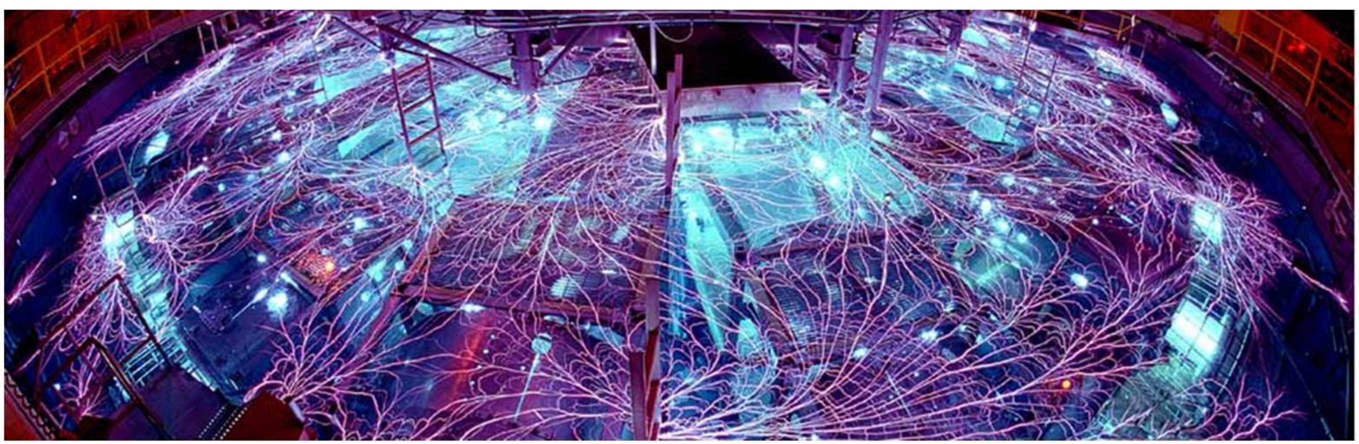
SAND2017-6334C

High Voltage Crowbar for Protection of Marx Trigger Generator (MTG) Systems on Z



William White,
Mark Savage

Pulsed Power Conference 2017

Brighton, England

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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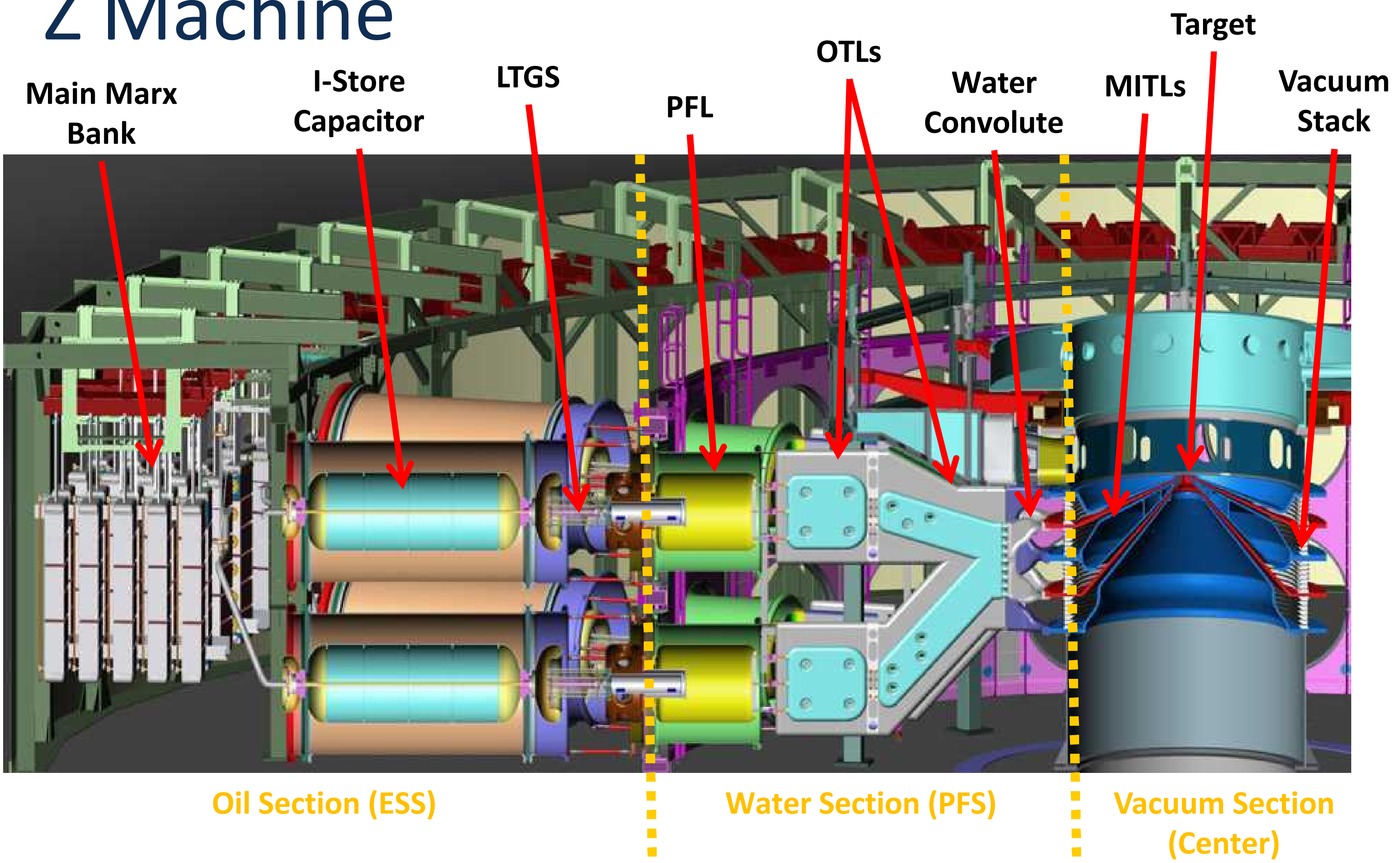
Sandia National Laboratories
Z Machine



