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X-RAY TRIGGERED SWITCHING IN SF_6 INSULATED SPARK GAPS*

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Abstract

Several methods are being investigated for triggering low-jitter pressurized, SF_6-insulated spark gaps operating at 3 MV with the capability of switching hundreds of kiloamperes. One method, which is located external to the main current carrying plasma channel, uses pulsed x-rays to generate ionization within the working gas volume to initiate low jitter gas breakdown. In this paper, a model of gas breakdown with x-ray ionization is developed and results of two series of experiments are described. One experiment used 35 kV with a 1.83 mm gap and the other used 1 MV with a 7.62 cm gap. Both experiments used a 600 kV Febetron 706 flash x-ray source to demonstrate the feasibility of using pulsed x-rays as a means of triggering SF_6 insulated gaps with nanosecond jitter.

Introduction

Multimegavolt, SF_6-insulated spark gaps are used in the power compression process of large particle beam accelerators. The switch closure jitter becomes critical when many switches are required to close simultaneously. In large, physically-distributed, multimodule, short-pulse accelerators, such as the 30 TW Particle Beam Fusion Accelerator PBFA, 36 switches must close within a 7 ns time window. Trigatrons and other gaps with trigger electrodes located in the path of the current carrying plasma suffer erosion of the triggering electrode, which increases the jitter in switch closure time. Electron beams[1] and lasers[2] may be used to initiate the breakdown process. However these triggers suffer damage to input windows or lenses in switches carrying several hundred kiloamperes. Illumination of the switch cathode surface with UV radiation reduces the statistical time lag in starting avalanches,[3] and UV illumination of the gas volume can control the velocity of the streamer phase in the breakdown process.[4] This paper presents experimental results using a pulsed x-ray source to liberate electrons from the electrode surfaces. These electrons in turn deposit charge in the insulating gas volume, preionize the gas, and thus control the switching time.

Breakdown Modeling of SF_6 Insulated Gaps

DC Applied Field Case

Electronegative gases, such as SF_6, exhibit an electron capture process which competes with the first Townsend ionization process in a gap with an applied field. Below a critical value of E/P, the ratio of the electric field to the pressure, the attachment process removes electrons from the avalanche faster than they are generated. At 117 volts/cm/mm of Hg in SF_6, the attachment and generation coefficients are equal.[5] Breakdown can occur at this or any greater value of E/P provided the gap is wide enough to allow the number density at the tip of the avalanche to reach 10^8/cc. This is the Raether condition for conversion of the avalanche to a streamer.[6] A gap with a non-uniform field distribution has a DC breakdown field given by

$$E_{DC} = 88.7 \left(\frac{P}{P_0}\right)\left(\frac{1}{FEF}\right) \text{ kV/cm} \qquad (1)$$

where FEF is the field enhancement factor for the most highly stressed region in the gap. P/P_0 is the normalized pressure in atmospheres. An avalanche growing into a region where the FEF is decreasing may enter a region with a local value of E/P below 117 volts/cm/mm of Hg. The electron number density will then decrease and the avalanche process will stop. The effect of spatial variation in the FEF over the avalanche growth length, for the gaps discussed in this report, was evaluated by numerical integration of the Townsend growth equation. The non-uniform FEF changed the DC breakdown value, as calculated from Eq. (1), by less than 1 percent. Fields only slightly in excess of those given by Eq. (1) are sufficient in SF_6 to cause the avalanche to reach the Raether criterion in a few nanoseconds while traveling a few tenths of a millimeter.

Pulsed Applied Field Case

The time required for spark gap breakdown in a pulsed field is composed of three time intervals. First, the time required for the appearance of the initial electron to start the avalanche is known as the statistical delay. The initial electron may be pulled from the cathode surface by field emission or the initiating electron may be detached from a negative ion by the applied field.

