AN ELECTRON BEAM TRIGGERED SPARK GAP

by

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ABSTRACT

The triggering of a high-voltage gas-insulated spark gap by an electron (e) beam has been investigated. Rise times of approximately 2.5 ns with sub-nanosecond jitter (~ 0.2 ns) have been obtained for 3 cm gaps charged at voltages as low as 50 percent of the self-breakdown voltage (varied up to 0.5 MV). The switch delay (including the e-beam diode) was 52 ns. The triggering e-beam pulse has a duration of 15 ns and a 0-50 percent rise time of 1.5 ns. The e-beam current is 0.5 kA, and the electron energy can be varied in the range from 80 to 145 keV. The working media were N_2 , mixture of N_2 and Ar, and N_2 and SF_6 at pressures of 1-3 atm. Voltage, current and jitter measurements have been made for a wide range of gap conditions and e-beam parameters. The effects of varying the e-beam cross-sectional area and the beam energy are discussed.

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CHAPTER I

INTRODUCTION

The purpose of the research program discussed in this thesis is to help develop the physical understanding of e-beam switching processes for the subsequent development of an advanced, low inductance, fast risetime, high voltage, command fired spark gap switch. The e-beam switch has the potential to function as either an opening or a closing switch, both of which can be repetitively operated. The research reported on in this thesis was limited to the e-beam closing switch.

Advantages of Electron Beam Triggered Switching

The electron beam provides an ample supply of electrons to initiate the breakdown process, which virtually eliminates the statistical portion of the delay; hence the jitter is expected to be very low. The large number of initial electrons insures that the switch will break down, and that it will do so at a small (safe) fraction of the self-breakdown voltage. The large number of initial electrons also causes the breakdown to proceed via a multiple electron initiation process. This type of breakdown takes the form of a large cross-sectional

area or "volume" discharge, as contrasted to the typical narrow channel discharge found in conventional spark gaps. This observation has been made in several experiments [1, 2, 3, 4]. Low jitter, high reliability and volume discharge are the most important advantages offered by electron beam triggered switching (EBTS).

Delay and Jitter of An Electron Beam Triggered Switch (EBTS)

It will be helpful to discuss delay and jitter as they apply to the EBTS. We are interested in determining the characteristics of the EBTS itself and not the system as a whole, i.e., the delay and jitter of the generator for the electron beam is of no major concern to us in this experiment. The electron beam source (a vacuum diode), however is an integral part of the EBTS; hence, its characteristics are taken into consideration. The delay can be defined as the time elapsed from the arrival of the trigger pulse at the diode to the beginning of the rise of current in the spark gap (collapse of voltage across the gap). The statistical delay is the time between the arrival of the trigger pulse at the diode and the appearance of the first electrons (e-beam pulse front) in the gap, and the formative delay is the elapsed time from the arrival of the e-beam pulse in the gap to the rise of current. The total delay can be relatively long since the diode "turn-on" time is included.

The statistical nature of the delay is a function of the diode alone (this is due to the diode jitter), and since the switch jitter is a function of the statistical portion of the delay it follows that the switch jitter is virtually equivalent to the diode jitter. A properly designed diode can have very low jitter; hence, the EBTS is expected to be a very low jitter device also. This has been confirmed through experimentation [1, 2, 3].

Reliability of Electron Beam Triggered Switching

The EBTS can meet the reliability requirements on a single shot basis and promises to meet them on a modest rep-rated basis. An EBTS will close on command providing the diode emits a beam, and the diode will emit a beam providing: (a) it is designed properly and there are no electrical failures (i.e., surface flashover, diode arc formation, etc.) in either the diode proper or in the input transmission lines, (b) an adequate vacuum exists in the diode region, and (c) the diode driving generator produces an adequate pulse. The diode system can be designed properly so that electrical failures are reduced. On a single shot basis the diode vacuum can be monitored and thus assured of being adequate. A relatively low voltage, diode driving generator can also be made quite reliable. One of the most important features of an EBTS is that it will close on command, and even more important

is the fact that it will do so for gap voltages much lower than the static breakdown voltage. Thus, the second criterion for reliability is automatically satisfied; that is, the gap voltage can be operated far enough below the self breakdown voltage that the chance of the gap closing before the command is virtually zero.

The Volume Discharge

The volume discharge is one of the most important features of the EBTS. There are several advantages that stem directly from the volume discharge, including a reduction in the switch inductance, enhanced rep-rateability, and scalability, which is perhaps the most important aspect of the EBTS.

Risetime

The inductance of a spark gap switch is a function of the radius of the discharge channel. The volume discharge can increase this radius by more than an order of magnitude, which can reduce the gap inductance a significant amount (in our case the calculated inductance was lowered by a factor of 2.56, from 34 nH for the self-break case to 13.3 nH for an e-beam initiated discharge). A reduction in gap inductance will reduce the current risetime. It is not obvious how the resistive phase of the risetime is affected by the volume discharge case. The growth of the conduction processes is different for the volume and channel discharge

cases, e.g., the volume discharge plasma does not undergo a radial expansion as does the channel discharge plasma.

The volume discharge will certainly reduce the time of the inductive phase of the current rise (this effect is very pronounced for low impedance systems), and it conceivably could reduce the time of the resistive phase also. It is expected that the risetime of an EBTS should be improved over that of ordinary, single, narrow channel discharge spark gaps.

Rep-rateability

The volume discharge reduces several of the problem areas of rep-rated spark gaps, including the thermal load, the erosion, and the recovery time. In a typical spark gap, the dense, hot plasma heats the working medium and the electrodes. It also vaporizes portions of the electrode material which erodes the electrodes. The volume discharge is relatively cool and neither the working medium nor the electrodes are heated severely, hence both the thermal load and the erosion problems should be alleviated. The voltage recovery time is also reduced simply because the plasma is relatively cool and is not highly ionized. The rep-rated problem areas of the spark gap have been reduced in the EBTS; however, an EBTS also has to be concerned with the diode and this is perhaps its major obstacle to rep-rating. It would appear, however, that a reliable low jitter, rep-rated diode can be developed.

Scalability

The single most important feature of the EBTS is probably that the volume discharge permits it to be scaled up to very large electrodes and transmission lines while maintaining a low switch inductance (an annular geometry presents a particularly attractive concept [5]). Other triggered switches cannot maintain a low inductance for large electrodes unless multiple, current sharing channels are formed, which is not easily accomplished. Multiple channels have been formed with laser triggered switching [6], with multiple channel trigatrons [7, 8], and with an array of trigatrons mounted in the same co-axial transmission line [9]. All of these methods suffer from erosion and trigger problems and rep-rating could be difficult.

Questions About and Potential Problems With Electron Beam Triggered Switching

It is much too early in the developmental stage of this type of switch to determine either the character or the severity of all the possible problem areas. Many of the most obvious potential problems are associated with the gas discharge, however. The e-beam initiated discharge may have a relatively large resistivity, thus requiring a large cross-sectional area in order to provide a low resistance switch. It is not known for how long and under what conditions a volume discharge can be established

and maintained, e.g., what is the maximum possible current density which may be conducted through the switch without altering the volume discharge, and what effects do the gap polarity, gas types, electric field, beam duration - energy - risetime - or density profile have on the gap resistance and discharge? A great amount of research will be required before these and many other questions can be answered.

E-Beam Characteristics

Two of the most important design features of an EBTS are the geometry and the electron beam. In many cases (as in ours) the geometry is established by the application and the available materials and equipment. Once the geometry is established, the characteristics of the electron beam are left to the discretion of the designer. Only a few of the desired characteristics are intuitively obvious; some of these are the desire for the e-beam source to have a very low jitter, the beam current pulse should have a very fast risetime, and, in order to obtain a volume discharge, the beam should not be pinched or focused. These e-beam characteristics can be obtained from a cold cathode, field emission, vacuum diode operating in the space charge limited regime. Such a diode was chosen as the e-beam source for our experiment. The remaining desirable e-beam

characteristics are not so obvious and not many experimental or theoretical results are available to help make the choices. Some of the other e-beam characteristics include: (a) the beam energy, (b) the beam current, (c) the current density, (d) the beam uniformity (cross-sectional energy or density profiles), and (e) the pulse length. A computer aided theoretical gas breakdown study is currently being conducted at Texas Tech University [10], and should help to resolve some of these questions. A continued program of both theoretical and experimental research will be required to develop and optimize the EBTS. Some of the questions raised above are being addressed in a continuing experimental study at Texas Tech University.

CHAPTER II

THEORETICAL CONSIDERATIONS

Introduction

This chapter discusses streamer formation in gases, pulsed nanosecond gas discharges, and e-beam initiated gas discharges. A detailed discussion of the e-beam source (diode) is presented in Appendix A.

Streamer Theory

Early gas discharge experiments confirmed that gas breakdown may be explained using Townsend's theory [11, 12]. In most of these experiments the spark gaps were statically charged and the values of Nd (gas density times gap distance) were low. However, later experiments [13, 14], which utilized high pd 's and overvolted, pulse-charged gaps, demonstrated that the gap closure times could be much faster than could be explained by the electron drift velocity. It was originally thought that these deviations from classical theory were due to pd 's much greater than those at which the breakdown potential is a minimum (i.e., $Nd \geq 10^{19} \text{ cm}^{-2}$) [13]. However, evidence now indicates that the percent of overvoltage, in a pulsed charged gap, dictates whether the breakdown proceeds via a Townsend type mechanism or some other mechanism [15].

For overvoltages of a few percent or more, the breakdown is thought to develop via a "streamer" formation [15]. A streamer, in contrast to the weakly ionized and exponentially growing Townsend avalanche, is a conducting filament of highly ionized gas which constitutes the initial stage of a spark channel through which the external circuit discharges. It has been postulated that streamers (which can be both anode and cathode directed) are developed due to the space charge that forms at the head of an electron avalanche. The highly mobile electrons and the quasi-stationary ions are accelerated in opposite directions by the external field, hence the head of an electron avalanche generates a field pattern as in Fig. 1.

