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on

INTENSE RELATIVISTIC ELECTRON BEAM INVESTIGATIONS

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From the

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During this period research was performed at North Carolina State on collective ion acceleration in a vacuum diode geometry and in collaboration with a group from the Naval Research Lab on collective ion acceleration within an evacuated dielectric tube. Diode voltage and current wave forms along with transmitted beam energy and current were measured for a series of linear diameters and lengths. Beam energy loss was linear at the rate of approx 12 J/cm. For the 8.3 and 15.9 cm length tubes, the Alfen limiting current was exceeded, indicating the creator of enough plasma for some current neutralization.

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Below the Alfen limit the current propagates in a pinched beam. The beam from velocity was 1.4 cm/nsec. Equipment for experimental work on electron beam propagation in evacuated magnetized pipes has been assembled and a theoretical study was made of intense electron beam equilibrium in magnetized pipes using a relativistic cold fluid model.

Unclassified

TABLE OF CONTENTS

I. ABSTRACT

The work accomplished during the first year of AFOSR Contract Number F49620-76-C-0007, Intense Relativistic Electron Beam Investigations, was discussed in the progress report submitted on March 7, 1977 and is included herein by reference. Progress accomplished with second year support by AFOSR Contract Number F49620-76-C-0007, Intense Relativistic Electron Beam Investigations, is summarized in this report. In particular, the following topics are discussed: (a) development of the relativistic electron beam laboratory and associated instrumentation, diagnostic equipment, and computational techniques at North Carolina State University, (b) collective ion acceleration experiments at NCSU, (c) electron beam transport experiments in dielectric liners at NCSU, and (d) electron beam transport and ion acceleration experiments at NRL's VEBA machine in collaboration with Dr. Robert K. Parker of NRL and Major Richard L. Gullickson of AFOSR. The relativistic electron beam laboratory at NCSU which was made possible by Dr. Parker's arranging for the loan of an NRL constructed 0.5 MeV, 70 kA, 60 nsec, 7 ohm intense relativistic electron beam machine is now fully operational. With joint support from NCSU and AFOSR this laboratory is now well equipped with fast oscilloscopes, nuclear activation detection, analyzing and counting equipment, TRW streak and Beckman Whitley image converter cameras, fast vacuum pumping equipment, pulsed magnetic fields, a pinhole X-ray camera, a Thomson parabola ion spectrometer, a 1-meter McPherson spectrometer, and a microphotometer for scanning spectrometer plates and blue cellophane witness films for electron beam current density measurements. Three Ph.D. graduate students are underway with their dissertations on collective ion acceleration and electron beam propagation experiments and three other students will begin their Ph.D. dissertation experiments using the relativistic electron beam machine during the next year.

II. PROGRESS

Progress made after the last written report in February, 1977 and including the second year of funding is reported in this section. The original period of performance for the second year funding from July 1, 1977 to June 30, 1978 was extended to April 30, 1979 with no additional funding requested. A complete list of the publications (7), dissertations (3), thesis (1), and papers presented (9) during this period is given in Section IV. Six copies of this material were forwarded to the AFOSR contract monitor in April, 1979. Copies of the abstracts of these publications, dissertations, thesis, and papers presented are also included in Section IV. The data presented in these works will be only briefly summarized in the following sections, and particular emphasis will be given to recent unpublished results.

A. Development of Relativistic Electron Beam Laboratory at NCSU

With the splendid cooperation of Dr. Robert K. Parker of the Naval Research Laboratory and Major Richard K. Gullickson of AFOSR, an NRL designed and constructed, pulsed 0.5 MeV, 70 kA, 60 nsec, 7 ohm intense relativistic electron beam machine was made available to the plasma physics research program at North Carolina State University during the first year of this contract. The principal investigator with the assistance of a machinist and two graduate students disassembled, crated and moved the machine from Rome Air Force Base, NY to NCSU. A 24' x 24' room in our laboratory has been extensively modified for the installation and operation of the machine. A ground plane, an EMI screen room fed with coax cables in copper pipes, air pressure lines, new electrical service, and extensive X-ray shielding have been installed. During the first year the entire machine including the Marx bank, switch gaps, Blumlein section, vacuum system, pneumatic valves, water spark gap switch, water purification systems and power supplies were disassembled, cleaned and repaired as needed. An oil transfer and filter system and a safety interlock system were designed and assembled.

The Radiation Protection Council of NCSU approved operation of the facility early in the second year of the contract. An extensive X-ray radiation survey using TLD dosimeters indicated the need for some additional overhead shielding. It was decided to use a portable semicylindrical iron shield after locating and installing an electrically actuated overhead hoist.

Most of our experiments are of a one-shot nature, requiring opening the vacuum system up to atmospheric pressure between shots. Since the vacuum diffusion pump furnished with the electron beam machine was sized to hold vacuum rather than to achieve rapid pump down, we were limited to 2 or 3 shots a day. We have located and installed a 10 inch diffusion pump (3850 liters/sec) and a larger mechanical vacuum pump and can now pump down to firing conditions in 15 minutes.

In order to obtain a jitter-free trigger pulse as far in advance of the electron beam pulse as possible, we have made penetrations in the outer and intermediate cylinders of the water Blumlein pulse shaping section in the region of the water filled spark gap that self-breaks down when sufficiently overvolted by the Marx capacitor bank charging circuit. The light produced by this gap's self-firing is brought out by a lucite pipe to a fiber optics cable and is fed into the optical input of our TRW Model 46A trigger delay generator for pulsing our image converter camera and lasers as well as providing an advance synchronized trigger pulse to the oscilloscopes. Since this water filled spark gap switch initiates the pulse in the Blumlein circuit, the optical signal from it occurs at an essentially jitter-free time increment before the electron beam pulse and is early enough to pulse the image converter electronic shutter open before the end of the electron beam pulse.

The machine is operating very reliably with repairs to date involving only replacing a capacitor, a section of the charging wire, the Blumlein inductor, rebuilding the water circulating pump, and repairing the water gap mechanism.

The laboratory is now reasonably well equipped with the following equipment for diagnostic measurements.

Equipment	Source
NRL 0.5 MeV 7 ohm relativistic electron beam machine	Government furnished
Capacitor bank and magnetic field solenoid 4' long with an 8 1/4" inner diameter for electron beam propagation experiments	Government furnished
2 Tektronix 7844 dual beam 400 MHz oscilloscopes with C-51 cameras	Joint AFOSR and NCSU
Tektronix 7704 single beam 400 MHz oscilloscope with C-12 camera	Joint AFOSR and NCSU
Tektronix 556 dual beam 50 MHz oscilloscope with C-12 camera	Joint AFOSR and NCSU

Equipment	Source
Beckman-Whitley 511A image converter camera	AFOSR
TRW Model 1D image converter camera with Model 28B submicrosecond 3 frame plug-in Model 46A trigger delay generator Model 21A precision recording camera Model 1'A, 19A heavy duty tripod and dolly	Occasionally available on loan from another research group at NCSU
Korad Model K1 ruby laser system (burst mode)	Occasionally available on loan from another research group at NCSU
Leeds-Northrop Model 6700-I1 microphotometer modified to use a He-Ne laser as a light source for reading blue cellophane film transmission	Available at NCSU
Nuclear coincidence counting equipment with 3" and 2" NaI detectors and Ortec 456 high voltage supplies Ortec 486 and 490A pulse height analyzers Ortec 775 and 715 counters/timer Ortec 777 line printer LeCroy 3001 qVt multichannel analyzer	Joint AFOSR and NCSU
VUV spectrometer with Bausch and Lomb grating with 1500 A blaze wavelength	Under construction at NCSU
Thomson parabola ion spectrometer	Constructed at NCSU
Hard X-ray camera with 0.010" pinhole	Constructed at NCSU
HP Model 9800 B calculator-plotter system modified for digitizing oscilloscope traces	NCSU

Rogowski coils for current measurements and a nanosecond rise time combination Faraday cup current monitor and calorimeter have also been constructed. The transient voltage output from the thermocouple in the calorimeter is recorded digitally at 15-second intervals after a shot and extrapolated back to the firing time to obtain the temperature rise from which the deposited beam energy can be calculated.

Dr. C.M. Armstrong has received an equipment grant from the Research Corporation for "Time Resolved Studies of Relativistic Electron Beam Propagation in an Evacuated Dielectric Guide" which will allow the plasma laboratory to purchase a TRW model 7B high speed streak unit, two additional vertical amplifiers for our NCSU purchased Tektronix 7844 oscilloscope, and PIN X-ray detectors for our electron beam research program.

Dr. J.J. Kim has arranged with NASA for the loan of a McPherson Model 216 1-meter spectrograph - polychromator with wavelength range 2,000-10,000 A. This unit is now in operation in our electron beam laboratory.

It is hoped that a rhodium activation detector can be obtained next year for the detection of prompt neutrons produced by (p,n) and (d,n) reactions when accelerated ions strike suitable targets. We also need a magnetic tape cassette recorder for storing digitized oscilloscope trace data and the output data from our LeCroy nuclear spectrum multichannel analyser for subsequent input to our central IBM computing facilities.

B. Machine Calibration Experiments

Considerable effort has been directed toward carefully calibrating the capacitive voltage divider and magnetic loop current monitor in the diode region and combination Faraday cup - calorimeter used to measure the transmitted electron current and beam energy. By modifying a HP plotter - calculator system, we are able to digitize our oscilloscope traces at equidistantly spaced points with about 1-2% accuracy. These data can be manually fed into a computer for processing and plotting. We have therefore been able to compute and compare $\int_0^t V dt$ versus $LI(t)$ (from the relation $V = -L dI/dt$ where L is the diode tube inductance) for short circuit shots, $\int_0^\infty (V - L dI/dt) I dt$ versus energy delivered to the calorimeter, as well as to make comparisons of amplitudes and wave shapes of the traces of the diode current monitor, Faraday cup, and a calibrated T&M Research Products current viewing resistor for determining calibration factors. The calibration techniques described in Dr. Robert K. Parkers dissertation[1] were invaluable during this phase of the project.

Initial differences in the waveforms between the diode magnetic loop current trace and current viewing resistor were traceable to the apparent use of a magnetic paper clip for the loop. Waveform tracking occurred when this wire was replaced with nonmagnetic copper wire. Similarly, initial differences in the risetimes of ∫Vdt versus LI for short circuit shots were eliminated by modifying the compensating capacitor in the voltage divider. We believe our diode current and voltage measurements have a 2-4% accuracy, and we have obtained approximately 4% agreement between the deposited electron beam energy as measured with the calorimeter and as computed according to ∫(V-LdI/dt)Idt. A detailed account of this work will appear in a dissertation.

C. Collective Ion Acceleration Experiments

A series of ion acceleration experiments was conducted on the VEBA accelerator in collaboration with Dr. R.K. Parker of NRL and Major R.K. Gullickson of AFOSR. The results of these experiments are reported in publications A1 and A4 listed in Section V.

A typical experiment consisted of injecting a 65 kA, 1.5 MeV, 60 nsec, $\nu/\gamma \sim 1.4$ electron beam from a tapered brass cathode into an evacuated dielectric tube with 6.4 cm inside diameter and 15 cm length as shown in Fig. 1b.

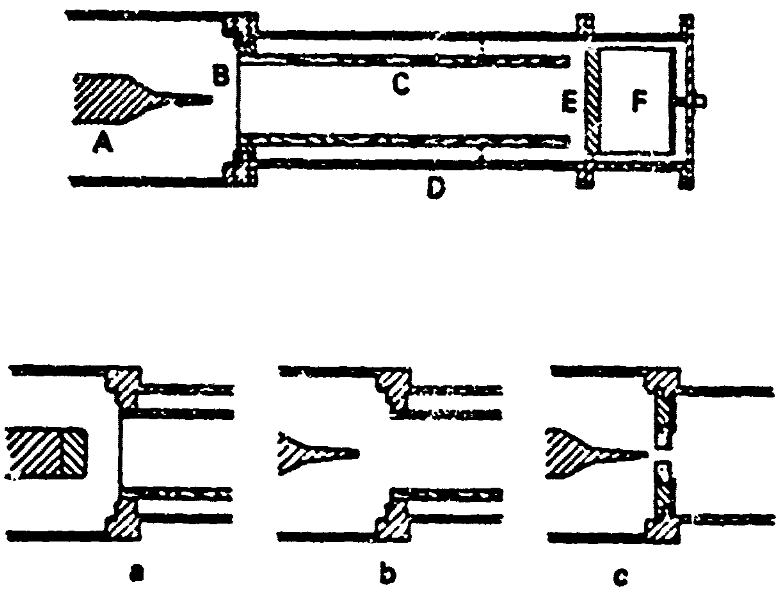


Fig. 1. Experimental configuration: A, cathode; B, anode foil; C, dielectric guide; D, outer conductor; E, graphite current collector; F, Faraday cup. (a) propagation configuration. (b) acceleration configuration. (c) Luce-type diode.

