DESIGN CRITERIA FOR THE Z VACUUM INSULATOR STACK

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ABSTRACT

The Z (formerly PBFA Z) vacuum insulator system consists of four stacks of Rexolite rings about 11-ft. in diameter, immersed in water, that insulate four biconic vacuum power-flow regions. The power flows are combined by a post-hole convolute just outside the imploding plasma load. Each ring stack is driven by nine similar water transmission lines connected around its perimeter. The different inductances between each stack of insulators and the load lead to a different voltage magnitude and waveform across each stack; therefore two stacks consist of five 2.25-inch-high insulators, and two stacks consist of six such insulators.

The design criteria for the insulator stacks were developed using the analysis described in Ref. 6. This treats the case of multiple stack modules each composed of a number of series insulators and each having a large circumferential transit time. The analysis tries to take account of the fact that when one flashover occurs at a particular location in one insulator stage, or even a number of flashovers at various locations, effective breakdown may not have occurred, because it takes time for series stages to flash locally in the same stack, while other parts of the stack are transit-time-isolated. To develop criteria for Z the analysis was first applied to Saturn, and was normalized by assuming a safe level for Saturn based on experience; it was then applied to Z. The analysis is presented, and results to date for the Z stack are described.

INTRODUCTION

PBFA-II (Ref. 1) included thirty-six coaxial, multi-stage pulseforming lines that produced 40 ns pulses. Each pulseforming line drove two biplate lines in parallel, and then the voltage was in effect transformed up by inverting the voltage in one biplate and connecting it in series with the other. The thirty-six outputs were then connected in series-parallel at a set of 11-ft. diameter vacuum insulator stacks.

For the conversion to Z (Ref. 2), the switches in the second and third lines of each water coaxial pulseforming lines are shorted to leave the pulse duration at the $\gtrsim$ 100 ns produced by the first line, and all thirty-six modules are connected in parallel to drive a single Z-pinch. Parallel connection is effected by fitting each coaxial water line output with a single water biplate and bringing the biplates radially inward in

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The Z (formerly PBFA Z) vacuum insulator system consists of four stacks of Rexolite rings about 1l-fl. in diameter, immersed in water, that insulate four biconic vacuum power-flow regions. The power flows are combined by a post-hole convolute just outside the imploding plasma load. Each ring stack is driven by nine similar water transmission lines connected around its perimeter. The different inductances between each stack of insulators and the load lead to a different voltage magnitude and waveform across each stack; therefore two stacks consist of five 2.25-inch-high insulators, and two stacks consist of six such insulators.

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four rings of nine; the biplates in each ring merge outside one of four vacuum insulator stacks, again 11-ft. in diameter, Figure 1. The stacks in Z use new 45-degree Rexolite rings.

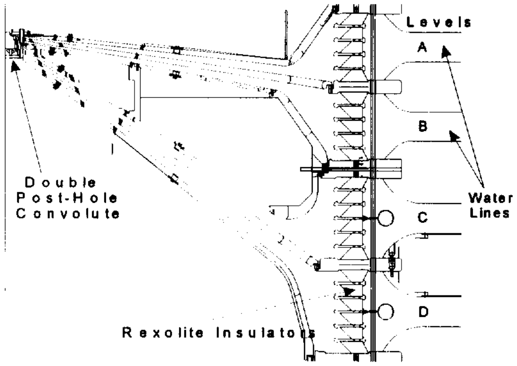

Figure 1. Z insulator stacks and MITLs.

After flowing through each insulator stack the power continues in a conical MITL (magnetically insulated transmission line), and the four MITLs are connected in parallel at a radius of about 7.62 cm by a double post-hole "convolute". From the vacuum stacks inward, the power feed is essentially an inductance, and to achieve the desired 20 MA in a 100 ns pulse the inductance had to be minimized by using the smallest spacings predicted to be safe against breakdown or loss. This paper deals with the design of the insulator stack against vacuum surface flashover and presents some results. Other papers in this Proceeding deal with design against electron emission from the stack's metal gradient rings (Ref. 3) and with the design and performance of the MITLs and convolute (Refs. 4 and 5).