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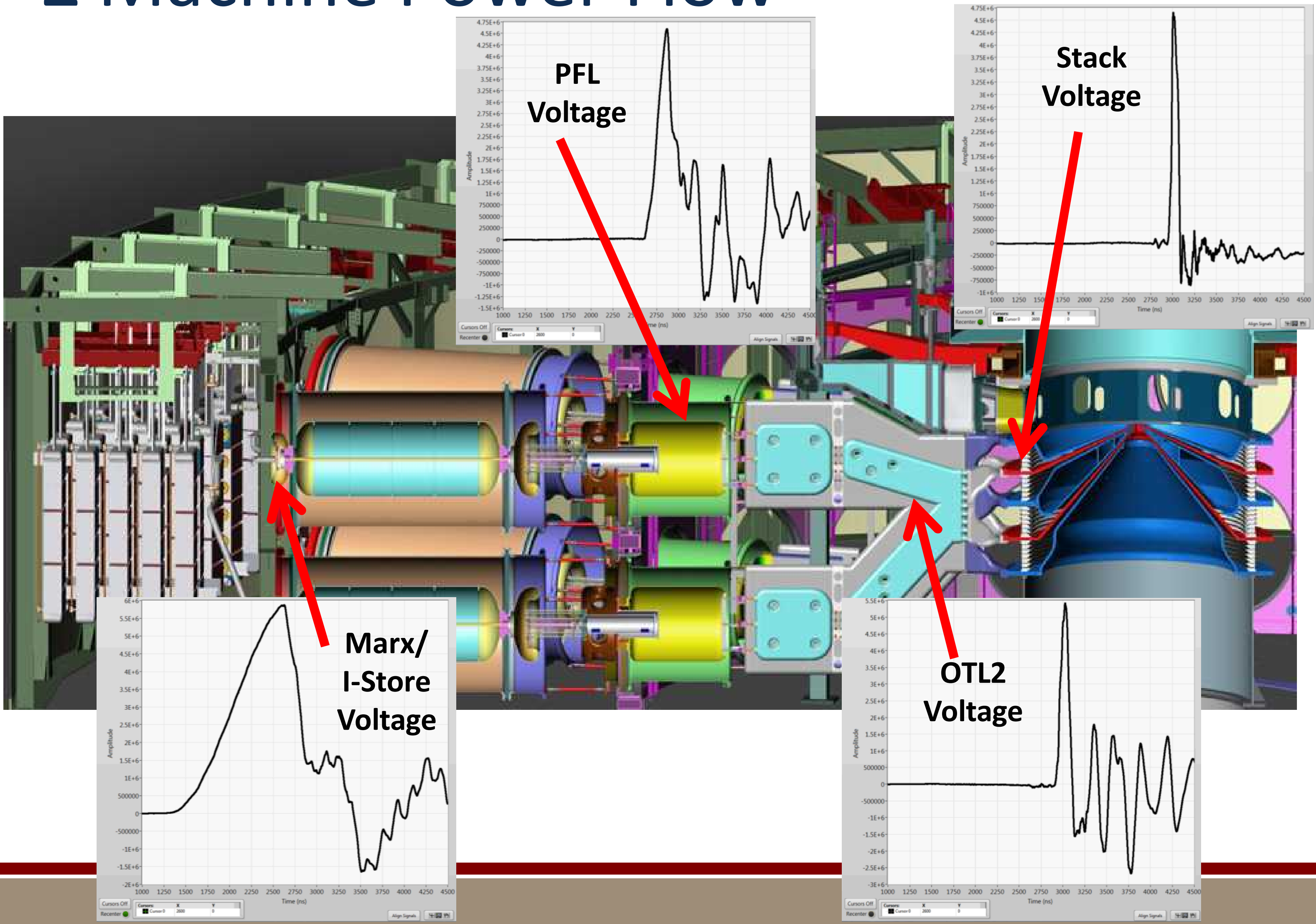
Z Machine Power Flow



Scale Comparisons

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Energy

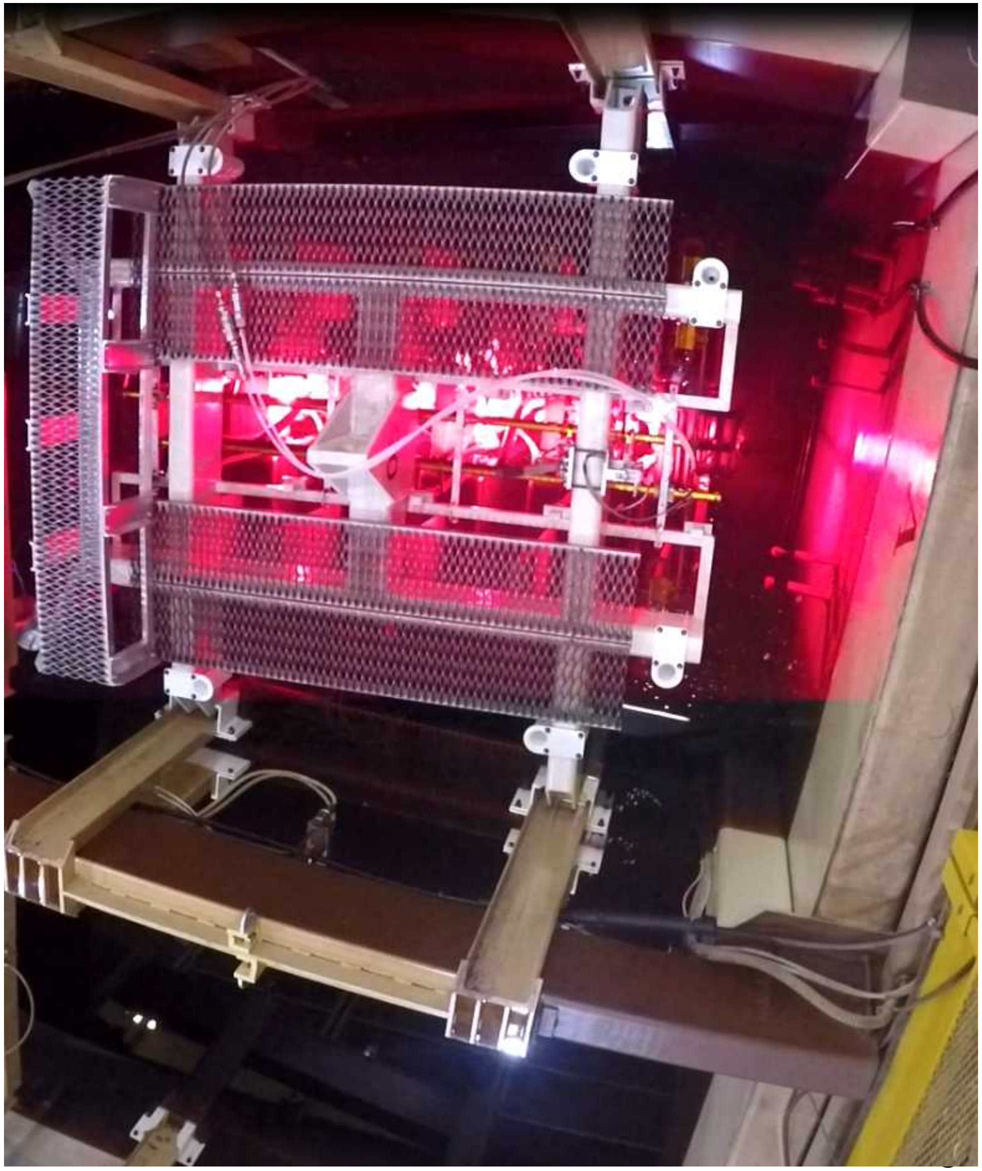
- Z Marxes: **25 MJ**
- Z X-ray production: **2.7 MJ**
- NIF Lasers: **4MJ**
- World Electricity Use: **567 EJ per year** (2012)
- Stick of Dynamite: **1 MJ**
- Jelly Donut: **1.3 MJ**
- .30-06 rifle: **4 kJ**
- 70 mph SUV collision: **1.2 MJ**