According to the model of Little, Greenwald et al.[2], the electron beam (whose current exceeds the space-charge limit) is stopped by the formation of a virtual cathode and expands radially, striking the dielectric wall and causing surface flashover and the liberation of ions. These ions provide sufficient charge neutralization for the beam to propagate a bit further, so that the potential well at the beam front travels down the guide at a velocity determined by the rate of ion release from the walls. Some of these ions are expected to be accelerated by the potential well, and it should be possible to optimize ion trapping and acceleration by appropriately choosing the system parameters (e.g., guide shape and size, cathode diameter, etc.). One purpose of these experiments on the VEBA at NRL and subsequent experiments on the NRL 7-ohm line at NCSU was to examine ion acceleration in evacuated ($\leq 2 \times 10^{-4}$ Torr) dielectric guides at higher electron energies and currents than in previous studies[2].

At VEBA a rhodium activation detector[3], located above a target attached to the front of the Faraday cup, was used to measure neutron yields from (p,n) and (d,n) reactions. In addition nuclear activation techniques[4] were used to determine the number and energy of ions accelerated in two ways: (1) by the use of targets with different reaction thresholds, and (2) by using stacked foil targets and relating the depth of activation to ion energy through range-energy relations.[5]

With the diode shown in Fig. 1b, consisting of a small diameter cathode but no anode foil, protons with kinetic energies up to 14 MeV (nine times the electron energy) were detected on axis with an energy spectrum given by 7×10^{13} exp(-E) protons per MeV with E in MeV. The maximum observed yield was $\sim 10^{13}$ protons (E > 3.8 MeV). The reactions $^{13}C(p,n)^{13}N$ and $^{63}Cu(p,n)^{63}Zn$ with reaction thresholds of 3.2 and 4.2 MeV, respectively, were used. Similar yields were observed with the Luce diode geometry shown in Fig. 1c.

There was considerable shot-to-shot variation and irreproducibility in the yields in these experiments, probably due in part to the random nature of the beam-induced surface flashover process which produces the ions to be accelerated. Alternative methods are proposed in Section III for next year's effort for creating ions prior to electron beam injection in an attempt to eliminate this erratic ion acceleration behavior.

Ion acceleration experiments are now underway at NCSU using the NRL 7-ohm line which produces a 0.5 MeV, 70kA, 60 nsec, $\nu/\gamma \sim 2.4$ electron beam. In addition to injecting into dielectric guides and using the Luce-type diode geometries shown in Figs. 1b and 1c, we have injected into an evacuated pipe 10.2 cm in diameter and 15 cm long as shown in Fig. 1 without the dielectric guide C and with thin plastic films or nylon filaments at B instead of an anode foil, similar to our previous experiments on the 4.5 MeV, 50 kA FX-75 electron beam machine at the Boeing Radiation Effects Laboratory.[6] A 0.13 mm thick graphite activation target was placed at position E and was sometimes used as a lining on the inside of the pipe section D to detect ions accelerated radially outward as well as axially. Our experiments have been largely exploratory in an attempt to discover those changes in diode configuration which would produce significant changes in ion acceleration. We have found that the basic statistical nature of the process has obscured the effect of most changes made to date.

The nuclear reaction used to detect accelerated protons was $^{12}C(p,\gamma)^{13}N$ which has resonances at 0.457 MeV and 1.7 MeV with yields of 7.5 ^{13}N atoms per 10^{10} protons with energy $0.6<E<1.5$ MeV and 18 ^{13}N atoms per 10^{10} protons with energy above 1.8 MeV. ^{13}N is a β^+ emitter with a half life of 9.97 minutes. The decay of the ^{13}N nucleus is observed by detecting the two 0.51 MeV annihilation gamma rays in an energy discriminating nuclear coincidence counting system using 2" and 3" diameter NaI scintillation detectors. Coincidence counting reduces the background count rate (in our case to 2.2 counts/min), thereby increasing the sensitivity and statistical accuracy in determining the ^{13}N yield. Using a calibrated ^{22}Na source, we arrived at a counter efficiency of 0.0424 coincidence count per positron emission, and an expected initial count rate of 1 count per minute per 4.5×10^{11} protons incident on a thick (for protons) carbon target with energy $0.6<E<1.5$ MeV. The experimental method consisted of removing the graphite target after each shot, counting for a series of contiguous 5-minute intervals, and extrapolating the count rate back to the time of the shot.

The initial experiments were conducted with the Luce-type geometry of Fig. 1c in which the tapered brass cathode was placed 15 mm in front of a 1.27 cm thick polyethylene anode with a 1.27 cm diameter hole on axis. Single shots produced no activity. The machine was then fired 10 times during a 20 minute period before removing the graphite target. Activity was produced and the initial count rate was 344 cpm indicating that 1.5×10^{14} protons were accelerated (assuming an energy $0.4<E<1.5$ MeV). The intense electron current $\sim$ 50 kA blasted away part of the polyethylene anode, enlarging the hole to 2.5 cm on the cathode side.

In another series of experiments, a 2 μm thick (0.26 mg/cm^2) polycarbonate film (Kimfoil $C_{12}H_{14}O_3$) was placed behind a 1.27 cm thick graphite anode with a 3.8 cm diameter opening as shown in Fig. 2. The tapered brass cathode shown in Fig. 1b was used in this series. With a cathode-anode gap spacing of 18 mm, four successive shots gave an initial count rate of 70, 52, 26, and 19 cpm (1 cpm = 4.5×10^{11} protons), indicating a fairly large (factor of 3.7) scatter of data. The diode impedance was changed by varying the gap spacing over the range 13-28 mm, and various thicknesses of film (4, 6, 12 μm) were tried. All count rates fell within the range for the initial single shot variability, and no trends were observed.

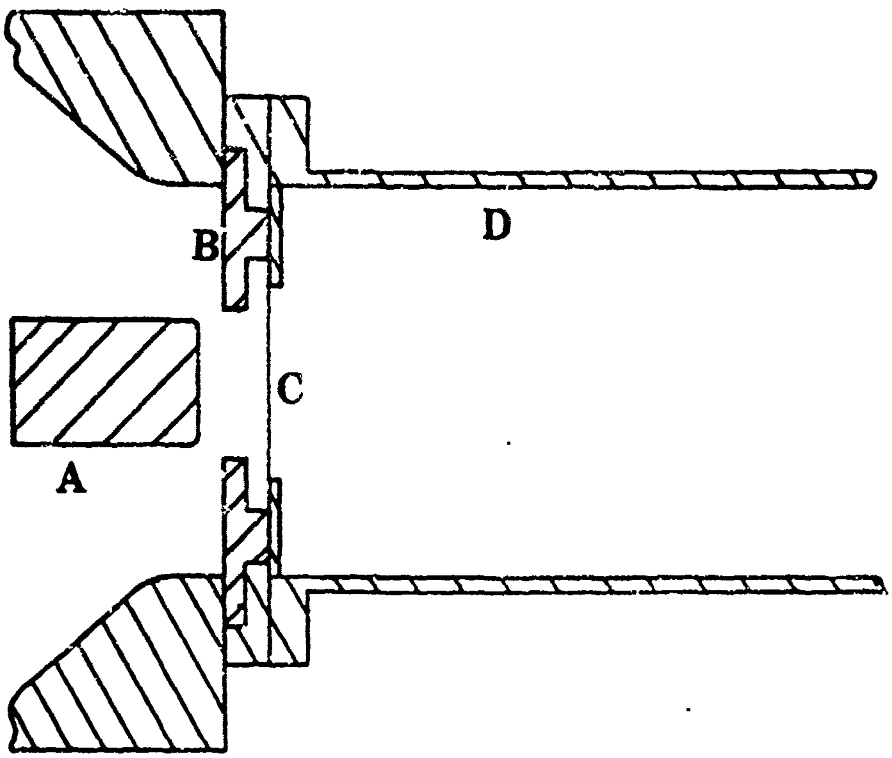


Fig. 2. Experimental configuration for ion acceleration: A, graphite cathode; B, graphite anode; C, plastic film or nylon filament; D, outer conductor

The greatest proton yields were produced by replacing the film with a single 0.044 mm diameter filament of 15.6 denier nylon 66 with density 1.13 gm/cm^3 and chemical composition $H\{HN(CH_2)_6NHCO(CH_2)_4CO\}_nOH$. Four shots with a cathode-anode gap of 18 mm yielded 730, 188, 102 and 62 cpm. On several shots the carbon block in the calorimeter on which the 16 mg/cm^2 graphite target was mounted became activated, indicating that some protons were accelerated to energies above 3 MeV (six times the electron energy) in order to penetrate the target with sufficient residual energy (0.4 MeV) to activate the calorimeter.

When the graphite anode was removed but with a single nylon filament located in the same position as before, the count rate yield dropped to values less than those for the films.

The brass cathode was next replaced with a 3.18 cm diameter graphite cathode (see Fig. 2). The best yield (477 cpm) was obtained when 15 filaments were arranged in a spoke-like manner with 3 bundles of 5 filaments each.

A summary of these results is given in the following table.

Summary of Ion Acceleration Experiments at NCSU

Diode Type	Variation in Count Rate counts/min ($1\ cpm = 4.5 \times 10^{11}$ protons)
Polyethylene anode with 1.27-cm-dia. hole, brass cathode (Luce-type)	344
Polycarbonate film (graphite anode with 3.8-cm-dia. hole, brass cathode)	12-70
Nylon filaments (graphite anode with 3.8-cm-dia. hole, brass cathode)	62-730
Nylon filaments (no graphite anode, brass cathode)	0-23
Nylon filaments (graphite cathode, no graphite anode)	84-477

A Thomson parabola ion spectrometer has been constructed for the measurement of energy and momentum spectra and charge states of various ions accelerated by the electron beam. A small quantity of ions on the beam axis is selected by an aperture, and subsequently deflected by parallel E and B fields. Individual ions are recorded on cellulose nitrate film, which can be read with a low power microscope after developing. This spectrometer is designed to observe protons in the energy range 150-500 keV. These measurements will augment the nuclear activation measurements and should help us develop a theoretical model for the acceleration mechanism. This system is now being calibrated with a ^{241}Am alpha particle source and will be put on line this coming year.

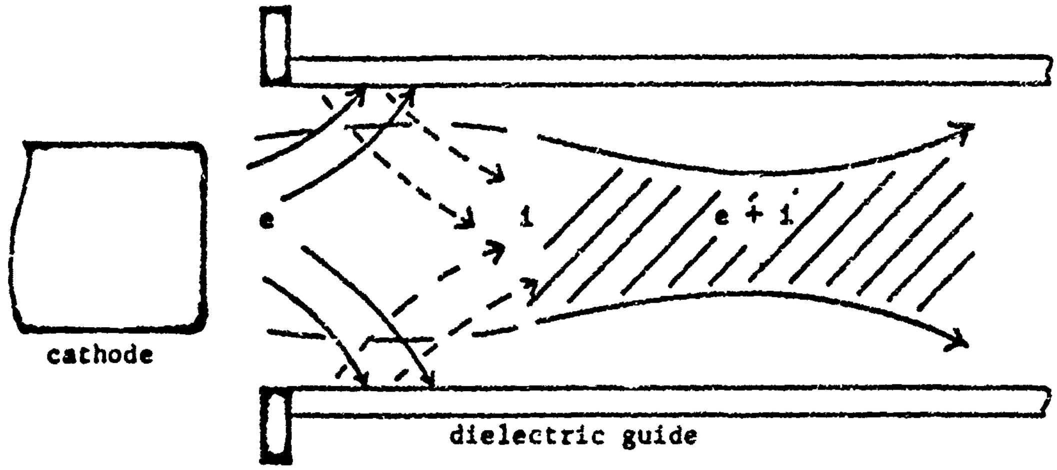
D. Beam Propagation Experiments in an Evacuated Dielectric Guide

In collaboration with Dr. R.K. Parker, the propagation characteristics of an intense electron beam injected into an evacuated dielectric tube were studied at the VEBA facility at NRL along with the ion acceleration series of experiments discussed in section II.C. Detailed results were reported in publications A1 and A4 listed in Section IV. When a 1.5 MeV, 65 kA, 60 nsec, $\nu/\gamma \sim 1.4$ intense relativistic electron beam was injected into an evacuated ($\sim 2 \times 10^{-4}$ Torr) 7.6 cm diameter lucite pipe, the beam front advanced over the first 50 cm length at a velocity of 2 cm/nsec. As described in Section II.C., this velocity is related to the rate of ion release from the wall[2]. The delivered electron beam energy decreases almost linearly with guide length, and the best transport in a series of three diameters (0.3 cm, 1.3 cm and 4.1 cm) was obtained with the largest diameter. For the 4.1 cm diameter tube, the calorimeter indicated that approximately 25% of the energy injected into the guide propagated a distance of 60 cm. Since this energy agreed within 10% of the $\int VIdt$ calculation based on the diode voltage and Faraday cup current, the electrons reaching the end of the guide had essentially their injected energy. Furthermore, the peak current delivered was generally of the same order as the diode current, but the pulse width decreased with guide length. This result indicates that most of the energy loss resulted from beam-front erosion.

Electron beam propagation in an evacuated diode is also under investigation on the 0.5 MeV 7-ohm line at NCSU.

