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Fielding and analyzing performance of a prototype high voltage output gas switch for Saturn

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ABSTRACT

Timing spread between the thirty-six Saturn modules affects peak electrical power delivered to the Bremsstrahlung diode and can affect vacuum power flow and impedance behavior of the load. To reduce the module spread, a new megavolt gas-insulated closing switch was developed employing design techniques developed for the Z-machine laser triggered switches while retaining Saturn's simpler electrical triggering. Two modules were temporarily outfitted with the new switches and used separately into local resistive loads (instead of the usual Saturn electron beam load). A reliable operating point and switch time jitter at that point were the goals of the experiments. The target switch reliability is less than one pre-fire in one thousand switch-shots, and a timing standard deviation of 4 nanoseconds. The switches were able to meet both requirements but the number of tests at the chosen point are limited.

ACKNOWLEDGEMENTS

The authors are deeply grateful to the Saturn operations crew for these results. The hard-working Saturn team provided support and advice that made the experiments possible.

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EXECUTIVE SUMMARY

The Saturn pulsed power driver delivers energy from thirty-six nominally identical pulsed power modules to an electron beam Bremsstrahlung load to generate intense nanosecond X-radiation pulses. Using multiple modules to generate the electrical power facilitates shorter pulse duration for a given total energy, but those modules must be tightly synchronized in time to exploit the short pulse duration. The Saturn modules each generate an electrical pulse with a full width at half-maximum of 35 nanoseconds. Recent Saturn experimental data with the existing switches shows the arrival time of module pulses to the load varies by 30-40 ns (first to last). This level of module time spread reduces the peak electrical power delivered to the load and can cause issues with magnetic insulation of the power flow electrons due to large azimuthal variations in the insulating magnetic field.

The time synchronization of the Saturn modules is most influenced by the closure time of the electrically triggered, multi-megavolt gas insulated switch. This switch holds off voltage while its respective Marx generator charges the intermediate store capacitor to about 2.5 megavolts. On command, the gas switch closes and allows energy to flow from the intermediate store capacitor to subsequent pulse-forming stages in a time shorter than the Marx output duration. The megavolt gas switches thus allow the use of energy-dense (relatively slow) Marx generators while maintaining nanosecond precision and coupling to simple and reliable self-closing water switches in the rest of the pulse compression process.

This report describes the design of the new switches and results obtained from two switches tested into resistive loads during two dedicated switch test series. The switch design uses a different trigger mechanism than the present Saturn switches (though still electrically triggered) and overall lower electric fields to keep the required gas pressure at a more desirable value. At moderate SF_6 pressures, hold-off is nearly directly proportional to pressure even with electrode imperfections. In this geometry, pressures less than 4 bar (absolute) are preferable. At higher pressures, reduced charge mobility in the gas makes the switch behavior more affected by localized electrode enhancements such as normal arc damage.

The new switch design achieved the goal of 4 ns jitter (one-sigma) at a low probability of pre-fire. The estimated machine spread from a 4 ns one-sigma (assuming a normal distribution) would be 18 ns or about half the present spread.

In addition, improved switch trigger diagnostics and detailed analysis uncovered a contributing factor to the present Saturn module spread. Different length cables between the gas switch trigger generator and the switches being triggered caused 23 ns variation in the arrival time of trigger pulses at the switches. This configuration error has existed for many years and the cause or justification is unknown. It has been remedied after the gas switch test series but the effect on switch spread has not been shown as Saturn is not presently conducting experiments.

No switch damage or anomalous behavior was observed in the second round of testing in June. The first round of testing in March revealed some undesired breakdown behavior which was rectified with minor component redesign. The switch was designed with flexibility in configuration. Additional analysis will be done in the coming months to ascertain if additional modifications to the switch insulating spacers should be considered.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
MV	Megavolts, millions of volts
V/n	Voltage dividing switch trigger mechanism
ns	Nanoseconds, billionths of a second
E/p	Pressure-normalized electric field, typically given in kV/cm/bar
psia	Gas pressure pounds per square inch absolute (relative to vacuum)
SF_6	Sulfur hexafluoride gas

Figure Caption

1.1. Background

The goal of the project was to develop a new megavolt triggered switch design for Saturn [1] (**Error! Reference source not found.**) that could improve the module time synchrony, while employing the features used on the Z megavolt switches for reliability. It was strongly desired to retain electrical triggering because of its simplicity compared to laser triggering. The chosen design was a “V/n” switch topology, which has been used in high voltage, high current systems before. To improve performance at the required operating voltage, the V/n trigger is used in combination with a cascade section. The Saturn gas switch requirement is 2.55 MV peak voltage before triggering and 300 kA peak current on closure.

The Saturn megavolt gas switch is a critical part of the pulse-forming chain on Saturn (Figure 1). Two switches were assembled in March 2021 (Figure 2). Several minor design and fabrication issues were noted and resolved. Testing was performed over five days. In June 2021, a second round of testing was completed. In that series, eight days of switch testing were completed.

Figure 3 shows the switch assembly with the intermediate store conductor to which the switch is attached, and the electric field shapers that cause the potential to be distributed nearly uniformly along the switch axis. Equipotentials wrap around the intermediate store cathode making the electric field highest close to the intermediate store conductor while the switch is in the open state. The electric field shapers act to push the equipotentials to improve the field uniformity. It is impractical to make the voltage distribution along the switch perfectly uniform. Electrostatic simulations are used to compute the ideal spacing between cascade electrodes along the axis of the switch. The cascade electrodes nearest the intermediate store have the largest spacing. Figure 4 shows the trigger gap region at the anode end of the switch, farthest from the intermediate store conductor. While the switch is in the open state, about 24% of the total switch voltage (600 kV at 2.55 MV total voltage) is across the trigger gap.

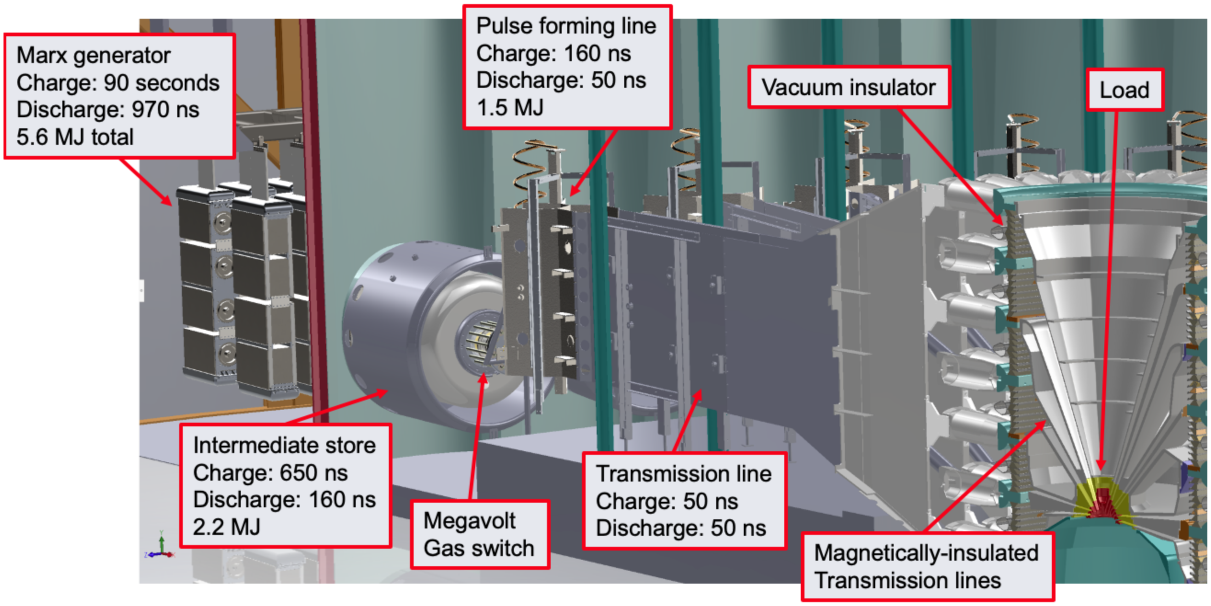

Figure 1. Overall layout of Saturn's pulse-forming system, showing one of thirty-six modules. The megavolt gas switch is the component under discussion here.