Fig. 1 The Field Pattern Generated by an Electron Avalanche (The Arrows Denote the Field Lines) [16]

Streamer theory was developed independently by Loeb [12], Meek [14], and Raether [13]. Although their approaches were different, the basic premise was the same, that is, streamers were thought to develop due to photo-ionization of the gas molecules. Photons, which are emitted from the ionized gas in the avalanche, photo-ionize the gas molecules surrounding the avalanche thus releasing "photo-electrons" which start new avalanches. These avalanche-initiating photons travel at the speed of light, thus high speed propagation is possible via a succession of short avalanches.

Loeb and Meek felt that streamers traveled from the avalanche towards the cathode. Meek [14] developed the first mathematical criteria for cathode directed streamer development, "a streamer will develop when the radial field about the positive space charge in an electron avalanche attains a value on the order of the external field". The process of cathode directed streamer development is shown in Fig. 2. A positive ion space charge (shown at the anode surface) is developed by avalanche effects. Photons ionize the gas surrounding the avalanche, producing "photo-electrons" which start auxiliary avalanches directed towards the positive space charge (Fig. 2a), providing that the space charge field is significant compared with the external field. The positive ions left behind by these avalanches effectively lengthen and intensify the space

charge of the primary avalanche in the direction of the cathode (Fig. 2b). The process continues to develop as a self propagating cathode directed streamer (Fig. 2c).

Fig. 2 The Process of Cathode Directed Streamer Development [16]

Raether conducted numerous cloud chamber experiments which led him to propose that, for a given α (Townsend's first ionization coefficient) and a single initiating electron, an anode directed streamer will develop when the electron avalanche has traveled a certain critical distance X_{cr} , that is when

$$\alpha X_{cr} \approx 20 \quad [13] . \quad (1)$$

The critical number of electrons in the avalanche is thus

$$N_{cr} = e^{\alpha X_{cr}} , \quad (2)$$

or from Eq. (1) $N_{cr} \approx 5 \times 10^8$ electrons. When X_{cr} is less than the gap length d , the avalanche goes over into

a streamer discharge. The time required to form a streamer is

$$t_{cr} \approx X_{cr}/V_e , \quad (3)$$

where V_e is the electron drift velocity, hence the higher the gap voltage the earlier the occurrence of the transition.

Anode directed streamers can be explained by assuming that photons ionize the gas in advance of, but near, the head of the avalanche and thus start new avalanches along the breakdown path. For the photons to be effective in the formation of an anode directed streamer they must ionize the gas in front of the avalanche head at distances comparable to the radius of the negative space charge.

The most important difference between the avalanche and the streamer is the velocity of propagation. The avalanche progresses at about 10^7 cm-sec⁻¹, whereas 10^8 cm-sec⁻¹ or higher is typical of streamer propagation. In gaps that break down via streamers, the breakdown time is thus determined by the avalanche propagation time (t_{cr}) required to reach a critical density, since the streamer propagation time is usually insignificant in comparison. The theory of streamer breakdown is understood but it is highly qualitative and thus remains a controversial subject.

Pulsed Nanosecond Gas Discharges

Rectangular voltage pulses with amplitudes greatly exceeding the gap static self-breakdown voltage and with risetimes shorter than the characteristic development times of the discharge in the gap have been applied to gas gaps [17]. In these experiments it has been observed that discharge channels are absent for prolonged periods of time even though the discharge current can attain high values (10^5 A). The formation of channels can occur after the current has reached its maximum value and several channels can be produced rather than just one. This "volume" discharge has been observed when using gas pressures on the order of several atmospheres and higher and field intensities of 10^5 V/cm and higher. Neither Townsend nor streamer theory can explain this phenomenon. Mesyats [18] has extended basic gas breakdown theory to include the pulsed nanosecond discharges. Mesyats has suggested [17] that the growth of the gap current during the initial stage of the discharge is due to the development of "avalanche chains". Such chains are produced when new avalanches are formed ahead of the preceeding avalanches. These avalanche chains grow together to conduct the current and bridge the gap. The conductivity of the avalanche chains is low, thus they must be numerous to pass a large current. The new avalanches could be

produced when: (a) electrons at the extreme head of the avalanche(s) are expelled from the avalanche(s) (they are accelerated by the field formed between the negative electron space charge and the anode); (b) the gas ahead of the avalanche(s) becomes photoionized by photons which are emitted from the avalanche(s); or (c) the gas is ionized by "runaway" electrons, e.g., for gap field intensities exceeding 10^5 V/cm and large E/p , the energy lost by the electrons in collisions becomes smaller than the energy acquired by them from the field, thus the electrons are progressively accelerated and "runaway" [19].

Loss of Streamer Character By the Breakdown

The character of the discharge in a gas depends essentially on whether the avalanche can acquire N_{cr} electrons over the length of the gap, i.e., if $X_{cr} < d$, then the dominant role in the breakdown is played by the primary avalanche, which goes over into a streamer and then into a discharge channel. For a streamer discharge to exist it is also necessary that the avalanche radiate enough photons to ionize the gas molecules near the head of the avalanche. Photons are emitted due to the deexcitation of excited gas molecules, which are typically excited for a lifetime of $\tau_{exc} \sim 10^{-9} - 10^{-8}$ s [13]. If the avalanche reaches its critical dimension in a time, t_{cr} , which is shorter than τ_{exc} , the development of the streamer from the primary

cascade will be difficult. A characteristic feature of a pulsed nanosecond discharge is that the time required for an electron avalanche to grow to its critical size is commensurate with or less than the average lifetime of the excited gas molecules. Thus, the two conditions for the development of a streamer are:

$$\underline{1} \quad X_{cr} < d, \quad (4)$$

or from Eq. (2),

$$\underline{1'} \quad \frac{\ln N_{cr}}{\alpha} < d, \quad (5)$$

and,

$$\underline{2} \quad t_{cr} > \tau_{exc} \quad (6)$$

or from Eq. (3),

$$\underline{2'} \quad \frac{\ln N_{cr}}{\alpha V_e} > \tau_{exc} \quad (7)$$

It is possible to use Eq. [5] to determine the maximum value of the electric field for which the streamer mechanism can no longer operate; e.g., $\tau_{exc} \sim 3\text{ns}$ and $\ln N_{cr} \sim 20$, for nitrogen at atmospheric pressure, thus, Eq. [5] will not be satisfied when $\alpha V_e \geq 10^{10} \text{ s}^{-1}$, i.e., at $E \geq 6 \times 10^4 \text{ V/cm}$. Consequently the initial discharge will not be of a streamer character when the

electric field exceeds this value. It has been shown that [17]

$$N_{cr} \sim \frac{T_e}{\alpha} \quad (8)$$

where T_e is the electron temperature. Since α increases faster with increasing fields than does T_e , it follows that N_{cr} decreases with increasing electric field intensity. Since the number of excited molecules in the avalanche is $N_{exc} \sim N_{cr} \sim T_e \alpha^{-1}$, it follows that the number of photons emitted from the avalanche is reduced. This effect, together with the decrease of photon yield from the avalanche as a result of the short avalanche development time, leads to a sharp decrease in the photon yield. Photons greatly influence the mechanism of the gas breakdown, e.g., decreased photon yield makes the formation of streamers much less likely, therefore the breakdown loses its streamer character.

The Source of Initial Electrons Due to Strong Electric Fields

The theory of explosive field emission from microscopic projections on the cathode, developed for vacuum gaps, has been extended to explain the source of initial electrons in gas gaps under the influence of strong, pulsed, electric fields ($E \geq 10^5$ V/cm) [17]. The Fowler and Nordheim [20] formula for field emission in vacuum gaps predicts that an electric field of 2×10^7 V/cm will

produce a current density of 10^{-10} A/cm², yet investigations [21] have found that fields of $10^5 - 10^6$ V/cm can produce current densities of $10^{-5} - 10^{-3}$ A/cm². This discrepancy is attributed to the presence of microscopic inhomogeneities on the surface of the cathode, at which the field intensity greatly exceeds the average macroscopic field in the gap. These irregularities in the electrode surface often take the shape of elongated points or "whiskers". The enhanced fields at the whisker tips can be 10-300 times the average macroscopic field in the gap [22, 23]. In some cases the field emitted current from the whiskers can become so strong that ohmic heating can cause them to explode, which enhances the breakdown of vacuum gaps [24, 25].

Explosive emission is also thought to influence the breakdown process of gas gaps by providing an intense source of initiating electrons [17]. This theory has been substantiated by experiments which prove that the surface of the cathode affects the delay time of the breakdown and the breakdown field intensity when nanosecond pulses are applied to gas gaps [26, 27]. Initiating electrons are thus thought to be supplied by field emission when gas gaps are broken down by strong, pulsed, electric fields.

Initiation by a Small Number of Electrons

When gas-filled gaps undergo breakdown, a certain delay time t_d elapses between the application of the

application of the voltage pulse and the breakdown of the gap. The delay time consists of "statistical" (σ) and "formative" (τ) time components. For highly overvolted gaps the statistical portion is determined by the initial current (i_0) from the cathode [17]:

$$i_0 = e/\sigma_0, \quad (9)$$

where e is the charge on an electron and σ_0 is the average statistical delay time. It follows from Eq. (9) that σ_0 can be interpreted as the average time between the appearance of two initiating electrons. If the time t_{cr} for avalanche development is less than σ_0 , it can be assumed that the discharge is initiated by single electrons.

For highly overvolted gaps breakdown proceeds from the initial avalanche via the avalanche chain mechanism. Because of the low photon yield, a streamer discharge does not develop; hence, a secondary process must take part in order to complete the breakdown, i.e., large numbers of electrons, hence electron avalanches, must be produced at the cathode by the photo electric effect. The pulsed nanosecond discharge is similar to a Townsend discharge in this regard. The two discharges differ, however, in the development of the electron avalanches. The Townsend avalanche growth is exponential and in the pulsed nanosecond discharge the avalanche growth is exponential only for a very short time, after which the ion space-charge

field decreases the rate of particle multiplication. The total growth of the number of electrons with time can be regarded as linear [17]. A gas gap current comparable with the maximum current determined by the discharge circuit parameters is produced in such a discharge several nanoseconds before spark channels are produced in the gap. The reason for the formation of a large number of spark channels (≥ 10) has not been determined. Since secondary processes are involved, the discharge formative time is longer, e.g., in the case of a small current of initiating electrons from the cathode, the discharge formative time exceeded the time required for the avalanche to develop a critical size by one or two orders of magnitude [17]. This does not violate Mesyats' condition for the formation of a volume discharge since it is not the delay time, but rather the avalanche formation time that is important, i.e., the condition is that the avalanche must reach its critical size in a time $t_{cr} < \tau_{exc}$.

