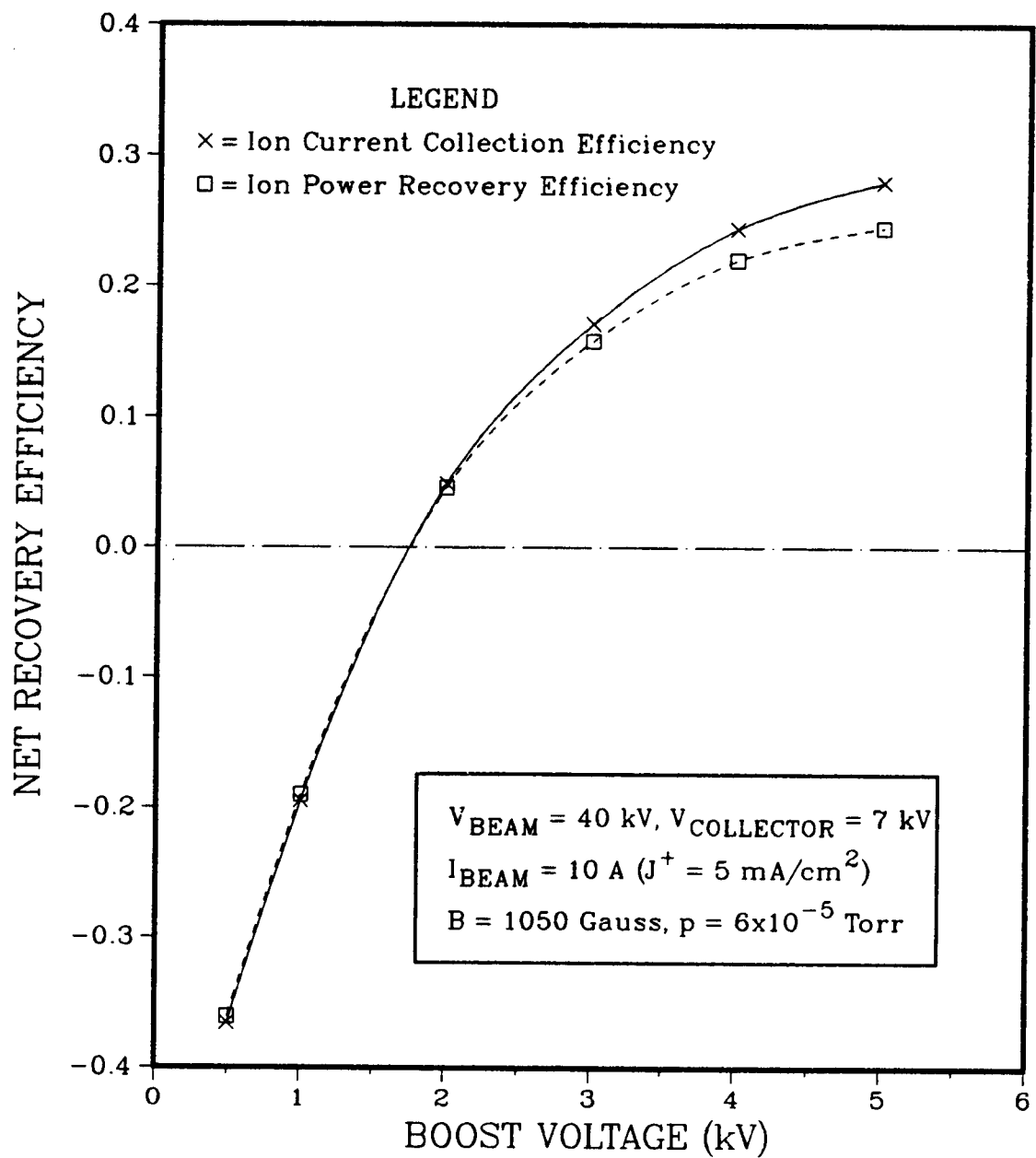


Fig. 5.9. Net recovery efficiencies vs. boost voltage in the slanted neutralizer experiment.

recovery efficiency; the power recovery efficiency merely reflects the efficiency loss due to the power expended by the boost supply to collect the full energy ions.

The ion collection efficiency calculation is less straightforward than the calculation in Section 5.A.1, where the boost voltage was high and the magnetic field was varied. Decreasing the boost voltage has the effect of collecting ions on ground surfaces that are also accessible to energetic electrons; such surfaces are the top ground plate and the magnet pole faces. Accordingly, the ion collection efficiency is calculated by subtracting the electron ground current from the net recovery current. The electron ground current is determined from net current and power measurements on individual ground surfaces.

The current and power on ground surfaces come from five sources: (1) full energy beam ions, (2) neutralizer plasma electrons, (3) volume-produced electrons, (4) secondary emission electrons, and (5) beam neutrals. Power loading from charge-exchange neutrals is not considered.

$$I(\text{ground}) = I(\text{ions}) - I(\text{neut}) - I(\text{sec}) - I(\text{volume}) \quad (5.10)$$

$$P(\text{ground}) = I(\text{ions})V_{\text{boost}} + I(\text{neut})V_{\text{neut}} + I(\text{sec})(V_{\text{neut}} - V_{\text{ec}}) \\ + I(\text{volume}) \frac{V_{\text{neut}}}{2} + P(\text{neut}) \quad (5.11)$$

Here it is assumed that secondary electrons arise from ion impact on the electron collector. Electrons created by ionization in the recovery region are assigned an average energy corresponding to half the neutralizer potential. This has been verified by the volume ionization results of the Monte Carlo calculations.

Other assumptions needed to reduce the number of unknowns in the equations are suggested by the results of the computer modeling. The ion current to the top ground plate is ignored at  $V_{\text{boost}} = 5 \text{ kV}$ ,  $B = 1050 \text{ G}$ . Secondary electron currents are also assumed to be negligible, since ion trajectories do not intercept negative potential

surfaces at these operating conditions. These assumptions do not hold at lower boost voltages.

Under the above assumptions, the electron leakage current from the neutralizer plasma and the electron current from beam interactions with the background gas can be determined for a 5 kV boost potential. Since these currents should not be a function of boost potential, these values are used at lower boost voltages in order to calculate the ion and secondary emission currents. The calculated ion collection efficiency as a function of boost voltage is displayed in Figure 5.10. The results of the computer modeling are also plotted in Figure 5.10 for the purposes of comparison.

A side view of the ion trajectories as a function of the boost voltage is given in Figure 5.11. As the excess ion velocity provided by the boost supply is decreased, the upward electrostatic forces begin to dominate the downward magnetic forces, and the ions begin to intercept the upper electron collector plate and the upper neutralizer. Figure 5.12 demonstrates this increase in upper neutralizer (section 1) power loading with decreasing boost voltage; the gas cell sections are defined in Figure 4.8 (p. 80). The power loading on the adjacent neutralizer (section 2) is constant.

The decrease in ion collection efficiency was more dramatic in the experiment than in the two-dimensional results shown in Figure 5.11. The discrepancy is due to increased beam blowup along the magnetic field lines as the boost voltage is lowered; the code assumes an infinitely wide neutralizer in this dimension and thus ignores this effect. The amount of electrostatic blowup in this dimension can be estimated through the application of the code to the geometry considered in Figure 5.13. This represents a top view of the midplane of the energy recovery device. The neutralizer wall, the side electron collector plate, and the magnet pole face attached to the front ground plate can all be discerned. At the bottom of the device is the beam centerline, which is employed as an axis of symmetry. What appears to be spectral reflection of ions at the beam

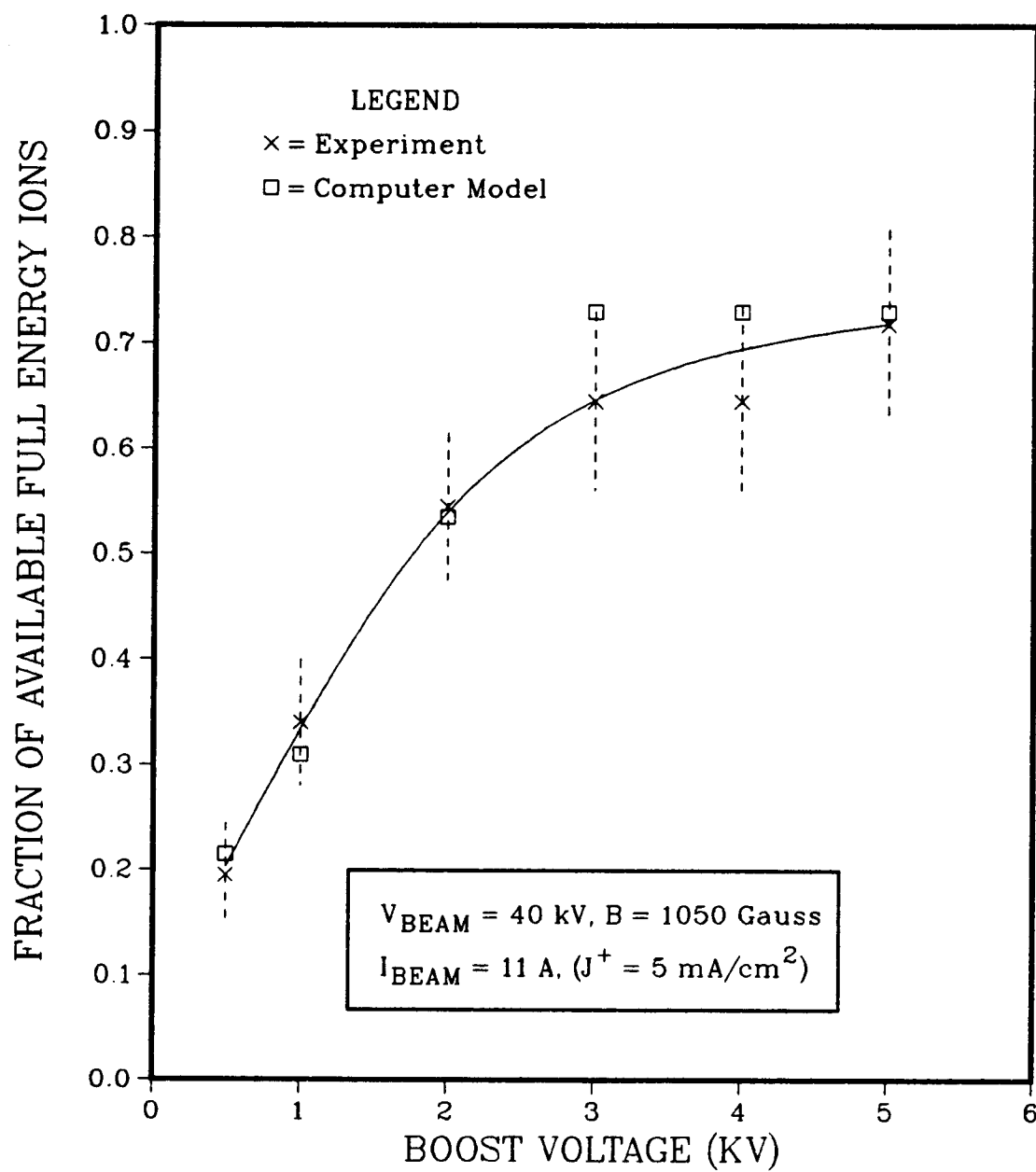


Fig. 5.10. Ion collection efficiency vs. boost voltage; comparison of computer model to experiment.

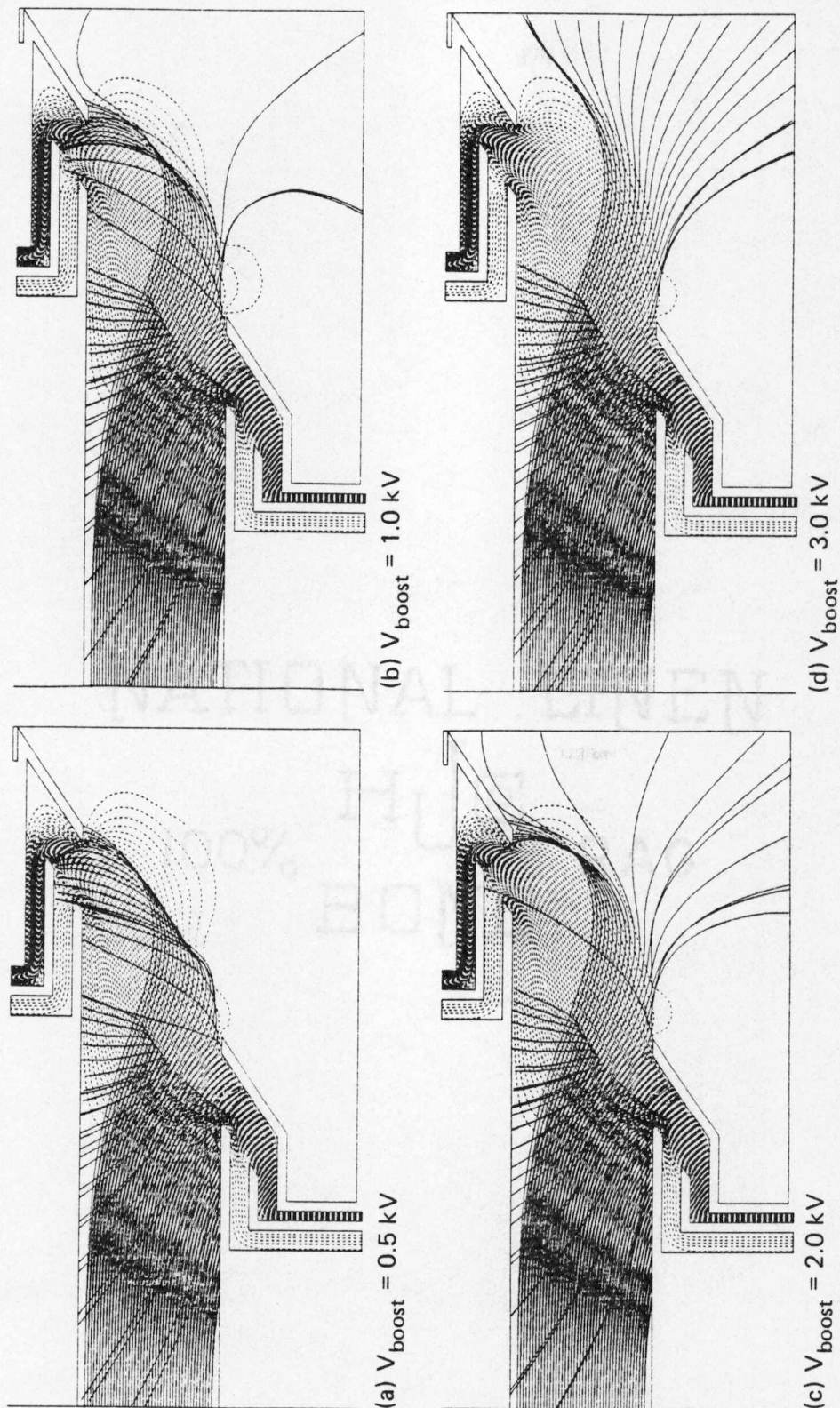


Fig. 5.11. Side view of ion trajectories as a function of boost voltage in the slanted neutralizer experiment.

( $V_{\text{beam}} = 40 \text{ kV}$ ,  $V_{\text{ec}} = 5 \text{ kV}$ ,  $B = 1000 \text{ gauss}$ ,  $J^+ = 5 \text{ mA/cm}^2$ )

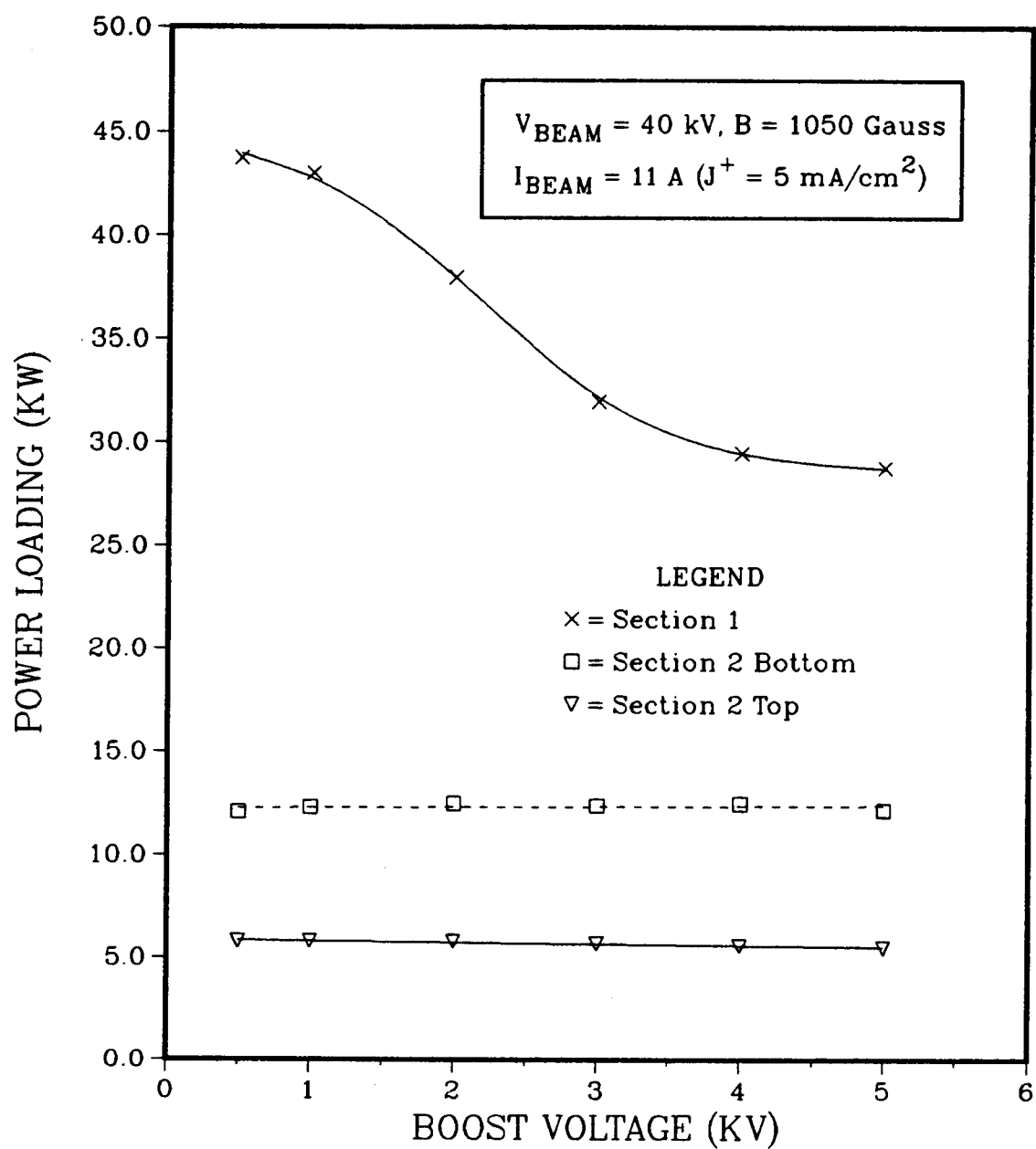


Fig. 5.12. Power loading on the slanted neutralizer end sections as a function of boost voltage.

