Jitter Improvement of the 12-MV Oil Switches on Aurora *

F.T. Warren and H.G. Hammon
Physics International Company

and

B.N. Turman and K.R. Prestwich
Sandia National Laboratories

SAND--88-3169C

DE89 013809

ABSTRACT

The Aurora Prompt Gamma Flash Simulator has been undergoing a series of machine upgrades in response to recent simulation requirements. One outgrowth of these new requirements is the need for improved synchronization of the four Blumlein modules. Physics International and Sandia National Laboratories have developed and tested an innovative oil-switch trigger scheme consisting of a charged transmission line pulse generator switched by a 3-MV, electrically-triggered, Rimfire gas switch. Recently, we have tested the oil switch trigger pulser on one of the 12-MV, Blumlein oil switches. In these tests, we have achieved shot-to-shot jitter of 5 ns. By comparison, jitter of the present trigger scheme has been measured to be 10 ns. In this paper, we will discuss the jitter-reduction techniques, the design of the low-jitter, oil switch trigger pulser, and the tests results achieved on Aurora.

INTRODUCTION

The Aurora Prompt Gamma Flash Simulator is a four module, 14-TW pulsed power machine that has been operated by Harry Diamond Laboratories (HDL) since it was commissioned in 1972.[1] In response to new simulation needs, Aurora has been undergoing a series of machine upgrades aimed at providing a more flexible simulation environment. These upgrades have included developing multi-pulse and short-pulse capabilities, and improving machine reliability with new Marx generators.

One outgrowth of the new machine capabilities is the requirement for improved synchronization of the four Blumlein modules. This improved synchronization has been the subject of a joint program between Physics International (PI) and Sandia National Laboratories in Albuquerque (SNLA) funded by Harry Diamond Laboratories.

In the first phase of the program, PI assisted SNLA in a study effort to assess replacing the 12-MV, Aurora oil switches with laser-triggered, Rimfire gas switches.[2,3] The results of the study indicated that such a replacement was indeed feasible and that the resulting four Blumlein output pulses could be well synchronized. However, the gas switches would have been much more inductive than the original oil switches and the risetime of the output pulse of each Aurora module would have been greatly increased, resulting in substantially lower dose rate for each individual module. This dose rate degradation could not be tolerated.

The second phase of the program was a new study to: (1) evaluate how the jitter of the Aurora oil switches might be reduced, (2) develop an improved triggering scheme, and (3) develop a concept for testing the improved scheme at PI. In the third phase, we designed, fabricated, and

* This work was sponsored by US Army, LABCOM, Harry Diamond Laboratories.

tested the triggering concept that was developed in the second phase. In the forth phase of the program, a new, low-jitter, oil-switch trigger pulser was fabricated, installed and twice tested on one of the four Aurora Blumlein modules.[4,5] This paper discusses the Aurora short pulse synchronization requirements, discusses our approach to jitter reduction, describes the trigger pulser hardware that was installed and tested on Aurora, summarizes the results of the conceptual validation tests performed on the 737, and reports the results of the two Aurora testing periods.

SHORT PULSE SYNCHRONIZATON REQUIREMENTS

The Aurora radiation simulator consists of four pulsed power modules operating in parallel. This machine was designed to produce fairly long radiation pulses with a very high total dose. This high dose specification requires simultaneous operation of the four modules. In the normal long pulse operation mode, synchronization is not too difficult to achieve. The combination of long risetime and long pulse duration relaxes the requirement for close pulse spacing from the four-module Aurora machine.

New simulation requirements have emphasized the importance of shorter radiation pulses. Aurora has been upgraded in several respects to respond to these short pulse requirements. Among these upgrades are the installation of diverter switches to truncate the end of the high voltage pulse, nose-erosion techniques to shorten beam risetime, and next summer, replacement of the aging Marx generators for reduced Marx timing jitter as well as improved reliability. As long as only one pulse is required, the diverter/nose-erosion scheme produces excellent short pulse results. However, high dose requirements necessitate simultaneous short pulse operation of two or four Aurora modules. One additional machine upgrade will be required to accurately synchronize the shortened pulses to yield the highest dose rate possible.

APPROACH TO SYNCHRONIZATION IMPROVEMENT

There are three considerations regarding synchronization of the Aurora Blumlein modules. First, each component of the Blumlein switch trigger system must individually possess low-jitter characteristics. The only way to achieve low trigger system jitter is to use low-jitter components. Secondly, each of these four low-jitter systems must have equal runtimes so that the resulting output pulses "overlay." (The runtime for a switching device is the time between trigger application and switch closure.) If timing adjustment is required to ensure equal runtimes, and these adjustments are made by varying gap spacing and/or gas pressures, then low jitter must be preserved with whatever adjustments that are made. Last, due to Marx jitter, each of the Blumlein modules will not always have identical pulse charge voltage. Therefore, the runtime of the ideal trigger system would have a small dependence on charge voltage. This last goal is perhaps the most difficult to achieve.

Faced with the task of improving the Aurora output pulse synchronization, we must look to improving this oil switch triggering system. The three components of timing uncertainty that have the greatest effect on output pulse synchronization are the Marx generator erection jitter, the master switch closure jitter, and the oil switch closure jitter.

The Marx generator jitter presently varies between about 50 ns and 100 ns depending on the condition of the charging and triggering resistors and the gas switches. This Marx generator jitter is being addressed by the current Aurora Marx Replacement Program, which will provide new Marx generators that should have substantially less jitter (probably 10 to 20 ns). However, as the Marx switch components and the charging and triggering resistors see extended service, the Marx jitter will inevitably increase. The total extent of the jitter increase will depend on the time elapsed between Marx maintenance periods.

Obtaining the lowest jitter for the master gas switch requires operating the switch at the appropriate gas pressure and applying the correct trigger pulse. Beyond these, the only way to lower the jitter is to replace the switch with one of a proven low-jitter design. For the 12-MV low-jitter trigger system we have selected the lowest-jitter, high-voltage gas switch available.

The jitter of the oil switch is related to the timing accuracy of the streamer initiation and to the total streamer closure time. Thus, to reduce the oil-switch jitter, we must first swing the oil switch midplane from the initial -2 MV as quickly as possible minimize the initiation uncertainty. Secondly, we must provide a large total voltage swing to drive the streamers as quickly as possible to minimize both streamer transit time and jitter. The 12-MV, low-jitter oil-switch trigger system uses a fast-rising (35-ns 10%-to-90% risetime), high-voltage (6 MV) pulse to accurately launch and quickly close a large number of oil streamers.

HARDWARE DESCRIPTION

To satisfy this difficult timing constraint, an innovative pulse generator design has been developed that, when coupled with the current Aurora oil switch hardware, results in an extremely low jitter, 12-MV oil switch. The design shown in Figure 1 generates a 5-MV to 6-MV trigger pulse with a 35-ns 10%-to-90% risetime.

The low-jitter trigger pulser is charged by tapping off the intermediate conductor with a 3-inch outside diameter, $CuSO_4$ resistor. This charging resistance and the capacitance of the trigger pulser form an RC integration circuit. (The charging inductance has a very low impedance and has very little effect on the charging circuit.) The value of the resistor is chosen so that the trigger pulser is charged to between 2 and 3 MV while the main Aurora Blumlein is charged to between 9 and 11 MV. At 1.8 µs into the Blumlein pulse charge, the TGS is triggered and closes, launching the output voltage pulse. Figure 2 shows the measured charge voltage waveform for the low-jitter trigger pulser.

