A SIMPLE SELF-BREAKING 2 MV GAS SWITCH*

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Abstract

We describe a simple self-breaking 2 MV gas master switch for the LLNL 2 MV general purpose relativistic electron beam (REB) accelerator. The switch cavity has been hollowed out in a 17.8 cm-thick acrylic slab. The switch gap is 3.55 cm. At 2 MV the maximum field at the cathode is 740 kV cm^{-1} and the maximum envelope field is 172 kV cm^{-1}. The maximum measured switching voltage is 1.90 ±0.1 MV (10 bar abs). The minimum switching voltage is 1.1 MV (4.3 bar abs). The operating characteristics break away from the 89 kV/(cm atm) DC breakdown strength of SF_6 at 5.5 bar abs. Careful electrical and mechanical design as well as strict quality control during assembly and operation have resulted in reliable and reproducible operation.

Introduction

This paper describes a 2 MV self-breaking gas master switch that connects the transfer capacitor to a pulse forming line in the 2-MV LLNL water dielectric REB accelerator. The present version of the accelerator uses the shell of a Physics International 422 accelerator that was converted from oil to water dielectric and subsequently mothballed. The water dielectric version was modified to improve the risetime and recommissioned in a configuration we describe below.

The 2 MV accelerator [1] is part of a general purpose relativistic electron beam facility. This accelerator presently consists of an oil-insulated Marx generator and three cascaded water dielectric pulse-forming stages that deliver a pulse to a field emission diode. The Marx generator has an erected capacitance, inductance and resistance of 7.7 nF, 10.6 μH and 20 Ω respectively (52-0.4 μF elements). A polyurethane diaphragm separates the Marx from the three water dielectric pulse-forming stages shown in Fig. 1. The first stage, a 6.5 nF transfer capacitor (TC), is configured as a 4.6 Ω, 30 ns one-way transit time (OWT) coaxial transmission line. The peak resonant charging voltage for this stage is 2.1 MV with a time to peak of 660 ns. The single channel 2 MV gas master switch we describe in this paper connects the TC to the second stage, a pulse-forming line (PFL). The PFL, nested between the master and output switch, is a 5.9 Ω 30 ns OWT coaxial transmission line that tapers to a 2.6 Ω impedance proximally to the multichannel 80 nH self-breaking output switch. The third pulse forming stage is a 5.9 Ω, 60 ns OWT output line (OL) that begins at the output switch and penetrates into the vacuum through a diaphragm type water-vacuum interface. The inductance of the vacuum region is 75 nH and the risetime of the pulse in the vacuum is about 15 ns.

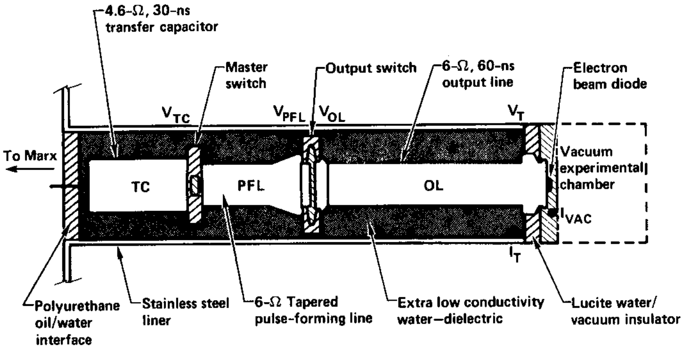

Figure 1. Water dielectric pulse forming sections of 2-MV accelerator. This paper describes the master switch between the TC and the PFL.

Motivation for Improved Switch Design

The self-breaking gas master switch, incorporated in a cavity machined in an acrylic slab existed in the water dielectric version of the accelerator. An initial examination by the authors indicated that the concept was sound and recommissioning of the accelerator could begin even though operating curves for the switch had been lost when the accelerator was mothballed. The new design, shown in Fig. 2 differs only in some small, but important, details from the switch that failed during the accelerator recommissioning In this section we outline the reasons for the switch failure and the steps taken to prevent a reoccurrence.

