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D. S. Prono

R. Clark

K. Prestwich

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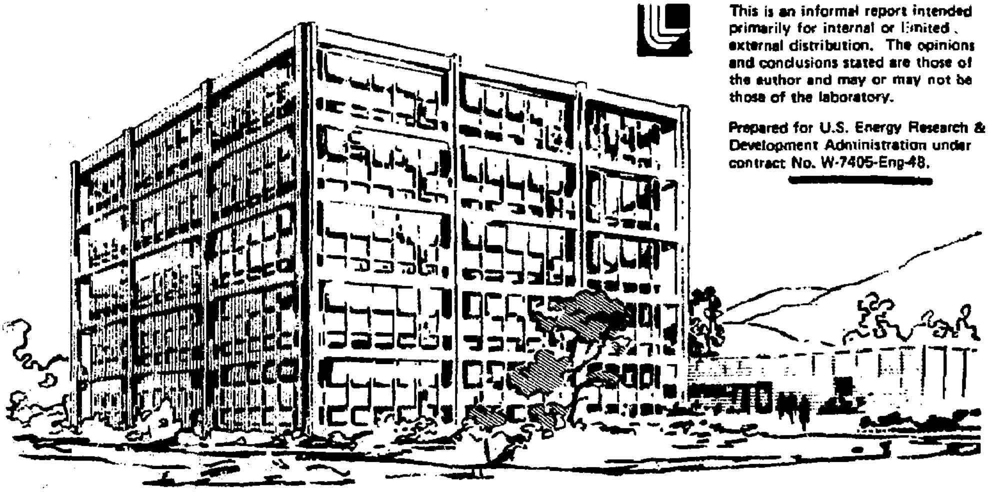

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EXPERIMENTAL OBSERVATIONS ON LONG PUSLE INTENSE ION DIODE OPERATION

BY

D. S. Prono

Lawrence Livermore Laboratory, University of California

Livermore, California 94550

R. Clark and K. Prestwich

Sandia Laboratories, Albuquerque, New Mexico 87115

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ABSTRACT

An experiment in which a long pulse electron beam diode is converted to a reflex ion diode is reported. The results further substantiate the model of reflex ion diode behavior as well as extend the duration of ion mode operation to >500 nsec.

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INTRODUCTION

Normal electron beam diode operation begins by applying a negative pulse to a cathode plane. Electrons are emitted by field emission and are accelerated across the gap to an anode plane which consists of a range thin material. A drift region containing a plasma or neutral gas held at ~1 torr pressure immediately follows the anode foil. As the electron beam emerges from the anode foil it enters the plasma column or very rapidly ionizes the neutral gas thereby creating a plasma column. This plasma shorts out magnetic and electrostatic fields thus allowing the beam to propagate the length of the drift chamber.

For the virtual cathode ion diode mode of operation(1,2) the drift chamber is evacuated. To offset the self magnetic fields of the beam, an external B_z field is applied. However, the beam's electrostatic fields are not shorted out and if the injected current is above a limiting value(3) then beam propagation is prevented and a "virtual cathode" is formed. The beam electrons are continually reflected between the virtual and the real cathode and cross back and forth through the anode, each time being scattered and losing energy. The effect of these refluxing electron trajectories is to create an electric field highly peaked around the anode. When sufficient anode plasma has been formed these electric fields extract an intense ion current from the anode plasma. Because this ion current is accelerated back into the diode gap the diode's space charge is lowered and significantly higher diode currents at reduced voltages result.

The key to the intense ion diode process is that the anode foil which causes electron scattering and energy loss controls the electron energy spectrum within the diode. Since the diode voltage results from a self consistent solution of diode space charge, the material and the thickness of the anode foil also controls diode voltage.

