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Electrical Safety Community of Practice

Impact of NFPA 70E 2021 Article 360 on R&D Capacitor Work: A User's Perspective

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Organization 1659, *Advanced Capabilities for Pulsed Power*

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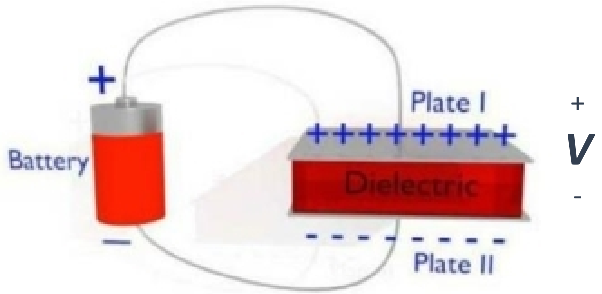
An Outline

- Capacitor Theory Review and Risk Assessments at Sandia
- Review of significant changes in SNL Electrical Safety with Article 360
- A ***few*** case studies of capacitor work at Sandia
- Collected feedback regarding outstanding issues, suggestions for Article 360 improvement

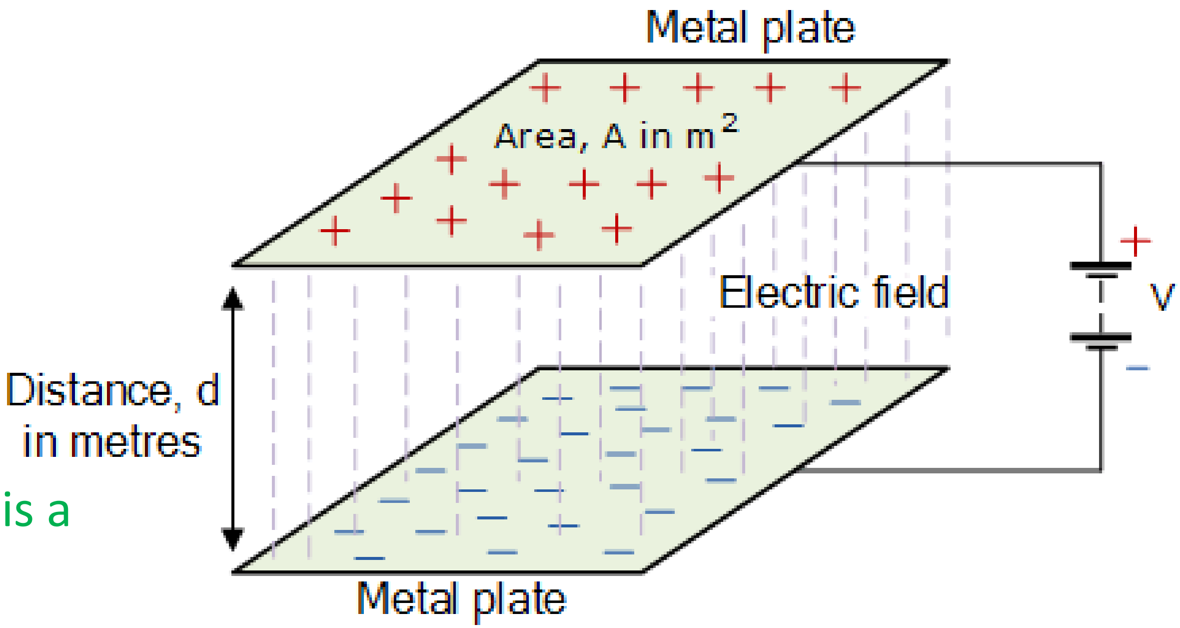
Capacitor Theory Review and Risk Assessments at Sandia

Capacitors are ubiquitous in commercial, R&D electrical systems

- A capacitor is two conductive elements separated by any nonconductive dielectric element
- A capacitor ***C*** stores energy in the electric field between two conductors charged to a voltage ***V***
- Discrete capacitors and distributed capacitance must be considered
- Capacitors are able to discharge energy much more quickly than chemical batteries
  - Applications in NW, explosives, pulsed power
- They also are useful in AC and DC applications to condition power, buffer, smooth, pulse, etc.
- These same properties make them hazardous to employees working with them (shock, arc flash hazards)
- Safely draining and verifying a capacitor's zero energy state is a strong focus of SNL's Electrical Safety Program



Stored Energy $\boldsymbol{E = \frac{1}{2}CV^2}$



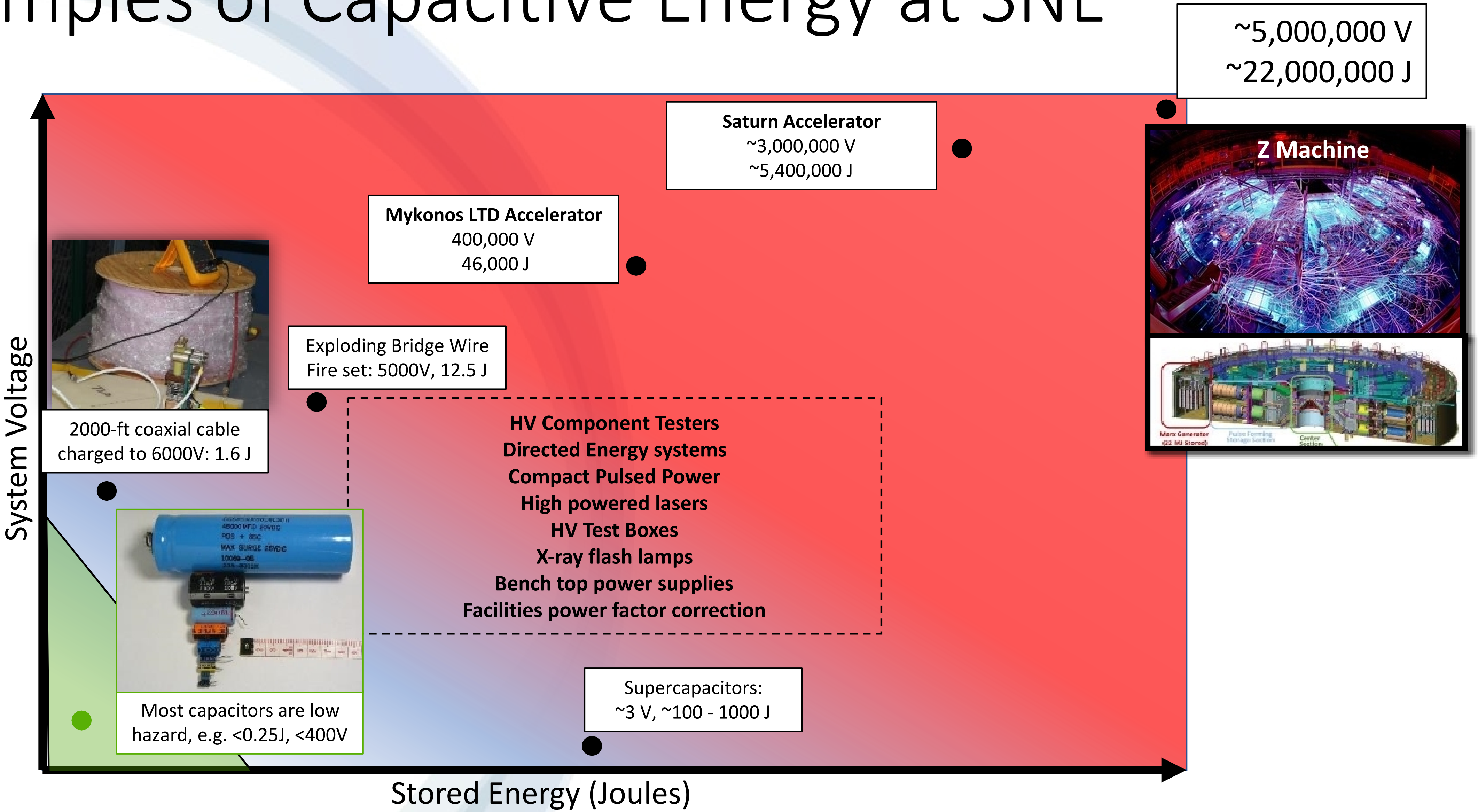
From https://www.electronics-tutorials.ws/capacitor/cap_4.html

Rule of Thumb for common capacitors in Electrical/Electronics Work

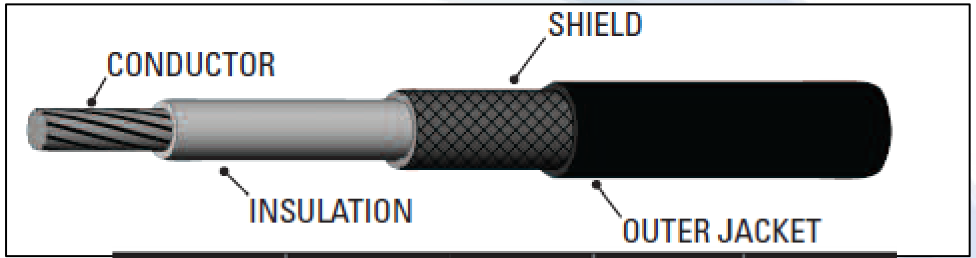
- It is ***Voltage*** and ***Energy*** that define the magnitude of hazard for a capacitor system
- A capacitor's **Energy** will scale with its **Volume*****; the bigger the capacitor, the more Energy it'll store***
- **Most** surface-mounted, axial- and radial-lead capacitors will not store hazardous levels of energy
- Rule of thumb: if a thousand can fit in a cabinet drawer, it's probably low-hazard and OK left unshorted
- **When in doubt, Calculate the ENERGY**

Drawers of capacitors are likely low-hazard and OK to be stored unshorted (left)
Larger caps can store more energy and need to be shorted when not in use (right)

Examples of Capacitive Energy at SNL

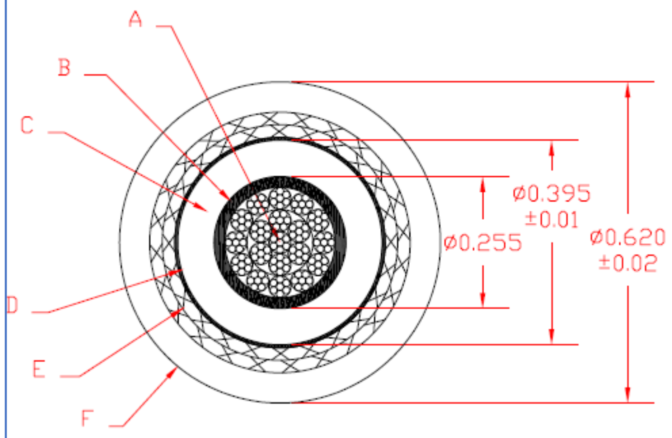


Distributed capacitance in cables can be a hazardous capacitor



Part Number	Operating Voltage (kVDC)	Imp. (Ohms)	Atten. dB/100 ft @ 400 MHz	Cap. pF/ft @ 1 kHz
167-2669[3]	20	31	16.0	48.0

Teledyne-Reynolds HV cable http://catalog.teledynereynolds.com/item/high-voltage-wire-and-cable/high-voltage-coaxial-shielded-cable/high-voltage-coaxial-shielded-cable-3



LEGEND

A. #6 AWG, 133 (19x7) OF #27AWG T.C., ø.213
B. SEMICON POLYETHYLENE, .02 MIN. WALL., ø0.255
C. LDHMW POLYETHYLENE, 0.07 WALL.
D. SEMICON TAPE, 0.0055 THK, HALF LAPPED.
E. # 30 AWG TC SHIELD (DOUBLE SHIELD), 7 ENDS, 24 CARRIER, 95% COVERAGE.
F. JACKET, BLACK POLYETHYLENE, .06 WALL.

