1995 Pulse Power Mtg

REPRODUCIBLE PULSES FROM AN IMPROVED OIL SWITCH ON AURORA

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Abstract

The blumlein switch on Aurora has been improved over the years. We describe recent developments and the latest version of this switch. Excellent results are obtained with a half-size (50 cm diameter) trigger electrode that initiates only a single arc in the oil. Placing the arc in the symmetry plane of the downstream prepulse switch, and using only two of its self-breaking arcs, gives output pulses that are reproducible almost to within measurement error.

Introduction

Aurora[1] is a nominally 12 MV electron accelerator originally intended for flash γ-ray production. Its four parallel oil-filled Blumleins generate four separate electrical pulses, each with nominally ~ 50 ns risetime, 120 ns width, 300 kA peak current, and total energy just under 0.5 MJ. The original design can, with careful operation, create pulses whose total dose per shot is the same[2] to within 2%, with peak dose rate within 5%. Also, the time window for the four different pulses can be as low as 10 ns, about 5% of the typical 200 ns needed for the switch to close.

Improving the reproducibility of each separate pulse, and reducing the jitter between pulses, is important for most upgrades implemented on or contemplated for Aurora. These include a faster pulse risetime by eroding the front end of the pulse,[3] and shortening the pulse by chopping its tail with a self-breaking oil diverter.[4] On a single line the best pulse obtained to date[3] has a 3 ns risetime and a 30 ns pulse width.

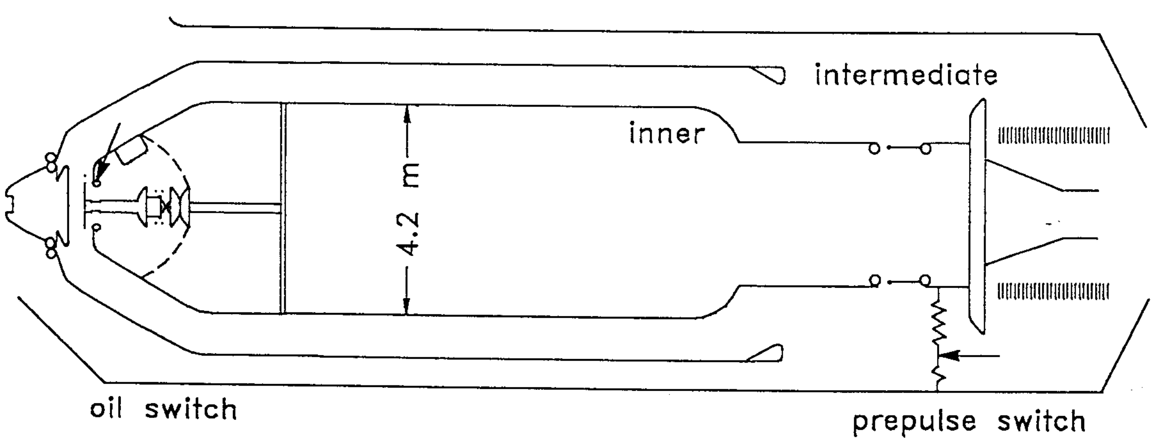

Figure 1. Aurora's blumlein geometry.

Figure 1 depicts Aurora's blumlein. It consists of 3 nested conducting cylinders with respective diameters 7 m, 5.6 m, and 4.2 m. The intermediate and inner electrode are closed off on the side of the switch, except for a 0.75 m radius hole (not shown) in the intermediate electrode (for mechanical support of the inner electrode), and a 0.7 m diameter hole for the oil switch trigger in the inner electrode. On the other side the inner cylinder sticks out 1.8 m beyond the intermediate with a reduced diameter of 2.75 m. Oil gives the entire volume a relative dielectric constant $\varepsilon_r \simeq 2.3$.