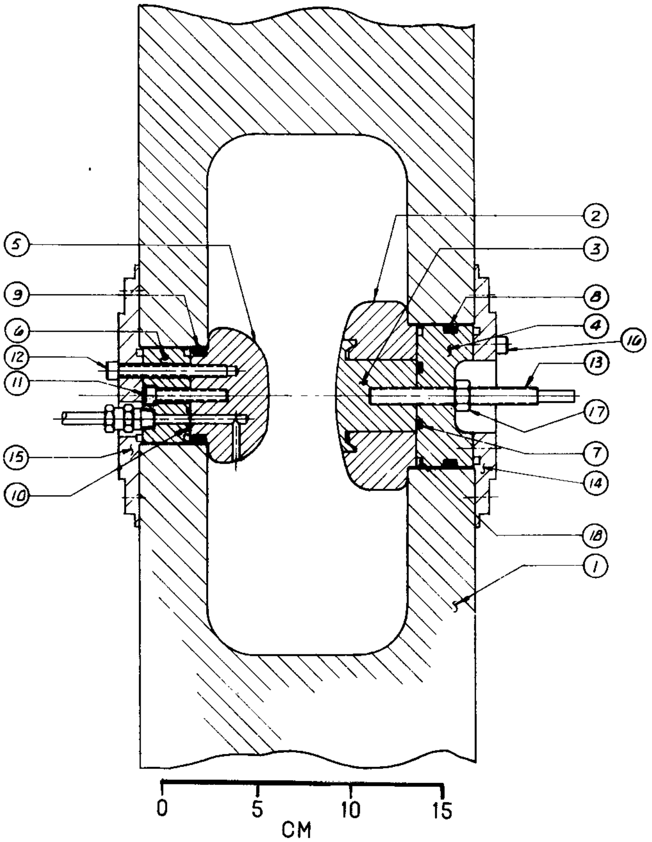

Figure 2. Assembly drawing of the switch. Some numbered items are described in the text.

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14. ABSTRACT

We describe a simple self-breaking 2 MV gas master switch for the LLNL 2 MV general purpose relativistic electron beam (REB) accelerator. The switch cavity has been hollowed out in a 17.8 em-thick acrylic slab. The switch gap is 3,55 em. At 2 MV the maximum field at the cathode is 740 kV cm-1 and the maximum envelope field is 172 kV cm-1, The maximum measured switching voltage is 1.90 Â±0.1 MV (10 bar abs). The minimum switching voltage is 1.1 MV (4.3 bar abs). The operating characteristics break away from the 89 kV/{cm atm) DC breakdown strength of SF6 at 5.5 bar abs. Careful electrical and mechanical design as well as strict quality control during assembly and operation have resulted in reliable and reproducible operation.

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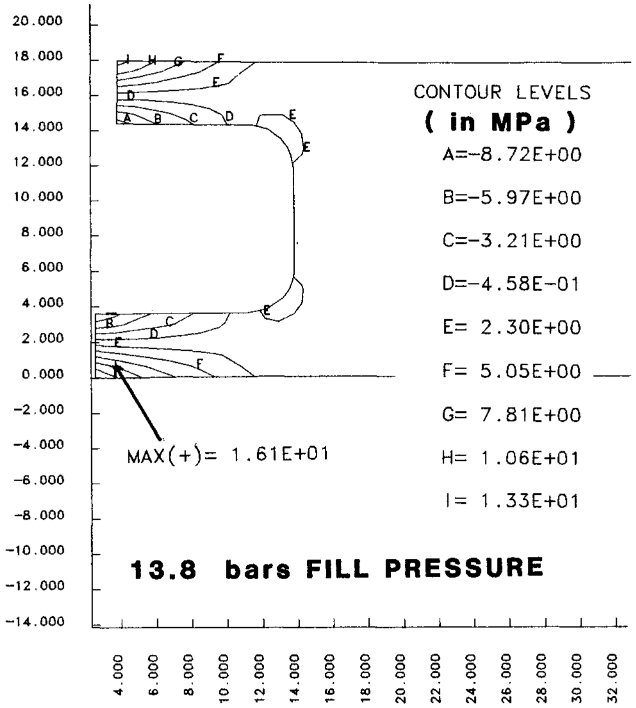

Figure 3. Contours of hoop stress. Maximum stress occurs at location indicated by the arrow. Coordinates are in cm.

The gas feed and purging system is of conventional design. We replaced the gas lines that permeated oil [8] with gas lines impervious to oil [9]. The SF_6 passes through two gas dryers, to achieve a dew point of -73°C, a 2 micron gas filter and a moisture indicator located at the control console of the accelerator. The exhaust passes through a moisture indicator (to reveal water contamination) and there is an attachment to collect samples of the exhaust gases for analysis.

Electrical Design

The electrical design of the switch was tedious but straightforward. The JASON [10] electrostatic solver produced the equipotential plots of Fig. 4. The maximum electric field per unit Volt (0.37 V/(cm V)) appears at the convex outer edge of the cathode button. Since the gap is 3.55 cm, this implies an enhancement factor of 1.3 above the mean field in the gap. The maximum field per unit Volt at the envelope wall is 0.086 V/(cm V) yielding a ratio of 4.3 between the envelope and gap fields. This ratio was the minimum considered acceptable to guarantee that breakdown would occur across the main gap rather than along the envelope.