The charging inductor functions as a protection element for the charging resistor. The closure of the TGS launches one cancellation wave down the line toward the oil TIG and another wave toward the charging resistor (see Figure 1.) The charging inductor serves to delay this second wave, which would otherwise add to the voltage stress of the resistor, allowing time for the main Blumlein pulse to remove the high field stress from the charging resistor.

This charging scheme avoids the requirement for an auxiliary charging supply by making use of the energy stored in the main Aurora Marx generators. Suppling this energy reduces the main Blumlein voltage by 4%. However, with the implementation of the new Marx generators this reduction will be completely compensated.

The low-jitter trigger pulser employes a highly-developed gas switch designed at Sandia National Laboratories. This electrically triggered version of Sandia's Rimfire switch family is currently installed on all 36 modules of th Saturn radiation simulator, where it has a measured trigger jitter (standard deviation) of 1 ns.[6] The Rimfire switch has a short and consistent 30-ns closure time.[7] The switch can be routinely charged to 3 MV and has been tested here at PI to 3.5 MV. However, in the low-jitter trigger pulser, the gas switch is operated at a maximum of 2.8 MV to provide an additional measure of safety.

The charged transmission line, XML, is the pulse forming section of the pulser design. It is a "parallel plate" line suspended above a ground plane. The ground plane is formed from perforated plate sections, which are narrow enough to be brought into the inner line through a small hatch in the outer wall of the Blumlein. These plate sections are welded to I-beam supports that are attached to support ribs of the inner Blumlein conductor. The "parallel plate" line is

88-10-291

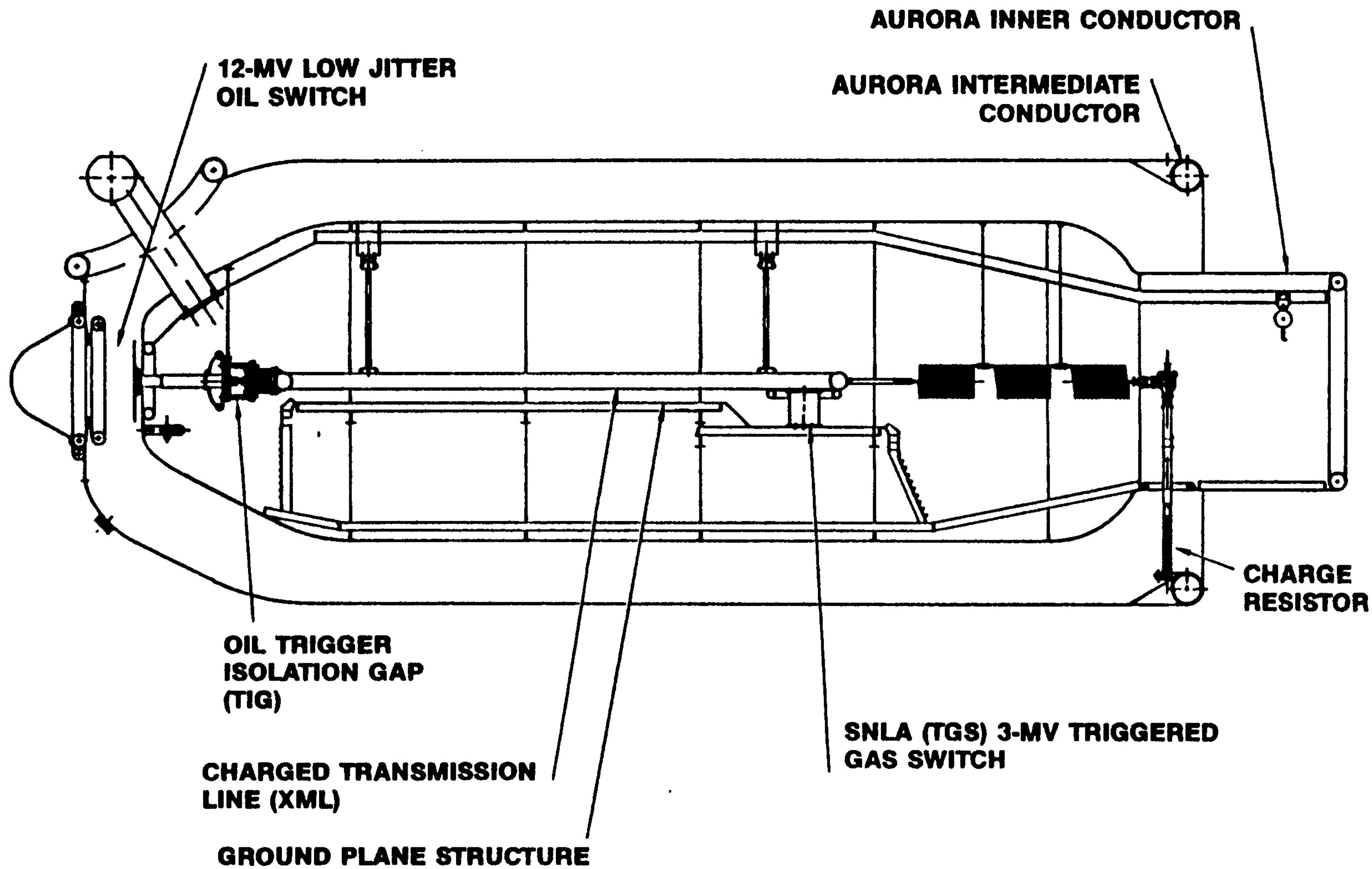

Figure ~~2.1~~ 1. 12-MV low-jitter oil switch trigger pulser (upper Blumlein installation).

