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RADIAL ELECTRON BEAM LASER EXCITATION
THE REBLE REPORT

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ABSTRACT

The results of an investigation of techniques to generate high-power radially converging electron beams and the application of these beams to gas lasers is discussed. The design and performance of the PEBLE accelerator that was developed for this program is presented. Reliable operation of the radial diode has been obtained at levels up to 1 MV, 200 kA, and 20 ns. It has been demonstrated that the anode current density can be made uniform to better than 15 percent over 1000 cm^2 areas with $100\text{--}250\text{ A/cm}^2$ intensities. The measured total and spatially resolved energy deposition of this radial electron beam in various gases is compared with Monte Carlo calculations. In most cases, these codes give an accurate description of the beam transport and energy deposition. With the electron beam pumping xenon gas, the amplitude of xenon excimer radiation (1720 Å^0) was radially uniform to within the experimental uncertainty. The efficiency of converting deposited electron beam energy to xenon excimer radiation was 20 percent.

Radial Electron Beam Laser Excitation

The REBLE Report

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I. INTRODUCTION

Relativistic electron beams (REBS) have found increasing use in excitation of gas laser systems. The high power capability of REBS make this pumping scheme highly promising for use in high power lasers. Three different geometries have been used to excite gas lasers with REBS: axial, transverse, and radial excitation. In these geometries the electron beam is injected axially, transversely or radially with respect to the laser optical axis.¹

A drawing of the axial injection scheme is shown in Fig. 1. After passing through the anode of the REB accelerator, the electron beam is magnetically guided through a bend into the laser cell. An axial magnetic field is used to guide the beam along the cell and to reduce scattering of electrons into the cell walls. A transverse magnetic field near the far end of the cell is used to dump the remaining beam into the walls to prevent damage of the laser window by the electron beam. This geometry has been used for low pressure systems or when the ratio of laser length to diameter is large.

Another scheme which has been widely used is the transverse excitation geometry. A schematic representation of this arrangement is shown in Fig. 2. The beam generated at the cathode passes through the anode-high pressure window and propagates transversely through the laser cell. An external magnetic field can be applied in the diode region to prevent beam pinching effects. The length of the excitation region is determined by the length of the electron beam, i.e., the length of the cathode. One negative feature of this scheme as it is normally implemented is that, in order to get uniform energy deposition across the laser cell, only a small fraction of the electron beam energy can be deposited in the gas;

Fig. 1. Axial excitation scheme

Fig. 2. Transverse excitation scheme

the remainder of the electron beam energy is dumped into the far wall of the laser cell. One possible method of improving on this situation is to use a double transverse injection scheme as shown in Fig. 3.

The radial electron beam excitation scheme is shown in Fig. 4. In this geometry the anode and cathode are concentric cylinders with the anode as the inner cylinder. The anode also defines the volume of the laser cell. Although a number of advantages exist with this geometry, limited use has been made of it in laser excitation studies.²

Due to the symmetry of the radial diode it should be capable of producing uniform current densities at the anode along the azimuthal direction. Computer calculations using Monte Carlo electron/proton transport codes³ show that a large fraction of the electron beam energy can be uniformly deposited in the gas laser medium. One further advantage of this excitation scheme is that it can readily be adapted to modular construction for large energy systems. Figure 5 is an artist's sketch of a four module radial electron beam accelerator. The radial discs that separate the individual diodes provide the return current paths and magnetically isolate each of the cathodes. Each diode would operate below I_c , the current at which strong pinching effects are observed. In this arrangement it is easy to add as many diodes as necessary to obtain the total required electron beam energy.

As was noted earlier, a comprehensive study of the radial electron beam diode has been lacking and only limited use has been made of the radial excitation scheme. This manuscript reports on results of investigations into high power radial diodes and their application to high power laser systems. A detailed description of the REBLE accelerator⁴ built for these investigations is given in Section II. Investigations into the

Fig. 3. Double transverse excitation scheme

Fig. 4. Radial excitation scheme

Fig. 5. Four-module radial electron beam accelerator

operating characteristics of the radial diode are discussed in Section III. Results of beam transport through the anode foil and the gas are given in Sections IV and V respectively. Measurements of the total and spatially resolved energy deposition are presented in Section VI together with calculational results from a Monte Carlo electron/photon transport model.⁵ In Section VII results of xenon excimer light output measurements are presented.⁶ Section VIII is a discussion of a brief attempt to operate the REBLE diode as an H-F laser cavity.

II. REBLE ACCELERATOR

A. General Description

The REBLE accelerator was designed to produce a nominal 1 MV, 180 kA, 20 ns electron beam pulse. The design for this accelerator was based on the pulse power technology under development at Sandia for the particle-beam fusion program.⁷ A block diagram of the accelerator components is shown in Fig. 1. A Marx generator pulse charges an intermediate energy store capacitor (I. Store) through a 5 μ H inductor. The I. Store is then discharged through a self-breaking gas switch into two sets of oil dielectric pulse-forming transmission lines (PFL's) which are equipped with self-breaking, multichannel, oil switches. The output pulses from the PFL's are fed to the diode via oil dielectric transmission lines. A triggered gas switch is used to divert, through a resistive load, the energy which remains in the Marx after the intermediate store was charged. This crowbar system was required due to the poor matching between the Marx generator capacitance and that of the intermediate energy store. An artist's rendering of the final configuration of REBLE is shown in Fig. 7. A description of the individual components is given below.

Fig. 6. Block diagram of REBLE accelerator

Fig. 7. REBLE accelerator with a water-dielectric capacitor for the intermediate energy store

B. The Marx Generator

REBLE was built in a pre-existing, multipurpose test facility. The pre-existing Marx generator, used as the main energy store for REBLE, is an adaptation of the REBA⁸ and HERMES II⁹ Marx generators. The operating configuration of this Marx is one which results in a lower inductance per stage than the above two Marxes. Its relevant characteristics are summarized in Table I.

TABLE I
Marx Generator Parameters

Number of stages	20
Capacitance per stage	0.5 μ F
Maximum charge voltage	± 100 kV
Maximum total energy	50 kJ
Output capacitance	25 nF
Series resistance	10 Ω
Series inductance	5 μ H

C. The Intermediate Energy Storage Capacitor

The dielectric breakdown strength of liquids is strongly time dependent. If the Marx generator was used to directly charge the PFL's, the resulting charging time would be ~ 800 ns. By using an intermediate storage capacitor, the PFL's can be charged in ~ 120 ns thus allowing the use of lower impedance PFL's constructed with electrodes that have a substantial field enhancement at the edges.¹⁰

The first intermediate store used consisted of stacked set of five parallel plate lines immersed in oil. The lines were 1.22 m wide by 2.44 m long by 10.2 cm thick. The edges of the lines were fully radiused. The

distance between each line was 10.2 cm and they were held together by means of polyethylene spacers shown in Fig. 8. This version of the intermediate store can be seen installed in the artist's sketch shown in Fig. 9.