Figure 2. A new Saturn switch being assembled (left) and lowered into the Saturn water tank (right).

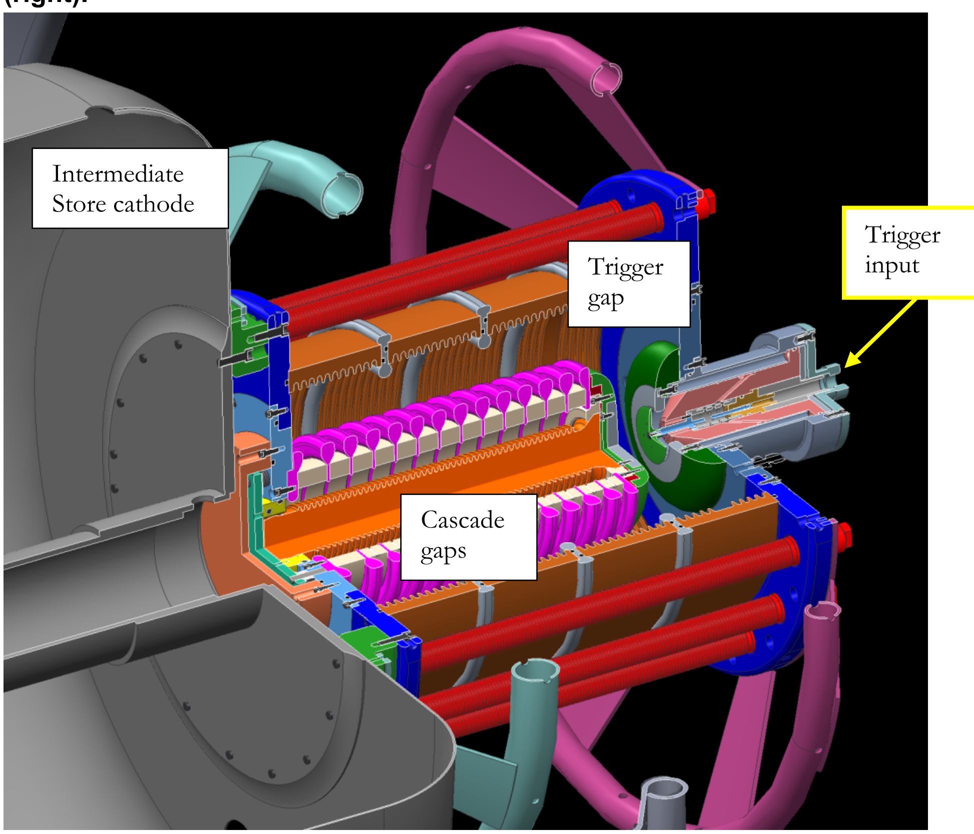

Figure 3. The V/n with cascade switch design tested on Saturn in 2021. The intermediate store cathode electrode is on the left side of the switch (colors). The right side of the switch as shown is the anode electrode and locates the trigger stage. The trigger input is connected to a cable source that supplies a ~50 kV forward-going pulse with ~15 ns rise time. The switch is pressurized with SF_6 gas and is submersed in deionized water.

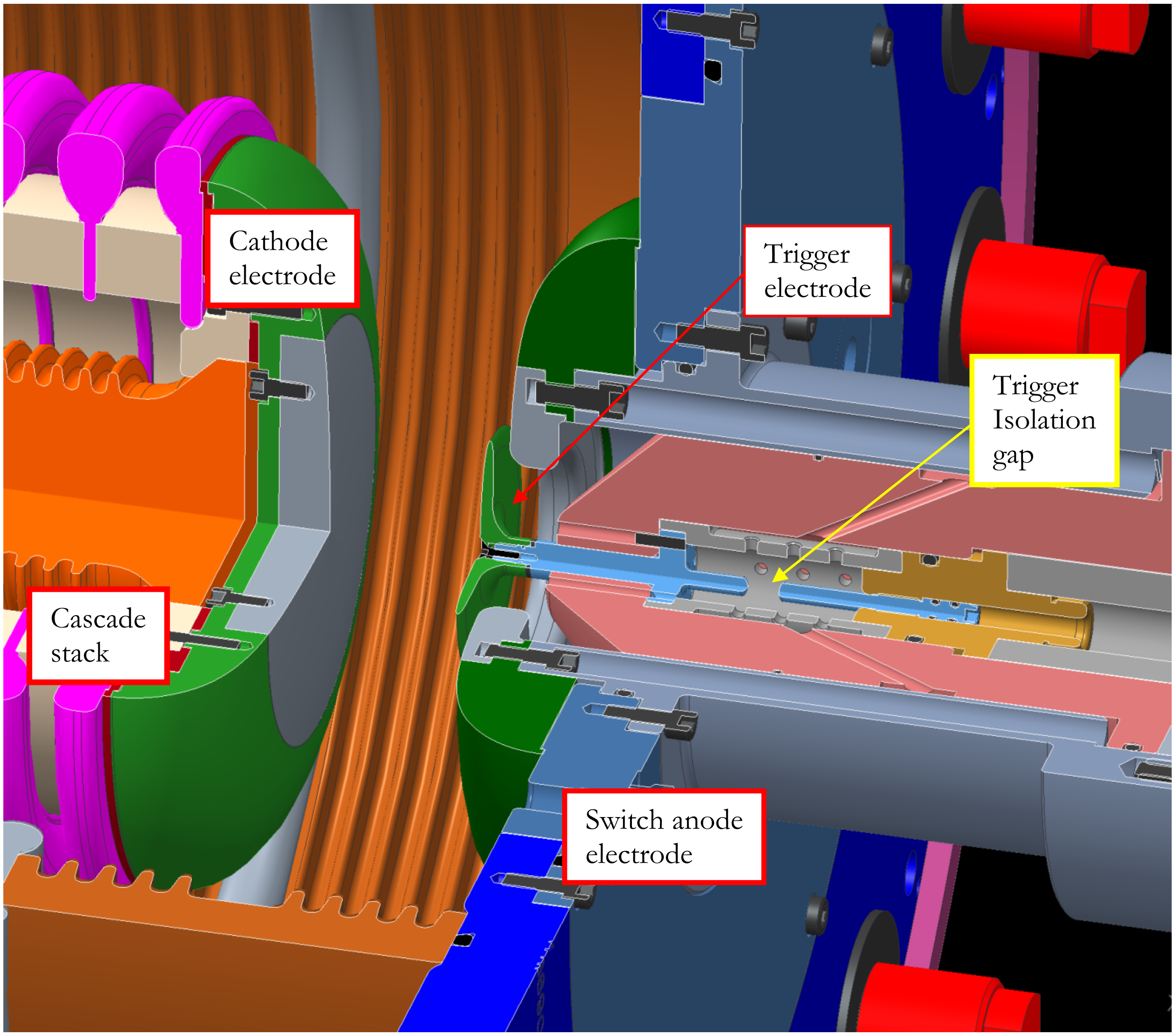

Figure 4. Closeup of the trigger gap used in the new gas switch design. The trigger isolation gap (TIG) allows the trigger electrode to float to about 2% of the total switch voltage (~50 kV negative) until the trigger pulse (~100 kV positive) breaks down the few-mm TIG gas gap and causes field enhancement on the trigger electrode edges. Streamers from that enhancement point propagate towards the cathode side of the trigger gap. Those streamers cause closure of the trigger gap, which in turn causes closure of the entire switch as each of the cascade gaps closes in sequence towards the switch cathode.