Initiation by a Large Number of Electrons

The effect of initiation by a large number of initial electrons is twofold: (a) (from Eq. (9)) the statistical portion of the delay time can be virtually eliminated (studies conducted by Fletcher [28] have experimentally confirmed that about 10^4 initial electrons are sufficient to completely eliminate the spread in the discharge delay

time ($\sigma \rightarrow 0$); and (b) a space-charge current comparable to the maximum circuit current can be obtained without participation of secondary processes, but only through development of primary electron avalanches (this has the effect of substantially reducing the discharge formative time (hence, delay) as compared to the case of single electron initiation).

Gas Discharge Initiated by an Electron Beam

Mesyats has extended his theory to include the case of discharge initiation by an intense source of preliminary ionization. For this case the breakdown can occur at voltages far less than the static breakdown voltage ($> 50 \% V_{sb}$). A discharge can be initiated by an electron beam or an intense ultraviolet flash [29], either of which can result in the production of a large number of initial avalanche initiating electrons (ultraviolet radiation incident on the cathode produces large numbers of electrons as the result of the photoelectric effect). According to Mesyats [17], the main requirement for the discharge to proceed without streamer formation is to insure an initiating electron-current

$$i_0 = (eN_0V_e/d) A \quad (10)$$

large enough such that the space-charge current will reach a value at which the gap voltage begins to fall

off before each individual avalanche can attain a total number of electrons $N \geq 10^8$ (the condition for streamer formation). If the initiating electrons are distributed over a large enough area, the breakdown will proceed via ionization in the gas volume without the formation of localized spark channels.

Mesyats has formulated his theory for the case where the initial electrons originate at the cathode, i.e., the e-beam originates from the cathode and propagates toward a positively charged target electrode (anode). Hence, this theory is not directly applicable to the case where the e-beam originates at the anode and propagates toward a negatively charged target electrode (cathode). When introduced against an external gap field (a negative target electrode) an electron beam of 200 keV would not be able to traverse a long gap insulated with a high pressure gas, e.g., for a gap field of 85 kV/cm and 3 atm of N_2 in a 3.2 cm gap, 200 keV electrons would travel approximately 1.2 cm into the gap, hindered primarily by the electric field (this was one of the conditions that existed in our experiment). Obviously when longer gaps, denser gases, and higher fields are used the beam will penetrate only a small fraction of the gap length, e.g., with approximately 6 atm of SF_6 and a retarding field of about 0.3 MV/cm, a 350 keV beam will penetrate only about 0.7 cm.

When the beam is introduced from the anode, towards a negatively charged target electrode, the primary mechanism for e-beam initiated breakdown appears to be a large number of electrons released from the surface of the cathode via the photo-electric effect. These electrons would be accelerated by the gap field, initiating multiple electron avalanches (photo-ionization in the gas volume may also contribute to breakdown). This situation is simply the equivalent of the case where the breakdown is initiated by an ultra-strong photon-flux incident on the cathode. Mesyats' conditions and theory for breakdown (without streamer formation) of a gap charged to less than its self-breakdown voltage, are applicable.

CHAPTER III

EXPERIMENTAL ARRANGEMENT AND DIAGNOSTICS

The Experimental Arrangement

Introduction

A block diagram of the experiment is shown in Fig. 3. The basic experimental arrangement shown in Fig. 4 consists of: (a) an energy storage element, (b) a gas insulated, pressurized spark gap, and (c) a source of energetic electrons. This chapter describes the overall system arrangement as well as the individual system components. Attention is given to the grounding and shielding techniques that were implemented to insure low-noise diagnostic signals.

It is important to note that the entire experiment was designed around two major components: (a) an "FX-15" [30], which contained both the energy storage element (a co-axial pulse forming line - PFL) and the spark gap (an interruption in the center conductor of the line), and (b) a "Heds Pulser" [31], which served as the driver for the electron gun (a vacuum diode). Designing the system around these components resulted in some rather severe limitations on both component and overall system design. These limitations and the resulting problems are discussed in Appendix A.

FX-15

Fig. 3 Block Diagram of E-Beam Initiated Switch

Fig. 4 The Basic Experimental Arrangement

System Firing Sequence

The normal operating sequence of the system is as follows (see Fig. 5): with both the PFL and the Heds pulser charged to desired voltage levels, a "fire" command is issued to the trigger system of the Heds pulser, which then erects and launches a pulse down a transmission line where it appears across the anode-cathode gap in the diode. A burst of electrons is thus emitted from the diode and enters the spark gap region where it ionizes the insulating gas by impact, resulting in the subsequent formation of a conducting path and voltage collapse across the gap. The PFL is thus discharged and the resulting wave propagates down the output transmission line where it is monitored by several probes, displayed on oscilloscope screens, and recorded on photographic film.

The FX-15

The FX-15 can be described as a Van de Graaff charged line pulser. It is basically a $50\ \Omega$, high pressure, gas dielectric, co-axial line, whose center conductor is interrupted by a spark gap (see Fig. 5). The section of this line in front of the spark gap (formed by the terminal of the Van de Graaff generator and the surrounding high pressure vessel) represents a charged, open-ended, co-axial line, which is capable of producing a $1/2$ MV rectangular pulse with a duration equal to twice the one way transit

Fig. 5 The FX-15/Heds Pulsar/Diode Arrangement

time of a propagating wave into a matched load [32]. For this machine the pulse duration (τ) is about 10 ns, FWHM.

The electrodes for the spark gap are made of stainless steel. They are 21.5 cm in diameter and have a Bruce profile [33] (see Fig. 6).

Fig. 6 The Bruce Profile Electrode

The Diode

The source of energetic electrons that best suited our needs was a field emission vacuum diode. A detailed description of the diode in terms of its design consideration, individual components, and the restrictions imposed by the FX-15 is presented in Appendix A. The beam characteristics that are of interest are listed in Chapter IV.

The Heds Pulser

The driving generator for the diode was a Heds pulser (Fig. 7). "Heds" stands for "high energy density system". The unit is a modified Marx generator, where the capacitive elements have been replaced by lumped-parameter transmission lines. Thus, the Heds pulser combines the voltage multiplicative feature of the standard Marx circuit with the pulse shaping characteristics of a lumped parameter network.

Fig. 7 The Heds Pulser

The Heds unit consists of 25 energy storage or pulse forming modules. An array of 5 barium titanate disk capacitors comprise the energy storage element for each module (Fig. 8). The LC lumped parameter line is formed by grounding the bottom surface of the capacitors to each

Fig. 8 A Heds Pulsar Module

other with a broad strap and by connecting the top with a small diameter wire which forms the inductance for each section of the line (module). A module is shown schematically in Fig. 9.

Fig. 9 Schematic of a Heds Pulser Module

The 25 modules are stacked in an array, and the modules are interconnected with gas pressurized spark gap switches that connect the Marx generator in series for discharge. A schematic of the module stack is shown in Fig. 10. The module stack is enclosed in an aluminum case which is pressurized with N_2 to insulate the spark gaps. The Heds pulser is discharged into a co-axial, oil-filled, transmission line. The overall arrangement makes for a relatively noise-free pulser.

The Heds pulser has a characteristic impedance of 70Ω . At the maximum module charging voltage of 32 kV, the unit delivers a 4.6 kA, trapezoidal shaped current pulse at 320 kV into a matched 70Ω resistive load. The pulse length is 50 ns (FWHM) and has a rise time of approximately 4 ns

Fig. 10 Schematic of the Heds Pulser Module Stack

between the 10% and 90% points. The pulser has 100 J of energy for these conditions. In the experiment, the Heds was charged for a maximum output voltage of only 250 kV, due to frequent module failures when charged to higher voltages.

The Heds Pulser Trigger System

The Heds pulser was triggered by applying a 10 kV pulse to a needle-point trigger pin, which broke down the first gap (Fig. 10). Succeeding gaps were closed due to the resulting overvoltage.

The trigger pulse was generated by discharging a capacitor through a 4C35 hydrogen thyratron switch tube into a cable which was terminated in a 1:4 pulse transformer, and, hence, the trigger pin. The 4C35 was triggered by a krytron pulser which was triggered by a Tektronix type 162 waveform generator. The 162 was triggered either manually or with a pulse generated by a Tektronix 555 oscilloscope. The scope monitored the FX-15 Van de Graaff column voltage (gap voltage), and could be adjusted to generate a pulse when the amplitude rose to any desired gap voltage. This enabled us to determine the gap voltage at the time of e-beam initiation and eliminated the judgement involved in manual operation.

FX-15 and Heds Pulser Considerations

In order to introduce the e-beam into the gap axially it was necessary to mount the diode inside the FX-15 ground

potential electrode. It was desirable to minimize the distance between the diode foil and the point where the e-beam entered the spark gap, since the electrons would lose energy in traversing this high pressure gas region. This placed a limitation on the diameter of the diode (assuming a planar anode) that could be positioned inside the electrode, since the Bruce profile electrode began to curve away from the plane of the gap after its diameter exceeded 3". A larger diameter diode would, therefore, cause an increase in the foil to gap distance (see Figs. 5 and 6).

The problems encountered in arranging for the diode transmission and vacuum lines were significant also. The solution was to let the diode transmission line enter the FX-15 in a tri-axial configuration (Fig. 5), i.e., the outer conductor of the Heds pulser to diode transmission line also acted as the inner conductor for the FX-15 output transmission line. The diode vacuum region was evacuated through the hollow inner conductor of the diode transmission line.

There were several problems associated with incorporating this arrangement into our system. These included the limitations on the dimensions of both the diode and the diode transmission line and the fact that the Heds pulser case was connected to the high potential conductor of the FX-15 output line; thus it would rise to a high potential every time the FX-15 was discharged.

