UW IEC Group 2012: Building a 300kV Switch for Device Selection – Surprises, Lessons Learned, and Mitigation Techniques

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College Park, Maryland, USA

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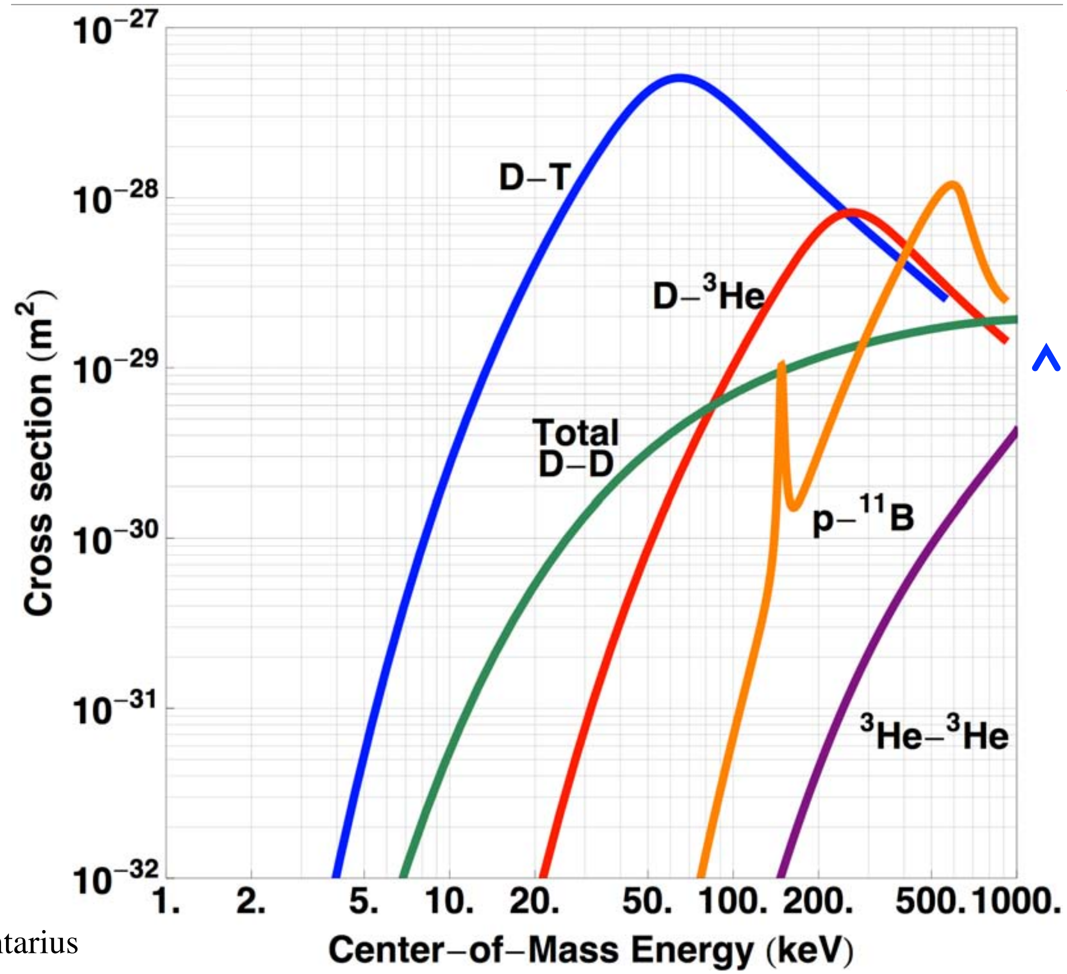
Motivation for this Presentation

To inform colleagues considering operating at higher voltages of challenges that they may encounter as a consequence

Motivation for Using Greater Cathode Voltages

Improved access to Advanced Fuel Fusion Regimes



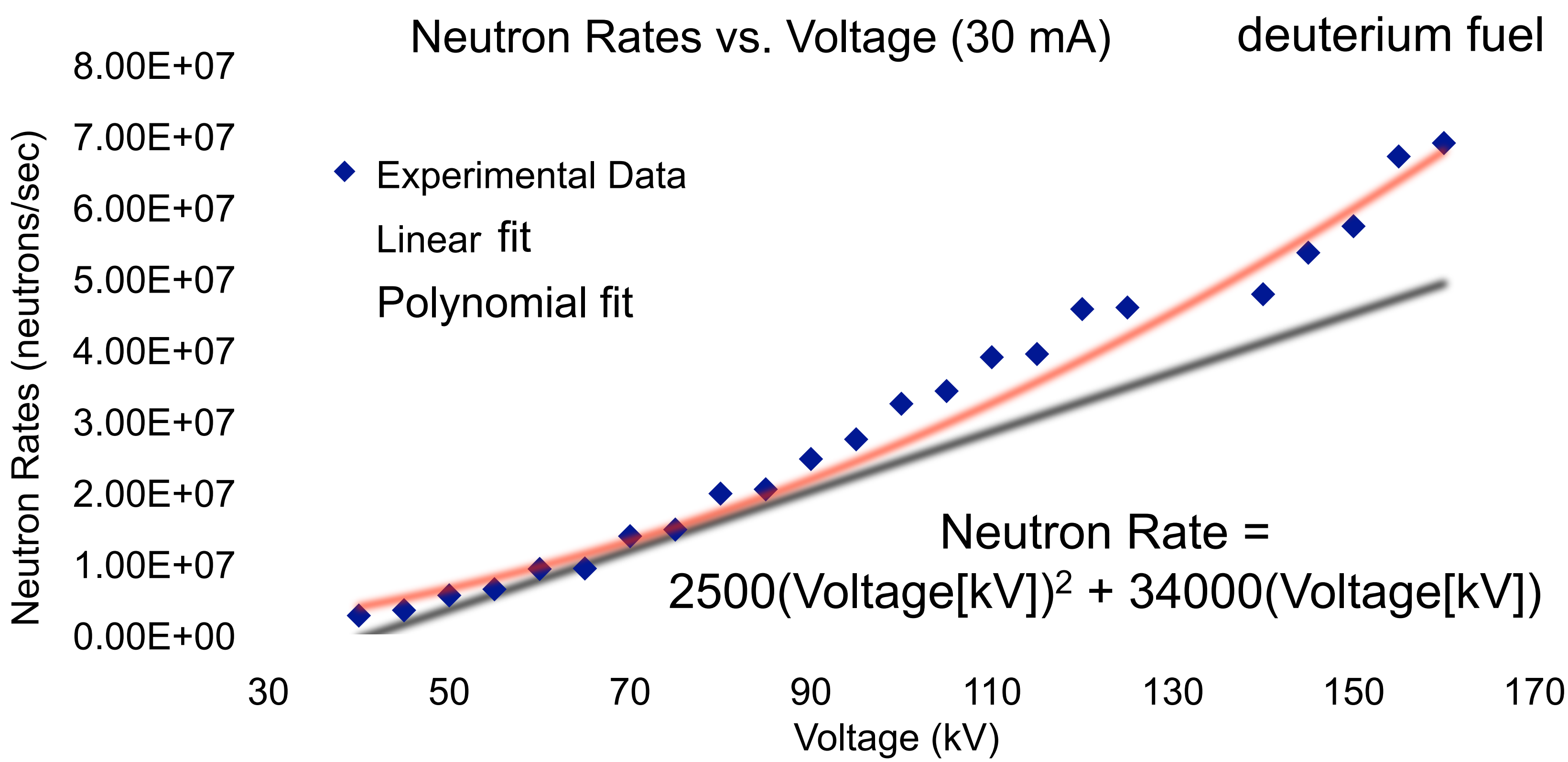
Source: J. F. Santarius

Greater Cathode Voltages ➔ higher reactant kinetic energies

Higher reactant kinetic energies generally imply greater collision cross-sections