Dielectric Sciences Pulsed Power Cable #2323 (https://www.dielectricsciences.com/wire-and-cable-products/)

- Coaxial cable and other transmission lines have characteristic impedance
- Have fundamental capacitance per unit length
- **Cables <u>long enough</u> with enough <u>high voltage</u> can store hazardous levels of energy**
  - **Must be assessed and safed as a capacitor!**

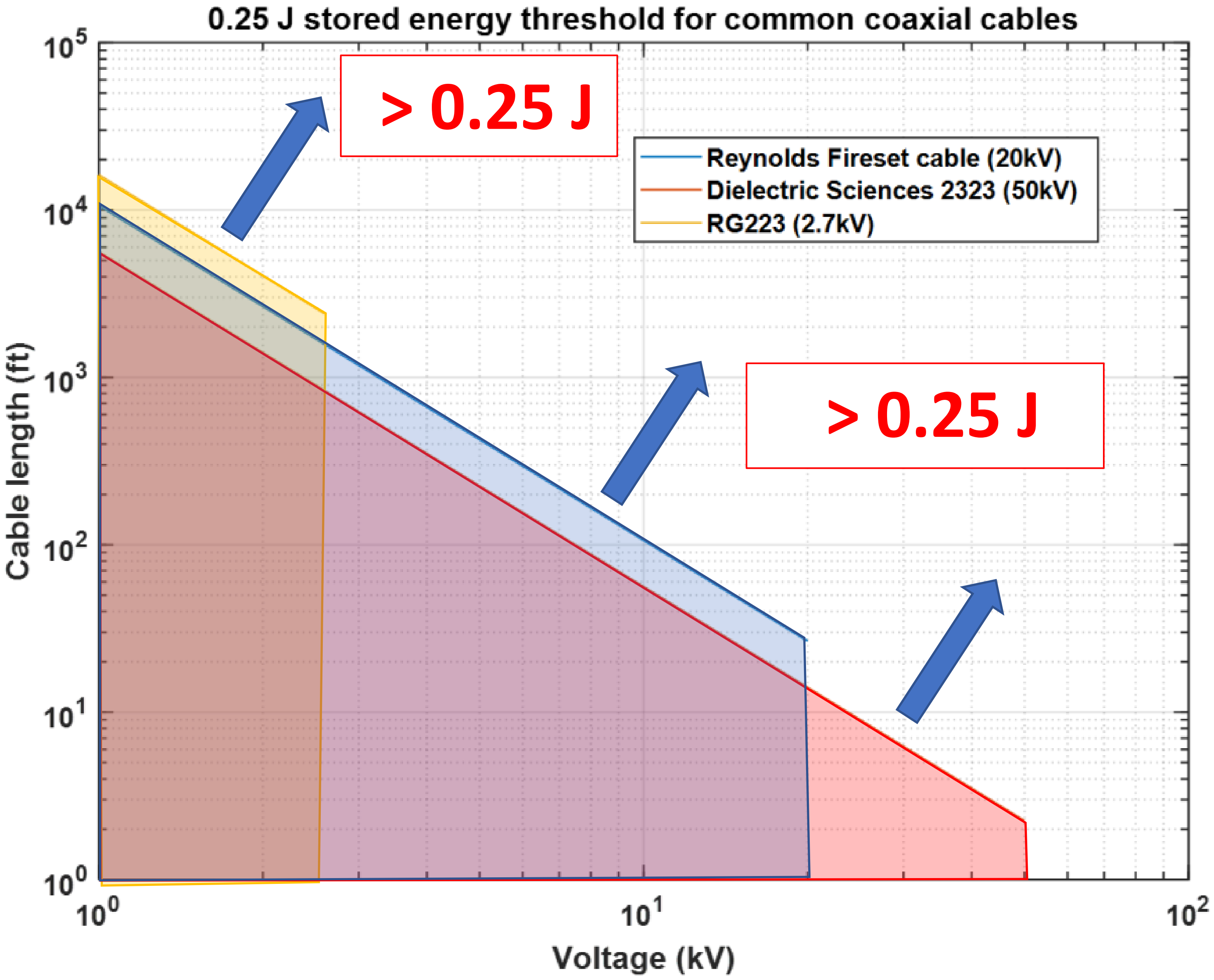
Example capacitance per unit length:

- RG223 (HV signal bias cable): $31\frac{pF}{ft}$
- Teledyne Reynolds 167-2669: $47\frac{pF}{ft}$
- Dielectric Sciences (Pulsed Power): $89\frac{pF}{in}$

$$E_{stored}\,[J] = \frac{1}{2} C_l \left[\frac{pF}{ft}\right] l\,[ft]\, V^2$$

$$E_{stored} = \frac{1}{2} C_l\, l\, V^2$$

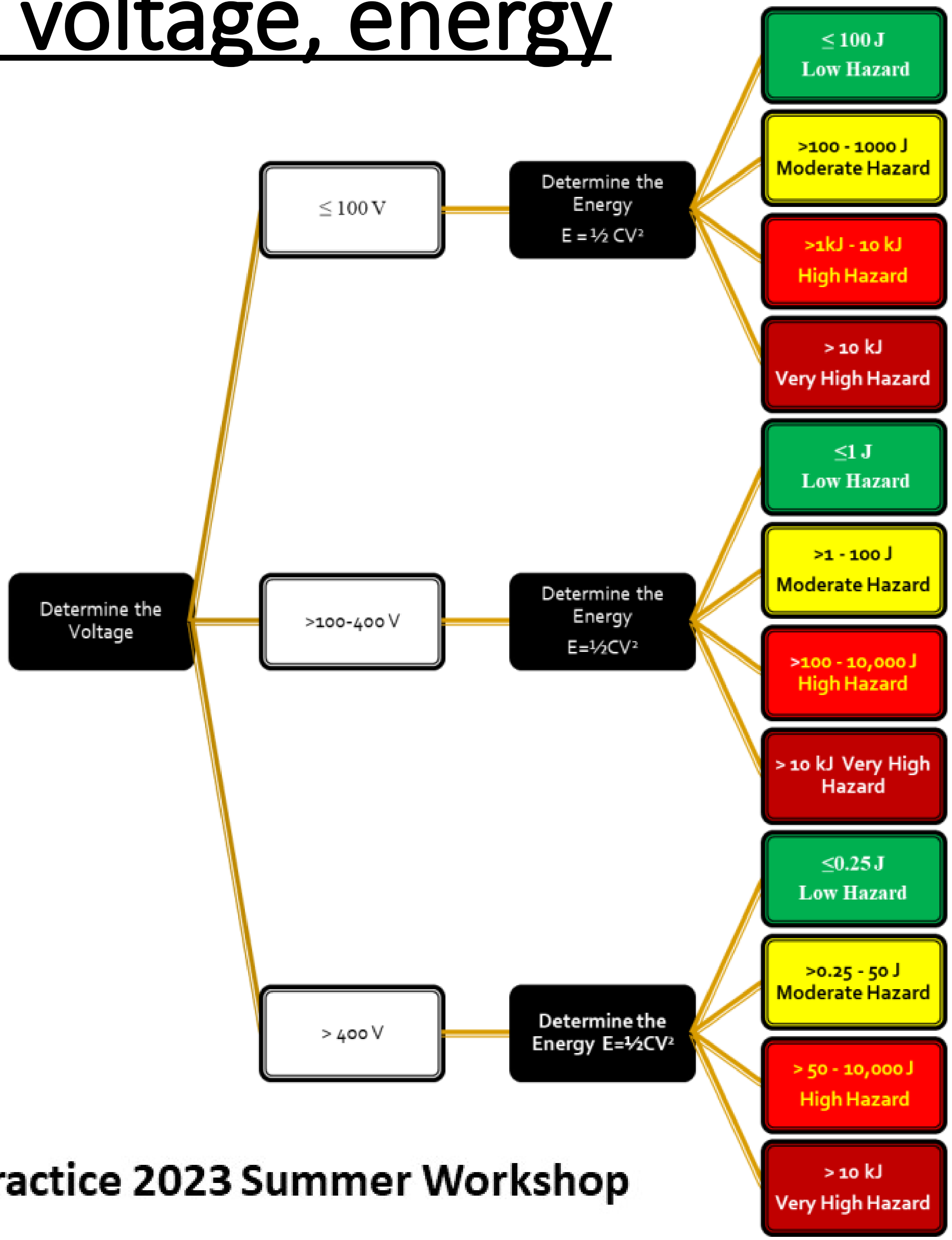
Voltage AND cable length must be considered for assessing distributed capacitance



$$E = \frac{1}{2} C_l l V^2$$

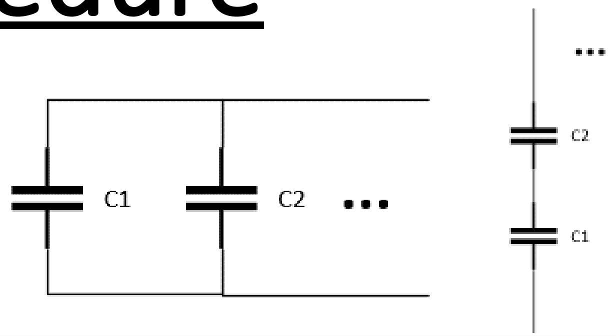
SNL risk assessment is based on voltage, energy

- **Three bins representing different shocks**
  - **< 100 V, > 100 J**
    - Super capacitors
    - Thermal hazard
  - **100 V to 400 V, > 1 J**
    - Facilities: e.g. power factor correction, line filters
    - Shocks limited by skin resistance
  - **> 400 V, > 0.25 J**
    - High voltage, low capacitance systems are mostly relevant to R&D systems
    - HV supplies, buffering, filtering, pulsed systems, x-ray sources, fire sets, parallel capacitor banks, Marx Banks
- Energy thresholds lower at higher voltages to reflect skin breakdown
- Low Hazard is essentially treated as No Hazard in terms of required controls

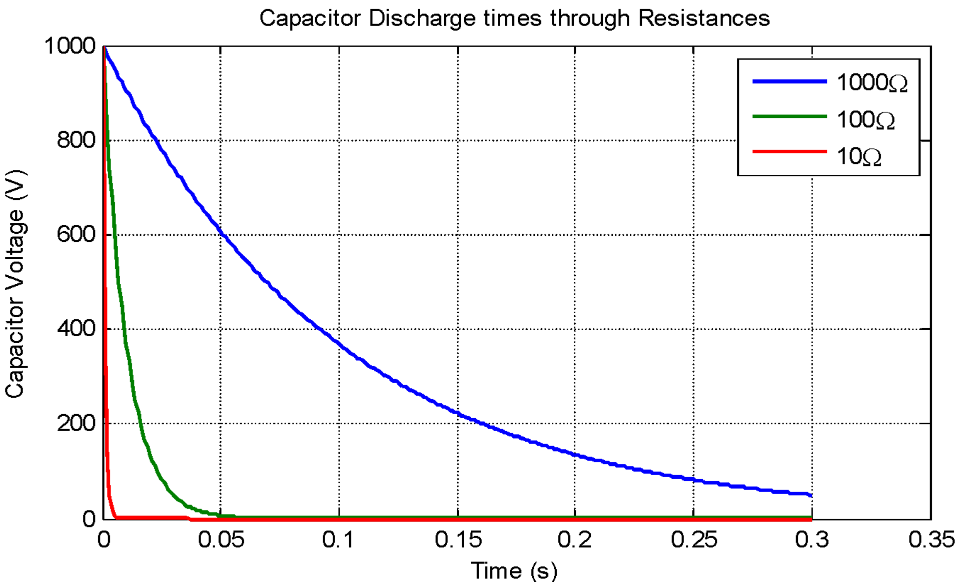


Risk assessment and safing procedure

- Determine total capacitance to be discharged
- Identify operating voltage
- Determine stored energy
- Assess hazard class
- Identify required PPE
  - Thermal, hearing, eye, shock if necessary
- Establish and respect approach boundaries
- *[pre-Article 360]* Use shorting sticks longer than RAB
  - Discharge stored energy
  - Verify it has been discharged
  - Keep it discharged



Capacitors in parallel (left) series (right) have different electrical characteristics



Discharging a Capacitor into a Resistor removes stored energy, eliminates shock hazard