Pulse timing and pulse shape reflect the resistance and inductance of the various switches in pulse power chain. After the marx the first switch is the blumlein closing switch. Optimization of the switch, including triggering with an improved trigger pulse and a single trigger pin, is discussed in another paper.[5]

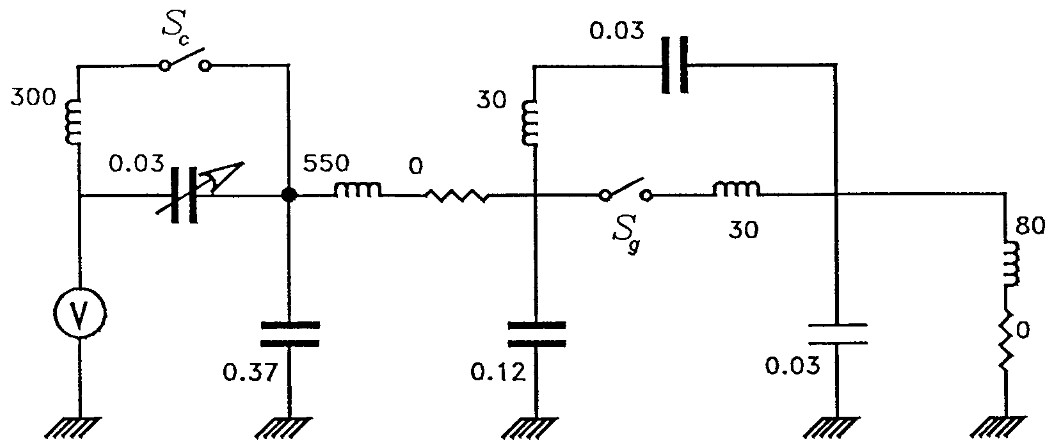

Figure 3. Equivalent circuit for the trigger.

Figure 2 is a typical $\dot{V}_t$ for a positive polarity shot, 8822. Nothing is visible during the pulse charge, because $\dot{V}_t$ is too low. At $t = 0$ the switch triggers, creating an oscillation on the trigger electrode that starts arcs in the oil. After about 300 ns the arcs connect the trigger to the high voltage, and the trigger voltage changes increases rapidly. Immediately ($\lesssim$ 20 ns) thereafter the voltage drops precipitously because arcs connect the trigger electrode to ground.

Figure 3 is an equivalent circuit for the switch, with the values for the various circuit elements in nF, nH, and Ω. Careful matching of the circuit elements to the data, see Ref. 5, gives excellent agreement with the data at least until the end of the trigger phase, when the arcs comes into play.

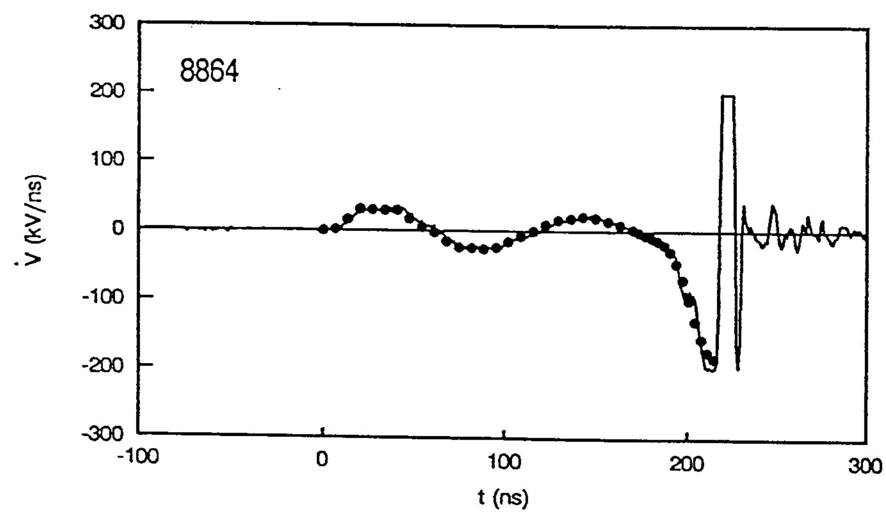

Figure 4. Arc phase of trigger voltage.