Power

- Z Marxes: **25 TW**
- Z X-ray production: **350 TW**
- NIF Lasers: **500 TW**
- World Electricity Use: **18 TW**
- Stick of Dynamite: **120 GW**
- Jelly Donut: **60 W**
- .30-06 rifle: **4 MW**
- 70 mph SUV collision: **124 MW**

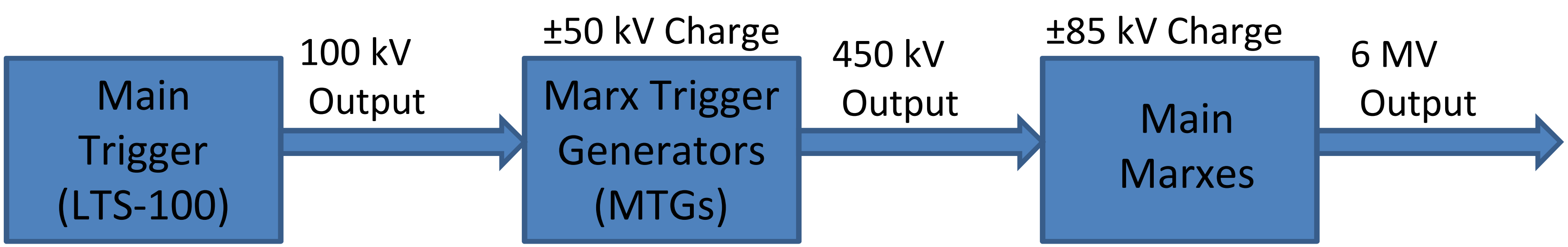
Main Marx Generators on Z

- 36 Marxes
- Sixty, 2.6 µF capacitors
- ~±55 to ±95 kV charge voltage
- 10% to 90% risetime is ~850 ns
  - ~1.5 µs to peak
- 6.1 MV peak voltage; 20.3 MJ stored energy
  - (at 85 kV charge)



Z Triggering Systems

- The Z Main Marx banks are themselves triggered by smaller Marx banks
  - Marx Trigger Generators (MTGs)
- The MTGs consist of 12 capacitors (0.15 µF) , charged to ±50 kV
  - The output of each MTG is ~450 kV, and is routed to four main Marxes
  - The nine MTGs themselves are triggered by a single, laser-triggered, spark gap operating at 100 kV output



(Diagram of SNL Z Triggering)