The primary thrust of these experiments, as originally proposed by Little and Greenwald[2], was the possible utilization of dielectric guides as efficient ion accelerators. A thorough knowledge of electron beam transport under these conditions is necessary since proposed models have indicated that one must control the motion of the beam front in order to maximize ion acceleration. The purpose of the experiments at NCSU is to study the gross features of relativistic electron beam transport in these guides, such as: energy transport efficiency, beam size and beam front velocity.

Figure 3 shows qualitatively the physical processes involved in this method of beam transport. After injection into the dielectric guide or liner, the beam immediately strikes the liner wall due to the initial electron trajectories caused by the diode configuration and radial expansion due to virtual cathode formation. These electrons release ions from the liner walls by surface flashover and other undetermined physical processes which create a plasma at the liner surface. The ions are drawn toward the liner axis by the electron space charge, at least partially neutralizing this space charge allowing



SPACE CHARGE LIMITED CURRENT $I_{SC} = \frac{17,000\ (\gamma^{2/3} - 1)^{3/2}}{1 + 2\ \ln\ (R_o/R_b)} = 5.3$ kA

ALFVÉN CURRENT $I_A = 17,000\ (\gamma^2 - 1)^{1/2} = 29$ kA

$$\gamma \equiv 1 + (eV_D/m_o c^2)$$

Fig. 3. Model of electron beam propagation in evacuated dielectric guide. When the beam exceeds the space charge limit, it expands and releases atoms and ions. These ions neutralize the electron space charge and the beam propagates down the guide.

the beam to propagate further down the liner where the process repeats. The original idea was that some of the ions would be accelerated and/or trapped by the potential well at the beam front. Formulas are shown in the figure for the space charge limiting current I_{sc} and the Alfvén limiting current I_A. We are injecting currents above the space charge limit although we use no confining magnetic field and in certain cases propagate currents above the Alfvén current.

The experimental configuration is shown in Fig. 4. The accelerator is of the Marx generator-Blumlein water filled transmission line type. In this experiment, the diode voltage and current were 400-600 kV and 30-70 kA respectively (pulse length $\tau \sim 60$ nsec, vacuum $p = 5 \times 10^{-5}$ Torr, no confining magnetic field). The diode consists of a 3.2 cm diameter cylindrical graphite cathode located approximately 5 mm from an annular graphite disc which served as the anode. Backing the anode was a dielectric liner coaxial with a 10.2 cm ID stainless steel drift tube. A 1 mil stainless steel foil was used at the exit of the liner to stop low energy plasma electrons. Three mm behind this foil was a blue cellophane film which was used to measure the beam size. Transmitted beam energy and current were measured by a combination

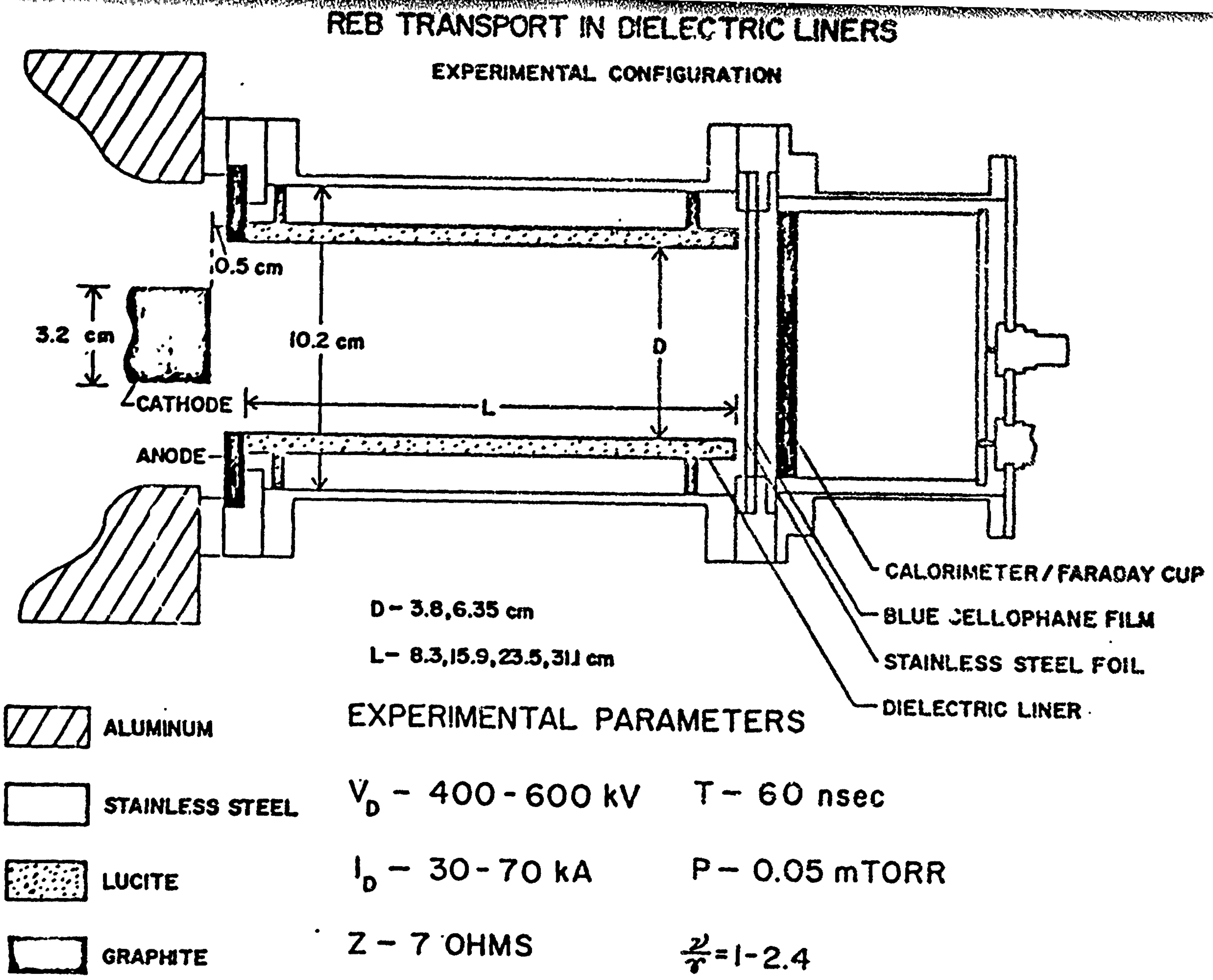


Fig. 4. Experimental configuration

calorimeter/Faraday cup located behind the foil and film assembly. The main variables in this series were the liner diameter (3.8 and 6.35 cm) and length which ranged from ∿ 8-31 cm. The liner in all cases was a lucite tube with a 6.4 mm wall-thickness. To protect the leading edge of the liner from direct electron bombardment, the anode inner diameter was varied to match that of the liner. This variation also changed the diode impedance. A typical open shutter photograph of the large liner is shown in Fig. 5. Spectroscopic measurements are reported in the next Section E.

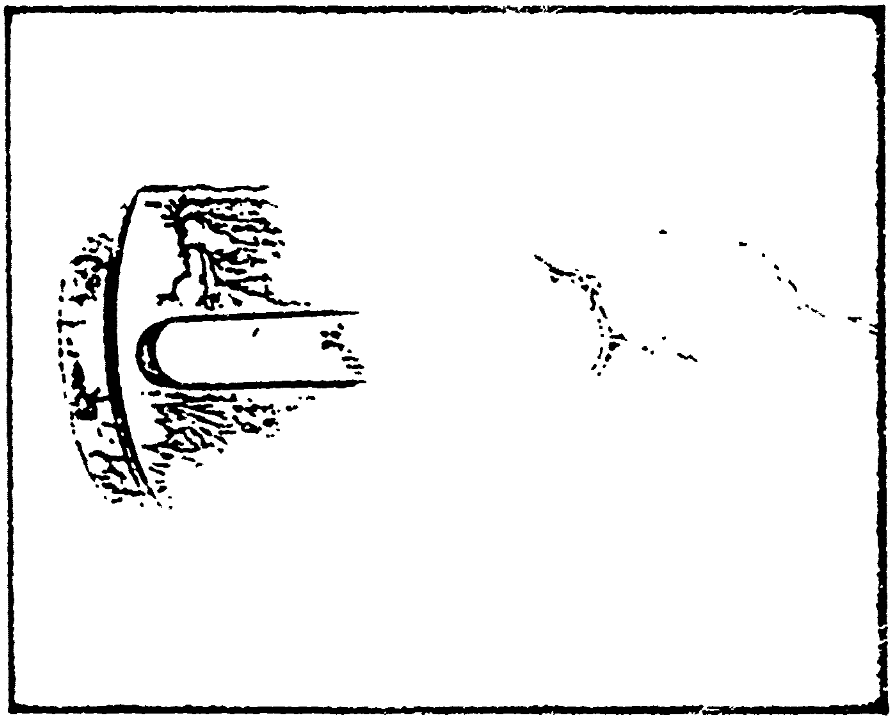


Fig. 5. Side-view photograph of the dielectric guide when a 50 kA, 0.5 MeV electron beam is fired into it. Lichtenberg-type discharges take place inside the dielectric. The slot is made to observe ultraviolet light for diagnostics.

Figure 6 shows typical waveforms for the 6.35 cm ID liner. The diode voltage in the upper right figure peaks at about 600 kV while the diode current peaks at about 30 kA. The bottom four traces show the variation in the transmitted current pulse I_T as the liner length is increased from 8-31 cm. Points to note are the initial sharpening and then rounding of the leading edge of the transmitted current pulse and the decrease of the peak current. Note also the increasing delay in the start of the current pulse. The delay as a function of length will be shown later. The Alfvén limiting current I_A computed from the diode voltage is shown as a bolder trace and lies below the transmitted current.

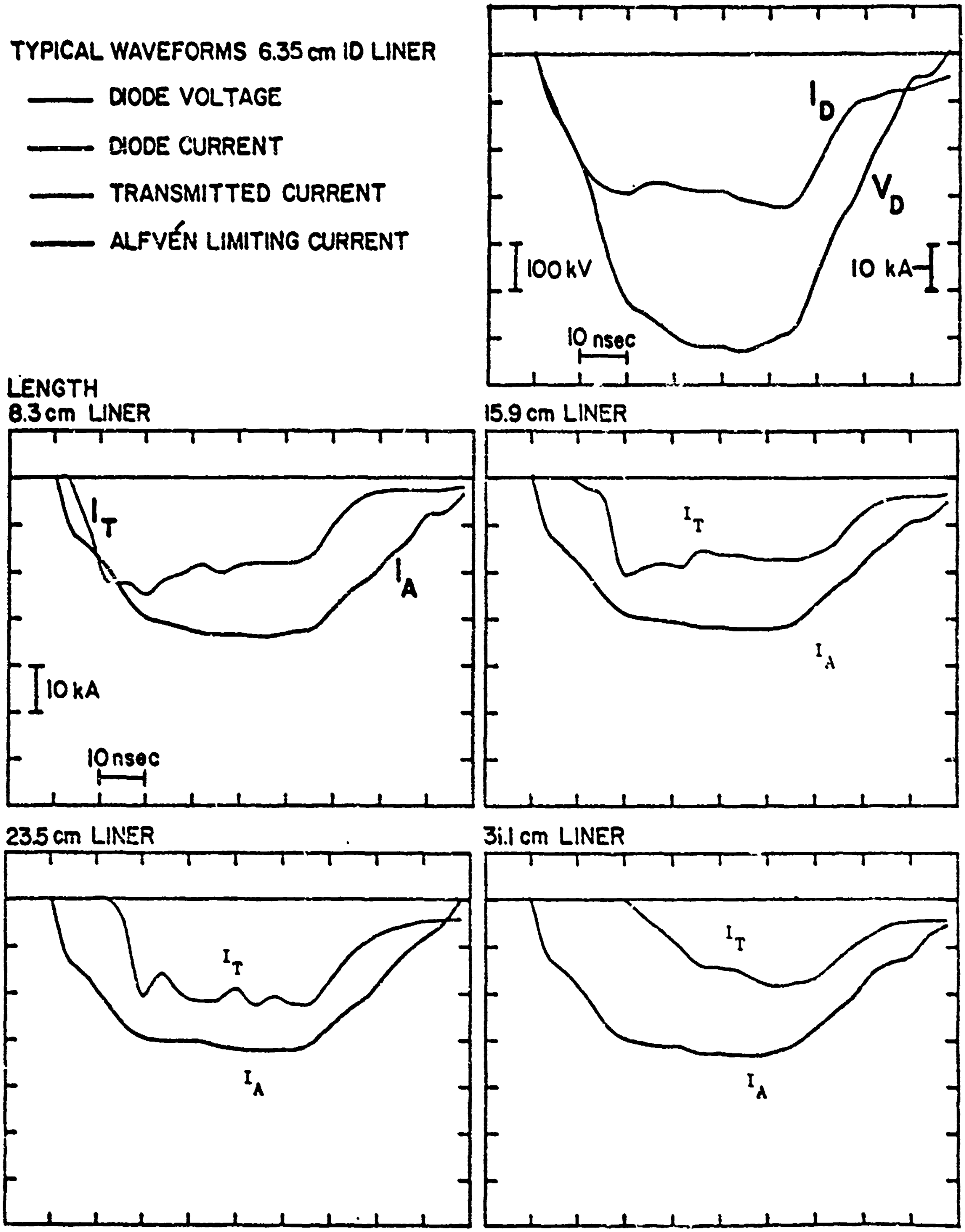


Fig. 6. Typical diode voltage and current waveforms and transmitted current versus tube length for a 6.35 cm ID dielectric guide.