Preliminary testing using the configuration shown in Fig. 9 encountered flashover breakdowns along the polyethylene support feet in the intermediate energy store. This flashover problem limited the output pulse amplitude to a maximum of 500-600 kV. After an alternate method for supporting the lines of the I. Store failed to correct these flashover problems, the entire unit was removed and replaced with a water capacitor.

This storage capacitor is a modified version of those used in the Proto I¹¹ and Proto II¹² accelerators. The modification consisted of removing the straight cylindrical section of the inner electrode in order to reduce the capacity from 7.5 nF to 2.9 nF (see Fig. 10). The capacitor was filled with deionized water and permanently sealed. It is shown installed in Fig. 7. After installation it worked reliably for a period of 1 1/2 years at a maximum charge voltage of 2 MV and required no maintenance or further deionization of the water.

D. Self Break Gas Switch

The intermediate energy store is discharged into the PFL's via a self-breaking SF₆ gas switch. This switch uses a segmented insulator housing designed for a maximum operating voltage of 3 MV.¹³ For this application the triggered electrode was replaced by a hemispherical solid electrode of equal diameter.

E. The Pulse-Forming Lines

The design for the PFL's was based on work done originally at Sandia by D. L. Johnson.¹⁰ The rapid charging of the PFL's allow the use of

Fig. 8. Polyethylene support-spacer

Fig. 9. REBLE accelerator with an oil-dielectric capacitor for the intermediate energy store

Fig. 10. Water-dielectric capacitor

thin (.95 cm) aluminum plates as electrodes. They are arranged in a configuration of two sets of double transmission lines as is shown in Fig. 7. This arrangement was chosen to provide as symmetric a feed to the diode as was possible given the constraints imposed by the main oil tank. The relevant characteristics of the PFL's are summarized in Table II.

TABLE II

Oil Dielectric PFL Characteristics

Electrode dimensions	122 cm x 203 cm x 0.95 cm
Spacing	10.2 cm
Single-line impedance	22 Ω
Output impedance	5.5 Ω
Two-way transit time	20 ns
Characteristic charge times	120 ns
Maximum charge voltage	2 MV

The lines were supported with polyethelene spacers shown in Fig. 8. They were also equipped with metal rings to shield the triple point edges. This support method proved reliable up to the maximum charge of 2 MV.

F. The Self-Breaking Multichannel Oil Switches

The edge-plane, self-breaking oil switches are located at the output end of the PFL's as can be seen in Fig. 7. The edge is made of brass and the plane is steel. Both are 91 cm long. The switching work by Johnson¹⁰ indicates that the simultaneity of breakdown between two self-breaking edge-plane oil gaps can be as small as 2 ns for a charging time of 130 ns or less. With the slightly different geometry of the switches in REBLE, the average difference in breakdown times are 3.8 ns and 4.7 ns for 1 MV and 0.5 MV operation, respectively. This measurement implies that the rms

jitter in the closure time of each switch is 2.7 ns at 1 MV and 3.3 ns at 0.5 MV. During testing it became apparent that symmetric charging of the PFL's was imperative, otherwise the difference in closure times of the two oil switches could be increased substantially.

The 10-90 voltage risetime in the transmission lines is 8 ns. This risetime implies that the switches are operating in a multichannel mode and damage to switch electrodes confirms this conclusion. The PFL's were not designed to allow observation of the number of channels. In previous edge-plane experiments, multichannel operation was observed. Analysis indicates that nine channels must close in each switch to give an 8 ns voltage risetime.

G. The Transmission Lines

The output of the PFL's are fed to the diode via parallel plate transmission lines similar in design to the PFL's (see in Fig. 7.). Polyethylene spacers with metal shields are also used in this section. Due to the geometric constraints placed by the main oil tank, the transmission lines must make 90 degree turns before reaching the diode. Analysis of the diode current waveforms indicate that this bend does not add significant inductance to the system.

H. The Marx Crowbar System

As mentioned earlier, the large mismatch that exists between the Marx generator and the other components in the system mandates that a means be provided for discharging the energy remaining in the Marx after the pulse-forming lines have been charged. This is accomplished with a crowbar system which uses a triggered gas switch to divert the remaining Marx energy through a 5 ohm load to ground. This switch is a minitrigatron similar in design to that used in Proto II¹⁴ and is shown in Fig. 11. The

Fig. 11. Minitrigatron gas switch

trigger pulse is provided by a 2-stage Marx generator charged to ± 50 kV. The crowbar triggering sequence is initiated by a signal from the Marx voltage monitor of the Marx and delayed the proper amount.

1. The Radial Diode

The radial diode shown in Fig. 12 is the unique feature of REBLE. The anode and cathode are concentric cylinders. The inner cylinder is grounded and acts as the anode. The volume inside this cylinder defines the laser gas chamber. The design of the diode allows for relatively easy changes in the cathode configuration (outer cylinder). In Fig. 12, the cathode shown consists of a cylindrical holder for two sharp edge annular emitters; the anode is a thin, 20 cm diameter, self supporting, cylindrical metal foil, 28 cm long. Typical diode waveforms are shown in Fig. 13.

III. DIODE OPERATION

A. General

Cathodes of various types were investigated to determine their operating characteristics with mean electric fields of 250-400 kV/cm. A solid aluminum cylindrical cathode displayed a very spotty emission pattern. The total diode current rose slowly up to the end of the voltage pulse. Spraying a graphite coating on this cathode did not significantly improve its emission characteristics. A cathode surface made from a wire mesh (~ 1 mm diameter wires) did not give any improvement over the solid aluminum cathode. Of the various cathode types investigated, cathodes made of thin annular metal foils exhibited the shortest turn-on times, gave more uniform current emission, and displayed the best shot to shot reproducibility.

Fig. 12. REBLE diode

Fig. 13. Typical diode waveforms

B. Blade Impedance Characteristics

For these measurements, the anode was either 20.3 cm or 10.2 cm diameter. The cathode consisted of one or more annular blades made from .005 cm thick stainless steel foil. The A-K gap was varied by changing dimension of the inner diameter of the annular blades. The outer diameter of the blade was such that the blade "stick-out" was always greater than 2 cm.