The second time interval in the spark breakdown process is known as the formative time. During this time interval the initial electron is accelerated by the applied field and generates new free electrons through collisions with gas molecules. The rate of generation is given by the first Townsend coefficient for the gas used in the gap. Electronegative gases have an equivalent coefficient which is made up of attachment and generation coefficients, usually given as a function of E/P. Data on experimentally measured spark formative times in SF_6 by Felsenthal and Proud[3] have been combined with data on attachment and ionization coefficients by Bhalla and Craggs[5] to give an equation for the electron drift velocity, in the avalanche phase, as

$$V_d = 2.39 \times 10^7 + 1.49 \times 10^5 \text{ E/P cm/s} \qquad (2)$$

where E/P is in volts/cm/mm of Hg.

The time and distance required for an avalanche to reach an electron number density of 10^8/cc have been computed by assuming a uniform field enhancement factor over the avalanche growth length for the time varying fields used in the experiments. The formative times calculated are a few nanoseconds with avalanche growth lengths of from a few tenths of a millimeter to a few millimeters. Exact values are given in the discusssion of the experimental results.

The third time interval in the spark breakdown process is the streamer phase. Propagation of ionization fronts across the gap in the streamer phase may reach 10^{10} cm/s. Streamer velocity has been shown to be a function of the charge density present in the gas volume[4] and is proportional to one over the cube root of such existing charge density.[7] The streamer phase is terminated with the appearance of a low impedance plasma channel which then carries the full switched circuit current.

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Experimental Results

1.83 mm Gap Experiments

The initial experiment used a DC or pulse charged, SF_6 insulated, 1.83 mm long gap. The brass anode is 5 cm in diameter with 0.5 cm radius of the edges while the cathode is a 3.2 mm thick aluminum sheet. Both electrodes were bead blasted and cleaned before beginning the breakdown experiments.

A DC self-break curve versus pressure for this gap is given in Fig. 1 and agrees with values obtained from Eq. (1) when allowance is made for the short gap length. Since scatter in the breakdown voltage was observed to increase significantly above 25 psia, this pressure was used in all x-ray triggered experiments.

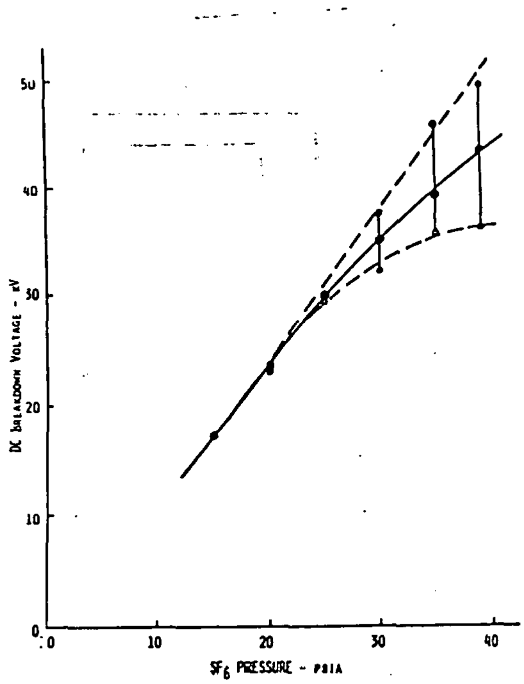


Fig. 1. DC breakdown voltage vs. SF_6 pressure 1.83 mm gap.

The circuit shown in Fig. 2 was used to pulse charge a 0.04 μF capacitor, across which the gap was placed, in 1.1 μs. Breakdown timing information was obtained from a B-dot coil monitoring gap current and from a resistive voltage monitor mounted across the gap. The output of the 600 kV Febetron was monitored with a PIN diode which was time correlated with the other monitors.

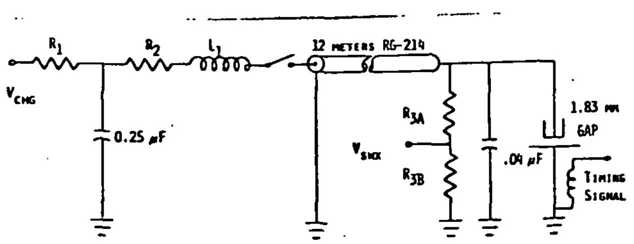


Fig. 2. 1.83 mm pulse test circuit.