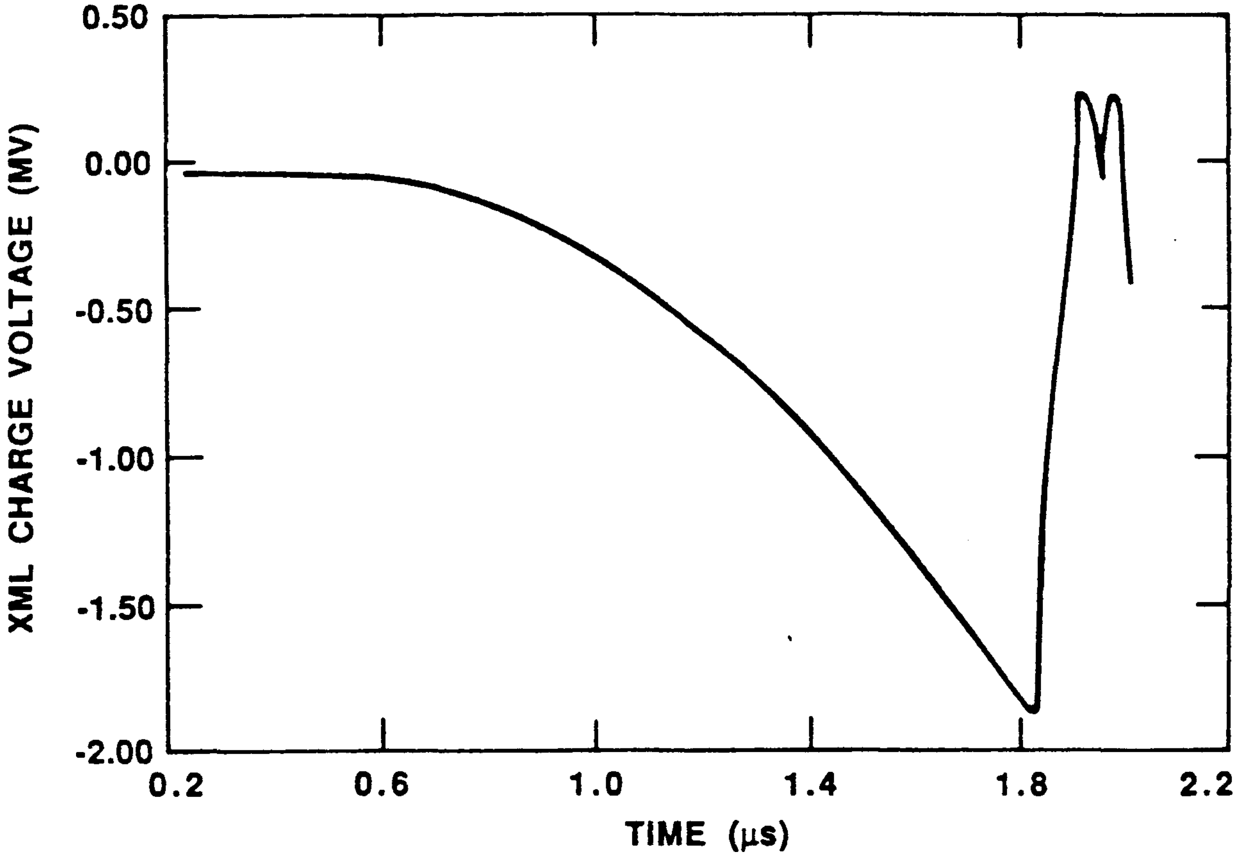

Figure 5.3. Measured XML charge voltage (note TGS switch-out at 1.85 μs).

88-10-292

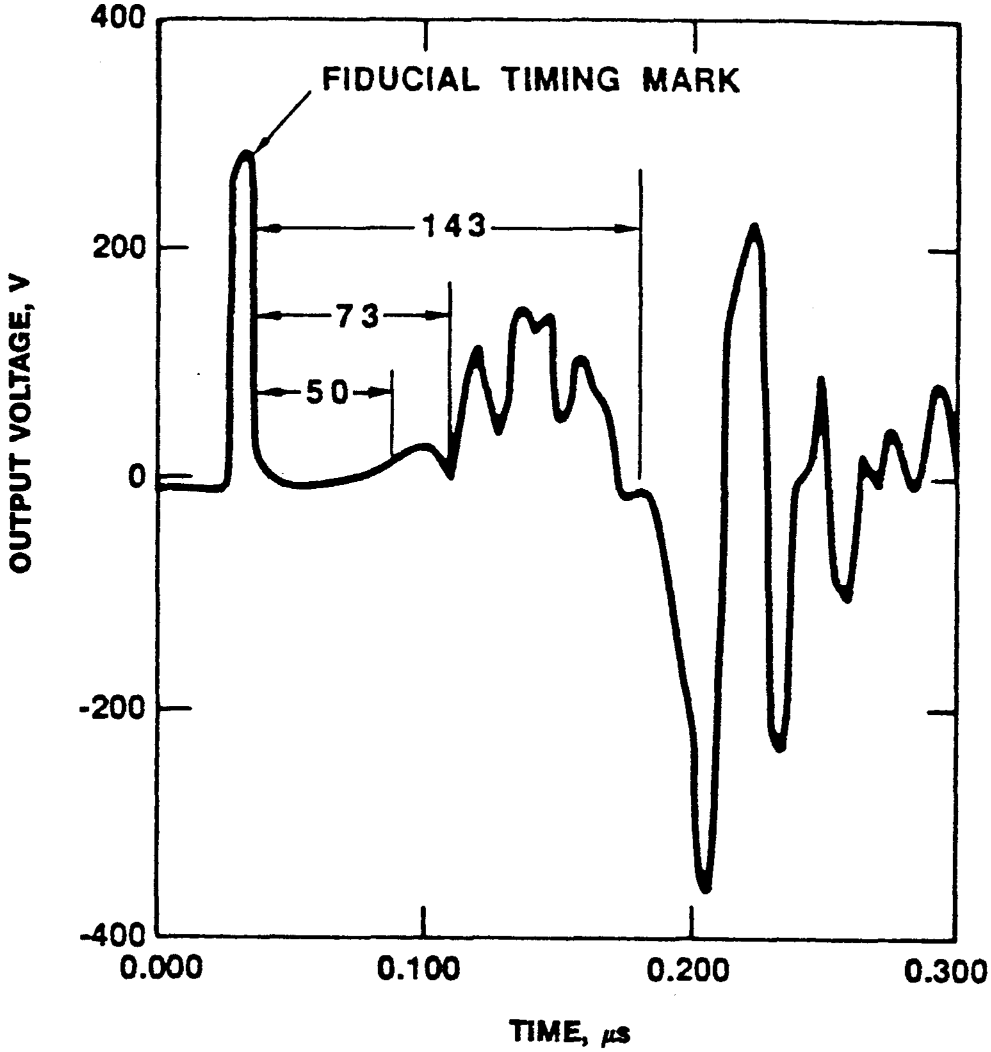

Figure 5.10. Derivative of the oil switch trigger voltage pulse (D-DOT voltage monitor).