The impedance of a single annular blade can be expressed as

$$Z \text{ (1-blade)} = K (X^2/AV^{1/2})$$

where X is the A-K gap spacing in cm, A is the area in cm^2 covered by the beam at the anode surface, and V is the diode voltage in MV.¹⁵ It was experimentally determined that the height (h) of the beam at the anode was within 10 percent of twice the A-K gap. The area can thus be written

$$A = (2\pi R_o) (2X)$$

where R_o is the radius of the cylindrical anode. Rewriting we obtain

$$ZV^{1/2} = \frac{K}{4\pi R_o} X \text{ (1-blade)}$$

We thus see that the impedance is linearly dependent on the A-K gap spacing.

Data taken for a single blade and a 20.3 cm diameter anode is shown in Fig. 14. The curve is a straight line drawn through the data points and corresponds to a value of $K = 675$. For a cathode consisting of two blades arranged such that no significant overlap of the individual beamlets exists, the area covered at the anode is

$$A \text{ (2-blades)} = (2) (2\pi R_o) (2X)$$

Fig. 14. Impedance of a single annular blade cathode of radius $R_0 + X$.

The impedance in this case is given by

$$ZV^{1/2} = \frac{K}{8\pi K_0} X \quad (2\text{-blade})$$

Figure 15 shows data obtained for a 2-blade cathode, with the blades separated by 10.8 cm. The anode diameter was 20.3 cm. The solid line was obtained using the above given formula with the constant $K = 675$ obtained from the single blade data. In Fig. 16 data is shown for a similar cathode but with a 10.2 cm diameter anode. Again the curve was calculated using $K = 675$.

It can be seen from these data that the above empirical formulas give an accurate description of the diode impedance using $K = 675$, $h = 2x$, and Area (n-blades) = $N \times$ Area (1-blade). This is valid as long as no significant overlap of the individual beamlet occurs.

In contrast to the above three cases, Fig. 17 presents data for a 3-blade cathode. Here the separation between blades was 5.4 cm. Two curves are shown in this figure. Both curves were calculated assuming that the area covered at the anode by the three blades was three times the area covered by one blade. It can be seen that, above $x = 3$ cm, $K = 675$ does not give a good description of the data. A value of $K = 920$ must be used to describe the data. Similarly, using the previously obtained value of $K = 675$, the effective area covered by the three blades is obtained.

$$A_{\text{eff}} = (0.73) (3 \times A_{1\text{-blade}})$$

This is a physically more meaningful way of interpreting the data since one would expect significant overlap of the beamlets at the larger gap spacings.

Fig. 15. Impedance of a two-bladed annular cathode of radius $R_0 + X$.
The distance between the two blades was 10.8 cm. $R_0 = 10.2$ cm.

Fig. 16. Impedance of a two-bladed annular cathode of radius $R_0 + X$. The distance between the two blades was 10.8 cm. $R_0 = 5.1$ cm.

Fig. 17. Impedance of a three-blade annular cathode of radius $R_0 + X$. The distance between blades was 5.4 cm.

The above data can be summarized as follows: In cases where little or no overlap exists between individual beamlets, the diode impedance can be obtained from the above equations and the empirically determined constant $K = 675$. When substantial overlap exists between the emission patterns of the individual blades, the impedance of N -blades is always greater than the impedance of one blade divided by N , and is not easily calculable.

C. Current Density at Anode

In applications of electron beams to laser excitation, it is highly desirable to have a spatially uniform current density at the anode. To determine the relative anode current density, strips of radiochromic film material¹⁶ were placed on the surface of a thick brass anode. These strips were covered by a .013 cm thick copper foil which stops electrons with energies below 250 keV. The radiochromic film undergoes a change in optical density proportional to the amount of energy deposited in the film. Since the film is only .005 cm thick, x-rays do not deposit a significant amount of energy in the film and the overwhelming contribution is by the electron beam. By scanning the exposed film a spatially resolved measure of the dose delivered to the film, and thus a measure of the relative localized current density, is obtained. Two sets of data were taken. First, several strips of film were placed along the surface of the anode and running along its full length. This gave a profile of the beam current density along the Z-axis. In a separate measurement, several strips of film were placed in series at a given Z-location and covering the entire anode diameter. This gave a profile of the beam current density in the azimuthal direction.

Using these diagnostic techniques it was found that the current density pattern at the anode surface could be easily manipulated by making suitable changes in the number of blades, the separation between blades, and the anode-cathode spacing. By making such changes the current density uniformity at the anode could be maintained to better than ± 15 percent. The anode current densities investigated were 100-250 A/cm². Figure 18 shows a typical scan along the Z-axis and Fig. 19 a scan along the anode circumference.

One observed feature characteristic of blades was the appearance of a regular striation pattern at the anode.¹⁷ This pattern consists of regions of higher current density placed at regular intervals and running perpendicular to the plane of the blades. This feature has been interpreted previously as arising from a tearing mode instability in the cathode plasma.¹⁸

D. Beam Pinching

A series of measurements were made to observe a beam pinching effect on REBLE. An expression for the critical current (for concentric cylindrical diodes) was obtained by Creedon.¹⁹

$$I_c = 8500 \beta \gamma g \text{ (AMPS)}$$

where $\beta \gamma$ is the normal relativistic factor and g is a geometrical factor given by

$$g = \frac{1}{\ln(R_2/R_1)}$$

where R_2 and R_1 are the radii of the outer and inner cylinders respectively.

Due to the double-sided return current geometry used in REBLE, the critical current is twice the above value, i.e.,

Fig. 18. Relative anode current density along Z-axis. Profile was obtained by time-integrated, radiochromic dosimetry techniques.

Fig. 19. Relative current density along the circumference of the anode. Strips A-C encircled the anode completely at a given value of Z . The anode-cathode configuration is the same as that given in Fig. 18.

$$I_c = \frac{17\beta\gamma}{\ln(R_2/R_1)} \text{ (kA)}$$

These tests were conducted using the 10 cm diameter anode since larger values of I/I_c could be obtained with this anode than with the 20 cm diameter anode. The highest value of I/I_c obtained was 1.16. Time integrated measurements of the anode current density using radiochromic dosimetry techniques did not show evidence of any significant pinching.