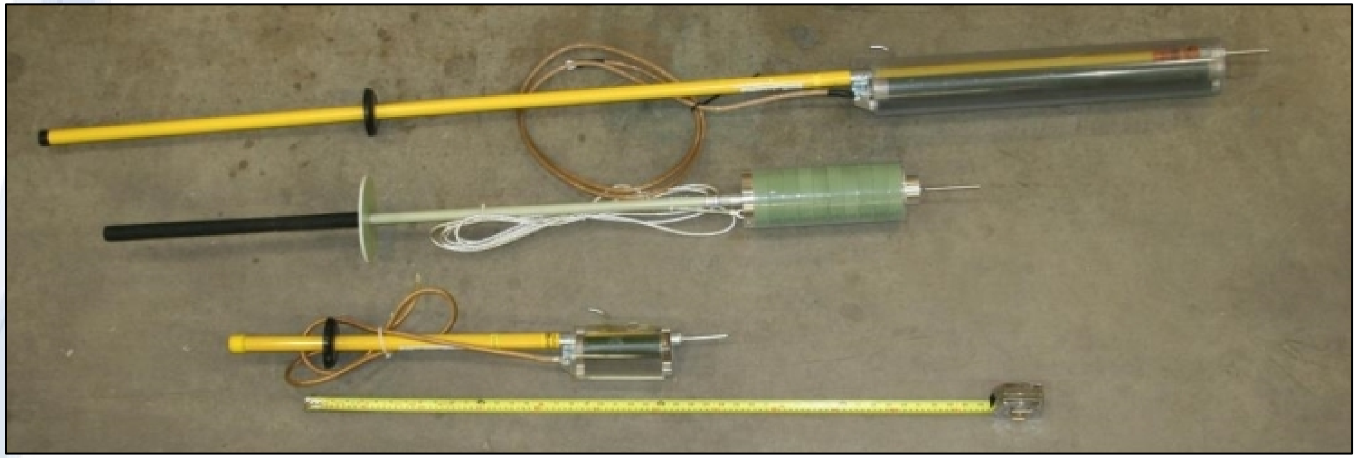
Use of shorting sticks as primary means of discharging (and verification of zero energy) capacitors

If E > 1 kJ, use a **Soft Ground for 5τ**… Follow with a **Hard Ground**.

Use a **Hard Ground** for **1s ON, 1s OFF, 1s ON**… Follow with a **Permanent Short.**

Leave the **Permanent Short (Drain Wire) for $\infty\tau$ …** or until the next time you use the system …

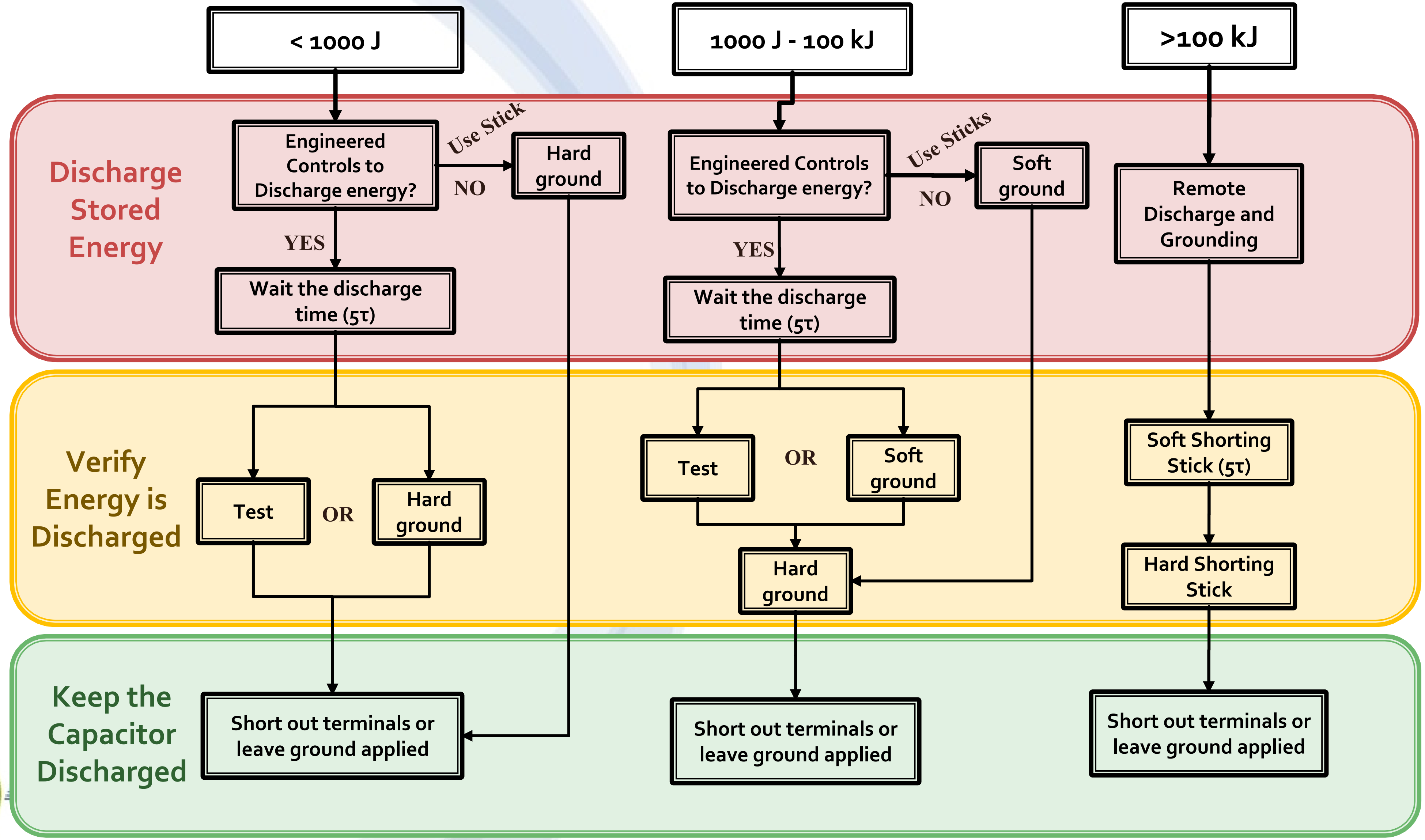
Hard grounding sticks provide direct, low-resistance path to ground. **Can generate significant arcs in high-energy systems!**



Soft grounding sticks provide resistive path to ground to limit peak discharge current and rate of energy dissipation.
Shock hazard still remains if user does not wait 5τ to complete discharge!

Review of significant changes in SNL Electrical Safety with Article 360

Test method codified as alternative to zero energy verification with shorting sticks



Test method codified as alternative to zero energy verification with shorting sticks

- This change dramatically improved engagement with electrical safety with multiple organizations working with ~1 – 100 J systems
- Many board-based systems were not easily accessible with a shorting stick, and much resistance was felt to their required use
- Many engineers rightly design their capacitive systems with redundant engineered controls
- Verifying test points or capacitor leads on a complex circuit board with a multimeter is often much preferred to requiring grounding sticks

(We appreciate the note on requiring testing of meters on live sources)

Required visual inspection of grounding stick and discharge path

- 360.6(A) – **Visual inspection**
  - Requirement to inspect a shorting stick before **each use** and remove from service if anything does not meet expectations

  - Physical condition, Resistor intact, shield intact, lead undamaged and insulator undamaged, clean
  - No opaque shrink tubes at mechanical connection points
  - Continuity measurement with multimeter (<1Ω).
  - If resistive element in place, multimeter confirms faceplate value

- This had been a good safety practice before, but now we have the backing to require it. Shorting sticks are the most important piece of PPE!

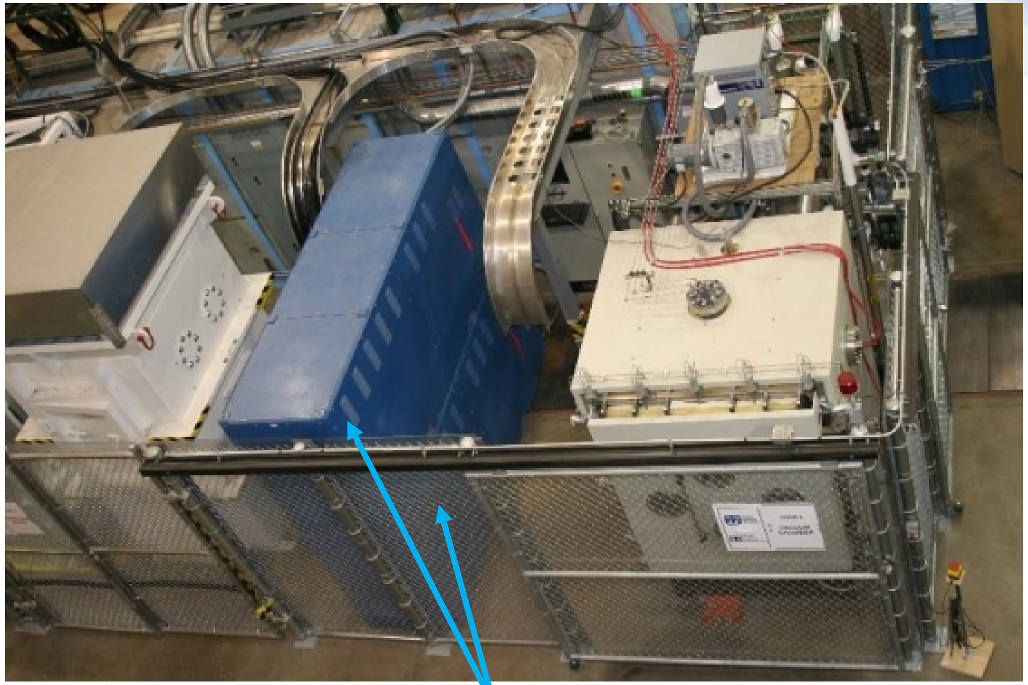
Removed ambiguity on shorting stick length and Voltage rated shock PPE

- Article 360 and Informative Annex R give interpretation that shorting sticks ***may*** be used that are shorter than the Restricted Approach Boundary (RAB) ***if*** voltage-rated shock PPE is worn
- Before, we required sticks to be longer than the RAB by default
- Many applications existed where dexterity and limited access precluded the use of long sticks
- Use of shorter sticks while wearing PPE allows for safer operation in these cramped quarters

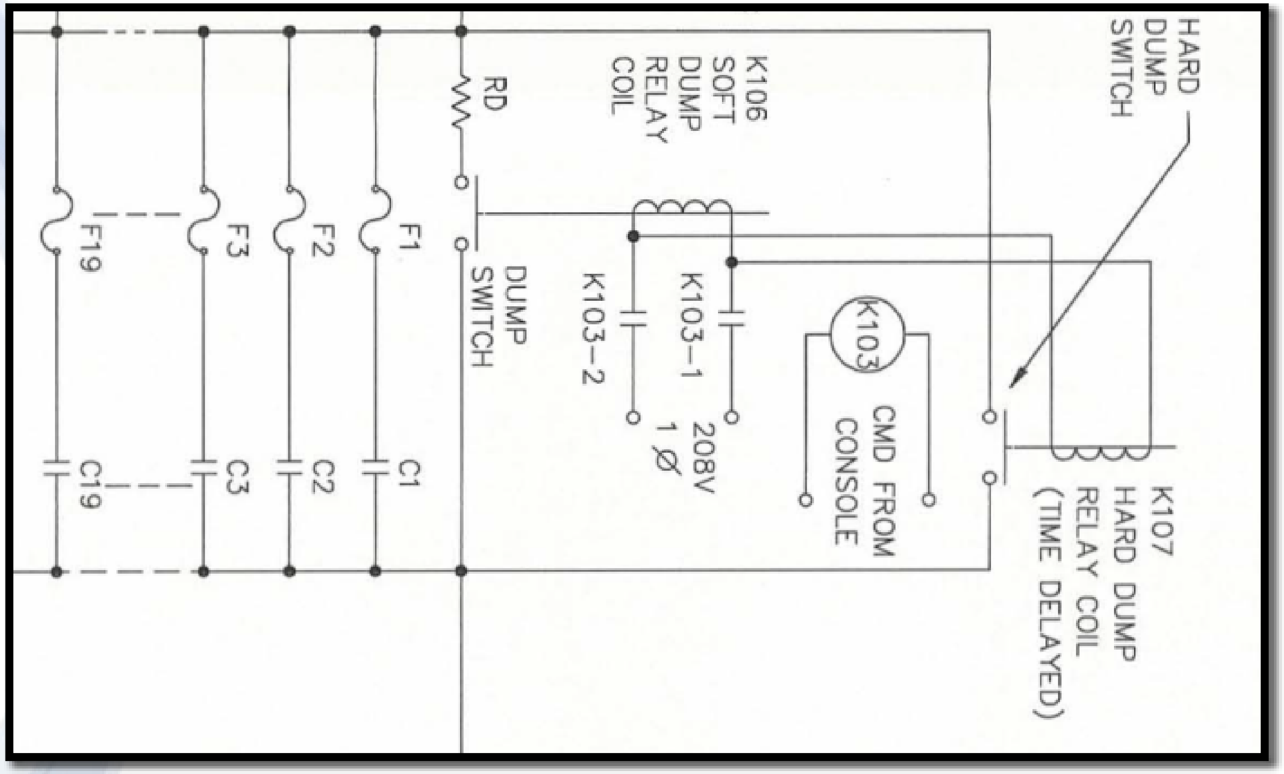
- Allowed for simple, clear statement of when shock PPE was required.