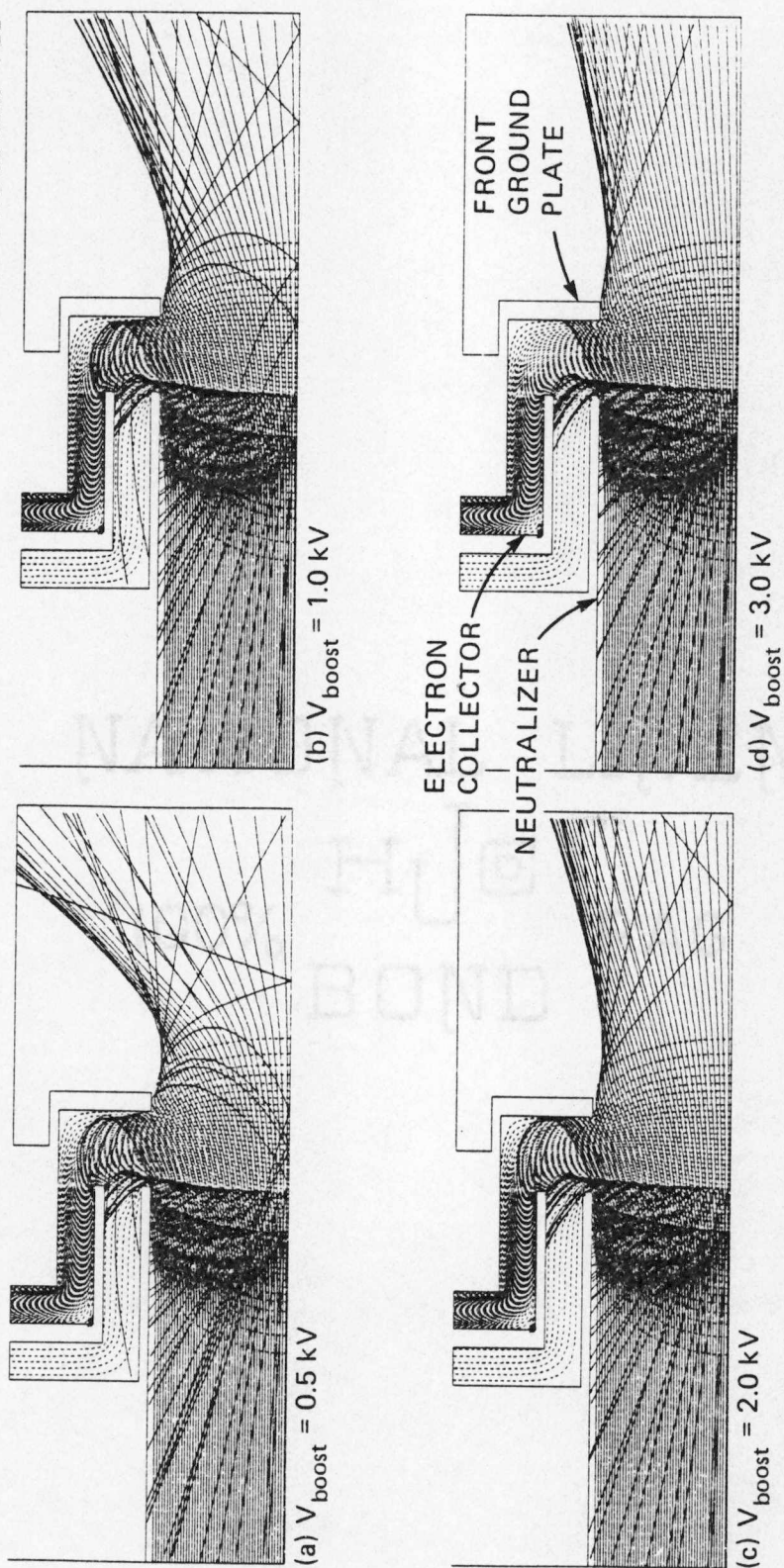


Fig. 5.13. Top view of ion trajectories as a function of boost voltage in the slanted neutralizer geometry.  
 ( $V_{\text{beam}} = 40 \text{ kV}$ ,  $V_{\text{ec}} = 5 \text{ kV}$ ,  $J^+ = 5 \text{ mA/cm}^2$ )

centerline is actually the appearance of symmetric ions from the missing portion of the device.

The magnetic field is set to zero in these calculations, since the magnetic forces would now operate in the ignorable dimension in this orientation. Hence the problem is now purely electrostatic, and fractional energy ions penetrate farther into the recovery region than they would in the presence of a deflecting magnetic field. Still, the extent of the electrostatic blowup is demonstrated; full energy ions begin to intercept the exterior side of the collector plate at reduced boost voltages. These will produce secondary electrons that will follow field lines to ground (magnet pole face).

It should be noted that fractional energy ions strike the interior of the collector side plate even at elevated boost voltages. This should not create secondary electrons that have a path to ground, but will impair the voltage holding of the neutralizer/collector gap. Although it should be borne in mind that these fractional energy ions do penetrate farther into the recovery region in the absence of a magnetic field, this side collector interception is not inconsistent with the net ion current to the collector that is seen when  $V_{ec} = 0$  (Figure 5.5, p. 102).

The net ion collection efficiency plotted in Figure 5.10 is thus the product of the efficiencies obtained from considering the side view and top view of the device. This is indicated in Table III.

TABLE III  
ION COLLECTION EFFICIENCY VS. BOOST VOLTAGE

$$E = 40 \text{ keV}, J^+ = 5 \text{ mA/cm}^2, B = 1000 \text{ G}$$

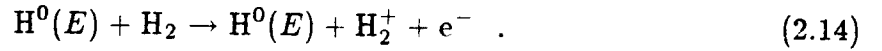
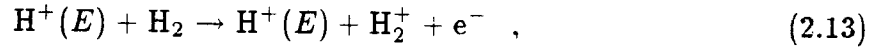
| $V_{\text{boost}}$ (kV) | Side View | Top View | Net |
|-------------------------|-----------|----------|-----|
| 5.0                     | .73       | 1.00     | .73 |
| 4.0                     | .73       | 1.00     | .73 |
| 3.0                     | .73       | 1.00     | .73 |
| 2.0                     | .66       | .81      | .54 |
| 1.0                     | .45       | .69      | .31 |
| .5                      | .34       | .63      | .21 |

#### A.4 The Effect of Gas Pressure

The gas pressure in the recovery region was a major source of electron losses in this experiment. It can be seen in Figure 5.1 (p. 92) that a 50% increase in gas pressure as measured on an ion gauge at the end of the tank changed the current recovery efficiency from 25% to zero. The pressure in the recovery region could be raised by feeding hydrogen gas through an aperture in the bottom ground plate; this did not affect the operation of the ion source. The minimum pressure achievable in the recovery region was determined by the minimum gas flow into the ion source at which reliable, repeatable discharges could be established. Gases absorbed onto electrode surfaces are released when the surfaces are heated by the beam, contributing to the pressure rise. This outgassing is particularly noisome after the tank has been up to atmosphere. It takes hundreds of beam pulses over a wide range of operating parameters to condition electrode surfaces sufficiently to attain net recovery. It is speculated that outgassing

continues indefinitely, with hydrogen being reabsorbed onto surfaces between beam pulses. Barr reports that the residual gas analyzer indicated a significant hydrogen component from a previous experiment even after operating a helium beam for two days.<sup>28</sup>

Ion-electron pairs are created in the recovery region by beam ions and neutrals interacting with the background gas.

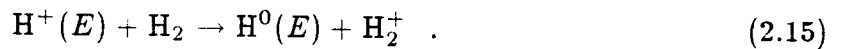


The ions are attracted to the negative neutralizer and the electrons to ground, creating a neutralizer to ground loss current. This volume ionization current can be represented by

$$I_{\text{ionization}} = n_0 I_{\text{out}} \int_0^L [f_{1\infty}(E_0)\sigma_1(E_0) + f_{0\infty}(E_0)\sigma_2(E)] dx , \quad (5.12)$$

where  $n_0$  is the background gas density,  $I_{\text{out}}$  is the total beam particle flux out of the neutralizer ( $\eta_N I_{\text{beam}}$ ),  $f_{1\infty}(E_0)$  and  $f_{0\infty}(E_0)$  are the ion and neutral equilibrium fractions for a beam of energy  $E_0$ ,  $\sigma_1(E)$  is the cross section for ionization of  $\text{H}_2$  by  $\text{H}^+(E)$ ,  $\sigma_2(E)$  is the cross section for ionization of  $\text{H}_2$  by  $\text{H}^0(E)$ , and  $L$  is the length of the recovery region or deceleration sheath.

Losses also occur for positive ions which are neutralized by charge exchange with the background gas in the recovery zone:



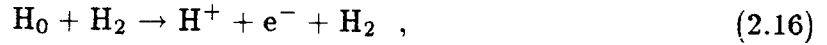
These particles are considered a system loss since the ion trajectory is altered by the electric and magnetic fields before the charge exchange, causing the resulting neutral trajectory to depart the neutral beam. The slow ion created in the recovery region is

accelerated back to a negative potential surface, draining power from the system. This charge-exchange current can be represented by

$$I_{ce} = n_0 I_{out} f_{1\infty}(E_0) \int_0^L \sigma_3(E) dx , \quad (5.13)$$

where  $\sigma_3(E)$  is the charge-exchange cross section for a  $H^+$  beam in  $H^2$ .

Reionization of fast neutrals through electron stripping by the background gas,



is a loss mechanism for all neutral beams and enters into the system efficiency without energy recovery; hence it is not considered here. Reducing the gas pressure in the system reduces both the reionization losses and the volume energy recovery losses.

Ionization of background gas by fractional energy ions and neutrals is neglected in this analysis, as is ionization by electrons. The ionization cross sections for electrons are more than an order of magnitude smaller than those for ions and neutrals. The volume loss current can thus be represented by

$$I_{loss} = n_0 I_{out} \left\{ f_{0\infty}(E_0) \sigma_2(E_0) L + f_{1\infty}(E_0) \int_0^L [\sigma_1(E) + \sigma_3(E)] dx \right\} . \quad (5.14)$$

The integration of the fast neutral ionization term was accomplished by noting that the energy of the neutral is not a function of  $x$ . The other two integrals are dependent on the fast ion energy variation with distance  $x$ . The ion energy can be expressed as

$$E(x) = -\Phi(x) + V_{boost} . \quad (5.15)$$

The potential variation with distance would be expected to lie somewhere between the linear vacuum variation

$$\Phi = \Phi_0 \left( \frac{L-x}{L} \right) \quad (5.16)$$

and the space-charge limited variation

$$\Phi = \Phi_0 \left( \frac{L-x}{L} \right)^{4/3} . \quad (5.17)$$

The linear approximation will suffice for the purposes of estimating the volume loss current. This allows the loss current to be expressed as

$$I_{\text{loss}} = n_0 L \left\{ f_{0\infty}(E_0) \sigma_2(E_0) + \frac{f_{1\infty}(E_0)}{\Phi_0} \int_{V_{\text{boost}} - \Phi_0}^{V_{\text{boost}}} [\sigma_1(E) + \sigma_2(E)] dE \right\} I_{\text{out}} \quad (5.18)$$

For a 40 keV beam with 5 kV boost voltage ( $\Phi_0 = -35$  kV), and using the energy dependent cross sections from reference 59, the integrations yield

$$\begin{aligned} I_{\text{loss}} &= 3.79 \times 10^{-16} n_0 (\text{cm}^{-3}) L (\text{cm}) I_{\text{out}} \\ &= 12.2 p (\text{torr}) L (\text{cm}) I_{\text{out}} . \end{aligned} \quad (5.19)$$

The net current recovery efficiency is

$$\begin{aligned} \eta_c &= \frac{\text{ion collection current} - \text{volume loss current}}{\text{available ion current}} \\ &= \frac{\eta_i f_{1\infty}(E_0) I_{\text{out}} - 12.2 p L I_{\text{out}}}{f_{1\infty}(E_0) I_{\text{out}}} \\ &= \eta_{ic} - 32.11 p L \end{aligned} \quad (5.20)$$

As the line density  $pL$  is decreased or the ion equilibrium fraction  $f_{1\infty}(E_0)$  is increased, the net recovery efficiency approaches the ion collection efficiency. The degradation of the ion collection efficiency as a function of  $pL$  is shown in Figure 5.14.

The line density at which the experiment is operating may be calculated from Figure 5.1 (p. 92), which shows a zero to 25% increase in the net current recovery efficiency for a 33% decrease in pressure. This corresponds to a line density decrease from  $2.3 \times 10^{-2}$  torr·cm to  $1.56 \times 10^{-2}$  torr·cm in Figure 5.14.

The computer model indicates a deceleration length  $L$  of about 30 cm at these current densities. This would imply pressures in the recovery region of  $5.2$  to  $7.8 \times 10^{-4}$  torr, as opposed to  $6$  to  $9 \times 10^{-5}$  torr as measured on the ionization gauge at the end of

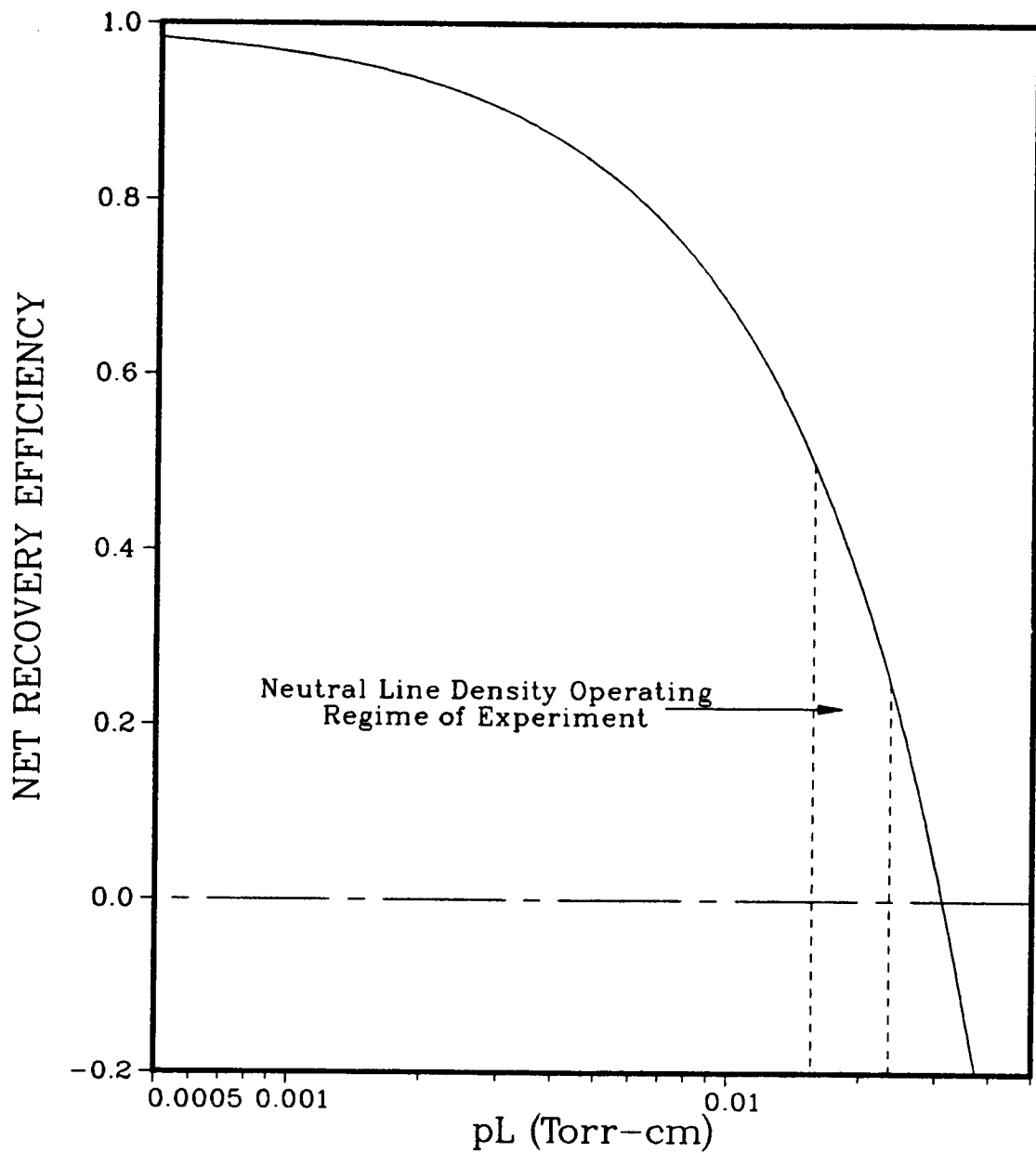


Fig. 5.14. The effect of neutral line density in the recovery region on the net current recovery efficiency. The slanted neutralizer experiment operated in the region between the dashed lines.

the tank. Ion and electron trajectories arising from beam/background gas interactions in the recovery region are shown in Figure 5.15 for gas pressures of 2.0 and  $5.0 \times 10^{-4}$  torr. The average birth potential of the ion/electron pairs is calculated to be about half the neutralizer potential.