The measured DC breakdown voltage of the 1.83 mm gap at 25 psia was 29.5 kV while the minimum pulsed self-breakdown was 56 kV. The calculated formative time for these conditions is 4.5 ns with an avalanche length of 1.83 mm. The overvoltage present in the pulsed breakdown may be due to a long statistical delay. Since the volume of gas between the electrodes is small and since the initiating electron has to appear near the cathode in order to reach the Raether condition within the gap length, a long statistical delay might result.

X-ray breakdown of this gap was initiated with the Febetron source located 5 cm behind the aluminum cathode. A CYLTRAN[8] code simulation for these conditions predicts an ion density in the gap of 4×10^{13} pairs/cc. The timing of the flash x-ray source was adjusted to provide ionization in the gap at 35 kV on the applied voltage waveform. This corresponds to an applied field of 191 kV/cm and an E/P value of 148 volts/cm/mm of Hg which is above the DC breakdown value. The standard deviation in gap closure time, as measured from the time difference between the PIN diode signal and the break in the voltage waveform, was 1.3 ns. The total spread in 12 shots was 3 ns with a delay of approximately 2 ns. The intensity of the source was then reduced 8 to 9 orders of magnitude with shielding blocks. The delay in switch closure increased to 10 ns but nanosecond jitter in the gap closure time was maintained. In this x-ray triggered gap, the Febetron supplies the electrons to initiate the avalanche and the breakdown time is governed by the formative time of the avalanche.

7.62 cm Gap Experiments at 1 MV

The second series of experiments used a modified 3 MV trigatron with conditioned hemispherical stainless steel electrodes spaced 7.62 cm apart. Figure 3 shows a cross sectional view of the gap with 10 percent equipotentials plotted by the electrostatic field solver JASON.[9] The variation in field enhancement factor with axial position is given in Fig. 4.

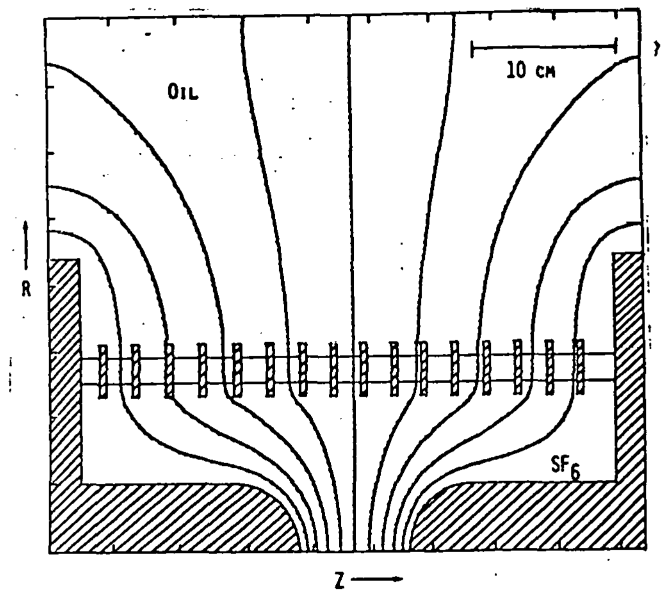


Fig. 3. Modified 3 MV trigatron - 10 percent equipotentials.