Switch Performance

The performance of the switch is summarized in Fig. 5 that shows the breakdown fields at the cathode (as obtained from the measured breakdown voltage and the JASON results) as a function of the absolute pressure of SF_6 in the envelope. Also shown in the figure is the 89 kV/(cm atm) line which corresponds to switches of small areas [2]. Agreement is good up to 5.5 bar abs when results begin to diverge from the DC breakdown curve as expected [2]. The largest standard deviation is 8% at 8.4 atm and deviations of 5 % are more typical for the rest of the data.

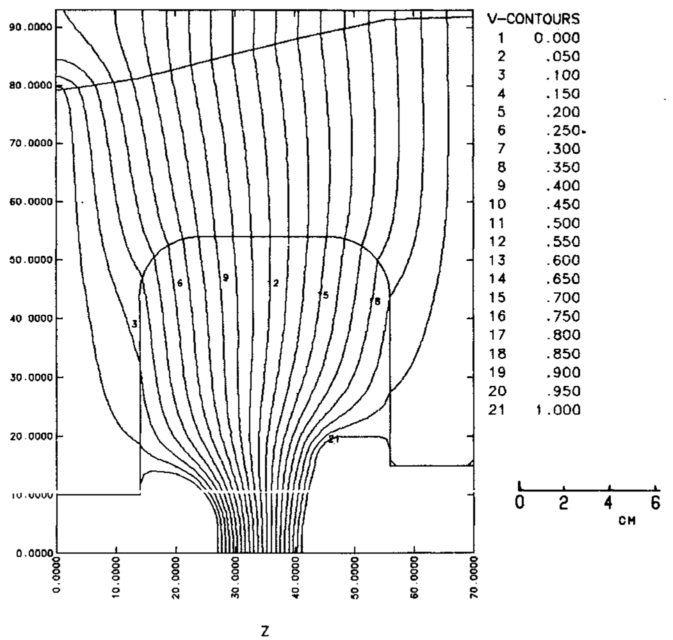

Figure 4. Equipotential plots for the switch. Applied voltage equal to 1 Volt.

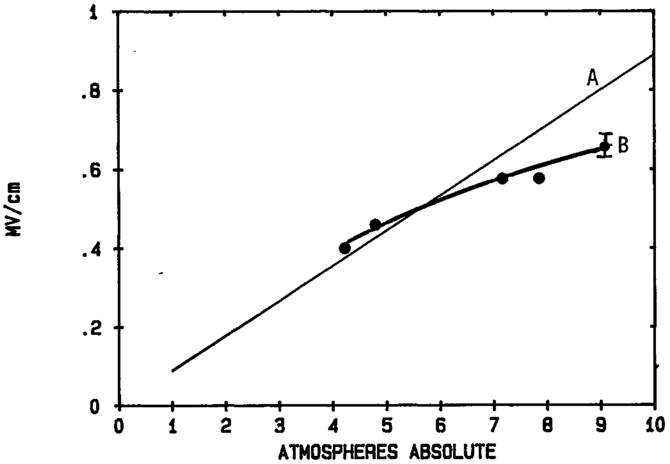

Figure 5. Breakdown fields as a function of absolute pressure for SF_6 in the 2 MV switch. The straight line (A) has a slope of 89 kV/(cm atm). The operating curve (B) diverges at a pressure of 5.5 bar abs.

The switch has been in service for 18 months and 380 shots have been fired at 475 kV/cm^{-1}, 150 at 630 kV/cm^{-1} and 25 at 690 kV/cm^{-1}.

To maintain this performance we followed a strict operating procedure:

(a) Switch remains pressurized to 2.1 bar between firings.
(b) Three volumetric changes of SF_6 (6 liters at 2.1 bar) in 2.5 minutes before each firing.
(c) Switch is pressurized at the desired level.
(d) Switch is purged after firing (2.5 minutes at firing pressure).
(e) Pressure is dropped to 2.1 bar and maintained until the next firing.

From the very first firing the switch had difficulty holding voltage. However, its performance improved with subsequent firings and reached marginal levels with a voltage holdoff not very sensitive to fill pressure. This behavior could occur as field enhancement protrusions on the electrode surfaces partially eroded away. During a shorted shot to characterize the front end of the accelerator, the switch envelope failed.

To obtain some clues on the switch behavior we consulted the literature and found that despite the widespread use of SF_6 atmosphere self-breaking switches, detailed performance data is not widely available. The accepted data for DC SF_6 breakdown is 89 kv/(cm atm) at lower pressures (< 3 bar abs) [2]. The data from one source [3] was not sufficient to predict the performance of our switch and the data from a second source [4], 43 kV/(cm atm) for a 800 ns pulse charge, may be associated with envelope tracking. The data from a third source (250 ns pulse charge) [5] is 110 kV/(cm atm) up to 4 bar. This charging time is not applicable in our case. Moreover, inaccessibility of the switch precluded a physical inspection of the switch without a complete accelerator teardown.