88-10-288

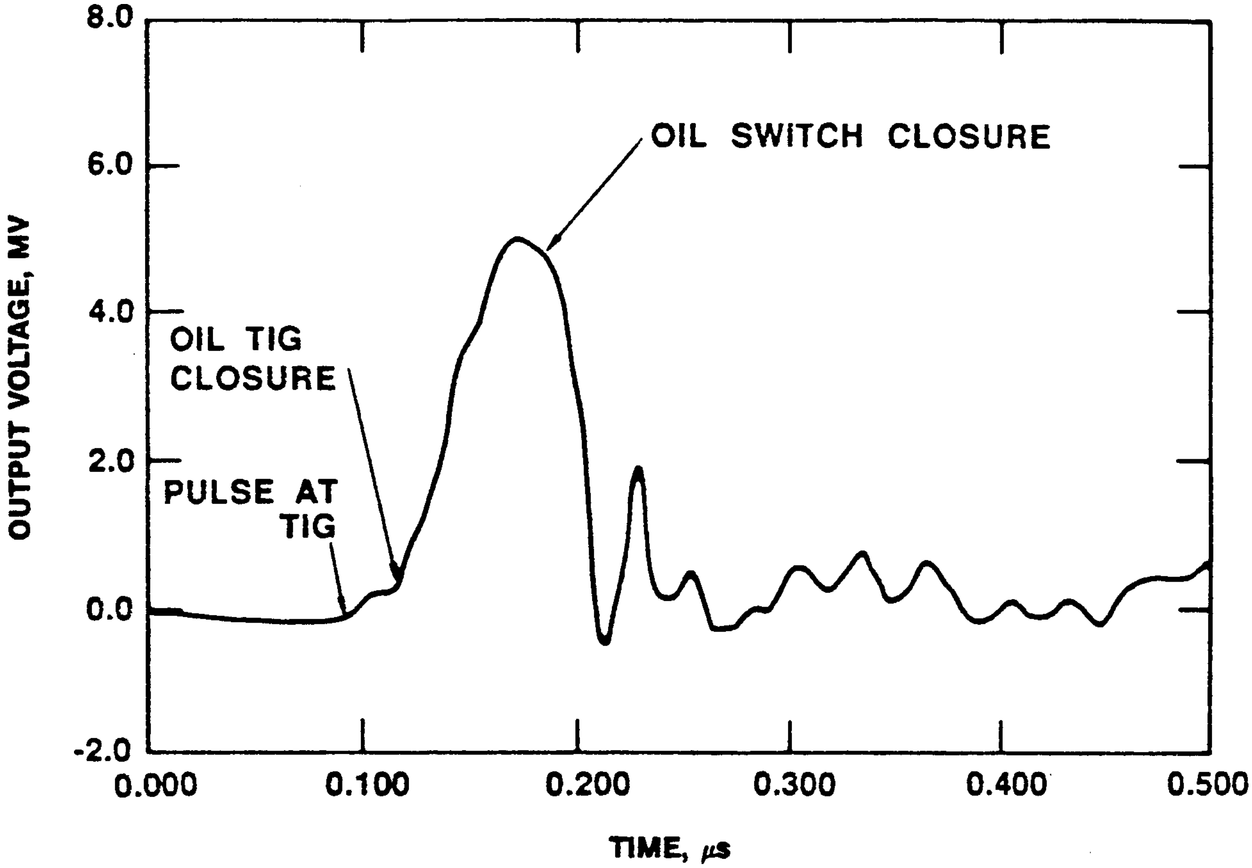

Figure 5.11. Oil switch trigger voltage pulse (integrated D-DOT voltage monitor).

constructed from six 8-inch OD, 20-feet long aluminum tubes connected together at the ends by a 8-inch OD, 6-foot long aluminum manifold section. The tubes and manifolds are separately brought into the inner Blumlein through the hatch then bolted together. The aluminum line is suspended with nylon support rods and positioned with nylon straps connected to the inside walls of the inner line. This transmission line configuration was selected to avert the difficulties associated with constructing a coaxial transmission line arrangement within the inner conductor of the Aurora Blumlein.

The transmission line is charged in 1.8 μs to a voltage between 2 and 3 MV. The closure of the TGS launches a 35-ns risetime, 70-ns-long cancellation wave down the line toward the oil TIG.)

The oil trigger isolation gap (TIG) provides a low capacitance isolation between the charged transmission line pulser and the Blumlein oil switch. This isolation allows the oil switch midplane electrode to electrically float on the a natural equipotential surface existing in the oil switch region. If the voltage of the electrode is substantially disturbed from this natural voltage state, a high electric field will form at the sharp edge of the blade launching oil streamers.

The oil TIG structure consists of one section containing a pair of 3-inch outside diameter, hemispherical brass electrodes and a second section containing ceramic/graphite composition resistors. The electrodes are attached to aluminum endplates using large hex-head draw bolts, providing good current contact. Steel cylinders are sandwiched between the electrodes and the endplates to establish proper TIG gap spacing. The endplates of the structure are supported by six 1.5-inch outside diameter nylon rods. The resistors in the second section, which are connected in series (both mechanically and electrically,) serve to absorb the trigger pulser energy, thereby limiting the charge transfer of the TGS.

The Aurora midplane oil switch is triggered by disturbing the potential of the trigger blade from the natural potential established during Blumlein pulse charge. We have devised a low-jitter, high-voltage pulse generator to rapidly swing the blade voltage. The trigger voltage pulse has two components. The first is the +2 MV output pulse of the XML. The second component results from the low capacitance of the oil switch pulse charging the higher capacitance XML. When the oil TIG closes, the capacitance of the midplane, which is initially charged to -2 MV, rings back into the XML capacitance resulting in a reversal of the blade voltage from -2 MV to +2 MV. These two distinct circuit responses add to result in a -2 MV to +4 MV voltage swing with a 35-ns risetime.

Figure 3 shows the derivative of the oil switch voltage as measured by a D-dot probe located adjacent to the oil switch support stalk. The first bump that occurs 50 ns following the fiducial timing mark represents the arrival of the XML output voltage at the oil TIG. The oil TIG closes 23 ns later and applies the trigger generator voltage to the oil switch. The three distinct bumps in the waveform following oil TIG closure represent the derivative of the actual applied voltage waveform. The large negative spike in the derivative waveform that occurs 143 ns following the timing marker represents the rapid voltage collapse as the oil switch closes. We may infer from this voltage waveform that the delay between the arrival of the XML pulse at the TIG and the closure of the oil switch is 93 ns. Figure 4 shows the integrated D-dot voltage waveform. Each of the three distinct phases, the voltage arrival at the oil TIG, the TIG closure, and the oil switch closure can be easily seen on the waveform.

PULSERAD 737 EXPERIMENTS

During the early development of the low-jitter oil switch triggering concept, we recognized that full-scale testing of an unproven triggering concept on Aurora could be an expensive and risky undertaking. We therefore decided to test the concept at PI in an older radiation facility known as the Pulserad 737. While the hardware that was tested in the 737 was not identical to that which was tested in Aurora, the results of these tests were nonetheless valuable for predicting the Aurora results and for designing the trigger pulser hardware for the Aurora experiments.

The trigger pulser hardware tested in the 737 experiments consisted of a Blumlein pulse-forming line, a SNLA RIMFIRE triggered gas switch, TGS, an oil trigger isolation gap, TIG, and a mock-up of the full-size Aurora oil switch. The trigger pulser was charged using a 2 MV Marx generator and a very large 250 μH series charging inductor. The inductor served to slow the trigger line charge time to approximate the 1.5-μs charge time expected at Aurora. The remaining details of the experimental hardware have been reported previously and will not be repeated here.[6,7,8]

JITTER TEST.

The goal of the jitter measurements was to characterize the jitter of the components of the oil switch trigger pulser. In the 737 experiments, we measured: (1) the delay between the application of the TG-70 trigger pulse to the TGS and the closure of the TGS, (2) the delay between the application of the voltage pulse to the oil switch and the closure of the oil switch, and (3) the delay between the application of the trigger pulse to the TGS and the closure of the oil switch. These measurements were used to calculate the timing jitter of the TGS, the oil switch, and the total low-jitter trigger system. The results of the experiments, summarized in Table 1, indicate that the TGS had around 2-ns to 3-ns jitter, the oil switch had between 0.5-ns and 1.5-ns jitter, and the total trigger system had approximately 4-ns jitter. This 4-ns jitter was much less than the 15-ns to 20-ns value reported for the original trigger scheme.[9] These positive results indicated that low jitter should be achievable at the full 11-MV Aurora potential.

Table 1. Pulserad 737 jitter experiments

Oil Switch Gap	2 in.	2 in.	2 in.	2 in.	3 in.	3 in.	3 in.
Gas Switch Voltage	2.2 MV	2.5 MV	2.8 MV	3.2 MV	2.5 MV	2.5 MV	2.5 MV
% Self-Break	90%	82%	80%	86%	68%	80%	86%
Oil Switch Voltage	3.9 MV	4.4 MV	5.1 MV	5.7 MV	5.0 MV	5.0 MV	6.0 MV
Sample Size	7	8	8	4	12	53	11
Gas Switch Jitter	2.4 ns	2.7 ns	1.8 ns	1.9 ns	-	2.2 ns	3.4 ns
Oil Switch Jitter	.83 ns	.58 ns	.31 ns	.38 ns	1.3 ns	1.5 ns	.45 ns
Total System Jitter	2.2 ns	3.2 ns	1.9 ns	2.5 ns	4.7 ns	3.4 ns	2.7 ns

RESISTOR ELECTRIC FIELD STRESS TEST.

