RISETIME SHARPENING USING MAGNETIC INSULATION IN THE AURORA DIODE

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ABSTRACT

Theoretical calculations indicate that Aurora diode geometrical reconfigurations that delay the onset of magnetic insulation should yield a decreased risetime. Experimentally these diode modifications have resulted in a decrease of the beam risetime from approximately 80 ns to 20 ns.

I. INTRODUCTION AND EXPERIMENTAL ARRANGEMENT

Consider the Aurora diode geometry shown in Figure 1[1-6]. The diode can be modified to include anode falsework as shown in Figure 2.

Figure 1. Cylindrically symmetrical Aurora diode fed by coaxial vacuum line connected to Blumlein triaxial transmission line. The second bend in the coaxial line points the diode axis parallel to the test cell floor. The transition region between the vacuum coaxial MITL and the oil-filled Blumlein region is not a good impedance match.

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Figure 2. Top view of diode geometries with and without falsework. The two spatial distributions of the five scintillation counters are also shown.

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Analytic calculations and particle-in-cell (MAGIC) computer calculations indicate the characteristic time scale for this transition will be much faster than the risetime associated with the usual Aurora diode operation. Figure 3 shows a measured MITL voltage pulse shape in the region of the diode.

**II. THEORETICAL DISCUSSION**

An examination of the voltage and current waveforms for the Aurora diode (Figure 3) indicates that the risetime of the primary pulse is typically around 90 ns. An examination of the photodiode data of the companion paper[9] indicates that risetimes of the order of 20 ns can be achieved by drifting the beam in air at pressures of nominally 50 mTorr. However, if it were possible to reduce the injected beam risetime to approximately 20 ns, the beam drifting techniques could further decrease the beam risetime into the desired range. Since the Aurora cathode stalk operates in a magnetically-insulated fashion, and since magnetic insulation is known to provide some beam-front erosion of an electromagnetic pulse under certain conditions, the possibility of decreasing the beam risetime through the use of magnetic insulation physics has been theoretically and experimentally investigated.

Magnetic insulation techniques have been investigated by Busby, et al.[10]. These workers covered the cathode surface of the MITL with velvet cloth in an effort to achieve pulse-front erosion. Unfortunately, the Aurora voltage risetime is so long (~90 ns) that emission can always occur in the A-K gap at early times. Thus, a fast rising, linearly eroding, magnetically insulated pulse is not launched down the vacuum coax, and the velvet cloth is ineffective. For this reason, we have concentrated on magnetic insulation control in the diode region only.

Consider the simplified Aurora diode geometry which has been modified to include anode falsework in Figure 4. A relatively simple calculation employing the geometry and dimensions shown in Figure 4 yields insight into the usefulness of the falsework.

![Figure 4. Schematic diagram of the modified Aurora diode showing anode falsework for beam risetime control.](image)

As already indicated, the purpose of this anode falsework is to divert electron flow in the diode region into the radial direction at early times. Finally, at some later time, the magnetic field will exceed the critical value for magnetic insulation, and a non-adiabatic transition to predominantly axial flow will occur. The characteristic time scale for this transition hopefully will be much faster than the risetime associated with the usual Aurora diode operation. Gas transport should then serve to further decrease the risetime[2-6].

Clearly, we require \( d_r < d_c \). More particularly, at early times in the pulse when the current is so low that magnetic bending of the electron orbits can be neglected, we require that space-charge-limited emission from the axial cathode face be much less than the space-charge-limited radial emission. An approximate expression for the current density in a one-dimensional relativistic diode with spacing \( d \) between anode and cathode is [2]

\[
j = \left(\frac{3^{1/2}}{16\pi}mc(e)[(\gamma^2 - 1)^{1/2}/d^2. \right)
\]

Using the dimensions shown in figure 4, we roughly have

\[
I_r \sim 3^{1/2}(mc^2/e)(\gamma^2 - 1)^{1/2} \left(\tau_\Delta r/d_r^2, \right)
\]

\[
I_r \sim 3^{1/2} (mc^2/e)(\gamma - 1)^{1/2} \left(\tau_w/d_r^2, \right)
\]

and \( I_r << I_\perp \) is required, or

\[
(\Delta r/d_r^2) << (w/d_r^2).
\]
Provided this condition is met, the impedance of the diode will be due to the radial current flow, or

\[ Z = (\gamma-1)mc^2/eI_r = 3^{1/2} (\gamma-1)(\gamma^2 - 1)^{-3/2} (d/e)^2/\gamma. \] (5)

Note that this impedance (apart from transit time effects) can always be made smaller than the MITL impedance.

