Magnetic Flashover Inhibition on Z

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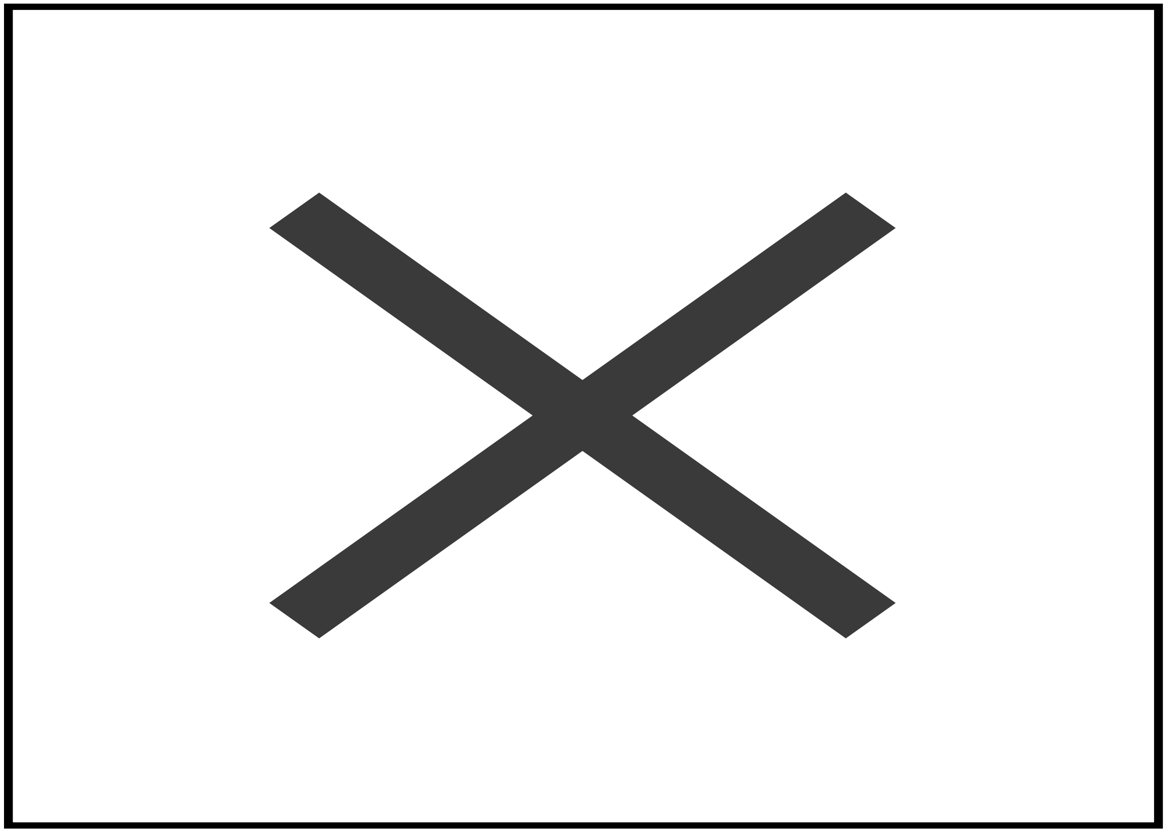
Abstract

Recent measurements have shown that magnetic insulation of the vacuum-insulator stack on the Z accelerator may be playing a large role in successful z-pinch experiments, and may be a large factor in design of future z-pinch drivers.[1] The cathode-triple-point regions of the Z insulator stack, where electron emission is likely to be generated, are strongly magnetically insulated. The electric fields at the anode triple point are also high, but still below electron-emission thresholds. These two factors may explain why the Z insulator stack is performing better than predicted by the JCM criteria.[2] In this paper we show the recently measured stack voltages and currents, discuss cathode-triple-point-magnetic insulation, discuss anode-triple-point effects, and look at the JCM criteria as it applies to the Z insulator.

[1]J. P. VanDevender, D. H. McDaniel, E. L. Neau, R. E. Mattis, and K. D. Bergeron, J. Appl. Phys. 53, 4441 (1982).

[2]J. C. Martin on Pulsed Power, ed. by T. H. Martin, A. H. Guenther, and M. Kristiansen, (Plenum, New York, 1996), pp. 255-259.

The Z accelerator is a 20 MA Z-pinch driver that produces 120 ns implosions and up to 1.9 MJ in x-ray radiation



Pulsed power consists of 36 identical lines, each of which includes:

- Marx bank
- Water capacitor
- Laser-triggered switch
- Pulse-forming section
- Water biplates

Each line connects to a 3.2 m diameter, four-level water-vacuum insulator.

Four conical MITLs conduct current to the center of the machine, where they are connected with a double-post-hole convolute.

Magnetic insulation can be important to Z-pinch physics

- Magnetic insulation can allow for **higher**-than-otherwise-allowed v**oltages** and electric fields, which lead to higher pinch currents
- Higher fields also lead to **lower inductance** designs, which also increase peak current
- Pinch kinetic energy is proportional to the square of the current, which is proportional to the voltage. Therefore, **doubling** the **voltage** will **quadruple** the pinch **energy**.

$$I_{pinch}(t) = \frac{1}{L} \int V_{stack}(t)\, dt$$

$$KE = \int F\, dr = \int \left[\frac{\mu_o I^2(t) \bullet}{4\pi r(t)} \right] dr$$