These characteristics of ion diode operation, along with measurements on intense ion currents, have been previously observed on short duration (100 ns) low impedance (3 ohm) beam generators[1,2]. For some applications, 1 μs pulse durations and low impedance generators (0.4 ohms) are desired. Such an experiment is presently being build at LLL, but as an interim step to further test the ion diode concept, an experiment was conducted using a high impedance 1 microsecond generator. This experiment was conducted using a facility at Sandia Laboratories (Albuquerque) and was undertaken with the full cooperation of Sandia pulse power staff. The purpose of the experiment was to test whether characteristic signatures of ion diode operation do occur on generators totally different from that previously used, to gain further information on diode operation, and to empirically determine if major problems preclude lengthening ion diode pulse durations.

EXPERIMENTAL APPARATUS

The experiment was performed on the Lili electron beam accelerator (600 kV, 20 kJ, 1 μs) at Sandia Laboratories. The generator consists of a 1.2 MV Marx generator, a voltage peaking network and a diode. Schematically, the circuit is shown in Figure 1A. The peaking capacitor is charged by the Marx and at peak voltage, both networks are discharge into the diode through a gas switch. The diode geometry is shown in Figure 1B. Regarding the external field coils, care was taken to insure that the field rise time was sufficiently long (7 ms) to allow uniform penetration through the drift chamber flanges, the tubular cathode shank, and the graphite cathode front surface. The applied B_z field strength of 4 to 6 kgauss always exceeded the diode current's self B -field which in the extreme reached 3.3 kgauss. The base pressure of the diode was 4×10^{-4} torr; the drift chamber was at 1 torr of Nitrogen when a normal electron beam mode was desired, and was at 4×10^{-4} torr when in the ion diode mode.

Since our purpose was to study gross observable features of an ion diode, only machine diagnostics were used; ion diagnostics were not employed. Voltage monitoring was by a copper sulfate resistor divider spanning the insulator. Current monitoring was by a $\dot{B}$ probe near the insulator and a resistor belt along the anode current return snout. Cathode shank emission or insulator flash-over were not observed. The amount of heating of the drift chamber end flange was observed and was used to determine whether beam propagation occured (an auxiliary indication of whether a virtual cathode was created). The $\dot{B}$ probe was used to correct the measured voltage for the inductive drop ($V_{diode} = V_{measured} - L\dot{I}$), and were properly calibrated using shorted shots. On this high impedance (low current) long pulse generator the inductive correction was always very small (80 kv) whereas on previous experiments[1,2] it was a substantial correction (500 kv) which caused some concern.

Unfortunately, the frequency response of the diagnostics and oscilloscopes used on this experiment were limited to 50 MHz. In previous work[2] the virtual cathode exhibited voltage oscillations in the 100 - 200 MHz range. Such oscillations could not be observed in this experiment. Finally, before establishing the reflex ion diode operational mode, a light surface layer of hydrocarbon pump oil was applied to the aluminized anode surface facing the cathode. Hence, the ion currents filling the diode were comprised primarly of protons.

EXPERIMENTAL RESULTS

Figure 2 shows two shots of normal operational characteristics for the UCI diode when in an electron beam mode. Alterations of these characteristics will signify the character of the ion diode mode. The anode foil was 1 mil of aluminized mylar with the aluminum facing toward the cathode; a 4 cm anode-cathode gap was sufficient to give a 1.6 micro second pulse duration (our plots only go to 1.2 micro seconds). B_z was 4 kgauss; other shots that were operated with 6 kgauss had essentially the same I-V characteristics. The drift chamber pressure was 1 torr and the heating of the end flange indicated that substantially all of the 18.5 k Joules of beam energy propagated the drift tube length. The diode impedance demonstrated the normal high early phase impedance and then falls to plateaus of 30 and 17 ohms at successive later times.