1.2. Experiments

In the two series on Saturn, two of the new switches were fielded in a configuration such that their respective energies were dumped into resistive loads. Using resistive loads rather than the full machine with the standard Saturn radiation-producing diode, the team was able to improve the data rate significantly and reduce the stress on the operations team. Full machine radiation-producing experiments on Saturn are nominally done three times per week; in the switch testing mode operators were able to execute as many as sixteen experiments per day. Five days in March and eight days in June produced 109 experiments fielding just the new switches, and in June, both new and old switches were fielded side by side for direct comparison. The testing produced useful results. First, the June modified design prevented the spurious breakdown in the trigger isolation gap seen in the March testing; those breakdowns negatively affected the switch performance in the first series. Second, a significant timing issue with the gas switch trigger system that would affect any switch installed in Saturn was observed and confirmed.

1.3. Performance

The desired timing performance from the Saturn modules (largely determined by the megavolt gas switches) is calculable by the electrical pulse duration from the pulse-forming section. Relatively fast pulses (e.g., Saturn, as compared to Z) require better module synchrony so that the pulses arrive at the load effectively simultaneously. The module pulse full-width at half-maximum (FWHM) adds to the timing spread FWHM in quadrature; total energy is delivered over the composite time and not necessarily the module pulse width. The modules will deliver a fixed amount of energy; if spread out by module asynchrony the total load power is reduced. Module spread thus reduces peak load electrical power, which in turn reduces dose rate. To maintain 90% of the peak available power (no module spread) would limit module standard deviation to 4.1ns, or a total spread of 18 ns, assuming normal distributions. Normal distributions are usually a reasonable approximation for random switch jitter. Assuming water switch jitter is negligeable (in most situations, water switch behavior generally *reduces* effective module jitter) the desired upper limit on gas switch jitter is 4 ns. Note that the desired gas switch temporal accuracy performance in Saturn is *more demanding* than that obtained on Z with laser triggering, but the Saturn switch voltage is only about half of the Z switch voltage.

The jitter of the new switches is in line with the jitter requirements, at a conservative operating point. In seven identical shots, the two new switches had shot to shot jitter of 3.1 and 3.3 ns with a peak intermediate store voltage of 2.5 MV. The old Saturn switches had runtime jitter of 1.3 and 1.7 ns for those shots but at lower voltage (2.4 MV) because of their faster switch run time. At the same pressure but later triggering, the new switches had jitter of 5.8 and 1.0 ns with a peak voltage of 2.8 MV. At the same setting the two old switches exhibited jitter of 2.7 and 2.0 ns at a peak voltage of 2.5 MV. Given the relatively small number of shots available for the statistics, these numbers are effectively similar.

- The new switch design operates at a lower gas pressure, primarily due to reduced field enhancement accomplished with careful electrostatic design optimization and partly because of slightly longer housing length. Lower switch pressures are desirable because SF_6 gas breakdown is more effective and predictable at lower pressures and less SF_6 will be consumed during each shot. The new design will operate at about 40% lower pressure than the existing switches and achieve the same reliability.
- The new switches operate with multiple discharge channels in the cascade section *and* the trigger section. All current megavolt switch designs in use on the multi-module machines at Sandia have two sections- *trigger* and *cascade*. Closure of the trigger gap initiates closure of the entire switch, conceptually like removing a crucial block from the bottom of a *Jenga* game tower causing collapse of the whole tower. The present Saturn switches (and the Z laser-triggered switches) operate with a single

channel in the trigger section of the switch. Multiple discharge channels are highly desirable because electrode erosion depends not only on charge transfer, but current as well. An added benefit of dividing total current into multiple channels in the trigger section is reduced debris accumulation inside the switch housing.

- The new switches have more material available for erosion before the electric field configuration changes significantly. The 3.2-mm diameter sintered nickel-iron-tungsten trigger pin carries the full switch current in one channel in the present switches. Erosion essentially recesses the trigger pin from the trigger gap electric field, which negatively affects (slows) the switch closure time. In the new switch design the much larger ~4-***cm*** diameter trigger electrode has significantly more mass available, and in addition, total erosion will be reduced because the switch current flows in multiple channels in the trigger as well as the cascade section. It is expected to reduce *long-term* jitter (switch run time changes over months or years) with the new switches.
- Using low impedance resistive loads kept the voltage stress on the load resistors at an acceptable level and caused increased peak current and charge transfer in the switches being tested. This combined with higher-than-normal switch voltage made the tests reasonably conservative.
- Data on self-break stability of the new switches was acquired. Due to electrode surface variations caused by erosion, the self-break voltage of such switches at a given pressure is a distribution and not a single value. The results suggest that whole-machine gas switch pre-fire rates will be at or below the present rate.
- Many diagnostic improvements and uncertainty reduction changes were made in the course of the switch testing and work leading up to it.
- In the present configuration the new switches run more slowly than the existing switches. In itself, longer run time is not a fatal flaw, but longer run times generally imply higher jitter (in the limit, a zero-run-time switch necessarily has zero jitter). Ascertaining how the total switch run time was distributed between the trigger and cascade sections with an optical diagnostic was attempted. The diagnostic results are being analyzed now.
- Every Saturn module has a self-closing, oil-insulated energy diverter. These devices function by exploiting the relatively slow and voltage-dependent streamer velocity in oil. A mechanical gap between two electrodes determines the closure time after voltage application. Closure of the diverter allows current to flow through a resistor, reducing voltage and dissipating energy. It was observed that the Marx energy diverters (designed to protect pulsed power components in the event of a Marx pre-fire or gas switch no-fire) are closing early enough to reduce the switch voltage slightly even in normal operation. In higher voltage testing it was necessary to open the diverter gaps to allow full switch voltage.
- The short-term jitter of the existing switches at normal voltage and pressure is excellent. Maintaining the jitter over long periods would require more attention to adjusting the trigger pin, compensating for normal erosion. This would require removal of each switch from the machine and disassembling on a bench to reset the

desired trigger pin position. The trigger pin position in the existing switches can be adjusted without removing the switch, but verification of the pin position cannot- the trigger pin changes length with erosion.

- In the new switches, the adjusting mechanisms to position and verify the trigger electrode and set the trigger isolation gaps without disassembling or even removing the switches from the water work well. It was originally intended not to include the adjustment features on the final switch implementation. The flexibility for switch adjustment, and engineering effort to remove the features made it a clear choice to leave the adjustment mechanisms on the production switches.
- As expected, the new switches have similar (but likely slightly smaller) inductance comparted to the existing switches. The effect on the charge time of the subsequent stage is negligeable. The new switch downstream field shaper geometry allows for a somewhat lower inductance connection from the switch to the pulse forming line but that was not implemented here for simplicity.

