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# SHORT-PULSE ELECTRON-BEAM PROPAGATION EXPERIMENTS IN A CONTROLLED-ENVIRONMENT CHAMBER

M.A. Greenspan

McDonnell Douglas Research Laboratories
St. Louis, Missouri 63166

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Propagation of a 500-keV, 6-kA, 3-ns electron beam in air has been studied in a 3.4 m diam controlled-environment chamber at pressures of 75-1600 Pa (0.56-12 Torr).

Open-shutter photography, Faraday cup, and magnetic-field probe measurements were performed, and results were compared with those obtained for beam propagation in a 7.6 cm diam glass tube. Over a propagation window of

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270-800 Pa, rectilinear propagation to within $\lesssim$ 5 mrad was observed despite the lack of guide tube walls. Propagation at the low end of the window was limited by rapid nose-erosion rates of up to 10 cm/ns. At optimal propagation pressures (400-550 Pa), magnetic probe data were used to estimate induced electric fields and nose erosion caused by ohmic energy loss. Results were consistent with Faraday cup and calorimeter data. At higher pressures, propagation was erratic, and appeared to be terminated by the lack of a stable pinch formation. For those shots where propagation was observed at pressures above 550 Pa, Faraday cup traces show a loss of the beam tail.
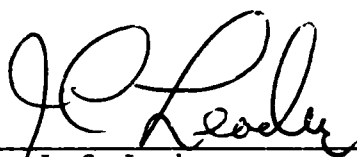
## PREFACE

This final report is an account of the work completed at the McDonnell Douglas Research Laboratories on Naval Surface Weapons Center Contract No. N60921-81-C-0152, sponsored by Defense Advanced Research Projects Agency ARPA Order No. 3718/35.

The work was conducted in the Radiation Sciences Department, managed by Dr. J. C. Leader. The principal investigator was Dr. M. A. Greenspan. The program monitor was Dr. C. M. Huddleston, Naval Surface Weapons Center.
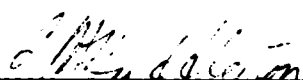
This report has been reviewed and approved.

Dr. J. C. Leader
Chief Scientist-Radiation Sciences
McDonnell Douglas Reserach Laboratories

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SUMMARY

The primary objectives of the research program entitled "Short-Pulse
Electron-Beam Propagation Study" performed by the McDonnell Douglas Research
Laboratories (MDRL) were to (a) study the propagation of a short-pulse relati-
vistic electron beam in an open but controlled environment and (b) compare
observed propagation results under open-chamber conditions with propagation
results measured in a drift tube.

This research was accomplished using a Febetron 706 electron-beam genera-
tor yielding an electron beam having a peak energy of 500 keV with a beam cur-
rent of 6 kA and a pulse width of 3 ns (FWHM). The primary diagnostics
employed for the propagation measurements were (a) open-shutter photography,
(b) Faraday cup measurements of beam current, (c) calorimetry measurements of
beam energy transport, and (d) magnetic-field probe measurements of net cur-
rent transport. Measurements were made in air over a pressure range of 75-
1600 Pa (0.5-12 Torr) at various axial and radial positions. Over a propa-
gation window of 270-800 Pa, rectilinear propagation to within 5 mrad was
observed despite the lack of guide tube walls. Measured open-chamber beam
current and total charge transport were greater than in a 7.6 diam drift tube
at optimum pressure (400-550 Pa), but less than in the drift tube at lower and
higher pressures. Propagation at the low-pressure end of the window was lim-
ited by rapid nose-erosion rates of up to 10 cm/ns, as was also observed in
the drift tube. At high pressures, propagation was limited by a lack of a
stable pinch equilibrium, with losses predominantly at the beam tail. At the
optimal propagation pressure (540 Pa), analysis of magnetic-field probe data
showed that nose erosion resulting from ohmic-energy loss provided the main
energy-loss mechanism of the beam.

The correlation observed between measured beam-energy loss and that
calculated from magnetic-field probe data indicates the importance of either
direct measurements of induced electric fields (e.g., via Stark broadening
measurements) or of magnetic-field profile measurements to establish an
experimental link between postulated beam-loss mechanisms and observed propa-
gation phenomena. Without this link, existing theoretical models could not be
compared with the data measured in this study because assumptions relating to
plasma conductivity and radial self-similarity were not well-fulfilled in the

experiments. Because significant net current density was observed out to a radius of 10 cm, it is clear that a drift tube of at least 20 cm in diameter would be required to establish experimental conditions where wall effects were negligible. Observed alterations of beam propagation at low pressures (270 Pa) resulting from the use of miniature magnetic-field probes indicate the desirability of nonintrusive field measurements, particularly at low pressures.

At the highest pressures used in this study (1600 Pa), observed conductivity levels indicated that avalanche ionization played a central role, whereas gas scattering was probably negligible. At pressures of $\sim$ 20 000 Pa, this situation could be reversed, providing experimental insight into this important parameter regime. Measured data suggest that beam rise-time is a crucial parameter in the conductivity generation. Also, it appears that the radial conductivity profile plays a central role in producing a stable pinch equilibrium. Therefore, further research is suggested on (1) high-pressure ($\gtrsim$ 10 000 Pa) propagation, (2) the influence of guide tube walls, particularly on the net current profiles (3) beam conditioning (e.g., in a low-presssure tube) to vary the beam rise time, and (4) radially resolved measurements of beam and net current profiles. The suggested research could be performed for beams of modest energy where beam propagation distances are not great and could still provide useful fundamental data needed to resolve beam propagation issues of interest to the DARPA Chair Heritage program.

# 1.0 INTRODUCTION

The present experimental investigation was undertaken to provide information about electron-beam propagation under conditions which heretofore have not received experimental study. In particular, the pulse length for these experiments of 3 ns was approximately ten times shorter than generally used in other experiments.[1-7] Also, these experiments were performed in a 3.4 m diameter controlled-environment chamber, rather than in a drift tube, so that the nearest wall was sufficiently distant (~ 1 m) to preclude any possible effects on the beam propagation.

Specific objectives of this study included 1) measurements of beam-current temporal evolution and total energy transport for selected propagation distances, 2) measurements of the circumferential magnetic field as a function of time and radial distance, 3) open-shutter photography of beam propagation, 4) analyses of nose erosion rates, and 5) data analyses to determine operative mechanisms.

In the following report the experimental equipment and calibration procedures are discussed at the outset. Experimental results of beam and net current measurements and examples of features observed in the open-shutter photographs are then presented. Finally, model comparisons are discussed.

## 2.0 EQUIPMENT

### 2.1 Beam Generator

The beam generator used for the MDRL experiments was the commercial Febetron 706.[8] In this device, a Freon-insulated Marx generator charges an oil-insulated Blumlein-like structure in about 20 ns. A six-channel switch shorts the center conductor to the intermediate electrode of the Blumlein, producing the 3-ns output pulse. The output current, measured by a Faraday cup, described later, is shown in Figure. 1a. The Febetron 706 does not have a diode voltage monitor. The diode voltage shown in Figure 1b was calculated by assuming a Child-Langmuir law dependence, i.e., $I_d = KV_d^{3/2}$, where $I_d$ and $V_d$ are diode current and voltage respectively and K is a constant depending on the diode geometry. K was found by setting $\int V_d I_d dt$ equal to the calorimetric measurement of total beam energy.