#### A.5 The Effects of Current Density

It was remarked in Section 3 that the double Vlasov code predicts complete space-charge blowup in the neutralizer for ion current densities above 5 mA/cm<sup>2</sup>. While the double plasma model yields results at such current densities that are in close agreement with the experimental results, it too predicts a precipitous decrease in ion collection efficiency as the current density increases. This is due to beam blowup in the recovery region rather than in the neutralizer, and the onset occurs at higher current densities.

Figure 5.16 views the recovery device from the side as the current density is increased: the magnetic field is 1050 G, which is near the optimum value for ion collection efficiency. At 20 mA/cm<sup>2</sup>, full energy ions can be observed striking both the upper electron collector and the lower neutralizer exterior. Increasing the magnetic field would decrease the upper electron collector interception at the expense of increased loading on the lower neutralizer. The blowup becomes more pronounced at higher current densities.

Figure 5.17 shows the top view of the recovery device, as discussed in Section 5.A.3. At 15 mA/cm<sup>2</sup> the full energy ions begin to strike the exterior of the electron collector side plates. The only way to prevent beam blowup for this geometry is to increase the boost voltage, thus decreasing the space charge in the recovery region. Of course, this expedient lowers the power recovery efficiency and the overall system efficiency.

Table IV shows the calculated ion collection efficiency as a function of ion current density. The net current recovery efficiency is expected to fall still more rapidly,

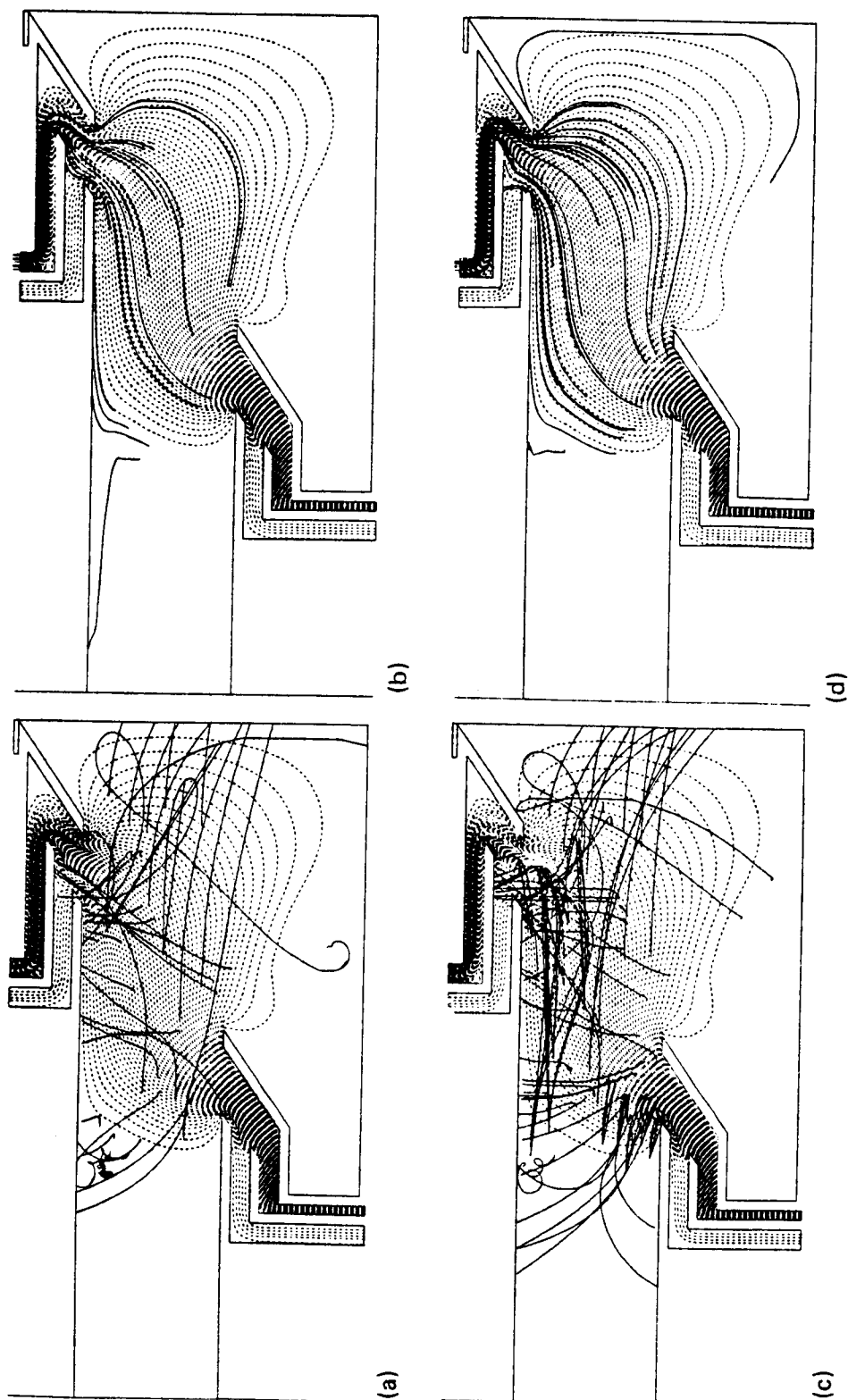


Fig. 5.15. Ion and electron trajectories arising from ionization and charge exchange in the recovery region.  
 ([a] ions, [b] electrons for  $p = 2 \times 10^{-4}$  torr; [c] ions, [d] electrons for  $p = 5 \times 10^{-4}$  torr)

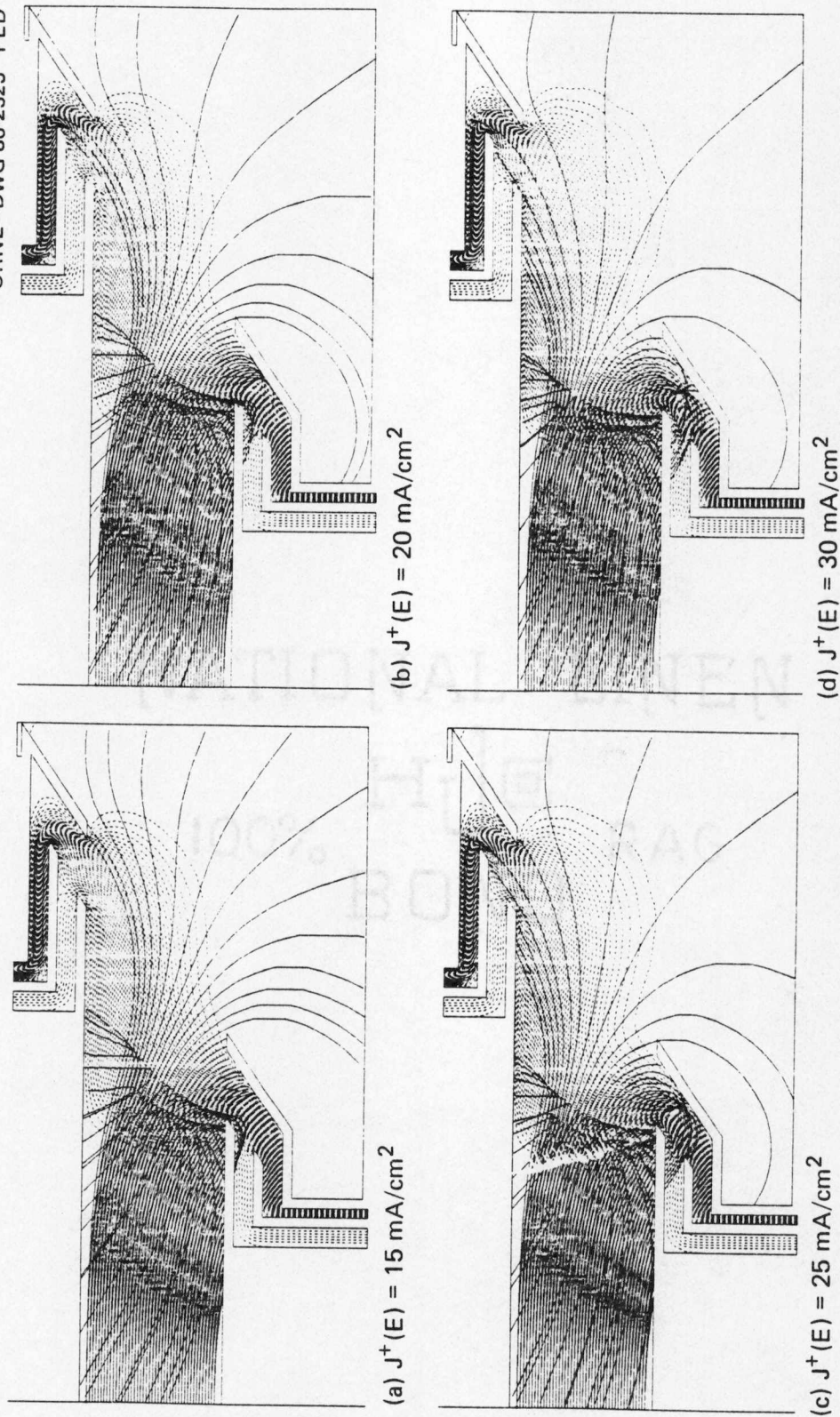


Fig. 5.16. Side view of ion trajectories as a function of ion current density in the slanted neutralizer geometry.

( $V_{\text{beam}} = 40 \text{ kV}$ ,  $V_{\text{boost}} = 5 \text{ kV}$ ,  $V_{\text{ec}} = 5 \text{ kV}$ ,  $B = 1050 \text{ gauss}$ )

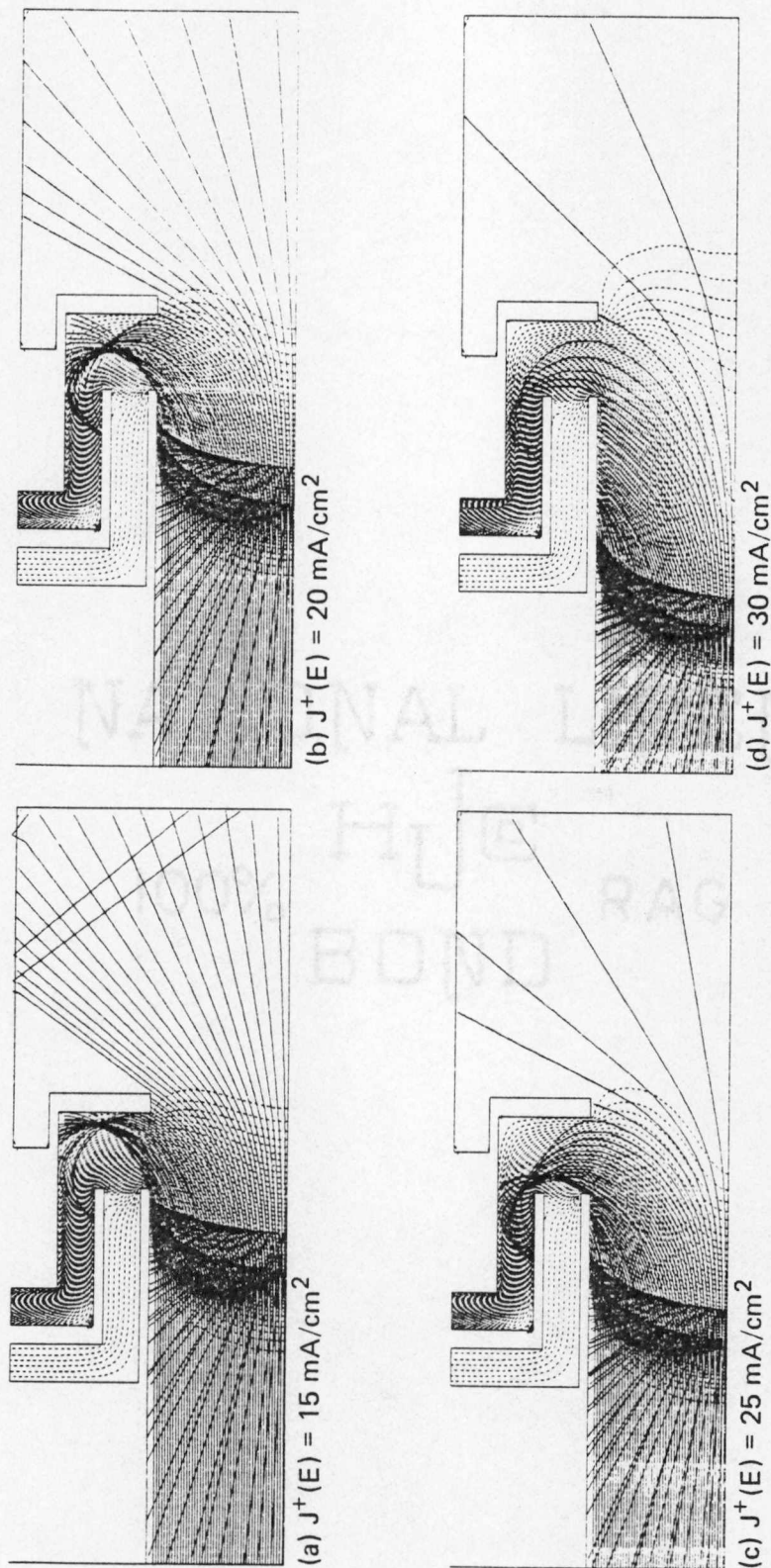


Fig. 5.17. Top view of ion trajectories as a function of ion current density in the slanted neutralizer geometry.

( $V_{\text{beam}} = 40 \text{ kV}$ ,  $V_{\text{boost}} = 5 \text{ kV}$ ,  $V_{\text{ec}} = 5 \text{ kV}$ )

TABLE IV  
ION COLLECTION EFFICIENCY VS. ION CURRENT DENSITY

$$E = 40 \text{ keV}, V_{\text{boost}} = 5 \text{ kV}, B = 1050 \text{ G}$$

| $J^+$ (mA/cm <sup>2</sup> ) | Side View | Top View | Net |
|-----------------------------|-----------|----------|-----|
| 5.0                         | .68       | 1.00     | .68 |
| 10.0                        | .68       | 1.00     | .68 |
| 15.0                        | .68       | .90      | .61 |
| 20.0                        | .55       | .67      | .37 |
| 25.0                        | .32       | .19      | .06 |
| 30.0                        | .20       | .06      | .01 |

since ions striking the exterior of the neutralizer and electron collector will generate secondary emission electrons. This will increase the loss current even while the ion collection current is decreasing.

An attempt was made to increase the beam current while keeping all other parameters fixed. Operation became difficult at 12 A for a 40 keV beam; it was not possible to operate above 16 A without high voltage breakdowns. The erratic operation precluded acquiring any calorimetric data; hence the net recovery efficiency and ion collection efficiency could not be calculated. Figure 5.18 shows the net recovery current plotted against the beam current. The net recovery efficiency drops to zero at about 14 A of beam current.

The ion current density at 16 A of beam current, the highest at which the experiment would run, can be estimated from the transmission efficiency  $\eta_T$ . The transmission through the neutralizer is a function of beam optics, which depends solely on the beam perveance,  $I(V^{-1.5})$ . The optimum perveance for this ion source was determined to be

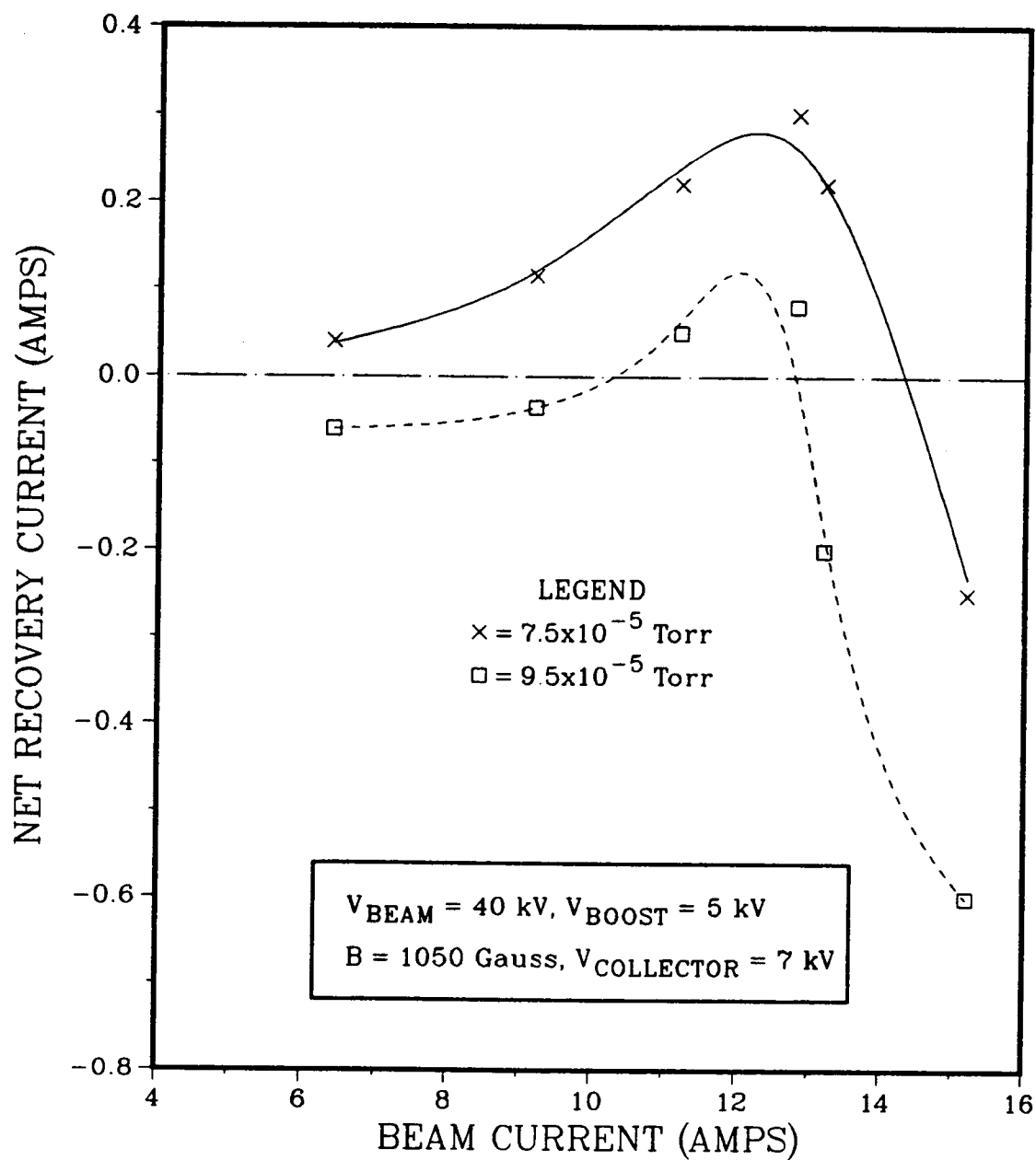


Fig. 5.18. Net recovery current vs. beam current as a function of gas pressure in the slanted neutralizer experiment.