Z MTG Failure Mode: Tracking from a Main Marx

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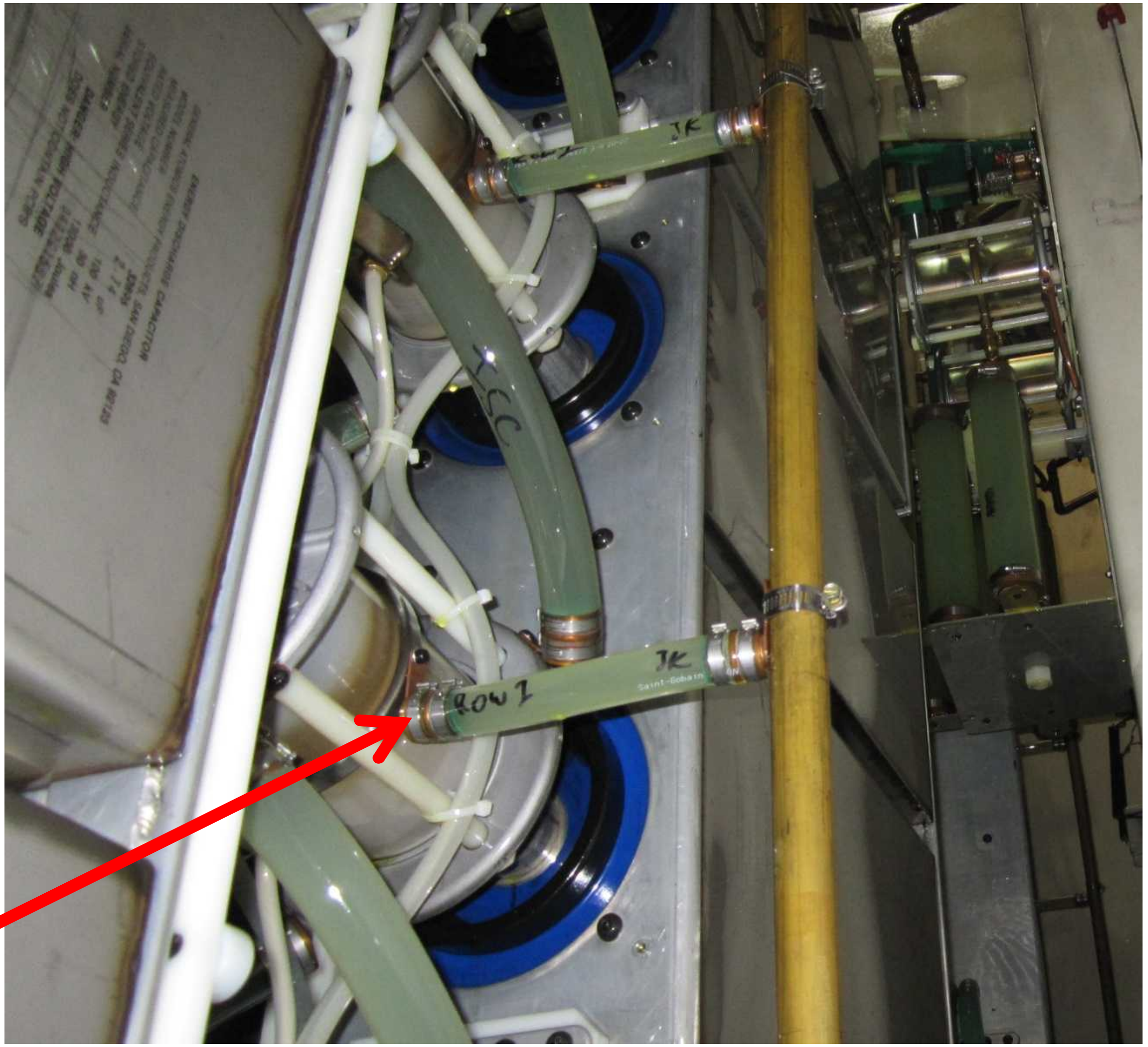
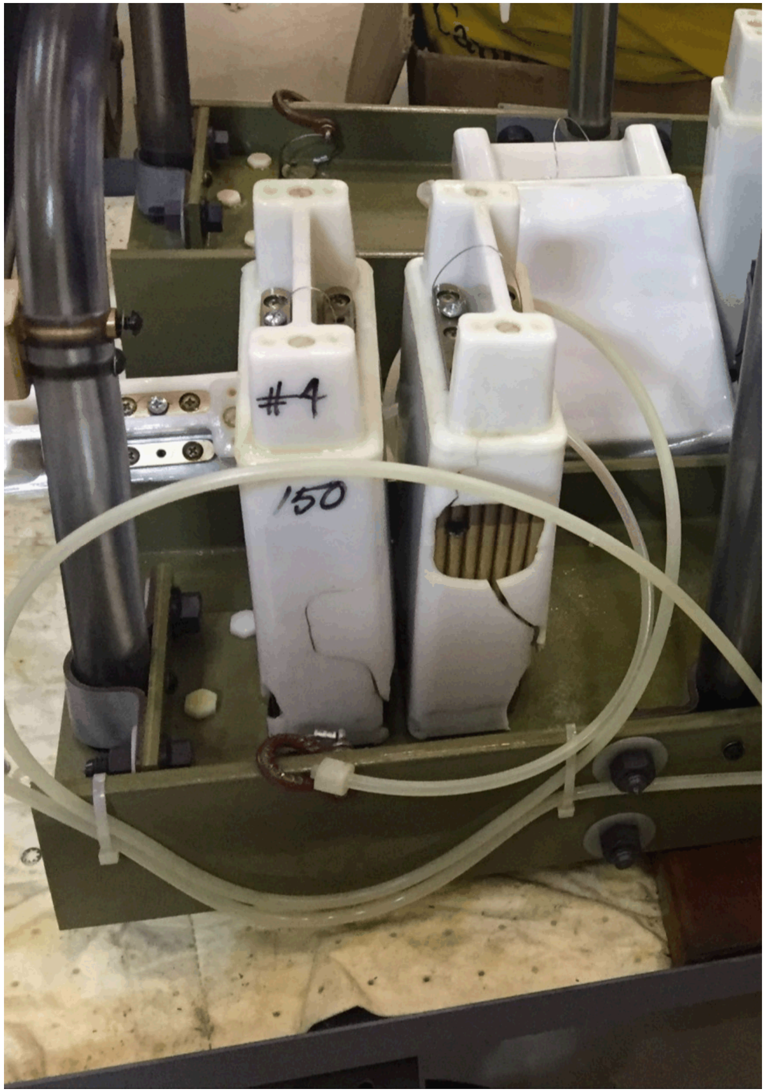
- The trigger for the Marx is distributed to the spark gaps by water resistors connected to a trigger bar
- Damage to an MTG has been attributed to tracking in one of these resistors



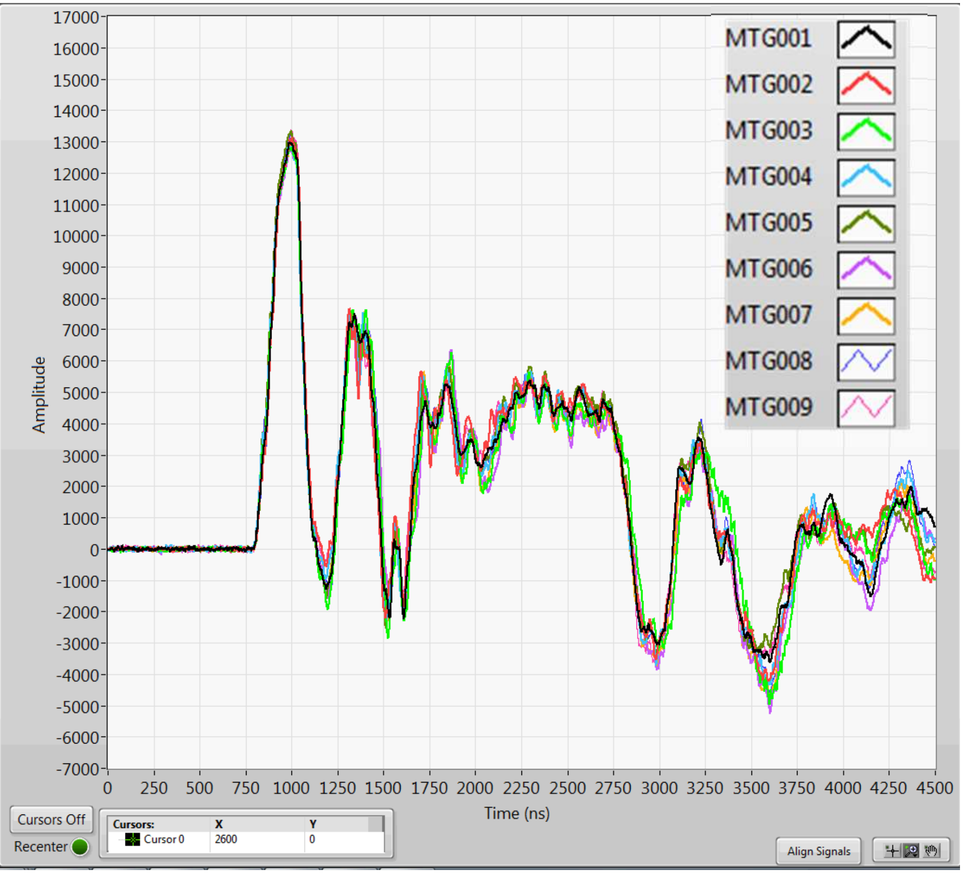
Z MTG Failure Mode: Tracking from a Main Marx