The time-integrated radial profile of beam current, Figure 1c, was found by using radiachromic film.[3] This film consists of a transparent nylon sheet 50 $\mu$m thick, doped with a dye which becomes colored upon exposure to ionizing radiation. The film was enclosed in a 25 $\mu$m thick aluminum shield to prevent exposure by ultraviolet light or low-energy electrons. Quantitative measurement of the optical density produced by the beam was obtained using a Joyce-Loebel microdensitometer. Interference filters with a 10-nm bandwidth centered at 508.5 nm were used in front of the light source so that the densitometry was effectively at a single wavelength. Calibration curves of absorbed radiation dose as a function of optical density change were given by the film manufacturer.[9]

### 2.2 Controlled-Environment Chamber

For the present experiments, the Febetron 706 was coupled to the primary lock of a large (9.1 m diam) environmentally controlled chamber. This primary lock is 3.4 m in diameter and 6.1 m long. Because of the placement of the available entrance port, the beam was about 1 m from the nearest wall. Figure 2 shows top and end views of the location of the Febetron 706 and of the observation ports from which photographs were taken. The chamber was typically evacuated to 20 Pa (0.16 Torr) and then backfilled with synthetic air to operating pressure.

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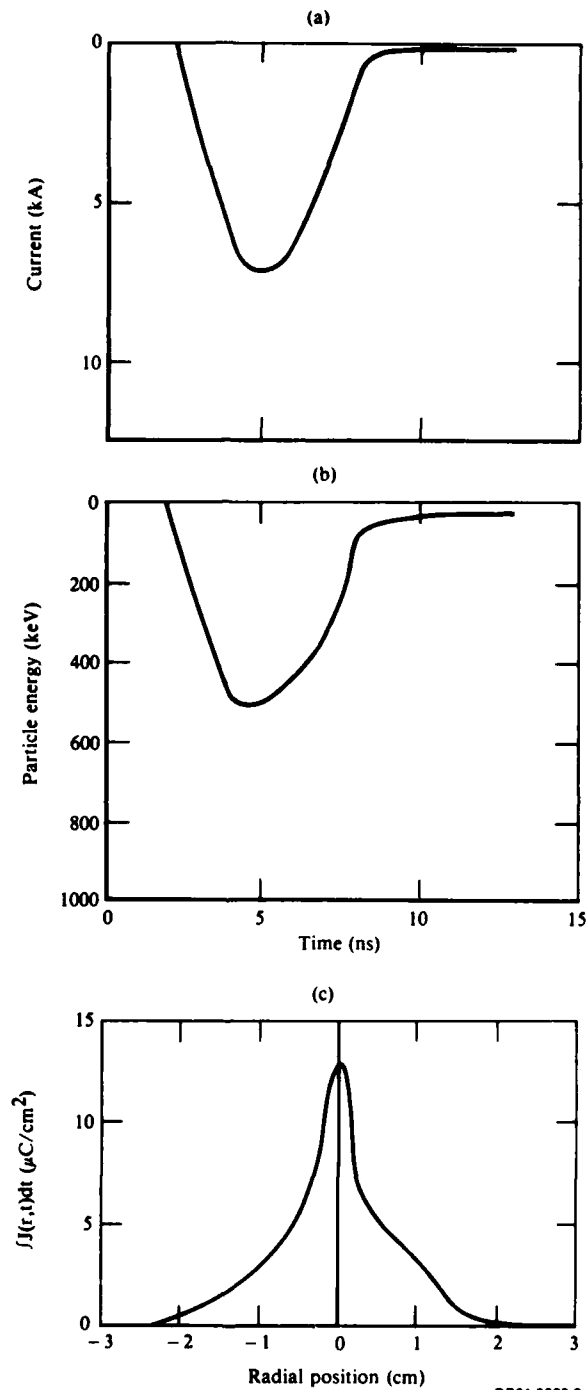
Figure 1. (a) Febetron electron-beam current,
measured with Faraday cup/calorimeter against anode
foil, (b) Febetron electron-beam energy, calculated
from (a) assuming Child-Langmuir-law voltage-current
relationship, with $\int V I dt$ normalized to agree with
calorimeter measurement, and (c) time-integrated
radial profile of electron-beam current density based
on radiachromic film data.

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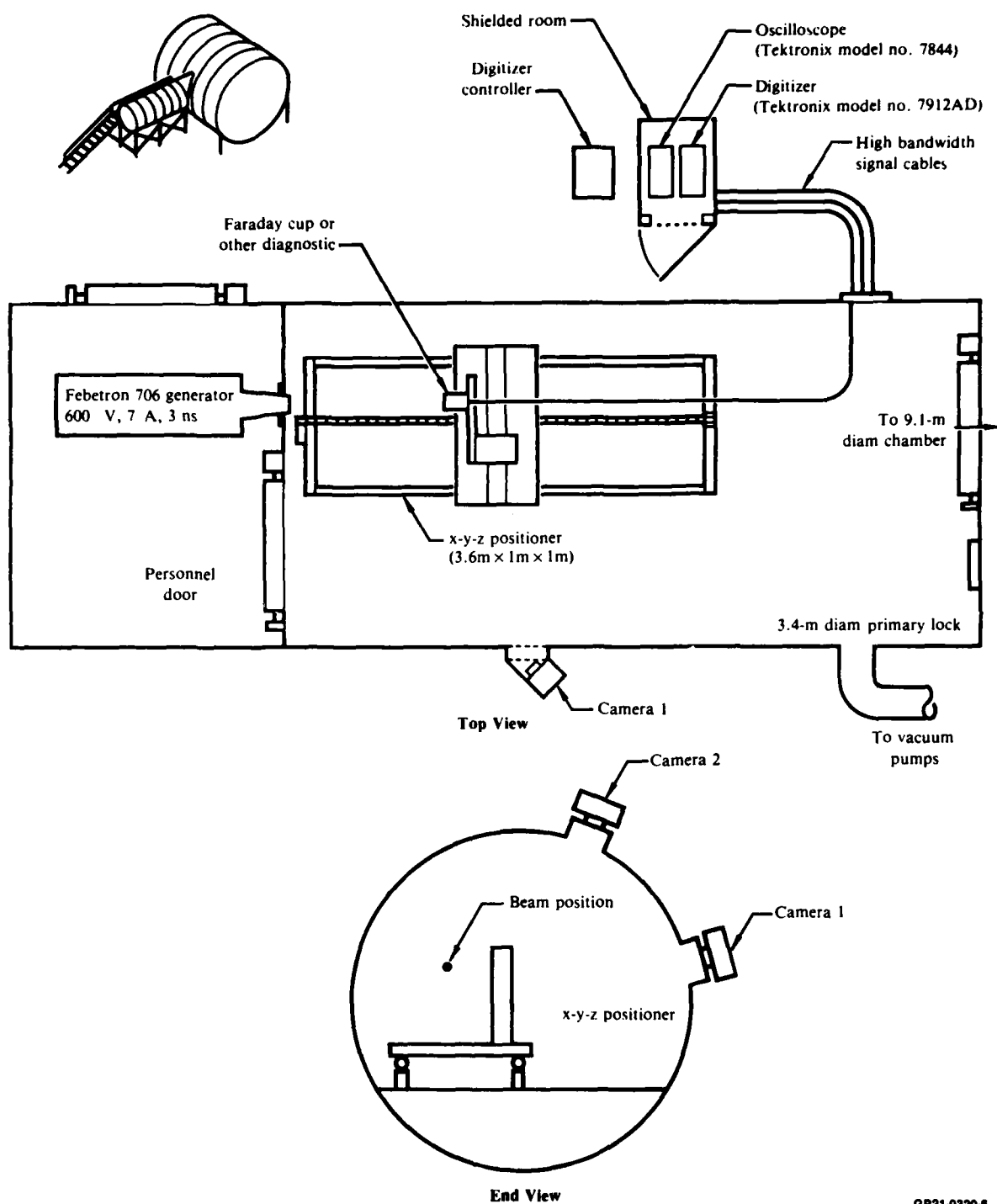
**Figure 2. Experimental arrangement for short-pulse electron-beam experiments in a 3.4-m diameter controlled-environment chamber.**

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## 2.3 Diagnostic Positioners

The xyz positioner (developed under an MDRL IRAD program), shown in Figure 2, permitted the remote positioning of diagnostics anywhere over a 3.6 m x 1 m x 1 m volume. A chain drive moved the carriage in the 3.6 m (z) direction, achieving a positioning accuracy of about 0.3 cm. Screw-drive mechanisms were used in the x and y directions, with an accuracy of 0.01 cm. Position was measured by rotation sensors coupled to the drive motors through magnetic clutches, needed to eliminate spurious signals from the rotation sensors caused by motor vibrations.