Figure 7 shows the same information for the 3.8 cm ID liner. In this case, the diode voltage peaks at about 430 kV and the current at 67 kA. Notice that for the 8.3 and 15.9 cm lengths, we have exceeded the Alfvén limiting current. We will return to this later. The other features are generally the same as for the larger liner except for the more drastic rounding of the current pulse leading edge.

Figure 8 shows the energy transmission efficiency of dielectric liners. The diode energy, E_D, is computed by integrating the product of the diode voltage and current over time. The transmitted energy E_T, is determined from the calorimeter thermocouple output. The energy loss is seen to be linear with length. (The error bars represent the standard deviation of at least 3 shots/liner length.) It should be noted that the transmission efficiency may appear low compared to other transmission schemes mainly because the transmitted energy is compared to the beam energy in the diode region and not the actual energy injected into the liner. A large fraction of the beam energy is lost at the anode due to the diode configuration. The diode geometry could be optimized to improve this fraction.

Figure 9 shows the determination of the beam front velocity. The transmitted current delay is the time (in nsec) between the start of the diode current pulse and the start of the transmitted current pulse. Refer to the representative waveforms presented in Figs. 6 and 7. The reciprocal of the slope is the beam front velocity which is $\sim$ 1.4 cm/nsec for both liner sizes.

Beam size information is given in Fig. 10 which shows representative blue cellophane films for the various liner lengths. Note that for the 8.3 cm length at 6.35 cm ID and 8.3 cm and 23.5 cm lengths at 3.8 cm ID, the beam current density is sufficiently high to burn a hole near the center. The blue cellophane film for the 8.3 cm length at 3.8 cm ID shows that the beam fills the liner. The cathode diameter is 6 mm less than the liner ID. This is consistent with our previous observation that we exceeded the Alfvén current for the 8.3 cm length, that is, we have created enough plasma for some current neutralization. The other films show that this is not maintained for longer lengths. Note also, by examining the diameter and opaqueness of the cloudy area that the beam appears to be pinching and that either the beam current density is decreasing or the pulse duration is shortening. This is in rough agreement with the work by Kolomensky[7].

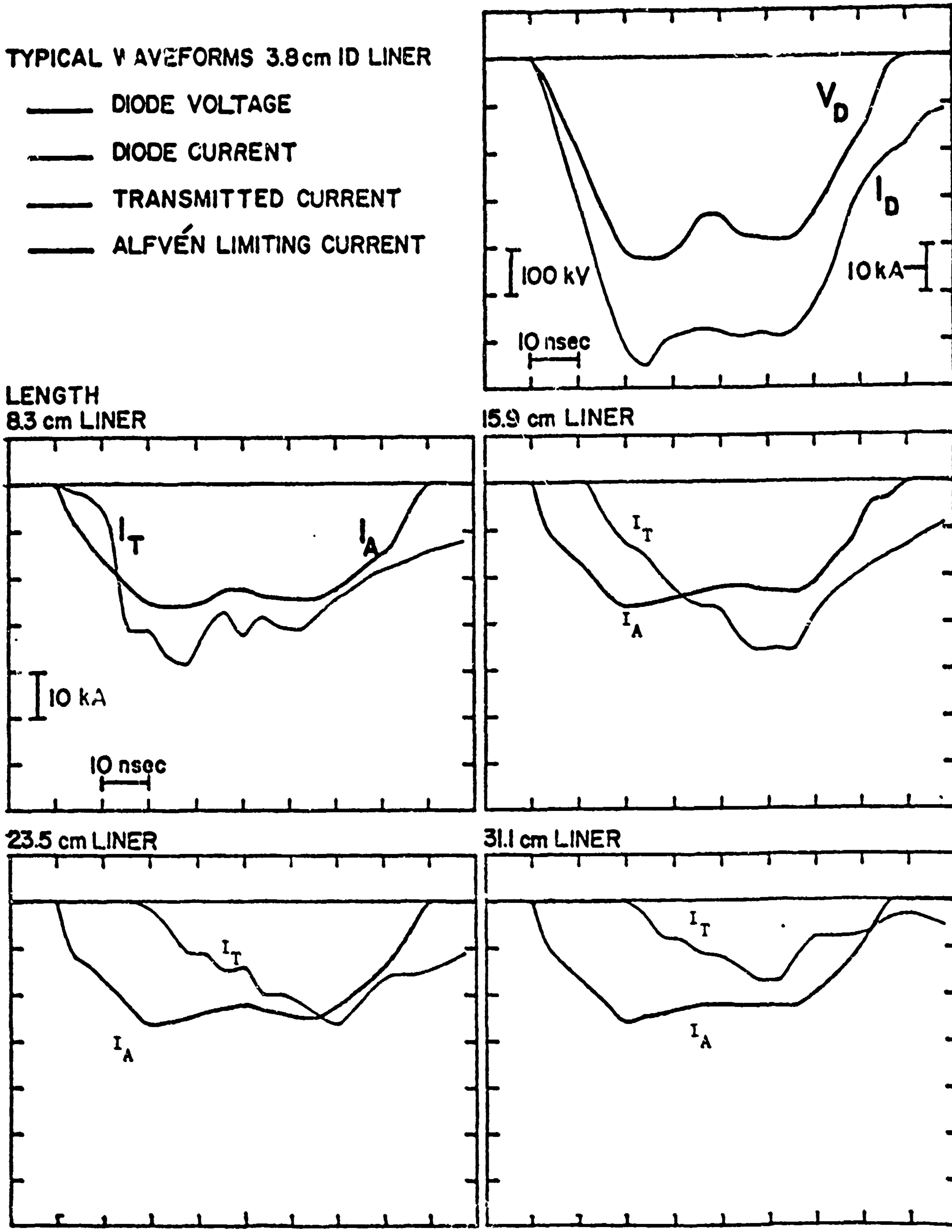


Fig. 7. Typical diode voltage and current waveforms and transmitted current versus tube length for a 3.8 cm ID dielectric guide.

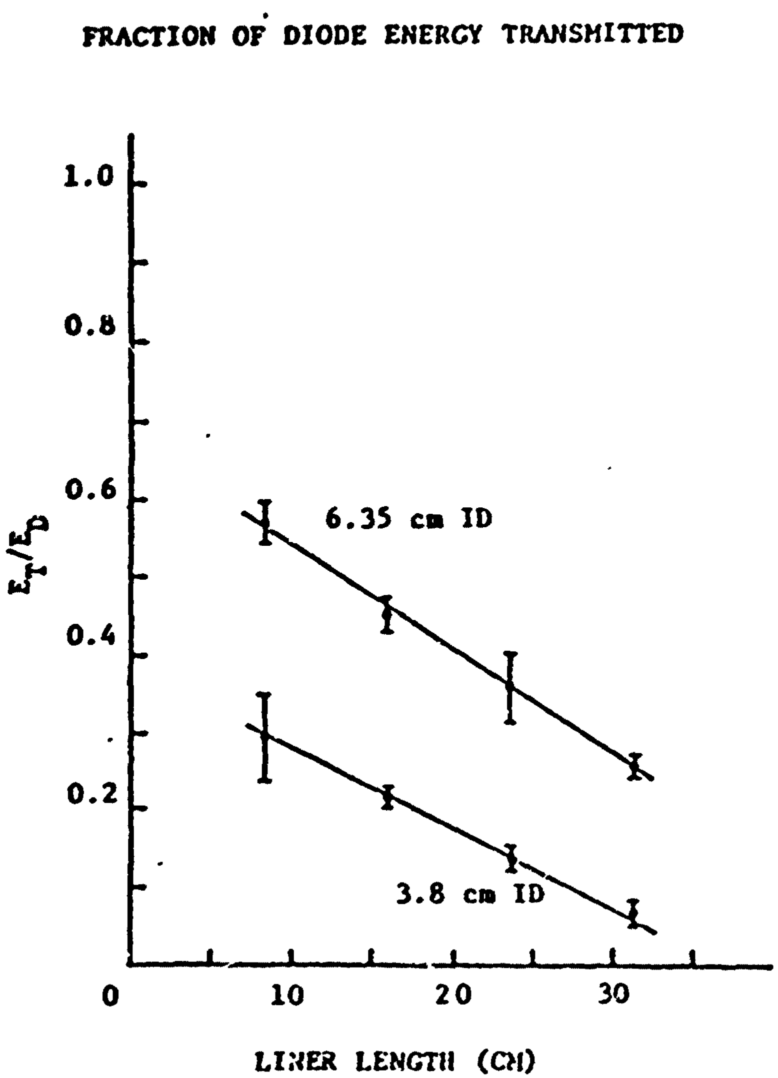


Fig. 8. Energy transmission efficiency as a function of dielectric tube length.

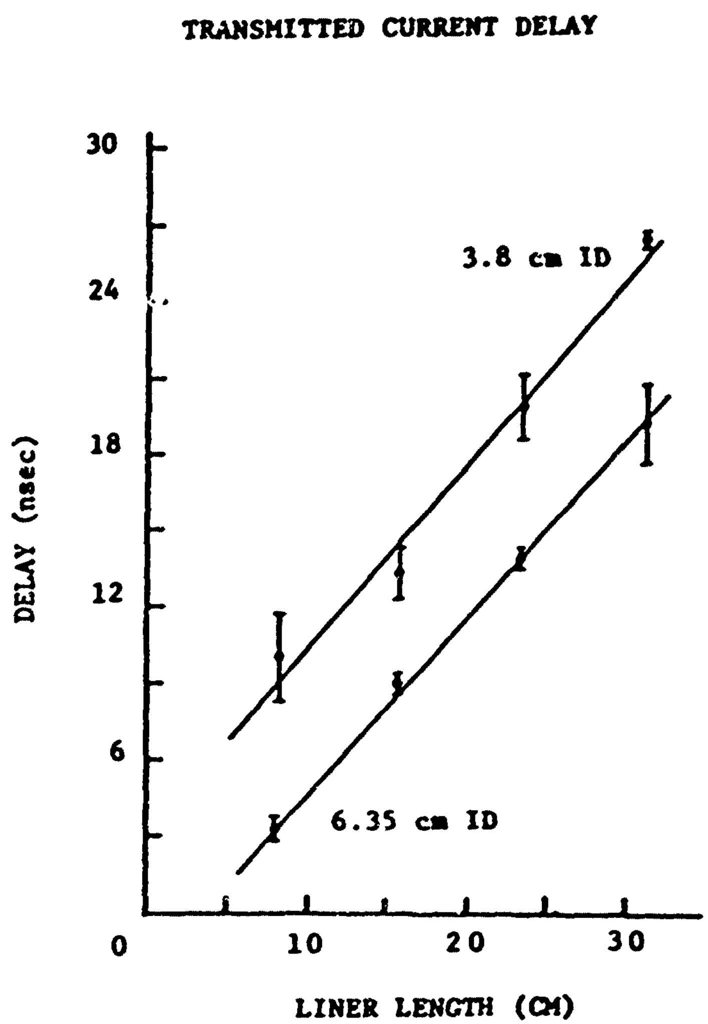


Fig. 9. Delay in arrival of transmitted current pulse as a function of dielectric tube length.