2.8  $\mu\text{perv}$ , which corresponds to a current of 22 A at 40 kV; the transmission efficiency was 51%. The lowest perveance measured in the normal mode operation was 2.0  $\mu\text{perv}$ , which corresponds to 16 A and a transmission efficiency of 44%. For an atomic species fraction  $\eta_1$  of 0.8, an equilibrium ion fraction  $f_{1\infty}$  of 0.38, a transmission efficiency  $\eta_T$  of 0.44, and a beam cross section of 177  $\text{cm}^2$ , the full energy ion average current density in the 16 A case is about 12  $\text{mA}/\text{cm}^2$ . This is in qualitative agreement with the onset of beam blowup as predicted in Table IV.

The inability of this geometry to operate at high current densities is a serious problem. It will be considered in more detail in Section 6, in which a higher current density design will be advanced.

## B. VERTICAL MAGNET/NEUTRALIZER EXPERIMENT

The vertical magnet/neutralizer experiment was not successful in achieving energy recovery. Figure 5.19 shows the net recovery current vs. magnetic field, where electron loss currents exceed the ion collection current. The experiment itself was difficult to operate and very unreliable. Some problems were due to errors in construction, assembly, and installation. Such errors are not uncommon during initial operation of an experiment and are usually corrected before subsequent operation. However, analysis shows that the neutralizer/magnet geometry has design flaws that would have prevented achievement of energy recovery under any circumstances. Operation of this experiment allowed these flaws to be identified and avoided in future designs.

### B.1 Experimental Difficulties

Operation of the rectangular neutralizer/vertical magnet experiment was beset with the following problems:

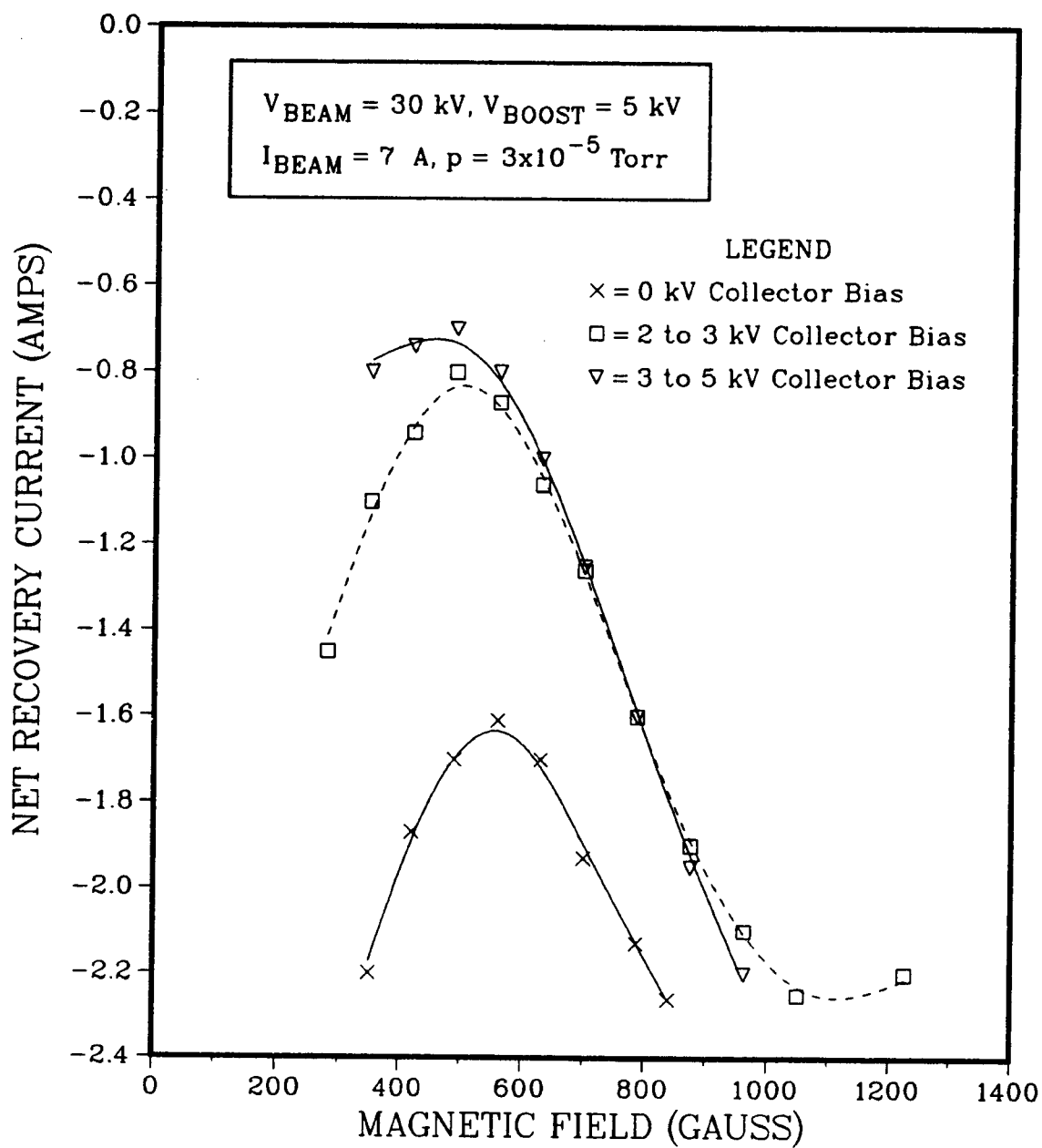


Fig. 5.19. Net recovery current vs. magnetic field as a function of electron collector bias for the vertical neutralizer experiment.

a) Electrical breakdowns to ground limited operation to beam voltages of 30 kV or less.

b) Electron collector to neutralizer voltage breakdowns limited collector biases to low values.

c) The experiment could not operate at the high magnetic fields needed to suppress electron leakage currents.

d) Electrical noise, high voltage breakdowns, and erratic source operation prevented calorimetric measurements from being made.

Inspection of the energy recovery apparatus at the conclusion of the experiment revealed damage that accounts for the low voltage holding values. The top ground plate had melted where it was supported by a guide rail mounted on the south magnet pole face (see Figure 4.10, p. 87). The distance from the electron collector side plate to this burn mark is 2.5 cm, and the path is along a magnetic field line. The neutralizer had been conditioned to  $-45$  kV with respect to ground under vacuum conditions.

The standoff insulators that support the electron collector from the neutralizer were placed on the sides as in Figure 4.10 (p. 87), where they would be out of the path of drifting neutralizer electrons. Although the collector withstood 7 kV with respect to the neutralizer in air, the maximum voltage holdoff quickly deteriorated after operation. Upon inspection, the insulators were found to be burned and coated with sputtered copper. As will be seen, the computer model indicates that fractional energy ions may be striking the collector and neutralizer sides. This would result in large copper sputtering yields from these surfaces, as well as secondary electron emission from the neutralizer and ion bombardment of the insulators.

Evidence of sputtering damage was found on the lower neutralizer exterior. The areas of greatest copper erosion were the waterlines, which are brazed to neutralizer

and project about 1 cm from its surface. It was also the lower electron collector insulators that suffered the most damage, although the neutralizer waterlines provided some shielding for the upper insulators.

In addition to the frequent high voltage breakdowns, electrical noise and erratic source operation made calorimetric measurements very difficult. The erratic source operation seems related not to the energy recovery operation per se, but rather to the accelerator/neutralizer geometry. The ion source, which operated well with a short neutralizer, ran very poorly with the long neutralizer used in this experiment. Ion source operation is dependent on proper pressures in the cathode and second anode chambers; this pressure ratio is controlled by the cathode-to-anode conductance relative to the accelerator and neutralizer conductances. The decreased conductance of the long neutralizer forced operation at either too low a pressure in the cathode chamber or too high a pressure in the anode chamber. This resulted in an ion source discharge that could vary by 20% from pulse to pulse.

The ion source operation was less troublesome than the electrical noise. This noise interfered with data acquisition, telemetry signals, and even the electronics of the acceleration supply's high voltage modulator. This noise was observed in the slanted experiment as well, and is related to the large electron leakage current at low values of magnetic field. The inability of this experiment to operate at high magnetic fields and the deleterious effects of ion trajectories will now be discussed.

## B.2 The Effect of Ion Trajectories on Performance

The computer calculations indicate that many of the experimental problems encountered with this experiment are the result of deleterious ion trajectories. Figure 5.20 shows a side view of a 30 keV beam at several magnetic field values; the boost voltage is 5 kV and the full energy ion current density a modest  $3.5 \text{ mA/cm}^2$ . Figure 5.21

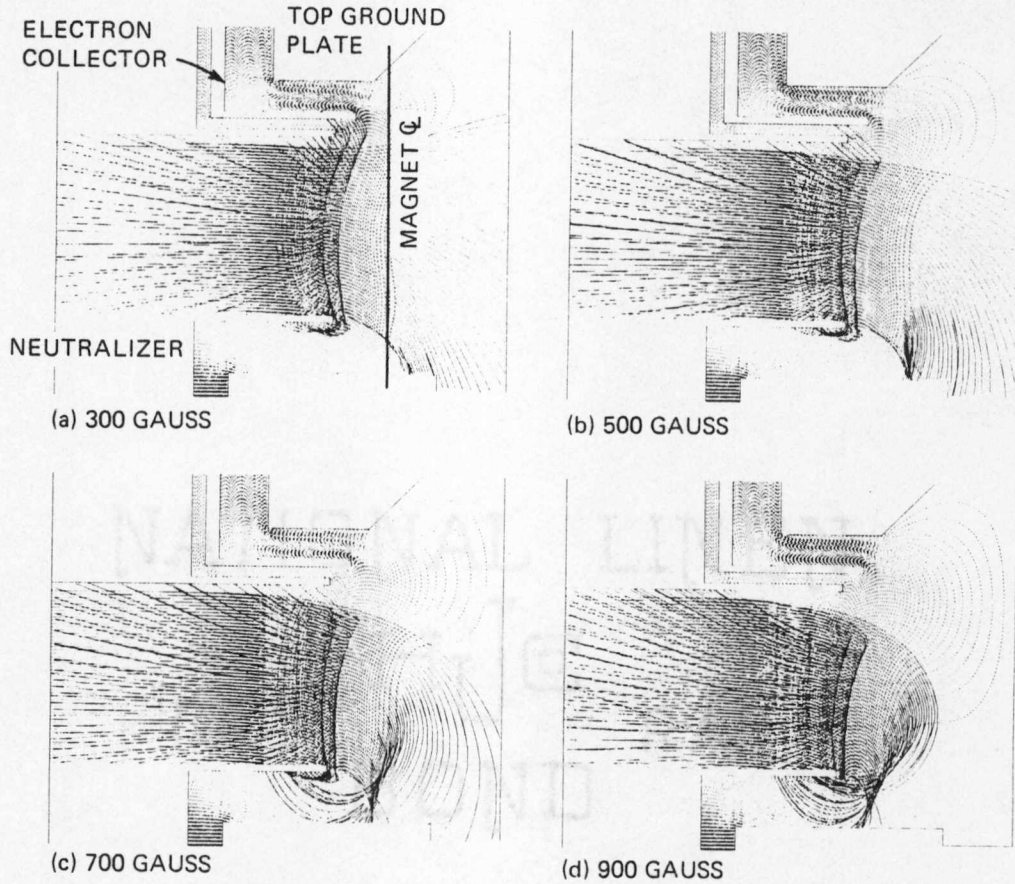


Fig. 5.20. Side view of ion trajectories as a function of magnetic field for the vertical neutralizer geometry. ( $V_{\text{beam}} = 30 \text{ kV}$ ,  $V_{\text{boost}} = 5 \text{ kV}$ ,  $V_{\text{ec}} = 4 \text{ kV}$ ,  $J^+ = 3.5 \text{ mA/cm}^2$ )

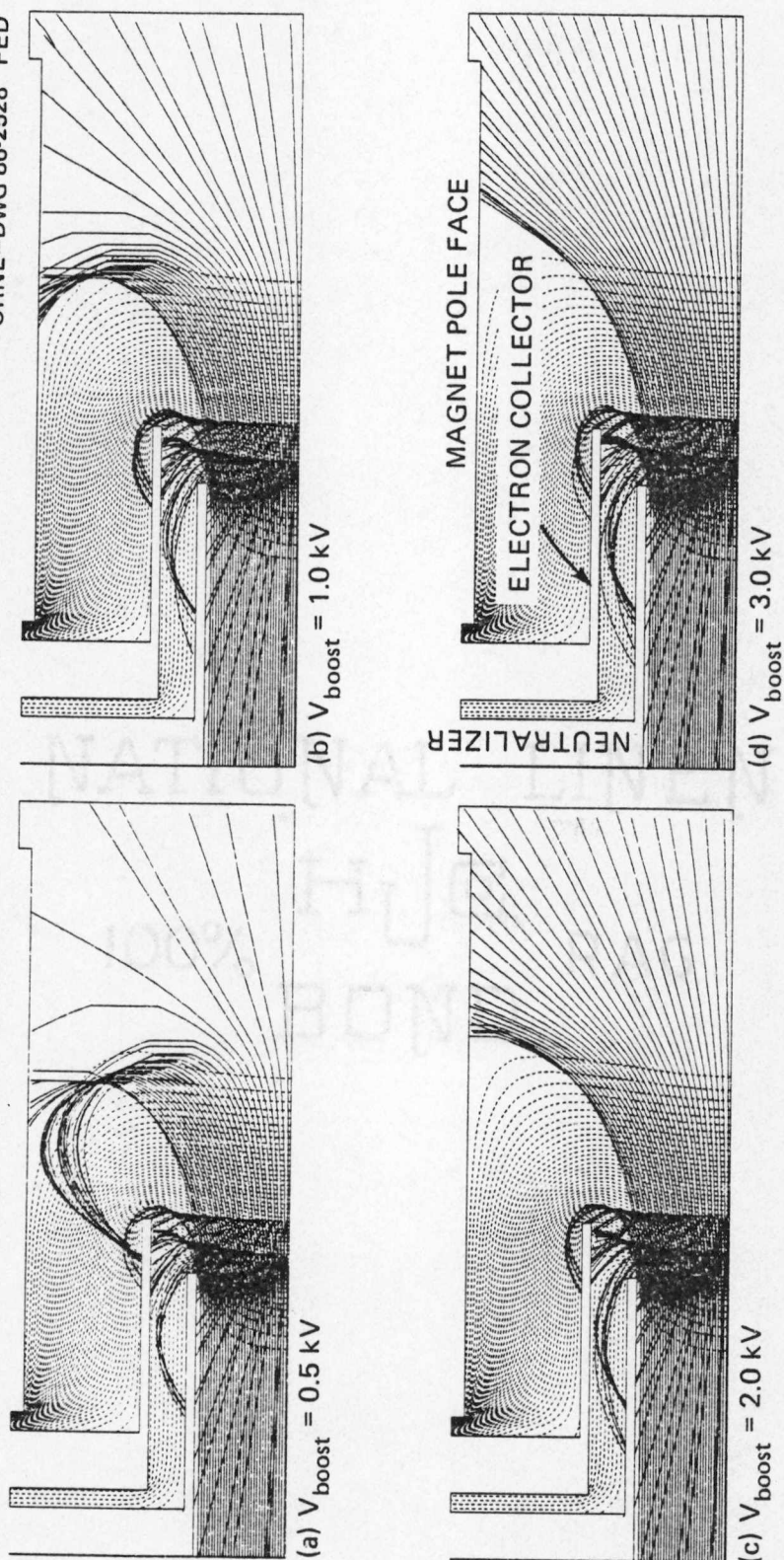


Fig. 5.21. Top view of ion trajectories as a function of boost voltage for the vertical neutralizer geometry.  
 $(V_{\text{beam}} = 30 \text{ kV}, V_{\text{ec}} = 5 \text{ kV}, J^+ = 5 \text{ mA/cm}^2)$

shows a top view of the device for several boost potentials. The experiment could not be operated at boost voltages below 3 kV, as the loss current passing through the boost supply bypass resistor was large enough to produce a bias potential that exceeded 3 kV. Moreover, the experiment became more difficult to operate at high magnetic fields as the boost voltage was lowered due to the prevalence of high voltage breakdowns.

It is apparent that the ion trajectories seen in Figures 5.20 and 5.21 will contribute to electrical breakdowns and poor system reliability, to say nothing of inefficient ion collection. Several features should be noted:

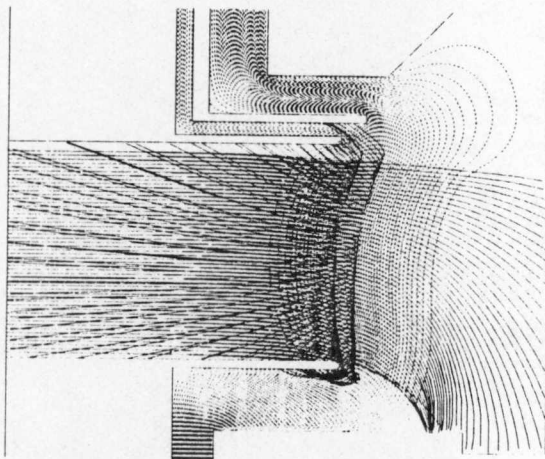
a) Figure 5.20 indicates that full energy ions strike the lower neutralizer exterior at magnetic field strengths of 700 G or higher. Fractional energy ions are seen striking this area at all values of magnetic field.

b) Fractional energy ions strike the upper electron collector at low values of magnetic field (Figure 5.20).