The transition from radial flow to axial flow should occur when the azimuthal magnetic field associated with the axial current flow in the cathode shank \( (B_\theta = 2I_c/mc) \) exceeds the critical field for magnetic insulation. The assumed diode voltage waveform is given in Figure 6. Note that at early times in the pulse the cathode shank is not magnetically insulated. While the emission is primarily radial, almost all the beam current appears at the anode foil. At higher voltages, the shank begins to emit, but the current is also higher and the flow is well-insulated. Since essentially all electrons emitted strike the anode, regardless of their time of emission, the beam current trace will generally follow the rise of the voltage pulse and the beam risetime will thus be about 90 ns.

\[ B_\theta = (mc^2/eI_r)[2(\gamma-1) + (\gamma-1)]^{1/2}. \] (6)

Roughly, the transition should occur when \( B_\theta > B_\gamma \), or

\[ (4/3)(\gamma^2 - 1)(\gamma^2 - 1)^{1/2} > (d/e)^2. \] (7)

In order to test these hypotheses, several particle-in-cell calculations were performed. These results are briefly summarized here for illustrative and comparative purposes. The usual Aurora diode configuration consists of an annular doughnut-shaped cathode with a major radius of about 25 cm and a minor radius of about 2.5 cm. A-K gap spacings can be easily varied over a 10 cm range from about 28 cm to 38 cm. For the case of this standard configuration, MAGIC particle plots at several different times in the pulse are presented in Figure 5 for reference.

\[ \gamma^2 = 1 + (\phi e/mc^2). \] An analysis of Equation (7) indicates that \( d/e \sim 0.8 \) should significantly decrease the risetime by erosion of the front end of the pulse, prior to magnetic insulation.

Figure 6. The assumed voltage waveform for the MAGIC simulation of figures 5 and 8.

In order to substantially decrease the beam current risetime, the transition to magnetically insulated electron flow should occur during the voltage rise near the peak of the diode voltage. Figure 7 shows a plot of the left hand side of equation 7 versus the relativistic parameter \( \gamma^2 \). A plot of the left hand side of expression 7.

\[ \gamma^2 = 1 + (\phi e/mc^2) \]

Figure 7. Plot of the left hand side of expression 7. The relativistic parameter \( \gamma \) can be expressed in terms of the diode voltage \( \phi \).
This prediction was checked with additional MAGIC calculations in which the axial A-K gap was held fixed at 26 cm and the cathode major radius was held constant at 25 cm. Anode falsework was then extended back from the anode foil over a range of axial distances and radii. The results of five representative simulations are shown in figure 8. An examination of these results indicates that for \( d/w \approx 0.5 \), the radial gap is too small and a significant amount of current is lost to the radial anode boundary during all of the voltage pulse. For \( d/w \approx 1.0 \), however, the radial gap is too large and too much current flows to the anode foil too early in the pulse. In addition to the standard annular cathode, an L-shaped cathode was tried in order to reduce the field enhancement.

Figure 8. MAGIC PIC code trajectory plots for 5 different cylindrically symmetric Aurora diode configurations. The dimensions corresponding to the parameters \( d_r \) and \( w \) are shown in figure 4. The top 3 cathodes are annular or doughnut-shaped.
at the cathode surface in the axial gap region. Somewhat better results were observed, although the differences were not large.

In summary, the qualitative features of the anode falsework design were observed in the MAGIC simulations, although the agreement with the simple one-d models of electron flow must be regarded as somewhat fortuitous. Nevertheless, the results of the simulations indicate that significant reductions in beam current risetime (< 20 ns) should be possible.

III. EXPERIMENTAL DETAILS

A. Exit Port Distributions

Based on the above analytical and computer analyzed results, a series of experiments were performed using the anode falsework approach in an effort to reduce the risetime of the beam current. The time variation of the beam current exiting normally from the 0.15-cm thick steel exit window was measured with five photodiode

Figure 9 Representative photodiode traces for the Aurora doughnut-shaped cathode with a 15-in. A-K gap.
scintillation detectors approximately evenly spaced radially on a horizontal line across the 30-in diameter window. The spacing between individual detectors was eight inches, with the middle detector located at the approximate center of the anode window (Figure 2a). The edge detectors (#1 and #5) were located near the outer edge of the exit window. The individual detectors consisted of 1-inch diameter, 1/8-inch thick Pilot B scintillators placed at the end of 12-inch long aluminum collimation tubes. An 8-inch length of each tube was embedded in lead, with the unshielded 4-inch portion of the tube protruding toward the exit window. Representative photodiode measurements are exhibited in Figure 9 (experimental arrangement shown in Figure 2a) for several values of the Marx generator charging voltage. The general features of the five data sets are very similar, and the behavior is consistent with the simulation predictions. Beam current rises first in the outer photodiodes, as evidenced by a sharp spike at the start of the pulse. Note that this first sharp spike is almost totally absent on the center photodiode (PD3). Evaluating the radial profile of the integrated beam current gives a beam current risetime of greater than 50 ns.