Using the same anode foil and gap spacing, a virtual cathode ion diode operational mode was established. In Figure 3 the dot-dashed curve (—·-·) indicates diode performance when B_z was left at 4 kgauss. For this arrangement only slight differences from Figure 2 are noticeable. Heating of the drift chamber end flange again indicated nearly the total beam propagated. Increasing B_z to respectively 5 (dashed curve, ----) and then to maximum capability of 6 kgauss (solid curve, ——) caused dramatic alteration of the diode performance. Although beam energy was reduced only 15 to 30% from the previous conditions, heating of the end flange was negligible. During the initial transition phase (first 100 ns) the diode impedance was higher than normal. Subsequently the diode impedance rapidly decreases to ~10 ohms, thus signifying the ion diode mode. The arrows indicate the time at which the diode impednace begins to drop significantly lower than normal; about 2.25 k Joules of beam energy is required to initiate this transition.

The diode voltage drops to ~275 kV, a value 40% lower than normal, and the current eventually rises to a value 90% greater than those shown in Figure 2. The diode voltage demonstrates bistable operation, a trait that will be further discussed in the following section. The pulse duration is limited by gap closure and is reduced to 1.1 to 1.2 microseconds.

For the data of Figure 4, the anode foil was changed to 1/4 mil aluminized mylar, all other parameters were unchanged (B_z = 6 kgauss). In this case, the diode voltage drops to ~90 kV and the current increases to 60 kA; the pulse duration has been further shortened to .7 - .8 microseconds. The diode impedance still exhibits values higher than normal during the early phase, and then rapidly changes to even lower impedances (2 to 4 ohms) during the ion mode. The beam energy required for the initiation of the low impedance mode is ~1 k Joule. The total beam energy is now drastically lower (3 to 6 kJ), due in part to the shorter pulse length but also resulting from high reflected power (high impedance mismatch between generator and diode load). However, there was still no indication of energy being deposited in the drift chamber end flange.

INTERPRETATION

In this section we discuss how the LILI experimental results further substantiate the reflex ion diode model. The main points are:

1. The importance of the reflecting virtual cathode and how it is controlled by the B_z field has been clearly indicated.
2. The validity of diode voltage being controlled by anode foil properties has been strengthened since, the inductive correction ($L\dot{I}$) for the LILI experiment is small.

3. Unlike previous work, B_z always exceeded the beam B_θ in the diode, thus the possibility of ion generation by focused electron flow[4] was avoided.
4. Even though LILI had beam and B_z field parameters completely different from previous work, the traits of the ion diode operational mode remain similar.

However, possibly the most significant finding is that long duration intense ion beam generation by this technique appears to have a reasonable chance of success.

The first of these points refers to the data of Figure 3. Briefly, for too low a magnetic field nearly complete beam propagation occured even though in vacuum; as the external B_z field was increased a virtual cathode was apparently formed which inhibited propagation and strongly initiated the ion flow mode. A qualitative explanation for this behavior involves the system limiting currents[3], (I_l) the maximum current which is electrostatically allowed due to system geometry and beam energy. If the injected diode current, I_d, exceeds the related I_l then beam stagnation occurs (i.e. a virtual cathode is formed). In Table I we use the information in Reference 3 to determine the value of I_l as a function of beam energy for two limiting conditions: first, the beam just filling the drift tube (b/a = 1); and second, when sufficient $\dot{B}_z$ field is applied so that the beam maintains its original cathode diameter (b/a = 2.33).

TABLE I

Limiting Current, I_L, versus $\frac{b}{a}$ and V (b = drift tube radius, a = beam radius, r_c = cathode radius)

	V = 500 kv	700 kv	1000 kv
I_L if $\frac{b}{a} = 1$	12 kA	18 kA	27 kA
I_L if $\frac{b}{a(=r_c)} = 2.33$	4 kA	5 kA	8 kA

An approximate B_z value that would allow the beam to just fill the pipe would be when the electrons in traveling from r_c to b execute one Larmor orbit of radius R_L = b-a/2, then

$$B_z = \frac{\sqrt{\gamma^2-1}\, mc}{R_L} .$$

For γ = 2.4 (700 kv) this gives a B_z = 1.5 kgauss. The external applied B_z must have a value larger than this since the net effect of the diamagnetic gyro-orbits and paramagnetic guiding center drift would be to reduce the field between the beam edge and the wall. Despite this inexact determination, the external B_z must be sufficiently larger than 1.5 kgauss so that b/a will be 2.3. Thus when I_d I_L a virtual cathode will be created. Experimentally the threshold was determined to be 4 kgauss.