- When this failure mode occurs, the energy from the erected Main Marx can flow backward along the trigger line
  - Can result in a catastrophic failure of MTG hardware due to over-voltage and voltage reversal
- MTG capacitors are expensive and long-lead items
  - Thankfully, this failure mode is uncommon

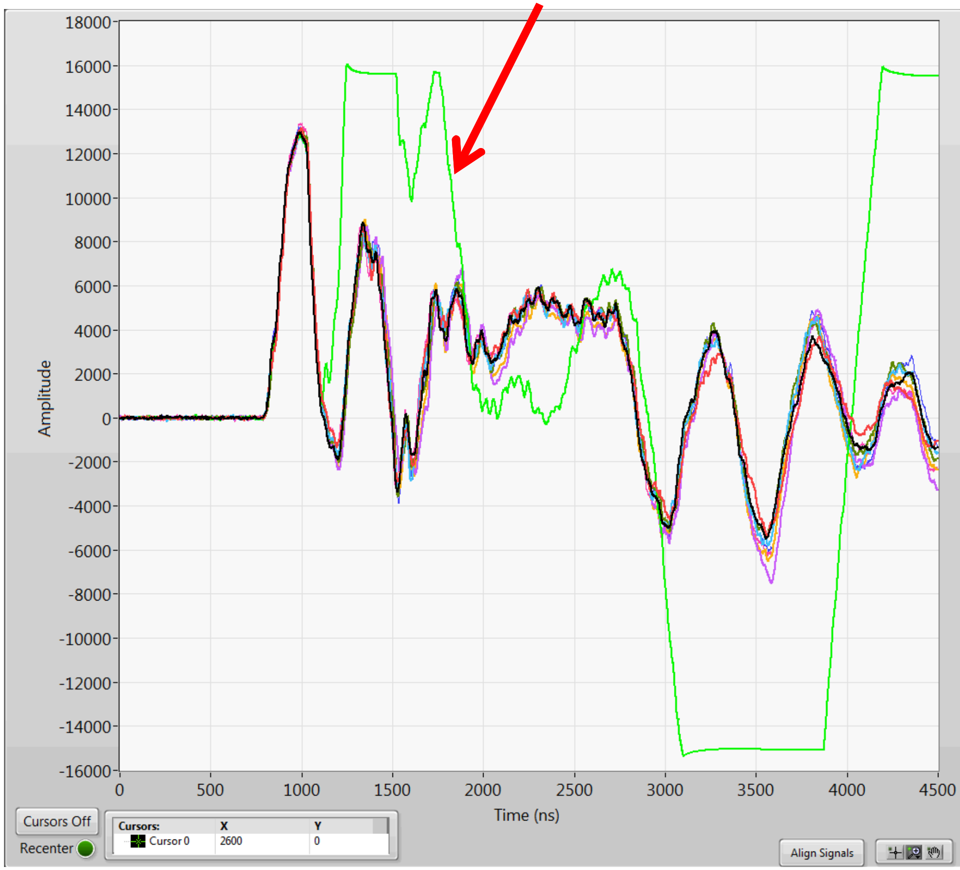


Z MTG Failure Mode: Tracking from a Main Marx

Normal MTG CVR Traces

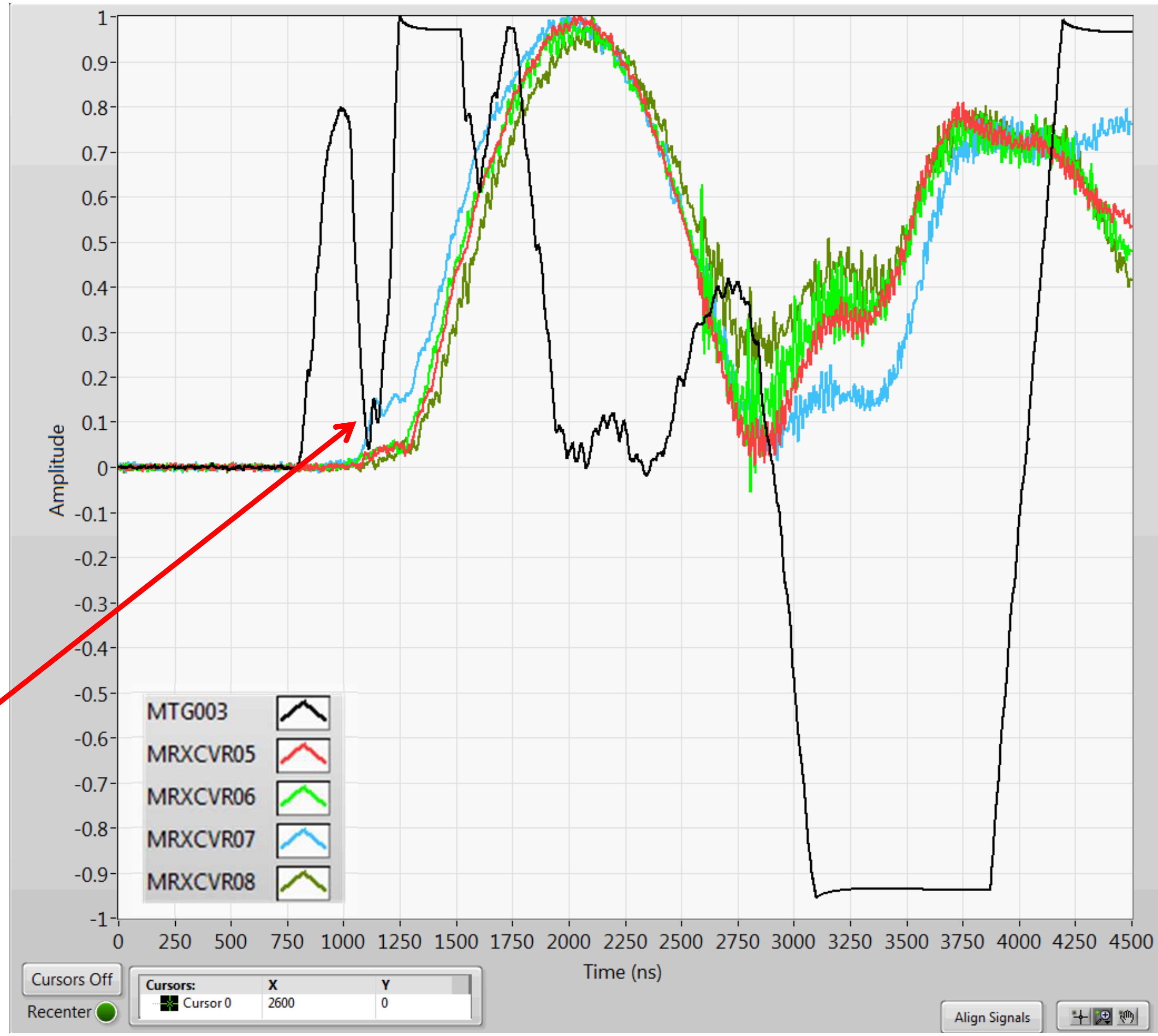


Fault Condition



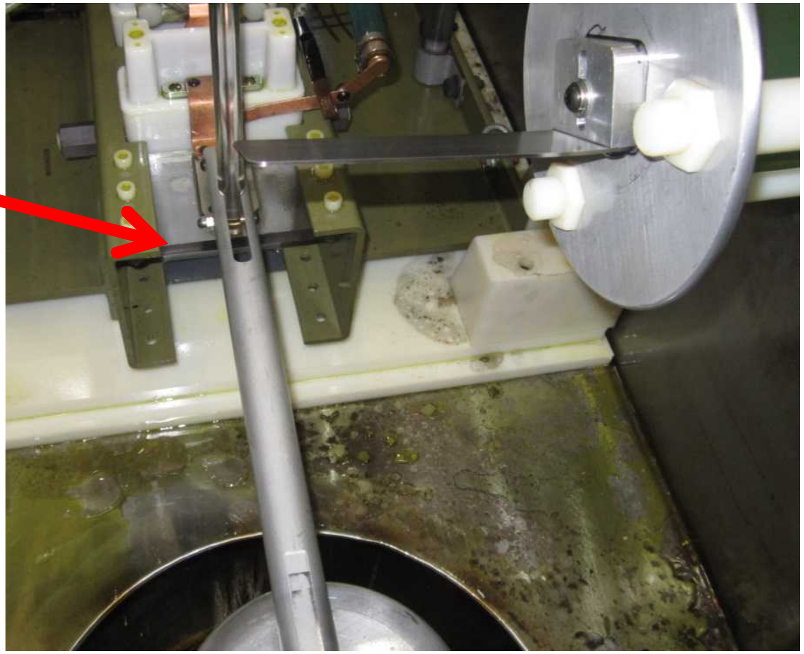
Z MTG Failure Mode: Tracking from a Main Marx

- Using the CVR signals on the MTG and the corresponding Marxes, we can locate which Marx caused the fault