B. Test Cell Measurements

Additional shots were taken using a different detector arrangement (Figure 10) in which three photodiodes (1, 2, and 3) were positioned at one meter axial distance from the beam exit port, and three more photodiodes (4, 5, and 6) were placed about two meters from the beam exit port. Photodiodes 2 and 5 were centered on the cylindrical exit port axis, while 1 and 4 were roughly one meter to the right of the axis, and 3 and 6 were one meter to the left. Several different cathode-anode falsework combinations were examined. While there are differences in these data, they are not large. In general, of the combinations that were tested faster risetimes were achieved with larger A-K gaps, and larger cathode-anode falsework overlap. In addition, significant risetime deterioration was observed when the Marx charge voltage decreased below 90 kV. The shortest observed risetimes were in the range of 16-22 ns as seen in Shot 6408 in Figure 11.

Figure 10. Experimental arrangement for measuring spatial and temporal dose rate distribution.
IV. PRESENCE OF RIPPLE

An examination of the photodiode data indicates the presence of ripples in almost every trace. An example of a ripply voltage waveform is shown in Figure 12. It clearly shows a rather jagged voltage rise. Presumably this fluctuating signal results from impedance mismatches in the Blumlein-MITL transition region. In fact, circuit simulations of the Aurora diode performed by Hutlin (ARL)[11] indicated this same behavior. The presence of these voltage ripples is potentially serious for all risetime shortening techniques, because of the tendency to produce small precursor pulses.

Reference 6 discusses much more extensive and accurate B-dot and electric field measurements in the magnetically insulated coaxial line leading to the diode region. Extensive work has also been done on yielding a consistent shot-to-shot pulse shape from the Blumlein section of the Aurora. These results should make it possible to make a rigorous comparison between PIC code prediction and experiment.

V. COMBINED DRIFT TUBE AND FALSEWORK RISETIME ENHANCEMENT

Finally, drift tube risetime enhancement was combined with falsework risetime enhancement. Figure 12 also shows a risetime measurement of a pulse that has been produced by combining falsework risetime with drift tube risetime enhancement. Unfortunately the 10 ns risetime is very sensitive to the pre-sharpened wave shape and magnitude and, therefore, a clean 10 ns risetime cannot always be obtained. Shot to shot reproducibility is very sensitive to Marx charging voltage reproducibility.

![Figure 11. Experimental photodiode traces obtained with setup outlined in figure 10: L-shaped cathode, 25-in length falsework, 15-in A-K gap, 100 kV, RT = risetime in ns. Shot #6408. The oscilloscope traces are in volts because the photodiode current was converted to a voltage across a resistor. The light-pipe length between the scintillator and the photomultiplier was not always the same (figure 10). The main object of these six measurements was to show variation in pulse shape as a function of position.](image-url)
The reproducibility of this parameter has been improved since the measurements described here were made. Another important factor in shot-to-shot reproducibility is the stability of the diode geometry. As seen in figure 1, the inner conductor of the MITL is cantilevered over a significant distance. It is very important that the inner and outer conductors of the MITL remain concentric. A small shift in concentricity can have a significant effect on diode behavior, especially if the dimension $d_0$ (figure 4) is small.

VI. CONCLUSION

To summarize, the use of anode falsework in the Aurora diode can easily decrease the nominal risetime of the beam current pulse from 50 ns to around 20 ns. Best results were achieved with Marx charge voltages in excess of 90 kV, using a 15-inch A-K gap and a 10-inch cathode-anode falsework overlap. (A 90 kV Marx charge corresponds to an erected voltage of 9 MV.) Because of voltage ripples associated with impedance mismatches in the Aurora pulser, we have probably reached the limit of risetime improvements using the simple anode falsework approach.

Based on the success of this technique, it is probably worthwhile to insert falsework much further back into the vacuum coax section[10]. The intent of this arrangement would be to produce a much faster rising pulse which would then further steepen as it propagated down the MITL, without causing premature diode emission. The same effect could also be achieved with a plasma erosion opening switch, although the passive falsework may be easier to implement.

REFERENCES

11. G. Hutlin, Army Research Laboratory, Adelphi, MD, private communication.