The second and third of the itemized points are self-apparent. As indicated in the fourth, in general terms, the virtual cathode ion diode mode on the LILI generator behaves in a manner identical to that observed in other experiments[1,2]. The initial higher-impedance-than-normal state occurs due to reflexing electrons increasing the diode space charge before ion currents begin. The onset of the ion currents requires sufficient energy deposited into the anode foil to create an ion plasma source. Diode voltage characterizing the ion-mode is controllable by anode foil properties and as the total diode current increases, the diode voltage is reduced.

In Table II the characteristic diode behavior for the LILI experiment is compared to the diode performance from previous experiments. The anode material and the cathode areas were identical for the two different experiments.

TABLE II

Comparison of Ion Diode Characteristics for different Experiments

	Anode thickness	LILI Experiment (4 cm A-K gap, normal peak voltage of 1 MV, and normal 34 ohm diode)	OWL Experiment (0.9 cm A-K gap, normal peak voltage of 750 kv, and normal 2.3 ohm diode)
Diode Voltage after transition into ion mode	1 mil	275 kv	260 kv
	$\frac{1}{4}$ mil	90 kv	150 kv
Diode impedance reduction $\left(\frac{\text{ion mode } Z_D}{\text{normal } Z_D}\right)$	1 mil	.29	.2
	$\frac{1}{4}$ mil	.09	.09
Beam Energy required before ion mode	1 mil	2.25 kJ	1.5 kJ
	$\frac{1}{4}$ mil	1 kJ	0.7 kJ
Duration of low impedance ion mode	1 mil	850 ns	60 ns
	$\frac{1}{4}$ mil	500 ns	60 ns

Other than the ion flow duration, the greatest discrepancy between these different experiments is in the ion mode diode voltage for the 1/4 mil anode material. This difference is unexplained.

The observed bistable diode voltage operation is reminiscent of early work[1] where the virtual cathode was destroyed (because of background ionization) partway through the beam pulse. When this occurs the ion flow terminates, thus the diode space charge increases and the diode voltage returns to normal values (diode inductance partially preserves the currents at higher than normal values). Similar problems relating to control of virtual cathode stability for 1 microsecond durations could account for the observed bistable behavior. With two real reflecting cathodes at fixed potentials, it is expected that such problems will be avoided.

A remaining topic is the limitations on diode life time. Experimentally (Figure 3 and 4), as anode foil thickness was decreased the pulse duration was shortened. For reflex ion-diode operation, the energy carried by the electron current is absorbed by the anode foil. Gauged by previous experiments[2] the ion current for these foils would constitute only 7 to 17% of the total current, thus the measured beam energy is nearly all electron energy. Hence, one would anticipate greater gap closure velocities and shorter pulse durations to accompany greater values of the ratio (beam energy/mgm-cm^2 of foil). However, for Figure 3 this ratio varies from 3.6 to 4.4 kJ/mgm-cm^{-2} while for figure 4 it ranges from 3.3 to 6.7 kJ/mgm-cm^{-2}. As it stands, the near equality cannot account for the pulse shortening, but yet it is not entirely ruled out.