- Note that the blue trace (Marx 7) corresponds with the onset of the fault in the MTG



Mitigation Techniques

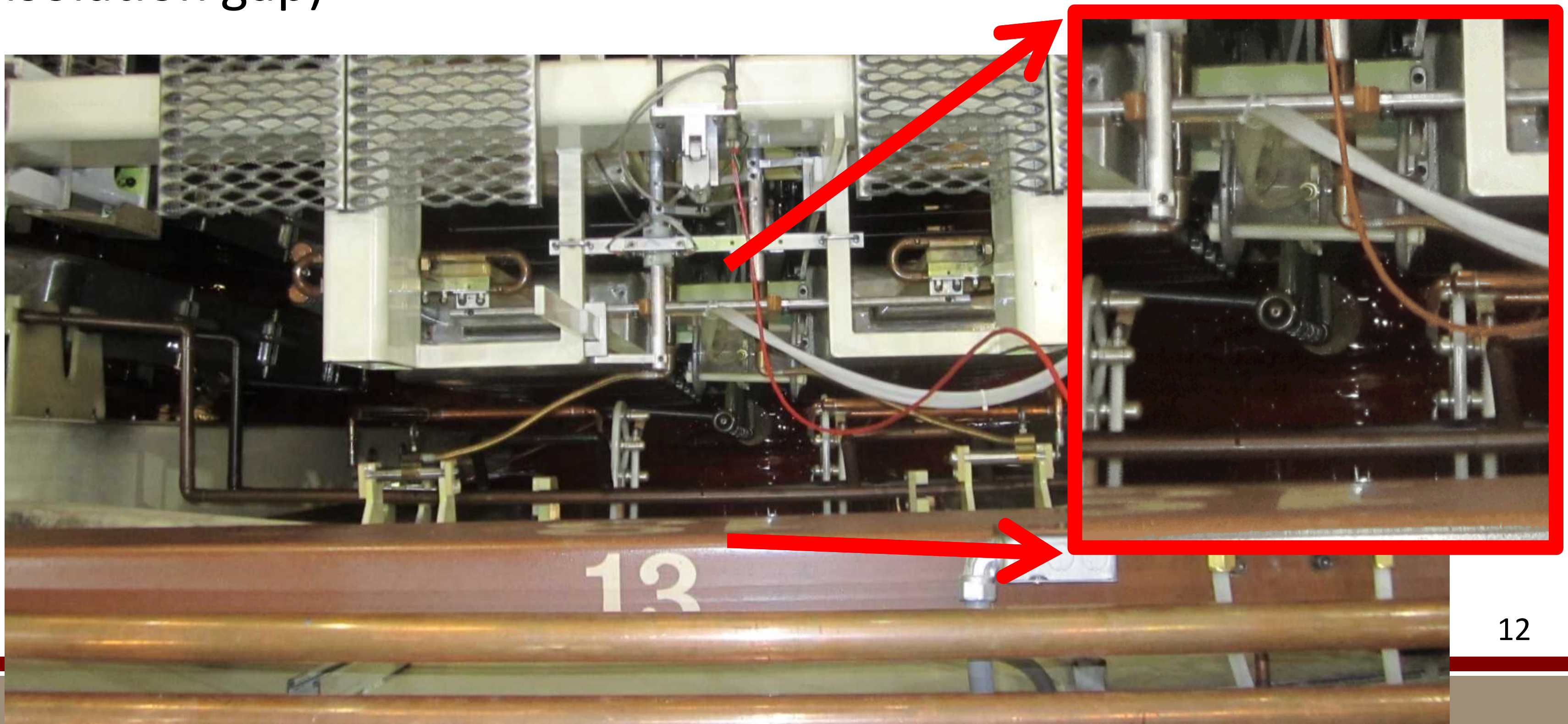
- Opening Switches
  - Impossible to move mechanical parts on the required time scales
  - Plasma devices require vacuum chambers and insulators
- Crowbarring/Shunting Switches
  - Provide a low-impedance path across the MTG output to quickly shunt higher-voltage transients
  - Similar to T/R switches used in high-power radar systems
    - A low energy pulse is able to transit the circuit without (appreciable) losses
    - A high energy pulse ionizes part of the shunt path, forming a low-impedance bypass



Photograph of the output swingarm on an MTG. The air-driven solenoid takes ~1 sec to actuate.