Motivation for Using Greater Cathode Voltages

- Neutron flux appears to be monotonically increasing with voltage (greater voltage ==> more neutrons)



From 2008 Workshop Donovan presentation (WE-08)

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Adaptations for 300 kVDC

Completed:

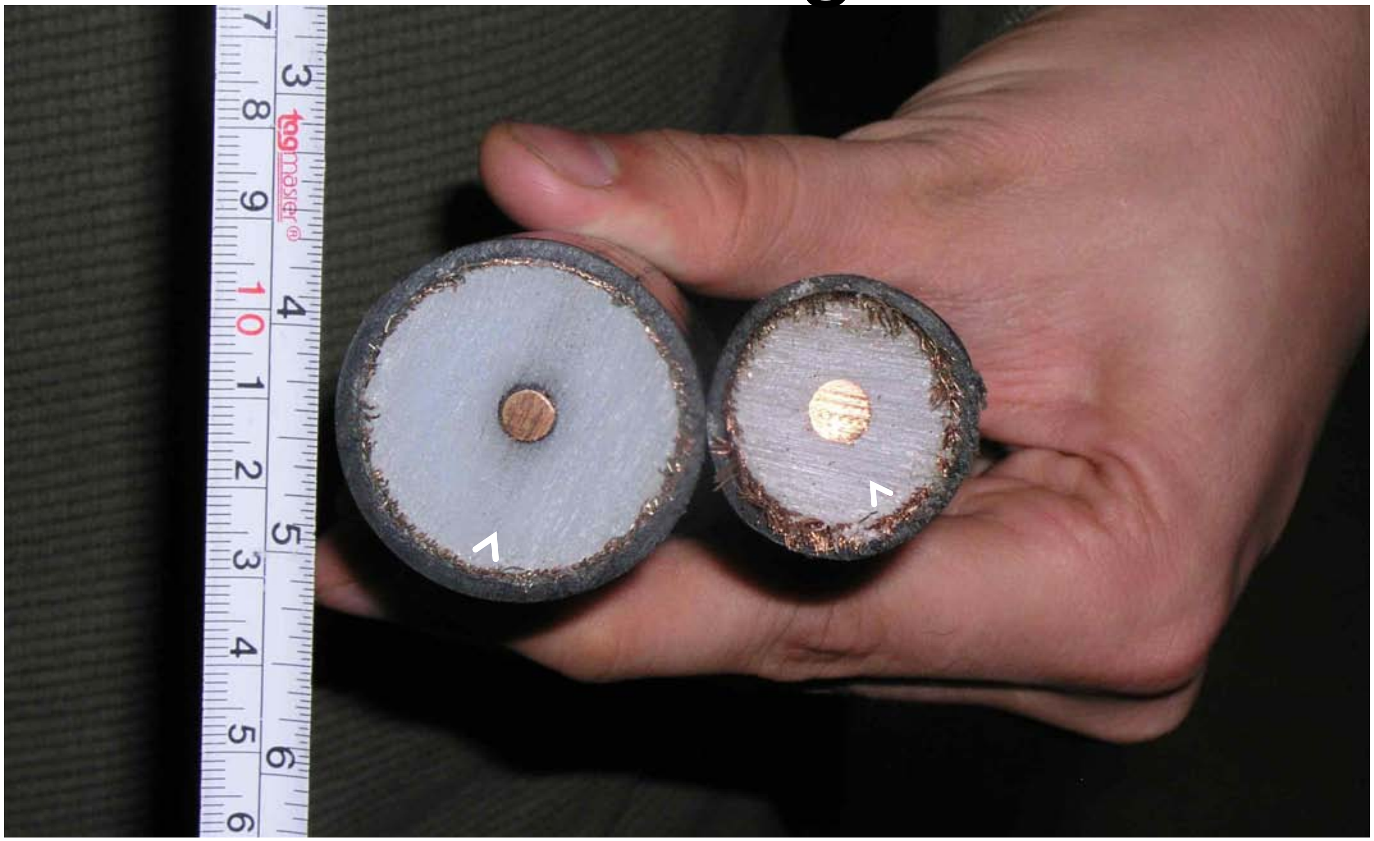
- High-voltage power supply upgrade
- Vacuum feed-through assemblies
- Construction of HVDC switch / series-resistance assembly

In Progess: Testing and “debugging” of HVDC switch

Near Future: Additional cabling necessitated by anticipated laboratory expansion

Anticipated: Cathode grid adaptations

Cabling



(New) 300 kVDC cable, left, and (current) 200 kVDC cable, right

The new cable is much less flexible, and more subject to flexure-induced failures.

UPDATE: newer, more flexible cable is now available

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High Voltage Switch and Series Resistance Assembly