INSULATOR STACK DESIGN CRITERIA

J.C. Martin's equation:

$$F t_{eff}^{1/6} A^{1/10} = k \quad (1)$$

where F (kV/cm) is the field normal to the electrodes, $t_{eff} = t_{89}$ is the effective stress time, taken as the time (μsec) above 89% peak stress, and A (cm^2) is the surface area, is widely used to predict the flashover of 45-deg. vacuum insulator surfaces. As is discussed in Ref. 6, the flashover probability at a field F_1 below breakdown is often taken to be

$$(F_1 t^{1/6} A^{1/10} / K)^{10} \quad (2)$$

As is also discussed in Ref. 6, predicting flashover becomes complicated when there are many insulator stacks in parallel, many insulators in each stack, and transit times around the gradient rings comparable to or greater than the pulse duration or t_{eff}. Following the method described in Ref. 6, we take Equation (1) to mean there is a probability 0.5 that a first flash will occur in the area A subjected to the field F for a time t_{eff}. A first flash only shorts one stage of one stack, however. For relatively small numbers ($\lesssim$ 6) of stages per stack, we consider that if two flashes occur within a region with transit time t_{eff} the remaining stages may break rapidly nearby as a result, and so we treat this situation as if it were stack breakdown. For Z, we attempted to make the probability of this of order 10% for a shot with the highest anticipated pulse charge. It should be noted that the total azimuthal transit time around the Z gradient rings was estimated as 170 ns, while t_{eff} ranged from 20-55 ns; therefore the first one or two breakdowns effectively increase the stress on only a small fraction of the circumference, of only one of the four stacks.

From the analysis of Ref. 6, the probability of two flashes is

$$p_2 = (p_1^2/N) \times [F(g_1) + F(g_2) \ldots + F(g_N)] \quad (3)$$

where p_1 is the probability of one flash occurring and g_1, g_2 ... are the factors by which a flashover will change the voltages on each of the N stages ($g = 0$ on the flashed ring, $g \geq 1$ on the others). The function F depends on the time dependence of flashover and is shown in Figure 2 for the 1/6 exponent in Equation (1) and also for a greater time dependence expressed by the equation

$$F t_{85}^{1/4} A^{1/10} = 120 \, . \quad (4)$$

Here t_{85} is the duration above 85% peak stress, replacing $t_{eff} = t_{89}$ in Equation (1) (because $0.85^4 = 0.89^6 = 0.5$). The form and derivation of F(g) are found in Ref. 6.

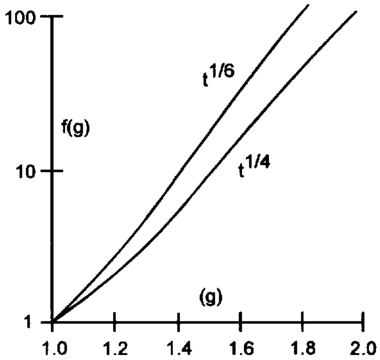

Figure 2. F(g) for time dependencies $t^{1/6}$ and $t^{1/4}$.

Martin's Equation (1) was based on data from single insulators with areas of only 10-40 cm^2, and the Z stacks would have total areas of a few $\times 10^5$ cm^2. So we tried to normalize the area extrapolation, and also the method of predicting breakdown, by applying it to Saturn and comparing the results with experience. The analysis for Saturn predicted that a failure probability of 10% occurs at 103% of the stress ("JCM") given by Equation (1). Saturn is believed to operate reliably at 112% of JCM. Thus our analysis seemed to be 9% pessimistic. However, if the time dependence is $t^{1/4}$ instead of $t^{1/6}$, the longer pulse of Z will result in a stress about 9% closer to breakdown. Therefore we applied the analysis to Z using Equation (1) to characterize stress and with zero correction based on Saturn. We also used the $t^{1/4}$ form of F(g) and we used the t_{85} definition of t_{eff} in considering transit times.