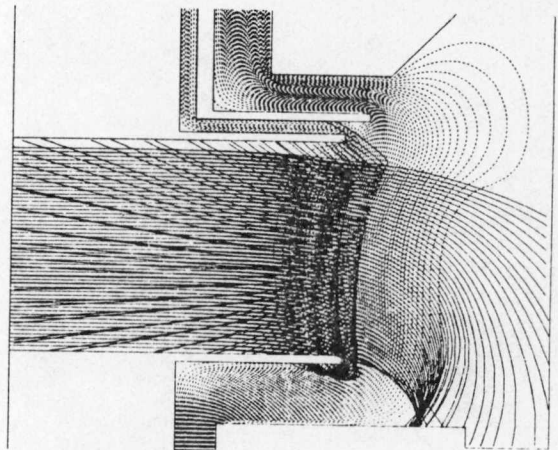
c) Fractional energy ions strike the exterior of the collector side plates (Figure 5.21). These will produce secondary electrons that will be accelerated along the magnetic field lines to the magnet pole face.

d) Fractional energy ions also strike the neutralizer exterior and the collector side plate interior. Those striking the neutralizer exterior will create secondary electrons that will be collected by the side plates. These fractional energy ions could be responsible for the sputtering damage and burn marks observed on the neutralizer surface and on the collector insulators.

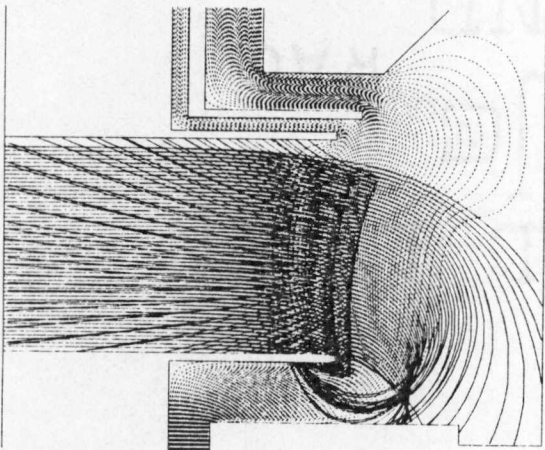
Figures 5.20 and 5.22 indicate that full energy ions begin to miss the bottom ground plate and strike the lower neutralizer at field values between 600 and 700 G for 5 kV boost potentials and between 500 and 600 G for 4 kV boost potentials. Although the ion current to the neutralizer cannot be determined, it is expected that a similar



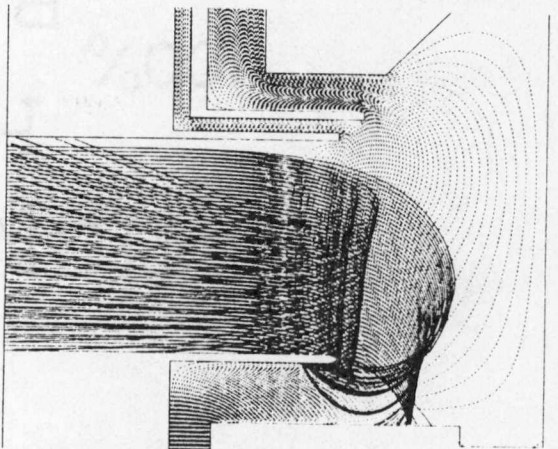
(a) 400 GAUSS



(b) 500 GAUSS



(c) 600 GAUSS



(d) 800 GAUSS

Fig. 5.22. Side view of ion trajectories as a function of magnetic field for a 4 kV boost voltage. ( $V_{\text{beam}} = 30 \text{ kV}$ ,  $V_{\text{ec}} = 5 \text{ kV}$ ,  $J^+ = 2.5 \text{ mA/cm}^2$ )

pattern will be observed on the electron collector side plates (not shown in the two-dimensional midplane solution). Figure 5.23, in which the collector side plate current is plotted against the magnetic field for two boost voltages, confirms this speculation. The intercepted ion current increases with increasing magnetic field and decreasing boost voltage; the increase begins at about 550 G for a 5 kV boost and at 450 G for a 4 kV boost.

Although calculation of the available full energy ion current cannot be made without calorimetry measurements, it can be estimated by the transmission efficiency through the neutralizer that was measured during normal mode operation. The transmission efficiency  $\eta_T$  was measured to be  $0.67 \pm .07$  for a beam perveance of  $1.77 \mu\text{perv}$ . Using an ion equilibrium fraction of 0.22 and an atomic species fraction of 0.80, a 30 keV, 7 A beam should have  $0.825 \pm .08$  A available for recovery. The positive current measured on the electron collector side plates exceeds this value; a substantial portion of this current must consist of secondary electrons that are accelerated to ground. The secondary emission coefficient for 30 keV  $\text{H}^+$  ions normally incident on a clean copper surface is 1.15;<sup>50</sup> the coefficient for 30 keV protons obliquely incident to a gassy surface may be an order of magnitude greater.

The most accessible ground surface for secondary electrons emitted from the collector side plates would be the magnet pole faces. The magnet pole face current will include leakage electrons, volume produced electrons, and full energy ions as well as secondary electrons. The leakage electron current should decrease as the magnetic field increases, and the volume produced electron current should not be highly dependent on the magnetic field. Figure 5.24 demonstrates the increase in electron current to the magnet pole faces as the magnetic field is increased; moreover, the current increases as the boost voltage is lowered. This is consistent with secondary electron production by full energy ions striking the collector side plates.

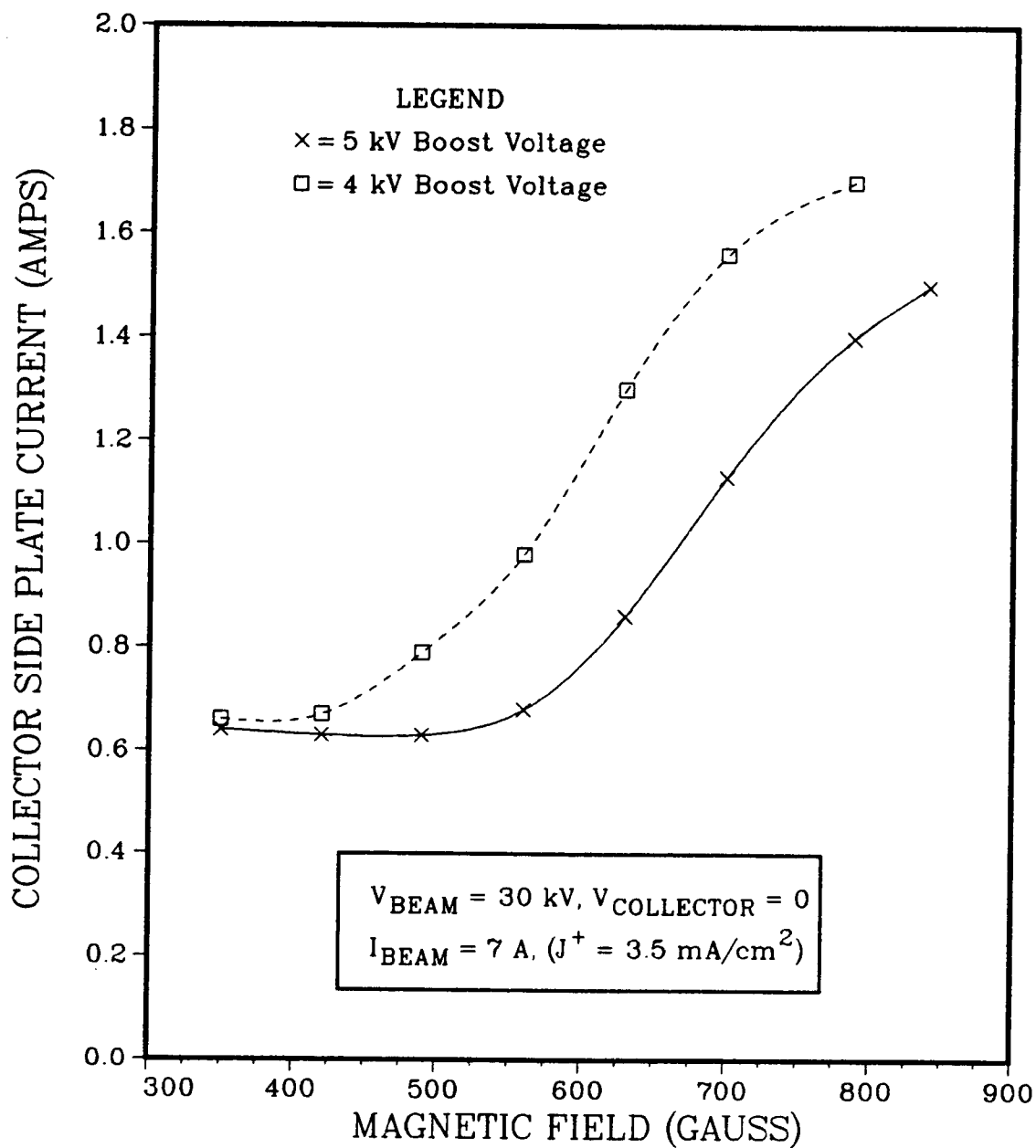


Fig. 5.23. Current to the electron collector side plates vs. magnetic field as a function of boost voltage in the vertical neutralizer experiment.

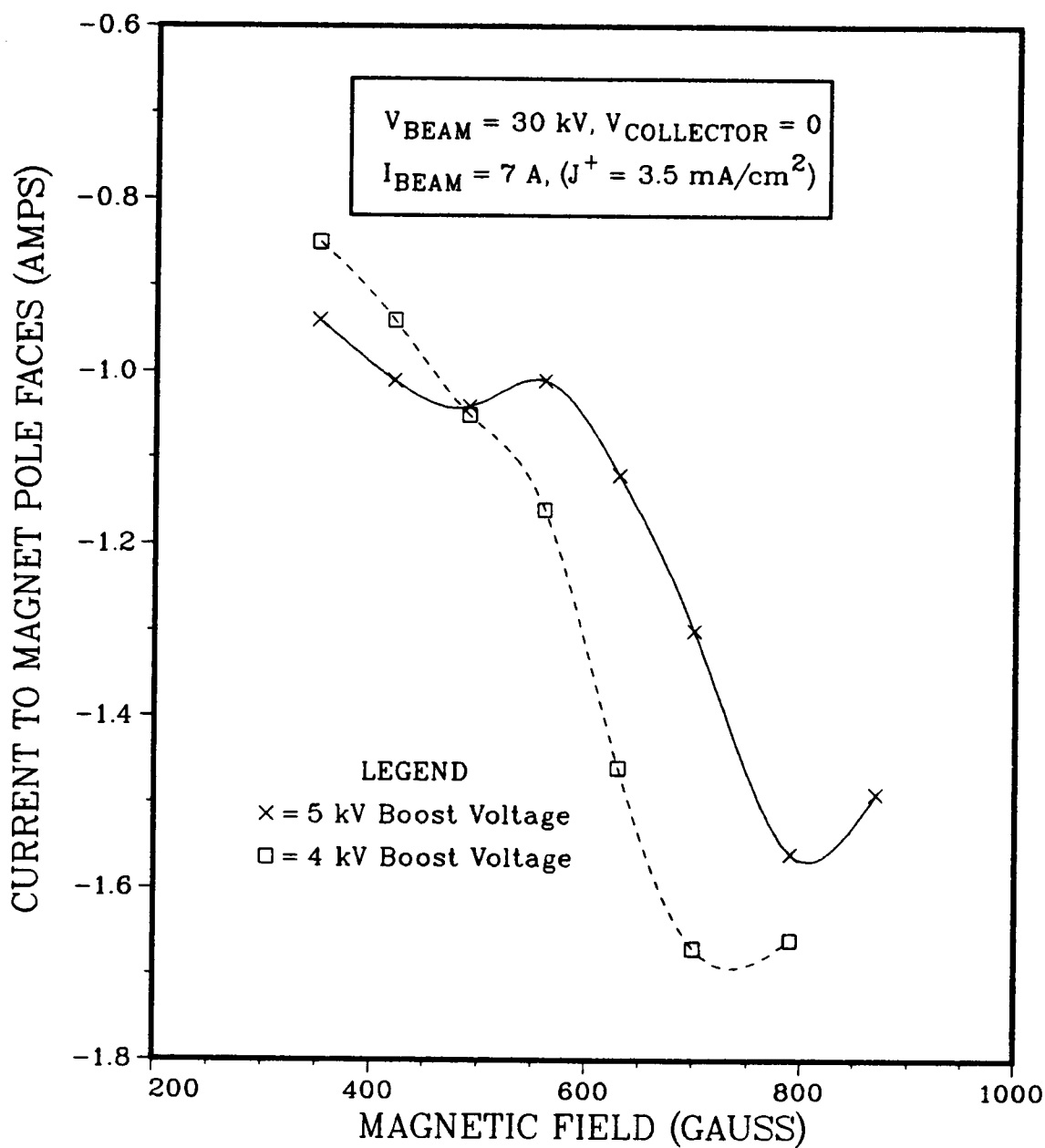


Fig. 5.24. Current to the magnet polefaces vs. magnetic field as a function of boost voltage in the vertical neutralizer experiment.

In general it is not possible to make quantitative comparisons between the computer model and the experiment without accurate power loading measurements to separate the components of the current. An exception is the bottom ground plate current. The vertical magnet and lack of a front ground plate cause the bottom ground plate to become a principal ion collection surface. The only other component to contribute to this current will be ground potential electrons from the background plasma. Figure 5.25 compares the measured bottom ground plate current with the values predicted from the computer code. The close agreement validates the computer calculations, which in turn explain the failure of this geometry to provide net ion recovery efficiency.

The vertical end of the neutralizer allows for no upward electrostatic force on the ions. This fact, coupled with the vertical magnet orientation, causes ions to strike the electron collector sides and lower neutralizer exterior, preventing operation at high magnetic fields and producing copious amounts of secondary electrons. Although ion collection efficiency appears high at very low magnetic fields, the electron leakage current becomes too great to obtain a net recovery current.

The principles learned from both the slanted and the rectangular recovery experiments will now be applied to the design of a recovery device that will operate at high magnetic fields and current densities.

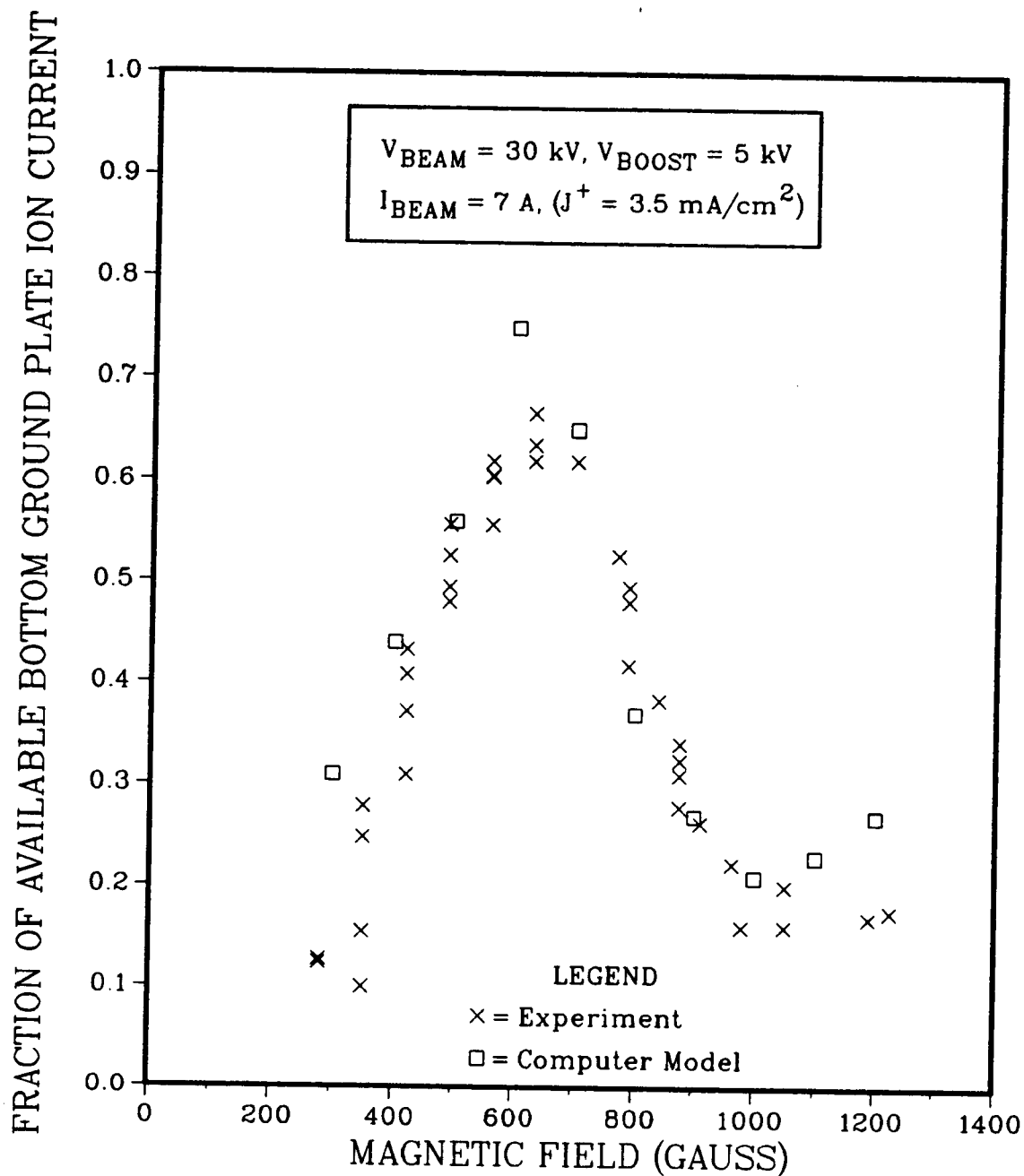


Fig. 5.25. Current to the bottom ground plate vs. magnetic field; comparison of computer model to experiment.