For magnetic-field-probe experiments, a special positioner was mounted on the xyz positioner which enabled the movement of two probes symmetrically in and out from the beam center in the radial direction. A single motor was geared to turn two screw-drives in opposite directions. A resistive slide wire provided positioning readout accurate to 0.1 cm. The probes were mounted on the screw-drives through long arms which were 35 cm away from the beam. Photographs showed that the probes could be held centered around the beam to within about 0.2 cm. A photograph of this positioner is shown in Figure 3.
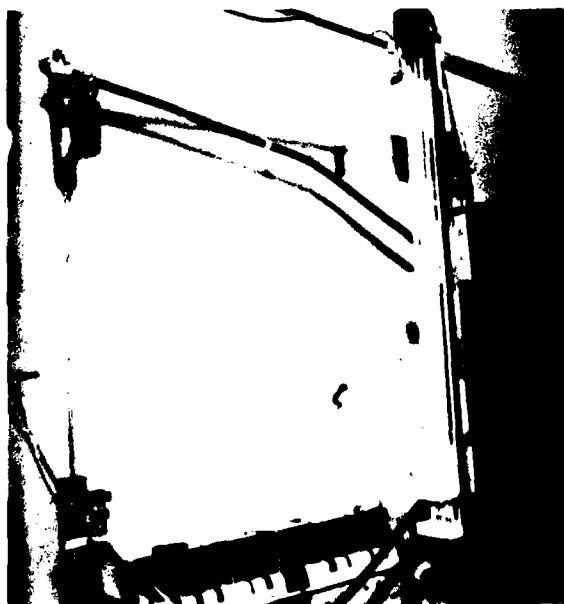


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Figure 3. Remotely controlled $B_\theta$ probe positioner installed in MDC controlled-environment chamber.

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## 3.0 DIAGNOSTICS

A diagram of the Faraday cup/calorimeter is shown in Figure 4. A 12.7 μm Ti entrance foil absorbed plasma electrons (under 50 keV)[10] and permitted a vacuum of $\lesssim$ 7 Pa (0.05 Torr) to be maintained in the cup, at which pressure electron multiplication by the beam should be negligible. Solid-outer-conductor coaxial cable with a diameter of 1.3 cm and foam dielectric insulation was used to bring signals to the oscilloscope, preserving the rise-time of the signals and shielding unwanted noise. Calibration and rise-time of the Faraday cup were checked by discharging a coaxial line charged to a known voltage through a 50 Ω resistor into the collector of the cup. Calibration accuracy of ± 3% or better is estimated. Figure 5 shows the calibration arrangement and a typical calibration trace. The combined rise time of the system is ~ 1.3 ns.
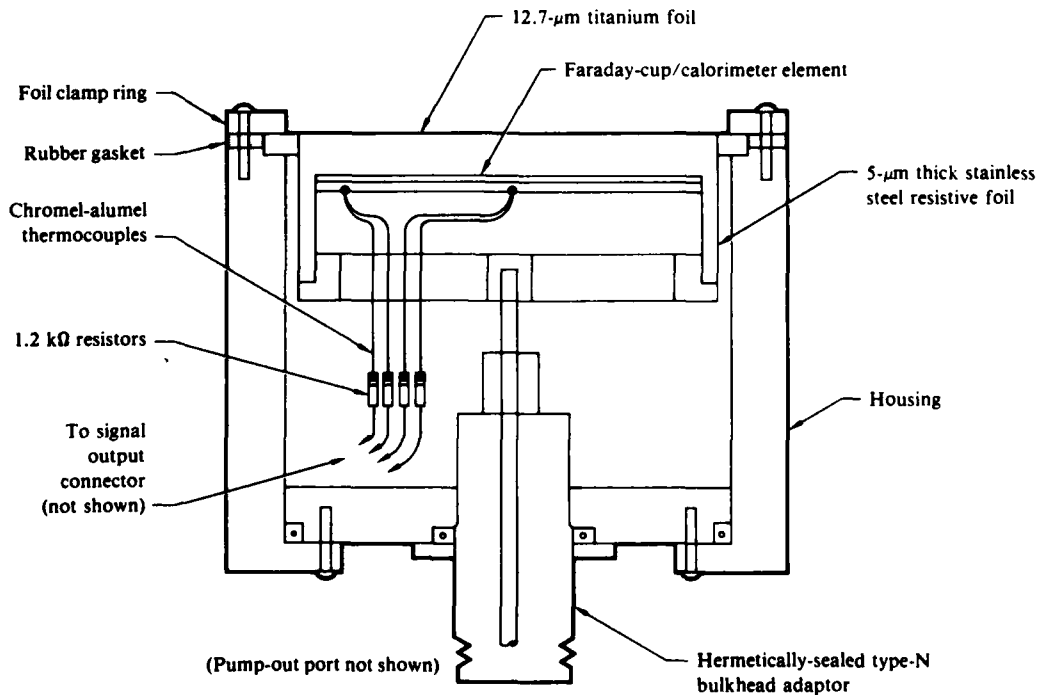


Figure 4. Faraday-cup/calorimeter used in short-pulse relativistic electron-beam experiments.

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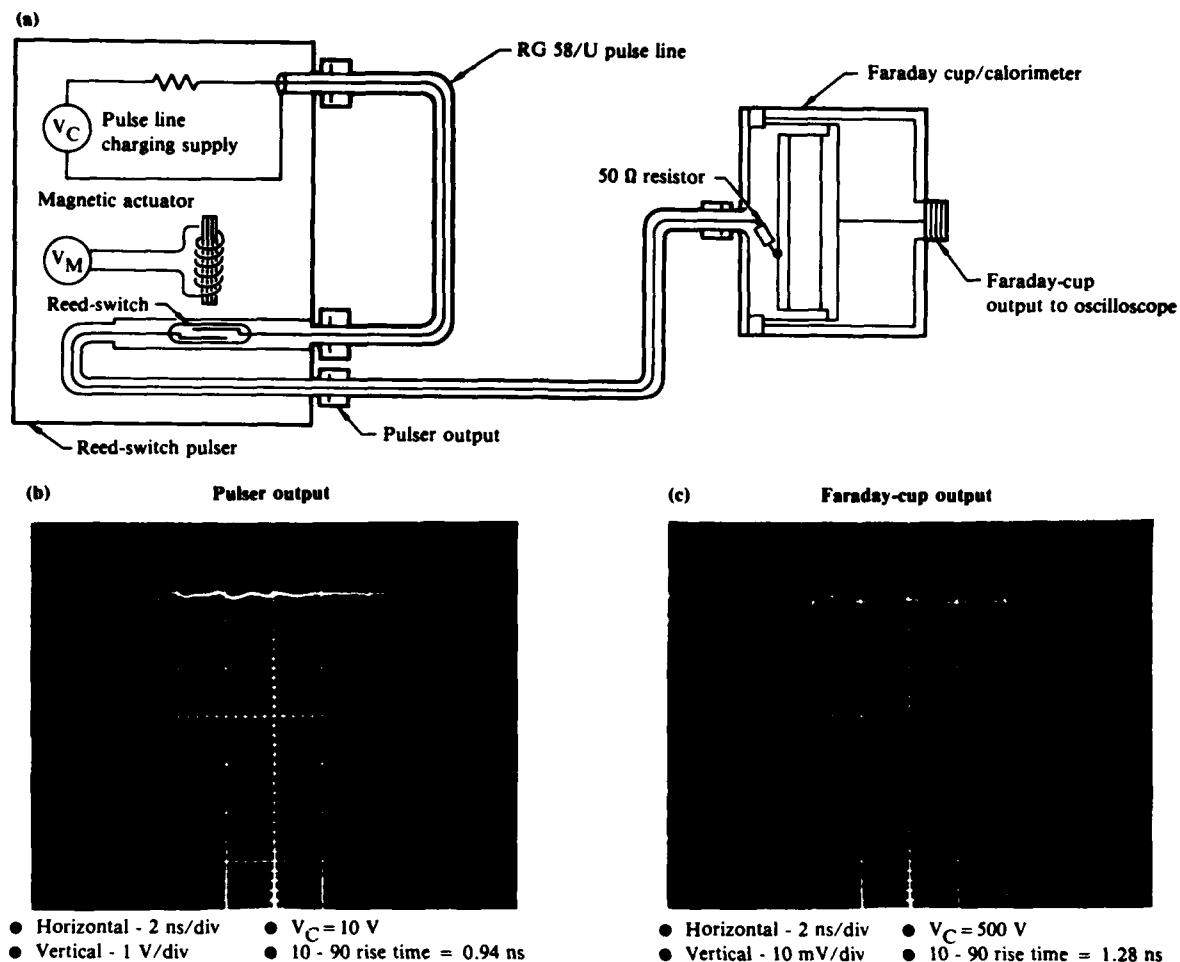
Figure 5. (a) Reed-switch pulser arrangement for calibration of Faraday cup, (b) pulser output, and (c) Faraday-cup output.