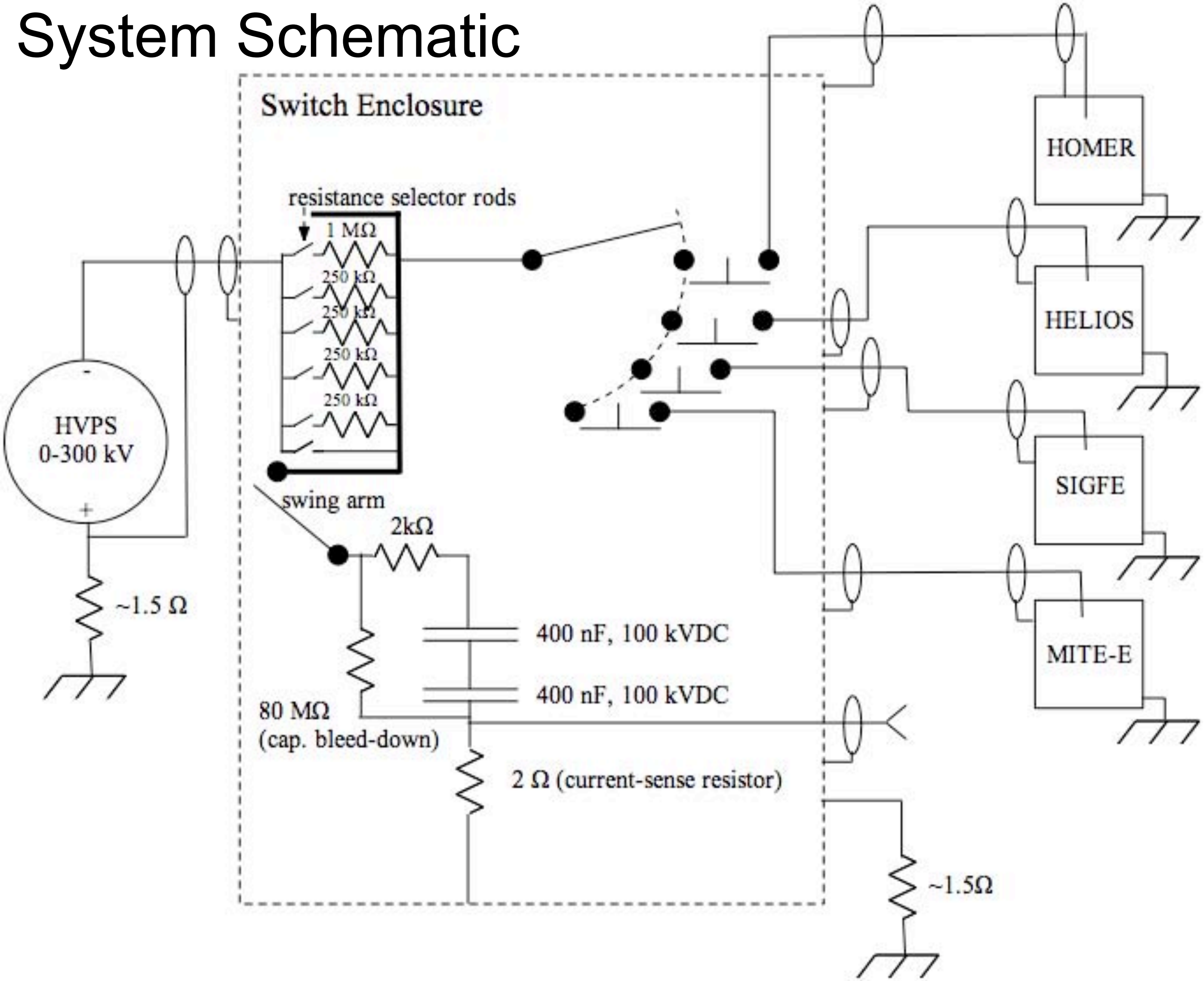
Specifications:

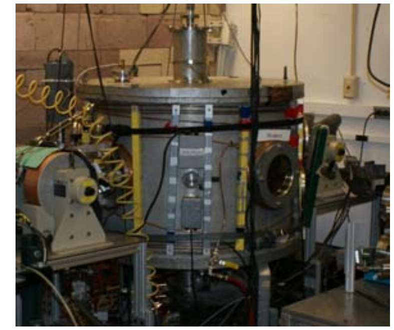
1. Cold-switch the high-voltage power supply among four different devices.
2. Removing and replacing cables not to be required.
3. Non-inductive series resistor of 50 kΩ able to carry 200 mA current in steady state.
4. Resistor to be adjustable to higher resistances (though at a lower current), and completely by-passable.
5. Pulsing capacitor and related equipment is to be in the same enclosure as the switch.

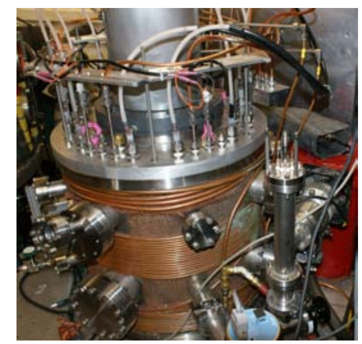
Switch Design Drivers

- Maintain minimum 35 cm path length between 300 kV surface and ground (to prevent track arcing).
- Maintain minimum 15 cm (oil filled) distance between 300 kV surface and ground (to prevent through-oil arcing).
- Maintain electric field below ~5 MV/m.
- Incorporate electrostatic shielding for the resistor system.

System Schematic







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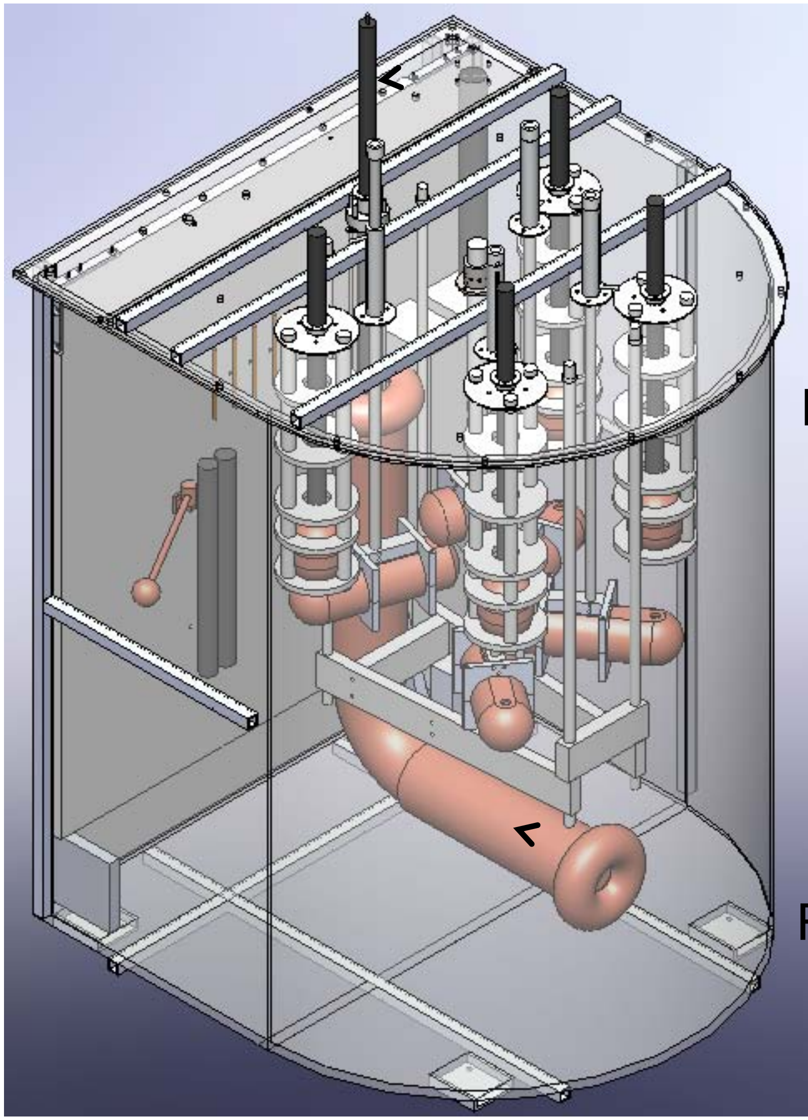
Final System Layout