## 6. DESIGN OF AN EFFICIENT ENERGY RECOVERY DEVICE

### A. DESIGN CONSIDERATIONS

The original mission of the ORNL energy recovery program was to design and test a proof-of-principle energy recovery device that would operate in conjunction with the ORNL half-scale Advanced Positive Ion Source (APIS) at the METF. The designs presented in this chapter are tailored to the available equipment and facilities, even though this activity is no longer funded. These design constraints will be briefly discussed before presenting the analyses of the designs.

The half-scale APIS source used in the 1982 experiments is the reference ion source.<sup>66</sup> It is capable of producing a 25 A hydrogen beam of  $10 \times 25$  cm cross section when correctly matched to the neutralizer; it can produce pulses exceeding ten seconds when using an indirectly heated LaB<sub>6</sub> or LM (molybdenum doped with La<sub>2</sub>O<sub>3</sub>) cathode in place of the short pulse oxide-coated filaments. Although this source has used a two-stage (tetrode) accelerator to achieve beam energies of 120 keV, operation at the METF would be limited to 80 keV using single-stage acceleration. As a result of the MFTF-B ion source development program, the METF now has access to an 80 kV, 50 A accel power supply, which would be more than sufficient for this purpose. The 5 kV, 20 A boost supply could have the secondary of its transformer reconfigured to provide 10 A at 10 kV; analysis shows that this additional boost voltage capability is necessary. Note that this will limit the net ion recovery current to 10 A, which should be sufficient for a 25 A source.

The existing magnet, which has a 28 cm pole gap and a maximum field strength of 2000 G, would be retained. This magnet has already been oriented at 0° and +45° to the vertical; it is expected that it could be oriented at -45° without

excessive effort. Use of this magnet puts limitations not only on the available design orientations, but also on the magnetic field distribution and the energy recovery apparatus which must fit in the pole gap. The distance from the ion source to the magnet also cannot be altered.

The 1.4 m long rectangular neutralizer section that was fabricated for the 1982 experiments would also be kept. The end of the neutralizer, the electron collector, and the adjacent ground surfaces can be completely redesigned as long as they can interface with the existing neutralizer segment and magnet.

Important design criteria may be gleaned from the previous experiments and analyses that will influence the proposed designs:

- 1) The device should operate at as high a magnetic field strength as possible. The electron leakage current out of the neutralizer is inversely proportional to the field strength, and the operation is more quiescent at high field values.
- 2) The device should employ a slanted neutralizer to balance the downward magnetic force with an upward electrostatic force.
- 3) The line density in the recovery region should be reduced in order to minimize volume losses.
- 4) The fractional energy ions should be confined to the neutralizer interior.
- 5) The impingement of full energy ions on the electron collector and neutralizer exterior must be avoided.

Some practical engineering considerations to increase the reliability of the device should also be mentioned, although most of these do not affect the computer design analysis. Particular care should be paid to eliminating electrical breakdowns. This involves increasing critical gaps, avoiding sharp corners, and avoiding regions that would be susceptible to P.I.G. discharges. Insulators should be positioned out of the path of energetic particles and should be shielded from line

of sputtering. The surfaces of the copper neutralizer and electron collector could be coated with a thin layer of sputter-resistant material such as nickel or chromium. Electroplating such materials onto copper swirl tubes reduced erosion on Faraday shields from energetic beam particles by a factor of two (Ni) to three (Cr).<sup>68</sup> It may also reduce the secondary electron emission coefficient, which could lower loss currents.

The line density in the recovery region may be reduced by decreasing the gas pressure or decreasing the width of the deceleration sheath. Neither the pumping speed of the cryopumps nor the gas conductance from the recovery region to the pumps can be altered very readily. The gas flow rate into the system is determined by the equilibrium line density needed for beam neutralization, which in turn is influenced by the length of the neutralizer. This length is fixed by the immobility of the bending magnet. The ultimate limitation on gas flow reduction is the gas efficiency of the source, which can be 30 to 50% for the half-scale APIS source. The gas flow rate would thus be about 8 torr·L/s for a 25 A beam, which would result in a minimum pressure at the pumps ( $2 \times 10^5$  L/s pumping speed) of  $4 \times 10^{-5}$  torr. The deceleration sheath width decreases naturally as the beam current density increases, which may be the only practical way to reduce these volume losses.

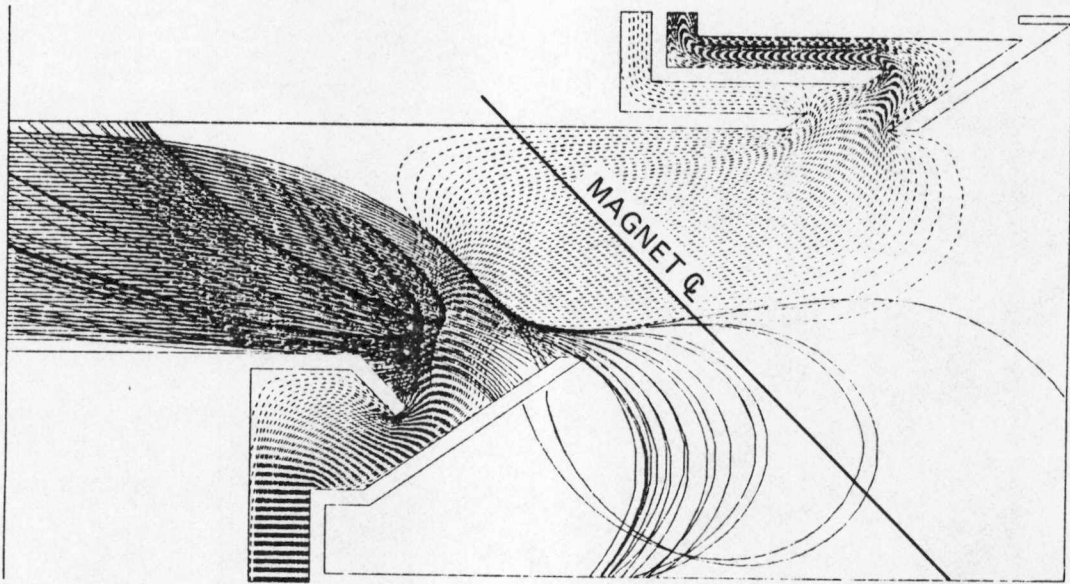
Before proceeding to the energy recovery device designs, it should be remarked that an effort would have to be made to properly match the ion source to the final neutralizer geometry. This is a part of every final source design and usually consists of changes in the intermediate electrode aperture(s) and the first anode geometry. Many of the problems encountered in previous experiments result from the failure to optimize this interface properly.

## B. DESIGN OF A 40 keV $H^+$ ENERGY RECOVERY SYSTEM

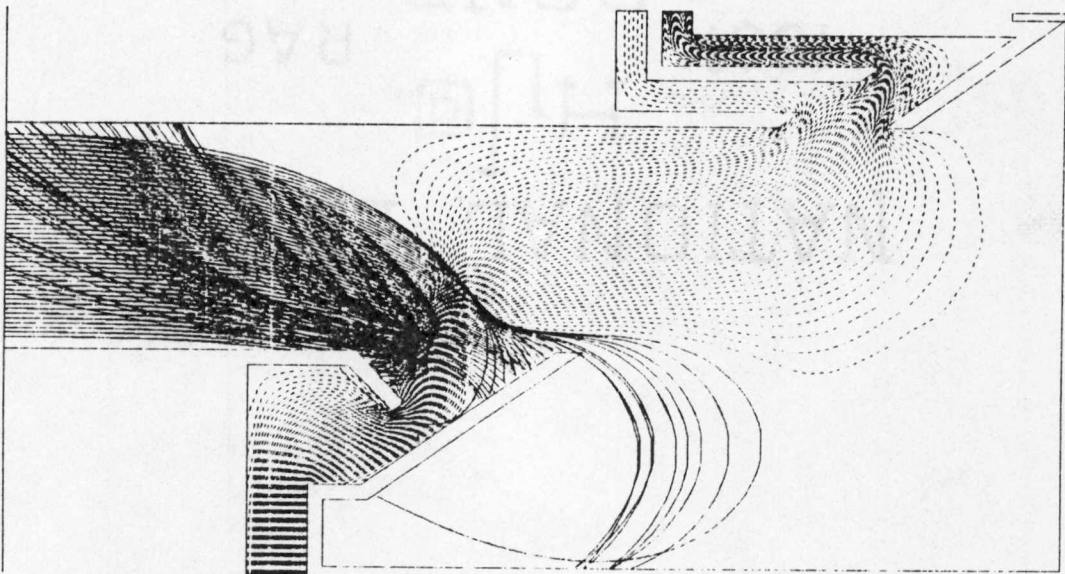
The first design exercise is the improvement in ion collection efficiency for the slanted neutralizer geometry that was extensively analyzed in Section 5.A. The purpose of this exercise is to demonstrate the effect of a new magnet orientation and neutralizer geometry on the ion trajectories. It was seen that the ion collection efficiency decreases sharply for full energy ion current densities of  $20 \text{ mA/cm}^2$  or greater (Table IV, p. 125). The space charge of the beam results in ion trajectories that do not terminate on ground surfaces. The ions that strike the upper collector and upper neutralizer could be recovered by increasing the magnetic field, but only at the expense of increasing the number of ions that strike the lower collector and lower neutralizer. The basic problem is that ions near the bottom of the neutralizer are being over-deflected, while ions near the top of the neutralizer are being under-deflected. This can be rectified by reversing the orientation of the magnetic field.

The magnet orientation in Figure 6.1 is at  $-45^\circ$ ; hence the field strength increases with vertical distance from the bottom of the neutralizer. The strong field at the top of the neutralizer counteracts the upward electrostatic force on the ions; the weaker field at the bottom of the neutralizer allows more full energy ions to emerge from the neutralizer. This magnet orientation, coupled with the slanted neutralizer, tends to focus the ions toward the lower front ground plate, which is the principal ion collection surface.

Another design goal is to confine the fractional energy ions to the interior of the neutralizer. This is accomplished by the extension of the neutralizer end to provide a surface to collect these ions. This extension is similar in concept to the large shroud placed around the end of the neutralizer in the "loose-coupled" geometry of



(a)



(b)

Fig. 6.1. Side view of ion trajectories for the 40 keV energy recovery design; 15 cm diameter neutralizer with  $-45^\circ$  magnet orientation. ([a]  $J^+ = 25 \text{ mA/cm}^2$ ,  $B = 1250 \text{ gauss}$ ; [b]  $J^+ = 50 \text{ mA/cm}^2$ ,  $B = 1400 \text{ gauss}$ )

Stirling and Kim. Since this surface is within the neutralizer, secondary electrons will drift upward and be collected on the upper neutralizer or electron collector. Note that the lower electron collector has been removed from this design. The gap between the neutralizer extension and the nearest ground surface is about 3 cm, across which 35 kV will need to be held. Increasing this gap would allow full energy ions to strike the lower neutralizer, which is to be avoided.

This design yields much higher ion collection efficiencies than previous geometries. For a magnetic field of 1250 G, a collection efficiency of 98% can be achieved at a current density of 25 mA/cm<sup>2</sup>. At 50 mA/cm<sup>2</sup>, the efficiency is still 95% for a magnetic field of 1400 G. Both cases use a boost voltage of 5 kV.

The ion collection efficiency along the magnetic field (i.e., top view) is determined primarily by the beam space charge in the recovery region. This space charge is in turn dependent on the ion current density and on the ion velocity *after* deceleration. Thus beam blowup is controlled by the boost potential, not by the acceleration potential. The ion trajectories along the magnetic field lines remain basically unaltered by the new magnet orientation, and so it is expected that the top view ion collection efficiencies of Figure 5.15 (p. 122) and Table IV (p. 125) will still apply.

While the ion collection efficiency  $\eta_{ic}$  is dependent on the boost voltage itself, the power recovery efficiency is dependent on both  $\eta_{ic}$  and  $\mu$ , the ratio of the boost voltage to the beam acceleration voltage,

$$\eta_{ip} = \eta_{ic}(1 - \mu) . \quad (2.19)$$

The ion collection efficiency can approach unity for any ion current density if the boost voltage is sufficiently high. The power recovery efficiency can then be increased by decreasing  $\mu$ ; this can be accomplished by increasing the beam energy, as will be seen in the 80 keV recovery design.

### C. DESIGN OF AN 80 KEV $H^+$ ENERGY RECOVERY SYSTEM

The 80 keV energy recovery system has been designed under the constraints imposed in Section 6.A. In particular, a  $10 \times 25$  cm neutralizer is assumed, with the short dimension along the magnetic field lines in order to fit the apparatus within the 28 cm magnet pole gap. The ratio of the full energy ion gyroradius to the vertical extent of the neutralizer is an important parameter. If it falls below unity, ions will be reflected back to the neutralizer interior without being collected. As the vertical extent of the neutralizer is increased, the magnetic field must be reduced or the boost voltage must be increased to prevent this from happening. Increasing the boost voltage reduces the power recovery efficiency, and decreasing the magnetic field increases the electron leakage current from the neutralizer.

Alternatively, the magnetic field can be increased if the short dimension of the neutralizer is oriented vertically. However, the magnet pole gap would have to be increased to accommodate the long dimension of the neutralizer. The cost of the magnet increases as the gap is widened, and fringing fields would become more of a problem. The wider beam would add to the space-charge blowup along magnetic field lines.

The full energy ion current density will increase for a higher beam energy, due to the lower neutralization efficiency. If an average extracted current density of  $100 \text{ mA/cm}^2$ , a neutralizer transmission efficiency of 90%, and an atomic species fraction of 90% are assumed, then the 80 keV ion equilibrium fraction of 0.685 will yield a full energy ion current density of  $55 \text{ mA/cm}^2$  in the recovery region. Designs have been analyzed for 50 and  $100 \text{ mA/cm}^2$ ; designing for  $100 \text{ mA/cm}^2$  allows for a margin of error in the analysis as well as anticipating improved ion source performance.

Figure 6.2 is a three dimensional sketch of such an energy recovery device for a  $10 \times 25$  cm ion source. Figure 6.3 is the two dimensional side view of this device, showing the computational results for an 80 keV hydrogen beam with a full energy ion current density of  $50 \text{ mA/cm}^2$ . No deleterious ion trajectories are present in Figure 6.3(a); the ion collection efficiency is 77% at 1400 G and a boost voltage of 5 kV, for a power recovery efficiency of 72%. In Figure 6.3(b), the ion collection efficiency is improved to 90% by increasing the boost voltage from 5 to 8 kV. The additional 13% improvement in the ion collection efficiency is accompanied by a decrease in the  $(1 - \mu)$  term from 0.94 to 0.90, yielding a power recovery efficiency of 81%. The magnetic field was reduced to 1200 G to prevent ions from striking the lower neutralizer exterior.

Figure 6.4 shows the design performance for a full ion current density of  $100 \text{ mA/cm}^2$ ; the boost voltage had to be raised to keep ion impingement on the neutralizer at a minimum. For a boost voltage of 8 kV at 2000 G, the ion collection efficiency is only 63%, as seen in Figure 6.4(a). This is increased to 81% in Figure 6.4(b) by increasing the boost voltage to 10 kV and decreasing the magnetic field to 1600 G. The corresponding power recovery efficiencies are 57% and 71% respectively.

The critical dimension in this geometry is the gap between the neutralizer extension for collecting fractional energy ions and the lower ground plate. This gap is about 3.2 cm; the mesh size of the Poisson grid dictates unrealistically large thicknesses for the electrodes, so that this gap dimension is only approximate. For a boost voltage as low as 5 kV, a field strength on the order of 25 kV/cm must be maintained across this gap. Although field strengths three times this value are routinely used in the ion accelerator, the presence of ions, secondary electrons, local