A diagram of the magnetic field probes, their calibration set-up, and a typical calibration output is shown in Figure 6. The balanced magnetic loop was constructed by removing 1.75 cm from the outer jacket of rigid 0.22 cm diameter coax at the midpoint of a 50 cm length, and then folding it in half about this point. Thus the center conductor and insulating dielectric are continuous, preventing breakdown from the large $dB/dt$-induced loop voltages ($\gtrsim$ 300 V under certain conditions). The probe is shielded by a wire cage consisting of ~ 80 enameled #36 wires (0.014 cm diameter), soldered at one end to the outer conductor of the rigid coax, but insulated from each other at the other end. This cage presents a nearly solid conducting shield to an electric field, but it presents little perturbation to a magnetic field line. The sig-

(a)

Wire cage
electrostatic shield

Magnetic loop

Rigid coax

Attenuators

Copper
shield

÷ 10

÷ 10

7-mm
glass envelope

Balanced-to-unbalanced transformer

Probe output

(b)

50 Ω coaxial structure

Resistive-foil current monitor

Current monitor
output signal

Step voltage
input from
reed-switch
pulser

(c)

Output (50 mV/div)

Time (1 ns/div)

Measured response
to step-function
magnetic field

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Figure 6. Diagram of a magnetic-field probe used in electron-beam experiments, (b) calibration arrangement
for applying an accurately-known step magnetic field to the probe, and (c) typical probe output recorded
with a sampling scope having a bandwidth >1 GHz.

nals from the two ends of the rigid coax were passed through 1/10 attenuators
with 1 GHz bandwidth (Tektronix 011-0059-02), a balanced-to-unbalanced trans-
former (Minicircuits Corp. ZFSCJ-2-1, with modified connector placement) and
brought to the oscilloscopes by 1.3 cm diam Heliax cable. Calibration accu-
rate to ~ 3% was achieved by numerical integration of the step response of the
probes and comparison of the result with the current monitor signal.

## 3.1 Signal Acquisition

A dual-beam oscilloscope (Tektronix 7844) with a P-11 phosphor and film fogger to give rapid photographic writing speed was used for Faraday cup and magnetic probe signal acquisition. In addition, a transient digitizer (Tektronix 7912AD), controlled by a microcomputer (Digital Equipment Corp. MINC-11) was used for magnetic probe signal acquisition. The scope-digitizer combination permitted a second probe signal to be recorded on the oscilloscope along with the Febetron monitor signal to obtain timing information.

## 3.2 Experimental Results

The first experimental question addressed was the degree of rectilinear beam propagation in the controlled-environment chamber. Previous experiments in a 7.6 cm diameter glass guide tube showed that the Febetron beam would follow a $10^o$ bend in the tube with little loss (Figure 7). This result indicated that rectilinear propagation in a straight tube might be due to the tube walls. Open chamber experiments, however, did not show a requirement for guiding wall effects for rectilinear propagation. Variation in the transverse beam position at a propagation distance of 180 cm in the chamber was reliably $\lesssim 1$ cm. At 120 cm distance, it was usually $< 2$ mm, the estimate being limited by the resolution of the photographs. The beam position was apparently unaffected by the position of the Faraday cup or the magnetic probes. Figure 8 shows an example of this immunity from the proximity of conducting bodies. Note that the beam position did not move measurably when the Faraday cup was moved off center.

To center the beam, it was necessary to use two cameras viewing the beam from different angles to measure the beam position with respect to the x and y axes. Figure 9 shows views from each camera of a typical shot with magnetic probes at $z = 120$ cm, after the probes have been carefully centered. For purposes of scaling, note that the diameter of the probe jacket is 7 mm.

Faraday-cup/calorimeter measurements were performed at propagation distances of $z = 5.7$, 10, 15, 30, 60, 120, and 180 cm at pressures of 75-1600 Pa (0.5 Torr - 12 Torr). Behavior is generally similar to that observed in an insulating 7.6 cm diam guide tube, with a low-pressure window for propagation at 270-800 Pa (2-6 Torr), and poor propagation at lower and higher pressures.

P = 400 Pa (3 Torr)
22.5° bend, f/5.6 aperture

P = 400 Pa (3 Torr)
10° bend, f/11 aperture

P = 1070 Pa (8 Torr)
10° bend, f/5.6 aperture

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Figure 7. Typical open-shutter photographs of propagation
in bent guide tubes.

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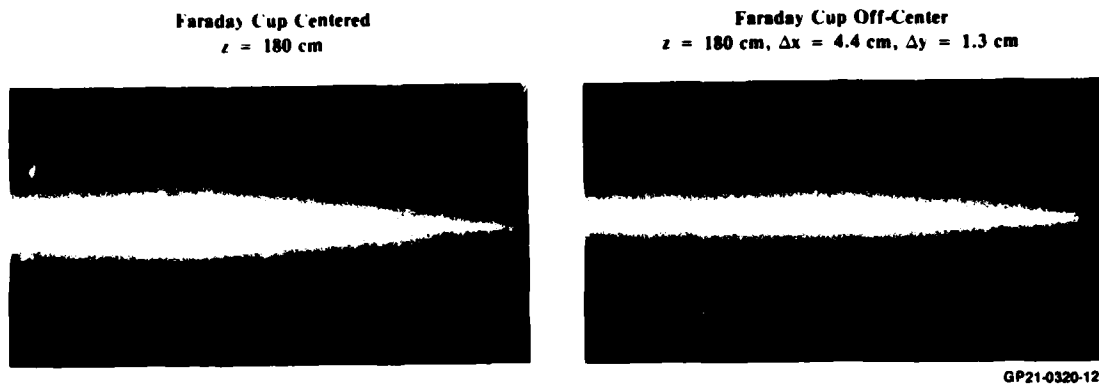
Figure 8. Open-shutter photographs of a Febetron 706 electron beam propagating in a controlled-environment chamber at 530 Pa (4 Torr) showing that the beam position is not affected by movement of the Faraday cup.