Diagnostics

This section discusses the diagnostics and the grounding and shielding techniques that were used in the investigation of the spark gap breakdown. It was necessary to characterize the e-beam before it was used to conduct breakdown studies. This process took place before the diode was installed in the FX-15 and it is reported on in Appendix A.

The characteristics of the spark gap breakdown that were investigated are: (a) the character of the breakdown (gas discharge), (b) the risetime of the transmitted voltage pulse from the FX-15, and (c) the delay and jitter. The diagnostics that were utilized are: (a) open shutter and streak photography, (b) a capacitive voltage divider probe, and (c) a $\dot{B}$ loop to monitor the current.

Optical Diagnostics

Open shutter photographs were taken of the discharge for both the self breakdown and the e-beam induced breakdown of the spark gap. Streak photographs were also taken for the e-beam triggered case.

Electrical Diagnostics

The locations of all of the electrical probes are shown in Fig. 11.

Fig. 11 The Location of the FX-15 Electrical Probes

The Capacitive Voltage Divider Probe

The capacitive voltage divider probe (Fig. 12) is located in the FX-15 output transmission line. This probe was used to monitor the FX-15 output voltage pulse. When the spark gap begins to conduct (self-break or triggered) an E-M wave is launched down the FX-15 output transmission line. The risetime of the E field in this wave is indirectly proportional to the voltage collapse across the gap (i.e., directly proportional to the current rise in the gap). The amplitude of the E field in this wave is directly proportional to the charging voltage on the FX-15 charge column (gap voltage), thus both the switching action and the gap voltage could be directly resolved with this probe. This was our primary switch diagnostic tool.

The $\dot{B}_2$ Current Probe

The $\dot{B}_2$ probe is located adjacent to the capacitive voltage probe in the FX-15 output transmission line. It was constructed by attaching a two-turn rectangular wire loop (3 mm x 8 mm) to a type N connector. This probe was used to confirm the validity of the results, particularly the risetimes, obtained by the capacitive probe.

The Current Viewing Resistor Probe

A current viewing resistor probe was also built into the FX-15 transmission line. It was formed by connecting the radial load resistor to the outer conductor of the

Fig. 12 The Capacitive Voltage Divider Probe

transmission line through 70, 1 Ω - 1/2 W carbon resistors. The current pulse was monitored by measuring the voltage drop across one of the resistors. This probe was also used to confirm the results of the capacitive probe.

The $\dot{B}_1$ Current Probe

The $\dot{B}_1$ probe is located in the Heds pulser output transmission line. Its construction is identical to that of the $\dot{B}_2$ probe. This probe was used to monitor the diode driving pulse.

Grounding and Shielding

The grounding and shielding techniques that were used to obtain "clean" signals from the FX-15 output pulse are illustrated in Fig. 13. Many of these ideas can be attributed to the personal assistance of fellow graduate student Edmond Chu and to Fitch [34].

Special Problems

It was mentioned that the Heds pulser case was connected directly to the high potential, inner conductor of the FX-15. This presented a variety of problems, including operator safety and the possibility of "noisy" signals resulting from the capacitive coupling between the high potential Heds and nearby components, particularly the oscilloscopes. These two problems were solved by housing the entire load end of the experiment, including the Heds

Fig. 13 The Grounding and Shielding System

pulser, in a shielded enclosure. This shield room was constructed by covering an angle iron frame with aluminum sheets. The room was made large enough to house the Heds power supply and high voltage trigger circuit (8' x 8' x 8'), since both of these components were connected electrically to the Heds and could conceivably rise to high potentials and present stray capacitance problems also, if left outside the room. Both of these components were inductively isolated from the high frequency pulses appearing on the Heds. The vacuum station was also placed inside the room to minimize the pumping distance.

Equipment Grounds, Power Lines and Cable Shields

The vacuum station, power supply, and high voltage trigger generator were all grounded to the shield room at their respective locations. The Heds pulser was grounded through the 50 Ω , FX-15 load resistor. The external components (low voltage trigger generators, time delay generator, FX-15 control panel, etc.) were all grounded to the exterior of the room with short leads. The scopes were grounded to the room through the braid of the signal cable. The FX-15 was grounded to the room. The room and thus the system was connected to earth ground for safety considerations.

The 110 V, 60 Hz line which supplied the room and interior equipment was filtered and equipped with an isolation

transformer to prevent high voltage transients from being introduced into the rest of the laboratory power system. The shield room power supply line came directly from the building transformer room and supplied power nowhere else. The scopes were connected to the regular wall outlet and light circuit. This enhanced the electrical isolation between the high voltage shield room and the scopes.

The probe signal cables (RG-8, 50 ohm/co-axial cables) were enclosed in copper tubes which were connected to the cable outer conductor at the probe end and to both the cable outer conductor and to the shield room at the point where the cables exited the room. This tubing contained the cables until they reached the scopes but was not physically connected to anything at that end. Thus the cables were protected from the influence of magnetic fields or potential differences between components in ground loops. The signal from the $\vec{B}_1$ probe in the Heds-to-diode transmission line was protected from noise in the same manner. That is, the cable was enclosed in a copper tube which was connected to the cable and to the shield room in the manner previously described. Since this cable was connected to the Heds pulser case which rose to high potentials, the tubing and the enclosed cable were wound into an isolation inductor. This provided an adequate pulse isolation between the Heds pulser and the shield room.

CHAPTER IV
RESULTS OF E-BEAM INITIATED GAS DISCHARGES

Introduction

A variety of individual experiments were performed, each designed to explore a specific aspect of the spark gap breakdown. The overall results of these experiments will be discussed. The experimental parameters that were varied include: (a) the e-beam target electrode (gap) polarity, (b) the gas pressure, (c) the gap voltage at the time of the e-beam injection, (d) the type of gas or gases, (e) the e-beam diameter, and (f) the e-beam energy. As mentioned before, the investigation was primarily concerned with the risetime of the pulse (t_r), the delay and jitter, and the general character of the discharge. Several other aspects of the breakdown process are being studied in follow-on investigations.

Unless otherwise specified, all the breakdown experiments were conducted for the following conditions: (a) the gap spacing was 3.2 cm, (b) the gas was nitrogen, (c) the diode aperture was 2.54 cm diameter, and (d) the diode driving pulse (Heds pulser output voltage, V_d) was 200 kV. This 200 kV diode pulse resulted in an electron beam, after

transmission through a 2 mil titanium foil, with the following characteristics: (a) the most probable energy (E_p) of the beam was approximately 145 keV, (b) the average energy of the beam was approximately 134 keV, (c) the spectrum of the beam energy ranged from 18 keV to 174 keV, (d) the 0% - 50% pulse risetime was 1.5 ns, (e) the pulse duration was approximately 15 ns, (f) the beam current was approximately 0.5 kA, and (g) the beam current density was approximately 100 A/cm². The beam's most probable energy, average energy, and energy spectrum were obtained from a study conducted by Seltzer and Berger at the National Bureau of Standards [35]. The pulse risetime, duration, current and current density are reported on in Appendix A.

Self Breakdown of the FX-15 Spark Gap

The self breakdown of the FX-15 spark gap resulted in a voltage pulse which, when monitored by the capacitive pulse (C_1), appeared typically as shown in Fig. 14. The self breakdown pulses were found to be surprisingly repeatable in both risetime and amplitude. The 10% - 90% risetime was approximately 2.5 ns (10 ns FWHM).

Fig. 14 A Typical Self-Breakdown Voltage Pulse,
Monitored by the Capacitive Voltage
Divider Probe

The Triggered FX-15 Pulse Shape and Risetime

The e-beam initiated breakdown of the FX-15 spark gap resulted in a voltage pulse which, when monitored by the capacitive probe (C_1), appeared typically as shown in Fig. 15. The pulse durations at FWHM were approximately 10 ns. The 10% - 90% risetimes (t_r) were approximately 2.5 ns. These pulse risetimes were observed to be virtually identical throughout most of the investigation. The self breakdown and triggered breakdown pulse shapes demonstrated close similarities which can be seen from the superimposed traces in Fig. 16.

$t \rightarrow 5 \text{ ns/div}$

Fig. 15 A Typical E-Beam-Triggered Voltage Pulse, Monitored by the Capacitive Voltage Divider Probe

$t \rightarrow 5 \text{ ns/div}$

$t \rightarrow 5 \text{ ns/div}$

Fig. 16 Superimposed E-Beam Triggered and "Typical" Self Breakdown Voltage Pulses

The Delay and Jitter

The EBTS delay was measured by observing the time spread from the appearance of the diode driving pulse (the time derivative of the current pulse is monitored by the $\dot{B}_1$ probe) to the rise of the FX-15 voltage pulse (monitored by the capacitive voltage divider probe, C_1). The diagnostic arrangement for measuring the EBTS delay and jitter is shown in Fig. 17. For lack of a fiducial generator, it was necessary to display both the diode input signal ($\dot{B}_1$) and the FX-15 output signal (C_1) on the same scope trace. The $\dot{B}_1$ signal had a long noisy tail due to the transmission line reflections between the diode and the Heds pulser, hence it was cable delayed to appear on the scope after the FX-15 output pulse so the FX-15 pulse would be clean. The scope was triggered internally by the incoming FX-15 signal. This can be observed in Fig. 18. The delay was determined as follows: (a) by accounting for the cable and transmission line transit times of both the diode input pulse and the FX-15 output pulse, and (b) by measuring the time between the two pulses on the scope trace (point A to point B, Fig. 18). The delay was found to be 51 ns in most cases.