A ***few*** case studies of R&D Capacitors at Sandia

2ea. 450-kJ Parallel plate capacitor bank to drive electromagnets that produce > 20 Tesla

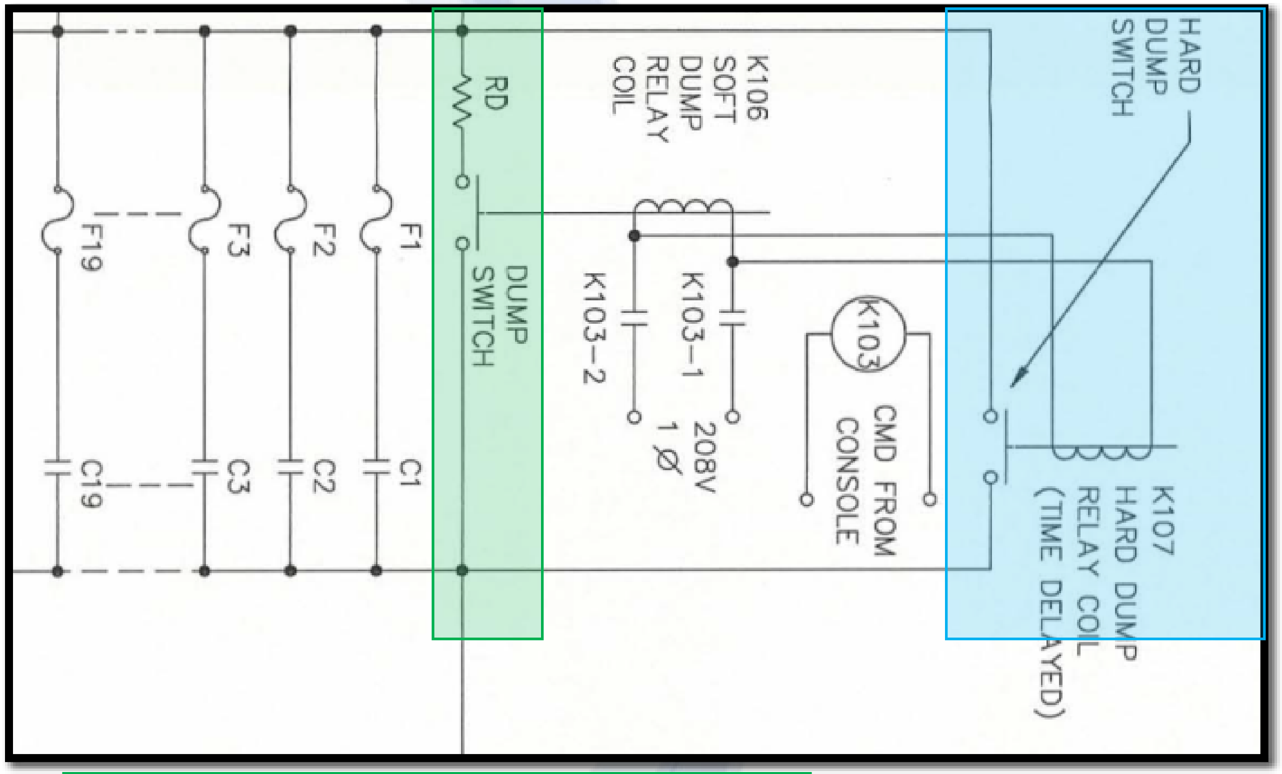


Blue enclosures are 2ea. Stacked 450 kJ, 15-KV capacitor banks to drive electromagnets.



Simplified circuit schematic showing 19 parallel ~210μF capacitors and safety circuitry.

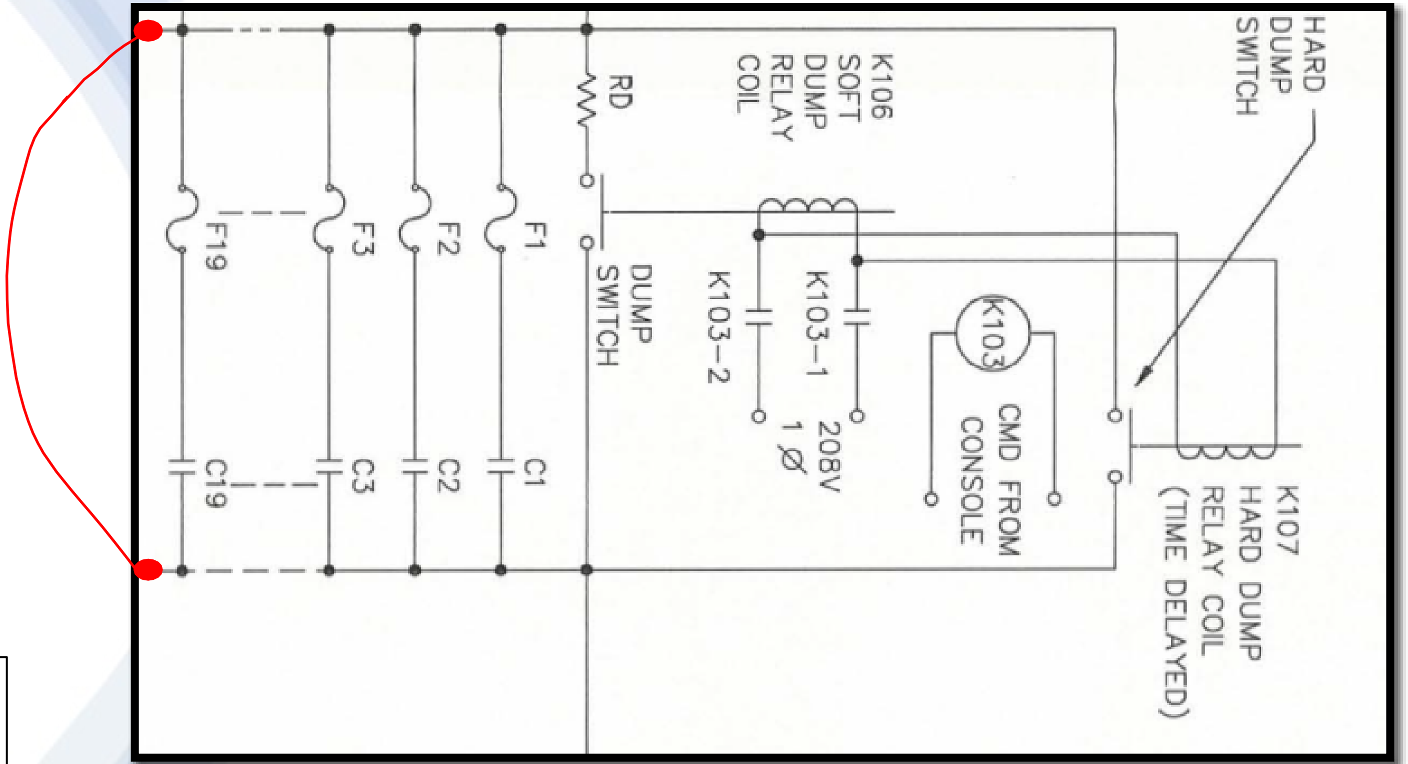
Each capacitor bank utilizes parallel soft- and hard-engineered discharge paths



“Soft short” Dump relay connects 78Ω resistor to 4 mF capacitor bank; $5\tau \sim 2 seconds$

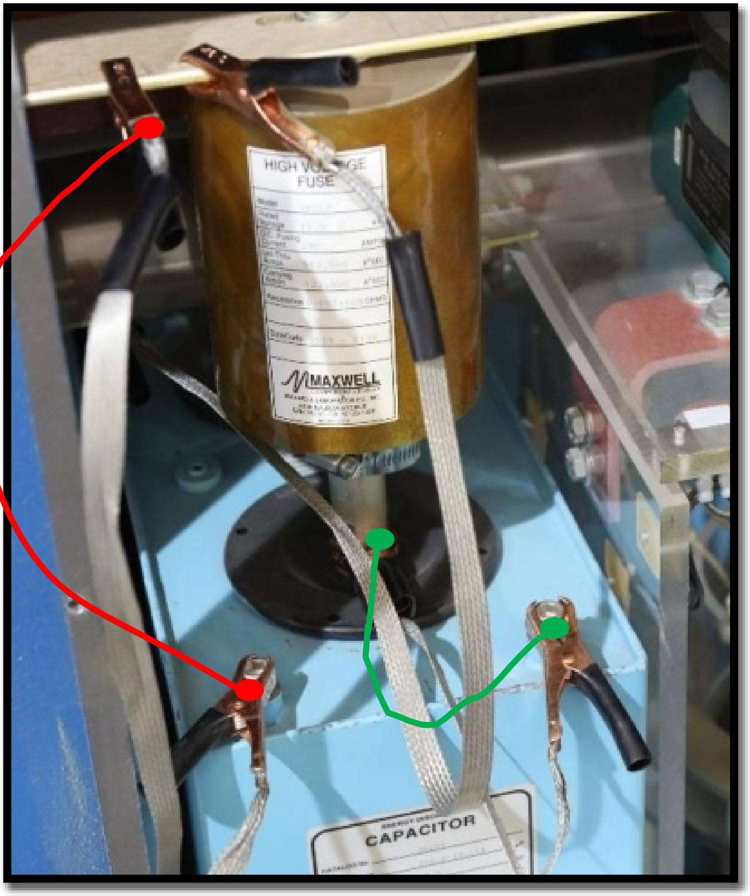
Hard shorting relay is hardware-timed to open >6τ after soft short closes.