Camera 1

Camera 2

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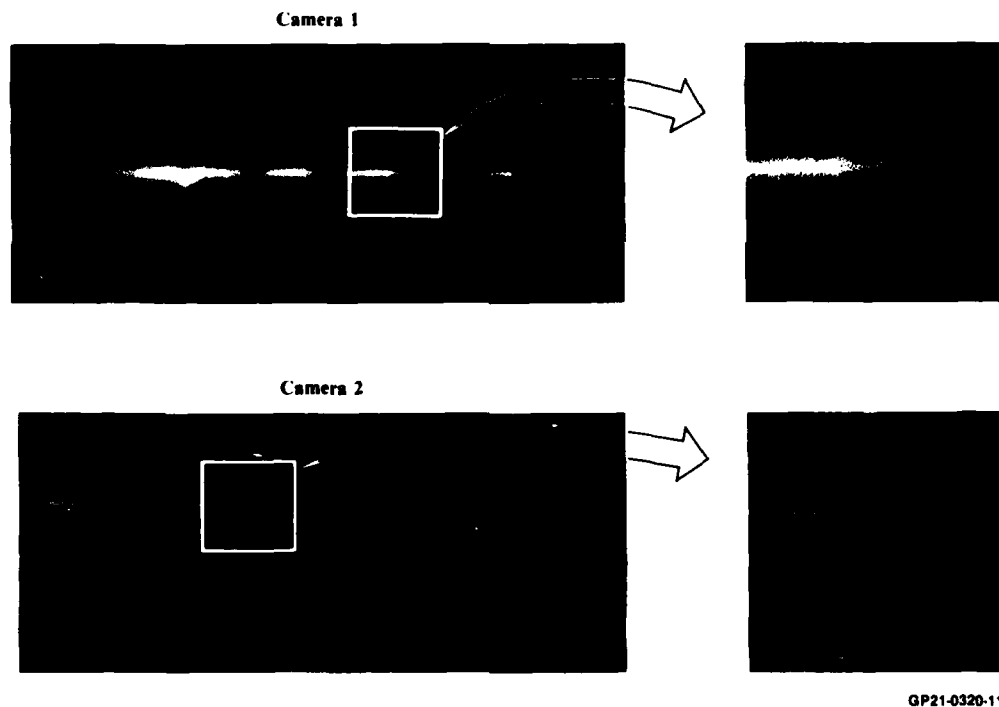
Figure 9. $\dot{B}_\theta$ probes at z = 120 cm, pressure = 530 Pa (4 Torr).

Figures 10 and 11 show data giving total energy and total beam charge transfer as a function of pressure with propagation distance z as a parameter. In Figure 11, drift tube data are shown for comparison. The primary difference is that the window is narrower, but with better propagation at the optimal pressure of 3-4 Torr.
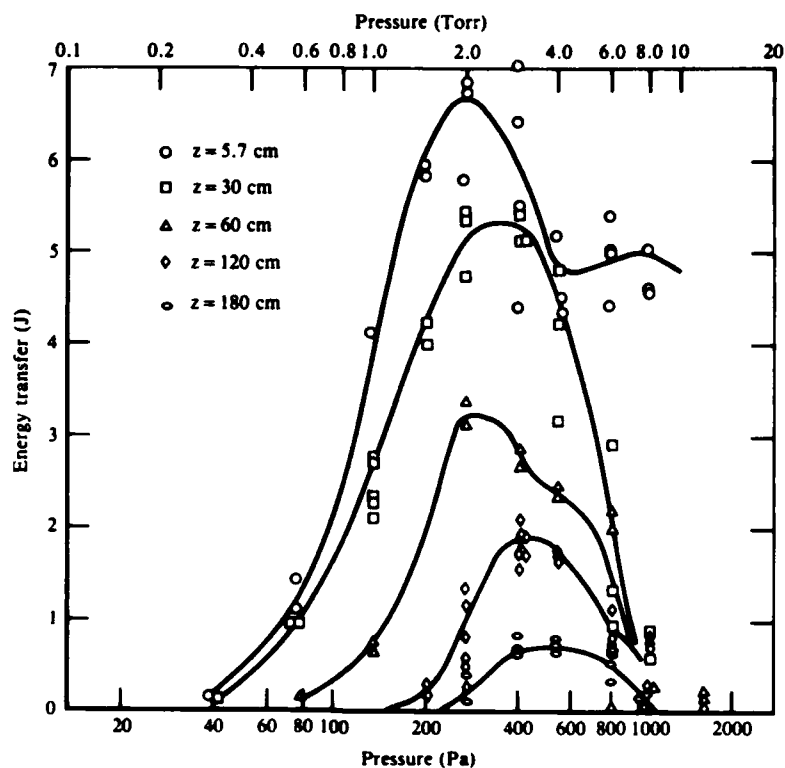
**Figure 10. Energy transfer measured by calorimeter in a controlled-environment chamber.**
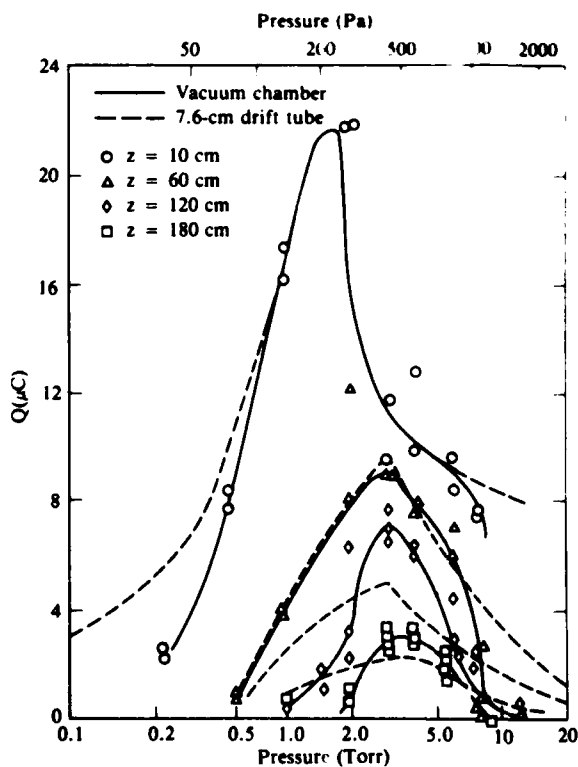


Figure 11. Total charge collected by Faraday cup as a function of pressure in a controlled-environment chamber (solid curves) with drift-tube data (dashed curves) shown for comparison. All symbols apply to chamber data; drift-tube data points are not shown.