1.4. Details

In multimodule pulsed power systems like Saturn, Hermes-III, and Z, the highest load power is achieved when the separately generated pulses arrive at the load simultaneously. Pulse generation in a single large module is generally inefficient in space and would be difficult to achieve the requisite low inductance for fast rise times. Water switches require faster rise times than a large Marx generator will supply, so an additional pulse compression stage is required. This compression stage is a natural place to correct for Marx jitter, and many large pulsed power systems employ command-triggered megavolt gas switches (Saturn, Hermes-III, RITS-6, Z). The systems at Sandia have thus evolved to use reasonably synchronized Marx generators (~10 ns jitter) with megavolt intermediate store capacitors and triggered switches (~5 ns jitter). Because the water switches used at ~100 ns charge times have low self-closing jitter (<10 ns), it is adequate to perform the time synchronization between the intermediate store and the water-switched pulse compression stages. The desired performance is generally withstanding voltage rising in hundreds of nanoseconds and closing with ~5 nanosecond jitter and discharging in about 100 ns. This allows the command-triggered switch to have relatively large inductance, far higher than the water switches.

Triggering a spark gap requires generating conducting plasma that distorts the equilibrium (nominally stable) voltage distribution. Generating this plasma in dense media such as water or oil requires much more energy than creating a plasma in gas. Creating a plasma in vacuum requires still lower energy, but plasma created on a solid surface requires considerable expansion time to close a gap. In gas, the existing insulation medium is made conductive with electrons, laser energy, or as on Saturn, streamer propagation from an enhancement.

The way the switches tested on Saturn in 2021 create this enhancement by changing the potential of an electrode that is capacitively coupled to adjacent electrodes. During the sub-microsecond intermediate store voltage rise time, the trigger electrode floats to a potential that does not greatly disturb the potential distribution. When closure is desired, the potential of that electrode is shifted considerably. This increases the electric field on the trigger electrode, allowing one or more ionized streamers to propagate towards the electrode of opposite polarity to the trigger. With proper choice of trigger pulse polarity and geometry, it is possible to achieve low jitter triggered closure.

An example of a single-stage switch using this "V by n", or "V/n" technique is shown in Figure 5.

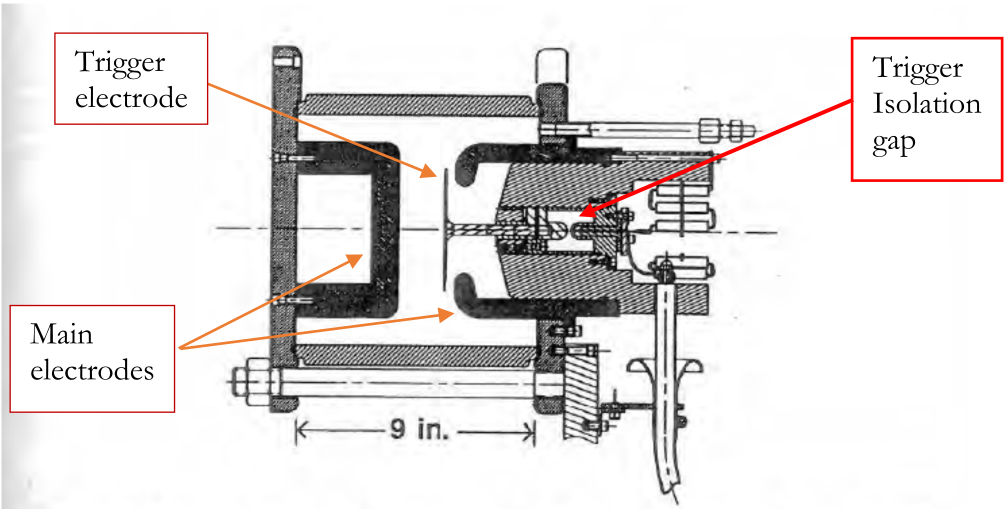

Figure 5. An example of a single stage triggered V/n switch. This switch operates at ~800 kV peak and up to 400 kA with ~5 ns jitter.

Such single stage switches have been used in previous pulsed systems. [2] The high voltage required by Saturn (2.5-3 MV) made the design more challenging. To maintain a reasonable trigger pulse amplitude, the present design uses a separate trigger stage in combination with a self-closing cascade section. This is the trigger gap/cascade concept used in PBFA-II, ZR, Hermes-III and RITS-6 laser triggered switches as well as the present Saturn switches. The two-stage design reduces the voltage that is actively triggered while allowing higher total switched voltage. The arrangement of a trigger gap (~4 cm length) with a series of ~1 cm cascade gaps allows for lower field enhancement which reduces the required gas pressure. The self-break cascade section adds non-zero jitter but can be managed with optimized designs.

A simulation of the gas switch region is shown in Figure 6 in the quasi-static state as voltage is applied from the Marx and intermediate store capacitor. The timescale over which voltage is applied to the switch is much longer than wave transit times in the switch region so static simulations are valid.

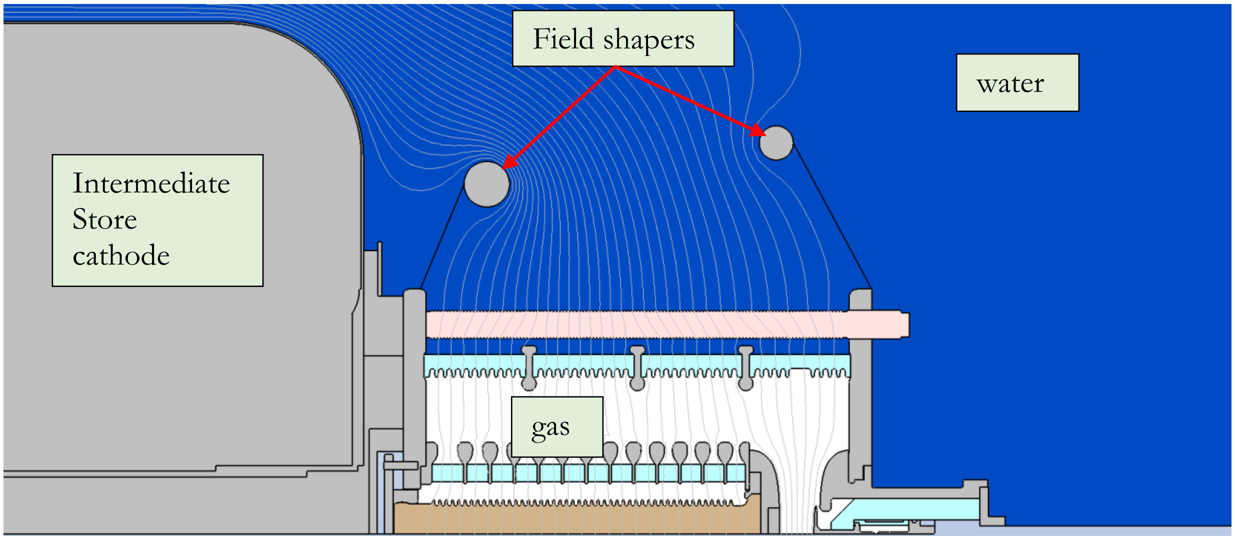

Figure 6. Electrostatic solution of the new switch design with the intermediate store cathode and the field shapers.