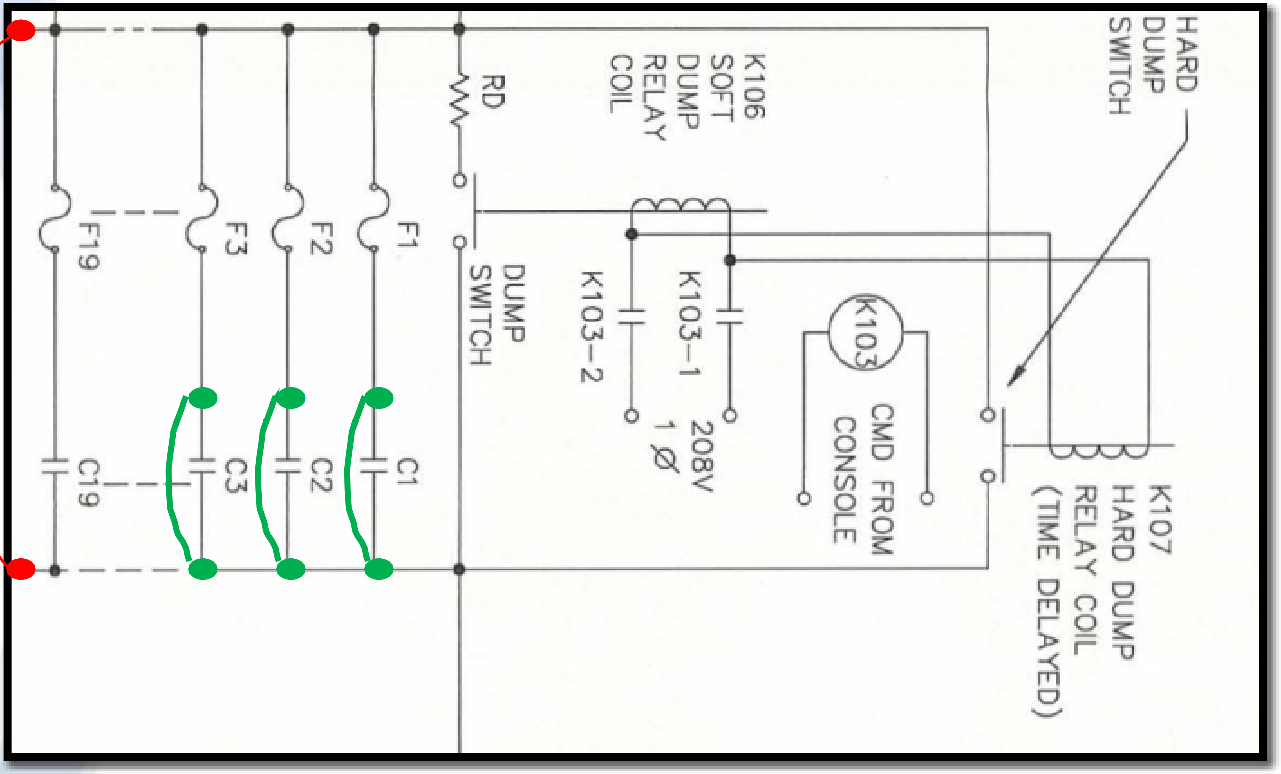
User maintenance – when removing panels from bank, must short out parallel capacitor bus



"Maintenance" requires panels to be removed. Worker uses soft shorting stick, then hard (soft shown above). (PPE shown is for demonstration only)

User maintenance – when removing panels from bank, must also short out individual capacitors upstream of fuses





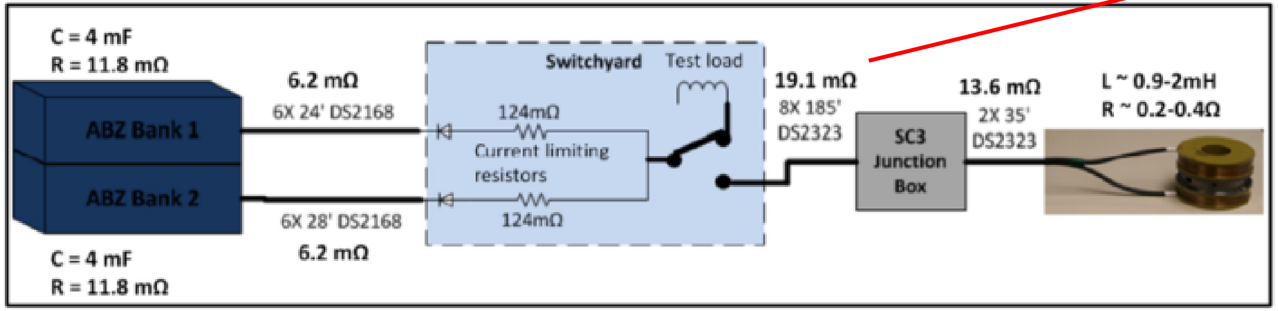
Exposed capacitors (with panels removed) are shorted upstream of fuse as well to ensure "opened" fuse is not isolating capacitor energy

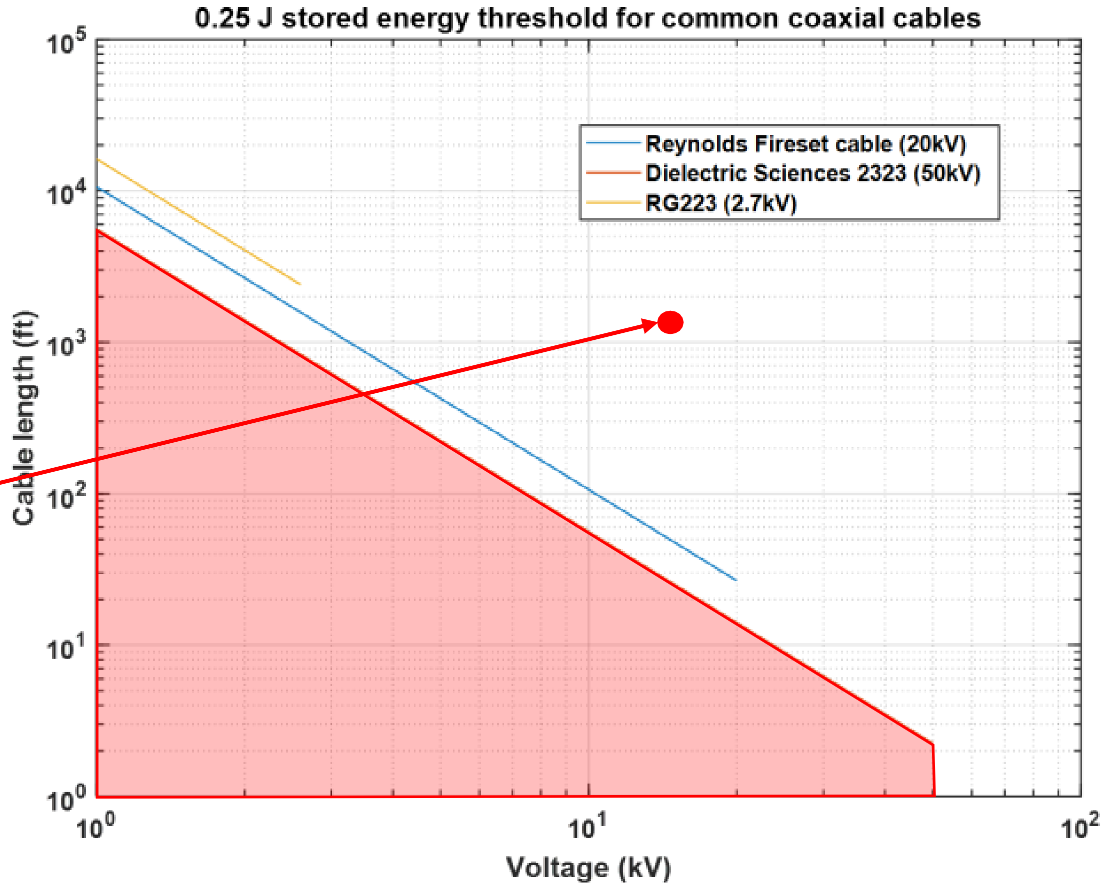
This capacitor bank system also has eight 185-ft cables connecting the banks to the coil load

- These eight parallel output cables could store 15 J at full 15kV charge if failures in system occur

$$E_{cables} = \frac{1}{2} \cdot 89\frac{pF}{ft} \cdot [8 \cdot 185\ ft] \cdot 15kV^2 = 15\ J$$

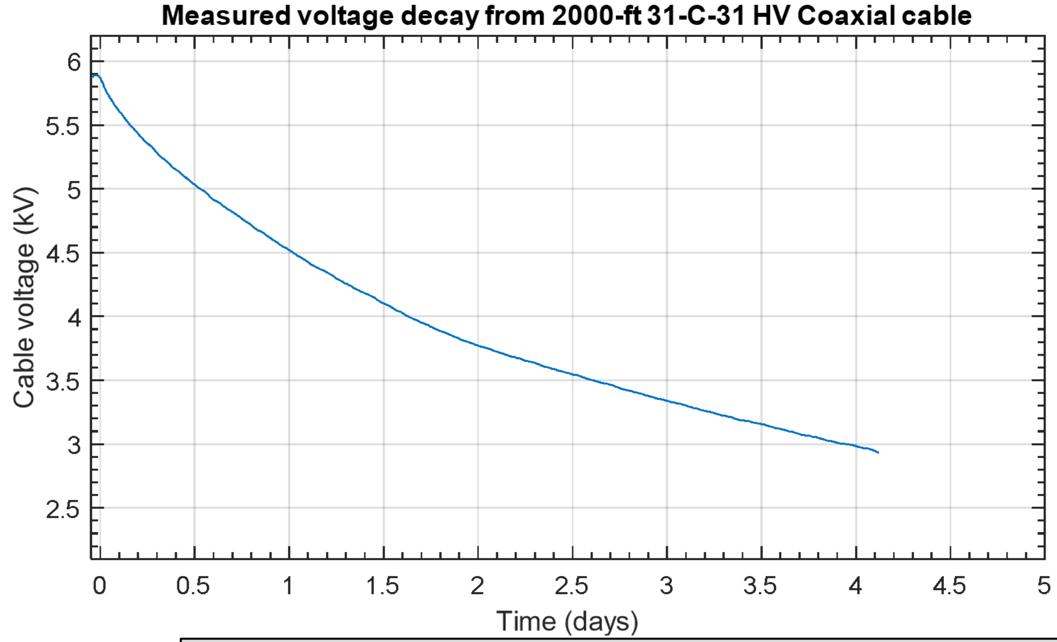
- We utilize a hard grounding stick to discharge and verify discharged this set of cables
- We keep a shorting strap across these outputs when not in use



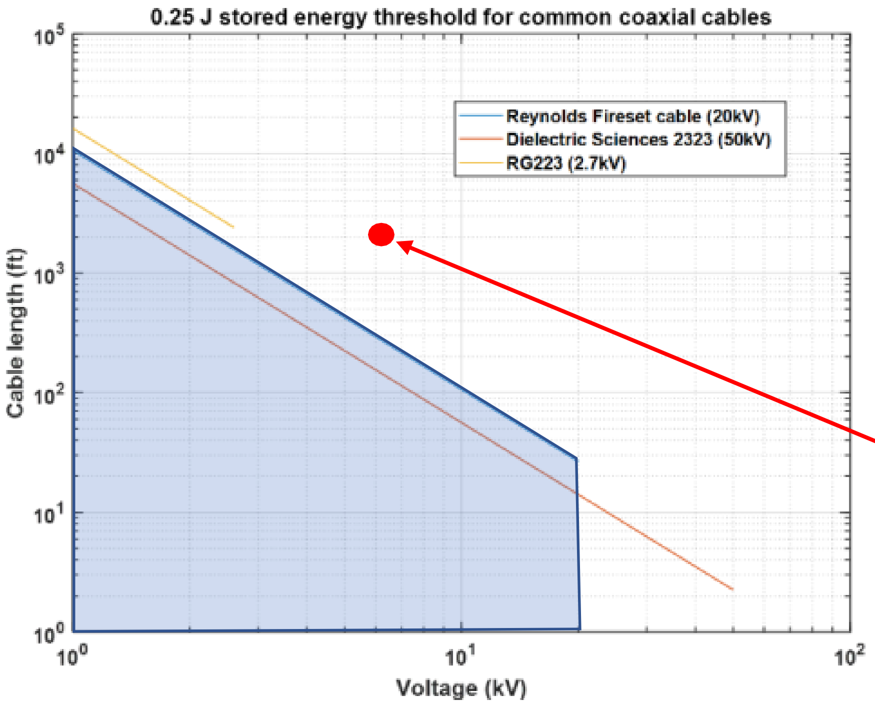


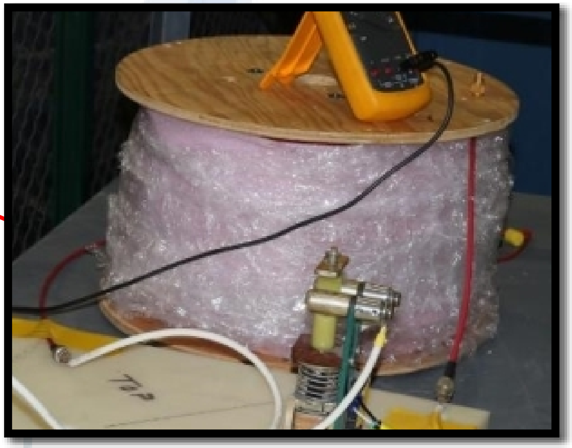
A mild shock in 2020 from a two thousand foot Teledyne Reynolds Fire set cable

- MOW was shocked by a 2000’ cable when applying a shorting plug to the end of a cable that had just been received from vendor.
- The cable had been hi-potted by the vendor and shipped, perhaps without first verifying zero energy
- The shock occurred 5 DAYS after the package shipped.
- The cable was rated at 7.5kV$_{DC}$
- At 2000-ft long and 6 kV, the cable had 94nF and stored 1.6 J!