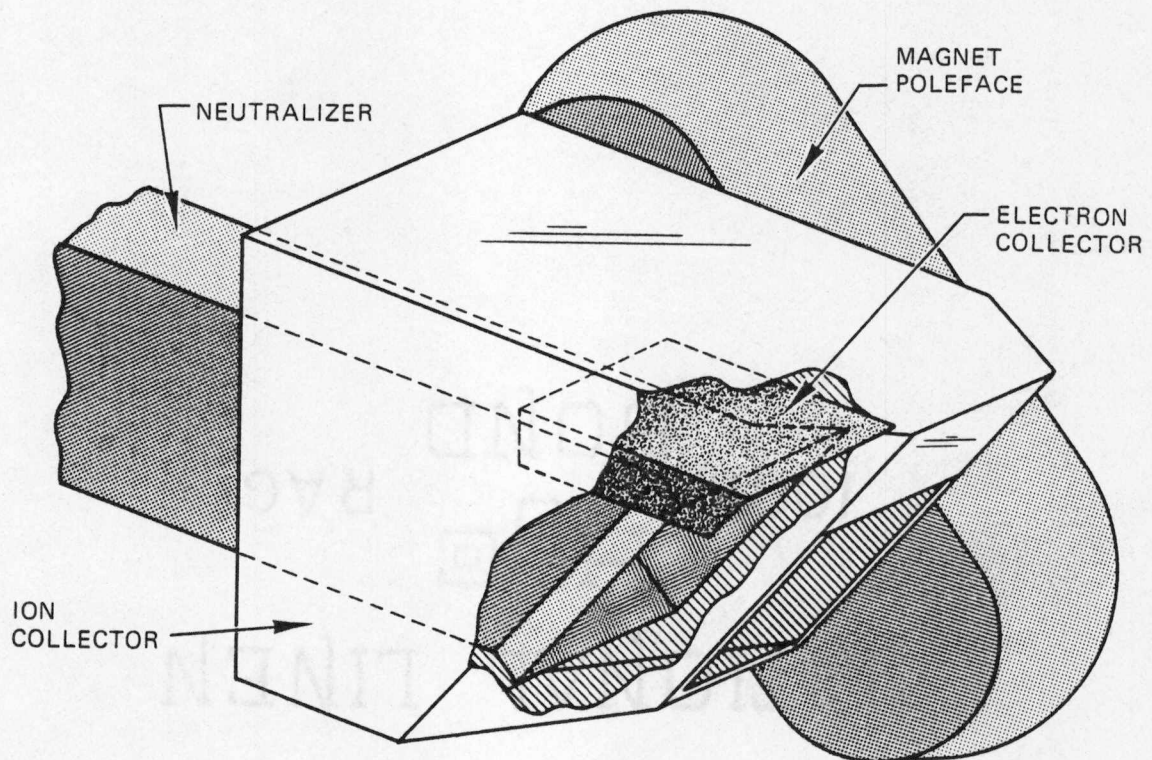
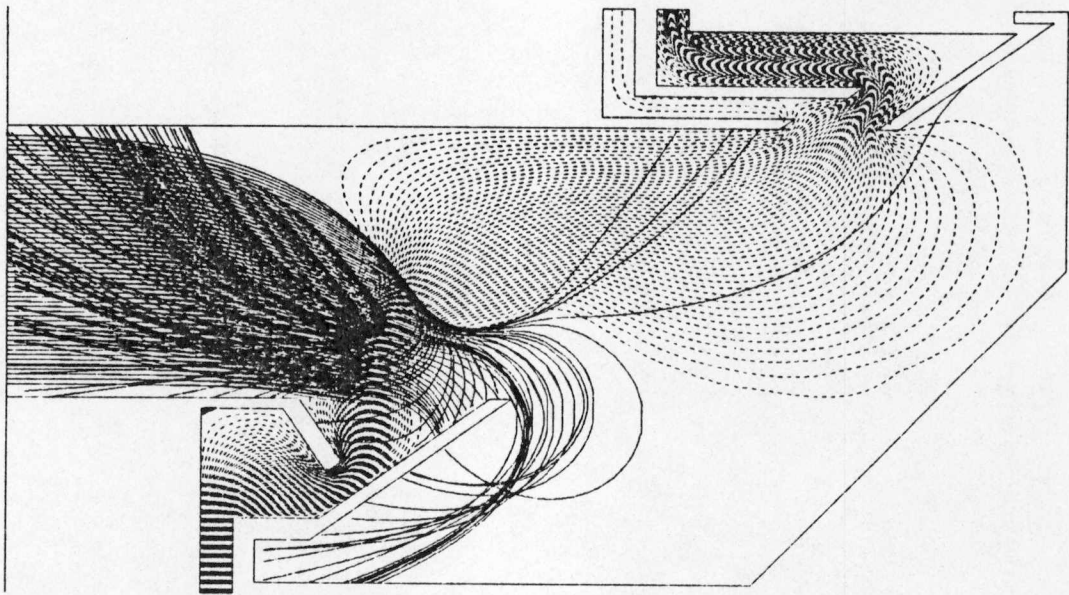
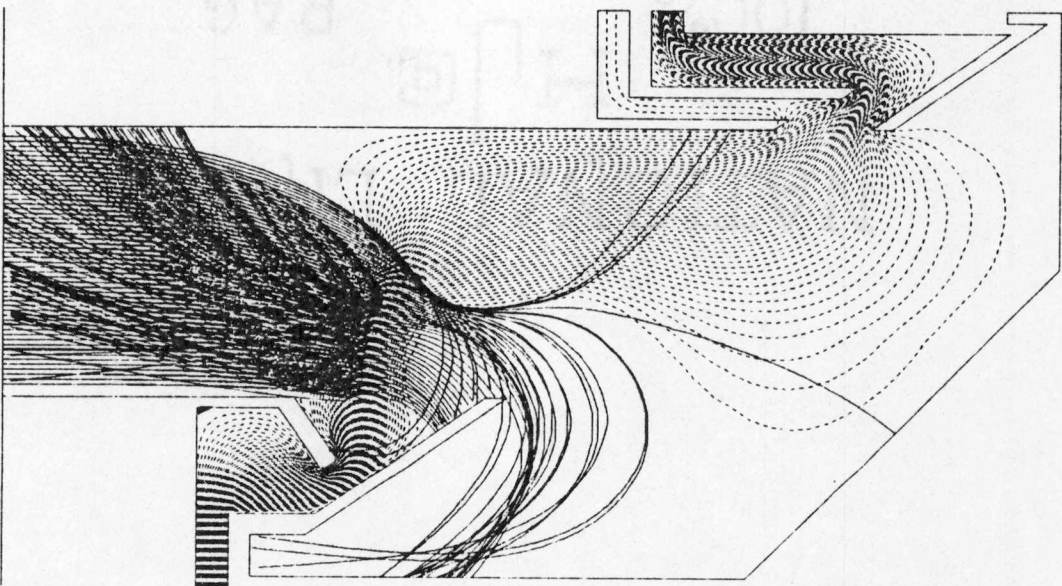


Fig. 6.2. Sketch of an 80 keV energy recovery design for a  $10 \times 25$  cm beam.

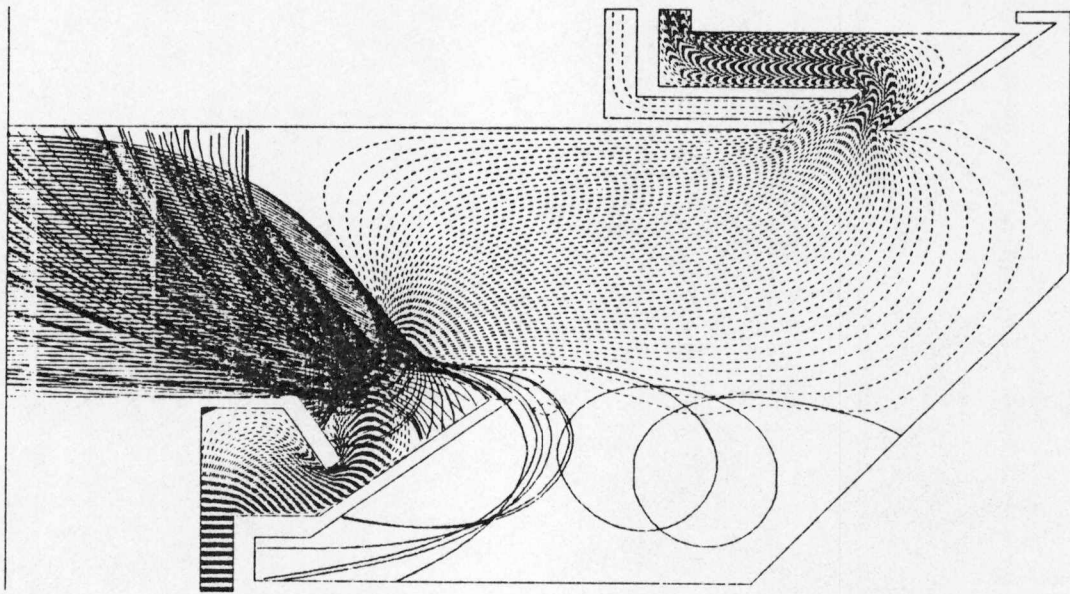


(a)

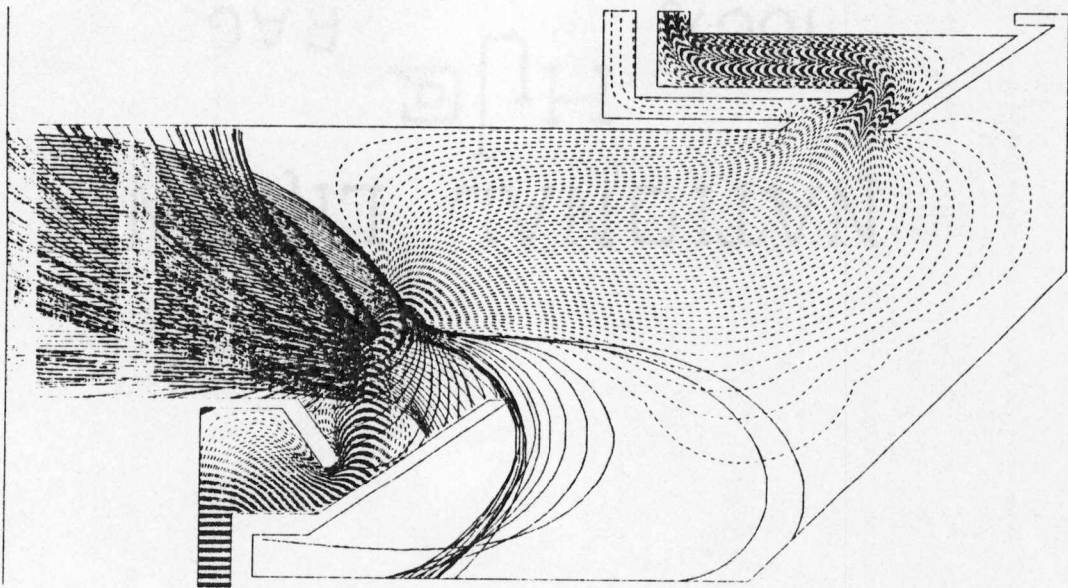


(b)

Fig. 6.3. Side view of ion trajectories for an 80 keV, 50 mA/cm<sup>2</sup> energy recovery design with 3.2 cm minimum neutralizer to ground clearance. ([a]  $V_{\text{boost}} = 5$  kV,  $B = 1400$  gauss; [b]  $V_{\text{boost}} = 8$  kV,  $B = 1200$  gauss)



(a)



(b)

Fig. 6.4. Side view of ion trajectories for an 80 keV, 100 mA/cm<sup>2</sup> energy recovery design with 3.2 cm minimum neutralizer to ground clearance. ([a]  $V_{\text{boost}} = 8$  kV,  $B = 2000$  gauss; [b]  $V_{\text{boost}} = 10$  kV,  $B = 1600$  gauss)

outgassing, and plasma in this region may cause reliability problems in holding this voltage.

This gap is increased to 5 cm in Figure 6.5, in which a  $100 \text{ mA/cm}^2$  beam is analyzed. The ion collection efficiency is 71% for a boost voltage of 10 kV and a magnetic field of 2000 G; the power recovery efficiency is 62%. This design pushes the boost voltage supply and the electron suppression magnet to their limits, and still full energy ions can be observed striking the lower neutralizer exterior.

At this point it is reasonable to question whether the blowup along the magnetic field lines will prevent operation at such current densities and boost voltages. Figure 6.6 shows the top view of the recovery device for two different ion current densities. Changes from the previous designs were made to improve collection efficiency and reliability. The front ground plate is placed at an angle so that the ion trajectories are more perpendicular to its surface. Fractional energy ions are collected within the neutralizer by an extension to the side, similar to that placed on the lower portion of the neutralizer end. This prevents fractional energy ions from causing breakdowns to ground by producing secondary electrons on the neutralizer exterior. The side electron collector plate has been eliminated, as it is not useful for collecting neutralizer electrons and its presence would increase the gap between the neutralizer and the front ground plate. Minimizing this gap is just as critical for efficient ion collection as is minimizing the analogous gap in the side view. The design in Figure 6.6 again uses a 5 cm spacing for this gap, for which 100% collection efficiencies can be achieved at the boost voltages employed in the side view analyses. The boost voltage is 5 kV for a  $50 \text{ mA/cm}^2$  beam in Figure 6.6(a), and 8 kV for a  $100 \text{ mA/cm}^2$  beam in Figure 6.6(b).

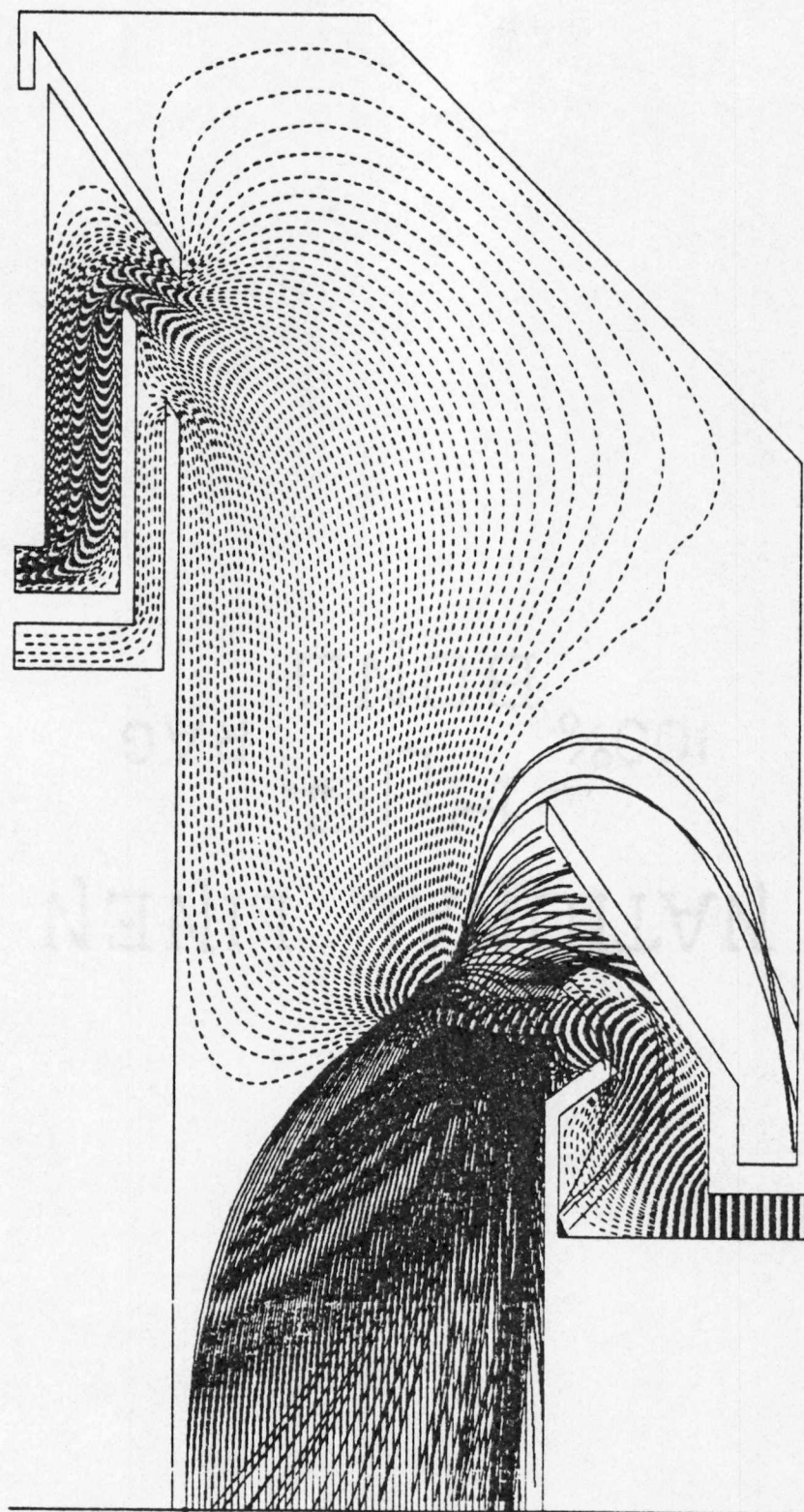
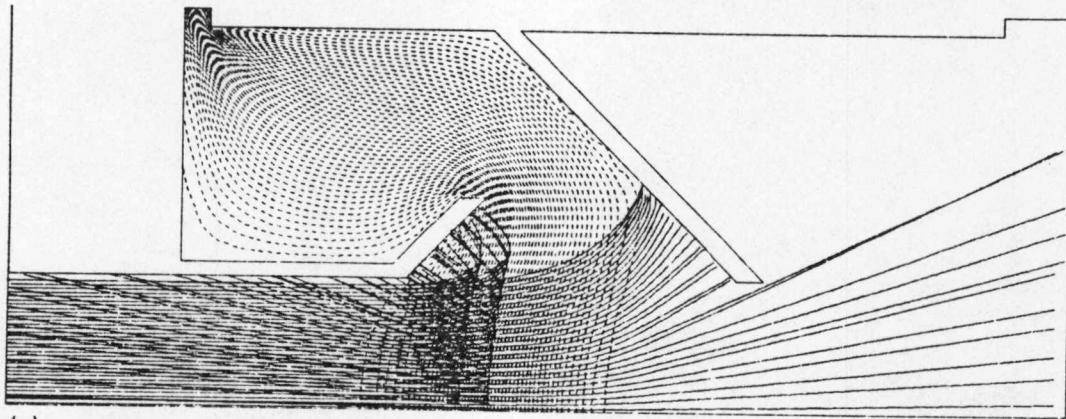
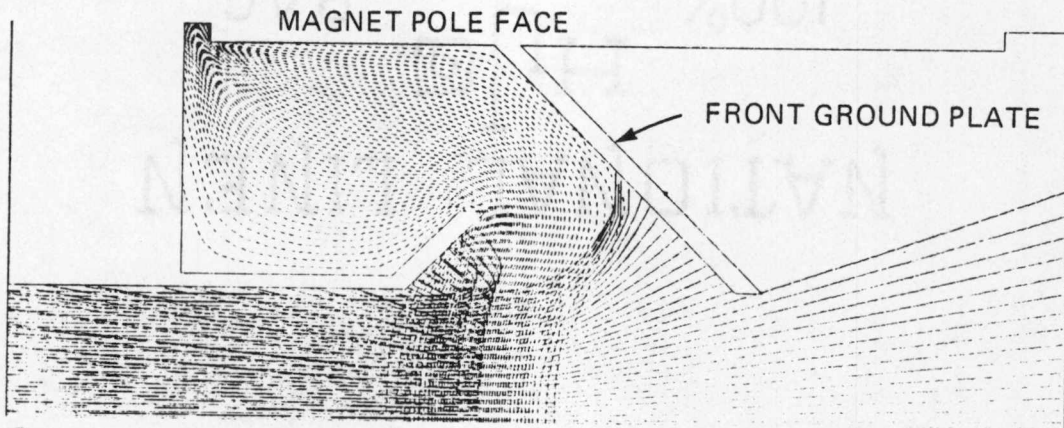


Fig. 6.5. Side view of ion trajectories for an 80 keV, 100 mA/cm<sup>2</sup> energy recovery design with 5 cm minimum neutralizer to ground clearance. ( $V_{\text{boost}} = 10$  kV,  $B = 2000$  gauss)



(a)



(b)

Fig. 6.6. Top view of ion trajectories in an 80 keV energy recovery design. ([a]  $V_{\text{boost}} = 5 \text{ kV}$ ,  $J^+ = 50 \text{ mA/cm}^2$ ; [b]  $V_{\text{boost}} = 8 \text{ kV}$ ,  $J^+ = 100 \text{ mA/cm}^2$ )

## D. DESIGN OF AN 80 KEV D<sup>+</sup> ENERGY RECOVERY SYSTEM

Deuterium beams cannot be operated at the METF since this is not a shielded facility. Energetic neutron production from D-D reactions between the 80 keV beam particles and the deuterium embedded in the beamstop target and other surfaces would be prohibitively high. However, deuterium beams are routinely used to heat tokamak experiments and thus should be considered in an energy recovery design.