However, a second explanation involves the ion currents that fill the diode. These ion currents have a far greater ability to ionize the low pressure (4×10^{-4} torr) diode gap than do electrons. The ionization cross section, σ_{01}, for H^+ ionizing nitrogen(5) is broadly peaked from about 50 to 100 kev at a value of 7×10^{-16} cm^2/atom and this cross section increases approximately as the square root of ion mass. A simple estimate for the total number of nitrogen ions produced by proton impact ionization (σ_{01}) would then be

$$N_+ = \frac{I_i}{q} t l n_g \sigma_{01}$$

where I_i is the ion current, l is the gap spacing, t is time and n_g is the neutral gas density ($= 2.6 \times 10^{13}$ cm^{-3}). In terms of number density ratios (degree of ionization), this would be $\frac{n_+}{n_g} = \frac{J_i}{q} \sigma_{01} t$. Using $J_i = 100$ A/cm^2 (10 total current density) determines that the gap can be 10 ionized in 230 nsec. Such a plasma could effectively short the acceleration gap. This model does correctly predict the trend of pulse duration since thinner anode foils have been observed(2) to produce greater I_i. However, the obvious test of improving diode base pressure has not yet been done.

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FIGURE CAPTIONS

Figure 1: A) Circuit of LILI generator.

B) Geometry of LILI diode.

Figure 2: Characteristics of normally operating LILI diode when in electron beam mode. Reproducibility is indicated by the two separate experiments shown.

Figure 3: Characteristics of virtual cathode reflex ion diode when anode foil is 1 mil aluminized mylar and for three different B_z field levels (see text).

Figure 4: Characteristics of virtual cathode reflex ion diode when anode foil is 1/4 mil aluminized mylar. Reproducibility is indicated by the two separate experiments shown.