Power In

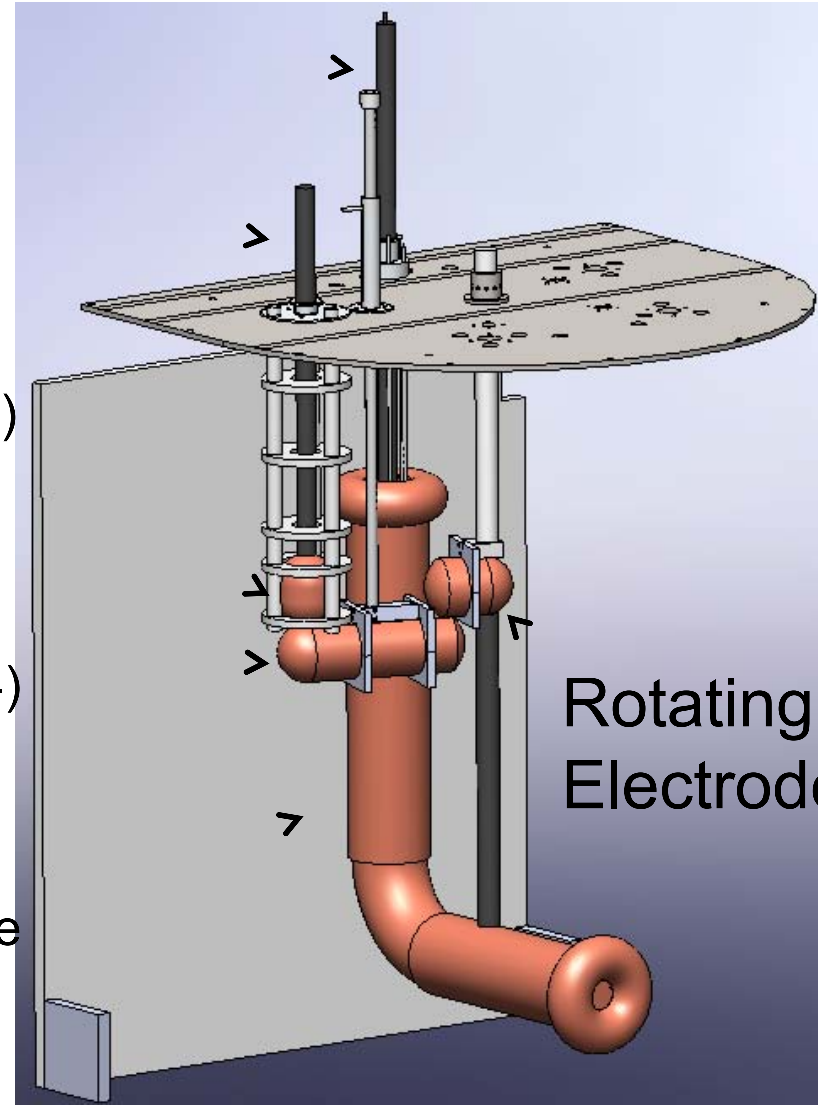
Power Out (4)

Output Electrode (4)

Bridge Electrode (4)

Resistor tube

Switching Electrodes



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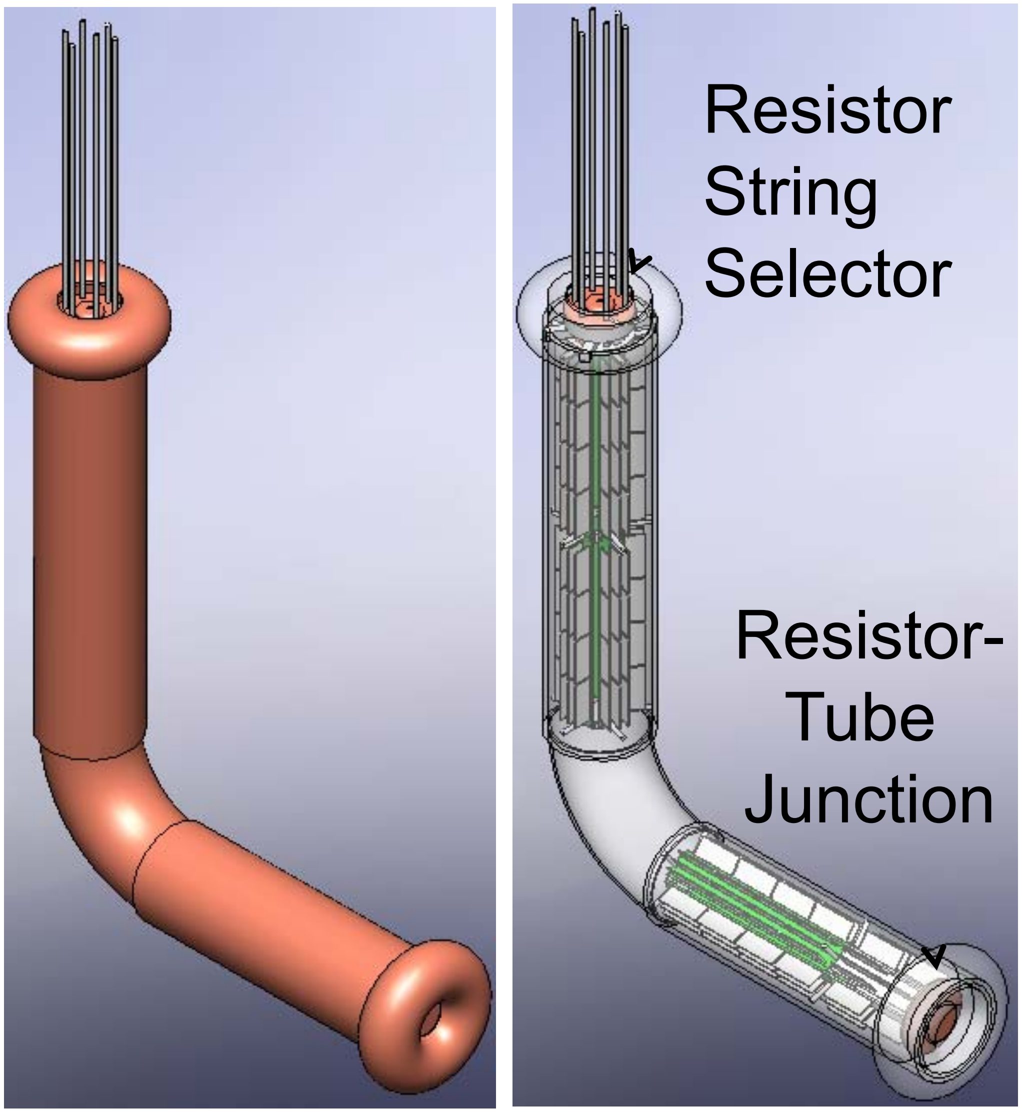
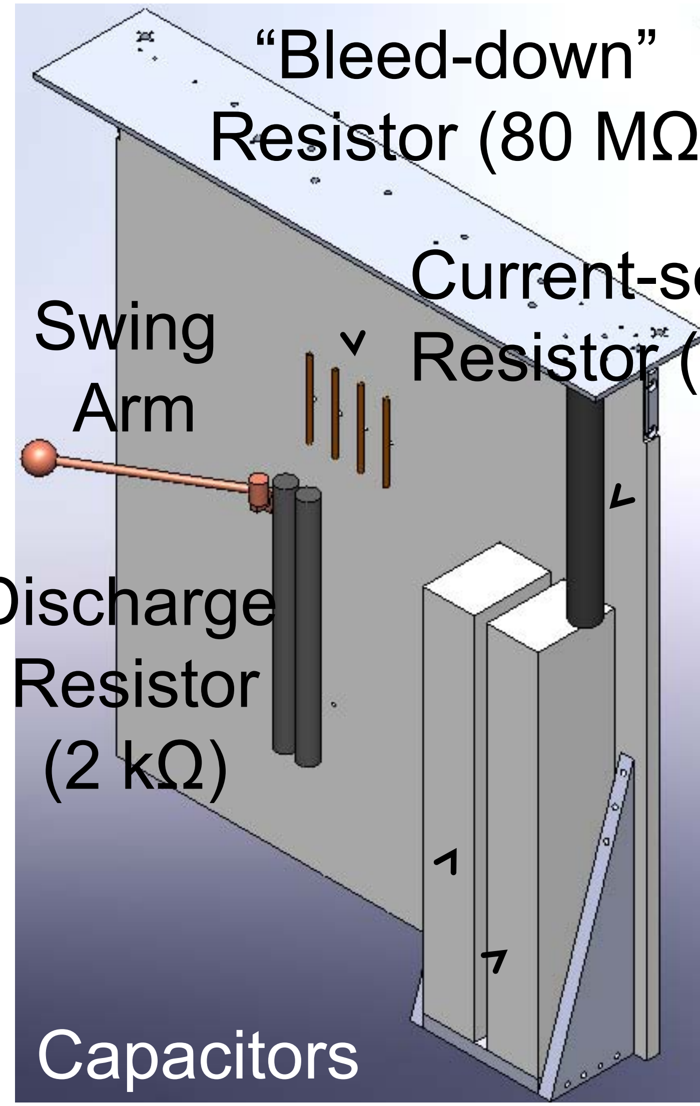
Resistor System