Fig. 17 The Diagnostic Arrangement for Measuring the EBTs Delay and Jitter

Fig. 18 A Typical E-Beam Triggered Spark Gap Delay Measurement

The jitter was found to be exceptionally small throughout the range of our investigation and is demonstrated by the photographs in Fig. 19. The jitter was determined with the same arrangement as was used to measure the delay. The jitter measurements are demonstrated by the photograph in Fig. 19-a, which overlays five individual shots. The time scale is 5 ns/div. A 2 ns/div sweep speed was chosen in order to resolve the jitter more accurately. It was necessary to trigger the scope externally with the diode input pulse ($\vec{B}_1$) since both signals (C_1 and $\vec{B}_1$) could not be displayed at this sweep speed. This meant the 519 scope jitter would be included in the EBTS jitter measurements. The EBTS jitter (scope jitter included) was demonstrated

(a) 5 ns/div

$V_{sb} = 250 \text{ kV}$

$V_t = 50\% V_{sb}$

5 Shots

(b) 2 ns/div

$V_{sb} = 250 \text{ kV}$

$V_t = 94\% V_{sb}$

15 Shots

(c) 2 ns/div

$V_{sb} = 250 \text{ kV}$

$V_t = 50\% V_{sb}$

15 Shots

Fig. 19 Typical EBTS Jitter Measurements

to be very small by the photographs in Figs. 19b and c, which overlay 15 individual shots each. The time scale is 2 ns/div; thus the time resolution is approximately 0.2 ns and the jitter is obviously not much larger than that. The $\vec{B}_1$ signal was confirmed to be triggering the scope by delaying the FX-15 output pulse with a 10 ns delay cable. The pulse was observed to move two divisions at a sweep speed of 5 ns/div. (Sorry, no photographs are available.)

The Character of the Discharge

The self breakdown of the FX-15 spark gap was always observed to be in the form of a thin filamentary channel or "lightening bolt" (Fig. 20), whereas the e-beam initiated breakdown resulted in a "volume discharge" (Fig. 21) throughout the investigation. The only deviation from this observation was for a gas mixture of 20% SF₆ and 80% N₂, where both volume and channel discharges were observed for e-beam triggering. These results are inconclusive, however, because the Lucite surface of the diode vacuum-dielectric interface had suffered visible signs of surface tracking during that part of the investigation. The breakdown may thus not have been the result of the multiple electron initiation process (due to the influx of an energetic electron beam) but, rather, due to a very few low energy

Fig. 20 Open Shutter Photograph of the
Self-Breakdown Discharge of the
FX-15 Spark Gap

Fig. 21 Open Shutter Photograph of the
E-Beam Triggered Discharge of
the FX-15 Spark Gap

electrons which entered the gap. In this case the breakdown would have occurred via a streamer process, hence a channel discharge. Further information on the optical diagnostics used and the results obtained therefrom may be found in Ref. [36].

The Effects of Changing the Target Electrode Polarity

With the FX-15 column and, hence, the e-beam target electrode charged positive, the injected e-beam was accelerated by the initial electric field in the gap, whereas the e-beam was decelerated in the negative target electrode case. The electrical diagnostics did not reveal any noticeable changes in the general pulse shape, risetime, pulse width, delay, or jitter as a result of the polarity change. The positive and negative pulses are basically mirror images of each other as can be seen in Fig. 22. For both cases the actual EBTS delay was determined to be 51 ns and the jitter was below the capabilities of our resolution.

The optical diagnostics revealed a dramatic difference in the visible character of the discharge, brought about by the target electrode polarity change which can be seen by comparing the open shutter photographs of the discharge for the positive and negative cases (Fig. 23). There is an obvious difference in the time integrated

Fig. 22 A Comparison of the E-Beam Triggered FX-15 Voltage Pulse for Positive (a) and Negative (b) Polarity Target Electrodes

Fig. 23 A Comparison of the Open Shutter Photographs of the E-Beam Triggered Discharge of the FX-15 Spark Gap, for Positive (a) and Negative (b) Polarity Target Electrodes

light emission for the two cases, indicating a probable difference in the physical processes that led to the respective breakdowns. A gas mixture of 10% argon and 90% nitrogen at 30 psig ($V_{sb} = 260$ kV) was used to increase the light emission and thus permit streak photographs of the discharge to be taken. These streak photographs are shown in Fig. 24. A comparison of these photographs reveals differences in the real time light emission from the discharge for the two cases. Consult Reference [39] for further information.

The Effects of Varying the Gas Pressure

A gas pressure variation between 5 psig and 30 psig of nitrogen was used to observe the effects of pressure on the breakdown. This pressure range corresponds to self breakdown voltages from 120 kV to 270 kV and, hence, to electric fields from 37 kV/cm to 85 kV/cm.

The electrical diagnostics did not reveal any noticeable changes in the pulse shape, risetime, width, delay, or jitter as a result of the pressure variation. This can be seen in Fig. 25. Fig. 25a is the voltage pulse recorded for a gas pressure of 11.5 psig ($V_{sb} = 175$ kV) and Fig. 25-b is the voltage pulse recorded for a gas pressure of 25 psig ($V_{sb} = 240$ kV). In both of these events the e-beam was injected into the gap when the voltage across the gap

Fig. 24 A Comparison of the Streak Photographs of the E-Beam Triggered Discharge of the FX-15 Spark Gap, for Positive (a) and Negative (b) Polarity Target Electrodes.

(a) $P = 11.5 \text{ psig}$

$V_{sb} = 175 \text{ kV}$

$V_g = 98\% V_{sb}$

(b) $P = 25 \text{ psig}$

$V_{sb} = 240 \text{ kV}$

$V_g = 98\% V_{sb}$

Fig. 25 FX-15 Voltage Pulses for Two Different Gas Pressures

when the voltage across the gap was equal to 98% of the self breakdown voltage, i.e., $V_g = 98\% V_{sb}$. This accounts for the difference in the pulse amplitudes. The difference in the intensity of the open shutter photographs (Fig. 26) was due to the difference in the gap fields that existed when the e-beam was introduced, e.g., the electric field was 37 kV/cm @ 5 psig, and 75 kV/cm @ 25 psig. No changes were observed in the breakdown characteristics that could be attributed solely to the pressure variation.

Fig. 26 Open Shutter Photographs of the FX-15 Discharge for Two Different Gas Pressures

The Effects of Injecting the E-Beam for Various Gap Voltages

The effects of injecting the e-beam when the gap was charged to various percentages of the self breakdown voltage can be seen by observing the voltage pulses (Fig. 27a @ $V_g = 98\% V_{sb}$, and Fig. 27b @ $V_g = 58\% V_{sb}$), and the open shutter photographs for the same conditions. Again there were no differences in the pulse shape, the delay, or the jitter. The pulse risetime was seen to increase for the special case when the gap was charged to a low percentage of self-breakdown ($\sim 50\%$) and the e-beam energy was very low ($E_p = 75$ keV). This will be discussed in more detail in a later section. The low jitter measurements for the $V_g = 58\% V_{sb}$ case are very important and will be discussed again in the summary.

No effects of varying the gap voltage were demonstrated by the open shutter photographs.

Gas Mixtures

The gas was changed to a mixture of 10% argon and 90% nitrogen to obtain more light emission and the above three experiments (variation of the target electrode polarity, gas pressure, and gap voltage at the time of e-beam injection) were repeated. No differences were observed in the pulse at any time and the jitter remained sub-nanosecond

(a) $V_g = 98\% V_{sb}$
5 ns/div

(b) $V_g = 58\% V_{sb}$
5 ns/div

Fig. 27 FX-15 Voltage Pulses for E-Beam Injection into the Gap Charged to Two Different Percentages of the Self-Breakdown Voltage

as before. The delay was not measured in this series of tests. The only difference observed was the expected increase of light intensity emitted from the discharge, which allowed streak photographs to be taken. The experimental equipment did not include an image intensifier and the light emission from the discharge was normally insufficient to record on film with the fast streak speeds needed.

The gas mixture was then changed to a mixture of 20% SF_6 and 80% N_2 in order to increase the self breakdown voltage and thus the triggered breakdown voltages. As previously discussed, the results for this particular experiment were inconclusive and will not be presented in further detail here.

The Effects of Varying the Diameter of the E-Beam

The effects of reducing the e-beam diameter can be seen by comparing the open shutter photographs of the discharge (Fig. 28a @ $d = 2.54$ cm, and Fig. 28b @ $d = 1.25$ cm). The open shutter photographs indicate that the diameter of the discharge is proportional to the diameter of the injected electron beam. This is a very important characteristic of the EBTS and will be discussed in the conclusions. No variations were observed in the pulse shape, risetime, width, or jitter.

Fig. 28 Open Shutter Photographs of the FX-15 Discharge Initiated by Two Different E-Beam Diameters

The Effects of Varying the E-Beam Energy

The effects of varying the e-beam energy can be seen by observing the voltage traces in Fig. 29, and the open shutter photographs in Fig. 30. The gas was 10% argon and 90% nitrogen at 29 psig. Figures 29a and 30a were recorded for the following conditions: $V_{sb} = 260$ kV, $V_g = 250$ kV = 96% V_{sb} , and $V_d = 240$ kV, hence, from [38], the most probable energy was $E_p \sim 190$ keV. Figures 29b and 30b were recorded for conditions identical to Figs. 29a and 30a, respectively, except that the diode voltage was reduced ($V_d = 160$ kV), hence the e-beam energy was reduced accordingly ($E_p \sim 80$ keV). Figures 29c and 29d were recorded for conditions identical to Figures 29a

$$(a) \quad V_g = 96\% V_{sb}$$

$$E_p \approx 190 \text{ keV}$$

$$t/d = 5 \text{ ns/div}$$

$$(b) \quad V_g = 96\% V_{sb}$$

$$E_p \approx 80 \text{ keV}$$

$$t/d = 5 \text{ ns/div}$$

$$(c) \quad V_g = 50\% V_{sb}$$

$$E_p \approx 190 \text{ keV}$$

$$t/d = 5 \text{ ns/div}$$

$$(d) \quad V_g = 50\% V_{sb}$$

$$E_p \approx 80 \text{ keV}$$

$$t/d = 5 \text{ ns/div}$$

Fig. 29 FX-15 Voltage Pulses Initiated by Beams of High ($E_p \sim 190 \text{ keV}$) and Low ($E_p \sim 80 \text{ keV}$) Energy Electrons Introduced Into a Gap Charged to Two Different Percentages of the Self Breakdown Voltage.

and 29b, respectively, except that the gap voltage was reduced ($V_g = 50\% V_{sb}$). A comparison of Fig. 29a with Fig. 29b and of Fig. 29c with Fig. 29d demonstrates that the amplitude and risetime of the voltage pulse are both functions of the e-beam energy, and a comparison of Fig. 30a with 29b demonstrates that the integrated light emission from the discharge is also a function of the e-beam energy.