STACK FLASHOVER PROBABILITY ANALYSIS

An example calculation of the operating fraction of JCM corresponding to a 10% probability of breakdown will be given for a Z level consisting of five insulators in each stack.

First, the effects of various rings flashing are estimated. The voltages produced on the parts of the other rings that are close enough to the flash to experience the over-voltages rapidly are estimated from gradient-ring to gradient-ring capacitances in the water for the case of flashes of an end ring, a ring adjacent to the end, and a middle ring. Table 1 shows the results for the g values. A zero in the table indicates the flashed ring; the other numbers show the voltage increases. Effects are assumed to be symmetrical about the stack midplane.

Table 1. Estimated voltage distributions after flashover of one ring in a five-ring stack.					
Ring Flashing	Voltages on Rings in Sequence				
End	0	1.57	1.21	1.13	1.09
Next to End	1.39	0	1.36	1.15	1.10
Middle	1.14	1.36	0	1.36	1.14

Next the probability p_2 is calculated of a second flashover occurring, in terms of the probability p_1 of a flashover occurring in some ring out of the ten rings in the two levels. Using the lower curve in Figure 2 ($t^{1/4}$ dependence) to obtain g values from the voltages,

$$p_2 = p_1^2/10 \, \Sigma \, g = p_1^2/10 \, (13.0 + 2.2 + 1.5 + 1.3) = 1.8 \, p_1^2$$

in the case of an end ring flashing. For the adjacent ring the result is $p_1 = 1.27 \, p_1^2$ and for a middle ring, $p_2 = 1.22 \, p_1^2$. Taking a weighted average gives $p_2 = 1.47 \, p_1^2$.

Similar results for levels consisting of two four-stage and two six-stage stacks are shown in Table 2. In Table 3 the relation giving the probability of two stages flashing in terms of the probability of a single stage

Table 2. Results for four and six ring stacks.						
Ring Flashing	Voltages on Rings in Sequence					
	Four Ring Stacks					
End Ring	0	1.62	1.24	1.14		
Next to End	1.56	0	1.42	1.14		
	Six Ring Stacks					
End Ring	0	1.49	1.20	1.15	1.10	1.07
Next to End	1.36	0	1.24	1.16	1.13	1.11
One of Middle Pair	1.15	1.30	0	1.27	1.12	1.11

Table 3. Summary of flashover probabilities estimated for pairs of Z stacks with 4, 5, and 6 stages, with comparison to perfectly re-graded tubes (transit time effects ignored).		
No. of Stages	p_2/p_1^2, Z	p_2/p_1^2, Perfect re-grading
4	2.20	1.39
5	1.47	1.04
6	1.08	0.85

flash is summarized for all three cases of four, five and six insulators. For comparison, the results are also shown for designs in which the voltage is perfectly re-graded after the first flash (as might be approximated if all gradient rings extended outwards across a common annulus of water bounded by a plastic cylinder). This re-grading would give the minimum probability of a second flash.

Next, the transit time around the tube is considered. The diameter is 11-feet and the velocity of propagation of waves on the gradient rings is estimated (from analytic approximations to the increases in capacitance due to the water and plastic dielectrics) as c/5, so that the transit time round the full perimeter is about 172 ns. Consider a case where the t_{eff} of the voltage pulse is about 55 ns, as calculated when the water switch gaps are set to half their maximum value. Following Ref. 6, the tube is thought of as made up of separate sections with transit times 55 ns, and there are $172/55 \simeq 3.13$ of these on each of the two levels, or 6.25 total. We seek the condition for which there is a probability 1/10 that effective breakdown, taken here as two flashes, occurs in some section. For each section the probability will be ~1/62.5, so that using the case of a five section tube as an example

$$1.47\,p_1^{\,2} = 1/6.25;\ \text{or}\ p_1 = 0.104\ .$$

This corresponds to a fraction of breakdown given by $(2p_1)^{0.1} = 0.855$. For the whole circumference of both stacks the fraction of breakdown will be $0.855 \times 6.25^{.1} = 1.027$.