Figure 1a

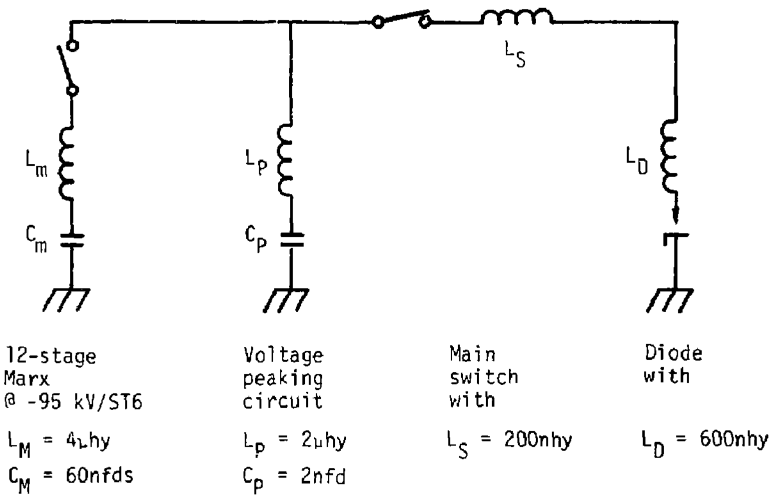


Figure 1b

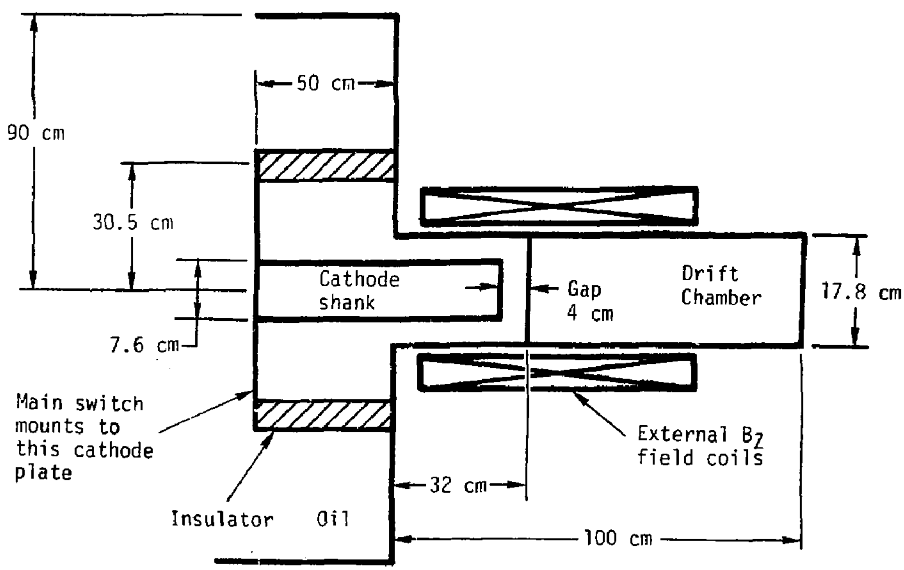