JC Martin Break-down formulae

Insulator flashover in vacuum

$$E(\text{kV/cm}) = 175\ t_{eff}^{-1/6}(\mu s)\ A^{-1/10}(\text{cm}^2)$$

t_{eff} is the time the voltage exceeds 89% of its peak value

Water break-down (as modified by Eilbert and Lupton, NRL)

$$E_{anode}(\text{kV/cm}) = 230\ t_{eff}^{-1/3}(\mu s)\ A^{-0.058}(\text{cm}^2)$$

$$E_{cathode}(\text{kV/cm}) = 557\ t_{eff}^{-1/3}(\mu s)\ A^{-0.069}(\text{cm}^2)\ \alpha^{-1}$$

where $\alpha = 1 + 0.12\left(\frac{E_{\max}}{E_{mean}} - 1\right)^{1/2}$

t_{eff} is the time the voltage exceeds 63% of its peak value

Both the water and vacuum breakdown formulae can be expressed in integral form

Vacuum breakdown

$$f_V(t) = \frac{A^{1/10}}{175}\left[\int_0^t E^6(t)\,dt\right]^{1/6}$$

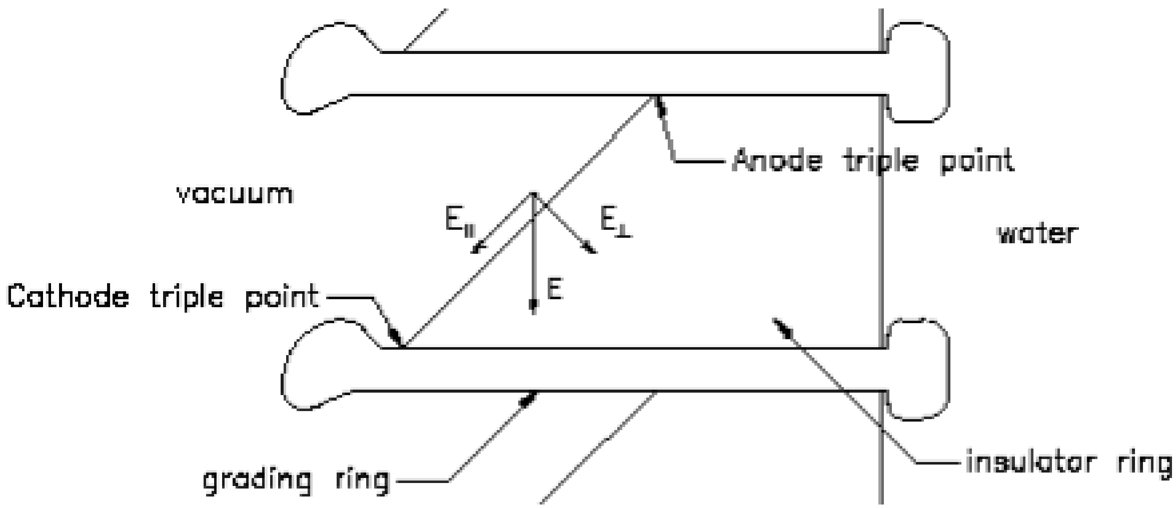
Water breakdown

$$f_W(t) = \frac{A^{0.058}}{230}\left[\int_0^t E^3(t)\,dt\right]^{1/3}$$

$f_V(t)$ and $f_W(t)$ are time-dependent parameters giving the fraction of the breakdown field in vacuum and water, respectively.

Magnetic insulation threshold depends on both the electric and magnetic fields at the cathode triple point

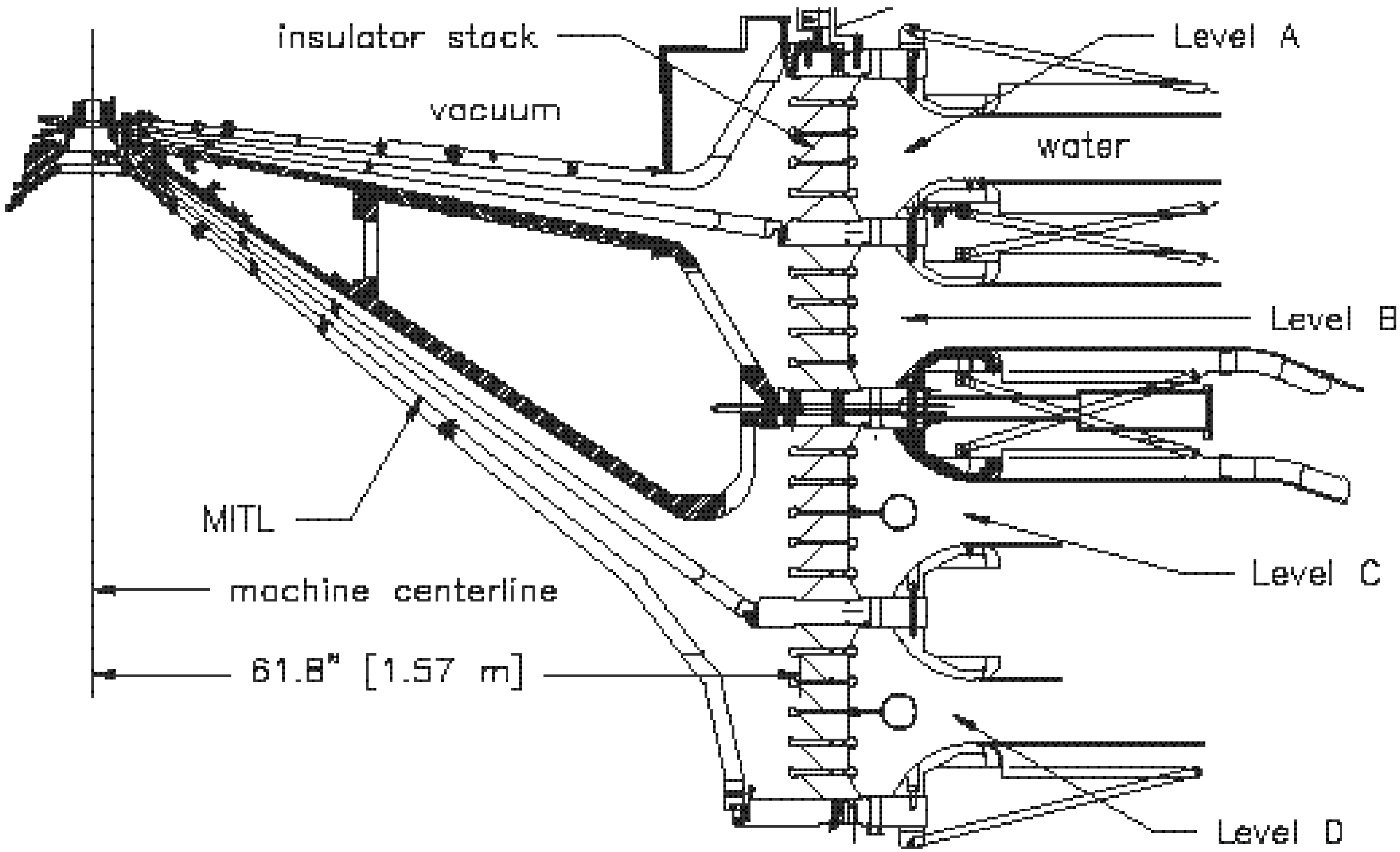
$$\frac{E_{\parallel}}{c\,B} < 0.07$$ Magnetic flashover inhibition (MFI) criterion