The concept for charging the oil switch trigger pulser when installed on Aurora requires a 900-Ω liquid resistor resistor located somewhere between the intermediate and inner Aurora Blumlein conductors. In order to produce a credible design for this resistor, we needed basic engineering data regarding the allowable electric field stress across a liquid resistor under oil.

To test the charge resistor concept, an 8 inch long, 10-kΩ, $CuSO_4$ resistor was mounted between the intermediate oil switch trigger Blumlein conductor of the 737 facility and the ground plane flooring of the tank. Voltages up to 3.1 MV, with 1.6 μs to peak, were applied to the resistor to simulate the average field expected during charging on Aurora. Four shots were fired with an average electric field across the resistor of 94 kV/cm, 7 shots at 112 kV/cm, 6 shots at 132 kV/cm, and 5 shots at 152 kV/cm. No arcs were observed across either the outside or the inside of the charge resistor tubing. The expected average electric field for the charge resistor in the Aurora application was 100 kV/cm. Since we tested up to 152 kV/cm with no failures, the Aurora design was conservative.

RINGING GAIN TEST.

Circuit simulations indicated at the oil switch voltage would swing from -1.8 MV to 3.7 MV (5.5 MV) with only a 2.5 MV charge voltage. This apparent gain of more than a factor of two is really the sum of two separate circuit responses. The first is the 2.5 MV output pulse of the charged transmission line. The second is the natural reversal of the trigger blade voltage as the capacitance of the trigger blade resonates with the capacitance of the charged transmission line. To assure ourselves that the two responses would indeed add, a ringing gain test of the 737 Facility was performed.

The 737 experiment was reconfigured such that the oil switch would charge to approximately the same voltage as the pulser. A 4-5/8-inch diameter rollup was attached to the sharp blade of the oil switch to spoil the field enhancement so that the switch would not breakdown. The oil switch and the transmission line were pulse charged to -2 MV and the gas switch triggered as usual. Figure 5 shows the oil switch voltage waveform. The voltage is observed to swing from -2 MV to 4.2 MV (6.2 MV) with a 35 ns 10% to 90% risetime. Thus, this test verified that the expected voltage gain should be present on the Aurora design.

OIL STREAMER ANALYSIS.

The relation most recently given for the average streamer velocity is given by:

$$u = \frac{d}{t_{eff}} = 40\, V^{1.3} \quad (1)$$

where t_{eff} is the effective time which is that time between (1) when the voltage exceeds 63% of the eventual breakdown voltage and (2) the breakdown time. Since this relationship has been shown to predict the point-to-plane streamer closure time for linear ramp and 1-cos(ωt) waveforms, it was used in the design of the oil switch trigger pulser hardware. Now that substantial data regarding the breakdown of the edge-plane oil switch gap had been acquired, we decided to determine if this equation did indeed predict the closure time. Knowledge of the equation governing streamer closure for this oil switch case was important to predicting the trigger pulser performance on Aurora. It became immediately clear that the equation is inaccurate for generalized waveforms because of the definition of t_{eff}. We therefore began modifying the equation.

If we substitute K for the constant 40 and α for the constant 1.3, and assume that the gap spacing d is raised to some power ß, then the streamer velocity equation above can be rewritten in the form:

$$\frac{d^{\beta}}{K} = V^{\alpha}\, t_{eff} \quad (2)$$

The voltage-time product is actually an approximation to the integral of the voltage with respect to time, and was originally used as a matter of convenience. Thus, the equation is more accurately written:

$$\frac{d^{\beta}}{K} = \int_0^{t_c} V^{\alpha} dt \quad (3)$$

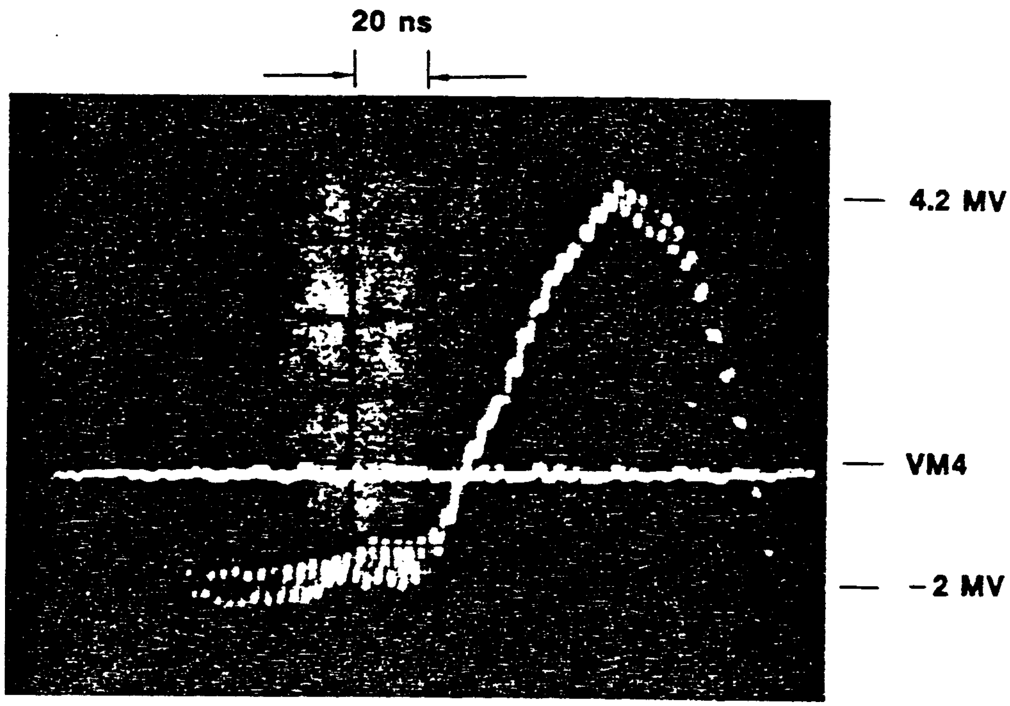

Figure 4.6. Oil switch voltage in ringing gain test.

89-02-101

where t_c is the closure time of the oil streamers. Solving for the constant K we have:

$$K = \frac{1}{\int_0^{t_c} \frac{V^\alpha}{d^\beta}\, dt} \qquad (4)$$

If α and ß are both equal to 1.3, then the equation can be rewritten:

$$K = \frac{1}{\int_0^{t_c} F^{1.3}\, dt} \qquad (5)$$

where F is the average electric field.

The oil switch voltage waveforms for 1, 2.25 and 3.25 inch gap spacings were digitized, the electric field was calculated, raised to the 1.3 power, and integrated with respect to time. These data are plotted in Figure 6. This figure shows that 1 divided by the integral of the average electric field to the 1.3 power is equal to a constant (≈47 with a 7% experimental error) for voltages between 2.5 MV and 6 MV and for gap spacing between 1 inch and 3.25 inches. This equation is much more useful than previous formulations because it establishes a relationship that is true for this particular geometry and it is independent of waveshape. Therefore, Equation 5 was very useful for calculating the streamer closure time for the Aurora oil switch trigger pulser design. The equation gave us greater confidence that the pulse length of the oil switch trigger pulser hardware design for the Aurora single arm test was sufficient to drive the streamers closed.