The increased atomic mass of deuterium as compared to hydrogen simplifies the design in many respects. The optimum extraction current for a given ion accelerator is inversely proportional to the square root of the ion mass; hence the beam current decreases by 28% when the working gas is switched from hydrogen to deuterium. Deuterons have the same equilibrium fractions as protons of equal velocity; therefore, an 80 keV D<sup>+</sup> beam will have the same ion fraction as a 40 keV H<sup>+</sup> beam. Both these effects reduce the full energy ion space charge that is of such concern in energy recovery systems.

The gyroradius of an ion can be expressed as

$$\rho = \frac{(2mE)^{1/2}}{qB}, \quad (6.1)$$

indicating that the magnetic field should be increased 40% for a deuterium beam of the same energy in order to preserve the same ion trajectories. This allows higher magnetic fields to be employed for electron suppression.

The full energy ion current density for a deuterium beam operating under the same assumptions as in Section 6.C would be:

$$\begin{aligned}
J^+(80 \text{ keV}) &= J_{\text{beam}} \eta_N \eta_1 (D^+) f_{1\infty}(80 \text{ keV}) \\
&= \frac{25 \text{ A}}{1.4 \times 250 \text{ cm}^2} \times 0.9 \times 0.9 \times 0.38 \\
&= 22 \text{ mA/cm}^2 .
\end{aligned} \tag{6.2}$$

Designs were analyzed at twice this current density to maintain a margin of error. Figure 6.7 shows an 88% ion collection efficiency for a full energy ion current density of 50 mA/cm<sup>2</sup>. The boost voltage is 8 kV and the magnetic field is 1680 G; the gap between the lower neutralizer and the lower front ground plate is 5 cm. The ion collection efficiency as viewed from the top will be similar to that of Figure 6.6(a); that is, 100% for boost voltages greater than 5 kV. Note that if the boost voltage is increased too much, fractional energy ions may escape from the neutralizer interior and cause problems. This is easily avoided by operating at the minimum boost potential. The power recovery efficiency for a boost potential of 8 kV is 79%.

The system losses are more difficult to quantify than the ion collection efficiency. The well-controlled ion trajectories of Figures 6.6 and 6.7 suggest that secondary electrons will be greatly reduced. The high value of magnetic field should also reduce the electron leakage current out of the neutralizer. It is anticipated that the principal contribution to system losses will be from volume ionization losses.

Equation (5.20) was derived for a 40 keV hydrogen beam and can be applied directly to an 80 keV deuterium beam in order to calculate the net current recovery efficiency,

$$\eta_c = \eta_{ic} - 32.11pL . \tag{5.20}$$

The increased beam current density reduces the width of the double sheath that defines the recovery region. The sheath width in Figure 6.6 is about 10 cm,

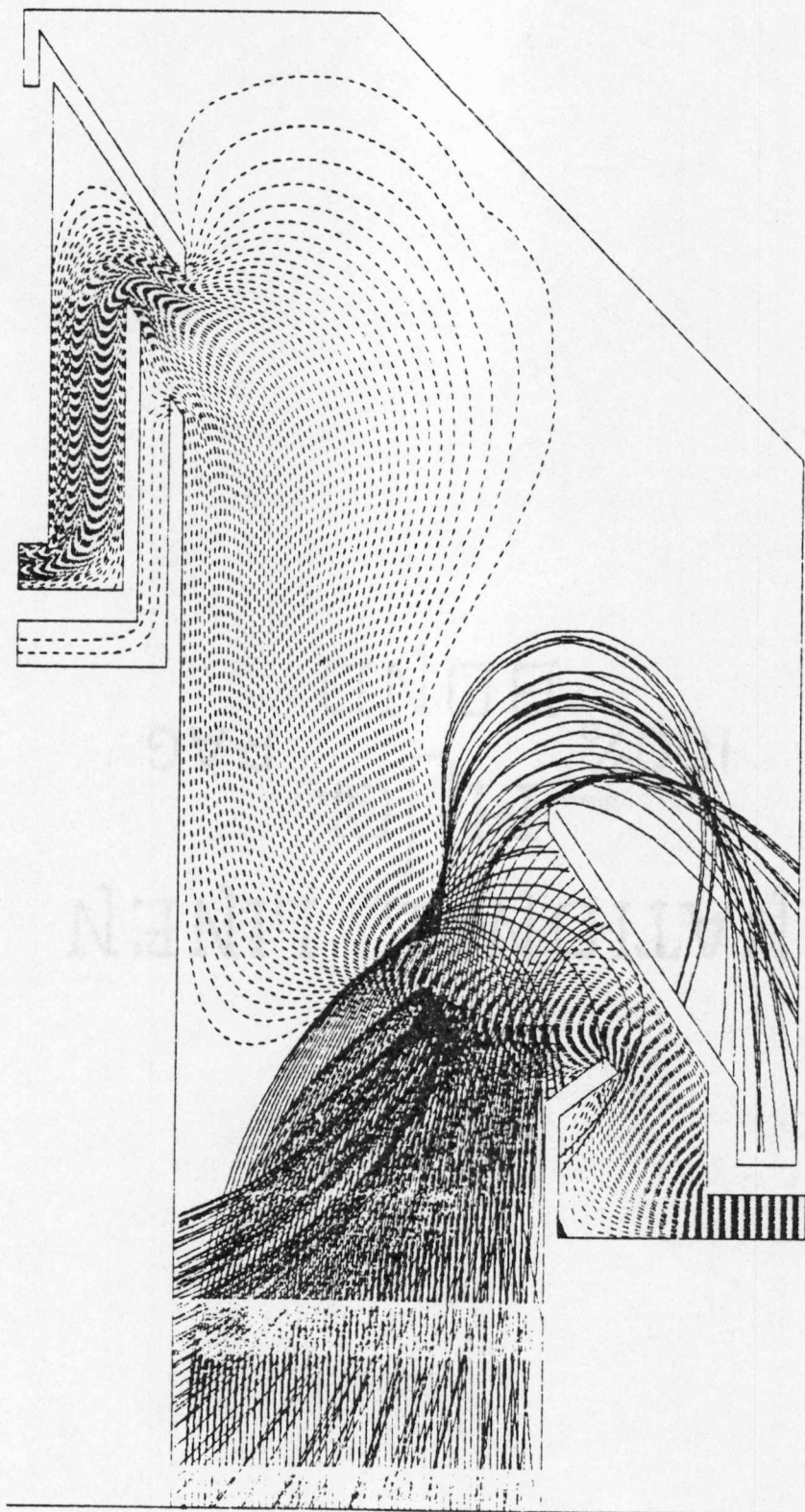


Fig. 6.7. Side view of ion trajectories in an 80 keV energy recovery design  
for a  $50 \text{ mA/cm}^2$  deuterium ion beam. ( $V_{\text{boost}} = 8 \text{ kV}$ ,  $B =$   
 $1680 \text{ gauss}$ )

as opposed to the 30 cm width that was computed for the experiment in Section 5. The line average pressure in the recovery region for that 40 keV experiment was deduced to be about  $5 \times 10^{-4}$  torr. If one assumes a similar pressure for the 80 keV deuterium design, then the net current recovery efficiency will be reduced from 88% to 72% by these volume losses. The net power recovery efficiency would be reduced to 65%.

It is possible that the pressure in the recovery region could be reduced by a factor of two by carefully matching the conductances of the ion source to those of the neutralizer. For a pressure of  $2.5 \times 10^{-4}$  torr, the net current recovery efficiency would be 80% and the net power recovery efficiency would be 72%. For a power recovery efficiency of 72%, Equation (2.24) indicates that the overall system efficiency for an 80 keV deuterium beam (40 keV per nucleon) would increase from 55% to 72%.

## E. CONCLUSIONS AND RECOMMENDATIONS

The two-dimensional finite difference code employing a double plasma model yields results which are in good agreement with experimental measurements. The analysis should be extended to three dimensions as ion motion along magnetic field lines is a important contributor to total system performance. The original ion optics code has been modified to include the third dimension;<sup>69</sup> these techniques could be applied to the energy recovery code without undue development activity. The two-dimensional electrostatic solution that neglects the magnetic field effects has been useful in analyzing the experiments and designing more efficient devices, but it is no substitute for a fully three-dimensional treatment.

The operation and analysis of the energy recovery experiments have provided design principles that allow higher performance systems to be designed. The magnet orientation can be changed to allow high field operation for electron suppression without sacrificing ion collection efficiency. The end of the neutralizer can be shaped to control fractional energy ion trajectories, thus reducing the problem of secondary electron emission that contributes to efficiency losses and high voltage breakdowns. A conceptual design of an energy recovery system for state-of-the-art deuterium beams is proposed that may provide overall power recovery efficiencies exceeding 65%; the design employs existing equipment wherever possible. Such an experiment would also test the extrapolation of the numerical model to higher current densities than have heretofore been achieved.

The finite difference code is not well suited for studying electron transport across the magnetic field. Experiments have indicated that this leakage current can be made quite small for high magnetic fields. However, analysis of the sheath stability at high beam currents and neutralizer plasma densities would be very desirable.

Volume ionization of the background gas in the recovery region would be the principal loss mechanism in a well-designed energy recovery system. Some reduction of the background gas density is possible by carefully matching conductances to provide proper source pressures and equilibrium neutralization while reducing the gas flow and by differential pumping of the recovery region. This problem is not dissimilar to the beam "choking" in the drift tube which plagued early injection experiments; this was solved primarily by increased pumping and by avoiding outgassing due to wall heating. Reduction of the recovery volume by reducing the sheath width is also possible; close positioning of the ground plane to the neutralizer will not only accomplish this but will aid in ion collection efficiency as well.

The minimum gap across which the deceleration voltage can be held will have to be determined experimentally.

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## APPENDIX

## POISSON ALGORITHM FOR THE DOUBLE PLASMA MODEL

The algorithm for solving the coupled Vlasov-Poisson equation for the double plasma model is similar to that followed for the basic ORNL ion optics code described in Section 3.A. The principal modification to the flowchart in Fig. 3.2 (page 42) is in the Poisson (Gauss-Seidel) loop, by which the potential solution  $u^{(k)}(x, y)$  is obtained for a given ion distribution  $\rho_i^{(k)}(x, y)$ . The modified Poisson algorithm is shown in Fig. A.1; it is nested within the major Vlasov loop.

The Poisson loop of Fig. A.1 is entered with a given charge distribution  $\rho^{(k)}(x, y)$  resulting from the most recent ( $k$ th) solution to the ion trajectories of Eq. (3.2); this charge distribution remains constant throughout the Poisson loop. The initial potential distribution  $u^{(k,0)}(x, y)$  is that generated by the previous space-charge distribution  $\rho^{(k-1)}(x, y)$ . All of physical space is considered during this iteration by sequentially sweeping through the Poisson grid. Each mesh point is examined to determine whether or not it lies within the neutralizer. If it is exterior to the neutralizer, Eq. (3.23) is solved; the "linear" potential is computed from the potential of its four nearest neighbors and the ion space charge at that point according to Eq. (3.22):

$$u_0^{(k,n)} = k_1 u_1^{(k,n-1)} + k_2 u_2^{(k,n-1)} + k_3 u_3^{(k,n)} + k_4 u_4^{(k,n)} + k_5 \rho_i^{(k)} , \quad (3.22)$$

$$\nabla^2 u = \rho_i . \quad (3.23)$$

If the spatial position lies within the neutralizer, Eq. (3.60) is solved:

$$\nabla^2 u = \rho_e . \quad (3.60)$$

Equation (3.22) is still used to compute the "linear" potential with the sign of  $k_5$  reversed to reflect the consideration of an electron charge rather than an ion charge. This "linear" potential is then modified by a Boltzmann distribution of

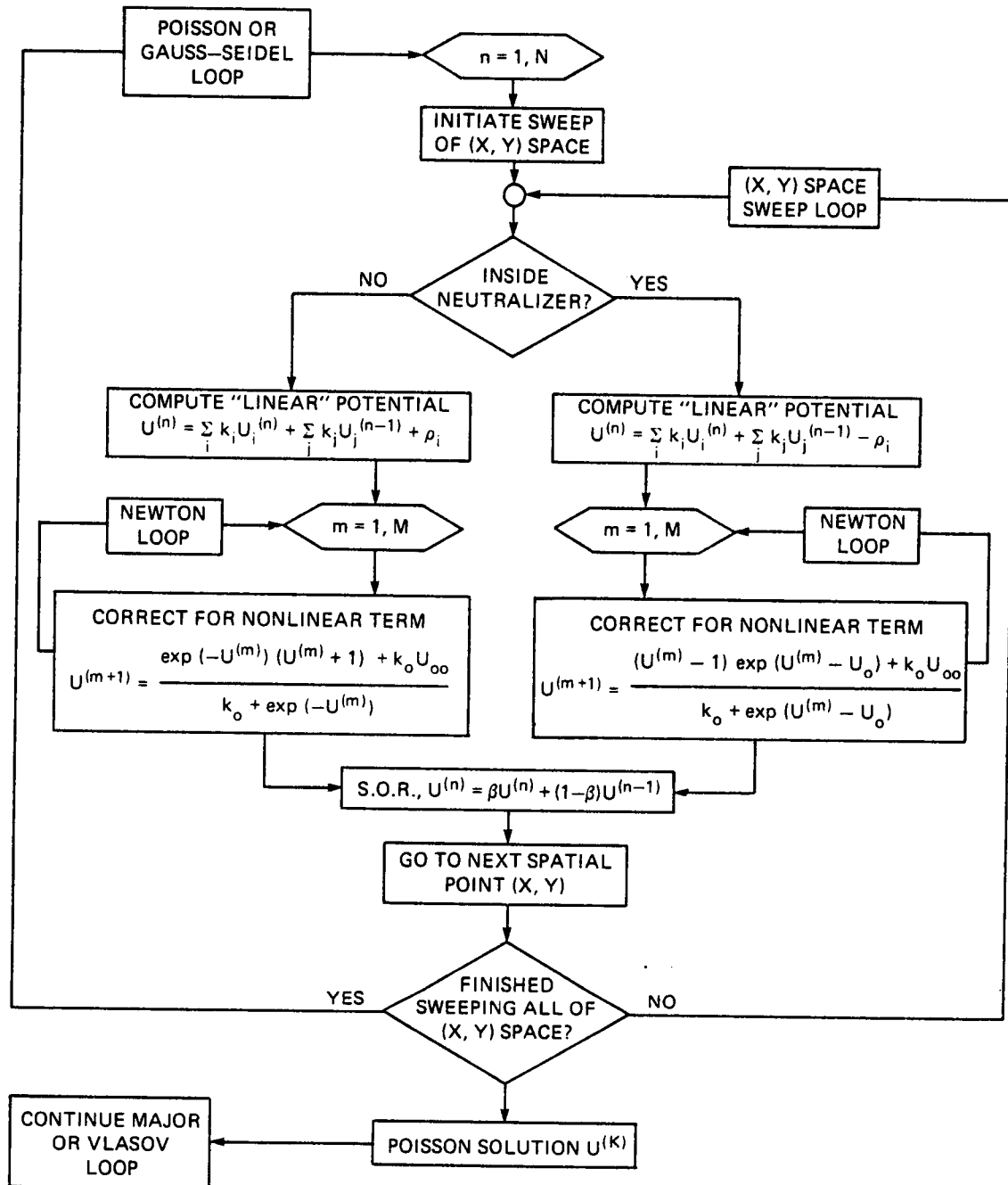


Fig. A.1. Poisson loop flowchart for the double plasma model.

ions if the point under consideration is within the neutralizer and by a Boltzmann distribution of electrons if the point is exterior to the neutralizer. This correction for the nonlinear Boltzmann term is accomplished by an iterative application of the Newton method, using Eq. (3.31) for points outside the neutralizer and Eq. (3.61) for points inside the neutralizer:

$$u^{(k,n,m+1)} = \frac{[u^{(k,n,m)} + 1] \exp [-u^{(k,n,m)}] + k_0 u^{(k,n,0)}}{k_0 + \exp [-u^{(k,n,m)}]}, \quad (3.31)$$

$$u^{(k,n,m+1)} = \frac{[u^{(k,n,m)} - 1] \exp [u^{(k,n,m)} - u_0] + k_0 u^{(k,n,0)}}{k_0 + \exp [u^{(k,n,m)} - u_0]}. \quad (3.61)$$

This modification of the potential by the Newton method can be bypassed for points within the sheath—that is, for spatial points at which the potential is far removed from either the neutralizer potential or the ground potential. This increases the efficiency of the code, since this computationally costly procedure has no effect on potentials that are distant from either plasma potential.

After completing the Newton loop, successive over-relaxation is applied to the potential  $u^{(k,n)}(x, y)$  through Eq. (3.32) to further speed convergence:

$$u^{(k,n)} = \beta u^{(k,n)} + (1 - \beta) u^{(k,n-1)} \quad (3.32)$$

The next point in the Poisson grid is then examined, and its potential is evaluated by the same procedure. The  $n$ th iteration is complete when the potential at each point in space has been evaluated. The  $(n + 1)$ th iteration is then initiated and the Poisson grid is again stepped through. The Poisson equation is considered solved for the given space-charge distribution after  $N$  iterations ( $N$  is typically on the order of 100). The major Vlasov loop is then continued, computing the ion trajectories through this new potential distribution  $u^{(k)}$  in order to calculate a new space-charge distribution  $\rho_i^{(k+1)}$ .

## VITA

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