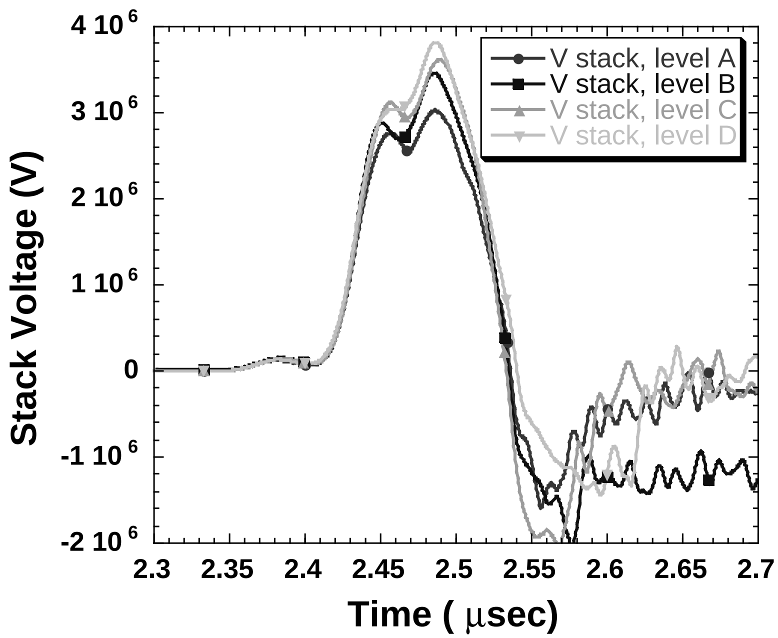
Factors which limit insulator performance

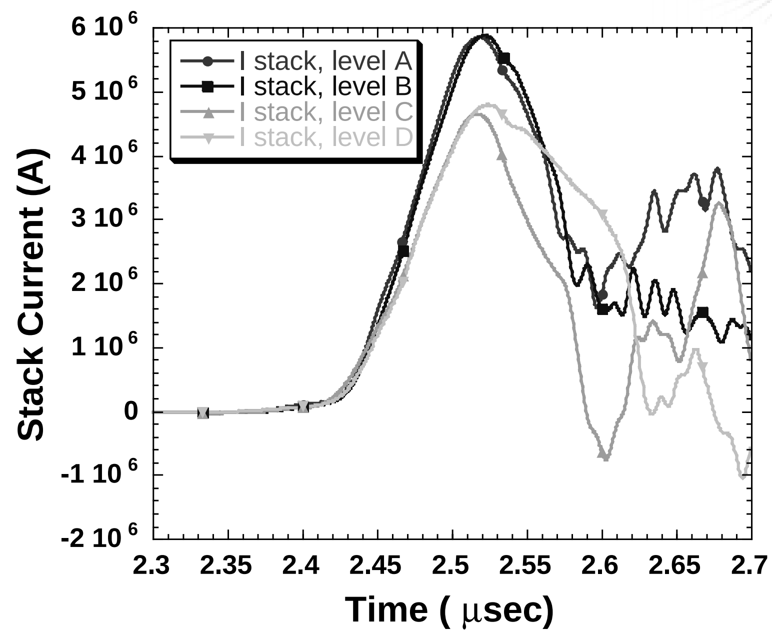
- Water side
  - Exceeding the JCM water breakdown criterion
  - Field enhancements in the water flare, at the flux excluders, and near the grading rings
  - Trapped air bubbles
- Vacuum side
  - Electron emission from the grading-ring tips
    - Anode versus cathode MITL flare at the insulator
  - Achieving the MFI criterion at the cathode triple point before the JCM criterion is exceeded
  - Excessively high field at the anode triple point

The Z-accelerator insulator stack



Measured voltage and current at the stack for Z shot 230

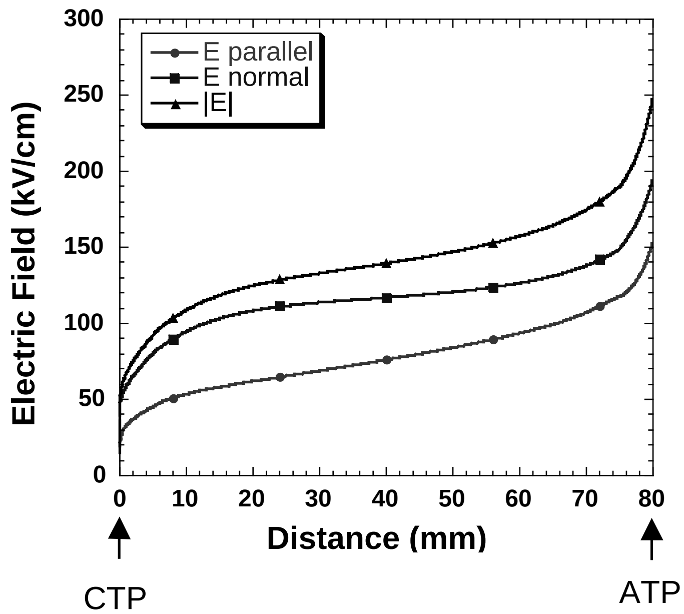




Level	Peak Voltage (MV)	Peak Current (MA)
A	3.03	5.86
B	3.46	5.91
C	3.61	4.64
D	3.82	4.81