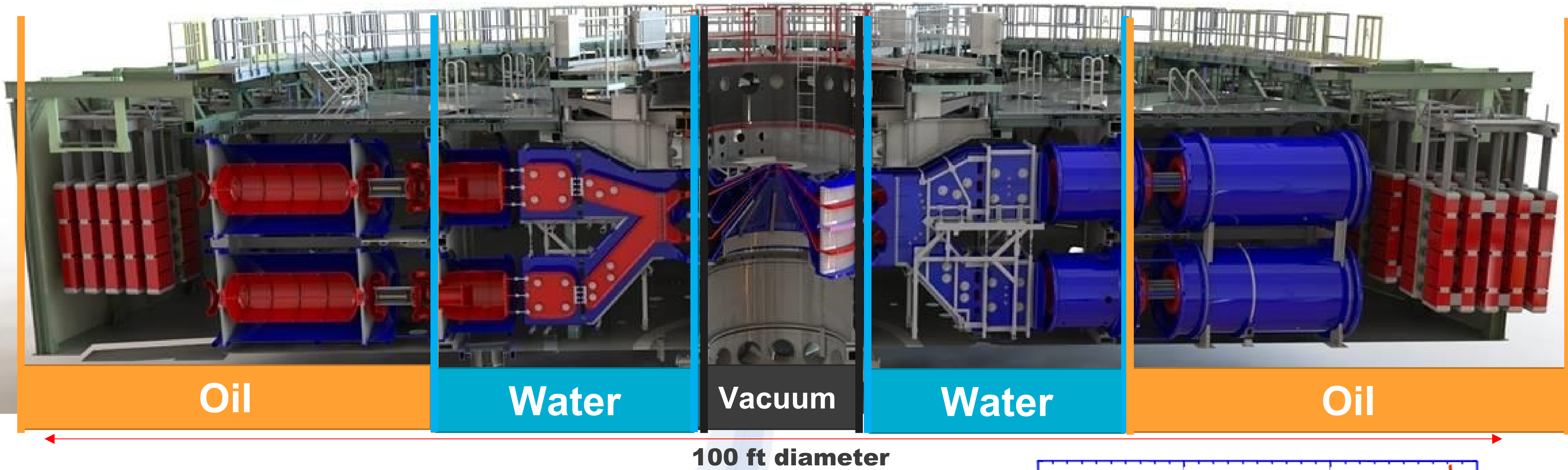


Measurement made with cable in question shows that 50% of voltage remained after 5 days!

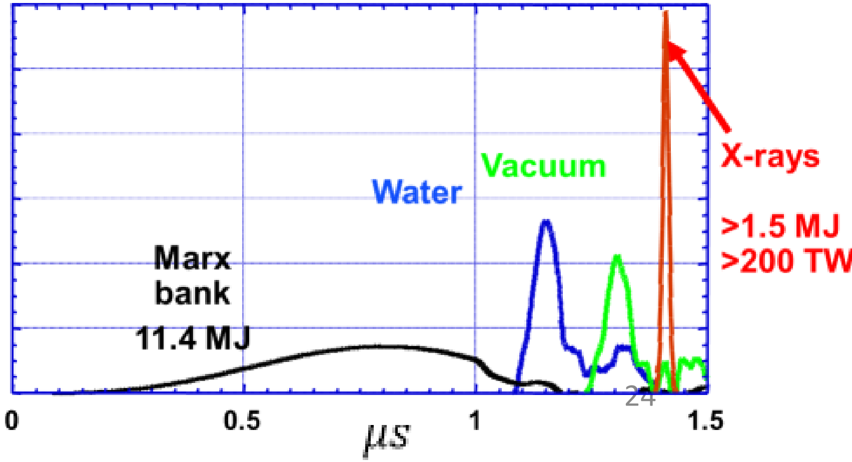




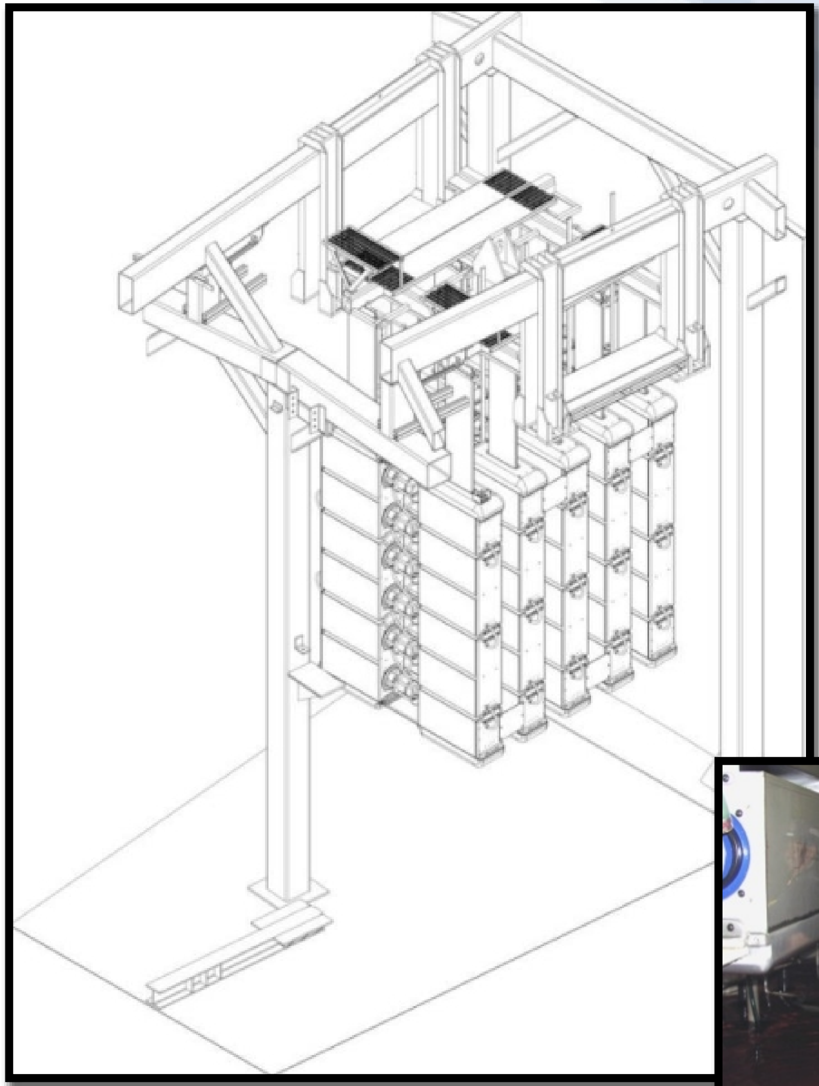
Marx banks in Sandia's world-class HED accelerator
The Z Machine



- 36 identical Marx banks can store 23 MJ
- Oil, water, and vacuum sections compress energy into ~100ns risetime, 20 – 26+ MA
  - Can produce 2 MJ radiated x-ray power
  - Can produce 8 Mbar pressure
  - Can create fusion conditions



Each (of 36) Marx bank has 60 individual capacitors (2160 in total!)



Let’s begin a detailed Circuit Analysis (slide 1 of 8)

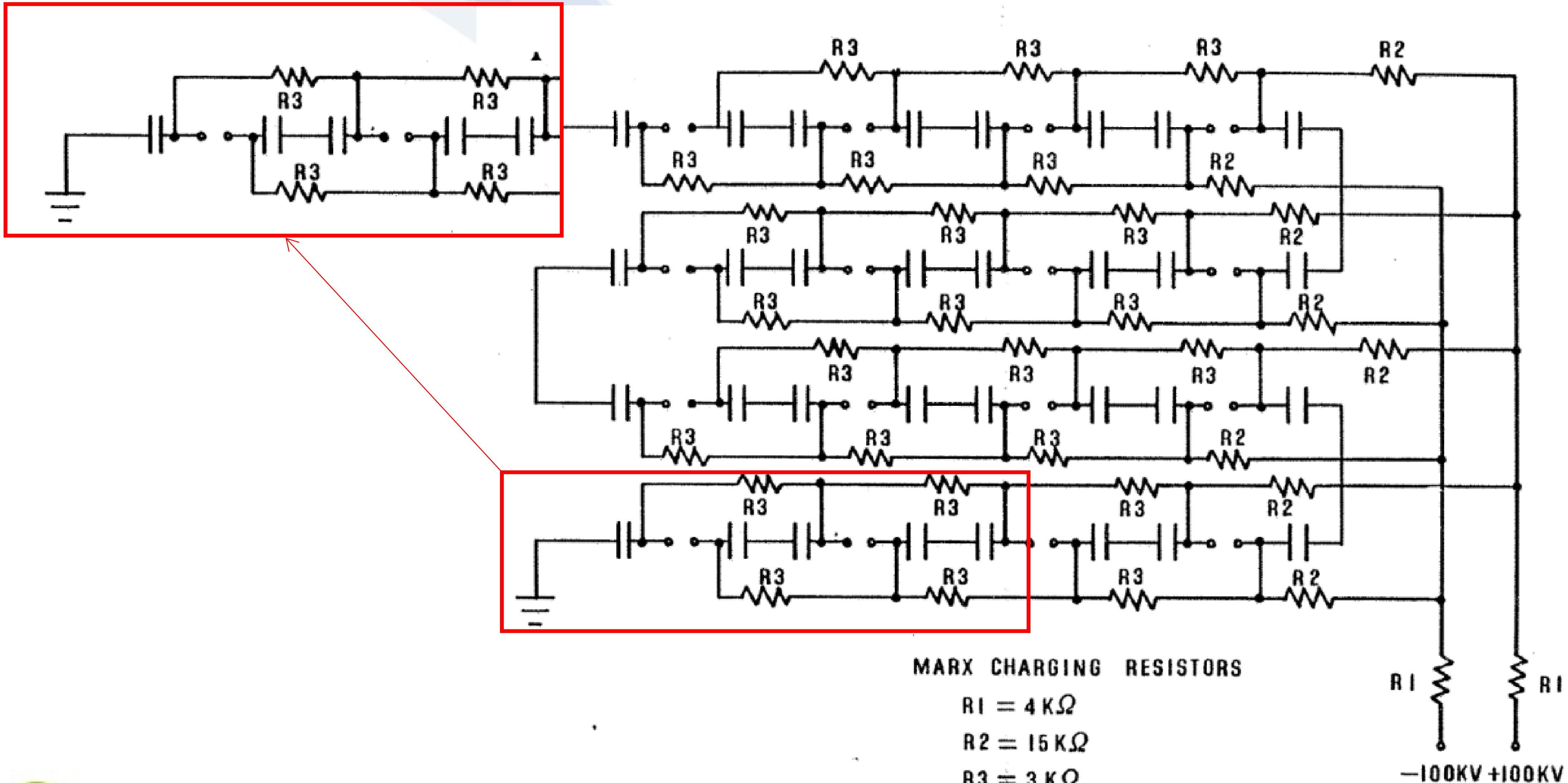
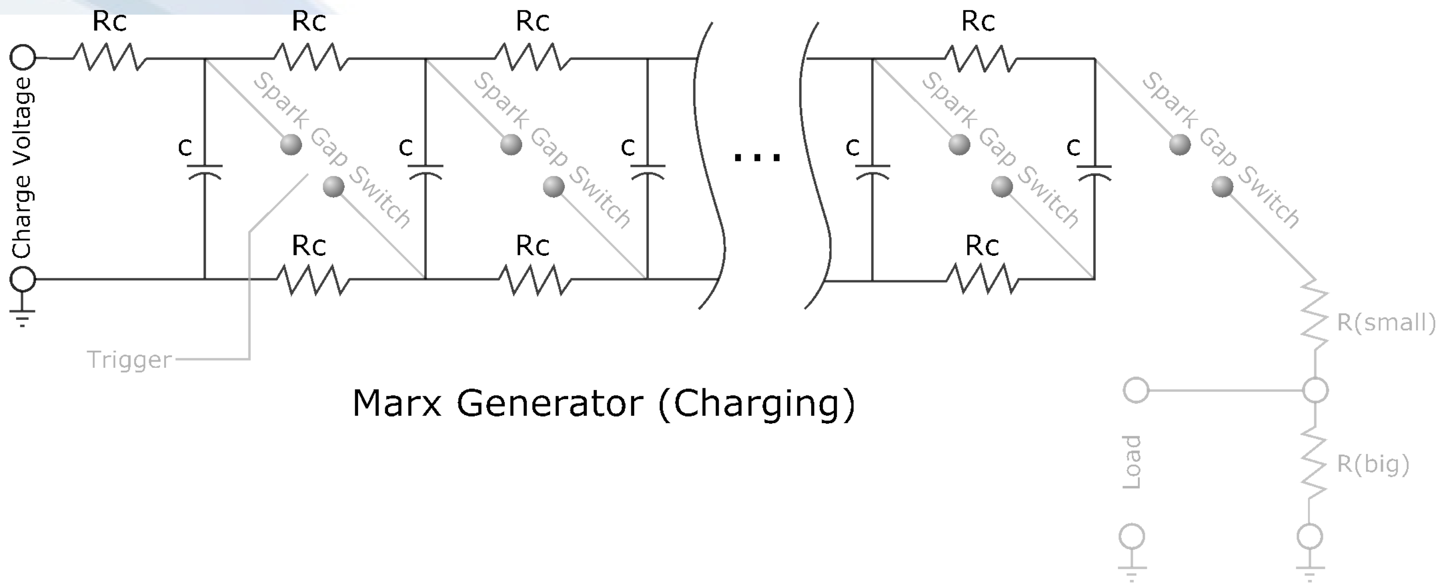