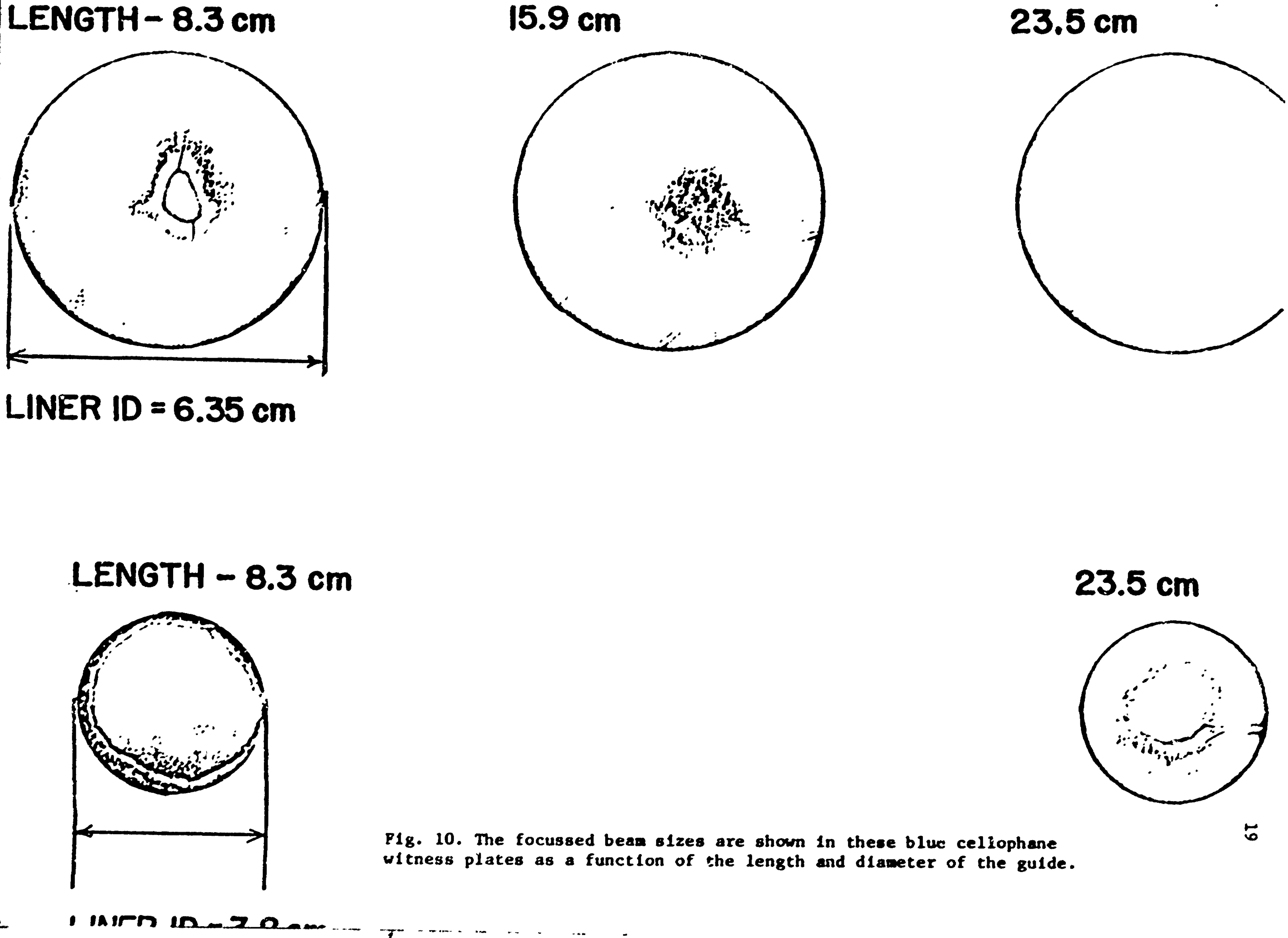


Fig. 10. The focussed beam sizes are shown in these blue cellophane witness plates as a function of the length and diameter of the guide.

In conclusion, we have shown:

1. Transport of injected beam energy is fairly efficient. Beam loses energy linearly with liner length ∿ 12 J/cm.
2. Sufficient plasma can be produced from an evacuated dielectric guide to provide some current neutralization.
3. As has been shown in other beam propagation studies, the current propagates in a pinched beam below the Alfvén limit.
4. Beam front velocity is approximately constant at 1.4 cm/nsec.

E. Spectroscopic Investigations at NCSU

A McPherson 216 1-meter spectrometer acquired on loan from NASA has been used to study the ionic species produced when the electron beam strikes the inside surface of the dielectric guide. Figure 11 shows the experimental set-up. The light is observed through a quartz window which transmits down to 1800 A. A slot was made in one side of the lucite guide, and the quartz lens was focussed on the axis of the tube. Figure 5 shows an open shutter photograph looking through the quartz window. Time integrated spectra were taken during the beam propagation studies reported in the previous section. A typical time integrated emission spectrum is given in Fig. 12 which shows a microdensitometer trace of the exposed film. Some of the identified species are indicated in the spectrum. Most of the prominent C^{+1} emission lines are observed as expected. The observed intensity ratio of C^{+2} (2297 A) and C^{+3} (2530 A) lines implies a temperature in excess of 8 eV for a plasma in thermal equilibrium if it is assumed that the triply ionized carbon ions are produced and excited by the interaction of the plasma electrons with carbon atoms which are evaporated from the anode or dielectric surfaces. The table on a following page lists the spectral lines identified to date. Silicon comes from the diffusion pump oil adsorbed on the anode and dielectric surfaces, and aluminum from the inner surface of the accelerator diode. Spatial as well as temporal variations of the emission lines will be determined in subsequent experiments. In addition, ion velocities will be measured by observing the Doppler shift of certain lines.

F. Blue Cellophane Witness Film Calibration

Blue cellophane film can be used to determine the current density of electron beams. Upon exposure to an electron beam, the blue dye bleaches out and the

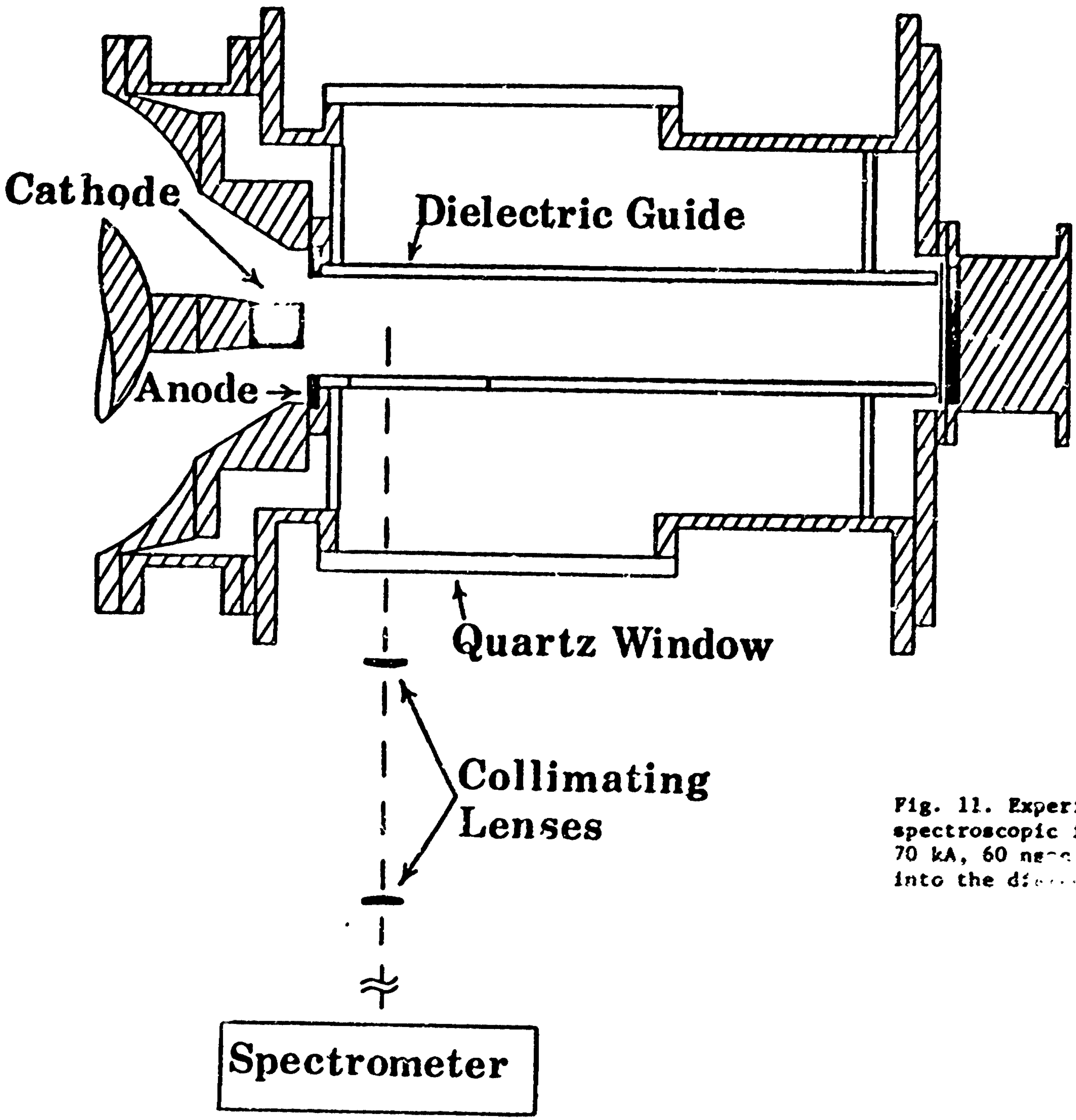


Fig. 11. Experimental arrangement for spectroscopic investigations. A 0.5 MeV, 70 kA, 60 nsec electron beam is injected into the di[illegible]ric guide.

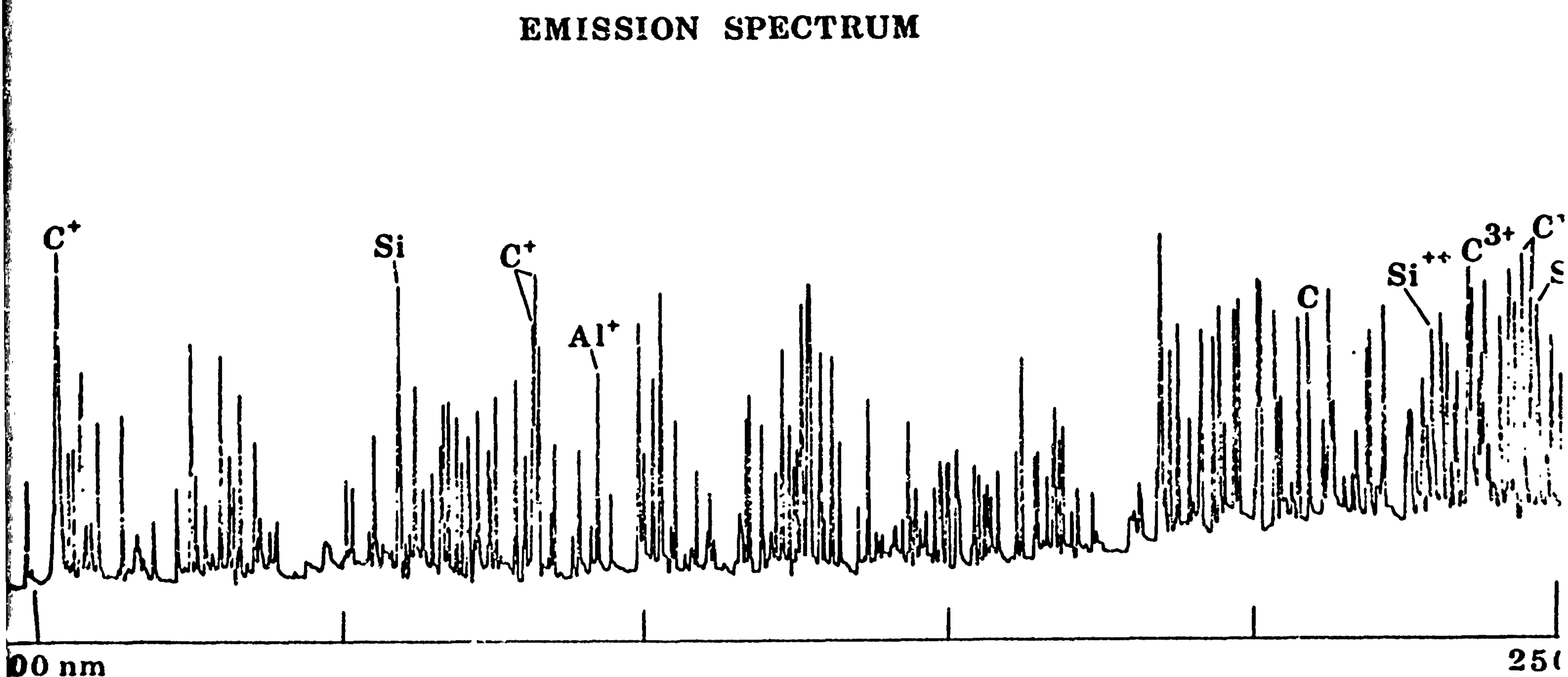


Fig. 12. Typical emission spectrum from the plasma generated by an IREB in the dielectric tube. Some of the identified emission lines are shown. C IV has been observed.

IDENTIFIED SPECIES

C	2478.56	SI	2435.15	Al	3082.15
	2582.90		2506.90		3092.71
			2513.32		3944.01
C^{+}	2509.12		2516.11		3961.52
	2512.07		2519.20		
	2836.71		2524.11	Al^{+}	2816.18
	2837.60		2528.51		
	2992.65		2881.58		
	3918.98		3905.52		
	3920.69				
	4074.52	SI^{+}	3862.60		
	4267.00		3856.02		
	4267.26				
	4075.85	SI^{2+}	2541.82		
			3086.24		
C^{2+}	2296.87		3093.42		
C^{3+}	2529.98				

change in fractional transmission coefficient is essentially proportional to the energy deposited by the electron beam as it passes through the film according to

$$D = \Delta T/K$$

where D is the absorbed dose in rad (100 ergs/gm), ΔT is the change in fractional transmission coefficient, and K is a calibration factor. Henley and Richman[8] obtained $K = 0.034 \times 10^{-6}$ (rad)$^{-1}$ with a low current accelerator. From the definition of stopping power S_p (MeV - cm^2/gm)

$$S_p = \Delta E/\rho\Delta z,$$

where ΔE is the energy loss by the electron beam in passing through a distance Δz of film with density ρ (about 20 keV in a 0.0025 cm thick film), the change in transmission can be related to the electron beam's current density J (amps/cm^2) as follows

$$J = 6.24 \times 10^7 \; e \; \Delta T/KS_p\Delta t,$$

where $e = 1.6 \times 10^{-19}$ coul, Δt is the duration of the beam pulse, and 6.24×10^7 MeV/gm = 1 rad.