Parallel and perpendicular components of the electric field on one of the rings of A level are calculated with the ELECTRO code for a peak voltage of 3.03 MV

Components of the electric field along the insulator surface



Magnitude of the electric field

The parallel field is found by multiplying the measured stack voltage by an enhancement factor derived from the ELECTRO calculations, and by dividing by the stack height

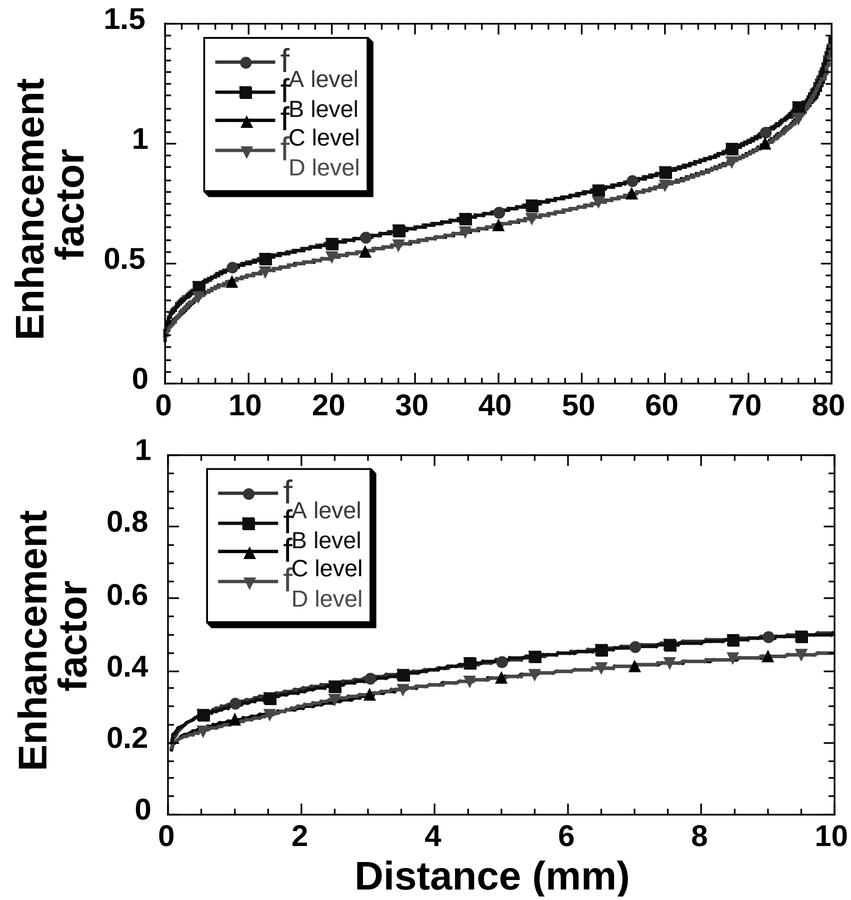
The enhancement factor is defined as

$$f(x) = E_{||}(x) / E_{ave}$$

where E_{ave} is the average field across the stack.

The parallel field is then

$$E_{||}(x,t) = f(x)\, V_{meas}(t) / d$$



The average electric field, the magnetic insulation criterion, and the JCM criterion for each of the four levels of Z, all as functions of time, follow in the next four slides

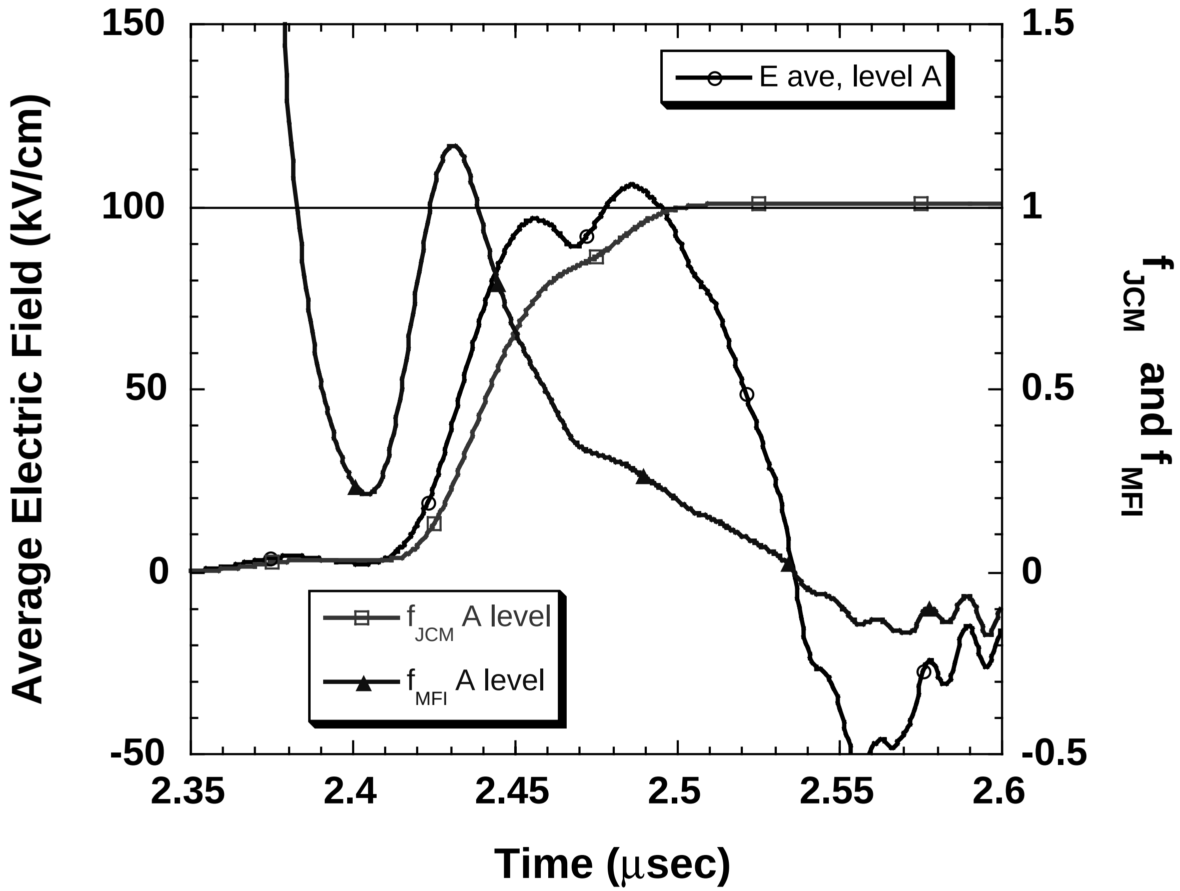
- MFI is plotted as the fraction that the magnetic insulation criterion is exceeded
  - The electric field is calculated from the measured voltage using an enhancement factor of 0.3 for levels A and B, and 0.25 for levels C and D
  - The magnetic field is determined from the measured stack current, that is, $B = \mu_o I_{meas} / 2\pi r$