Fig. 30 Open Shutter Photographs of the FX-15 Discharge Initiated by Beams of High (a) and Low (b) Energy Electrons

The results appear to indicate that the degree of ionization in the discharge plasma, hence the plasma resistivity and ultimately the resistance across the gap all vary with the beam energy. This leads to the important conclusion that the voltage drop across the gap is a function of the e-beam energy. A comparison of Fig. 29a with Fig. 29c reveals that there is no difference in the pulse risetime due to injecting a high energy beam into a gap charged to various fractions of the self breakdown voltage. A comparison of Fig. 29b with Fig. 29d shows, however, that there is a difference in the pulse risetime for the special case where a low energy beam ($V_d = 160$ kV, $E_p \sim 80$ keV) is injected into a gap charged to low percentages ($\sim 50\%$ V_{sb}) of the self breakdown voltage.

The Gap Resistance

The resistance of the gap can be determined by comparing the magnitudes of the triggered and self breakdown pulses. A comparison of the triggered pulse in Fig. 29a with the self breakdown pulse in Fig. 14 (see Fig. 16) shows that the triggered output pulse amplitude is about 93% of the self breakdown pulse amplitude. The gap was triggered by the electron beam ($V_d = 240$ kV, $E_p \sim 190$ keV) at a gap voltage of 96% of the self breakdown voltage.

The 3% difference represents the additional losses sustained in the triggered breakdown case. Three percent of V_{sb} is 7.8 kV, and this voltage was thus dropped across the gap due to the impedance of the discharge. The current was 5.2 kA; thus, the gap impedance was initially about 1.5Ω . It is important to note that this high impedance (large gap voltage drop) lasted for only 2.5 ns after the rise of the pulse, after which time the impedance and, hence, the voltage drop was reduced to a value comparable to that of the self breakdown pulse.

The minimum initial gap resistance that was observed for the triggered case was about $1.0 - 1.5 \Omega$. When the e-beam energy was reduced, the resistance across the gap increased and, thus, the gap voltage drop increased also. This effect can be seen by comparing Fig. 14 with Fig. 29b. The same experimental measurements were duplicated for a positive target electrode, yielding identical results.

CHAPTER V

SUMMARY

Risetime

The pulse risetime varied from about 3.0 ns to a minimum of about 2.5 ns. The majority of the work that was conducted resulted in the 2.5 ns risetime. The 2.5 ns risetime was virtually identical to the risetime of the pulse when the gap underwent self-breakdown (Fig. 16). These results have led to the conjecture that the pulse risetime could be generator limited rather than spark gap limited.

Delay and Jitter

The jitter was observed to be very small throughout the experiment. Low jitter is extremely important, especially those measurements which were recorded when the gap was charged to low percentages of the self-breakdown voltage ($V_g = 50\% V_{SB}$).

The Volume Discharge

Throughout the range of the investigation the breakdown of the EBTS has been observed to take the form of a volume discharge, the dimensions of which correspond to the cross-sectional area of the injected e-beam.

The E-Beam Energy

The results of our experiments confirmed that the principal factor determining breakdown is the e-beam energy. The breakdown was affected when a low energy beam was used. The beam energy was reduced by reducing the diode driving voltage which reduced the beam current also, however, the small aperture experiment demonstrated that reducing the current did not alter the breakdown. It is expected that the beam energy can and should be optimized for the particular insulating gas.

Conclusions

The results of this study and others indicate that EBTS has a considerable potential, brought about mainly by the volume discharge, the low jitter, and the ability to function at voltages well below the self-breakdown voltage. The volume discharge results in a low gap inductance (hence, fast risetime), advantages for rep-rating, and scalability. The low jitter makes EBTS ideal for use in simultaneous switching of parallel lines. The ability to function at low percentages of the self-breakdown voltage enables EBTS to eliminate dangerous transients due to prefires.

The potential of EBTS is sufficient to warrant further research and development.

APPENDIX

CHAPTER I

THE DIODE DESIGN

Introduction

The source of electrons that best suits our needs is a field emission vacuum diode. It is important to remember that the purpose of the diode is to emit a beam of energetic electrons which are used to initiate gas breakdown. A volume discharge is desirable; therefore, the e-beam should not be self convergent. The diode is described in terms of its individual components, keeping in mind the restrictions imposed by the FX-15 and the Heds pulser. The diode design is illustrated in Fig. A-1.

FX -15 and Heds Pulser Considerations

The diode and FX-15 transmission lines were constructed in a tri-axial configuration, i.e., the outer conductor for the Heds pulser to diode transmission line also acted as the inner conductor for the FX-15 output transmission line. The diode impedance was chosen to be $70\ \Omega$ to match that of the Heds pulser. The diode's geometry, dimensions, and impedance have thus been determined by the characteristics of the FX-15 and the Heds pulser.

Fig. A-1 The Diode

The fact that the Heds pulser case was connected to the high potential conductor of the FX-15 output transmission line and would thus rise to a high potential every time the FX-15 was discharged presented some special problems including safety and diagnostics. The solutions for these problems will be discussed later.

The Diode Impedance

The impedance of a coaxial transmission line is given by the equation

$$Z = \sqrt{\frac{\mu}{\epsilon}} \frac{\ln b/a}{2\pi} \quad (A-1)$$

where a and b are the diameters of the inner and outer conductors, respectively, and the permittivity ϵ , is proportional to the dielectric constant of the medium separating them.

The impedance of the diode can be determined from the Child-Langmuir law for parallel plate electrodes [37,38]. The current density

$$J = 2.3 \times 10^{-6} V^{3/2}/d^2 \text{ (A/m}^2\text{)} \quad (A-2)$$

where V is the applied anode-cathode voltage (volts) and d is the electrode spacing (meters). Thus,

$$I = 2.3 \times 10^{-6} A V^{3/2}/d^2 \text{ (A)} , \quad (A-3)$$

since $I = JA$, where A is the cross-sectional area of the cathode. The diode impedance,

$$Z = V/I = d^2 \times 10^6 V^{-1/2} / 2.3A (\Omega) . \quad (A-4)$$

The cathode diameter was already determined to be 2.37 cm, so the area, $A = 4.41 \text{ cm}^2 = 4.4 \times 10^{-4} \text{ m}^2$. The diode impedance is then

$$Z = 9.84 \times 10^8 d^2 V^{-1/2} (\Omega) \quad (A-5)$$

Choosing the diode impedance to be 70Ω and solving for the spacing as a function of the applied voltage we obtain,

$$d = (7.1 \times 10^{-8} V^{1/2})^{1/2} \quad (A-6)$$

Typical values are $d = 5.96 \text{ mm}$, for $V = 250 \text{ kV}$.

The Cathode

The cathode is shown in Fig. A-2. Graphite was chosen for the cathode material because it has been found to "turn on" faster than other commonly used materials [39], that is, the diode is capable of achieving its smallest delay with a graphite cathode. The graphite is a high purity, high density grade produced by Poco Graphite Co. Spiral grooves were cut into the cathode surface in order to achieve uniform emission.

Fig. A-2 The Cathode

The Anode

The anode consists of two parts: (a) the foil, which allows the transmission of electrons, and (b) the foil holder, which provides (1) support for the foil, (2) the means for achieving the vacuum seal, and (3) a method by which the anode is held parallel with the cathode surface.

The Foil

A variety of foils were tested during the characterization of the diode, ranging from 1/2 mil stainless steel to 2 mil titanium, one mil titanium was used most frequently during the diode testing stage and 2 mil titanium was used exclusively for the breakdown studies because its excellent strength characteristics enabled us to operate the gap at higher pressure without fear of pressure induced ruptures. Failure usually occurred due to a degradation of the vacuum as the foil was eventually eroded away by the beam. A study by Seltzer and Berger at the National Bureau

of Standards [35] shows that a high percentage of the energy of an electron beam can be absorbed by a foil. For example, a 2 mil titanium foil absorbs 82% of the energy a 150 keV beam, and 25% of the energy in a 300 keV beam. Hence, a more energetic beam should result in less foil damage, which has been substantiated by our results. The foil, then, is the major obstacle to extending the number of shots that can be extracted from the diode without repair. Much work remains to be done to optimize a foil in regard to the system parameters -- accelerating voltage, external gas pressure, frequency of shots, etc.

The Foil Holder

The foil holder is illustrated in Fig. A-3. The beam window was the same size as the cathode -- 2.37 cm diameter. In this arrangement, the foil was unsupported in the aperture region and worked quite well when the external pressure was ≤ 3 atm. The FX-15 can be pressurized to approximately 20 atm, however, and if we desire to operate in this pressure range, a screen or grid with high electron transmission percentage could be used to support the foil.

The Lucite Block

The Lucite (dielectric) block (Fig. A-1) seals the back side of the diode vacuum region and separates the

Fig. A-3 The Foil Holder

vacuum from the dielectric medium of the input transmission line. Lucite was chosen because of its low dielectric constant and its high resistance to tracking. The surface of the block at the Lucite-vacuum interface was cut at an angle of 45° . This angle was chosen as a result of studies on the surface flashover breakdown strengths of various dielectrics cut at different angles to the applied field [40]. The Lucite was coated with a DC-704 vacuum oil in the vacuum region in order to minimize the possibility of damage caused by surface flashover [41].

The Heds to Diode Transmission Line

The Heds pulser output transmission line (Fig. A-4) is a 70 ohm, oil-filled, coaxial line. The line conductors are simply lengths of aluminum tubing. The outer conductor is 1-1/2" o.d., 0.050" wall tubing and the inner conductor is 5/16" o.d., 0.050" wall tubing.

The Vacuum System

The vacuum was typically 1×10^{-5} to 3×10^{-6} torr at the station. The pressure was not checked in the actual diode region but was obviously somewhat higher than that recorded at the station. Other diodes have successfully operated at pressures as high as 4×10^{-3} torr [42].