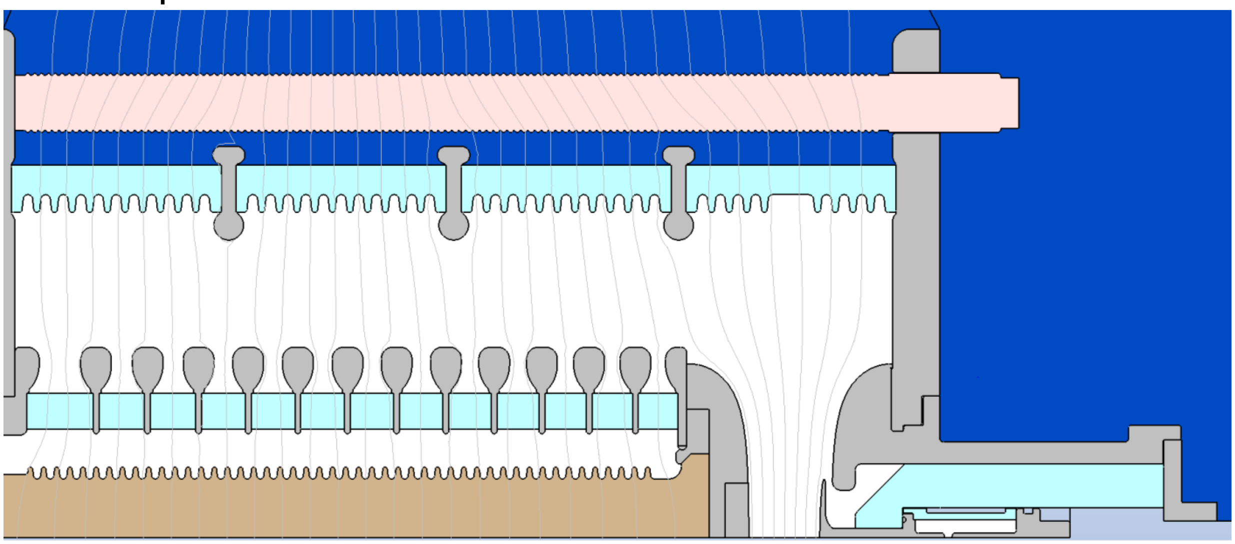

Figure 7. Switch voltage equipotentials before the trigger is applied. The peak electric field is similar on all the metal surfaces.

Figure 7 shows equipotentials in the switch region before the trigger pulse arrives. The peak electric field is similar on all the metal surfaces and is below the breakdown threshold.

Figure 8 shows the equipotentials in the trigger region of the switch when the trigger pulse is applied, causing the trigger isolation gap to close and distort the equipotentials in the trigger gap. The field is highly enhanced in the region of the trigger electrode causing it to launch streamers toward the trigger cathode electrode.

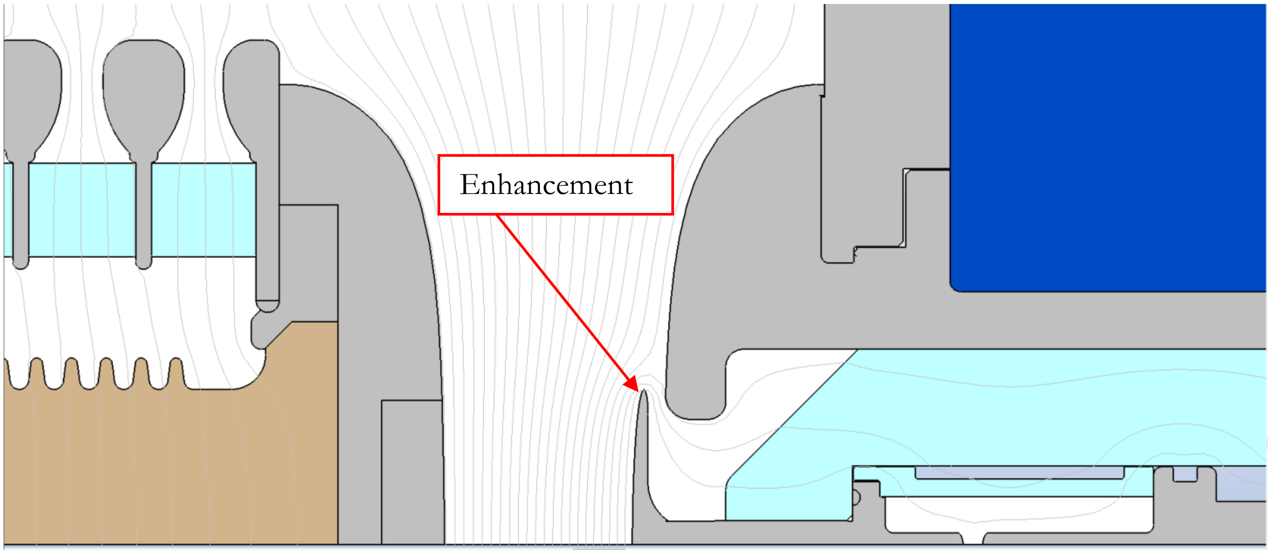

Figure 8. Electric field equipotentials after the trigger pulse is applied. After trigger application, the electric field on the trigger electrode is increased enough to launch streamers left toward the cathode.

Figure 9 shows the equipotentials in the switch after the trigger gap has closed completely. The electric field on the first cascade electrode is strongly enhanced, causing rapid closure of the first cascade gap. Subsequent cascade gaps are enhanced even more and close more quickly as the cascade progresses towards the switch cathode.

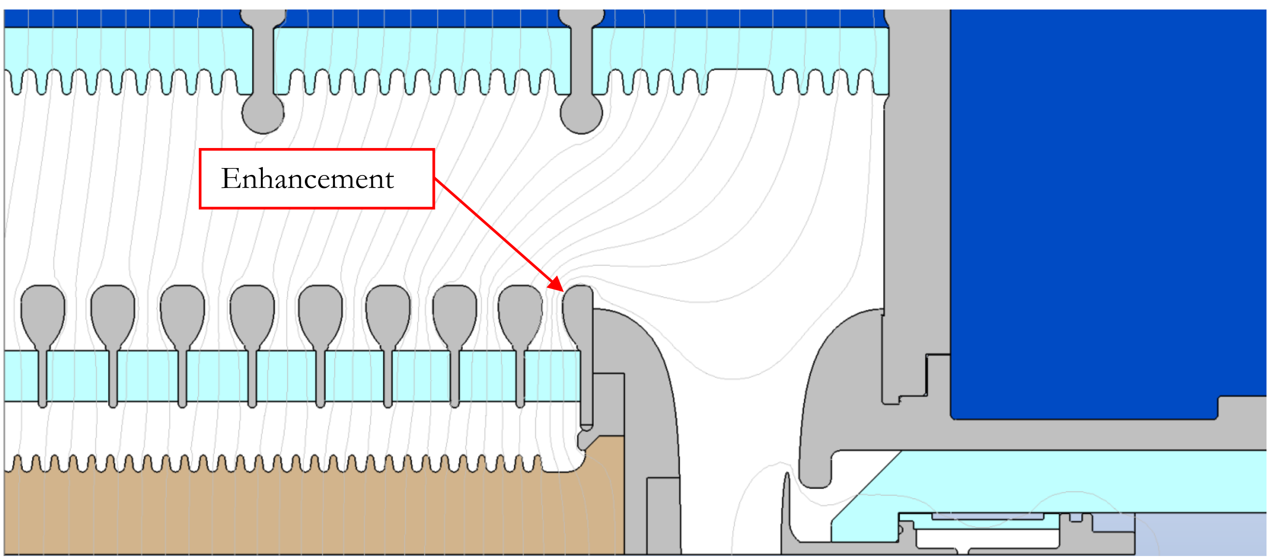

Figure 9. Electric field equipotentials after the trigger gap has closed. The electric field in the cascade gaps is increased initially a factor of 2.5. The enhancement causes few-nanosecond closure time of the ~1 cm gaps. The enhancement increases as the cascade closes causing ever-faster closure times of cascade gaps as the discharge proceeds to the left in this image.