$$f_{MFI} = E_{||} / (0.07\ c\ B)$$

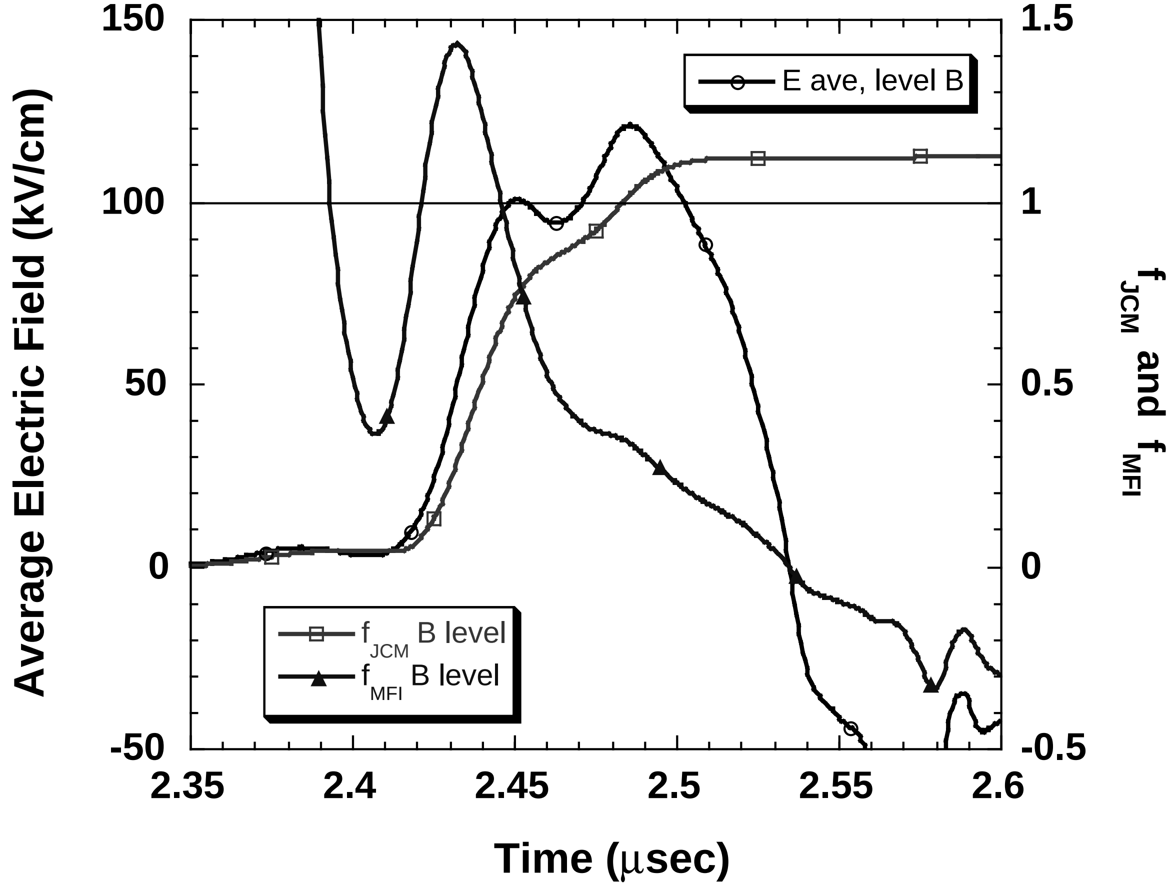
- JCM vacuum breakdown is plotted as the fraction of achieving the breakdown threshold, using the integral technique
  - This technique uses the average electric field, which is the measured voltage divided by the insulator gap height