The arc dominates the trigger circuit only close to breakdown. Figure 4 is $\dot{V}_t$ for a negative polarity shot 8864, on a scale that emphasizes the switch closure phase (compare Figure 2). The arc current is evident from the sharp increase in the $\dot{V}_t$ signal on the trigger electrode. The circuit element for this is the switch S_c, a resistance $R_c(t)$ that varies with time as some model. In series must be an inductance, because the arc looks like a long, thin conductor. For a single arc with 0.5 m length the inductance $L_c \simeq 300$ nH, corresponding to $L_c \simeq \mu_0/2\pi \ln r_a/r_r$ with arc radius r_a and return current radius r_r such that $\ln r_a/r_r \simeq 3$.

The oil switch resistance is represented reasonably well by the same switch model[9] that was successful in accounting for the resistance behavior of the gas switch.[5] However, for the oil switch the resistance decreases

The present account concentrates on the output pulse shape resulting from the improved switch. These two papers represent the latest developments in attempts to improve Aurora's blumlein switch.[2,6,7]

The original blumlein switch configuration has a 1 m diameter trigger electrode with a sharp edge, and a moderately fast rate of rise for the trigger voltage. The present configuration has a rounded trigger electrode about half the size, 0.5 m diameter, with a pointed rod sticking out vertically, and a faster rate of rise. The triggering rod is intended to initiate an arc in a predictable and symmetric manner.

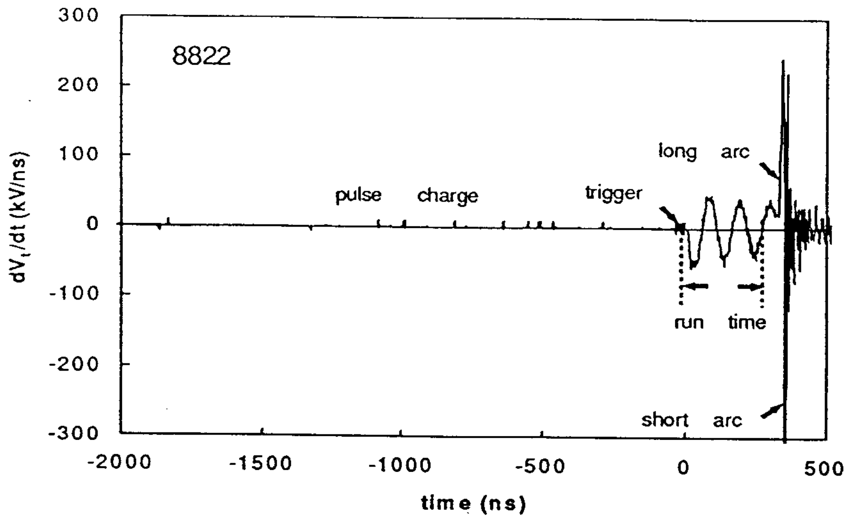

Figure 2. Overview of trigger $\dot{V}_t$ (positive polarity).

The motivation is the following. The pulse would be perfectly reproducible if the switch were to close through a single wire, with a reproducible position and a reproducible resistance. An arc is but an imperfect approximation to such an ideal switch, because the arc meanders about in the oil without apparent rhyme or reason. Moreover, arcs initiated by a circular trigger electrode rarely strike at the same azimuthal position(s) on the inner blumlein. Azimuthal position affects the timing and also the pulse shape, since the time delay from one side of the 0.5 m radius switch to the other is about $\pi R \simeq 1.5$ m, or 7 ns. Electromagnetic waves set up by different arc channels interfere to make the final pulse, which gets a complicated wave front. By implication, the most reproducible pulses should be generated by a single arc that strikes in a fixed position.

Discharge through a single arc limits the rate of rise of the pulse on the blumlein. However, the early part of this pulse is not seen on the output because the prepulse switch is in the way, see Figure 1. For this reason a single arc in the blumlein switch has no risetime penalty on the output pulse, whose rise time is given by the prepulse switch. A single arc in the blumlein switch does affect the prepulse, which comes from capacitive coupling across the prepulse switch. On many machines the capacitive coupling is reduced by additional hardware, and similar modifications could be made on Aurora.