Fig. A-4 The Heds to Diode Transmission Line and Diode Vacuum System

Electric Field Analysis

It was desirable that the primary electron emission be from the cathode surface only, and that emission from the cathode periphery and shank be kept to a minimum. The electric field at the cathode periphery would be enhanced by the presence of the edge, resulting in increased emission from the perimeter which might miss the aperture and be collected, uselessly, on the anode plate or result in an uneven beam density profile as was seen by Bradley [39]. In order to reduce these effects, the edges at the perimeter of the cathode were rounded off, thus reducing the edge fields to values less than the average field between the face of the cathode and the anode (foil). For a 250 kV pulse and a 5 mm gap, the average A-K field was approximately 500 kV/cm. The maximum field along the cylindrical sides, a short distance behind the cathode edge can be calculated by using the formula for the maximum electric field strength between co-axial cylinders [16],

$$E = \frac{bV}{a(b-a)\ln(b/a)} \quad , \quad (A-7)$$

where V is the potential difference between the conductors, a is the radius of the inner cylinder and b is the radius of the outer cylinder. The electric field behind the cathode edge was thus found to be approximately 262 kV/cm

for a 250 kV pulse, thus significant electron emission from this region was not anticipated. The electric field at the vacuum-insulator interface is increased according to $\frac{\epsilon_s}{\epsilon_a}$, where ϵ_s and ϵ_a are the dielectric constants for the solid (Lucite) and ambient (vacuum), respectively. One of the primary reasons for choosing Lucite is its low dielectric constant, thus minimizing this increased stress factor. The field strength at the Lucite surface is thereby calculated to be approximately 666 kV/cm. The flashover of dielectrics in vacuum has been found to depend, not only on the electric field, but also on the pulse duration, the pulse shape (i.e., the rise time), the separation between the conductors, the insulator material, the geometry, and the angle at which the electric field intersects the insulator surface [16]. Fortunately, in the fast pulse regime, breakdown is relatively insensitive to pressure [16], enabling this experiment to be conducted under relatively crude vacuum conditions. No appreciable differences have been noted for different electrode materials. No flashover strength test results have been found which have been conducted under conditions that fit this experiment, but a comparison can be made with those that have been conducted under other conditions. Milton [40] has confirmed that the holdoff strength for Lucite can be as high as 315 kV/cm.

(This is the average inter-electrode field -- field enhancement factors, and $\frac{\epsilon_s}{\epsilon_a}$ are not taken into consideration.) One of Milton's experiments was conducted with two parallel plate electrodes separated by a Lucite insulator in the shape of a conical frustum (the benefits of this geometry were first noted by I. D. Smith [16]). The best results were obtained for: (a) the fastest rising and shortest pulse, (b) an insulator angle of approximately 45° to the electric field, and (c) a narrow gap. The pulse in our experiment had both a faster rise time and a shorter duration than did Milton's, but the gap spacing was wider and the geometry was cylindrical rather than planar. The area of the electrodes was larger than Milton's and this increased the probability of failure, as did the field polarity effect, i.e., when the high field region is negative, vacuum insulation strength is much less than when it is positive, and in a co-axial geometry the inner conductor is the high field region, which must be negative in order to drive an e-beam diode. In short, it could not be determined beforehand whether or not the Lucite surface in the diode vacuum region would flash over, although it was definitely a very good possibility that it would.

At the opposite end of the Lucite block, the electric field in the oil filled input transmission line was calculated to be 541 kV/cm for a 250 kV applied pulse. At the

Lucite-oil interface the ϵ_s/ϵ_a factor yielded a field of 829 kV/cm. Contrary to the results in vacuum, when the high field region is negative in a liquid, the insulator strength is greater than when it is positive [16]. In the fast pulse case, the polarity effect in a liquid can be very pronounced. This field exceeded the 410 kV/cm limit for static breakdown [16] for the type of oil that was used. It was possible that the fast, short pulse from the Heds pulser would neither break down the oil in the transmission line nor flash over the Lucite surface. These size limitations were the most serious consequences imposed by the FX-15. The e-beam pulse duration was not required to be long, however, and it was hoped that if the electrical system were to experience flashover it would occur after the pulse had reached its maximum potential, so that the diode would at least emit a short burst of energetic electrons.

CHAPTER II

DIAGNOSTICS AND "GROUNDING AND SHIELDING"

Diagnostics

This section will discuss the diagnostics and the grounding and shielding techniques that were used to investigate the e-beam current pulse. A block diagram of the experiment is shown in Fig. A-5. The characteristics of the e-beam that were investigated are the beam current pulse (amplitude, risetime, and duration) and the spatial distribution of the beam. The diagnostics that were used are (a) a beam current collector (Faraday cup) with a Rogowski coil current monitor, (b) open shutter and streak photography, and (c) direct exposure of a film that was sensitive to energetic electrons (densitometer scans were taken on this exposed film).

Electrical Diagnostics

The Heds pulser output was monitored in order to observe the risetime, duration, and shape of the pulse. The voltage pulse was measured with a high voltage resistive divider probe and the Heds pulser current was measured with a Pearson coil. Both measurements were made by removing the cathode from the diode and extending the center conductor out of the vacuum region, through a Lucite block.

Fig. A-5 Block Diagram of the Diode Arrangement

This high potential center conductor was then connected back to the grounded outer conductor through a 70 ohm CuSO_4 water resistor. The voltage measurements were made across the water resistor and the current measurements were made simply by placing the Pearson coil around the lead from the water resistor to ground. These two probes were used to confirm that the Heds pulser performed as predicted.

The Faraday Cup

The e-beam current was measured by collecting the electrons in a Faraday cup (Fig. A-6). The current was monitored by a Rogowski coil and returned to the outer (ground potential) conductor of the diode through a low inductance co-axial path (Fig. A-7).

The Integrating Rogowski Probe

The integrating Rogowski coil [43] is shown in Fig. A-8. The signal ($\approx di/dt$) from the coil was integrated by shunting the coil with a low inductance, 0.2 ohm resistor. The resistor was an 8 mm x 15 mm rectangular piece of #304, 0.0001" stainless steel foil.

The Non-Integrating Rogowski Probe

Several non-integrating Rogowski probes were also constructed in a similar manner, except they were not shunted by the foil resistor. The output signal of

Fig. A-6 The Faraday Cup

Fig. A-7 The Faraday Cup Attached to the Diode

Fig. A-8 The Integrating Rogowski Probe

these probes was proportional to the time rate of change of the current (di/dt). The pulse rise and fall times, duration, and maximum slope could be determined with these probes.

Optical Diagnostics

Open shutter photographs were taken of the e-beam induced ionization of the atmospheric air surrounding the diode. Both on-axis and 90° off axis photographs were taken. These were used to help determine the time integrated spatial profile of the beam density.

Streak photographs of the light emission from a scintillator material, as a result of the e-beam impact, were recorded. The arrangement is shown in Fig. A-9. Once through the foil, the beam traversed a short vacuum region (~ 0.5 cm) and a 5 mil layer of graphite before striking the scintillator. The graphite was used to limit the e-beam energy in order to prevent damage to the scintillator. These streak photographs were used to help determine the time resolved beam density profile.

The beam profile was also recorded directly on Kodak S0-343 thick base film. The exposure of this film is essentially linear in the electron energy region used in our experiment. Densitometer scans were then made on the exposed film and the results were used, once again, to help determine the e-beam density profile. A more

Fig. A-9 The Scintillator Arrangement

complete description of the optical diagnostics can be found in Reference [36].

Grounding and Shielding

The grounding and shielding arrangement that was used to obtain "clean" signals of the e-beam current pulse, as monitored by the Rogowski coil, is illustrated in Fig. A-10.

The co-axial cable, which carried the signal from the Rogowski coil to the scope, was enclosed in a braided copper tube which was connected at the Faraday cup, the screen room and the scope. The braid shielded the probe, the signal cable, and the scope from stray $\vec{B}$ fields. Any ground loop currents were forced to flow harmlessly on the outside of the braid (via the skin effect) and not in the outer conductor of the signal cable, which would have induced currents to flow in the opposite direction in the inner conductor, resulting in false signals at the scope.

Fig. A-10 The Grounding and Shielding Arrangement

CHAPTER III

RESULTS

Introduction

Typical Heds pulser output pulses are shown in Fig. A-11a (voltage, as monitored by a high voltage resistive probe) and in Fig. A-11b (current, as monitored by a Pearson coil). The typical output pulse had a 10% - 90% risetime on the order of 4-5 ns, a FWHM pulse duration of about 50 ns, and an amplitude of about 250 kV, 3.57 kA. The measurements shown in Fig. A-11 were taken for voltages of about 70 kV.

Fig. A-11 Typical Heds Pulser Output Pulses

Typical diode e-beam current pulses are shown in Fig. A-12a (as collected by a Faraday cup and monitored by the integrating Rogowski coil) and in Fig. A-12b, which is the time derivative of the beam current as monitored by the non-integrating Rogowski coil. The typical pulse had a rise time on the order of 4-5 ns, a FWHM pulse duration of 7-8 ns, an amplitude of about 500 A ($J = 110 \text{ A/cm}^2$), and a most probable energy (E_p) of about 200 keV after the losses in a 1 mil titanium foil are incurred [35].

(a) Integrated
5 ns/div

(b) Non-Integrated
5 ns/div

Fig. A-12 Typical Diode E-Beam Current Pulses

The optical diagnostics revealed that the e-beam spatial density profile is quite uniform. This was confirmed by the open shutter photographs of the e-beam induced ionization of the air outside the diode (Fig. A-13), and by streak photography and densitometer scans of Kodak SO-343 film, which was exposed directly by the e-beam [36].

Cathode Conditioning Effects

No effects were observed on the pulse when the grooved graphite cathode was used. A smooth graphite cathode did seem to have a conditioning effect associated with it, however, since the amplitude of the current pulse was observed to steadily decrease over a period of about 100 shots to about 75% of its original value. The current pulses then remained stable for at least another 100 shots.

The Foil

There was a considerable difference between the beam pulses that were extracted through the 1 and 2 mil Titanium foils, as can be seen in Fig. A-14a and b. The maximum diode current that has been observed after traversing a 1 mil foil was approximately 750 A ($J = 170 \text{ A/cm}^2$), while the maximum current to pass through a 2 mil foil was only 150 A ($J = 34 \text{ A/cm}^2$).