In order to check out our procedure, we exposed film using the experimental arrangement shown in Fig. 4. A thin stainless steel foil placed in front of the film prevented low energy plasma electrons from rupturing or exposing the film. The transmitted electron beam current was simultaneously recorded by the Faraday cup monitor. A Leeds-Northrop Knorr-Albers microphotometer Model 6700-I1 was modified to accomodate a He-Ne (6328 Å, red) laser as the light source for reading the change in the fractional transmission coefficient of the exposed blue cellophane film. With these measurements we were able to independently determine a calibration factor. The result was

$$K = (0.031 \pm 0.006) \times 10^{-6} \text{ (rad)}^{-1}$$

which is within one standard deviation of Henley and Richman's result $K = 0.034 \times 10^{-6}$. Even though our total doses were comparable to theirs, our dose rate was 8 orders of magnitude greater than theirs. The range of current densities of 0.5 MeV electrons that we can measure with blue cellophane is 40-650 amps/cm^2, corresponding to ΔT changes of 0.01-0.16. Above this current density, the cellophane begins to become milky white and opaque rather than more transparent. This technique will be useful in obtaining radial current density profiles in future beam propagation studies.

G. Electron Beam Propagation in Evacuated Magnetized Pipes

One of the objectives of this research program is the study of intense nonneutral electron beam equilibrium profiles and quality in an axial magnetic field in an evacuated metal pipe. The magnetic field producing solenoid and capacitor bank have been checked out and calibrated, and the drift tube sections have been fabricated. Experiments on this phase of the project will begin during the next year.

One of our students, Robert Jackson, worked with the Parker-Granatstein free electron laser team[9] as an NRL summer employee in 1978 on the problem of electron beam quality. This work involved computer simulation of electron trajectories in the diode and magnetized drift tube region using a modified version of Herrmansfeld's SLAC electron optics code, and related experiments on the VEBA facility. These investigations are closely related to our basic studies of beam propagation and were continued by Jackson at NCSU. A summary of this work is contained in abstract C7 in Section

In addition to the simulation work, Jackson, jointly with two other students in the department, one of whom will be working on the NCSU experimental beam propagation experiments next year, has made a theoretical study of intense electron beam equilibria in magnetized pipes using a relativistic cold fluid model. These studies generalize Diament's[10] earlier work. A rough draft[11] of this work is attached to this progress report.

H. X-ray Pinhole Camera

One of the diagnostic methods for determining the current density of electron beams that are too intense for the blue cellophane technique consists of observing bremsstrahlung X-rays produced when the beam passes through a wire mesh or foil, or strikes a target. For this purpose we have constructed an X-ray pinhole camera from a set of plans obtained from Glen Kuswa of Sandia Laboratories. The 0.25 mm diameter pinhole was fabricated by pouring lead in a specially constructed mold. Diffraction of light from a He-Ne laser directed at the pinhole shows the expected pattern for a perfect circular aperture. This camera will be used in our studies of beam behavior in our beam concentration, propagation, and ion acceleration experiments this coming year.

I. Investigation of the Dielectric Cathode Guide

The dielectric cathode guide was introduced by this laboratory[12] with earlier AFOSR support for concentrating and guiding the delivery of beams, and it produced the greatest electron beam current density attainable at that time. This effort on the Boeing Radiation Effects Laboratory FX-75 machine has been completed and documented in publication A6 and dissertation B3 listed in Section IV. Abstracts of this work appear in Section IV.D. It is planned to investigate the properties of the dielectric cathode guide on the low impedance 0.5 MeV 7-ohm line machine at the NCSU laboratory this coming year.

J. Other Projects

The experimental effort on beam front scattering of electromagnetic radiation by a magnetized relativistic electron beam was completed during the first year of this contract. Two publications (listed as A2, A3 in Section IV and a dissertation (B3) were published after our last progress report. Abstracts of these works appear in Section IV.D.

The development of a computer simulation model for the FX-75 relativistic electron beam accelerator has been completed and documented in publication A5 and dissertation B2 listed in Section IV, with abstracts appearing in Section IV.D. Computed voltage and current waveforms, which depend on the machine configuration and electron beam characteristics, agree exceptionally well with observed waveforms.

A publication was prepared on the development and operation of a nanosecond response gasket-type magnetic loop current monitor for relativistic electron beam current measurements (see publication A7 in Section IV and the abstract in Section IV.D.

Deuteriopolymethylene (CD_2) is used in a variety of relativistic electron beam experiments ranging from ion acceleration to target preparation. It is commercially available in powder form, but machinable blocks have been needed in applications such as in the Luce-type diode for ion acceleration. With the mutual interest and cooperation of our Chemical Engineering Department, and some support for supplies from our previous and current AFOSR contracts, a pilot semi-batch process for the production of high deuterium content (97%) $(CD_2)_n$ in gram quantities was designed and set up. This project is now completed. A thesis, listed as publication B4 in Section IV, summarizes "The Effects of Process Variables on Properties of Deuteriopolymethylene in a Semi-Batch Scale System."

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IV. LIST OF PUBLICATIONS, DISSERTATIONS AND PAPERS PRESENTED DURING THE SECOND FUNDING YEAR OF CONTRACT AFOSR F 49620-76-C-0007

The following works have been published during the period July 1, 1977 - April 30, 1979. Abstracts are given in Section D.

A. Publications

1. J. A. Pasour, R. K. Parker, W. O. Doggett, D. Pershing and R. L. Gullickson, "Collective Ion Acceleration and Intense Electron Beam Propagation Within an Evacuated Dielectric Guide," Proceedings of the 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology, Cornell University, Ithaca, New York, Oct. 3-5, 1977, p. 623.

2. J. A. Pasour and S. P. Schlesinger, "Multichannel Grating Spectrometer for Millimeter Waves," Rev. Sci. Instrum., Vol. 48, No. 10, Oct. 1977, p. 1355.

3. J. A. Pasour, V. L. Granatstein and R. K. Parker, "Relativistic Mirror Experiment with Frequency Tuning and Energy Gain," Physical Review A, Vol. 16, No. 6, Dec. 1977, p. 2441.

4. J. A. Pasour, R. K. Gullickson, W. O. Doggett, and D. Pershing, "Collective Ion Acceleration and Intense Electron Beam Propagation Within an Evacuated Dielectric Guide," Proceedings of the 3rd International Conference on Collective Methods of Acceleration, University of California, Irvine, May 22-25, 1978.

5. Richard L. Copeland, Herbert P. Neff, Jr., Willard H. Bennett, David L. Morrow, and John L. Adamski, "A Simulation Model for the FX-75 Relativistic Electron Beam Accelerator," IEEE Transactions on Nuclear Science, Vol. NS-25, No. 3, June 1978, p. 1017.

6. Ray M. Stringfield, Jr., W. O. Doggett, and W. H. Bennett, "Flashover Speed and Surface Characteristics of Dielectric Cathodes in a Relativistic Electron Beam Accelerator," Paper D-5, Proceedings of the VIII International Symposium on Discharges and Electrical Insulation in Vacuum, 5-7 Sept. 1978, Sandia Laboratories, Albuquerque, NM.

7. Richard L. Copeland, John L. Adamski, Wesley O. Doggett, David L. Morrow, and Willard H. Bennett, "Nanosecond Response 'Gasket-Type' Magnetic Loop Current Monitor for Relativistic Electron Beam Current Measurements," Rev. Sci. Instrum. 50(2), Feb. 1979, p. 233.

B. Dissertations and Theses

1. John Alan Pasour, "Reflection of Electromagnetic Radiation from the Front of a Magnetically-Confined Relativistic Electron Beam," Ph.D. Dissertation, Dept. of Physics, North Carolina State University, Raleigh, NC, 1977.

B. Dissertations and Theses (continued)

2. Richard L. Copeland, "A Simulation Model for the FX-75 Relativistic Electron Beam Accelerator," Ph.D. Dissertation, Dept. of Electrical Engineering, University of Tenn., Knoxville, TN, June 1977.

3. Ray Modez Stringfield, Jr., "Surface Flashover Characteristics of Alumina Dielectric Guide Cathodes in an Intense Relativistic Electron Beam Accelerator," Ph.D. Dissertation, Dept. of Physics, North Carolina State University, Raleigh, NC, 1978.

4. Jorge Agustin Orozco Emmanuel, "The Effects of Process Variables on Properties of Deuteriopolymethylene in a Semi-Batch Scale System," M.S. Thesis, Dept. of Chemical Engineering, North Carolina State University, Raleigh, NC, 1978.

C. Papers Presented

1. Ray M. Stringfield, Jr., David L. Morrow, Wesley O. Doggett, Willard H. Bennett, Richard L. Copeland, John L. Adamski, and James R. Beymer, "Breakdown Characteristics of Dielectric Cathodes in a 3 MeV 80 kA Relativistic Electron Beam Accelerator," Bull. Amer. Phys. Soc. 22, 648 (1977).

2. J. A. Pasour, R. K. Parker, and V. L. Granatstein, "Production of High-Power Millimeter Waves by Reflection of Microwaves from a Relativistic Electron Beam Front," Bull. Amer. Phys. Soc. 22, 1110 (1977).

3. R. K. Parker, J. A. Pasour, W. O. Doggett, D. Pershing, and R. L. Gullickson, "Collective Ion Acceleration and Intense Electron Beam Propagation Within an Evacuated Dielectric Guide," Bull. Amer. Phys. Soc. 22, 1111 (1977).

4. R. L. Copeland, J. L. Adamski, W. O. Doggett, D. L. Morrow, and W. H. Bennett, "A Newly Improved 'Gasket-Type' Current Monitor for Return Current Measurements of Relativistic Electron Beams," Bull. Am. Phys. Soc. 23, 803 (1978).

5. J. J. Kim, D. L. Morrow, D. Pershing, J. R. Smith, and W. O. Doggett, "Emission Spectra from the Plasmas Generated by a Relativistic Electron Beam in an Evacuated Dielectric Guide," Bull. Am. Phys. Soc. 23, 840 (1978).

6. D. E. Pershing, C. M. Armstrong, J. J. Kim, D. A. Martin, D. L. Morrow, F. J. Murray, W. P. Sellers, J. R. Smith, and W. O. Doggett, "Relativistic Electron Beam Transport in a Dielectric Guide," Bull. Am. Phys. Soc. 23, 852 (1978).

7. R. H. Jackson, Jr. and R. K. Parker, "A Study of Beam Quality in Relativistic Crossed Field Injection Diodes," Bull. Amer. Phys. Soc. 23, 906 (1978).

C. Papers Presented (continued)

8. F. Murray, D. Pershing, J. Smith, and W. O. Doggett, Intense Relativistic Electron Beam Expanding into a Field-Free Vacuum," Bull. Amer. Phys. Soc. 24, 663 (1979).

9. D. L. Morrow, D. Pershing, J. R. Smith, D. A. Martin, C. M. Armstrong, J. J. Kim, F. Murray and W. O. Doggett, "Collective Ion Acceleration by Intense Relativistic Electron Beams," Bull. Amer. Phys. Soc. 24, 664 (1979).

D. Abstracts of Publications, Dissertations and Papers Presented

The full citation to these abstracts is given in Sections A, B, and C above.

A1. COLLECTIVE ION ACCELERATION AND INTENSE ELECTRON BEAM PROPAGATION WITHIN AN EVACUATED DIELECTRIC GUIDE

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Abstract

Experiments were conducted to extend a previous study[1] of collective ion acceleration and electron beam propagation within an evacuated dielectric guide to higher beam energies. The typical electron beam injection conditions were as follows: current ~ 65 kA, voltage ~ 1.5 MV, $\nu/\gamma \sim 1.4$ and pulse duration ~ 60 nsec. Beam propagation was found to depend upon space charge neutralization resulting from ions released from the walls of the dielectric guide. The primary energy loss mechanism was found to be erosion of the beam front. With a diode consisting of a small diameter cathode but no anode foil, protons with kinetic energies up to 14 MeV were detected on axis using nuclear activation techniques. The maximum observed yield was ~ 10^{13} protons (E > 3.8 MeV).

A2. Multichannel grating spectrometer for millimeter waves

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(Received 25 March 1977; in final form, 2 June 1977)

A multichannel grating spectrometer for use with high-power (~1 MW), short-duration (≲5 ns) pulses of millimeter-wavelength radiation is described.

A3.