1.5. Performance Data

The first series of tests happened in March of 2021. In that series, command-triggering was demonstrated but the jitter was larger than desired, and several other issues were observed. The main problem (confirmed after the series concluded and switches disassembled) was flashover of the plastic walls of the trigger isolation gap. If the trigger isolation gap does not remain in the open state until the trigger arrives, the trigger electrode will not remain at its natural potential. This situation will cause premature triggering and limited switch control.

Immediate design work produced a configuration with reduced field enhancement at the trigger isolation gap triple points. In addition, the maximum trigger isolation gap was limited in subsequent testing to reduce the peak voltage applied across the isolation gap.

In the second series, the isolation gap was checked once by removing and partially disassembling both switches and no spurious breakdown paths were seen in either switch. The second series also utilized a smaller but equally effective set of field shapers to distribute the potential axially along the switch length. The potential naturally wants to wrap around the intermediate store cathode while the switch is open; this would increase the electric field at the cathode end of the switch and decrease the field at the anode end. Nonuniform grading is undesirable in switches because pre-fires are determined by the highest field and jitter is determined by the lowest field (since the gas pressure is uniform in the switch). The lowest jitter for a given holdoff is generally with the most uniform field, allowing the lowest pressure.

The desired timing performance from the Saturn modules (largely determined by the megavolt gas switches) is calculable by the electrical pulse duration from the pulse-forming section. Relatively fast pulses (e.g., Saturn, as compared to Z) require better module synchrony so that the pulses arrive at the load effectively simultaneously. The module pulse full width at half-maximum (FWHM) adds to the timing spread FWHM in quadrature; total energy is delivered over the composite time and not necessarily the module pulse width. For a given energy, shorter duration is higher power, which for Saturn yields higher dose rate. Module spread comparable to or larger than the intrinsic module pulse width reduces peak load electrical power. To maintain 90% of the peak available power (no module spread) would limit module standard deviation to 4.1ns, or a total spread of 18 ns, assuming normal distributions. Normal distributions are usually a reasonable approximation for random switch jitter. Assuming water switch jitter is negligeable (in many situations, water switch behavior slightly *reduces* effective module jitter) the desired upper limit on gas switch jitter is 4 ns. Note that the desired gas switch timing accuracy in Saturn is more *demanding* than that obtained on Z with laser triggering, but the Saturn switch voltage is only about half of the Z switch voltage.

The jitter of the new switches is in line with the jitter requirements, at a conservative operating point (95% confidence in a pre-fire rate of less than 0.1%). In seven identical shots, the two new switches had shot to shot jitter of 3.1 and 3.3 ns with a peak intermediate store voltage of 2.5 MV. The old Saturn switches had runtime jitter of 1.3 and 1.7 ns for those shots but at lower voltage (2.4 MV) because of their faster switch run time. At the same pressure but later triggering, the new switches had jitter of 5.8 and 1.0 ns with a peak voltage of 2.8 MV. At the same setting the two old switches exhibited jitter of 2.7 and 2.0 ns at a peak voltage of 2.5 MV. Given the relatively small number of shots available for the statistics, these jitter numbers are effectively similar.

The behavior of gas switches is often characterized by the ratio of electric field to pressure. Higher electric field enhances triggering and increases closure speed, but higher pressure enhances reliability. At high values of E/p self-closure is likely, while at low values triggering is more difficult. Turman [3] notes that pre-fire is likely at fields above 75 kV/cm/bar at 2 bar. Triggering is difficult below 46 kV/cm/bar even with laser triggering. Those limits prove relevant in this switch as well.

As noted previously, the time from trigger pulse arrival to complete switch closure is relatively long at high pressures. A direction for analysis is to consider ways to reduce the run time and therefore closure jitter. Only two new switches were available for these tests, so statistics are limited with respect to unit-to-unit differences.

To characterize the voltage applied to the switches we used the Saturn intermediate store voltage monitors. The variation in signals from module to module was not plausible. All the Marxes are charged to the same voltage and are basically identical. The Marx-intermediate store circuit is simple and dominated by the Marx capacitors and the Marx inductance. For that reason, we were able to match a simple circuit model to the measured voltage with only amplitude adjustment to account for calibration differences, and a time shift to account for variations in Marx erection time.

A comparison of the circuit model and the measured voltage is shown in Figure 10. Basically, with known capacitance of the Marx and the intermediate store, there is a unique circuit model that matches the circuit temporal behavior. A constant series resistance of 2.5Ω is adequate for this modeling because the circuit inductance is the dominant impedance. The experimental Vdot monitors are affected by conducted current caused by nonzero water conductivity. The experimental waveforms are corrected for this effect but due to water processing, the water conductivity changes slightly through the series. This is a ~1% effect because of the relatively fast intermediate store charge time. A slight over-correction to the measurement is seen in the figure and is due to increasing water resistivity not exactly entered into the compensation routine for each experiment.

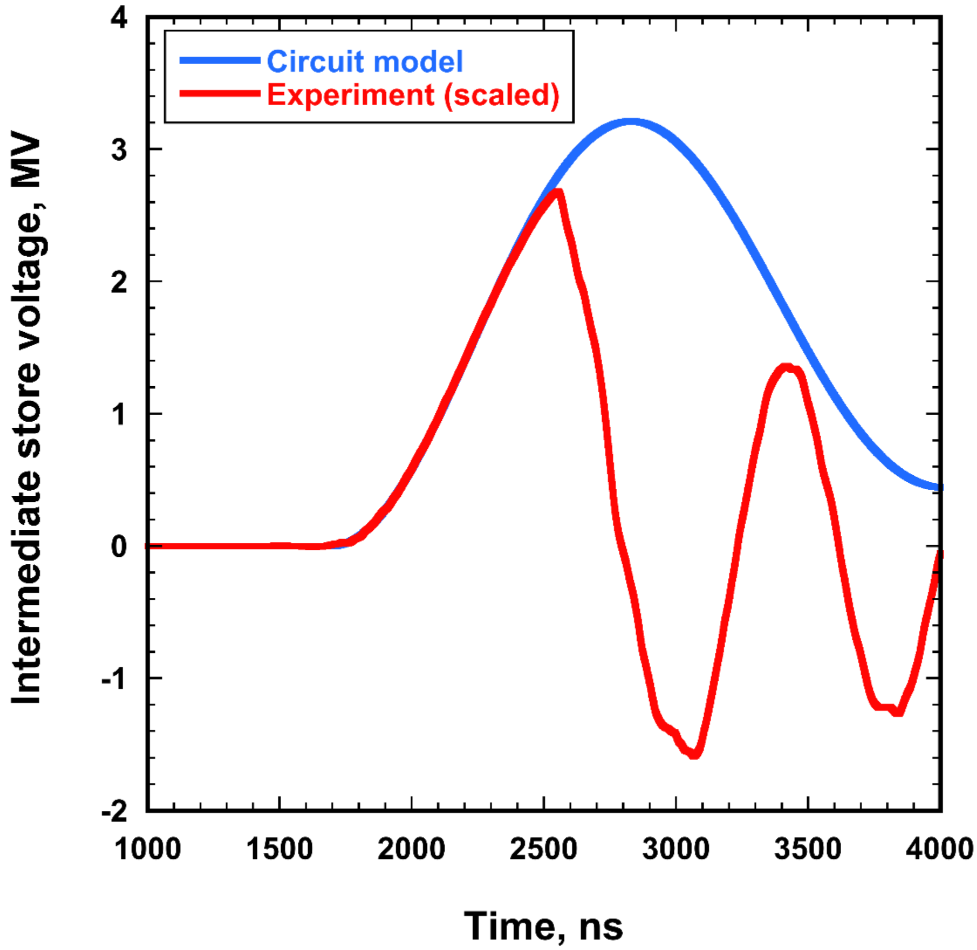

Figure 10. Intermediate store voltage calculated from known circuit values (without switch closure) and scaled measured voltage. Scaling the measured voltage is necessary because of calibration variations in the monitors. Scale values used are in the range 0.85 to 1.1 using the verified Marx charge voltage. Because the Marxes are identical and charged to the same voltage, it is reasonable to normalize the measurements to a standard such as a validated circuit model. In this example, the experimental waveform has been slightly over-corrected for water conductivity as evidenced by the measured voltage falling below the circuit model near the peak measured voltage.