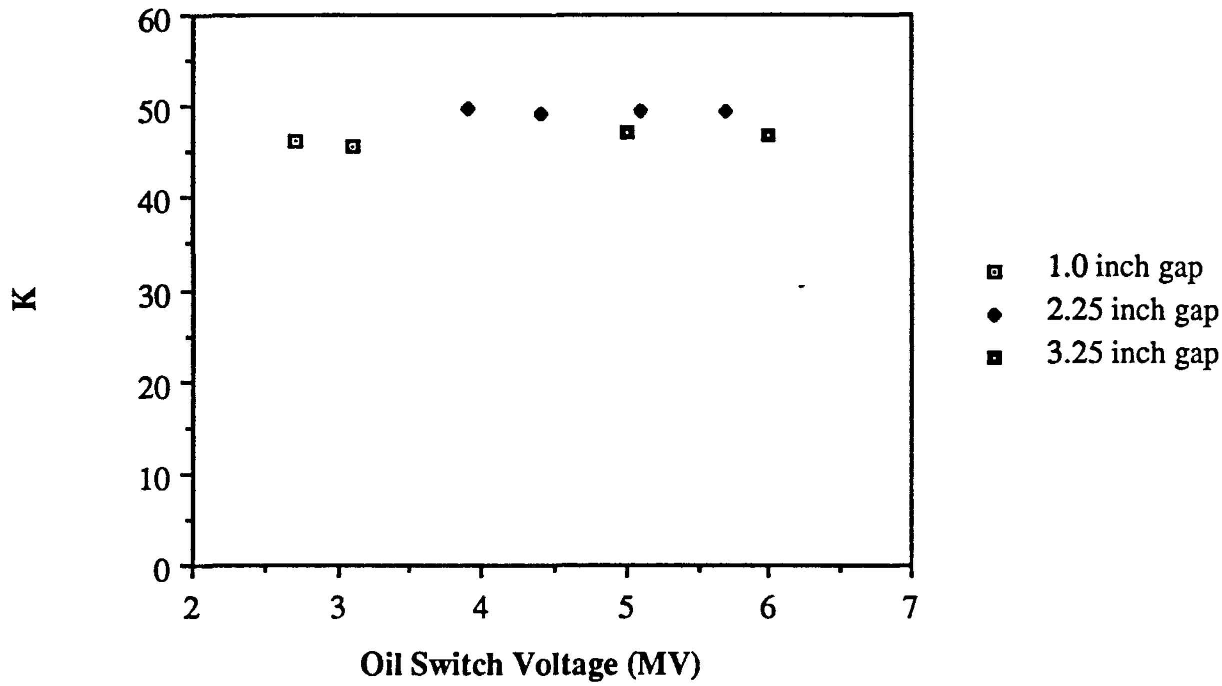

Figure 6. Constant K given by 1 divided by the integral of the average field to the 1.3 power.

AURORA EXPERIMENTS

There were four principal goals of this single arm (Blumlein) tests. First, the nominal operational parameters at various Aurora Marx charge voltage levels had to be established. Thus, we needed to determine the appropriate gas switch pressure, oil TIG gap spacing, and oil switch spacings, required for normal, low-jitter operation at 90 kV and 110 kV. Second, to assess the jitter reducing potential of the trigger system, the jitter (one sigma standard deviation) of the entire trigger system was measured. Third, we needed to characterize the jitter budget of the trigger system. That is, we needed to independently measure the jitter of the gas switch, the oil TIG, and the oil switch to know how the trigger system jitter is distributed. This information would make it possible to control and reduce the overall jitter. The finally goal was to determine the reliability of the hardware in the high-voltage, high-mechanical-shock environment.

The experimental data were collected in two separate testing phases.During the first test phase a total of 44 shots were taken. Of the 44 shots, only three were taken at 110 kV Marx charge voltage; all the rest were at 90 kV. Thus, additional data were required to characterize the operation at 110 kV.

Twelve good 90-kV Marx charge data shots were acquired between shots 22 and 43. The relative delay between the application of a trigger pulse to the low-jitter oil switch trigger pulser and the arrival of the Blumlein output voltage pulse at the tube was recorded as the trigger delay time. These data indicated that the total low-jitter trigger system jitter varied between 5 ns and 9 ns depending on the parameters of the gas switch, the oil TIG, and the oil switch. Since these shots were taken with three different sets of parameters, the average delay time for each data set was different. Thus, the data had to be normalized to make a direct comparison. Table 2 shows the normalized delay of each data set. Shots 22 through 25 werre arbituarily selected as the control group. The delay times of all other data were adjusted such that average for each set would equal to the average of the control group. The jitter was calculated to be 7 ns for the 12 shots. However, even the raw data suggesting a 9 ns jitter compared favorably to the 20-ns jitter reported for the original oil switch trigger scheme. This data suggested that the low-jitter trigger scheme can reduce the timing spread of the output voltage pulses by a factor of three.

Table 2. Trigger delay data normalization (first testing series)

Shot Number	Delay Time (ns)	Adjusted Delay (ns)
22	92.01	92.01
23	93.93	93.93
24	81.66	81.66
25	75.74	75.74
Mean	85.84	85.84
30	92.44	90.11
31	88.95	86.62
32	83.12	80.79
Mean	88.17	85.84
36	78.34	92.77
37	78.52	92.95
38	63.73	78.16
42	61.09	75.52
44	75.39	89.82
Mean	71.41	85.84
Total Mean	80.41	85.84
Standard Deviation	10.66 ns	7.05 ns

The total jitter measurements during the first test indicated that the total system jitter could be substantially reduced by the low-jitter trigger system. The low-jitter trigger system had about a third of the jitter of the original trigger system. There were, however, several areas that displayed electrical arcing activity, requiring further attention. Also, additional data on the operation at different voltage levels was required to completely assess the potential of the low-jitter trigger scheme. Therefore, an additional testing series was required to address these issues.

The second Aurora experiments focused on measuring the component jitter of each of the low-jitter trigger system components and on comparing the jitter of the present trigger scheme with that of the low-jitter trigger system. The specific measurements that were made included: (1) the delay between the application of the gas switch trigger pulse and the closure of the TGS, (2) the delay between the beginning of the oil switch voltage swing and the closure of the oil switch, (3) the delay between the application of the gas switch trigger pulse and the closure of the oil switch, (4) the delay between the application of the gas switch trigger pulse and the arrival of the low-jitter Blumlein output pulse, and (5) the delay between the application of the gas switch trigger pulse and the arrival of the output pulse of a Blumlein that has the original, unmodified oil-switch trigger scheme. These measurements have been used to calculate the timing jitter for the TGS, the oil TIG, the oil switch, the entire low-jitter trigger system, and the unmodified trigger system.

During the second single arm tests, 92 total shots were acquired. Of these, the Blumlein was resistively loaded (no radiation) for 47 shots. Forty-five of the shots produced radiation. Three shots were taken at each of 70 and 80-kV Marx charge. Sixty-nine shots were taken at 90 kV. Nine shots were taken at 100 kV, and eight shots were taken at 110 kV. Reasonable operational parameters were recorded for each of these Marx charge voltage levels.