The beam front velocity was determined by using a dual-beam oscilloscope with Faraday cup signals on one beam and the Febetron Blumlein monitor on the other beam. The sharp break in the monitor signal when the Blumlein switch fired provided a timing reference point accurate to $\sim \pm$ 0.25 ns. Figure 12 shows a series of Faraday cup traces showing the progress of the pulse in time at pressures of 270-1070 Pa. Table 1 gives front velocity data and computed nose-erosion velocity, based on $\langle v_z \rangle$ of the electrons of $\beta c$ $(1 + I_{net}/I_{Alfven})^{-1/2}$, calculated for a pinched-beam equilibrium.[11] For the average injection energy of 400 keV and $I_{net} \simeq$ 2 kA, this gives $\langle v_z \rangle$ = 24 cm/ns, with about $\pm$ 1 cm/ns accuracy estimated. Beam-front velocity values measured in an insulating drift tube are also given in Table 1. Within experimental error, the beam-front velocity results are the same in the drift tube as in the large chamber.
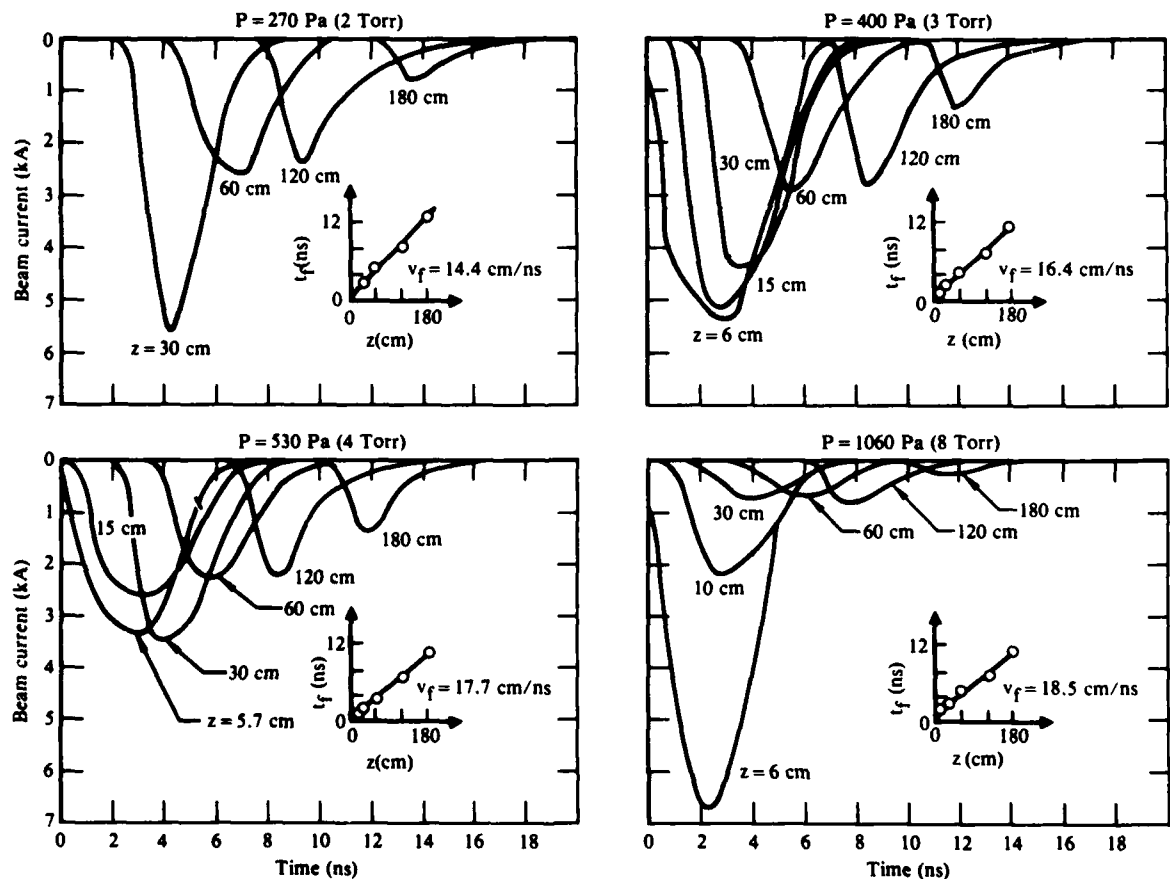


Figure 12. Time-correlated Faraday-cup traces showing beam-front velocity. The front arrival was taken at the time the beam current reached 500 A. A plot of the front arrival time, $t_f$, as a function of z is shown in the insets. $v_f$ is the beam-front velocity determined from the plots.

**TABLE 1. BEAM FRONT-VELOCITY DATA.**

| Pressure [Pa (Torr)] | 7.6-cm diam glass tube (cm/ns) | 7.6-cm diam glass tube w/conducting screen outside (cm/ns) | 3.4-m diam space chamber (cm/ns) |
|---|---|---|---|
| 75 (1.0) | 14.3 | 13.3 | — |
| 130 (2.0) | 15.4 | 13.0 | 14.4 |
| 270 (3.0) | 15.8 | 15.6 | 16.4 |
| 540 (4.0) | 17.6 | 16.7 | 17.7 |
| 1070 (8.0) | 18.2 | 17.3 | 18.5 |

● Nose erosion velocity $\equiv v_{ne} = <v_z> - v_{front}$

$\cong 24 \text{ nm/ns} - v_{front}$

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At high pressures (> 530 Pa), the loss of the beam tail appears to be important, as was the case in an insulating drift tube. This effect is shown by the time-correlated Faraday-cup signals shown in Figure 12. At 400 Pa (3 Torr), the difference in arrival times of the trailing edge of the beam between $z = 6$ cm and $z = 120$ cm is about 4.5 ns, which is consistent with the estimate given above for $<v_z>$ of the electrons. At 1070 Pa (8 Torr), the time difference is about 3 ns, showing that some of the beam tail is lost before reaching $z = 120$ cm. The effect appears to be more pronounced in the space chamber than in the drift tube, and more erratic, which explains the large scatter in data and narrow pressure window seen in Figure 10. Open-shutter photographs also show this scatter as evidenced by Figure 13 which shows two shots at 1070 Pa with injection parameters apparently identical. Note the complete lack of a beam pinch in Figure 13b. Apparently the guide tube wall (or possibly a plasma formed on the walls) exerts a stabilizing influence on the beam tail.

Magnetic-field probes were used to measure the radial magnetic field structure and to gain some understanding of the charge return mechanism. Figure 14 shows net current $I_{net}(r)$ contained within a circle of radius r as a function of r at pressures of 270 and 530 Pa (2 and 4 Torr). Data shown are at 2 ns from beam front arrival. The observed temporal behavior was similar at all positions. At 270 Pa, the B-fields rose to ~ 75% of their maximum level in 2 ns, gradually increased for 2-3 ns more, and then remained reasonably constant for the remainder of the observation time of ~ 20 ns. (Because

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**(a)**

**(b)**
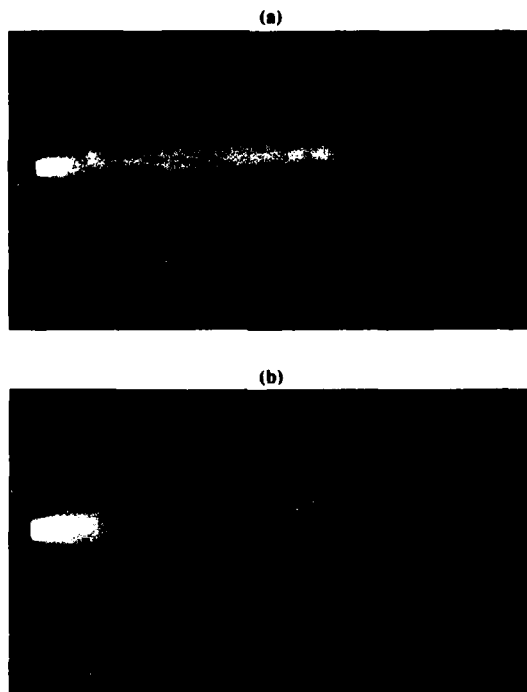
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Figure 13. Open-shutter photographs at 1070 Pa (8 Torr) showing large shot-to-shot variations.
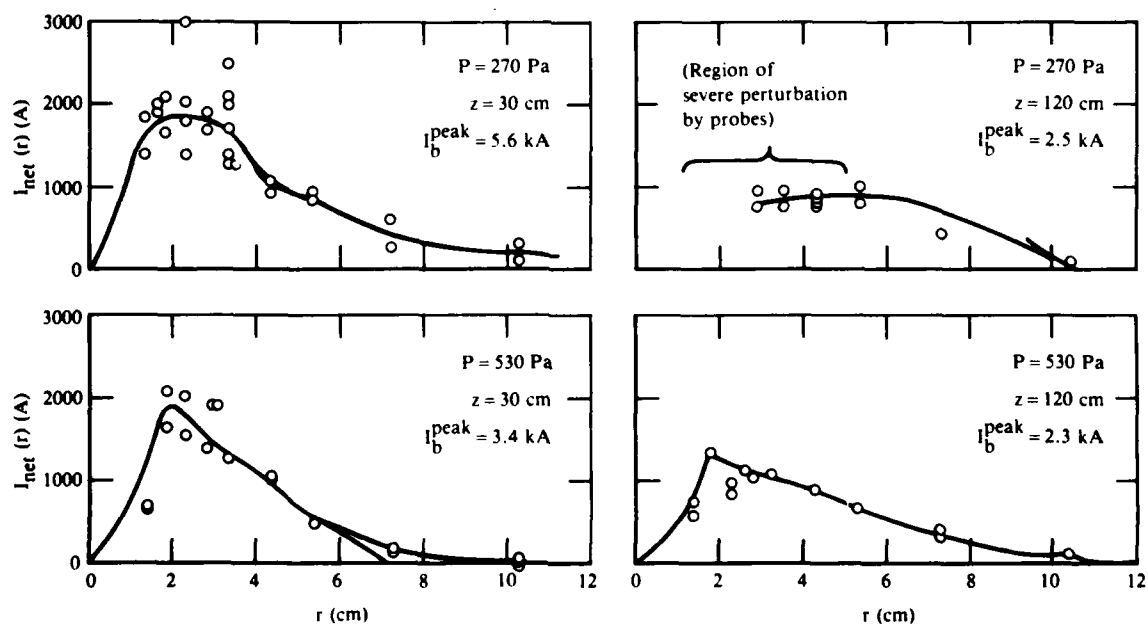