PHYSICAL REVIEW A VOLUME 16, NUMBER 6 DECEMBER 1977

"Relativistic mirror" experiment with frequency tuning and energy gain*

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(Received 22 August 1977)

The front of an intense relativistic electron beam has been used to reflect a counterstreaming electromagnetic wave (f_i = 9.3 GHz, P_i = 250 kW). A doubly-Doppler-shifted reflected wave with a pulse duration on the order of a nanosecond has been produced with a sixfold increase in frequency, a 13-dB power gain, and a doubling of wave energy. The output has been analyzed with a multichannel grating spectrometer and found to have a spectral width $\Delta\lambda/\lambda$ of ~5%. The reflected-wave frequency was tunable over a range of ~±20% by simply varying the external magnetic field, and over a much broader range by simultaneously changing the beam rise time. All these observations are in good agreement with a simple theoretical model of beam-front scattering. This mechanism represents a new kind of short-pulse, high-power, tunable source of millimeter (and probably submillimeter) wavelength radiation, and it could be immediately useful as an electron-beam velocity diagnostic.

A4. ... PROPAGATION WITHIN AN EVACUATED DIELECTRIC GUIDE

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An experimental study of collective ion acceleration and electron beam propagation within an evacuated dielectric guide has been performed. This experiment extends a previous study[1] to higher beam energies (voltage $\approx$ 1.5 MV, current $\approx$ 65 kA, $\nu/\gamma \approx 1.4$, pulse duration $\approx$ 60 nsec). The electron beam is injected into a Lucite tube which is located inside a stainless steel cylinder. When the beam current exceeds the space charge limit, a virtual cathode forms at the beam front and electrons are lost to the wall of the acrylic guide, thereby liberating ions. Beam propagation is facilitated by the space charge neutralization provided by these ions, and a potential well travels down the guide with the beam front. Both radial and axial acceleration of protons are observed. It is likely that acceleration arises both from trapping of ions in the moving potential well and from the break-up of the well. Protons have been axially accelerated to 10 times the applied voltage, and a total yield of $\sim 10^{13}$ protons with energy > 5.8 MeV has been detected using nuclear activation techniques.

A5. A SIMULATION MODEL FOR THE FX-75 RELATIVISTIC ELECTRON BEAM ACCELERATOR

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Abstract

A one-dimensional, time-dependent coaxial transmission line model is presented for analysis of the voltage, v(z,t), and current, i(z,t), response to an electron beam load for the FX-75 accelerator. The model consists of finite segments of coaxial transmission lines separated by lumped equivalent circuits representing the various abrupt discontinuity points. Each line segment is divided into two one-dimensional grids with a 0.1 nanosecond transit time grid separation for the backward and forward TEM waves. Results from program FXPULSE utilizing a thirty-eight line-load representation of the FX-75 accelerator for a time-invariant, high-impedance diode load show close

A6.

Paper D-5 Presented At The
VIII International Symposium on
Discharges and Electrical Insulation in Vacuum
5-7 Sept. 1978, SANDIA Laboratories, Albuquerque, NM

FLASHOVER SPEED AND SURFACE CHARACTERISTICS OF DIELECTRIC CATHODES IN A RELATIVISTIC ELECTRON BEAM ACCELERATOR*

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ABSTRACT

The propagation speed of the flashover light produced by the filamentary surface breakdown of alumina dielectric rod cathodes used in a 3 MeV, 80 kA, 35 ns pulse duration relativistic electron beam accelerator has been measured. The light propagates from the cathode-dielectric junction at mean velocities of $(0.070 \pm 0.033)c$ on uncoated alumina rods and $(0.044 \pm 0.011)c$ on a rod coated with Cr_2O_3. These results appear to support the secondary electron avalanche model of fast flashover proposed by Anderson.[1] The path followed by the discharges is very reproducible over fifty or more events on each rod, except when straight grooves are sawed into the rods along their lengths. In this case, the filamentary paths are irreproducible. The irreproducible filamenting on grooved rods can be stopped by depositing a thin layer of graphite in the base of the groove. Alterations of the rod surface after flashover have been studied with scanning electron microscopy and proton recoil analysis. Uncoated alumina rods reveal no change other than discoloration except within the first two millimeters of the dielectric-metal cathode junction, but the Cr_2O_3 on the coated rods appears to be thermally removed by the flashover.

*This work was supported by the Air Force Office of Scientific Research (Contract #F49620-76-C-007) and Boeing Aerospace Company.

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A7.

Nanosecond response "gasket-type" magnetic loop current monitor for relativistic electron beam current measurements

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(Received 14 September 1978; in final form, 30 October 1978)

A fast response magnetic loop current monitor has been developed to measure relativistic electron beam return currents. The monitor has a rise time of about a nanosecond and a high degree of symmetry with moderate sensitivity, variable from about 1 to 10 V/kA. This simple monitor, with a thickness of 0.254 mm or less, is thin enough to be placed between segments of return current path in the diode or drift tube regions, is insensitive to flashover, beam and plasma bombardment, and radiation effects, and measures net current, thus offering some advantages over conventional magnetic probes, since the main components are outside of the vacuum region. Design criteria, an equivalent circuit analysis, and typical calibration waveforms are presented. Experimental current measurements for a pinched electron beam diode configuration using both conventional magnetic probes and "gasket-type" current monitors with the FX-75 relativistic electron beam accelerator are presented.

B1.
ABSTRACT

PASOUR, JOHN ALAN. Reflection of Electromagnetic Radiation from the Front of a Magnetically-Confined, Relativistic Electron Beam. (Under the direction of WESLEY O. DOGGETT.)

Reflection of an incident microwave pulse ($f_i \approx 9.3$ GHz, $P_i = 520$ kW) from the front of a magnetically-confined, relativistic electron beam has been experimentally observed and theoretically analyzed. A Doppler-shifted reflected wave with a pulse duration on the order of a nanosecond has been produced with a six-fold increase in frequency and a power gain of 10 dB. By analyzing this output with a multichannel grating spectrometer, the spectral intensity profile has been determined to have a width $\Delta\lambda/\lambda$ of approximately 5%. The reflected-wave frequency was tunable over a range of ~20-30% by simply varying the external magnetic field, and over a much broader range by simultaneously changing the beam rise time. All these experimental observations can be explained quite well by a theoretical model of beam-front scattering, which predicts that reflection should occur near the cyclotron resonance in the spatially-varying beam front. The maximum beam-frame reflection coefficient predicted by the model is 15% for a right-hand-circularly-polarized wave, or 7.5% for the linearly-polarized wave used in the experiment. Although the 5-MW, 50-GHz output observed corresponds to a reflection coefficient of 16%, the difference can probably be attributed to the approximations used in the model. The beam-front scattering mechanism represents a new kind of short-pulse, high-power, tunable source at millimeter (and probably submillimeter) wavelengths, and it could have important applications as an electron beam diagnostic.

B2.

ABSTRACT

COPELAND, RICHARD L. A Simulation Model for the FX-75 Relativistic Electron Beam Accelerator. (Under the direction of Willard H. Bennett.)

Since the first report of pulsed high intensity electron beams, many advancements in pulsed power technology have been made.[1] Present accelerators are capable of delivering 100 KV-10 MV, 10 KA-3 MA, 20ns-100ns output pulses.

Usually, a high voltage coaxial transmission line is either d-c or pulse charged to slightly less than the high voltage limit due to streamer formation and flashover between the transmission line electrodes. Then, a spark switch is closed, propagating a backward and forward T.E.M. wave from the spark switch discontinuity point. The forward wave propagates down a coaxial vacuum field emission tube, where cold-cathode field emission of electrons occurs all along the cathode shank (inner conductor). Electrons emitted along the shank are usually magnetically insulated from the coaxial anode wall, forming an "electron sheath" between the metal concentric conductors. This electron sheath forms the effective inner concentric cylindrical conductor. Usually, the cathode shank dimensions are chosen such that the characteristic impedance is somewhat larger than the charged line because the effective line impedance is determined by the electron sheath radius and the outer conductor radius. Then, when the wave reaches the anode-cathode gap, the field-emitted electrons are accelerated across the gap, thus forming an electron beam load discharge.

Relativisitic electron beams have been used extensively since the early 1960's to generate intense x-ray bursts, for use in materials response studies, flash x-ray radiography, nuclear weapons environment simulations, and other various radiation effects studies. Recent applications include collective ion acceleration, where ions are accelerated to energies greater than the electron beam energy and move in the same direction as the beam electrons.[2] Also, recent experiments have demonstrated the feasibility of generating intense pinches with current densities up to 10 MA/cm^2 within the accelerator diode.[3, 4] Calculations by M. J. Clauser predict breakeven fusion burn conditions when 10^{15} W of electron beam power is applied for 5. ns to a 2 mm diameter hollow metal sphere filled with DT gas.[5] Note that these high power requirements are well beyond present pulse power technology capabilities. The production of large, several gigawatts, bursts of rf power for several ns duration has been reported by J. A. Nation when an intense relativistic electron beam interacted with a long periodic structure inserted into the electron beam drift tube.[6] Also, the possibilities of using these intense electron beams to pump high pressure gaseous media to excited states seems promising to the field of high energy pulsed lasers.

The purpose of this dissertation is to develop a numerical model to predict the one-dimensional voltage and current T.E.M. waveforms for the FX-75 relativistic electron beam accelerator. The model consists of finite segments of coaxial transmission lines separated by lumped equivalent circuits representing the various discontinuity points. Each line segment is divided into two one-dimensional grids with a 0.1 ns one-way transit time point-to-point grid separation for the backward and forward T.E.M. waves. The electron beam discharge at the anode-cathode gap position is represented by an R, L, C lumped equivalent circuit with generalized time-varying parameters.

A one-dimensional time-dependent four line-load model, Flash, was used to simulate the FX-75 accelerator. A more complete fifteen line-load model, X-Ray, will be utilized to make small corrections to the Flash results. Numerical results from Flash and X-Ray are presented for two diode configurations and these results are compared to typical experimentally measured waveforms. The results are in excellent agreement for the high impedance flash x-ray time-independent electron beam load case, while somewhat less agreement was found for the low impedance time-dependent electron beam load case.

This simulation modeling approach may be useful in redesigning the accelerator and field emission tube components to produce optimal parameters for specific applications. These simulations will be utilized by the Boeing Radiation Laboratory, located in Seattle, Washington, in redesigning and optimizing the FX-75 electron beam accelerator.

B2.

BIBLIOGRAPHY

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2. Craig L. Olson, The Physics of Fluids, Vol. 18, No. 5, May, 1975.

3. David L. Morrow, J. Daniel Phillips, Ray M. Stringfield, Jr., Wesley O. Doggett and Willard H. Bennett, Applied Physics Letters, Vol. 19, No. 10, 1971.

4. G. Yonas, K. R. Prestwich, J. W. Poukey and J. R. Freeman, Physical Review Letters, Vol. 30, No. 164, 1973.

5. M. J. Clauser, Physical Review Letters, Vol. 34, No. 10, March, 1975.

6. J. A. Nation, Applied Physics Letters, Vol. 17, Dec., 1970.

B3.

ABSTRACT

STRINGFIELD, RAY MODEZ, JR. Surface Flashover Characteristics of Alumina Dielectric Guide Cathodes in an Intense Relativistic Electron Beam Accelerator. (Under the direction of WILLARD H. BENNETT.)

The surface flashover characteristics of alumina (Al_2O_3) dielectric guide cathodes have been experimentally observed and interpreted in light of the mechanism of surface charging proposed by Boersch et al, de Tourreil and Srivastava, and the model of flashover propagation proposed by Anderson. Alumina rods with and without a coating of Cr_2O_3 were studied. Measurements of the temporal behavior of the discharge, including the time of breakdown, and the propagation velocity of the flashover light front along the rod length were made, as well as observations of the reproducibility of the flashover path over many discharges. A method of timing fast events is presented which can be used when the experimental conditions preclude more conventional methods of measurement. The light from the discharge is found to initiate at the junction of the alumina with the metal center conductor of the coaxial vacuum diode within 2 nanoseconds of the start of the beam current, propagating down the rod length toward the anode with a velocity of about 0.07 c for bare alumina rods, where c is the speed of light, and 0.044 c for a rod coated with Cr_2O_3. Examinations of the surface of the rods after the tests using a scanning electron microscope and proton recoil analysis indicate that the surface of bare alumina rods is substantially unchanged by the discharge but that the coating is removed from the Cr_2O_3 coated rods along the discharge filament path but not from elsewhere on the surface. Attempts to have

the filament form in a groove sawed along the length of two rods failed. However, by depositing a thin, non-conducting layer of graphite into the base of the groove, the discharge was induced to remain in the channel for the four discharges observed. Both the removal of the Cr_2O_3 from the filament path on the coated rods and the propensity of the discharge to follow a thin layer of deposited graphite suggest that either or both effects may be useful for inducing the electron beam to follow a prescribed path. The reproducible filamentary discharge observed on the rods used during the propagation velocity measurements could not be induced to form when a diode was used having twice as large a characteristic impedance (~250 ohms vs ~125 ohms). In this instance the form of the discharge varied without an apparent pattern between a uniform sheath, a filamentary discharge, and no apparent discharge, with only a centimeter long band of luminosity near the anode end of the alumina rod.

B4.

ABSTRACT

EMMANUEL, JORGE AGUSTIN OROZCO. The Effects of Process Variables on Properties of Deuteriopolymethylene in a Semi-Batch Bench Scale System. (Under the direction of EDWARD P. STAHEL).