In theoretical analyses of the V/n switch the electric field at the trigger's edge is considered to be an important ingredient of triggering. However, in our experience the edge can be sharp or dull, close to electrostatic equilibrium or not so close, without an obvious effect on switch operation. The optimum switch trigger electrode on Aurora tested up to now, a 0.25 m radius disk with a dull edge that supports a 5 mm radius pin sticking out radially for 0.1 to 0.15 m, could not work if electrostatic equilibrium of the trigger electrode were essential.

Measurements.

Figure 1 gives the position of the monitors by the arrows. A resistive divider looks at the output pulse, at the far end of the prepulse region between the output electrode and ground. Capacitive probes monitor the time derivative of the voltage on the oil trigger electrode, $\dot{V}_t$. For timing accuracy the preferred signal is $\dot{V}_t$ itself, not an integrated $\int dt \dot{V}_t = V_t$. Our $\dot{V}$'s consist of a 1/2" thumbtack epoxied into an HN connector. Time limitations made it impossible to get the calibration accuracy better than 25% or so. Fortunately, the calibration is not needed for determining switch reproducibility and closure time,[5] but it affects the absolute values of voltage, current and especially power or energy.

with increasing energy input as

$$\frac{dR}{dt} = -\frac{1}{W} R^2 I^2 \times (1 - \frac{R_\infty}{R}),$$

proportional to the power $I^2 R$ but with an additional single power of resistance on the right (compared to R^2 for a gas switch). The result is an exponential decrease of the resistance from an initial value R_a to R_a/e after depositing a characteristic energy W. The resistive time τ_a is $\tau_a = W/P$, where P is the typical power dissipation $P = V_a^2/R_a$ in the arc at the initial time, when the voltage across the arc is V_a. Eventually the resistance asymptotes to R_∞, here 5 Ω: this low resistance is not reached in the modeling because the corresponding $\dot{V}_t$ exceeds the measurement limits.

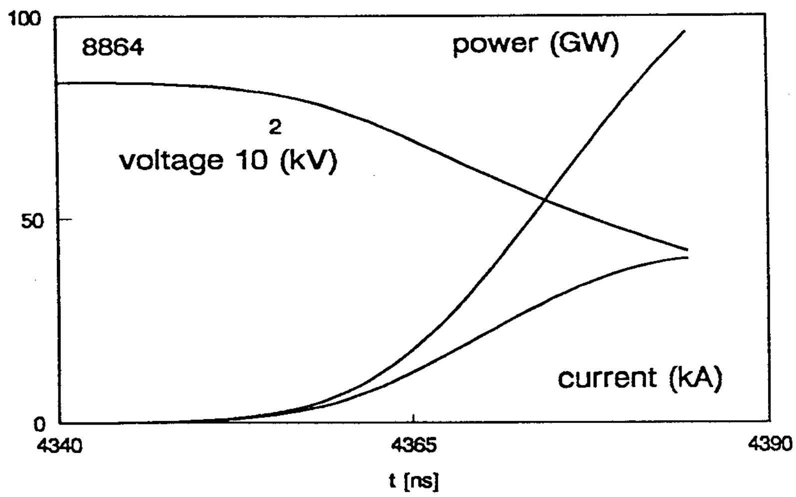

Figure 5. Electrical properties of an arc.

Figure 5 splits out the arc's electrical parameters for shot 8864. It takes about 10 ns for the arc current to increase an order of magnitude, from 1 kA at 4350 ns to about 8 kA at 4360 ns. The 10 ns time scale is comparable to the natural response time of the voltage on the trigger, $\tau \simeq \sqrt{L_c C_t} \simeq 12$ ns. During this time the arc resistance decreases from about 10 kΩ to 1 kΩ, with a power input increasing from 8 to 100 GW and a total energy about 1.5 kJ.