IV. BEAM TRANSPORT THROUGH ANODE

The design of an anode for the radial diode involves the compromising of a number of conflicting requirements. A detailed discussion is presented in Appendix A. Two types of anodes were investigated: a thin (.005 cm thick), self-supporting, cylindrical stainless steel foil and a Hihachi-type anode (see Appendix A). Although stainless steel is not the best material for maximizing the amount of beam energy transported through the anode, it was chosen because it allowed simple manufacturing of self-supporting anode cylinders. This was of great advantage initially since, until experience was gained in using these foils, a large number of them were destroyed. All of the experiments performed were thus not aimed at obtaining the maximum possible energy deposition in the gas.

The total beam energy transported through the anode was measured using a 60-element cylindrical calorimeter. These measurements indicated that, with the .005 cm thick self-supporting stainless steel anode, $1.2 \pm .2$ kJ was transported through the anode out of $1.7 \pm .2$ kJ total diode beam energy. The relatively low current densities and the corresponding energy densities were just marginally above the sensitivity

threshold of the calorimetry system and the accuracy of the measured energies was somewhat in question. This value is in good agreement, however, with a one dimensional Monte Carlo code²⁰ calculation.

By pressurizing the interior gas chamber defined by the anode cylinder, and measuring the energy deposited in the gas, a measure of the total beam energy transported through the anode could be obtained. (Details of these measurements are presented elsewhere in this report.) These measurements confirmed the segmented calorimeter measurements and allowed a comparison between the self-supporting and the Hibachi anodes. In order to make this comparison, the Hibachi anode was assembled using a .005 cm thick stainless steel liner. Measurements were made using Hibachi structures with two different wall thicknesses and different anode-cathode gap spacings. Results are summarized in Table III.

TABLE III

Beam Energy Transport Through Hibachi Anodes

A-K Gap (cm)	Hibachi Wall Thickness (cm)	Total Diode Beam Energy (kJ)	Energy Transported Through Hibachi (kJ)
1.59	0.635	1.55	0.44 (28%)*
2.54	"	1.75	0.62 (35%)
3.81	"	1.69	0.65 (38%)
2.54	0.318	1.77	0.83 (47%)
3.81	"	1.78	1.02 (57%)

*Percent of incident beam energy

As might be expected, the thinner wall Hibachi transmits a larger fraction of the incident beam energy. Another evident feature of this data is that a larger fraction of the beam energy is transported at the

larger gap spacings. This feature is related to the effect of the A-K gap spacing on the electron trajectories as these approach the structure apertures.

These results are to be compared with the self-supporting anode which transmits ~71 percent of the incident beam energy. Thus only for the 3.81 cm gap and 0.318 cm wall thickness does the beam transparency of the Hibachi reach its calculated optical transparency of ~80 percent.

V. BEAM TRANSPORT THROUGH THE GAS

A. Axial Faraday Cup

A 2.3 cm diameter Faraday cup (F.C.) was used to measure the beam arrival at the chamber axis. It was constructed so that only electrons with energies greater than 150 keV were collected, i.e., it was sensitive only to the primary beam electrons. The chamber was pressurized with xenon, krypton, argon, nitrogen or SF_6 gas at pressures ranging from 100 to 2200 torr. Time correlated measurements were made of the F.C. and total diode currents. Figure 20 shows the ratio of the peak F.C. current to peak diode current as a function of pressure for the various gases investigated.

It can be seen from this data that the current ratio, extrapolated to zero gas pressure, is in the order of one percent. This might be somewhat surprising in lieu of the radial nature of the incident beam, however, it is indicative of the amount of scattering which the beam undergoes in traversing the anode foil. An estimate of this scattering was obtained by doing a one-dimensional Monte Carlo calculation using the TIGER code.²⁰ Here a 700 keV spectrum of electrons (obtained from V and X monitor waveforms) were normally incident on a .005 cm thick stainless steel foil and the angular distribution of the outgoing electrons was

Fig. 20. Ratio of peak Faraday cup current to peak diode current for five gases investigated.

calculated. This distribution is shown in Fig. 21; it approximates a gaussian with a FWHM of ~88 degrees. Thus it is apparent that, inside the anode foil, the electron beam source distribution approximates an inward directed isotropic source. One advantage of this is that spatial inhomogeneities of the current density on the outside surface of the anode are further reduced by scattering in the anode foil.

Another feature of the F.C. data, particularly for xenon and SF_6 , was the narrowing of the current pulse as the gas pressure was increased. This appears to occur because, at higher pressures, only the most energetic electrons reach the F.C., i.e., electrons corresponding to the "wings" of the power pulse drop below the detector threshold of ~150 keV and are not collected thus effectively narrowing the pulse width of the collected current.

The scatter in the data of Fig. 20 is related to the shot-to-shot variation in peak diode voltage. For these measurements it ranged from 700-750 keV. The sensitivity of the amplitude of the F.C. current pulse to the maximum incident electron energy was most evident at the higher SF_6 pressures. It can be seen that, from 1400-1800 torr SF_6 , there occurs a sharp change in the slope of the curve drawn through the data points.

B. Axial Calorimetry

A 1.6 cm diameter segmented tantalum calorimeter was placed along the chamber axis to measure the energy of the beam at this location. These measurements proved difficult to make in that the signal levels recorded were just marginally above the threshold sensitivity of the detection system. Figure 22 shows the energy recorded by the calorimeter as a function of xenon gas pressure. Due to the large uncertainty in

Fig. 21. Outgoing angular distribution for a 750 keV electron spectrum incident on .005 cm thick stainless steel.

Fig. 22. Energy recorded by 1.16 cm diameter axial calorimeter.

these measurements, the actual beam energy on-axis could differ by a factor of 2 from the measured values. It is interesting to note however that, at 5 torr, only about two percent of the incident beam energy was recorded by the calorimeter. This value is consistent with the peak current ratios discussed earlier and with the large amount of beam scattering in the anode foil.

C. Open Shutter Photography

A sequence of shots were taken wherein the open end of the gas chamber was covered with an acrylic plate and the chamber pressurized with nitrogen or SF_6 gas. Open shutter photographs viewing the gas region were taken through the acrylic window. For cases where the volume was pressurized with one atmosphere or more of SF_6 , a uniform glow throughout the gas volume was observed. This is shown in Fig. 23. For a one atmosphere nitrogen fill, scattered electrons were able to reach the lucite window; charging up it's interior surface and eventually resulting in a surface breakdown as shown in Fig. 24. Catastrophic breakdown in the gas was never observed with open shutter photography although, had they existed, they should have been detectable.