Capacitor System

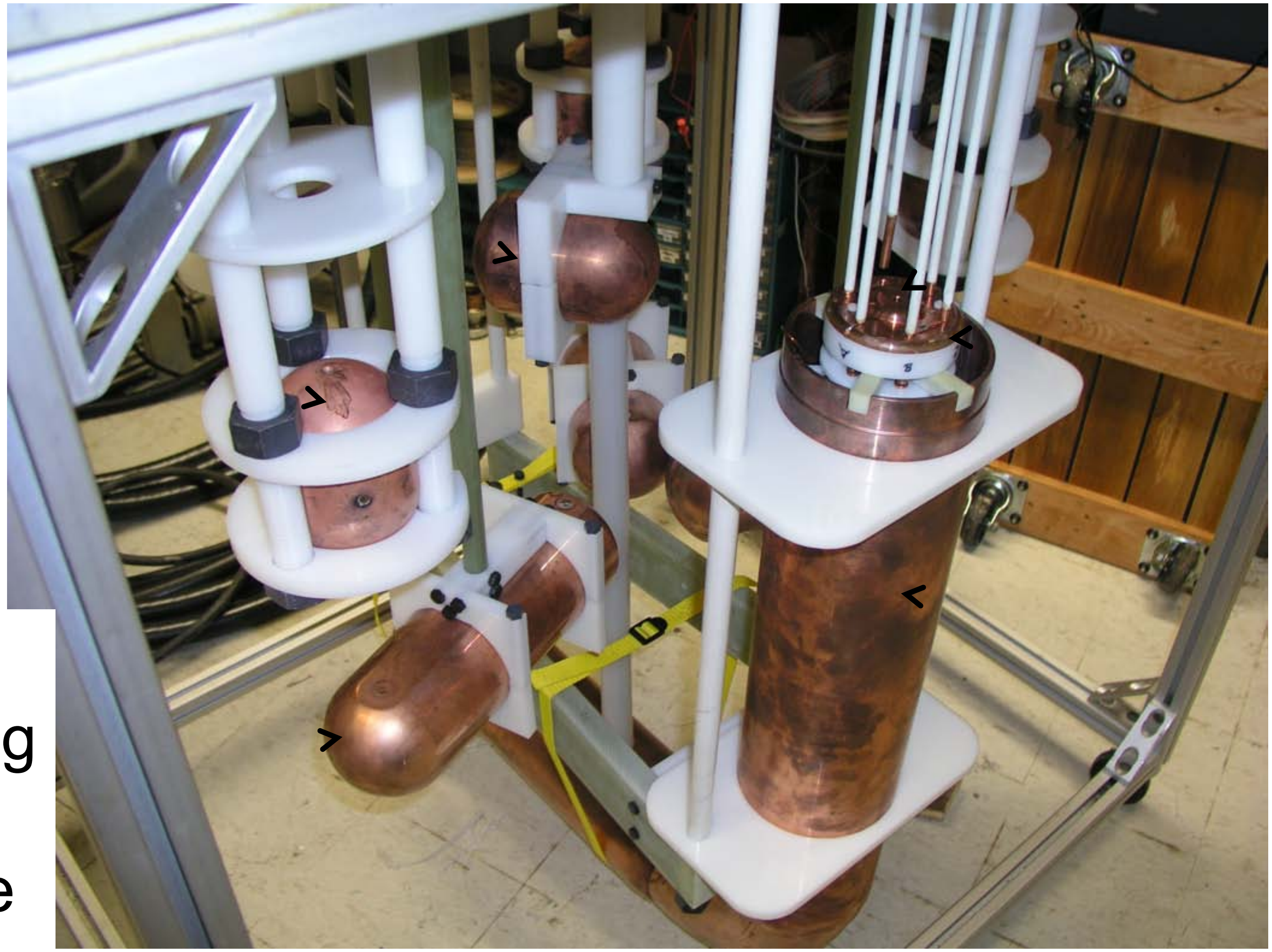


Implementation: Electrode Assembly

Rotating Selector Electrode

Output Electrode 1 of 4

Vertically Translating Bridge Electrode 1 of 4



Power Input Contact

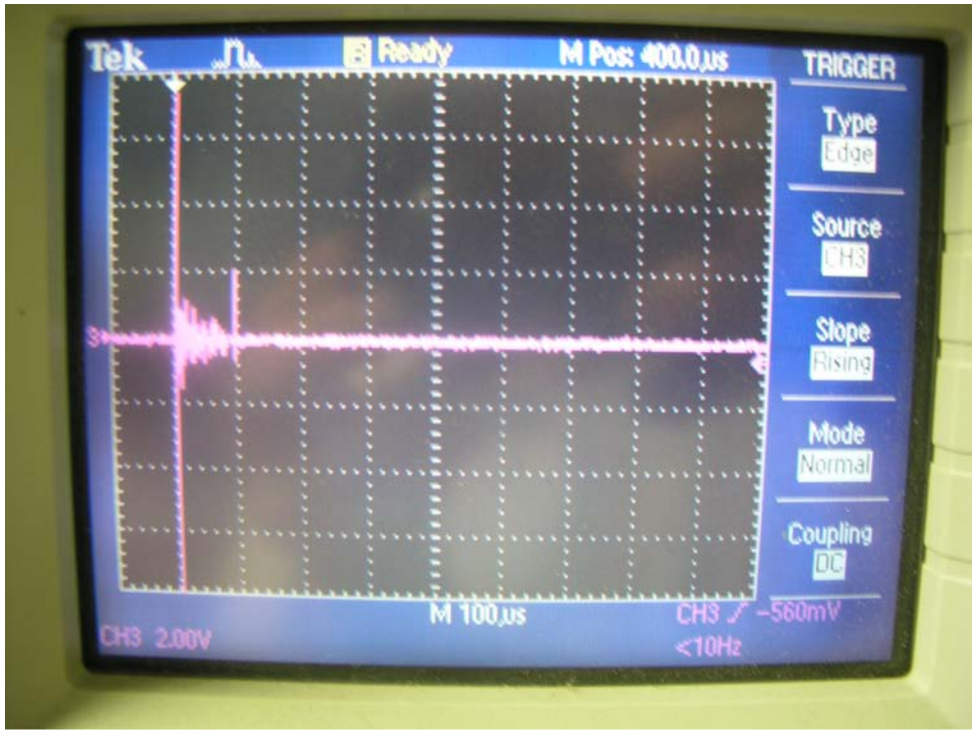
Resistor String Selector

Resistor Tube

System Testing: High-Potential Test to 100 kV Without Dielectric Oil

Result: Unexpected, very short-time-scale arcs occurred in IEC devices (NOT the switch) when they were connected via the new switch, but not otherwise!

Vertical scale is 1 A / division: arc peak current is off scale!



Arc duration is approx. 100 µsec.