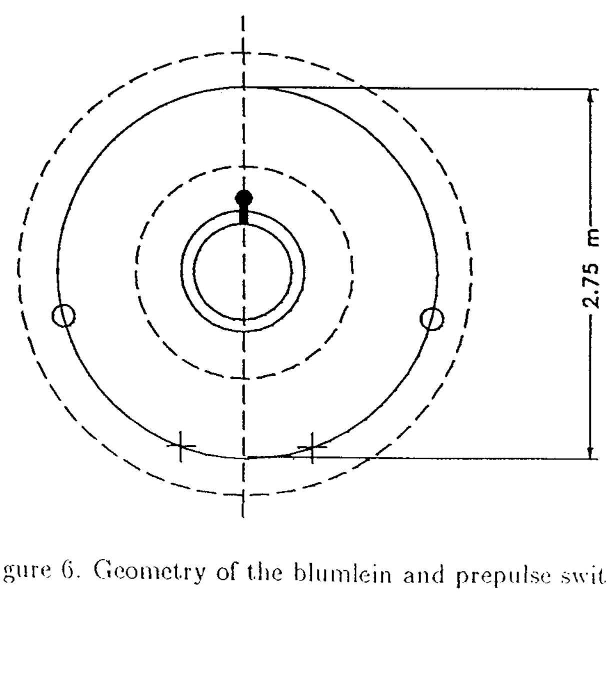

Figure 6. Geometry of the blumlein and prepulse switches.

Two or more parallel arcs that are trying to close are unstable. While one arc already conducts to the trigger electrode, and the voltage difference between trigger and high voltage electrode decreases, another arc may still be trying to close. Small timing differences between arcs would then affect the arc resistances and the subsequent blumlein discharge.[10] Timing problems from multiple parallel arcs can be avoided by triggering only a single arc.

Single arc closure.

Closure with a single arc may be unacceptably inductive for the rise time requirement on a low-impedance machine, but there is no rise time penalty on Aurora, whose impedance is 10's of Ω. A single arc's location can be chosen to get the best output pulse.

Figure 6 projects Aurora's blumlein along its axis, parallel to the paper in Figure 1. The largest dashed circle is the widest part of the inner blumlein electrode, while the smallest dashed circle gives the radius of the conical section close to the switch (compare Figure 1). The solid circles give the size of the hole in the inner blumlein at the switch, and the size of the prepulse switch at the output end of the blumlein. The smallest solid circle is the trigger electrode, with the trigger pin indicated by the thick vertical line. The arc comes from the solid dot at the top. The trigger capacitance is now smaller, only 0.012 nF, allowing for a faster trigger pulse.[5]

In the prepulse switch the original design has 12 parallel untriggered switches. The multiple current paths are intended to reduce the inductance as much as possible. However, multiple parallel current paths again enable unstable development of one arc over another. Therefore, the most reproducible pulse should use only two breakdown points. These are best placed symmetrically with respect to the single arc in the blumlein switch, spatially separated and more or less in the horizontal symmetry plane (the solid dots) or close together and out of the horizontal plane of symmetry (the crosses).

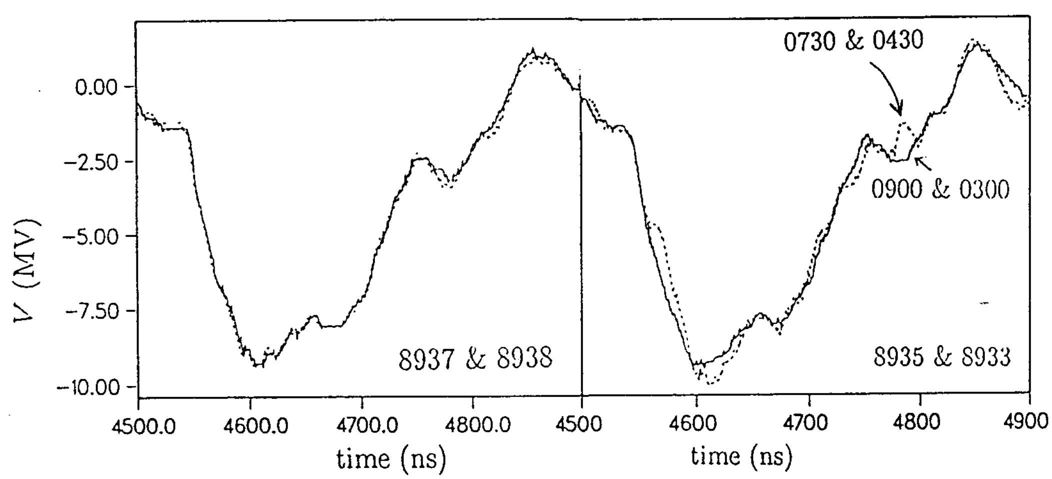

Figure 7. Voltage wave forms with a single arc oil switch.