VI. TOTAL AND SPATIALLY RESOLVED ENERGY DEPOSITION

A. Radiochromic Dosimetry

One of the most important criteria for the pumping of gas lasers is that the radial energy deposition profile in the gas be uniform. One would expect, and CYLTRAN²¹ calculations confirm, that for a given gas and pressure, the chamber dimensions and beam parameters can be chosen to give energy deposition profiles that are uniform to within 10 percent. It thus becomes important to experimentally determine the accuracy with which the Monte Carlo codes predict the deposition profiles for high

Fig. 23. Open shutter photograph of gas region viewed through an x-ray window for a 1 atm SF_6 gas fill.

Figure 1. A photograph of the sun taken from the ground in the United States. The sun is visible in the center of the image. The image is a high-contrast, black and white photograph, showing the sun as a bright, circular disk against a dark, textured background. The sun's surface is not clearly visible due to the high contrast.

current electron beams where self and induced fields may be important factors in beam transport. This was accomplished by using passive radiochromic dosimetry techniques.

Measurements of energy deposition by the radial electron beam were conducted for nitrogen, xenon, krypton, argon and SF₆ gases at fill pressures ranging up to three atmospheres.⁵ The 20 cm diameter, 30 cm long anode was a 0.005 cm thick stainless steel foil. For these measurements the peak diode voltage was nominally 750 kV.

The spatially resolved deposition measurements were made using the radiochromic film package shown in Fig. 25. The package was 1 cm wide and 30 cm long; it was placed at a given radial position inside the gas chamber and ran the length of the volume. The black paper on either side of the film assured that the deposition in the film was from the high energy electron beam. After placement of the film package, the chamber was evacuated, pressurized and irradiated by the incident radial electron beam. By scanning the film with a densitometer, a spatially resolved measurement of the energy deposited in the film was obtained.

The experimentally determined dose delivered to the radiochromic film was compared with detailed Monte Carlo code calculations using the CYLEM code.³ CYLEM is a derivative of the CYLTRAN²¹ Monte Carlo code and allows the inclusion of externally applied, static electromagnetic fields. The applied electric fields are restricted to void regions. Figure 26 shows the geometry used for the code calculations. Only the radial electric field in the diode gap was used in the calculations. This allowed electrons which had random-walked out into the diode gap to be reflected back into the material region. By sampling the incident electron spectrum obtained from the diode voltage and current waveforms, both the initial

Fig. 25. Radiochromic film package used for passive dosimetry measurements.

CYLEM CODE — REBLE

- Only E-field in Diode Region
- Incident Electron Spectrum $\rightarrow$ I, V waveforms
- Diode Potential $\rightarrow$ Incident Electron Energy
- Axial Incident Electron Distribution
- Normal Electron Incidence
- Symmetry about source midplane

Fig. 26. Problem geometry employed for CYLEM code calculations.

energy of the primary electron and the radial electric field applicable during that primary electron history were obtained. The incident electron axial distribution was measured and approximated by a triangular source distribution symmetric about its mid plane. All primary electrons were started normally incident to the anode foil. Because the code assumes a cylindrically symmetric materials geometry, the radiochromic package was modeled by a complete cylindrical package. Since the measurements were conducted using ~1 cm wide strips, an experiment was conducted and verified that the dose measured with the strips was not significantly different from that which would be obtained using a complete cylindrical package.

Figures 27a and 27b show a comparison of the experimental and calculated dose when the chamber was pressurized with xenon gas at 1200 torr and 2400 torr respectively. The solid lines are the experimental dose and the histograms are the Monte Carlo calculations. The code results were converted into joules/gram by using the total incident beam energy as obtained from the diode voltage and current waveforms. The cross-hatched area indicates the total error in the calculations including both the statistical error and the uncertainty in the determination of the total incident beam energy. The disagreement between theory and experiment near the "wings" of the distributions is primarily due to the slight inaccuracy of the model used for the axial and angular distribution of the incident beam electrons.

Quantitative agreement similar to that shown in Fig. 27 was obtained for argon and krypton gas fills over the entire pressure range measured. Figure 28 shows comparisons for nitrogen gas fills of 400 and 1600 torr. In Fig. 29 comparisons are shown for gas fills of 400 and 1000 torr SF_6 .

Fig. 27. Comparison of measured and calculated dose delivered to radiochromic film for xenon fill pressures of 1200 torr and 2400 torr.

DOSE DELIVERED TO RADIOCHROMIC FILM .
 THE SOLID LINES ARE EXPERIMENTAL DOSE.
 THE HISTOGRAMS ARE MONTE CARLO CALCULATIONS.

Fig. 28. Comparison of measured and calculated dose delivered to radiochromic film for nitrogen fill pressures of 400 torr and 1600 torr.

**DOSE DELIVERED TO RADIOCHROMIC FILM.
THE SOLID LINES ARE EXPERIMENTAL DOSE.
THE HISTOGRAMS ARE MONTE CARLO CALCULATIONS.**

Fig. 29. Comparison of measured and calculated dose delivered to radiochromic film for SF_6 gas fills of 400 torr and 1000 torr.

Although reasonable agreement was obtained at 400 torr of SF_6 , the calculated dose is about four times higher than the measured dose at 1000 torr and $R = 1.4$ cm. This discrepancy in calculated and measured dose delivered to the film at the $R = 1.4$ cm position occurs for SF_6 at all gas fill pressures above ~600 torr.

Since agreement between experiment and calculations was obtained for all gases and pressures except SF_6 , one can postulate that this discrepancy is due to the strong electronegative nature of SF_6 . Electrons are attached leaving low mobility negative ions with an associated space charge buildup which prevents the beam from readily penetrating to the center of the chamber. Although other mechanisms cannot be ruled out, this is a plausible explanation for the disagreement between experiment and the Monte Carlo calculations since collective effects, such as space charge buildup, cannot be included in the calculations.

The remainder of the comparisons made between experimental and calculated deposition profiles are presented in Appendix B. It should be emphasized that the comparisons presented here are absolute dose comparisons, i.e., no arbitrary normalization factors are invoked to fit the data. This was possible because, in this case, no transport region is required to propagate the beam from the electron beam diode to the gas region.