Table 3 summarizes the results of the second set of jitter measurements. While we have demonstrated operation of the trigger system at all Marx charge voltage levels between 70 kV and 110 kV, nearly all of the jitter measurements to date have been at 90 kV charge. For some of the data at this 90 kV level, the synchronization of the Marx generators was excellent (shots 6460-6471.) However, most of the time the erection jitter was disappointing causing shot-to-shot variations in the voltage applied to the oil switch. To help account for the shot-to-shot voltage variation, the delay data was plotted as a function of applied voltage, a curve was fit to the data, and the jitter was calculated with respect to the curve fit. The jitter in the trigger delay time, for both the low-jitter trigger scheme (σ_a) and the original trigger scheme (σ_b), with and without this voltage fitting are reported in Table 3. The data indicate that in all cases the jitter of the low-jitter trigger system (σ_a) is half that of the unmodified trigger system (σ_b.)

Table 3. Aurora low-jitter trigger pulser experiments (90 kV charge)

Shot Number	PI78-86	PI101-104	PI105-106	PI107-118	6417-6427	6460-6471
TGS Pressure	27 in.	24 in.	24 in.	24 in.	24 in.	-
Oil Sw Gap d1	4 in.	4 in.	4 in.	3.5 in.	3.5 in.	3.5 in.
Oil Sw Gap d2	12 in.	12.5 in.	13 in.	13.5 in.	13.5 in.	13.5 in.
No voltage fit σ_a	33 ns			4.3 ns	6.5 ns	3.3 ns
No voltage fit σ_b	46 ns			11.5 ns	11 ns	4.8 ns
With voltage fit σ_a	7 ns			4 ns	5.1 ns	3 ns
With voltage fit σ_b	10 ns			10 ns	8.5 ns	5 ns

Notes: σ_a is the jitter of the low-jitter trigger scheme; σ_b is the jitter of the original trigger scheme; all data for PI101-PI118 have been averaged together and listed under PI107-118.

A fairly large number of samples is required to minimize the uncertainty in the jitter measurement. A 90% certainty requires approximately 30 samples. None of the data sets above has more than 11 samples. However, the data can be normalized (to remove systematic variations due to changes in parameters) to obtain a larger data set, then the standard deviation calculated for this larger data set. The data in the right-most five columns of Table 3 has been normalized in Table 4. The mean for the normalized data for the low-jitter trigger system (A) is 240 ns with a standard deviation of 4.5 ns. By comparison, the mean for the normalized data for the original trigger system (B) is 213 ns with a standard deviation of 9.5 ns. Thus, the low-jitter trigger system again has half the jitter of the original unmodified trigger system.

Table 4. Trigger delay data normalization for both trigger schemes (second testing series)

Shot Number	A Delay Raw (ns)	A Delay Adjusted (ns)	B Delay Raw (ns)	B Delay Adjusted (ns)
107	247.8	247.8	209.5	209.5
108	243.4	243.4	226.4	226.4
109	238.6	238.6	223.7	223.7
110	246.2	246.2	202.2	202.2
112	232.4	232.4	192.3	192.3
113	241.4	241.4	232.4	232.4
114	235.2	235.2	202.3	202.3
115	238.2	238.2	221.5	221.5
116	238.8	238.8	208.7	208.7
118	237.1	237.1	213.8	213.8
Mean	239.9	239.9	213.3	213.3
6417	248.8	249.4	254.0	225.3
6418	239.6	240.2	255.8	227.1
6421	240.3	240.9	240.8	212.1
6422	230.3	230.9	239.7	211.0
6423	242.0	242.6	249.8	221.1
6424	232.9	233.5	242.1	213.4
6425	246.3	246.9	236.8	208.1
6426	239.3	239.9	240.1	211.4
6427	234.7	235.3	218.9	190.2
Mean	239.4	239.9	242.0	213.3
101	237.8	241.4	228.6	227.4
102	234.2	237.8	214.0	212.8
103	237.0	240.6	217.5	216.3
105	238.6	242.2	204.3	203.1
106	234.0	237.6	208.2	207.0
Mean	236.3	239.9	214.5	213.3
6460	245.8	239.0	241.9	204.5
6461	253.9	247.1	253.7	216.3
6462	247.0	240.2	246.7	209.3
6463	248.9	242.1	256.7	219.3
6464	246.3	239.5	247.7	210.3
6465	241.1	234.3	254.5	217.1
6466	244.1	237.3	250.1	212.7
6468	245.1	238.3	253.4	216.0
6470	246.4	239.6	256.5	219.1
6471	248.5	241.7	245.7	208.3
Mean	246.7	239.9	250.7	213.3
Total Mean	241.2	239.9	232.1	213.3
Standard Deviation	5.7 ns	4.3 ns	19.4 ns	9.5 ns

Note: A = Low-jitter oil switch trigger system, B = Original trigger scheme

The normalized trigger delay data of Table 4 can be plotted as histograms to yield further insight into the character of the distributions. Figure 7 and 8 show the resulting histograms for the low-jitter trigger scheme and for the original trigger scheme respectively. For the histograms, the delay time values have been sorted into 2 ns windows and the number of shots having delay times within these 2 ns "bins" are plotted against the bins. For example, 2 shots in the A adjusted column have delay times between 233.0 ns and 234.9 ns. Thus the 234-ns bin for the low-jitter trigger scheme histogram has a value of 2.

The distribution for the low-jitter trigger scheme, shown in Figure 7, has a shape approximating the normal or Gaussian distribution. This indicates that the variations are essentially random about the central mean. By comparison, the distribution for the original trigger scheme, shown in Figure 8, shows a marked tendency toward long trigger delay times. That is, an inordinate number of shots exist with closure times longer than the mean. We do not know why this long runtime tendency exists. The narrow distribution of the low-jitter trigger system, as compared to the original trigger scheme, further supports the factor of two reduction in trigger jitter (4.3 ns versus 9.5 ns) shown in Table 4.