The left side of Figure 7 overlays the voltage of two output pulses, with the prepulse switch at the solid dots. The wave shape is highly reproducible, with all wiggles seen on all pulses. The command jitter is about 10 ns. The right side of Figure 7 illustrates the effect of the prepulse switch. The solid line is another shot (8935) with the prepulse switches in the horizontal symmetry plane at 3 and 9 o'clock, the same configuration as on the left. The dashed line is for a previous shot, 8933, where the two active prepulse switches were below the horizontal symmetry plane around 6 o'clock, at the crosses. The resulting hiccup during the pulse rise is reproducible. The hiccup's timing corresponds approximately to an rf cavity oscillation in the prepulse region. Apparently, maintaining the symmetry of the different switching elements helps in getting good pulses.

The left part of Figure 8 is the dose rate $\dot{D}$ from a test of the original switch, shots 7986 to 7992. These pulses are quite satisfactory, but with a single arc the pulses are substantially better. The right

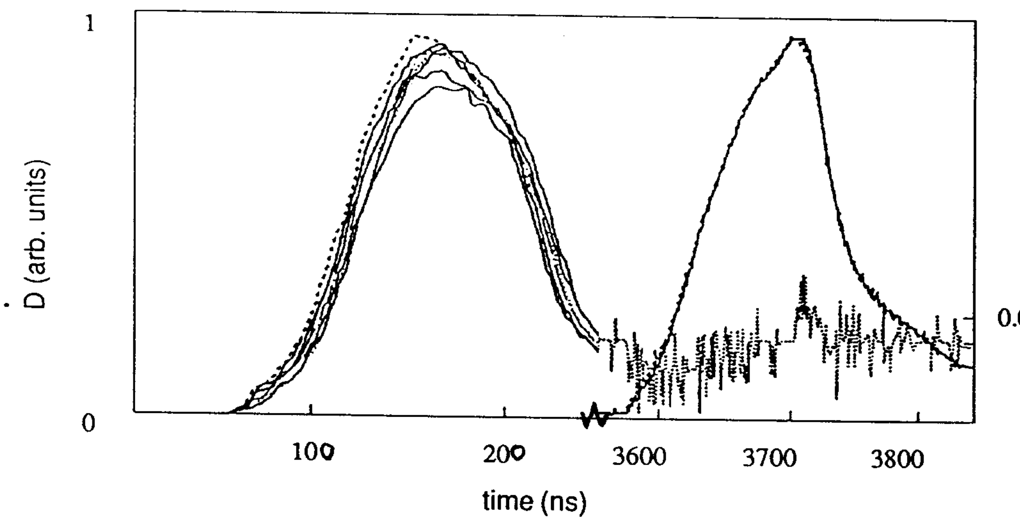

Figure 8. Radiation pulses with multiple arcs (left) and with single arc (right).

part of Figure 8 shows the dose rate on the two shots (8972 and 8973) with the single-arc switch and a symmetric prepulse switch. As expected from the voltage wave forms, the radiation pulses are now almost identical. The difference between the dose rates, the dashed line at the bottom on the scale at right, is around 2% at 3600 ns but otherwise in the noise. Part of the slow rise time is a feature of the available instrumentation, but another part may reflect the limited number of channels in the prepulse switch. Future work, or implementation of similar modifications at other machines, might resolve this issue.

Acknowledgements.

It is a pleasure to thank Dr. G. Merkel (ARL) for triggering this work, Dr. J. Agee (HDL) for the initial support, and Mr. J. Corrigan for his indulgence. Early contributions by Dr. K. Stricklett (NIST), D. M. Weidenheimer (BRA), and cheerful help with data handling by D. C. Judy (ARL) are gratefully acknowledged. Special thanks go to A. R. Poirier and his Operations and Maintenance crew for their tremendous cooperation. The initial research was supported by DNA and the Army's Productivity Improvement Funds, with later support from BRA's IR&D.

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