FIGURE 7

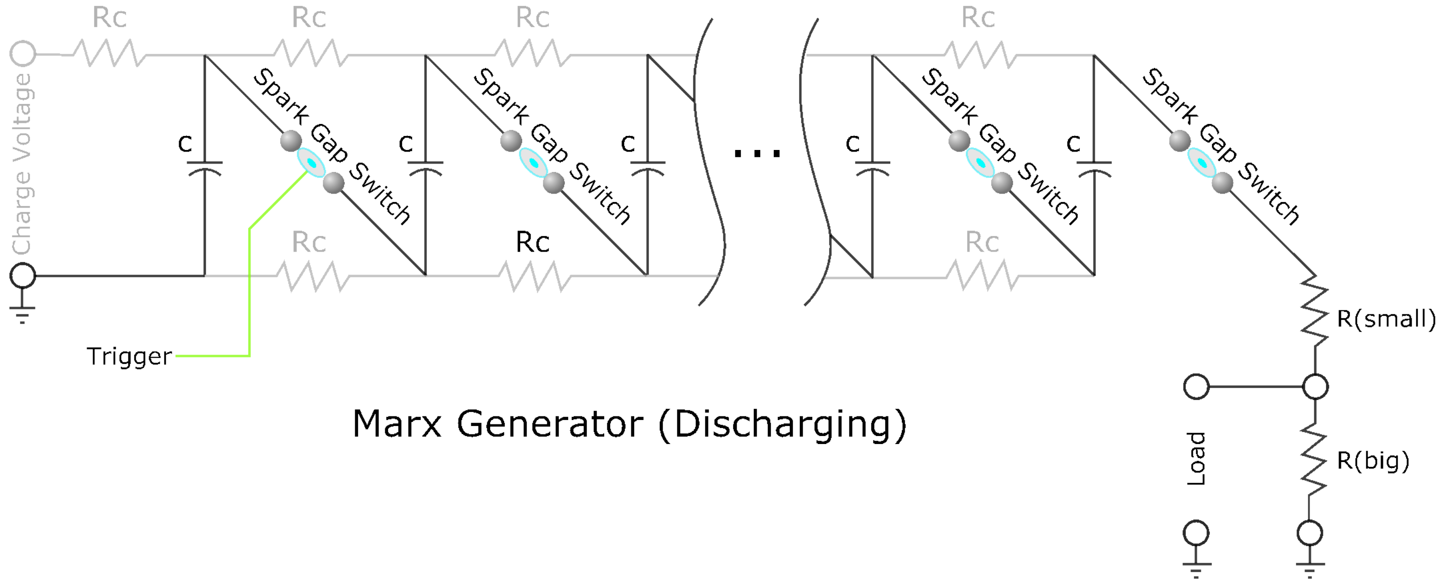
Just kidding. Marx banks charge in series and discharge in parallel.

Charging



Marx Generator (Charging)

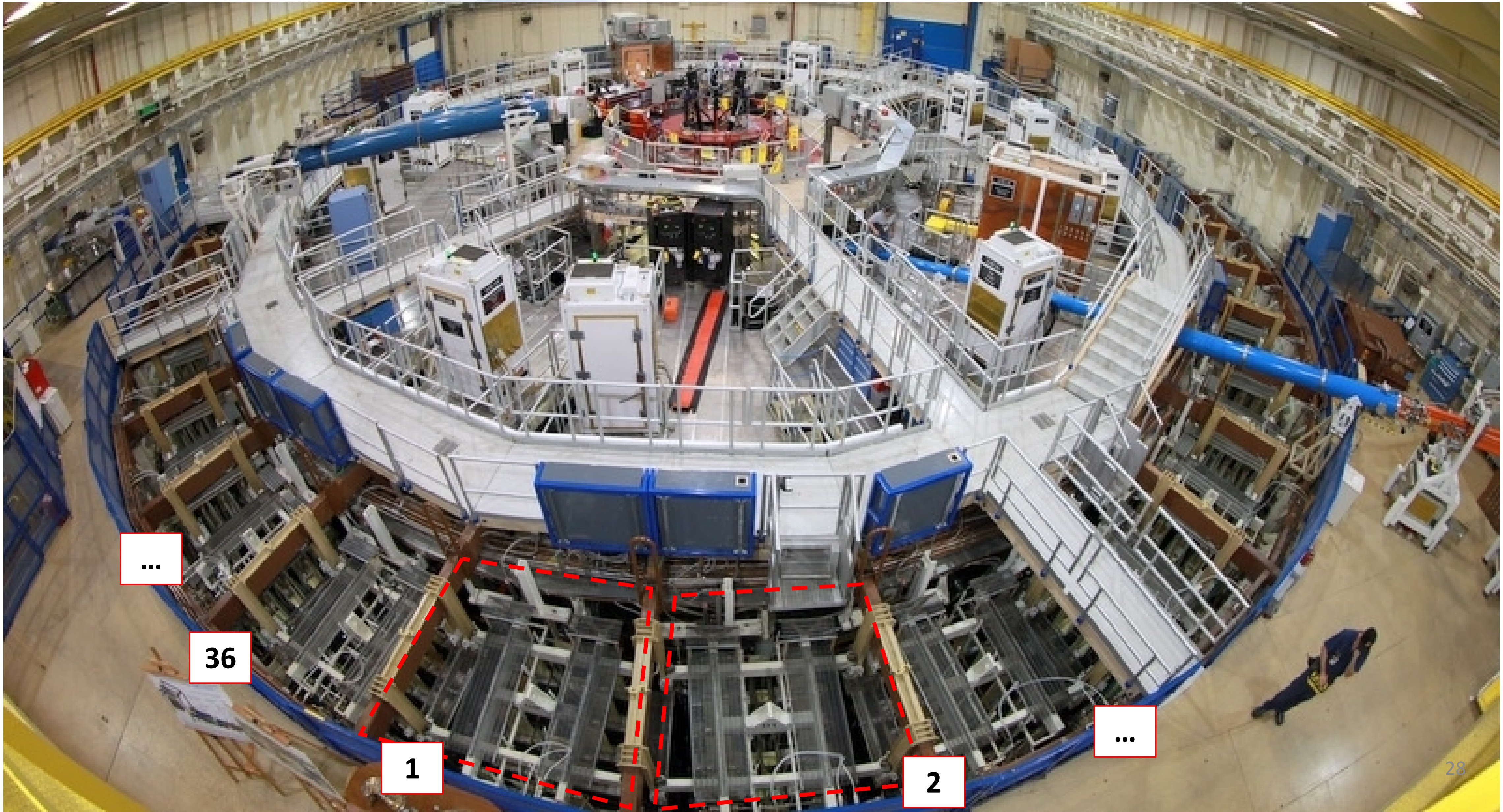
Triggered (Discharging)



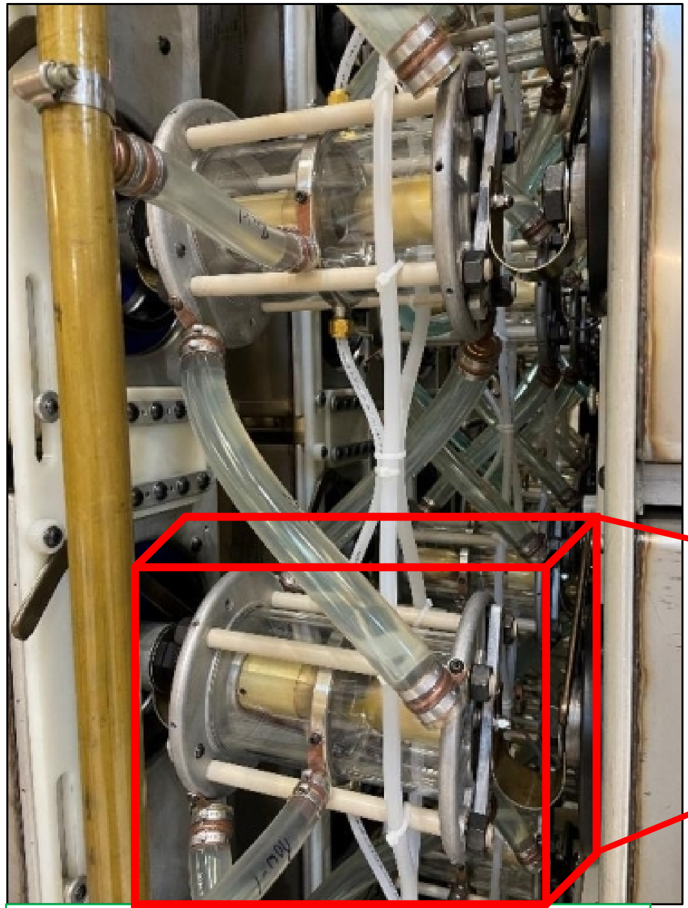
Marx Generator (Discharging)

By ZooFari - Own work, Public Domain,
https://commons.wikimedia.org/w/index.php?curid=8321326