It was observed in this testing that the new switch in module 36 ran consistently later than the new switch in module 1. Detailed study of diagnostics prompted a reflectometry test of high voltage trigger cable lengths from the trigger pulser to the switches. It was verified that the trigger cable lengths varied by 15 feet (~23 ns) from the longest to the shortest. It is not known how such a large error could have been made but it is now rectified. This discovery was possible because of the new trigger diagnostics added before the switch testing began. The previous gas switch trigger diagnostics were located in the Saturn water tank just upstream of the trigger isolation inductors at each switch. The signals from those monitors were generally unreliable and unusable. Because of the design of those monitors, the mechanical shock environment, and the difficulty in maintaining signal path quality through the water floor ports, alternatives were considered. Clearly there is no advantage to locating the trigger monitors near the switches, and in fact considerable disadvantages. New monitors were built and characterized that measure the trigger signal pulse in the Saturn basement.

The signals from these monitors does not have to deal with water shock or failure-prone water floor port and are more reliable. With the new signals verifying offline cable measurements, the cables were trimmed and the transit time variations are now one nanosecond as shown in Figure 11. We expect a reduction in Saturn module spread solely because of this improvement.

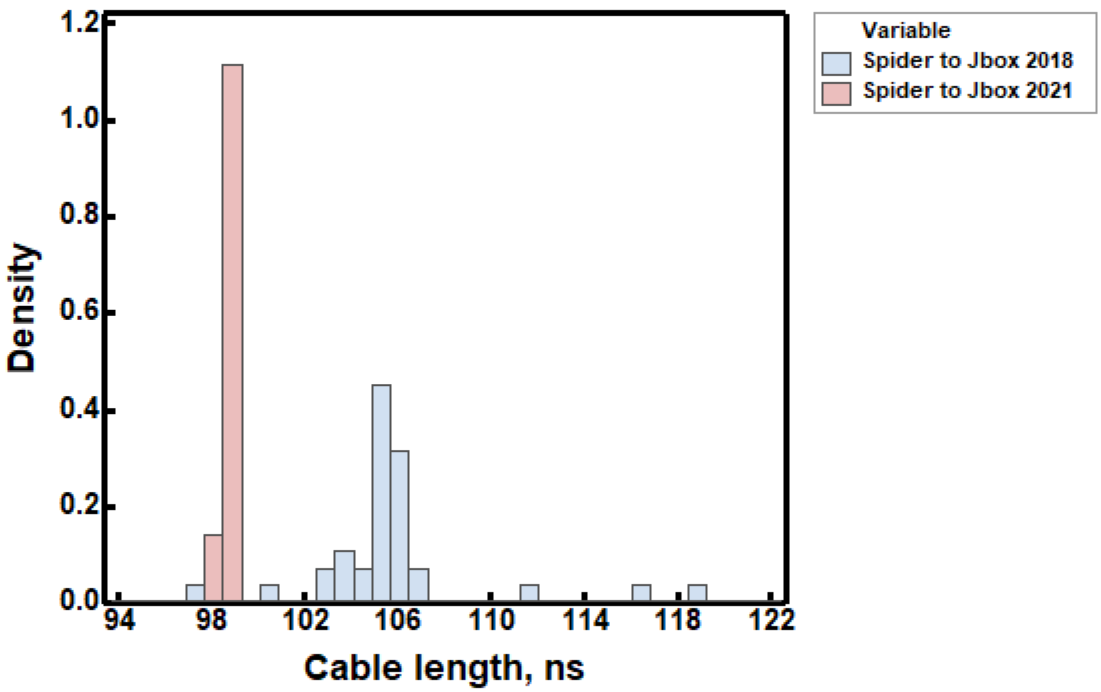

Figure 11. Trigger cable transit times as used in the switch tests (blue) and corrected after switch testing (red, 2021).

A plot of switch run time versus switch voltage when the trigger arrives is shown in Figure 12. Self-break testing in which the trigger was delayed was also done and shown in the figure as zero run time (a reasonable description of a self-break). The self-closing oil diverters affected some of these tests by decreasing the voltage before the gas switch closed. To minimize this, we opened the diverter gaps on the modules with new switches from the 3.5 inch normal value to 5 inches for the switch testing only. The curve of runtime vs E/p goes through the self-break points at a reasonable value of 80 kV/cm/bar, in agreement with Turman. [3]

A reasonable switch operating point is well below the lowest self-break and above the regime of difficult triggering. In Figure 12 below, that would be in the region of 65 kV/cm/bar. The measured jitter on a small number of shots is of order 4 ns. Future testing would be directed to increase the number of shots in the interesting range, as well as investigating possible switch improvements.