B. Total Energy Deposition

The total energy deposited in the gas was measured for nitrogen, xenon, krypton, argon and SF_6 gases as a function of pressure. These measurements were made by recording the instantaneous pressure rise in the gas chamber after exposure to the electron beam. The fraction of the incident beam energy deposited in xenon is shown in Fig. 30 and that

Fig. 30. Total energy delivered to xenon gas vs. fill pressure. The solid lines are results from Monte Carlo calculations.

for SF_6 in Fig. 31. The error bars are the estimated uncertainty in the measurements. The solid lines are the energy deposited as calculated by the CYLEM code.³ Data and comparisons for nitrogen, argon and krypton are given in Appendix C.

It is apparent from the data presented here that the Monte Carlo codes are capable of giving an accurate description of the energy deposition by the radial beam. The limitations of these codes appear to be from uncertainties in the electron beam source distributions and from the neglect of self electromagnetic fields.

Although the radiochromic dosimetry measurements provided a very good method for checking the Monte Carlo codes, it may be argued that these measurements were not actual measurements of energy deposited in the gas. While this is strictly correct, it is apparent that the deposition profiles measured by radiochromic dosimetry techniques can be used to infer deposition profiles in the gas.

VII. XENON EXCIMER LIGHT MEASUREMENTS

Another approach to obtain the energy deposition profiles in the gas is to make spatially resolved measurements of the light output resulting from the direct excitation of the gas by the electron beam. The advantage of this technique lies in that no external probe needs to be inserted inside of (and thus disturb) the system under investigation. The assumption involved in these measurements is that there is a well understood relationship between energy deposition and light output. In this case, measurements were made of the light emitted by the xenon excimer (~ 1720 Å) in a direction parallel to the chamber axis.⁶ It was assumed that the amount of light measured was directly proportional to the energy deposited in the gas.

Fig. 31. Total energy delivered to SF_6 gas vs. fill pressure. The solid lines are results from Monte Carlo calculations.

A schematic of the experimental configuration is illustrated in Fig. 32. Three different photodiode arms were used so that the measurements at the different radial positions were made on the same electron beam shot. The windows were magnesium fluoride. The apertures (0.76 cm diameter) that defined the volume of gas viewed by each photodiode were located immediately adjacent to the windows and to the photodiodes. The other apertures in the system were used to prevent the scattered light in the arm from reaching the photodiodes. Since 1720 Å radiation is absorbed strongly by air, the photodiode arms were evacuated to less than 10^{-5} torr. The rear surface of the gas cell opposite the window was made of black anodized aluminum to make it fully absorbent to the excimer radiation. In this way reflected light did not reach the photodiodes.

Due to the geometric arrangement, the photodiodes detect the light emitted by a volume of gas approximately delineated by a cylinder of 0.76 cm diameter and of the length of the electron beam. The volume was determined precisely by numerical calculations. The results of these measurements thus determine the intensity of radiation emitted from the xenon excimers excited by the electron beam. Typical photodiode signals are shown in Fig. 33. By integration over the full temporal extent of the xenon radiation, the energy radiated per cm^2 along a direction parallel to the axis of the gas chamber was determined. The photodiodes used in these measurements were calibrated against a reference diode, both before and after the experiment. There was essentially no change in their quantum efficiency during the experiment.

Results of these measurements are shown in Fig. 34. The estimated total error in the absolute value of the measured emitted energy is ± 10 percent. To within the accuracy of the measurement, the profile of

Fig. 32. Schematic arrangement of apparatus for xenon excimer light output measurements.

RADIAL POSITION 1.5 cm

RADIAL POSITION 7.3 cm

RADIAL POSITION 9.3 cm

XENON PRESSURE 1200 TORR
SWEEP SPEEDS 50 nsec/div

Fig. 33. Typical photodiode signals

Fig. 34. Xenon excimer photon energy radiated. Note suppressed zero and typical 10 percent error bar.

the emitted energy as a function of radius is uniform at a pressure around 1600 torr (note the suppressed zero in the ordinate of this figure).

The total energy deposited by the electron beam in the gas was determined as discussed earlier in this report. By dividing the energy radiated by the energy deposited in the gas (in joules/liter), the conversion efficiency of deposited electron beam energy to Xe_2^+ -photon energy was obtained and is shown in Fig. 35. The maximum conversion efficiency is about 20 percent. Furthermore, it can be seen that there is an increase in conversion efficiency from 1000 torr to 1600 torr. This gain in efficiency saturates about 1600 torr. Around 2000 torr a radical change in the deposition profile occurs. The exact pressure at which these characteristic changes occur depends on the incident beam energy. For these measurement, the peak electron energy was about 750 keV. These results show that within the experimental uncertainty it is possible to choose the diode voltage and gas pressure to obtain a uniform radial deposition profile. In the case studied here, this was achieved at a xenon gas pressure of ~1600 torr where ~20 percent of the incident beam energy deposited in the gas was converted into xenon excimer radiation.

VIII. H-F MEASUREMENT

Since one of the applications originally envisioned for the high power radial diode was pumping a large H-F amplifier module, there was interest in making some H-F light measurements on REBLE. A limited effort was devoted to these measurements since it was recognized that parasitic oscillations would make it difficult to operate REBLE as an H-F laser cavity. Because H-F is a high gain medium, and in view of small aspect ratio of the REBLE gas chamber (20 cm diameter by ~40 cm length), it was

Fig. 35. Conversion efficiency of deposited electron beam energy to radiated xenon photon energy.

known that parasitic oscillations would present a strong loss mechanism and it would be difficult to extract much energy from the cavity. In applying the radial diode to a large H-F amplifier system several modules would be stacked together, as discussed in the introductory section, to give a better aspect ratio. Techniques for further damping of the parasitic oscillations were also envisioned.

The experimental arrangement used for these measurements is shown in Fig. 36. An aluminized mirror was placed at the far end of the gas chamber while the open end was covered by a quartz window. The energy from the cavity was measured with a 20 cm diameter calorimeter which was placed within 1 cm of the window. A 10 percent - 90 percent mixture of ethane-SF₆ was used for these measurements.

Using this arrangement only a few joules of extracted energy was recorded with the calorimeter. This amount could be increased by a factor of two or three by dividing the gas volume into several regions with smaller cross sectional area.

A final series of measurements were made wherein a 1.0 cm diameter cylinder (.0025 cm thick mylar sprayed with a thin coating of black paint) was placed at a given radius inside the gas volume and extending the full length between mirror and window. A small diameter calorimeter was used to measure the energy extracted from the volume within the cylinder. The energy per unit cross sectional area is a function of the total gas pressure obtained from these measurements is shown in Fig. 37 for three different radial positions. It can be seen that for the $R = 0.0$ cm and 4.3 cm positions the amount of light collected peaks at a pressure of 600-700 torr and then decays slowly. For the $R = 8.9$ cm position the light output is independent of pressure above 500 torr.