Physical examination of the failed switch, chemical analysis of the debris, and a review of the operational procedures revealed:

1. Chemical changes of the electrode surfaces consistent with operation in a water-SF_6 environment. This is consistent with water introduced during the assembly or seepage during operation.

2. Contamination of the switch with oil that permeated across the walls of gas feed lines.

3. Loose assemblies that resulted in arcing between internal current conductors.

4. Misinterpretation of diagnostic warnings.

The reason for poor switch performance and envelope failure was not determined with certainty. Most probably, failure was due to a combination of factors that complicated immensely the diagnosis of the problem. There was probably water contamination at first. Hydrogen fluoride, resulting from decomposition of the SF_6 in a water atmosphere attacked the surface of the stainless steel electrodes. The water then cleared. However, contamination combined with loose components caused breakdowns at lower fields. Eventually hydrocarbon contamination began as the oil permeated through the gas feed lines. Oil decomposition produced sooty by-products that led to tracking of the envelope.

The improvements we incorporated in the new switch are:

1. Positive mechanical location and tight fit of all parts.

2. Good electrical contacts (including current gasketing) throughout the switch.

3. Use of oil-compatible tubing.

4. Relocation of "O" ring seals to prevent water seepage during shock loading.

5. Develop and enforce quality control procedures for assembly and operation. These include purging of the switch, gas analysis at regular intervals, filters and dryers for the SF_6, and permanent pressurization to prevent oil and water seepage.

6. Banning of short circuit firings to prevent excessive energy dissipation in the gas switches.

We describe the new switch in more detail in the sections that follow.

Mechanical Design of the Switch

The mechanical design of the switch was constrained by the thickness of an available acrylic casting (~18 cm), the radius of the cavity that could be machined and polished at a reasonable cost and a conservative derating (~60 %) of the DC breakdown fields (89 kV/(cm atm)) [2] for SF_6, a maximum pressure of about 13 bar for safety considerations, and a gap of 3 to 4 cm between electrodes.

On the basis of these initial constraints we iterated between the electrical and mechanical design of the switch until we arrived at the assembly shown in Fig. 2. The pressure vessel (1; the numbers in parentheses correspond to Fig. 2) is an acrylic (PMMA) 18 cm-thick, 55 cm-radius casting [6]. The cavity machined within the casting has a 13.8 cm-radius and is 11.2 cm-long. The fabrication method involves casting the blank, annealing it to relieve stress in the unshrunk material with a 28°C/hr temperature rise to 110°C, holding 110°C for 40 hours and allowing the casting to cool 1.7°C/hr to ambient temperature. The casting is then rough machined to within 0.5 mm of the final dimensions and is annealed again (to relieve stresses developed during machining) with a similar process at a slightly lower temperature (102°C for 26 hrs). At this point the final machining and polishing is completed. Overall, we follow procedures for Rohm and Haas Type G Plexiglas.

We performed the structural design of the switch with the finite element 2-D code NIKE2D [7]. Results of the calculation appearing in Fig. 3 show the contours of hoop stress. The maximum stress (16.1 MPa) appears as tension in the external circumference of the penetration for the cathode of the switch (bottom left hand corner of the housing outline shown in Fig. 3). Since the measured yield strength of the envelope material is 65.5 Mpa this design allows for a safety factor of 4 at a maximum pressure of 13.8 bar abs. We measured the axial displacement of the electrodes under pressure (1.53 mm at 20.1 bar abs) and compared it to the displacements predicted by the code (1.60 mm). The agreement is excellent.

Other elements of the design that are evident from Fig. 2 are: the cathode button (5) that contains a radial gas inlet and outlet, an anode button where part (3) positively locates part (2), extensive current gasketing (18) and well sized "O" rings (8, 9) to prevent water from penetrating into the switch as the shock loaded parts undergo unavoidable motion during firing. Other "O" rings (7, 10) seal the gas lines. The anode rim (2) is cut in two semicircles (not apparent from the figure) to permit assembly of the electrodes inside the cavity. The flanges (14, 15) attach the switch to the OL and PFL respectively. The lead free (naval) brass electrodes (2, 3, 5) are bead blasted before assembly. Pressurization of the switch with dry nitrogen prevented contamination of the switch during assembly of the pulse-forming stages.

(f) Samples are obtained for mass spectrometry at regular intervals or whenever switch contamination is suspected.

Conclusions

The modifications we incorporated in the switch of the 2 MV accelerator have produced a device with excellent reproducibility and reliability. The most important ingredients of our success have been: careful electrical and mechanical design, painstaking attention to details and strict quality control during assembly and operation.

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