Thus the two levels treated as one area and considered alone can operate at 102.7% of breakdown according to Equation 1. The effect of transit time has increased the allowed stress by $(3.1)^{.05} \sim 1.06$; if it is ignored, we would conclude we must operate at 97% of breakdown. If multi-stage effects were also ignored we would simply conclude that for probability 0.1 of a flashover we must operate at $(2 \times .1)^{.1}$ = 85% of breakdown. Note that it is not possible to include transit time effects without including multi-stage effects.

Using all the results of Table 3, the percentage of JCM for which there is a 10% probability of two stages flashing was calculated as 100.5%, 102.7%, and 104.3% of JCM for four, five, and six stages respectively.

Calculations were then made of the stack waveforms for two different Z-pinch loads, with load masses 5 mg and 15 mg over a 2 cm length, imploded from radii of 0.95 cm and 2 cm respectively and with the half-maximum switch gaps. The insulator stack inductances were initially fixed at the value for four stages. Using the calculated voltage waveforms for the 5 mg load, which was found to be the most stressing case, it was found that five insulators were required in A and B level and six in C and D level in order to bring the fractions of JCM below the fraction that is calculated to give 10% flashover probability for that number of stages. The inductances of the stacks corresponding to five and six stages were then substituted in the simulation; at the same time the MITL configuration was adjusted slightly to match the finally selected one (Ref. 4). Results for all four stacks are shown in Figure 3 for the 15 mg load, and the waveform for the C stack with the 5 mg load is shown in Figure 4.

For the 5 mg load it was calculated that at 5 ns before implosion, which is the latest time that an insulator flash could reduce current at implosion, the six stage C and D level was at 108% JCM compared with a calculated flashover criterion of 104.3%, while the five stage A and B level was at 105% compared with a calculated flashover criterion of 102.7%. These results can be interpreted to mean that there is a 33% probability that one or other level will flash. This was considered acceptable because not all shots would use the 5 mg load or one with equivalently early implosion; also the load length could be reduced a little if necessary, reducing the peak voltage. The alternative of increasing the number of insulators by one per stack would have introduced an excessive inductance penalty, while going to a non-standard insulator was not justified considering the uncertainty of the calculation.

Calculations were also made with waveforms corresponding to full switch gaps on the water lines. These gave higher voltages but shorter effective times. For example, on the C and D stacks the voltage increased from about 3 MV to 3.26 MV, but the time above 89% fell to about 20 ns. The stress on a $Vt^{1/6}$ basis fell four or five percent, and the allowable stress rose a few percent because of the reduced pulse duration compared to the tube transit time. Therefore the large water gap setting appeared less stressing to the insulator stack.

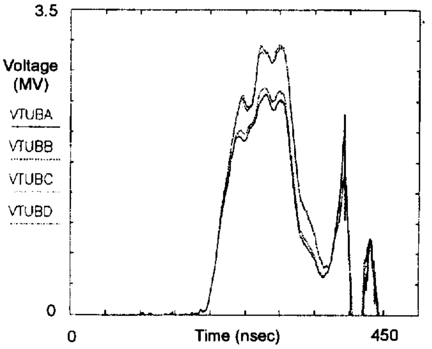

Figure 3. Stack voltage waveform from circuit simulations.

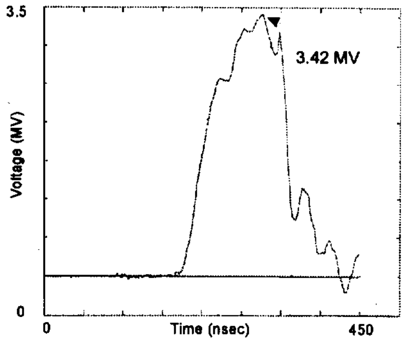

Figure 4. Stack voltage waveform from circuit simulations.