Fig. 36. Schematic of experimental arrangement used for H-F light measurements.

Fig. 37. Energy per unit cross-sectional area recorded with calorimeter at three different radial positions.

Although the data collected was admittedly very limited, it does show that parasitic oscillations represent an extremely strong energy loss mechanism. It should be said, however, that this is a problem characteristic of high gain laser systems independent of the excitation geometry employed; thus it must not be construed as a weakness of the radial excitation scheme.

IX. SUMMARY AND CONCLUSIONS

The main goal of the REBLE program was to investigate high power, radially converging electron beams and their possible application to gas laser excitation. For this purpose the REBLE accelerator was built using the pulse power technology developed for Sandia's Particle Beam Fusion Program. The operating characteristics of the radial diode were determined. Reliable, single-shot operation was obtained at 1 MV, 200 kA level.

An investigation of various cathodes showed that blade-cathodes made of thin annular metal foils exhibited the shortest turn-on times, gave more uniform current emission, and displayed the best shot to shot reproducibility. It was determined that by making suitable changes in the number of blades, the separation between blades, and the anode-cathode gap, the current density at the anode could be made uniform to ± 15 percent or better. These measurements were made using time-integrated, radiochromic dosimetry techniques. Current densities of $100\text{--}200\text{ A/cm}^2$ were investigated. In an investigation of beam pinching, no strong evidence of beam pinching was observed at currents of 1.16 times the calculated critical current.

Measurements showed that the beam was readily transported through a thin-foil anode. For the case in study, a 0.005 cm thick stainless steel

foil was used due to ease of manufacture so that the experiments were not intended to minimize the energy deposition in the anode foil. For this case, scattering of the beam in traversing the anode foil resulted in essentially an inward-directed, isotropic electron distribution incident on the gas. A result of this was that the beam nonuniformities measured on the outside surface of the anode were further reduced when the beam exited into the gas volume.

Time resolved measurements using a filtered Faraday cup showed that no anomalous time delays were present in the arrival time of the main beam at the gas chamber axis, thus the beam appeared to propagate readily through the gas. This was supported by open shutter photography of the gas volume as seen through an acrylic window. Although the sensitivity of the film was limited to the visible region, any catastrophic breakdown in the gas should have been observed.

Total and spatially resolved measurements of energy deposition were made for nitrogen, argon, krypton, xenon, and SF_6 gases. These measurements were compared with calculations using the CYLEM Monte Carlo code.³ This is a three dimensional, cylindrically symmetric code which allowed the inclusion of a radial electric field in the diode region to reflect any electrons which are scattered back into the A-K gap. These comparisons showed excellent agreement with both total and spatially resolved measurements for all cases except SF_6 at pressures above ~600 torr. A plausible explanation for this case might be the strong electronegative properties of SF_6 . It causes electrons to be attached leaving low mobility negative ions with an associated space charge buildup which prevents the beam from readily penetrating to the center of the gas chamber. *Collective effects such as space charge buildup cannot be included in*

the Monte Carlo calculations. It should be emphasized that the comparisons presented are absolute dose comparisons, i.e., only the total incident beam energy, as determined from the voltage and current diode waveforms, was used to normalize the calculated values.

Measurements were made of the xenon excimer light emitted from the gas volume when irradiated by the radial electron beam. Measurements of a three-point radial profile show that a uniform light output profile can be obtained. Under these conditions, approximately 20 percent of the electron beam energy deposited in the gas was converted into excimer light.

A short series of measurements were made operating the REBLE diode gas chamber as an H-F laser cavity. These measurements confirmed that parasitic oscillations are a strong energy loss mechanism as is the case in other excitation geometries.

A Hibachi-type anode was tested in the REBLE diode. This anode was capable of operation up to pressures of at least five atmospheres. The ribs of the anode support structure did not seem to have much effect on the impedance behavior of the diode, however, only for A-K gaps of 3.81 cm or greater did the beam transparency of the support structure approximate its calculated optical transparency of ~80 percent.

In summary, the REBLE program has demonstrated that reliable, high-power, radially converging electron beams can be generated and used for gas laser excitation. Existing electron/photon Monte Carlo transport codes can be used to predict the beam energy deposition profiles if the actual experimental conditions are carefully included in the calculations. The codes are not capable of handling collective effects such as space charge buildup which resulted in a discrepancy with the measured profiles in the electronegative SF_6 gas.

The advantages of the radial geometry to effectively couple the incident electron beam energy into the gas, with uniform deposition profiles were demonstrated. It was also shown that the REBLE diode is readily adapted to a modular geometry which allows it to be scaled up to larger energy systems. One problem identified for the radial geometry (for repetitively pulsed applications) is the problem of gas flow while maintaining the gas density uniformity profiles required for optimum laser performance. If the problem of gas flow can be solved, radial electron beams provide a very promising excitation mechanism for the high power gas lasers envisioned for the future.

APPENDIX A, ANODE CONSIDERATIONS

Special attention must be paid to the design of an anode for the radial diode. As might be expected the requirements are, in general, conflicting in nature and depend on the specific applications intended. In order to minimize the beam energy lost to the anode a thin, low Z, low density foil is desirable. The anode must be strong enough to support the pressure of the gas medium and to survive any shock stresses generated by the electron beam; it should be a good electrical and thermal conductor and should not be susceptible to chemical or physical deterioration such as fluorine corrosion and hydrogen embrittlement.

The stress on a cylinder of radius R_0 and thickness t , subjected to an internal pressure P , is given by

$$\sigma = \frac{R_0 P}{t}$$

If σ is taken to be the working stress of the material then the required thickness is

$$t = \frac{R_0 P}{\sigma}$$

It is evident that, all other things being equal, materials with a high working stress are desirable. Using these equations and assuming a working pressure of 10 atmospheres, the required thicknesses for various materials can be calculated. Results are shown in Table A-I for the 20 cm diameter REBLE anode.

Figure A-1 shows the specific energy deposition for 1 MeV electrons in titanium vs. penetration depth in fractional values of the electron range R . It can be seen that most of the incident electron energy is deposited in a distance $R/2$. A similar curve exists for all metals and

Fig. A-1. Specific energy deposition for 1 MeV electrons in Titanium vs. penetration depth in fractional values of the electron range R .

TABLE A-I.