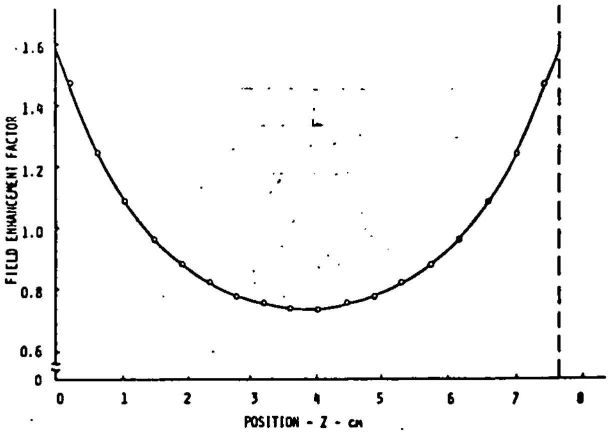
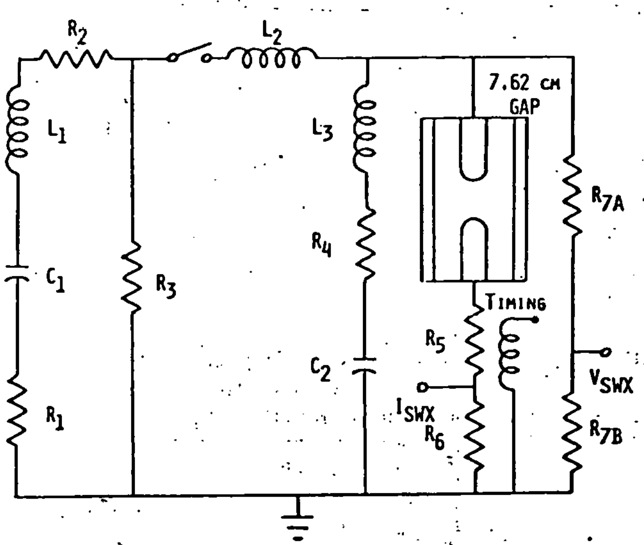


Fig. 4. Field enhancement factor vs. axial gap position, 7.62 cm gap.

The Marx generator and intermediate store capacitor in the Mite accelerator[10] were used to pulse charge the gap to peak voltage in 900 ns using the circuit shown in Fig. 5. The 1.75 Ω load resistor limited peak currents through the switch to 144 kA with an applied voltage of 1.2 MV. The closure of the switch was monitored by a Rogowski loop in the switch ground circuit, and the firing time of the 600 kV Febetron x-ray source was monitored with a PIN diode. Accurate measurements of the time difference between the Rogowski and PIN diode signals was obtained with a CAMAC digital system which has a time resolution of 250 ps. All signals were simultaneously displayed on fast dual beam oscilloscopes. The Febetron source target was physically located 135 cm from the axis of the switch. The dose at the switch axis was approximately 0.75 mr which corresponds to a deposited charge density of 5×10^{10} pairs/cc in the gas volume.



R_1 = 5.1mΩ CVR, R_2 = .916Ω, R_3 = 862Ω, R_4 = 1.1Ω
R_5 = 1.75Ω, R_6 = 5mΩ CVR, R_{7A}, R_{7B} = 3000:1 Monitor
C_1 = 41.5 nF, C_2 = 19.4 nF
L_1 = 5.35 μH, L_2 = 0.2 μH

Fig. 5. Mite switch test circuit.

The pulse-charged self-breakdown curve for this switch is given in Fig. 6 in addition to the calculated DC breakdown curve. The gas pressure in the switch and the Marx charging voltage were adjusted in each case to maintain switch breakdown at 600 to 650 ns into the charging waveform. An operating pressure of 25 psia was selected for x-ray triggering experiments and 17 self-break shots gave an average pulsed self-break voltage of 1.21 MV with a standard deviation of 1.8 percent.

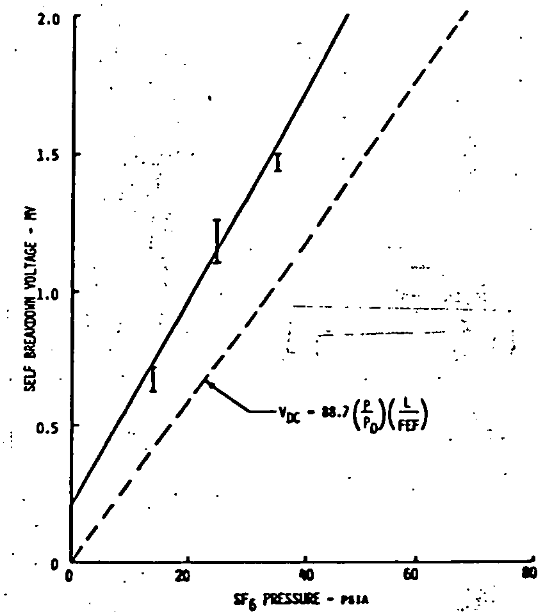


Fig. 6. Self breakdown voltage vs. pressure, 7.62 cm gap.