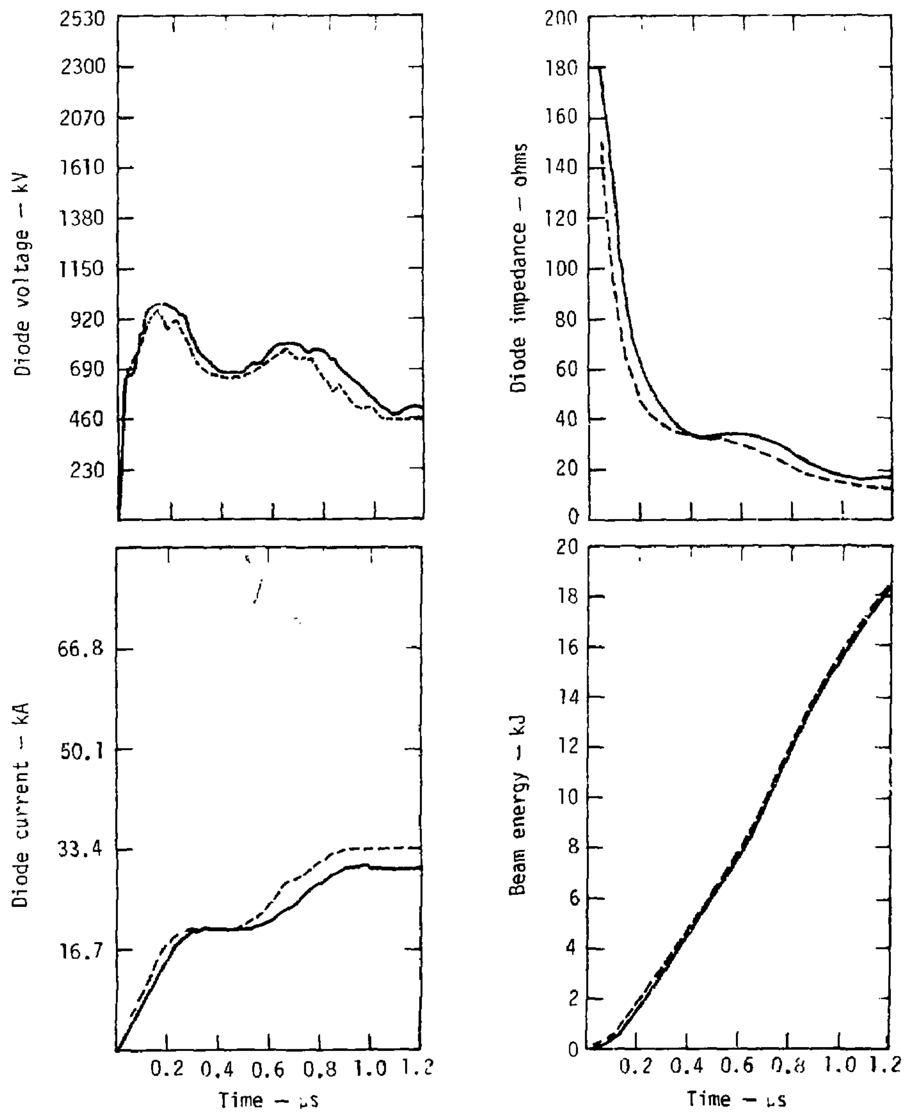
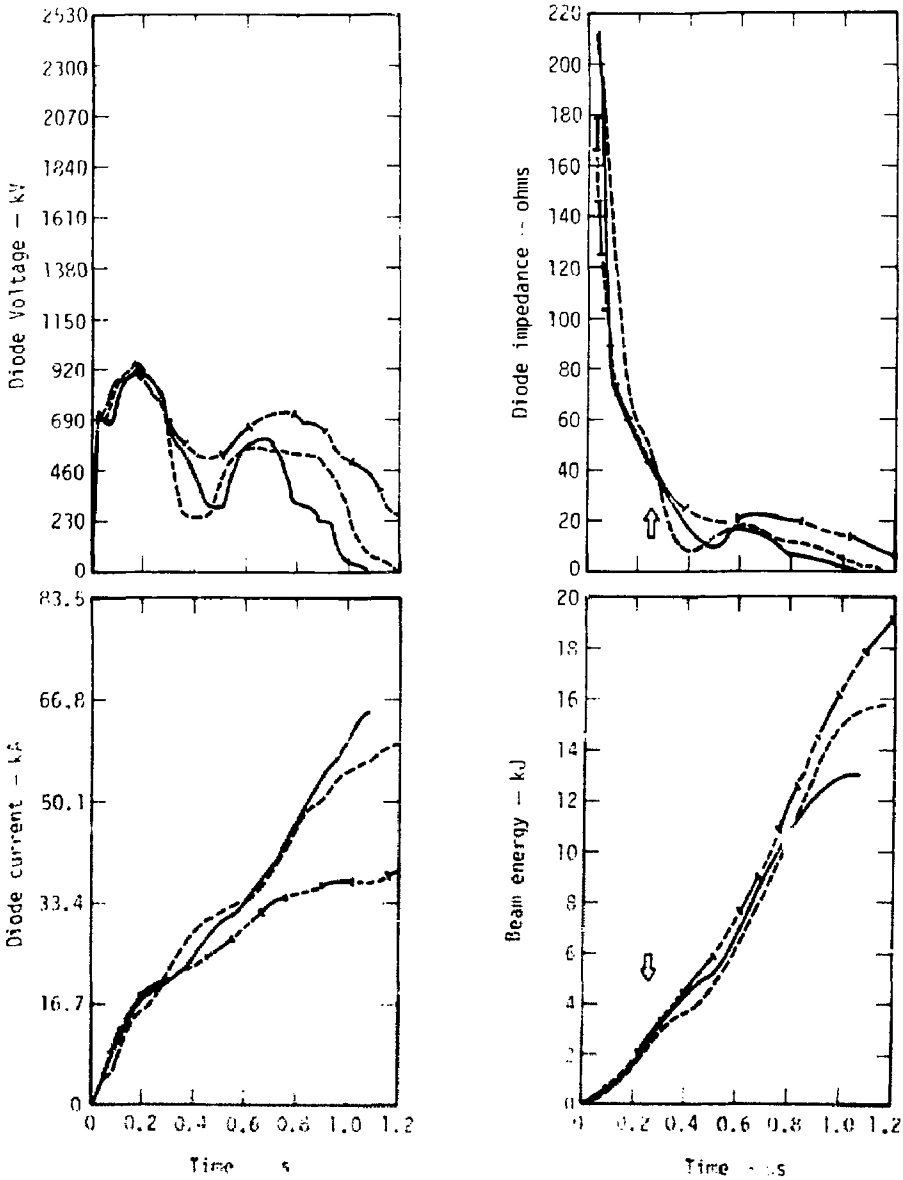