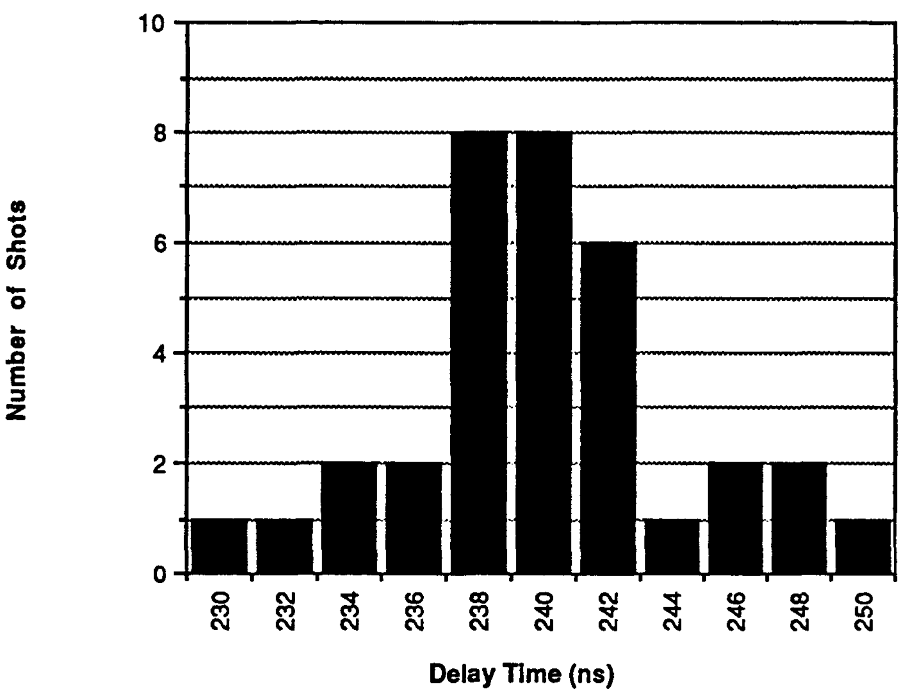

Figure 7. Low-jitter trigger scheme normalized delay histogram

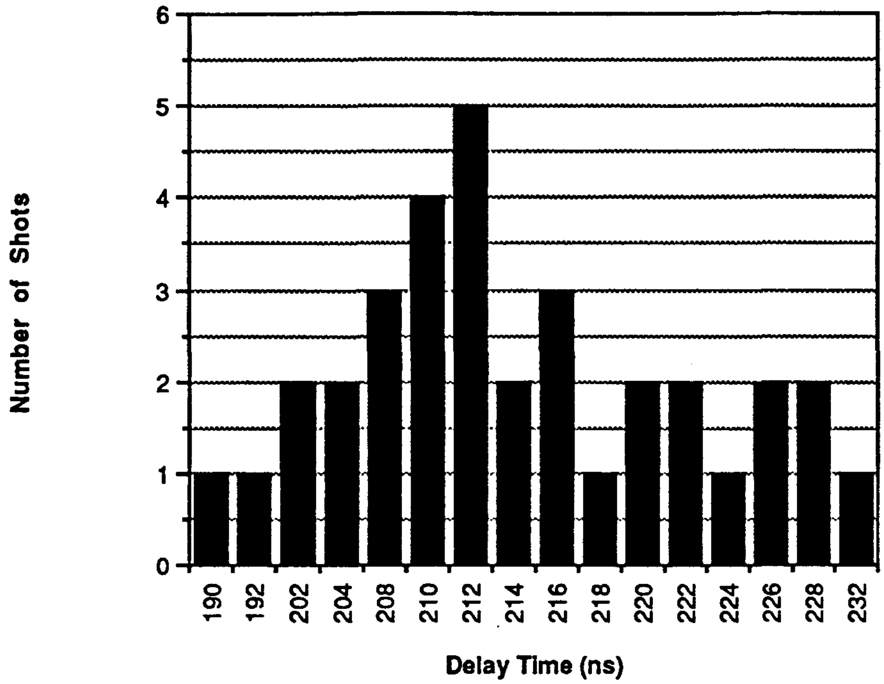

Figure 8. Original trigger scheme normalized delay histogram

Photographs of the oil switch streamers were taken during the jitter measurements. Figure 9 shows the streamer photograph for a 16-inch total oil switch gap spacing (d2 = 12 inches and d1 = 4 inches). This view shows approximately 1/3 of the circumference of the switch. Note the abrupt discontinuity located 1/3 the way from the left edge of the photograph representing the thin trigger blade. Quite a large number of streamers close from the blade to both sides of the switch. The large number of streamers indicates that the trigger pulser is suppling a fast-risetime pulse to the blade and that the closed inductance of the switch should be reasonably low.

CONCLUSIONS

The original goal for the low-jitter oil switch trigger scheme was to reduce the triggering jitter of the Aurora oil switches to 10 ns or below. The data in Table 3 and 4 indicate that the jitter for the A Blumlein (σ_a = 5 ns) is significantly lower than this 10-ns goal. However, the jitter of the original B Blumlein has been reduced to this 10-ns level. This has raised the question of if the low-jitter trigger scheme is really required to meet Aurora's synchronization goals. The decision on whether to install three more low-jitter oil switch trigger pulsers is awaiting additional assessment.

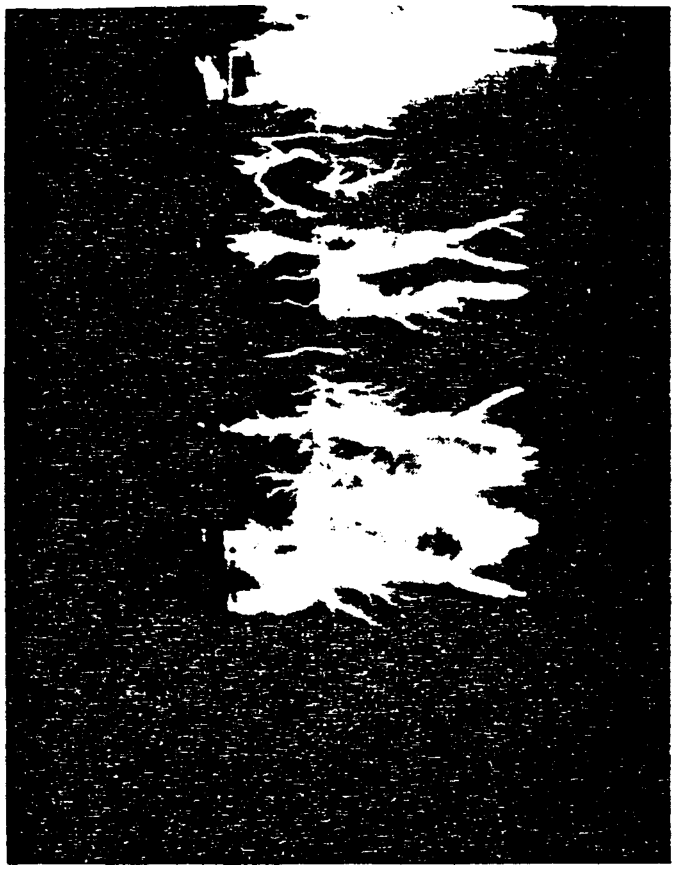

Figure 5.14. Open-shutter photograph of streamers on a 16-inch oil switch gap (d_1 = 12 inches, d_2 = 4 inches) on the Harry Diamond Laboratory Aurora facility.

REFERENCES

1. B. Bernstein and I. Smith, "AURORA, An Electron Accelerator," IEEE Transactions on Nuclear Science, NS-20, pp.294-300, June 1973.

2. Aurora Switch Upgrade Design Study, PIFR-3525, March 1986.

3. B.N. Turman, D.R. Humphreys, J.F. Seamen, K.R. Prestwich, R.A. Hamil, T.H. Martin, F.T. Warren, G. Frazier, "Design Study for a 12 MV Low-Jitter Switch for Aurora," Sandia Report SAND86-0061, August, 1986.

4. Aurora Oil Switch Upgrade Program, PIFR-3620, March, 1989.

5. Aurora Second Single Arm Tests, PIFR-4032, March, 1989.

6. D.D. Bloomquist, et al., "SATURN, A Large Area X-ray Simulation Accelerator," Proceedings of the 6th IEEE Pulsed Power Conference, Arlington, VA, pp. 310-317, June, 1987.

7. B.N. Turman, D.R. Humphreys, "Scaling Relations for the Rimfire Multi-Stage Gas Switch," Proceedings of the 6th IEEE Pulsed Power Conference, Arlington, VA, pp. 347-353, June, 1987.

8. F.T. Warren, Jr., G.B. Frazier, D.P. Simmons, J.F. Seamen, B.N. Turman, and K.R. Prestwich, "Design and Development of an Improved Aurora Blumlein Oil Switch Trigger System," Proceedings of the 6th IEEE Pulsed Power Conference, Arlington, VA, pp. 343-346, June, 1987.

9. Aurora Facility Development Program, Phase III Final Report, Volume II: Aurora Test Program, PIFR-225, October, 1974.