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**Figure 14. Magnetic-probe data (net current) as a function of radial position. Peak beam current, $I_b^{peak}$, averaged over three shots at each position is also shown. Data are at 2 ns after the beam-front arrival.**

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$\overset{\bullet}{B}$ was so small during the decay of the fields after the beam, a quantitative measurement of this decay was not possible because of the inadequate signal-to-noise ratio). At 530 Pa, the net current reached its peak in ~ 1-2 ns; in many cases, the rise-time of the $\overset{\bullet}{B}$ signals was limited by the 500 MHz bandwidth of the signal acquisition system. Both the 270 and 530 Pa magnetic-field data indicate that a significant return current flows out to a radius of ~ 10.3 cm.

The question of probe perturbation of the current flow was addressed experimentally only by observation with open-shutter photographs. It was observed (Figure 15) that at z = 120 cm and a pressure of 270 Pa (2 Torr), the probe perturbation was severe even witn the probes well outside the beam and intercepting a small percentage of the area of the current channel. The mechanism of this perturbation is unclear. It is true that probes can cool an area around them causing a "hole" in the conducting plasma which is larger than the physical size of the probe. However, over such a short time scale, the perturbation by the probe could travel a distance on the order of the electron thermal velocity times the time scale of interest, which is only a few millimeters.
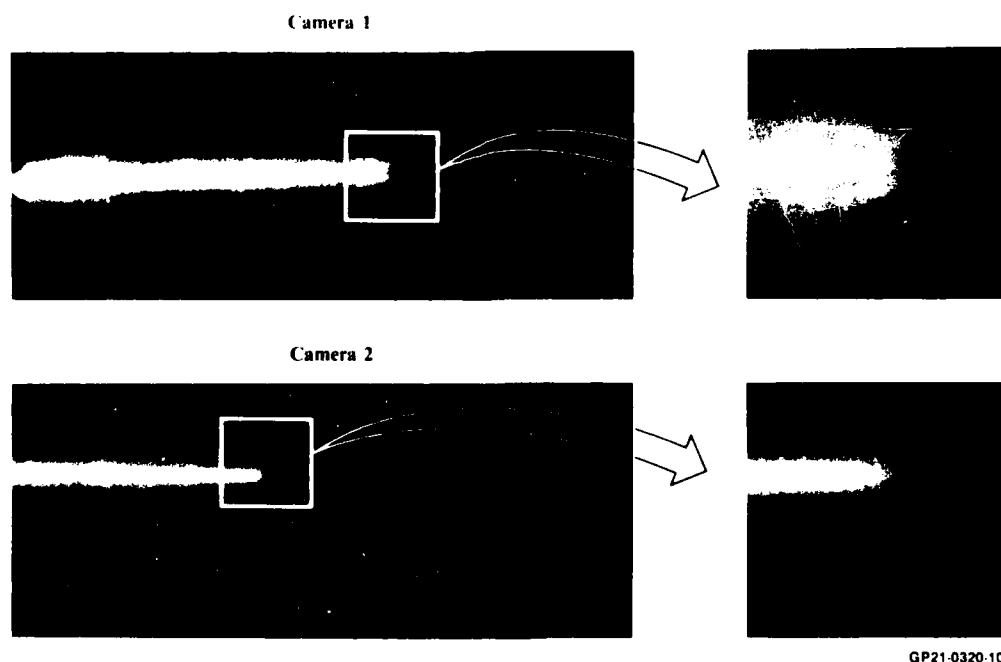
**Camera 1**

**Camera 2**

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Figure 15. Open-shutter photographs of beam propagation at P = 270 Pa showing severe perturbation caused by the magnetic-field probes. The probes are located at a propagation distance of z = 120 cm and at a radius of r = 4.3 cm (the end of the glass probe-envelope is at r = 2.9 cm).

A more likely explanation for the observed disrupting effects of the probes is as follows. In order to form a pinched beam equilibrium and still have adequate charge return for the beam to propagate, the plasma halo surrounding the beam is crucial. The formation of this plasma halo probably occurs primarily from ionization by the expanded beam nose and avalanche multiplication in the strong radial electric fields. If the probes short the electric fields around them, the formation of the halo could be disrupted, causing poor pinch formation.

The fractional current neutralization in the beam channel, as given by one minus measured peak net current divided by peak beam current, is in the range 40-60%. The actual peak net current is probably somewhat greater and thus the neutralization somewhat less, because when the probes are close to the edge of the beam channel, the glass shields intercept about 25% of the beam.

The net current measurements indicate that little net charge is propagated. A qualitative topological diagram of net current flow is shown in Figure 16. Each of the contours in Figure 16 depicts the radii beyond which 1 kA of set current flows out and returns. Plasma conductivity continues long after the beam is over, with the pattern of Figure 16 persisting for tens of nanoseconds. A crude circuit model of this configuration as an inductance L in series with a resistance R suggests a decay time of $L/R = \mu_o \sigma \, r_b^2/2$, where $\sigma$ is the conductivity and $r_b$ the beam radius.

At times of 4-6 ns after the beam arrival, large $\dot{B}$ signals are seen at radii from 4-10 cm, which are not symmetrical about the beam but are moder-
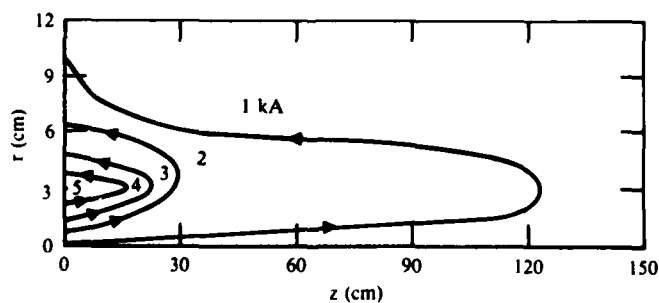


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Figure 16. Topology of net current flow. Each line represents the boundary of a flux tube inside of which ~1 kA of net current flows.

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ately reproducible on a shot-to-shot basis. At radii of 3.3 cm and less, these large assymetrical $\dot{B}$ signals never occur; they occur occasionally at 4.3 cm, and almost always at larger radii, though with variation in amplitude. The observed fluctuations may indicate instability of the beam tail, perhaps caused by the probe.

## 4.0 MODEL COMPARISON

Electron-beam nose models show erosion caused by the beam energy loss in the inductive fields at the beam nose[12,13] and the beam electrons scattering off the neutral gas background.[14,15] In the absence of these effects, Briggs has argued that erosion rates should approach zero asymptotically with propagation distance on a scale length of a few beam radii,[14] at least for highly relativistic beams where $1/\gamma^2 \ll 1$. Because the MDRL experiments have been performed at low pressures where gas scattering effects are probably unimportant, the following analysis concentrates on the inductive energy loss mechanism.