STACK GRADING

Electrostatic calculations, using the "Electro" code showed that the grading of the five insulator stacks of the A and B levels was within ± 6.5% (Figure 5) and that of the six insulator stacks of the C and D levels was within about ± 3.5%. Both the five- and six-insulator stacks used angles in the water on the end insulator to achieve this result, and the six insulator stack used a metal ring in the water attached to the middle gradient ring, Figure 1.

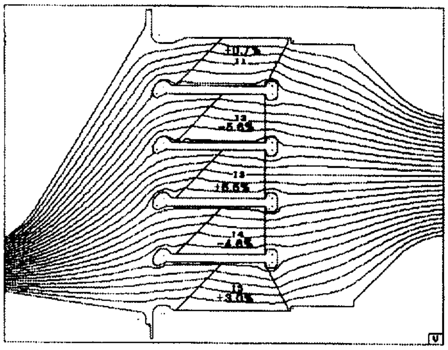

Figure 5. Electrostatic calculation of voltage distribution in stack A ("worst" graded).

If a tube of many stages has stage stresses that are distributed linearly over a range ± f where f represents a fraction of the average stress, then it is easy to show that the stack has to first order the same probability of first flashover as a uniformly graded stack that is shorter by a factor $1-(n-1)f^2/6$; here n is the area or Weibull exponent in the flashover probability distribution, and would normally be taken as 10 from Equation 1. With F = 0.065 and n = 10, this calculates to be equivalent to about 0.6% reduction. For the actual (not exactly linear) stress distribution in the five-stage A stack this equivalent reduction can be calculated as

$$\{1/5\,[(1+.007)^{10}+(1-.056)^{10}+(1+.065)^{10}\ +\ (1-.046)^{10}+(1+.03)^{10}]\}^{-1/10}=0.991\ ,$$

a 0.9% reduction. On this basis the grading appears more than adequate.

The six-stage C and D stacks are even better graded, but the central ring electrode will have an adverse effect by applying the increase in voltage from a first flash mostly to the other two stages on the same side. This effect was not evaluated.

PERFORMANCE OF THE INSULATOR STACKS

At the time of writing, 75 full-power shots have been fired on Z. The maximum insulator stresses - characterized using $Ft_{89}^{1/6}$ or $[\int F^6\, dt]^{1/6}$ - are within a few percent of the maximums predicted in the case of levels A, C, and D, and about 10% higher in the case of level B. Implosion times are typically intermediate between the 5 mg and 15 mg cases used in the design effort. The water switch closure timing is typically later than that in the calculation shown in Figures 3 and 4, resulting in slightly larger voltages and slightly lower t_{eff} values.

Below we present some insulator stack voltage waveforms. These are integrated waveforms from D-dot sensors distributed around the ground (positive) insulator of each stack, Ref. 7. It is important to note that the sensor calibrations assume good stack grading, and their signals will no longer represent stack voltage if an insulator flashes near-by. Some distortion of signals is also possible by electron emission from the 45-degree surface of the insulator or from any gradient ring. Complete flashover of a stack according to these sensors can be confirmed by the current waveforms inside them, in the MITLs. It is believed that a complete insulator stack has never flashed on the main pulse.

Around each stack there is some variation of voltage waveforms, probably due to scatter of water switch closure times. This variation is illustrated for level D in Figure 6. The main difference between measured

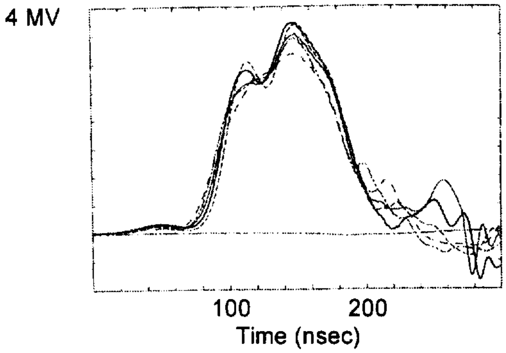

Figure 6. Azimuthal variation of voltage wave-form around level D stack.

voltage waveforms averaged around the stack (Figure 7) and those in computer simulations using the actual average switch timing is that the measured voltage is lower just before the implosion, indicating that current losses occur in the MITLs at that time, Ref. 4. This typically occurs on the fall of the pulse, and does not affect the total insulator stress much.