More Mundane Solutions
(being pursued in parallel)

- Longer resistors to reduce tracking (not much room here)
- Multiple, series trigger resistors instead of single resistors
- Shorten the Marx trigger bar to reduce chance of breakdown from nearby higher voltage components (e.g., the Marx isolation gap)



Requirements for a Z MTG Crowbar

1. Must be able to pass the ~450 kV MTG trigger output
2. Must be able to block the ~6 MV erected Marx voltage
   - May need to be able to block lower voltages, the peak voltage at Row 1 of the Marx is only ~1 MV at 85 kV charge
3. Must actuate on ~500 ns timescale

Photograph of Marx Test Bed MTG

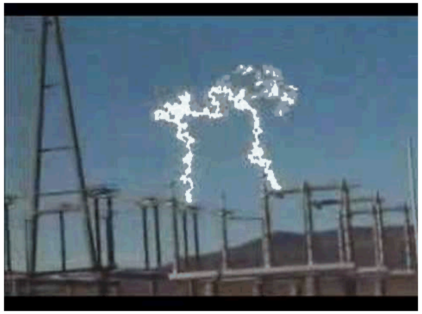
Requirements for a Z MTG Crowbar (continued)

4. Must not interfere with normal Marx output
5. Must operate ~150 shots per year
   - Must not add to the daily operational timeline
6. Must not add additional hazards to personnel or equipment
7. Should be self-actuating
   - Prefer no external triggering required
8. Should not add to Z maintenance/operational burden
   - Should not require specialized gases, fluids
   - Should not increase costs

Crowbar Topologies

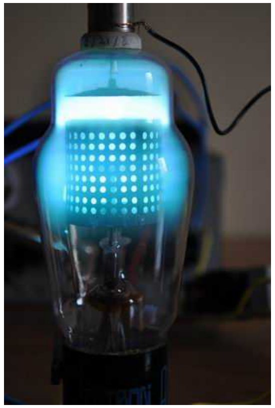
- Mechanical Switches/Fuses
  - Rated for high voltages, switchyards, etc.
  - Not feasible on these timescales (850 ns Marx risetime)
  - Not feasible at scales inside the oil tank
- Solid State Switches
  - Thyristors, diodes not available for this voltage or di/dt
- Gas Switches/Vacuum Switches
  - Again, Thyratrons not rated for this voltage and di/dt
  - Both require a trigger mechanism
- Asymmetric Oil Switches
  - A self-breakdown switch (as in a voltage tester)
  - Could modify existing trigger distribution hardware

youtube.com/watch?v=LHSVKuHqyKE



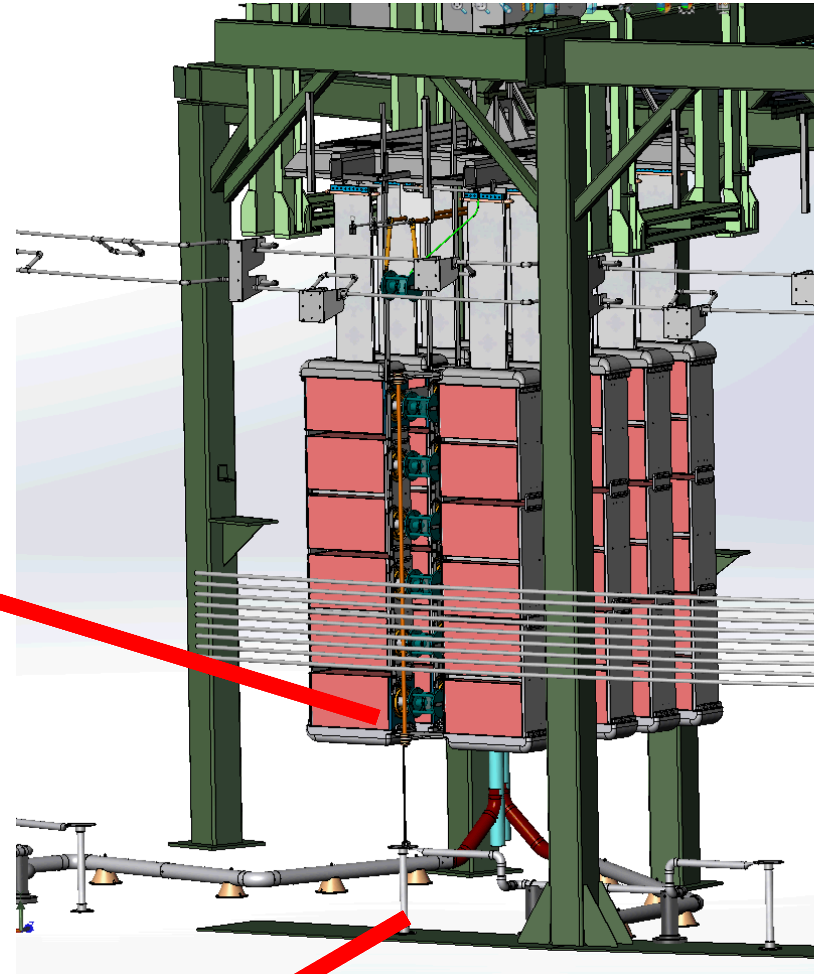
highpowersemiconductors.com

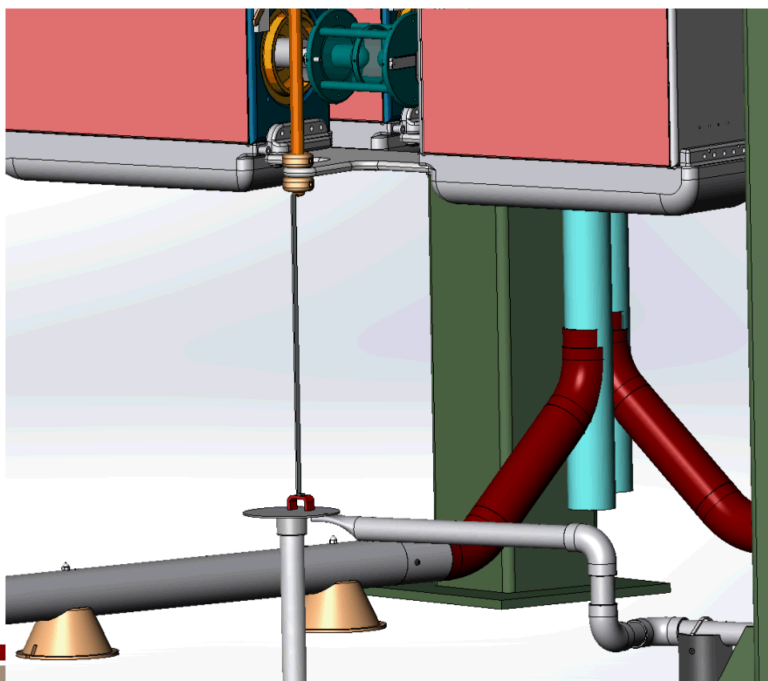
pocketmagic.net



Marx Trigger Distribution Hardware

- The output of the MTG is distributed to four Marxes by aluminum pipes supported by acrylic standoffs
  - A single crowbar switch could be installed before the trigger splits