$$f_V(t) = \frac{A^{1/10}}{175} \left[\int_0^t E^6(t)\, dt \right]^{1/6}$$

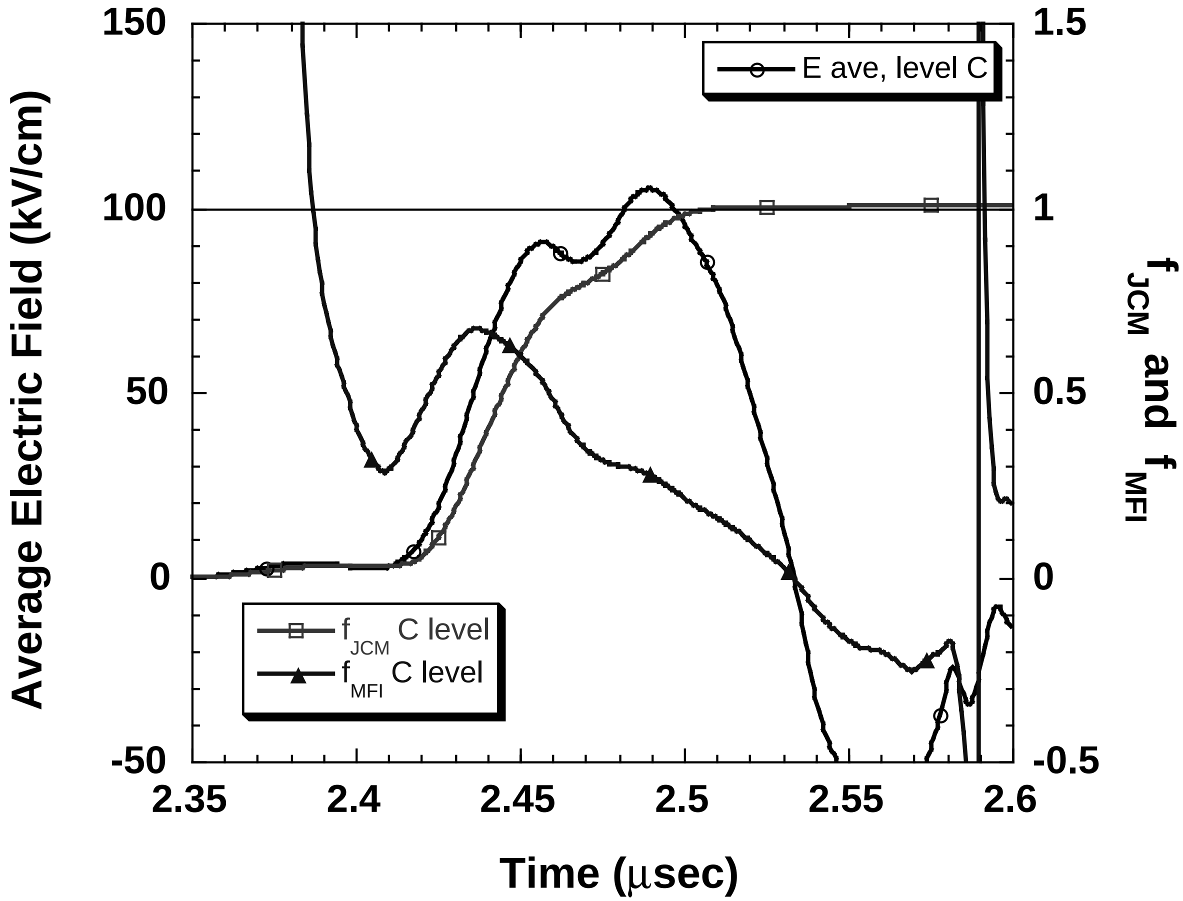
A level electric field vs MFI and JCM breakdown criteria



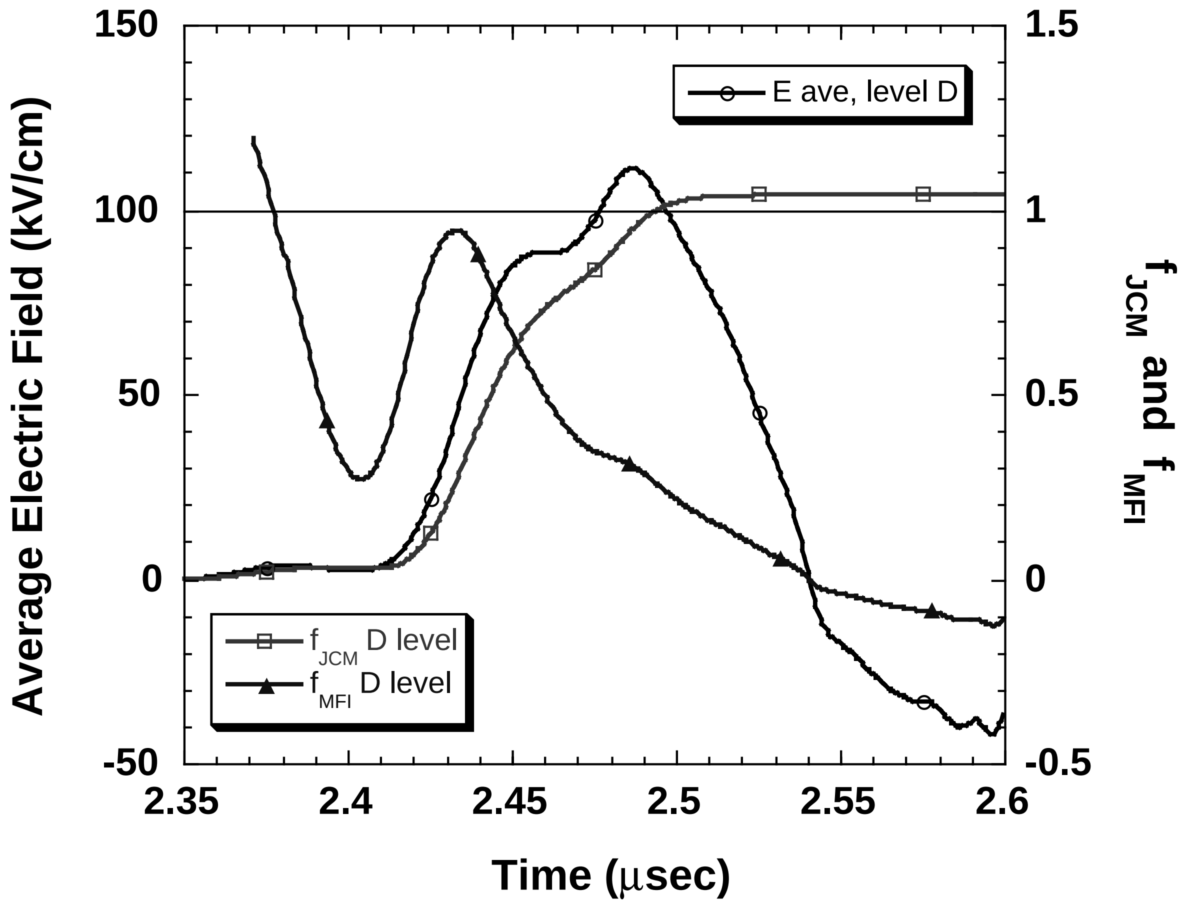
B level electric field vs MFI and JCM breakdown criteria