The insulator stacks hold off the entire main voltage pulse and flash on the subsequent voltage reversal. This is illustrated in Figure 8. It would be ideal if the insulator flashed as the voltage began to reverse, as this would tend to trap energy in the vacuum where it might contribute to the radiation output of the Z-pinch.

Figure 9 is a waveform from level D showing voltage flashover on the main pulse of the stage containing the voltage sensor. Current diagnostics indicate that complete stack flashover did not occur till after the main pulse. The insulator flashover is believed to have been caused by a more direct path for Z-pinch debris to reach this level D insulator through the central region of the MITLs and through pumping slots. This probably resulted in more debris building up on this stage, although all levels are cleaned on each shot. After level D was cleaned more thoroughly and the debris path was shielded, flashover of this stage in the main pulse appeared to be eliminated.

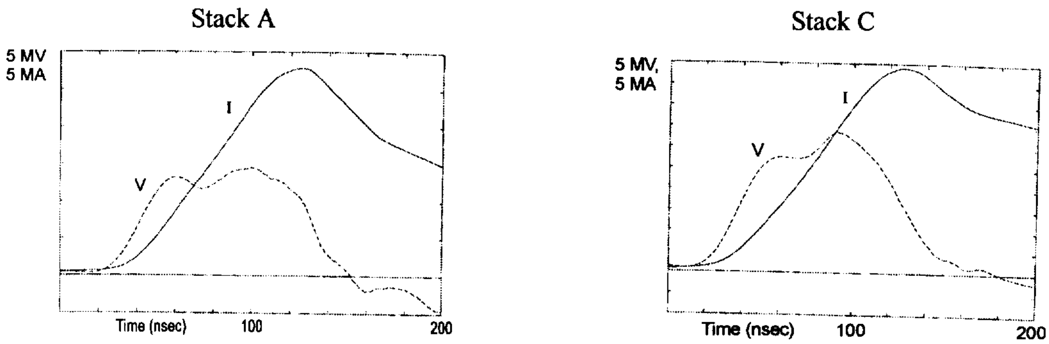

Figure 7. Voltage waveforms averaged around circumference, used in insulator stress assessments.

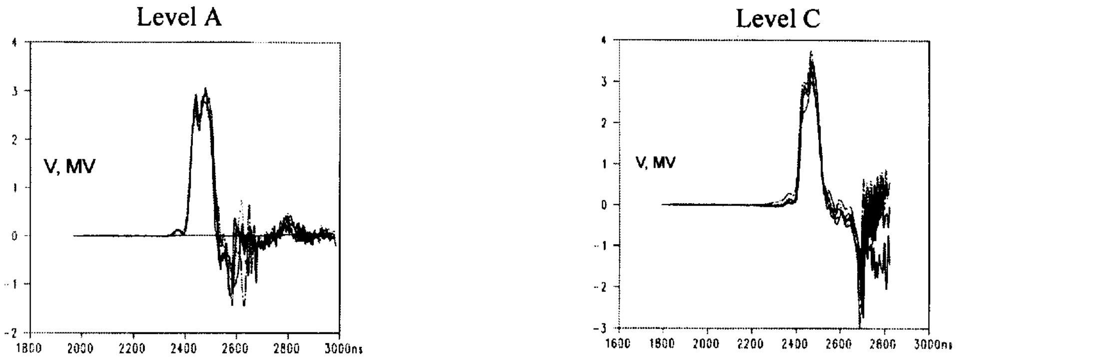

Figure 8.Typical flashover occurring well into voltage reversal. Highest voltage, shot 51.