A semi-batch semi-automated bench scale system for the production of linear and branched deuteriopolymethylene was developed. Linear polymer was produced by decomposition with BF_3 or $(CH_3O)_3B$ of dideuterodiazomethane, which in turn had been generated through the Diazald® route. Branching was achieved by polymerization of a mixture of deuterated diazomethane and diazoethane. The latter was obtained from the hydrolysis of N-ethyl-N-nitroso-p-toluenesulfonamide, the ethyl homolog of Diazald®.

A literature survey of diazoalkane precursors, various aspects of the polymerization and a comprehensive review of proposed reaction mechanisms of the reaction of diazomethane with BF_3 are provided.

The synthesis of the diazoalkane precursor is described and the results of its analysis are presented. Yield enhancement studies suggested the use of a carbitol-methanol catalyst-solvent system for the generation. Both precursors were simultaneously hydrolyzed to form the diazoalkanes. Considerations of economy and of safety, because of the toxicity and explosive potential of diazoalkanes, were inherent in the final design, which included a generator, two reactors and a safety vessel in sequence.

The resulting deuteriopolymethylenes of varying properties were characterized using infrared spectroscopy, differential scanning calorimetry, x-ray diffraction and viscosimetry. High molecular weight polymers were produced whose melting points, heats of fusion and crystallinities decreased with increasing degrees of branching. Deuteration was estimated between 60 to 70%.

Results of a nuclear magnetic resonance spectroscopic analysis raised some question regarding reaction mechanisms. Recommendations for future work were made providing guidelines for increasing deuteration in the final product, kinetic and gel permeation chromatographic studies.

C1.

KH 8 Breakdown Characteristics of Dielectric Cathodes in a 3 MeV 80 kA Relativistic Electron Beam Accelerator.* RAY M. STRINGFIELD, JR., DAVID L. MORROW, WESLEY O. DOGGETT, and WILLARD H. BENNETT, North Carolina State University, RICHARD L. COPELAND, University of Tennessee, and JOHN L. ADAMSKI and JAMES R. BEYMER, Boeing Radiation Effects Laboratory--Continuing studies[1] have been made of the breakdown characteristics of plain, grooved, and Cr_2O_3 coated alumina dielectric rod cathodes. A velocity of propagation of flashover light of the order of 0.1 c was inferred from traces from two photomultipliers viewing different locations along the rod. Image converter and time integrated photographs show that light filaments occur along the rod in some cases, but not in others.

*Supported by the Air Force Office of Scientific Research and the Boeing Aerospace Company.

[1]Ray M. Stringfield, Jr., et. al., Bull. Am. Phys. Soc. 21, 1138 (1976).

C2.

4I1 Production of High-Power Millimeter Waves by Reflection of Microwaves from a Relativistic Electron Beam Front.† J. A. PASOUR,* R. K. PARKER, and V. L. GRANATSTEIN, Naval Research Laboratory--Using techniques discussed previously,[1] a 5 MW, 50 GHz pulse has been produced by reflecting a 250 kW, 9.3 GHz microwave signal from the front of a magnetized, relativistic electron beam. The reflected wave energy is nearly twice that of the incident wave. The output frequency is tunable with axial magnetic field as well as with beam-front velocity. Typically, the spectral width (FWHM) of the output, as determined with a multichannel grating spectrometer, is ~ 5%. The above results imply a beam-frame reflection coefficient of 30%.

†Partially supported by AFOSR.

*North Carolina State Univ.; presently NRC Research Associate at NRL.

[1]J. A. Pasour et al., Bull. Am. Phys. Soc. 21, 1112 (1976).

C3.

4I8 Collective Ion Acceleration and Intense Electron Beam Propagation Within An Evacuated Dielectric Guide. R. K. PARKER and J. A. PASOUR,* Naval Research Laboratory, W. O. DOGGETT and D. PERSHING, North Carolina State University,** and R. L. GULLICKSON, Air Force Office of Scientific Research--Experiments were conducted to extend a previous study[1] of collective ion acceleration and electron beam propagation within an evacuated dielectric guide to higher beam energies. In these experiments, the typical electron beam injection conditions were as follows: current ~ 65 kA, voltage ~ 1.5 MV, $\nu/\gamma \sim 1.4$, and pulse duration ~ 60 nsec. Beam propagation depended upon space charge neutralization resulting from ions released from the walls of the dielectric guide. The primary energy loss mechanism was erosion of the beam front. With a small diameter cathode and no anode foil, protons with kinetic energies up to 14 MeV were detected on axis. The maximum observed yield was ~ 10^{13} protons (E > 3.0 MeV).

*NRC Research Associate.

**Supported by AFOSR under Contract F49620-76-C-0007.

[1]A. Greenwald, R. Lovell, & R. Little, Bull. Am. Phys. Soc. 21, 1147 (1976).

C4.

4P12 A Newly Improved "Gasket-Type" Current Monitor for Return Current Measurements of Relativistic Electron Beams* R. L. Copeland, J. L. Adamski, Boeing Aerospace Co., and W. O. Doggett, D. L. Morrow, W. H. Bennett, North Carolina State University -- Recent improvements in the frequency response of "gasket-type" current monitors has extended the low frequency response significantly over previous[1] work. The monitor has a risetime of about a nanosecond and no apparent voltage droop for up to 100 nanosecond pulsewidths. This monitor has the main components outside of the vacuum region making it relatively insensitive to flashover, and beam or plasma bombardment. Current measurements for two different diode configurations using both conventional magnetic probes and "gasket-type" current monitors with the FX-75 REB accelerator are presented.

*Work supported by the Air Force Office of Scientific Research and The Boeing Aerospace Company.

[1]R. L. Copeland et al, Bull. Am. Phys. Soc. No. 9, 1041, Oct. 1976.

C5.

6P13 Emission Spectra from the Plasmas Generated by a Relativistic Electron Beam in an Evacuated Dielectric Guide.* J. J. KIM, D. L. MORROW, D. PERSHING, J. R. SMITH, and W. O. DOGGETT, North Carolina State U., Raleigh--Collective ion acceleration and electron beam propagation have been previously observed in an evacuated dielectric guide.[1,2] They substantially depend upon the guide length and diameter. Beam propagation is facilitated by space charge neutralization due to ions released from the walls of the dielectric guide. Emission spectra in the near-ultraviolet to visible range are being studied for the plasmas produced by a REB (0.5 MeV, 30 kA, 60 nsec) in dielectric tubes of various sizes. The spatial variations and temporal behavior of the emission spectra will be presented in connection with beam propagation and collective ion acceleration experiments.

*Supported by AFOSR under Contract F49620-76-C-0007.

[1]A. Greenwald, Third Int. Conf. on Collective Methods of Acceleration, May 22-25, 1978, University of California, Irvine.

[2]J. A. Pasour, R. K. Parker, R. L. Gullickson, W. O. Doggett, and D. Pershing, ibid.

C6.

7D1 Relativistic Electron Beam Transport in a Dielectric Guide. D. E. PERSHING, C. M. ARMSTRONG, J. J. KIM, D. A. MARTIN, D. L. MORROW, P. J. MURRAY, W. P. SELLERS, J. R. SMITH, and W. O. DOGGETT, North Carolina State U.*--Earlier experimental investigations[1] of intense relativistic electron beam propagation characteristics in evacuated acrylic pipes have been extended to 0.5 MeV, 60 nsec beams produced with the low impedance (7 ohm) accelerator at NCSU. Ions created by electrons striking the interior surface of the dielectric pipe provide space charge neutralization for beam propagation.[2] Results will be presented of experiments in which the injected current exceeds the Alfven limiting current to determine the degree of current neutralization provided by the background plasma. Measurements include beam size, energy transport, and ion acceleration.

*Supported by Air Force Office of Scientific Research Contract No. F49620-76-C-0007.

[1]R. K. Parker, J. A. Pasour, W. O. Doggett, D. E. Pershing, and R. L. Gullickson, Bull. Am. Phys. Soc. 22, 1111 (1977).

[2]A. Greenwald, R. Lovell, and R. Little, Bull. Am. Phys. Soc. 21, 1147 (1976).

C7.

10D4 A Study of Beam Quality in Relativistic Crossed-Field Injection Diodes. R. H. JACKSON, JR. and R. K. PARKER, Naval Research Laboratory*--Experiments in collective ion acceleration and stimulated scattering require the use of cold electron beams for efficient interactions. Cold beam production in foilless diodes is particularly difficult due to the crossed-field nature of the flow. This difficulty can be overcome in part by quasi-adiabatic expansion of the beam. In this configuration the beam is launched in a high magnetic field and expanded into a low field region down the drift tube. Results of experiments to characterize conventional diode and expansion diode effects on beam quality will be compared with numerical studies and related theory.

*Work supported by ONR.

C8.

HI 8 Intense Relativistic Electron Beam Expanding into a Field-Free Vacuum*. F. MURRAY**, D. PERSHING, J. SMITH, and W. O. DOGGETT, North Carolina State Univ., Raleigh, N. C.--An intense relativistic electron beam produced in NCSU's 7 ohm diode (0.5 MeV, 70 kA) is fired through a hole in the anode plate into a field-free vacuum. The transmitted portion of the beam expands as a result of its own self fields. A principle diagnostic employed is blue cellophane film which is calibrated to give current density as a function of change in transmission coefficient for red light. The transmission coefficient is determined on an optical microdensitometer which has been modified to accommodate He-Ne laser as its light source. The calibration constant which relates the current density to the change in transmission agrees within experimental error with a previously published value at much lower dose deposition rate.[1] Preliminary results will be presented which show the radial beam profile as a function of axial position.

*Supported by AFOSR Contract No. F49620-76-C-0007
**On sabbatical leave from U. of Scranton, Scranton, PA
[1]E. J. Henley and D. Richman, Anal. Chem. 28, 1580 (1956).

C9.

HI 9 Collective Ion Acceleration by Intense Relativistic Electron Beams*. D. L. MORROW, D. PERSHING, J. R. SMITH, D. A. MARTIN, C. M. ARMSTRONG, J. J. KIM, F. MURRAY**, and W. O. DOGGETT, North Carolina State U.--A variety of collective ion acceleration experiments are being conducted on the NCSU intense relativistic electron beam accelerator (0.5 MeV, 70 kA, 60 nsec). Ions are produced by the electron beam striking (1) the periphery of a 1 cm orifice in a polyethylene anode plate, (2) a 0.01 mm thick plastic sheet in the anode plane, or (3) a plastic liner in an evacuated drift tube in a foilless diode geometry. Accelerated protons are detected with nuclear activation of carbon and BN. The results will be compared with previous experiments at Boeing's FX-75[1] (5 MeV) and NRL's VEBA[2] (1.8 MeV) accelerators.

*Supported by AFOSR Contract No. F49620-76-C-0007.
**On sabbatical leave from U. of Scranton, Scranton, PA.
[1]W. O. Doggett and W. H. Bennett, Second Symposium on Collective Methods of Acceleration, JINR, Dubna, USSR, 29 Sept., 1976.
[2]J. A. Pasour et al., Third Int'l Conference on Collective Methods of Acceleration, Univ. of Calif., Irvine, May 22, 1978.

V. PERSONNEL

In addition to Professors Wesley O. Doggett, Jin J. Kim and Carter M. Armstrong the following graduate students have contributed to this project during the second funding year:

Dean E. Pershing	Beam diagnostics and propagation in a dielectric liner, VEBA experiments
John R. Smith	Calorimeter calibration, spectroscopy, X-ray pinhole camera
David L. Morrow	Ion acceleration
Robert H. Jackson, Jr.	Computer simulation of beam propagation in magnetic field and theoretical study of beam equilibrium profiles
W. Preston Sellers	Thomson parabola ion spectrometer
R. Lawrence Ives	Interfacing calculator with laboratory equipment
David A. Martin	Mapping of X-ray radiation
Jorge A. O. Emmanuel	Study of CD_2 physical characteristics

Professor Willard H. Bennett, Burlington Professor of Physics, Emeritus, served as a consultant on certain aspects of the program. In addition, Dr. Frank J. Murray, Associate Professor of Physics at the University of Scranton, spent the 1978-79 academic year on a sabbatical leave in the NCSU plasma physics laboratory and participated in several phases of the project, particularly the blue cellophane calibration experiments.

Undergraduate students Dwight F. Price and David R. Wheeler (work-study student) worked on a variety of tasks in the laboratory.

Several former graduate students whose dissertation research was made possible by this contract are now successfully contributing to Department of Defense funded programs: Dr. John A. Pasour at the Naval Research Laboratory, Dr. Ray M. Stringfield, Jr. at the Physics International Company, and Dr. Richard L. Copeland at the Boeing Radiation Effects Laboratory. Another student Dean E. Pershing has been offered a National Research Council Associateship to work at the Naval Research Laboratory when he completes his dissertation this coming year. Mr. Robert H. Jackson, Jr. will perform the electron beam quality measurements and simulation calculations at NRL's facilities in collaboration with Drs. Robert K. Parker and Victor L. Granatstein who will serve on his Ph.D. committee as Adjunct Professors of Physics at NCSU.