C level electric field vs MFI and JCM breakdown criteria



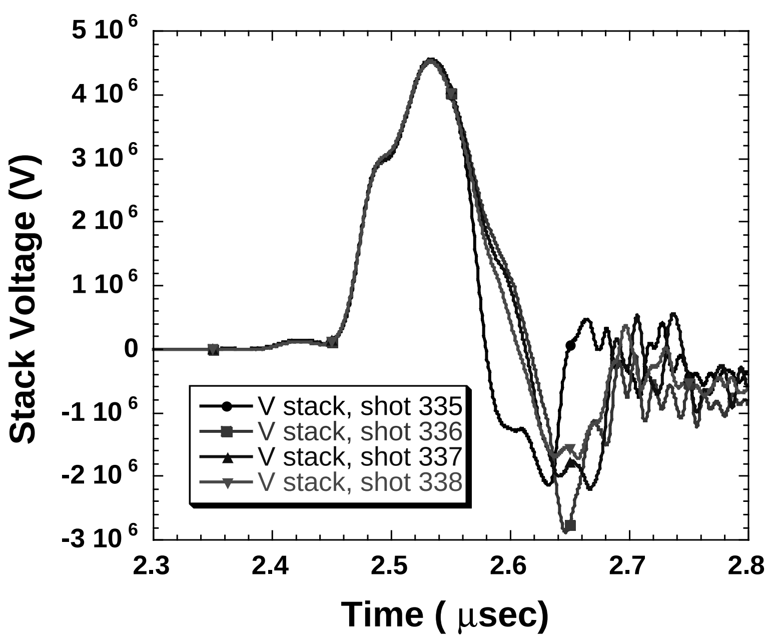
D level electric field vs MFI and JCM breakdown criteria



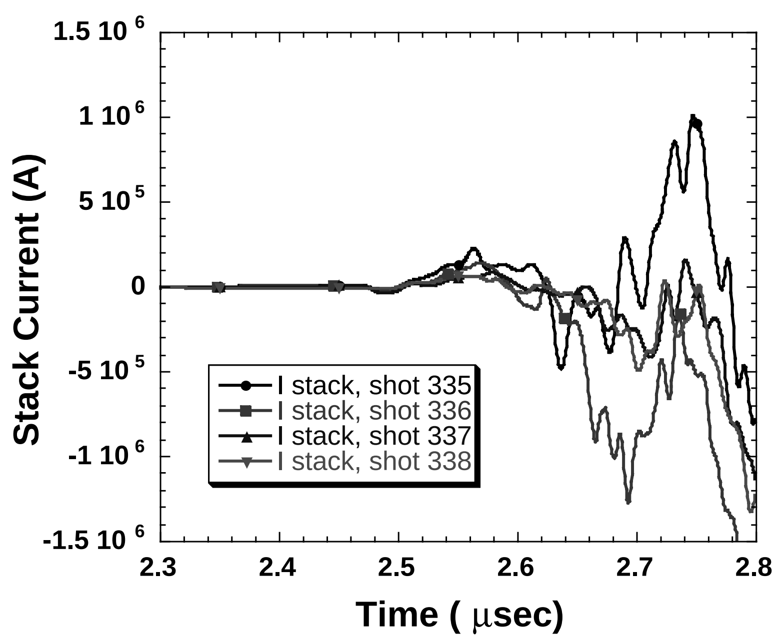
Recent no-current shots on Z have shown increased voltage hold-off on the the A-level stack

A-level pulse line fired into the A-level stack with MITLs removed. Voltage doubling raised peak voltage to 4.5 MV while current remained nearly zero.