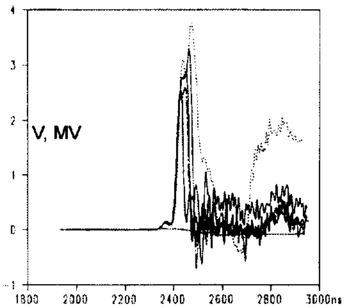

Figure 9. Some stages in level D flashing on main pulse (after accumulating debris).

The only other difficulty encountered with the stacks to date is the appearance of two dendrites near to each other in one insulator of level A. These grew from the vacuum surface into the Rexolite, rather than growing parallel to the surface like dendrites caused by high energy electrons injected into the plastic. The authors suggest that the dendrites may have been initiated by sharp metal debris from the Z-pinch that became embedded in the plastic. This particular insulator and the particular level have a relatively direct line of slight to the Z-pinch. Grinding out the dendrites has allowed operation to continue without replacing the insulator.

The stack performance near design levels appears to be as good as the analysis or better. This may reflect the inaccuracy of the analysis or its conservatism (in the assumptions about breakdown constants or $t^{1/4}$ dependence, or in considering only two insulators flashing to represent stack breakdown flash); or it is possible that the performance of Rexolite is slightly better than Equation (1). Another factor to consider is the possibility of magnetic flashover inhibition. It has been suggested that flashover is inhibited by the azimuthal magnetic field if F/cH < 0.07, Ref. 8. For a particular insulator this can be written as $V < \alpha I$, where α is a constant depending on insulator radius and thickness. Figure 10 shows, as the broken lines, the scaled current waveforms, αI for levels A and D. It is seen that the voltage falls below αI rather late in the pulse for level D, and the results are similar for levels B and C. For level A, which has the lowest inductance separating it from the Z-pinch, the criterion for MFI is reached rather earlier. Thus a contribution to insulator hold-off from MFI is possible.

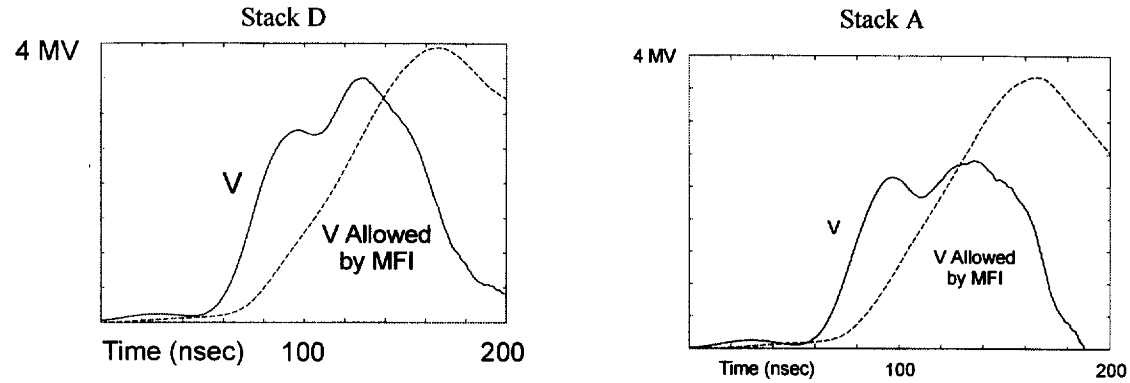

Figure 10. Illustration of possible magnetic flashover insulation for levels A and D.

CONCLUSION

A flashover analysis incorporating effects of multiple stages and transit times has been used in designing Z and the resulting insulator is at least as safe as predicted.

Tests with one ring removed from some or all stacks (the Z hardware was designed to make this possible) or with the MITL inductance deliberately increased could determine the operating margin and whether MFI plays a part. This information would help the design of other machines, especially X-1 (Ref. 9). McDaniel has pointed out (private communication) that MFI can result only in a small improvement for the present Z stack, and that identifying or using a large improvement from MFI on Z will require introducing a smaller diameter insulator stack.

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