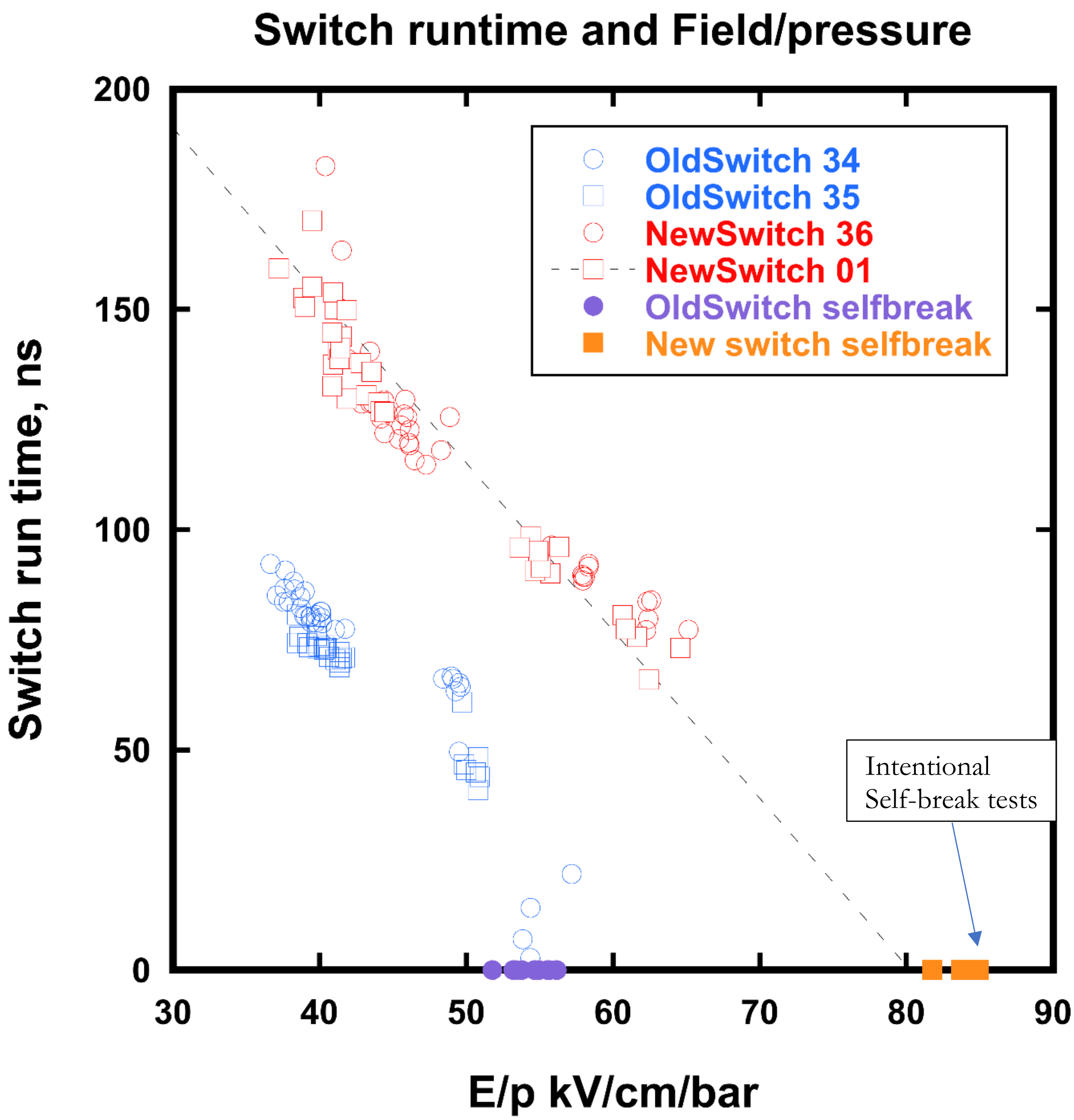

Figure 12. Switch run time from trigger arrival at the switch to the time of peak intermediate store voltage, as well as self-break testing (indicated by zero run time). The old switch self-break results are affected by the self-closing oil diverters located at the Marx outputs. The diverter gasps were increased for these shots only on the two modules with new switches. The line fit calculation does not include the intentional self-break shots.

All closing switches operate more quickly as the operating field comes closer to the limit of the insulating fluid or solid, and so exhibit more rapid closure and lower jitter. At some point there is a reasonable probability that the switch will close or start to close before being triggered. The self-break distribution is an important measure of switch stability and expected reliability at a given voltage relative to the self-break voltage distribution. Figure 13 shows the measured self-break voltages for all tests at 85 kV Marx charge and 30 psia switch pressure. These were intentional self-break tests where it was expected that the switch would close before the trigger pulse arrived. Using a Weibull distribution fit, it is reasonably estimated that the switch pre-fire probability at the chosen operating point (2.7 MV and 37 psia) is a reliable operating point that is highly unlikely to have more than one pre-fire in 30 full-machine Saturn tests (0.1%*36modules). Further testing is desirable to refine this number or develop an even more conservative operating point.

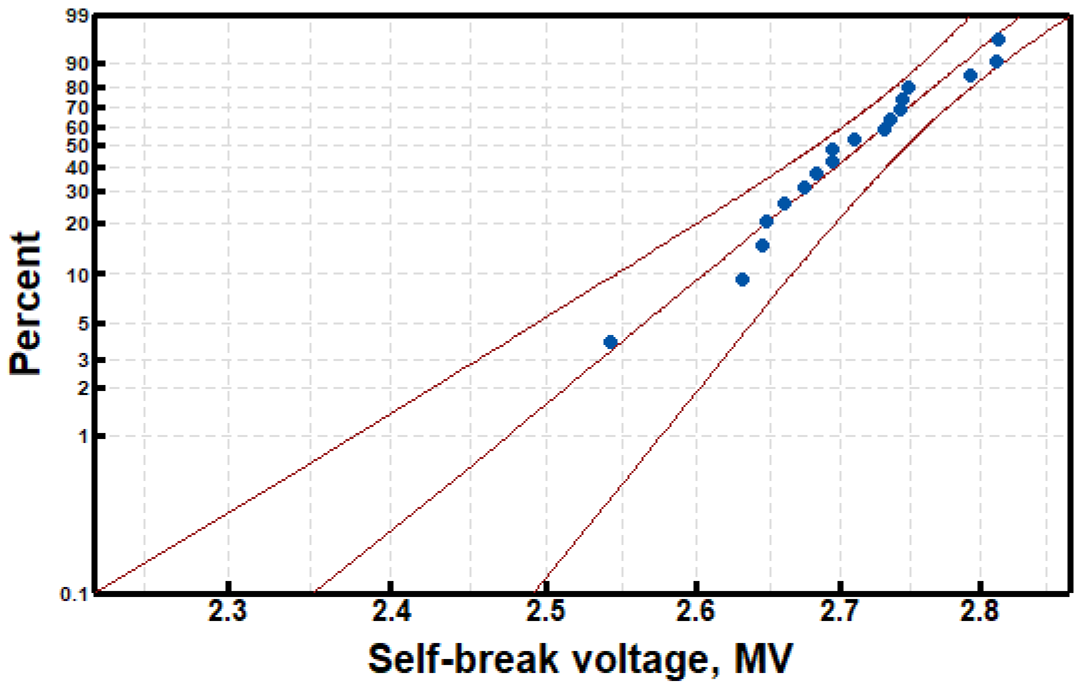

Figure 13. Probability plot of all new switch intentional self-break testing (both new switches) at 30 psia and 85 kV Marx charge using a Weibull model; 95% confidence bars are shown. The data show that a switch self-break is unlikely below 2.2 MV (0.1% probability at 95% confidence) at this pressure. The triggered testing was done at 37 psia so the estimated safe operating voltage is scaled by pressure to the 2.7MV assumed safe voltage at 37 psia and used for some of the triggered experiments.

1.6. Switch Improvements

Because the new switch run time at the same E/p is longer than the original Saturn switch run time, there is concern that the jitter will be worse. A study of reapportioning the voltage distribution to speed switch closure is underway now. This would only require replacing spacers in the cascade section and would be relatively inexpensive. An additional path would be to develop a multi-channel trigatron trigger section and has been proposed before. The switch design embodied in the parts tested in June would appear to be a viable and desirable replacement for the present switches.

Ideas to improve the performance of the switches without sacrificing reliability are being considered. Such changes would be relatively inexpensive and would require minimal mechanical engineering time.

1.7. Conclusions

Testing of a new switch design in Saturn were done as part of a significant effort to understand and reduce the temporal spread between modules. Other parts of the effort are quantifying timing errors in the data acquisition system, reducing errors in the trigger cable lengths, and measuring azimuthal variations in voltage and current inside the vacuum insulator. The gas switch has the largest effect on module timing and is the key part of reducing module spread. Because of Saturn's short pulse length, the requirements for gas switch jitter are more stringent than the measured performance of Z's laser triggered gas switches.

The gas switch testing showed the switch design can perform with the required jitter and reliability at the same time. We will continue to study ways to improve the design to increase timing accuracy and reliability margin. The existing Saturn gas switches perform well in the short term but suffer from long term run time drift as erosion changes the trigger pin location.

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A.1. Sub-Appendix Title

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