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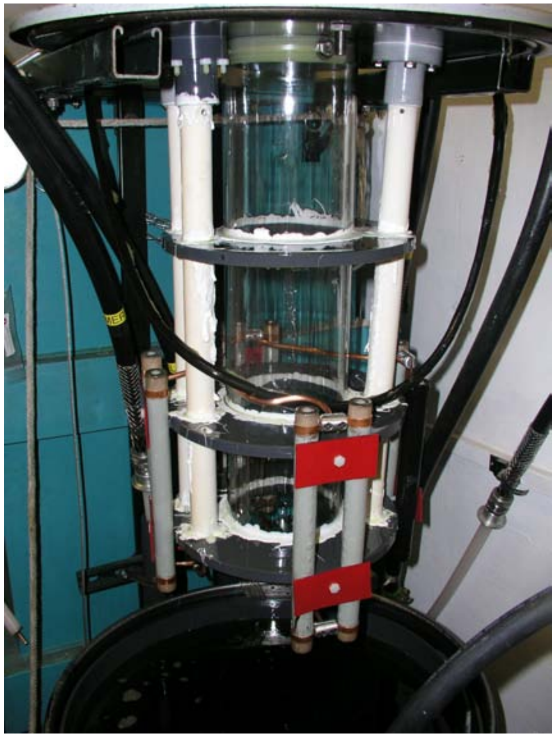
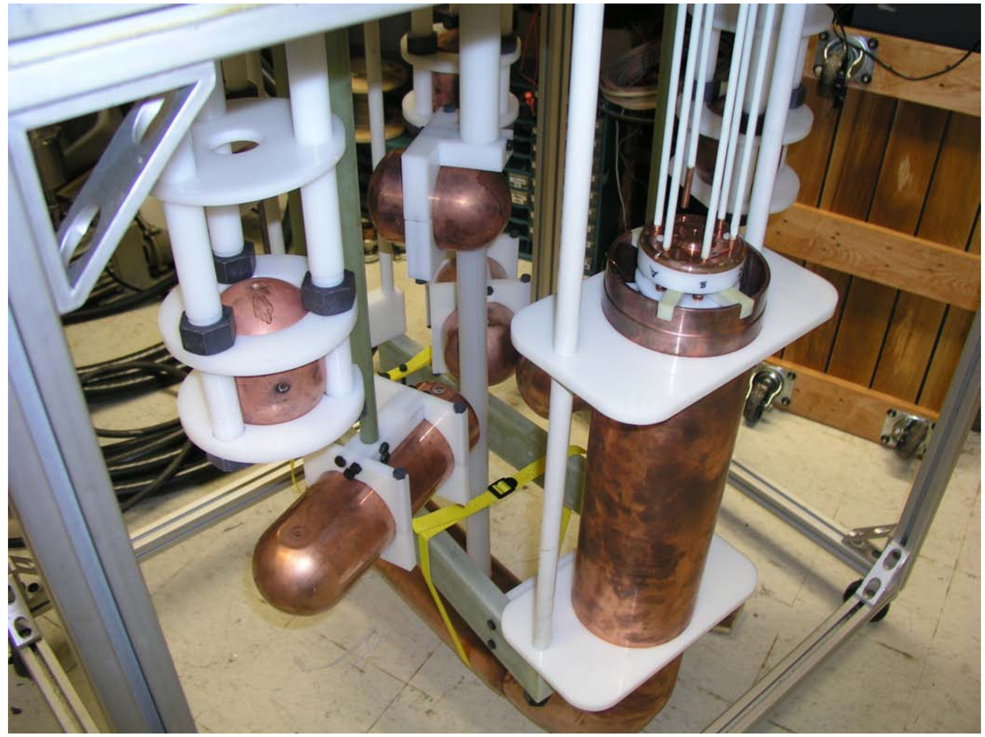
System High Potential Test to 100 kV DC (no oil)
システムテスト：高いポテンシャル 100 kV DC (まで；油を使用せずに)





Present Resistor Barrel → No arcs in IEC device during the test

現在の抵抗器バレル：テスト中にはIEC デバイスのなかで電気アークは発生しなかった

New Switch and Resistor → Arcs and auto-shutdown in IEC device @ 60 kV DC

新しいスイッチと抵抗器：電気アークおよび IEC デバイス の自動シャットダウン（60 kV DC）

WHY ?!?

なぜ ?!?

Selected Methodology for Determining Cause of Failure:

• Measure the impedances of the current resistor barrel and the new switch in various configurations at various frequencies.

• Develop lumped-parameter models.