Sharp and Lampe[13] give the simple expression

$$v_{ne}/c = \left(1 + \frac{mc^3}{e} \frac{\gamma - 1}{\lambda_\infty I_b}\right) \qquad (1)$$

for nose erosion velocity $v_{ne}$ caused by the beam energy loss in the inductive electric field. In Equation (1), $\lambda_\infty$ is $\ln\left(r_c^2/r_b^2\right)$, where $r_b$ is the beam radius and $r_c$ is the radius of the conducting channel. This formula agrees well with a more elaborate calculation which assumes $\gamma \gg 1$, self-similar beam expansion in the radial direction, and conductivity generation without avalanche processes.

Because of the foregoing assumptions, a direct comparison of this formula with the MDRL measured data is of little value. However, it is possible to estimate beam energy loss resulting from the induced electric fields using measured magnetic probe data. The procedure is to compute the induced electric field $E_z$ from the probe data, compute the energy loss rate of the beam, and compare these values with the measured energy loss rate.

Using Faraday's law, $\nabla \times E = \partial B/\partial t$ and neglecting $\partial E_r/\partial z$, $E_z$ can be estimated as

$$E_z(r, t) = \int_r^{r_c} \dot{B}_\theta(r', t) \, dr' , \qquad (2)$$

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where $r_c$ is the channel radius, taken as 10.3 cm, outside of which $\dot{B}_\theta$ is very small. Thus the energy deposited by the beam electrons per unit length per unit time is given by

$$\frac{\partial^2 W}{\partial z \partial t} = 2\pi \int_0^{r_b} dr \; r J_b(r, \, t) \int_r^{r_c} \dot{B}_\theta(r', \, t) \; dr' \; . \tag{3}$$

Equation (3) can be evaluated to a reasonable approximation by taking the lower limit of the inner integral as $r_b/2$, so that the inner integral is a constant independent of r.

$J_b(r, \, t)$ can then be integrated over the beam area, giving

$$\frac{\partial^2 W}{\partial z \partial t} \approx I_b(t) \int_{r_b/2}^{r_c} \dot{B}_\theta(r', \, t) \; dr \; . \tag{4}$$

Integration of Equation (4) in time gives beam energy deposition per unit length:

$$\frac{\partial W}{\partial z} \approx \int dt \, I(t) \int_{r_b/2}^{r_c} \dot{B}_\theta(r, \, t) \; dr \; . \tag{5}$$

Typically, the $\dot{B}_\theta$ signals are a spike of $\lesssim 2$ ns duration at the beginning of the beam pulse, confirming that most of this energy is taken from the nose of the beam.

The most straightforward comparison of this model with experimental data is with calorimetric data as plotted in Figure 17 to illustrate energy loss rate. The average energy loss at 530 Pa between 5.7 and 60 cm is 3.3 J/m. Using Faraday cup and magnetic probe data, numerical integration of Equation (5) at a pressure of 530 Pa and $z = 30$ cm gives a value of $\sim 2.5$ J/m. A fairly large uncertainty exists in this figure (perhaps $\sim \pm 30\%$) because of scatter in the data, possible probe perturbation of the current channel, degradation of the signal rise time, and a lack of precise time correlation
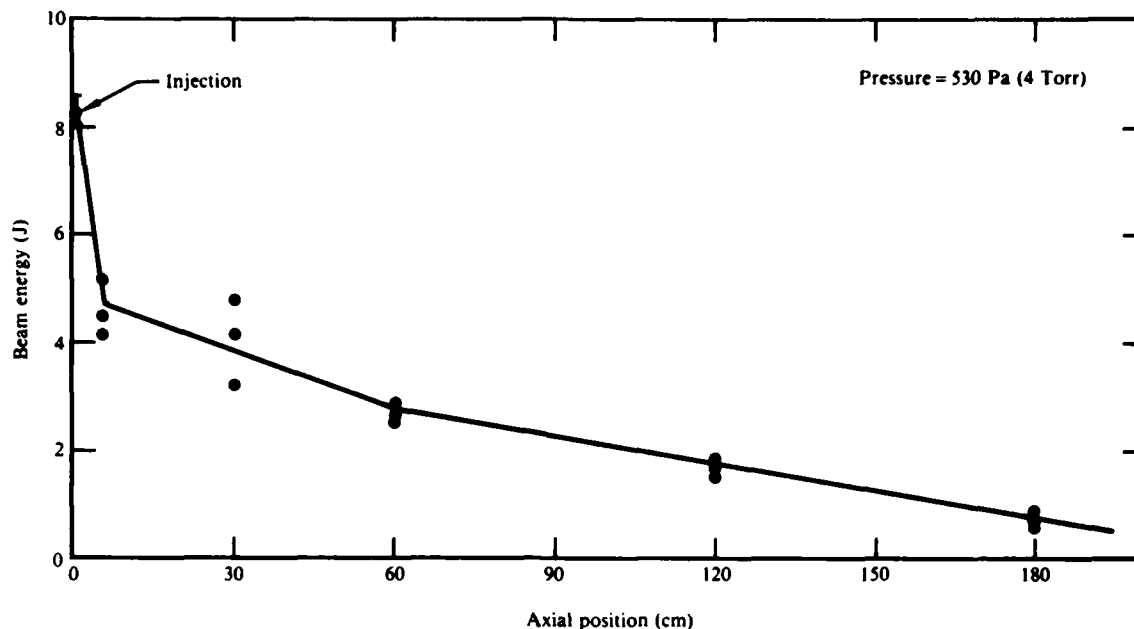
Figure 17. Calorimeter data at a pressure of 530 Pa, plotted as a function of axial
position (z) to show beam energy loss per unit length.

between Faraday cup and magnetic probe signals resulting from an an
unfortunate equipment failure (beam two of the dual-beam oscilloscope
failed). Nevertheless, the result is an indication that the inductive energy
loss mechanism at the beam nose is the primary limit to the beam propagation
at 530 Pa (4 Torr). At the same pressure and z = 120 cm, a value of 1.2 J/m
is obtained from Equation (5). Measured calorimeter data at this pressure
show an average energy loss of 1.8 J/m between 60 and 180 cm, which is in
reasonable accord with the predicted value.

Comparisons of this simple model with data at other pressures were not
made. At 1070 Pa (8 Torr), the shot-to-shot variation precluded any mean-
ingful radial $B_\theta$ profile measurements. At 270 Pa (2 Torr), the photographs
show that the probes perturb the beam propagation severely (Figure 15).
Nevertheless, some qualitative observations can be made. Front velocities
decrease substantially with decreasing pressure between 75 Pa and 530 Pa, in
the same manner as in an insulating drift tube. Magnetic probe data at 270 Pa
(2 Torr) in the drift tube (where the beam was not so severly perturbed)
showed larger $B_\theta$ signals than at 530 Pa (4 Torr) which correlate well with the
faster nose erosion rate observed.

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## 5.0 CONCLUSIONS

Propagation of a 500 keV, 7kA, 3 ns electron beam has been studied in a 3.4 m diameter controlled environment chamber at air pressures from 75-1600 Pa (0.56-12 Torr). A Faraday cup, magnetic-field probes, and open-shutter photography were the principal diagnostics used. Optimal propagation was observed at 3-4 Torr. At lower pressures, rapid nose erosion reduced the propagation efficiency, whereas at higher pressures, the beam suffered a lack of a stable reproducible pinch equilibrium, causing the beam to freely expand. Reasonable agreement was obtained between observed nose erosion of the beam and a model based on erosion caused by the induced axial electric fields at the beam nose. In the model, the induced fields were deduced from $\dot{B}_\theta$ probe measurements, rather than calculated from first principles.

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