Figure 2



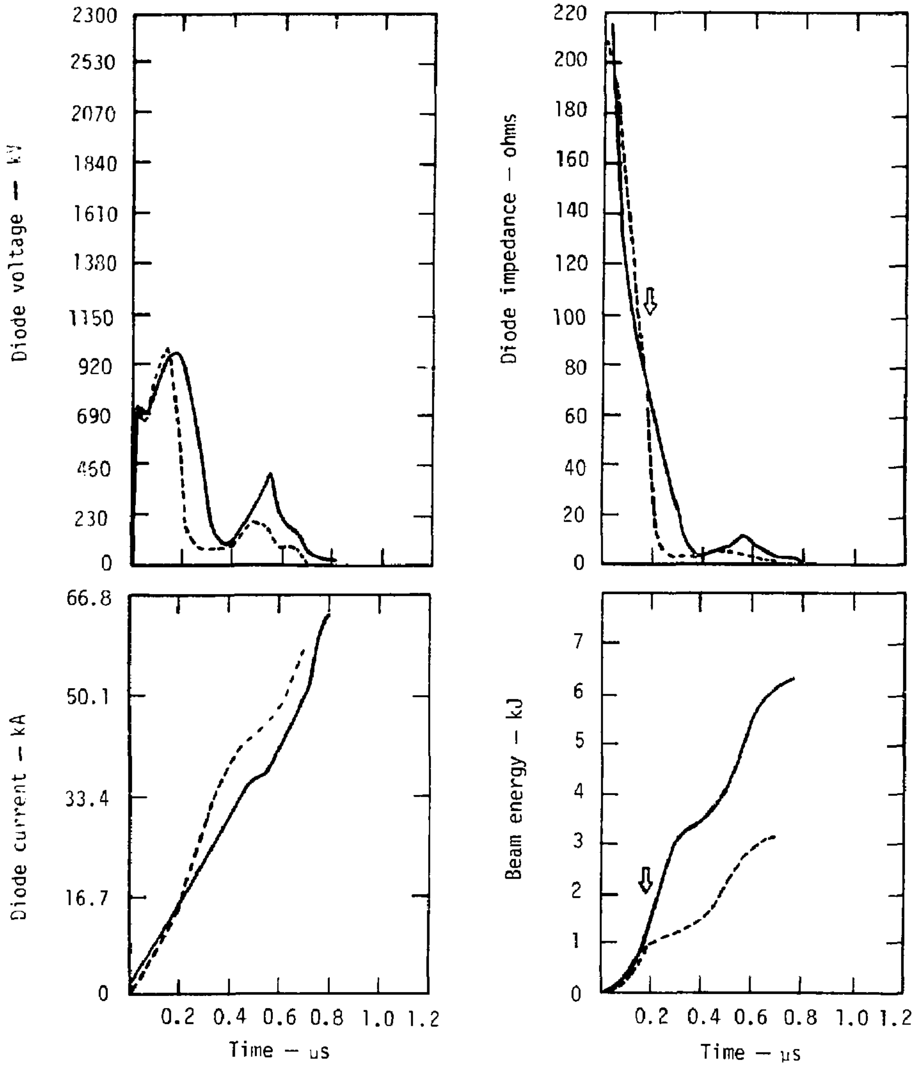
Diode voltage — kV
2530
2300
2070
1610
1380
1150
920
690
460
230
Diode impedance — ohms
200
180
160
140
120
100
80
60
40
20
0
Diode current — kA
66.8
50.1
33.4
16.7
0.2 0.4 0.6 0.8 1.0 1.2
Time — μs
Beam energy — kJ
20
18
16
14
12
10
8
6
4
2
0
0.2 0.4 0.6 0.8 1.0 1.2
Time — μs

Figure 3



Diode Voltage — kV
Diode impedance — ohms
Diode current — kA
Beam energy — kJ
Time

Figure 4



Diode voltage — kV
2300
2530
2070
1840
1610
1380
1150
920
690
460
230
0
Diode impedance — ohms
220
200
180
160
140
120
100
80
60
40
20
0
Diode current — kA
66.8
50.1
33.4
16.7
0
Beam energy — kJ
7
6
5
4
3
2
1
0
0.2 0.4 0.6 0.8 1.0 1.2
Time — μs
0.2 0.4 0.6 0.8 1.0 1.2
Time — μs