Initial Crowbar Switch Design

- JC Martin pulsed breakdown of oil criterion: $E t_{eff}^{1/3} \sim 0.5$
  - Implies ~1 cm gap for 500 kV operation and ~1 μs t_{eff}
- Pulsed-breakdown voltages are known to be different than AC/DC values
  - Also affected by PW, electrode conditions, etc.

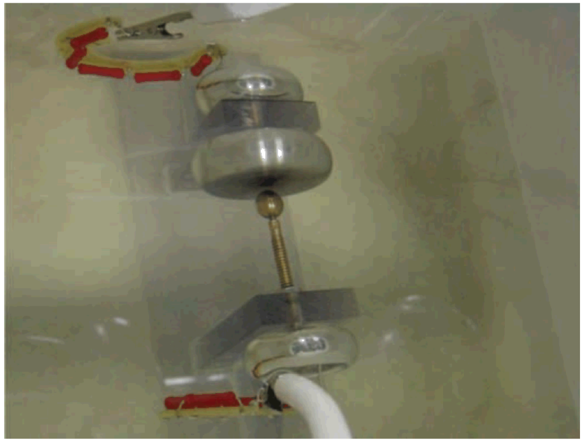
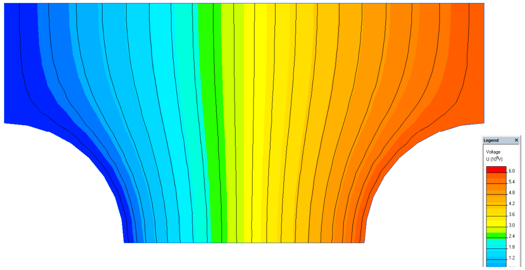
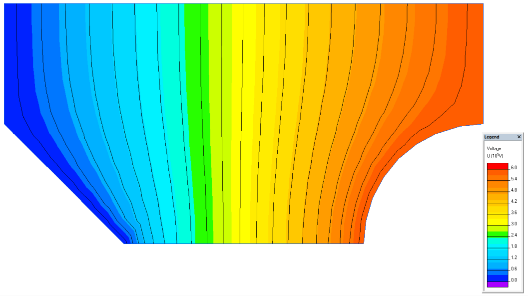


Image from: A. Pokryvailo and C. Carp, "Comparison of the Dielectric Strength of Transformer Oil Under DC and Repetitive Multimillisecond Pulses", *IEEE Electrical Insulation Magazine*, May/June 2012

2D QuickField simulations of electrode geometries in oil

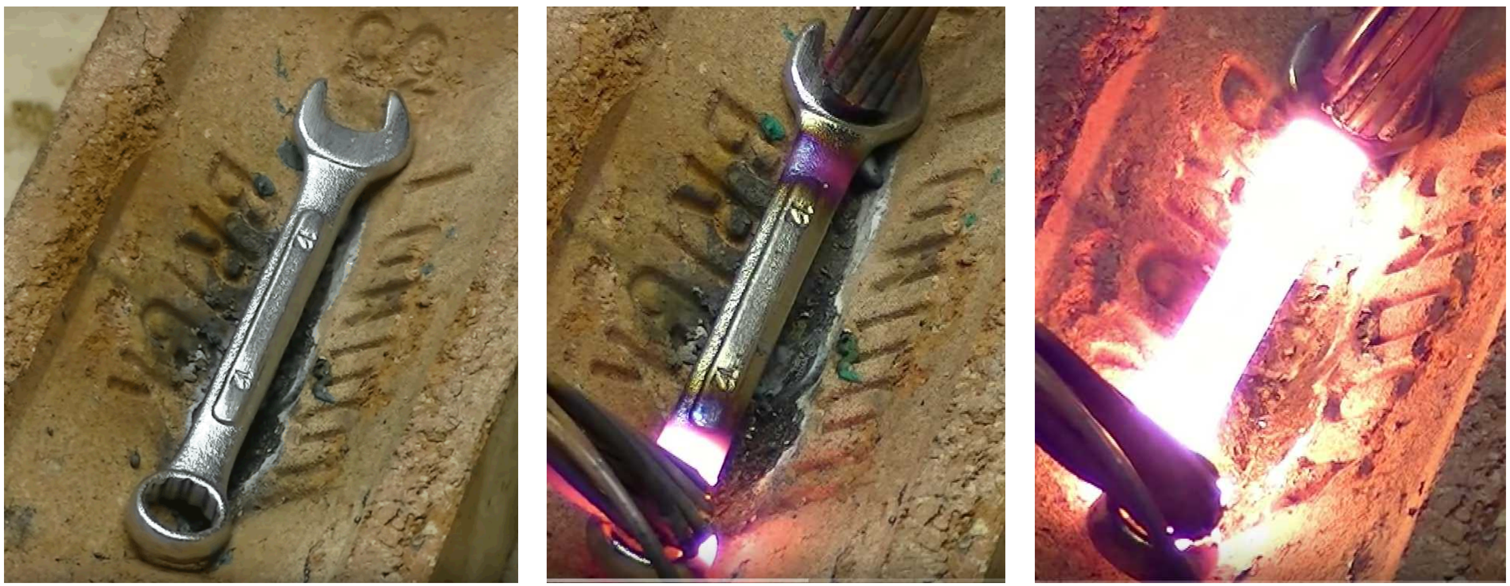




- Enhancement of the electrode geometry will affect
  - Switch lifetime/material ablation
  - The capacitance of the switch and associated closing time

Summary

- We have begun investigations into a self-breakdown crowbar switch in the oil section on Z
  - The goal of this switch is to protect the MTGs from excessive voltages



(Screen captures from youtube.com/watch?v=DJOX0c60wQE)

Questions?