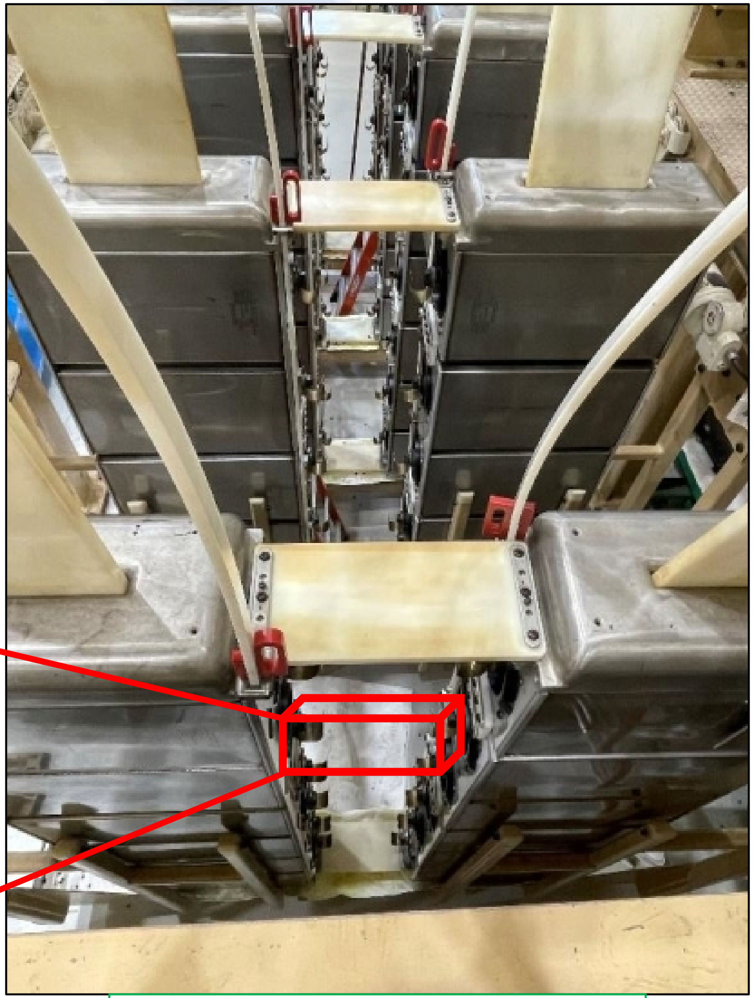
Entry into the oil tank requires circuitous path of touching Marxes around entire perimeter of machine before working on pulsed power hardware



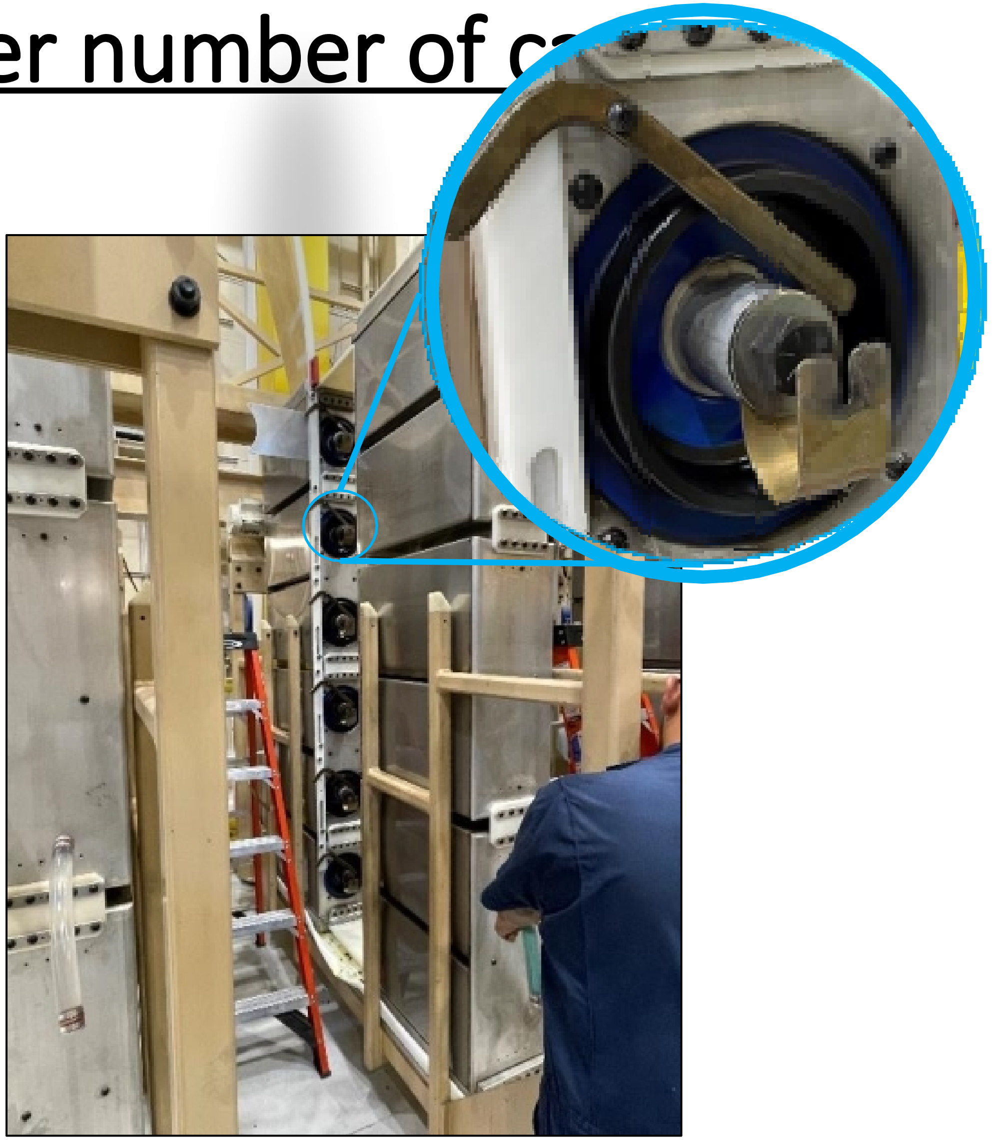
Complex ZEV procedures required to account for high energy, unique failure modes, and sheer number of ca



Complex mechanical connections between capacitors, resistors, switches



Preventative maintenance and Marx rebuilds require access to all columns.



Spring loaded shorting arms are employed to dump energy in oil tank; jumper bar locked in SHORTED position during maintenance

Collected feedback regarding discussion, suggestions for Article 360 improvement

Consensus about need for drain wires / shorting straps on capacitors with engineered controls

- New test method allows reliance on engineered controls to discharge stored energy in 5τ
- We must verify the capacitor to be at zero voltage (zero energy) after this time as passed
- If the engineered control discharge path remains in place after zero energy is verified, must we apply a shorting strap/drain wire while performing maintenance?

Issue new guidance for supercapacitors (<100V, > 100J) to be treated as battery systems

- To have > 100 J at ~ 5 V, need 8 F capacitor.
- Capacitance of this magnitude typically comes with significant equivalent series resistance from 0.010Ω to 1Ω+
- Arc flash seems impossible even with a direct short at the output (internal RC discharge dominates decay rate)
  - Case study: Eaton XLM Supercapacitor module 62 V, 130 F, ESR ~ $7m\Omega$, RC = 0.9s
- Standard capacitor safety protocols are hard to apply to super capacitors
  - Example above, fully charged supercap. Stores 250kJ, would require soft shorting stick to verify zero energy. Say discharge stick R = 10Ω. $5\tau = 108$ minutes.
- Thermal hazards yes, but shock and arc flash hazards unlikely.

Reduce Restricted Approach Boundary for R&D laboratory indoor environments

- RAB includes modifier for movement (?)
- Nearly all capacitor applications are in controlled indoor environments.
- ANSI/ASTM F711 requires a live line stick to hold off 100kV/ft surface electric field.
- This is a factor of 6 – 100x higher than normalized RAB for maximum voltage for most capacitor ZEV applications.

Nominal Potential Difference	Restricted Approach Boundary	Maximum stick surface electric field
< 100 V	Not Specified	
100 – 300 V	Avoid Contact	
301-1000 V	**1 ft**	**1 kV/ft**
1.1 – 5 kV	**1 ft 5 in**	**3.5 kV/ft**
5 – 15 kV	**2 ft 2 in**	**6.9 kV/ft**
15.1 – 45 kV	**2 ft 9 in**	**16 kV/ft**
45.1 – 75 kV	**3 ft 6 in**	**21.4 kV/ft**
75.1 – 150 kV	3 ft 10 in	**39 kV/ft**
150.1 – 250 kV	5 ft 3 in	**48 kV/ft**
250.1 – 500 kV	11 ft 6 in	**43.5 kV/ft**
500.1 – 800 kV	16 ft 5 in	**48 kV/ft**

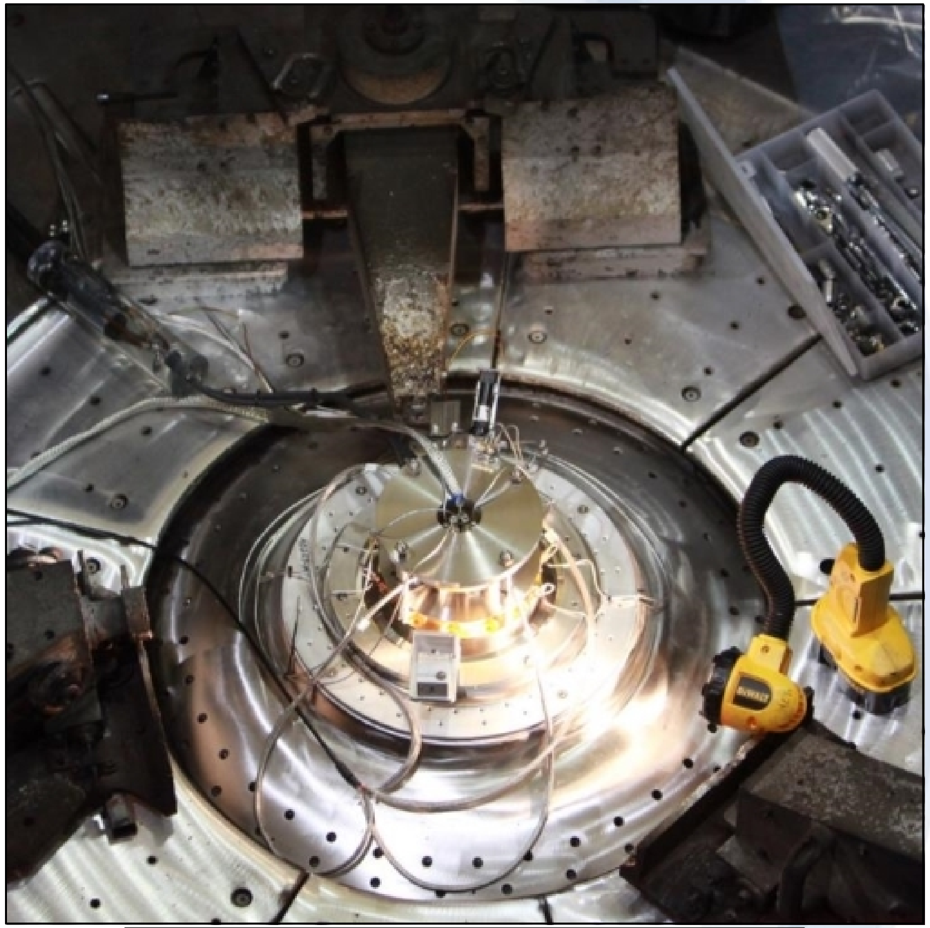
Issue guidance, clarification on custom shorting stick manufacture and testing

- Sandia's Committee for Electrical Safety just recently approved fabrication of custom shorting sticks internal to Sandia.
- Live line tool standard is overkill for what we need in R&D indoor environment.
- Required testing to ANSI/ASTM F711 is necessary but not sufficient to verify shorting stick integrity.
  - They test voltage standoff only. No drain wire inspection, resistor checks, Action verification.
- Issue suggested guidelines for in-house test capability
  - Suggested testing guidelines for hard, soft grounding sticks to discharge current handling
- Also, requirement for testing of <0.1Ω annually requires specialized impedance devices that most labs don't have. <1Ω with a Multimeter is fine.

How long after zero energy verification is complete can one wait before ZEV must be reestablished?

- Workers at accelerators like Z will "go around the machine" shorting marx banks working around the perimeter of the tank.
- It might take 10 – 20 minutes to get back to the starting point.
- Could a capacitor in a bank have recharged itself?
  - Dielectric absorption is a function of capacitor chemistry, time at full charge, nature of discharge, etc.
  - Must this be characterized for each system or are there rules of thumb?
- How long is too long before ZEV must be re-verified?

Questions?



Electromagnets Before Z Shot

Electromagnets After Z Shot