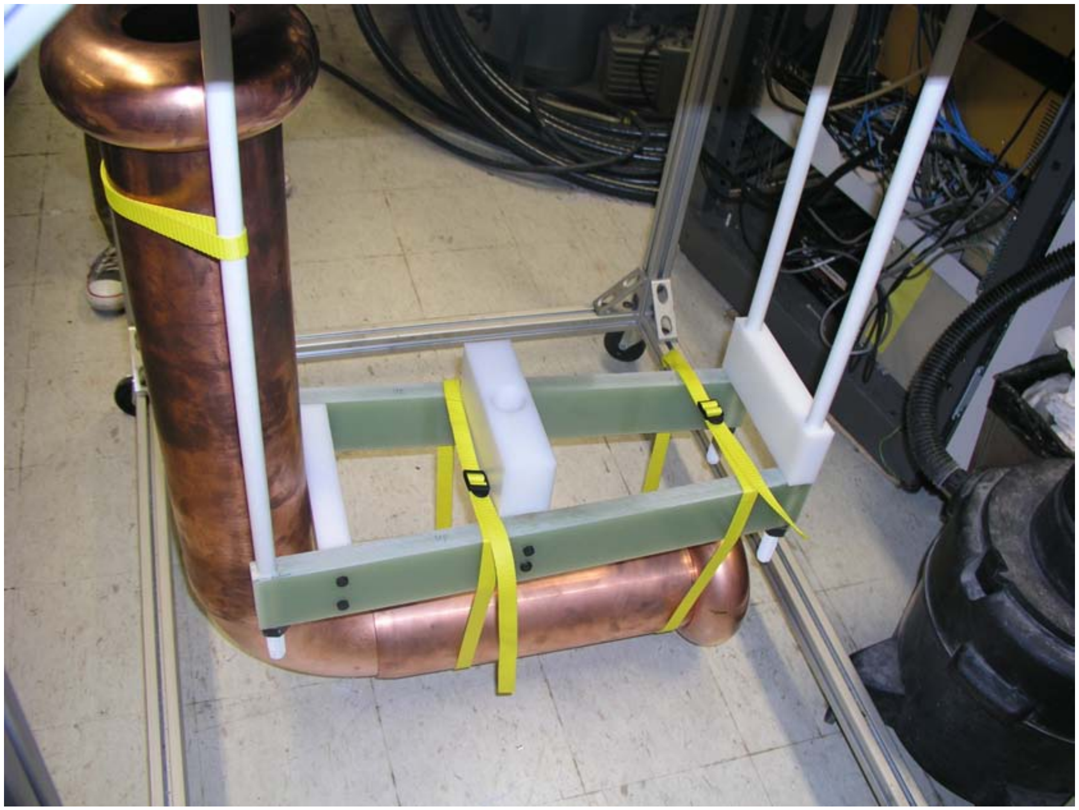
• Select and refine model of switch and connected systems using SPICE to approximately replicate observed behavior (SPICE: Simulation Program with Integrated Circuits Emphasis [集積回路に重点を置いたシミュレーションプログラム] – a commonly used electronic circuit simulator).

• Use developed model and SPICE to simulate various mitigation methods.

• Test selected mitigation method(s) experimentally.

Suspicion fell on the presence of a large conductive surface located, electrically, at the load end of the resistor string, namely, the copper-coated tube that is the resistor string's electrostatic shield, and the other large electrodes.

抵抗器ストリングの負荷端にある大型導電性表面、すなわち、抵抗器ストリングの静電シールドである銅被服管および他の大型電極を検討している



Parasitic capacitance between the large electrodes and the switch chamber wall may be responsible!

大型電極とスイッチ室の壁との間の寄生容量が原因になるかもしれない！

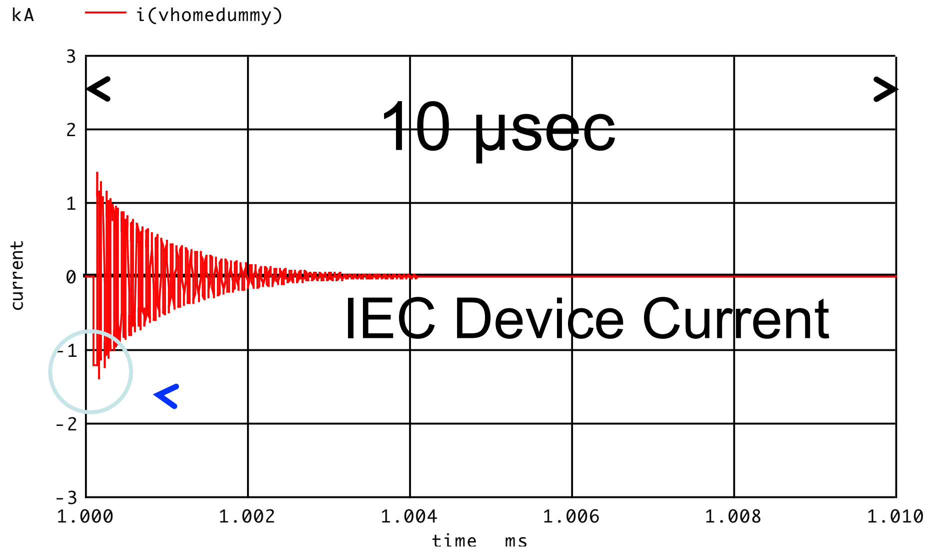
We analyzed the model using SPICE.

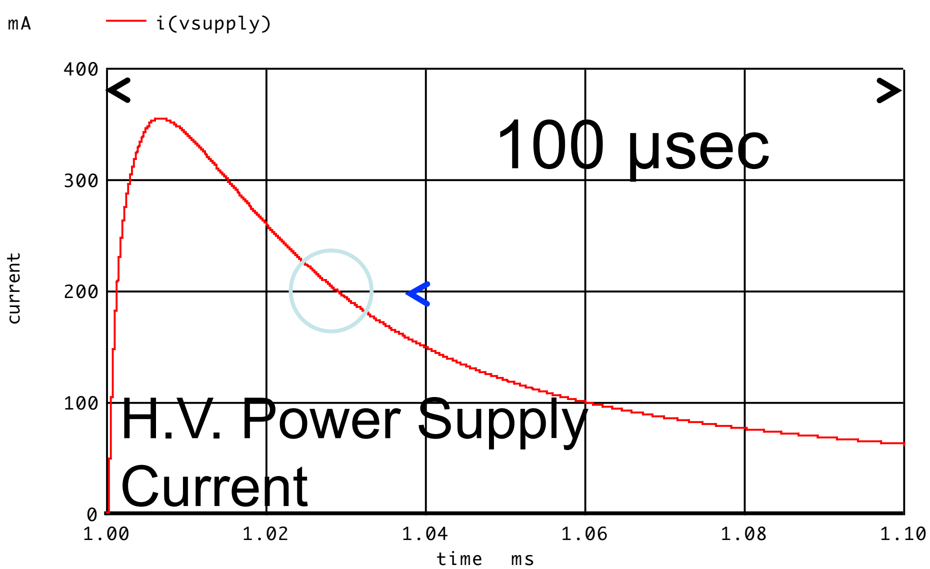
- It must be noted that in lieu of a proper model for the arc, this was crudely simulated as a 0.1Ω resistor and a switch.

- The model, even with a crude arc simulation, appears to produce results quite similar to those that are seen experimentally.