Required Thickness of Anode Cylinder

Material	σ (atm)	R_0 (cm)	P (atm)	t (cm)	R* (cm)
304 S.S.	2040	10	10	.05	.08
304 S. S.	4080	10	10	.03	.08
Titanium	2040	10	10	.05	.13
Ti-alloy	19050	10	10	.005	.13

*Range of 1 MeV electrons in material.

the same conclusion applies. Ignoring problems of fluorine corrosion and hydrogen embrittlement, the high strength titanium alloy is preferable over stainless steel. Due to ease of fabrication and availability considerations, all tests on REBLE using self-supporting anodes were made with .005 cm thick stainless steel.

Another approach to anode design is the use of a Hibachi-type support structure. This approach involves a compromise between foil thickness and the beam opacity of the support structure. The energy loss to the structure must be experimentally determined and is not necessarily given by the optical transparency (see Section IV in main body of this report).

Prior to the design of a Hibachi-type anode for REBLE, data was generated on the maximum stress capabilities for various foil thicknesses and support plate geometries. Results are tabulated in Table A-II.

Using this test data, the Hibachi anode shown in Fig. A-2 was designed for testing in REBLE. The apertured portion of the structure is 22 cm diameter and 31 cm long. The circular apertures are 3.18 cm diameter with their center placed 18.8° apart. The calculated optical transparency of this structure to a radially incident beam is ~80 percent.

Fig. A-2. Hibachi-type anode tested in REBLE diode.

TABLE A-II

BURST PRESSURE FOR SUPPORTED STAINLESS STEEL FOILS

Foil Thickness (cm)	Aperture Diameter (cm)	Burst Pressure (atm)
.0013	3.18	5.17
.0025	"	11.03
.0038	"	14.14
.0051	"	20.70 ⁺
.0013	3.81	3.79
.0025	"	8.96
.0038	"	9.66
.0051	"	13.79

⁺Did not fail at this pressure.

In the assembly of this anode, a cylindrical foil liner is placed inside of the support structure and held together with O-rings clamps. Two structures with wall thicknesses of 0.64 and 0.32 cm were built and tested.

Measurements using these Hibachi anodes indicate that the apertures in the support structure had little or no effect on the impedance characteristics of the radial diode for A-K gap spacings of 2.5 cm or larger.

Static pressure measurements of the 0.32 cm thick Hibachi with .005 cm stainless steel foil showed that it is capable of reliable operation at pressures up to 5 atm. The self-supporting foil of equivalent dimensions consistently failed at ~3 atm gas pressure. The ultimate working limit of the Hibachi was not determined.

APPENDIX B

In Section VI-A of this report, results of radiochromic dosimetry measurements are compared with Monte Carlo code calculations for xenon, nitrogen and SF₆ gas at two different fill pressures. The remainder of the comparisons made for xenon, krypton, argon, nitrogen and SF₆ are present in this appendix. The reader is referred to Section VI-A for details on the measurements and code calculations.

Fig. B-1. Comparison of measured and calculated dose delivered to radiochromic film for a nitrogen fill pressure of 800 torr. See Section VI-A of this report for details.

Fig. 8-2. Comparison of measured and calculated dose delivered to radiochromic film for a nitrogen fill pressure of 1200 torr.

Fig. B-3. Comparison of measured and calculated dose delivered to radiochromic film for an argon fill pressure of 1200 torr.

Fig. B-4. Comparison of measured and calculated dose delivered to radiochromic film for an argon fill pressure of 1600 torr.

Fig. B-5. Comparison of measured and calculated dose delivered to radiochromic film for an argon fill pressure of 2000 torr.

Fig. B-6. Comparison of measured and calculated dose delivered to radiographic film for a krypton fill pressure of 1200 torr.

Fig. B-7. Comparison of measured and calculated dose delivered to radiochromic film for a krypton fill pressure of 1600 torr.

Fig. B-8. Comparison of measured and calculated dose delivered to radiochromic film for a krypton fill pressure of 2000 torr.

Fig. B-9. Comparison of measured and calculated dose delivered to radiochromic film for a krypton fill pressure of 2200 torr.

Fig. B-10. Comparison of measured and calculated dose delivered to radiochromic film for a xenon fill pressure of 1400 torr.

Fig. B-11. Comparison of measured and calculated dose delivered to radiochromic film for a xenon fill pressure of 1600 torr.

Fig. B-12. Comparison of measured and calculated dose delivered to radiochromic film for a xenon fill pressure of 1800 torr.

Fig. B-13. Comparison of measured and calculated dose delivered to radiochromic film for a xenon fill pressure of 2000 torr.

Fig. E-14. Comparison of measured and calculated dose delivered to radiochromic film for an SF_6 fill pressure of 600 torr.

Fig. B-15. Comparison of measured and calculated dose delivered to radiochromic film for an Sf_6 fill pressure of 800 torr.

Fig. B-16. Comparison of measured and calculated dose delivered to radiochromic film for an SF_6 fill pressure of 1200 torr.

APPENDIX C

In Section VI-B of this report measurements of the total energy deposited by the radial electron beam in xenon and SF_6 are presented and compared with energy deposition values obtained from Monte Carlo code calculations. Similar results of measurements, and comparisons with theoretical calculations, are presented here for nitrogen, argon and krypton. The reader is referred to Section VI-B for details on the measurements and code calculations.

Fig. C-1. Total energy delivered to nitrogen gas vs. fill pressure.
The solid lines are results from Monte Carlo code calculations.
For details see Section VI-B of the report.

Fig. C-2. Total energy delivered to argon gas vs. fill pressure. The solid lines are results from Monte Carlo code calculations.

Fig. C-3. Total energy delivered to krypton gas vs. fill pressure. The solid lines are results of Monte Carlo code calculations.

XIII. ACKNOWLEDGEMENTS

A number of people contributed in various ways to the REBLE program. T. H. Martin and J. G. Kelly participated in the initial conceptual stages of the program. P. E. Bolduc performed some preliminary measurements on a 1.25 cm radius device on the REBA accelerator. Mr. J.P. Corley was extremely helpful in the design and construction of the REBLE accelerator. Mr. John Leija assisted in acquiring most of the data presented here. The help of J. A. Halbleib Sr. in instructing and assisting one of the authors (J. J. R.) on the use of the various Monte Carlo codes is gratefully acknowledged. *The xenon excimer measurements were performed in collaboration with A. W. Johnson. E. L. Patterson participated in the H-F light measurements.*

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