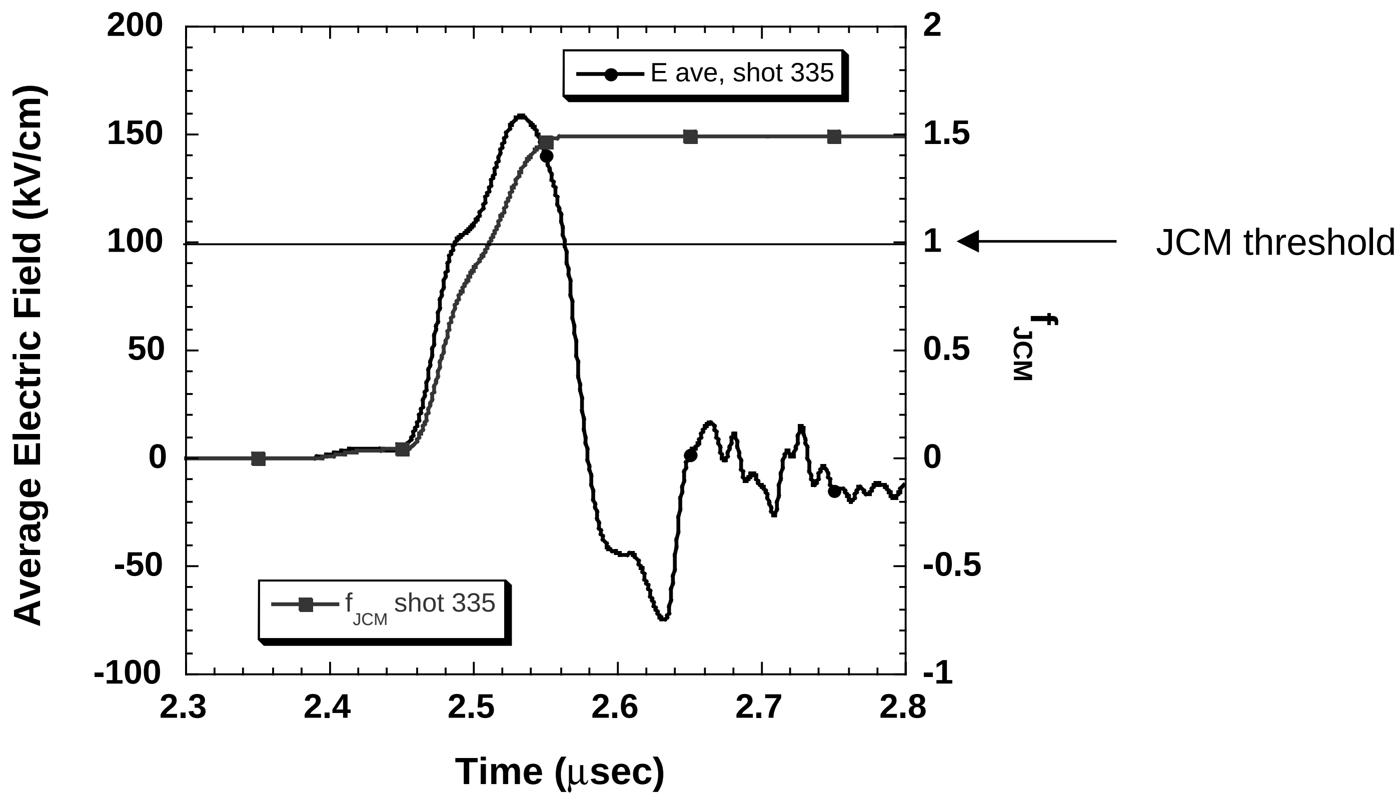
4.5 MV peak voltage achieved



Measured current less than 200 kA during pulse time



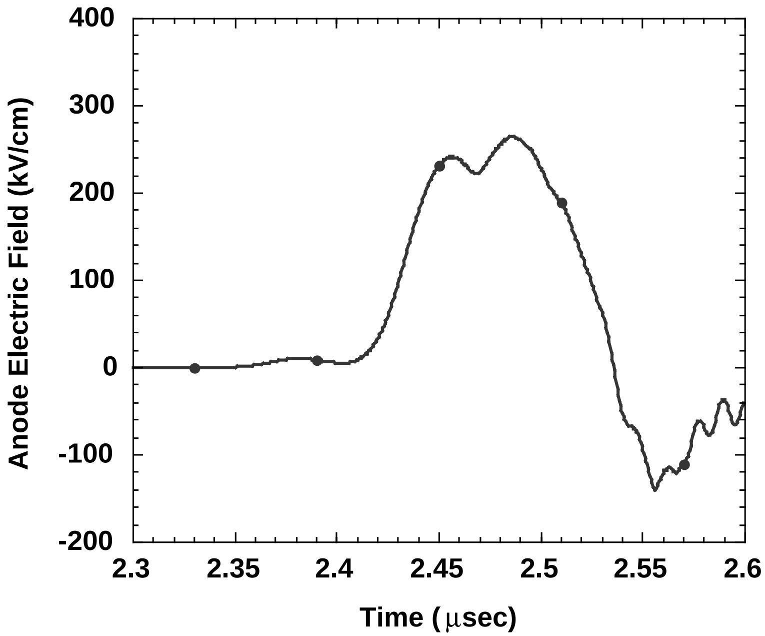
Analysis of the A-level high-voltage test shows that the insulator exceeded the JCM threshold by 50% with no magnetic insulation



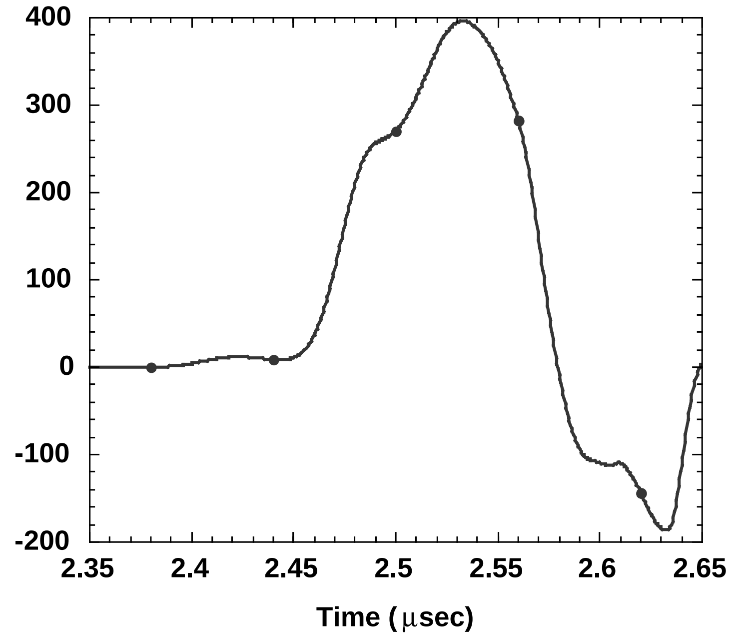
Anode triple point fields on Z can exceed 300 kV/cm with no evidence of insulator breakdown

The anode field is calculated from the measured voltage using a 2.5 multiplier

Z shot 230
(normal shot)



Z shot 335
(high-voltage insulator test)



Summary

- Conditions for magnetic insulation are met with the Z stack
- As presently operated, the JCM breakdown criteria is only slightly exceeded on the Z stack. Note that this assumes an area term that corresponds to one level of the stack. If all levels are used, current operation exceeds JCM breakdown by 15 to 20%
- Anode triple point fields are high but are not causing stack breakdown
- Insulator tests show that the breakdown field for the Z stack is probably more than 50% higher than JCM predictions
  - It may be possible to operate the Z stack at 50% higher voltages and currents
  - Voltage limit not yet established
- Magnetic insulation may contribute to yet higher voltages on the Z stack