The first test with the Febetron x-ray source, which had a 3 ns wide output pulse, involved firing the Febetron from 0 to 500 ns before the calculated DC breakdown level was reached on the pulsed waveform. Breakdown was stabilized at 923 kV with a standard deviation of 1.5 percent in 12 shots. Switch closure occurred 80 ns after the voltage exceeded the DC breakdown value and was independent of the time between the x-ray pulse and the DC breakdown point. If net ionization produced by the x-ray source removed any statistical delay in the start of the Townsend avalanche, then the time for the combined avalanche and streamer phases is 80 ns. The avalanche length for this geometry and field enhancement factor is 0.5 mm and the formative time required to reach 10^8 ion pairs/cc is approximately 1.1 ns. Therefore, the streamer transit time is 79 ns and the average steamer velocity is 9.6×10^7 cm/s. Without the Febetron, the time between the DC breakdown level of 732 kV and the pulsed self-break level of 1.21 MV was 220 ns. If statistical delay is neglected for the moment, then the average streamer velocity without x-ray induced charge is 3.5×10^7 cm/s. This is approximately the same as the electron drift velocity in the avalanche phase for the experimental conditions. The charge deposited by the Febetron increased the average streamer velocity by a factor of 2.7. Experimental results will be given in the next section to show that the statistical delay is in fact negligible for the 7.62 cm gap experiments.

The timing of the Febetron was delayed for the second series of experiments so that the Febetron would deposit charge in the gap after the DC breakdown level but before the streamers would normally have closed the gap. The mean delay between the x-ray induced ionization and gap closure was 55.1 ns with a standard deviation of 10.5 ns which is 1.75 percent of the total switching time. According to the model of switch operation presented in this paper, the streamer in this case starts out from essentially the DC level on the pulsed waveform (because of the short time and distance in the avalanche phase) and travels at 3.5×10^7 cm/s until the x-rays deposit charge in the switch gas. At this time the streamer velocity increases to 9.6×10^7 cm/s which is maintained until the switch closes. As an example consider the data for shot 5-20-13. The time between the DC breakdown level and the arrival of the additional charge is 90 ns. During this time the streamer, traveling at 3.5×10^7 cm/s, has moved 3.15 cm across the gap. The calculated time for the avalanche to cross the remaining 4.47 cm at 9.6×10^7 cm/s is 46.6 ns which is in good agreement with the measured value of 51.3 ns. These calculations have not included any statistical delay time but from the measurements it is less than a few nanoseconds. Lower breakdown jitter may be possible with higher x-ray doses or increased applied field strengths. It should be pointed out that the standard deviation in the breakdown time or amplitude remained approximately a constant fraction of the total switching time both with and without the extra charge from the Febetron despite the change in streamer velocity. Additional experiments are planned using other field geometries to further study overall switch jitter and streamer velocity modification.

Conclusion

Low jitter, pressurized SF_6 insulated spark gaps capable of operating at voltages of from 2 to 3 MV and currents of several hundred kiloamperes are desired for large, distributed, particle beam accelerators. This report shows that a pulsed x-ray source deposits charge within a switch gap volume without special windows. The injected charge eliminates statistical time lags and modifies streamer velocities. Experimental results for a 1.83 mm gap operating at 35 kV has demonstrated closure time jitter of 1.3 ns. This gap probably operates in a mode dominated by statistical and formative time delays which are subject to improvement by x-ray induced charge deposition. A mildly divergent field gap operating at 1 MV with a spacing of 7.62 cm has demonstrated both x-ray stabilized and x-ray triggered modes of operation. Gap operation, in this case, is dominated by streamer closure time and the charge produced by the x-ray source nearly triples the average streamer velocity. The standard deviation of the gap closure time is approximately 1.5 percent of the total switching time. The measured jitter of this 144 kA switch was 10.5 ns and is not directly suitable for use in large, multiple-switch, accelerators. Additional experiments are underway to understand and reduce this jitter.

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