(a) On axis

Front View

(b) 90° Off axis

Side View

Fig. A-13 Open Shutter Photographs of Beam Induced Ionization in Air, on the Beam Axis (a) and 90° Off Axis (b)

(a) 2 mil Foil
10 ns/div

(b) 1 mil Foil
10 ns/div

Fig. A-14 The E-Beam Current as a Function of the Foil Thickness

The Effects of Gap Variation

The most observable change in the pulse due to gap variation was found to be the amplitude of the current. This effect is demonstrated by Figures A-15 a and b, which show that the pulse risetime and general shape were not changed, whereas the amplitude was decreased for the longer gap. This was expected since the Child-Langmuir law indicates that the diode impedance will increase as the gap increases and that the current will decrease proportionately (Eq. A-4). It is worth noting that the long gap shots were taken first, eliminating any possibility that the loss of current was due to cathode conditioning.

The Diode Delay

The diode delay has not been measured; thus, the time location of the diode pulse, relative to the arrival of the applied voltage pulse, is not known. The delay for a graphite cathode has been estimated to be approximately 10 ns [39]. Using this figure for the delay, the applied voltage and the corresponding diode pulse would appear as in Fig. A-16. The diode pulse, then, would appear to fall off before the applied voltage pulse, which is a highly unlikely situation since the diode impedance should collapse from infinity to the Child-Langmuir limit where it should easily remain "turned on" until the voltage pulse

(a) Matched Load Gap

(b) Long Gap

Fig. A-15 E-Beam Current as a Function of Gap Variation

falls off. Evidently either the theoretical delay was wrong or the applied voltage pulse was terminated early by an electrical failure (breakdown somewhere in the system). The most likely explanation was presented in the section on electric field analysis where it was suggested that surface flashover at either the oil-Lucite or the vacuum-Lucite interface was a strong possibility, and that this flashover could result in the early termination of the applied voltage pulse and, hence, of the diode pulse.

Fig. A-16 The Simulated Appearance of the Diode AnodeCathode Voltage Pulse and Superimposed E-Beam Current Pulse, Using the Theoretical Delay

Surface Flashover

Strong evidence suggests that surface flashover along the diode insulator did occur on virtually every shot. Fig. A-17 clearly demonstrates that current pulses of up to 30 ns in duration did exist. Fig. A-17a represents the type of pulse duration that would be expected from the diode if no flashover occurred. Why then, if flashover occurs on almost every shot, would this series of events be exceptions? The answer is that they are not. A reduction in the A-K potential will result in a corresponding reduction in the diode current. The result of surface flashover is to reduce the A-K potential to a value dependent on the severity of the flashover (normally the result would be a total short circuit, reducing the A-K potential, hence the diode current to zero). It is clear from the events recorded in Fig. A-17 that the diode experienced surface flashover at a time corresponding to point A, hence the reduction in current. It is also clear that the severity of the flashover was increased with succeeding events (these shots were recorded at 30 second intervals beginning with a), thus reducing both the current amplitude and duration after the advent of the flashover.

There are several variables that might lead to increasingly severe flashovers in the diode vacuum region, including vacuum degradation and charge accumulation on

Fig. A-17 A Series of E-Beam Current Pulses (30 s between shots, beginning with a) Demonstrating the Increasing Severity of Flashover on the Lucite Surface in the Diode (the flashover begins at point A)

the Lucite surface. Degradation of the vacuum would not ordinarily cause problems since flashover strength is not reduced for short, fast pulses at pressures as high as 10^{-3} Torr [16], which has also been verified in our experiment. The vacuum in our diode could not be measured directly however, and since the conductance was very low this could have caused the problem.

Surface Tracking

The absolute proof of repeated surface flashover was the total failure of the Lucite surface due to tracking in the diode vacuum region, which resulted in a permanent loss of holdoff strength of the Lucite, necessitating its replacement. The diode had performed well for over 10^4 shots before the Lucite was damaged due to tracking. Diffusion pump oil was used on the surface of its replacement [41].

The E-Beam Pulse Length

In the gas breakdown studies the e-beam pulse was not required to be long because its purpose was to initiate a self-sustaining breakdown and a short pulse would work just as well as a long one for this purpose. There is, of course, a practical limit to the minimum e-beam pulse length that is required to optimally initiate the current

flow in the gap. It is reasonable to assume that the maximum time that the e-beam will be beneficial is that time until the discharge becomes self sustaining. This time is short compared to the 15 ns pulse produced by the diode in our experiment, thus the matter was not considered further. Another point to consider is that a short pulse offers some advantages, particularly extended foil life. The lifetime of a foil is a function of the energy deposited in and, hence, the energy of the electrons passing through the foil, so a short pulse can obviously be better than a long one. In many e-beam pumped lasers the e-beam pulse is crowbarred to protect the foil from arcing. The diode surface flashover in this experiment, then, was not actually harmful since it simply acted as a built-in automatic crowbar which chopped off the latter part of the pulse.

References

1. B.M. Kovalchuk, V.V. Kremnev, and G.A. Mesyats; Sov. Phys. - Doklady, 15, 267 (1970).
2. E.A. Abramyan, V.V. Borob'ev, A.A. Egorov, V.A. Elkin, and A.G. Ponomarenko; Priory i Tekhnika Eksperimenta, 1, 117 (1971).
3. Yu.I. Bychkov, Yu.D. Korolev, G.A. Mesyats, V.V. Savin, and A.P. Khuzeev; Sov. Phys., Tech. Phys., 20, 1502 (1975).
4. K.F. McDonald, M. Newton, E.E. Kunhardt, M. Kristiansen, and A.H. Guenther; "An Electron Beam Triggered Gap", Proc. 2nd IEEE Int. Pulsed Power Conference, Lubbock, Texas (November 1979).
5. A.H. Guenther; Personal Communication, AFWL, Kirtland A.F.B., Albuquerque, N.M.
6. A.H. Guenther and J.R. Bettis; J. Phys. D: Appl. Phys. 11, 1577 (1978).
7. A.S. El'Chaninov, V.G. Emel'yanov, V.M. Koval'chuk, G.A. Mesyats, and Yu. F. Potalitsyn; Instrum. Exp. Tech., 17, 416 (1974).
8. V.G. Emel'yanov, B.M. Koval'chuk, V.A. Laviniyich, G.A. Mesyats, and Yu. F. Potalitsyn; Instrum. Exp. Tech., 18, 1124 (1975).
9. D. Markins; IEEE Trans. Nucl. Sci., 18, 296 (1971).
10. E.E. Kunhardt; Personal Communication, Texas Tech University, Lubbock, Texas.
11. J.S. Townsend; Electricity In Gases, Oxford University Press, (1914).
12. L.B. Loeb; Fundamental Processes of Electrical Discharges in Gases, John Wiley, (1939).
13. H. Raether; Electron Avalanches and Breakdown in Gases, Butterworths, London, (1964).
14. J.M. Meek and J.D. Craggs; Electrical Breakdown of Gases, Clarendon, Oxford, (1953).

15. K.R. Allen and K. Phillips; Proc. Roy. Soc. A, 278, 168 (1963).
16. A.S. Denholm, J.J. Moriarty, W.R. Bell, J.R. Uglam, G.K. Simcox, J. Hipple, S.V. Nable, and A.H. Guenther; AFWL-TR-72-88, AFWL, Kirtland AFB, New Mexico (February 1973).
17. G.A. Mesyats and Yu.I. Bychkov; Sov. Phys. Tech. Phys., 12, 1255 (1968).
18. G.A. Mesyats, Yu.I. Bychkov and A.M. Iskoldskii; Sov. Phys. Tech. Phys. 38, 1281 (1968).
19. T.V. Tarasova, L.V. Khudyakova, T.V. Loiko, and V.A. Tsukerman; Sov. Phys., Tech. Phys. 19, 3 (1974).
20. R.H. Fowler and L.W. Nordheim; Proceedings of the Roy. Soc., A 119, 173 (1928).
21. W.S. Boyle, P. Kislink, and L.H. Germer; J. Appl. Phys., 26, 720 (1955).
22. C.J. Bennette; Amer. Inst. Aeronaut, Astronaut, 3, 284 (1965).
23. D. Alpert; J. Vacuum Sci. Tech. 1, 35 (1964).
24. G.A. Mesyats and D.I. Proskurovski; JETP. Lett. 13, 4 (1971).
25. G.K. Kartsev and G.A. Mesyats; Sov. Phys. Doklady, 15, 475 (1970).
26. Yu.L. Stankevich; Sov. Phys., Tech. Phys. 15, 1138 (1971).
27. Yu.L. Stankevich and M.S. Kalinin; Sov. Phys. Doklady 12, 1042 (1968).
28. R.C. Fletcher; Phys. Rev. 76, 1501 (1949).
29. T.F. Godlove; J. Appl. Phys., 32, 1589 (1961).
30. H.I. Milde; Personal Communication, Ion Physics Corp., Burlington, Massachusetts.

31. J.K. Trolan, F.M. Charbonnier, F.M. Collins, and A.H. Guenther; "A Versatile Ultrafast Pulse Power System," Exploding Wires III, 361, Plenum Press (1964).
32. G.N. Glasoe and J.V. Lebacqz; Pulse Generators, Dover Publications, New York (1948).
33. F.M. Bruce; Proc. of IEE., 94, 138 (1947).
34. R.A. Fitch; "Salving Diagnostics in the Pulse - Power Environment", Proc. 1st IEEE. Int. Pulsed Power Conference, Lubbock, Texas (June, 1976).
35. S.M. Seltzer and M.J. Berger; Nucl. Instr. and Methods, 119, 157 (1974).
36. M. Newton; Master's Thesis, (1979), Texas Tech University, Lubbock, Texas.
37. C.D. Child; Phys. Rev., 32, 492 (1911).
38. I. Langmuir; Phys. Rev., 2, 450 (1913).
39. R.K. Parker; AFWL-TR-73-92, AFWL, Kirtland AFB, New Mexico (January 1973).
40. O. Milton; IEEE Trans. Electrical Insulation, 7, 9 (1972).
41. J. Rameriz; Personal Communication, Sandia Laboratories, Albuquerque, New Mexico.
42. D. Albert, J. of Vac. Sci. and Tech. 1, 35 (1964).
43. D. Pellinen and V. Staggs; Rev. Sci. Inst., 44, 46 (1973).