SPICE Simulations

WithOUT additional parasitic capacitance

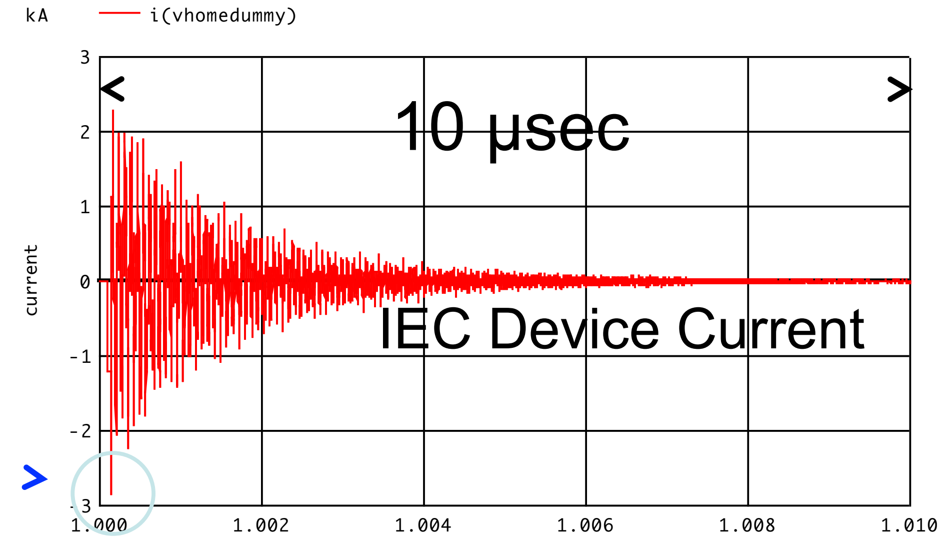


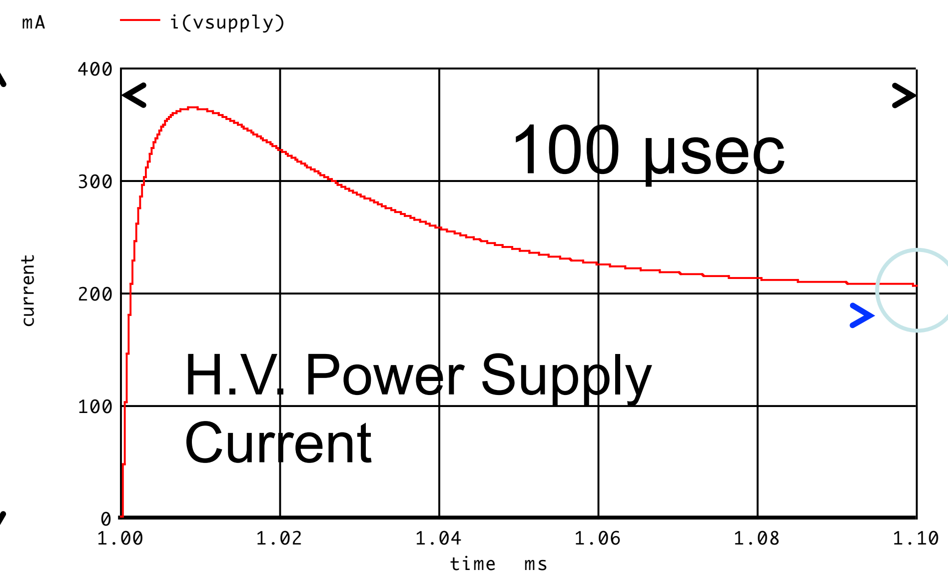


6 kA

400 mA

WITH additional parasitic capacitance





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Experiments and SPICE simulations lead us to the following working hypotheses:

1. Micro-arcs occur frequently, especially during conditioning.

2. When using the present resistor barrel, there is not sufficient capacitance in the barrel and interconnecting cables to allow these microsecond-length arcs to develop sufficiently to trip the power supply before quenching.

3. The additional parasitic capacitance present in the new switch DOES allow these micro-arcs to develop sufficiently to trip the power supply.

We appear to have found the problem. How may we mitigate it?

Possibilities:

1. Critically damp arcs by putting a resistor at the IEC device or at least at the switch output.

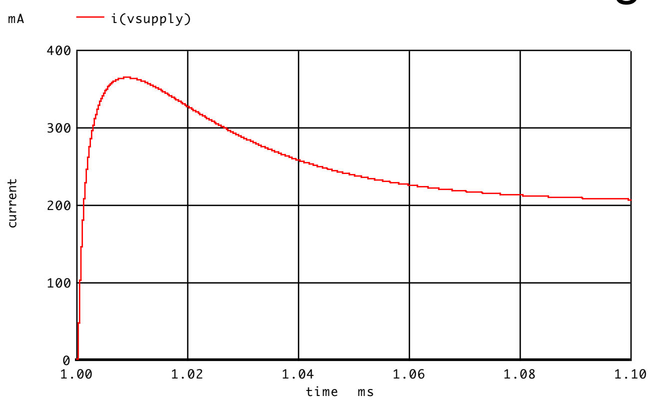
2. Adjust the power supply auto-shutdown to tolerate brief arcs.

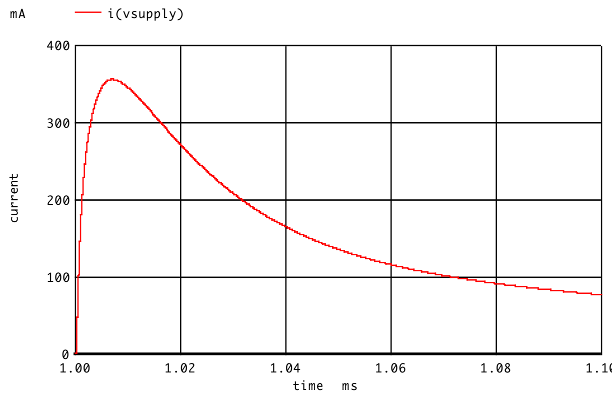
3. Re-design the resistor assembly to eliminate the need for the shield tube.

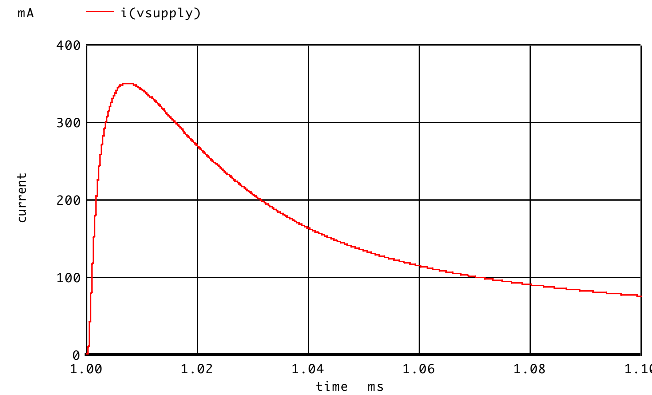
Simulation: Effect of Series Resistor
(note lack of quenching with crude arc model)

No Mitigation | 10 Ω Resistor @ IEC Device | 1 kΩ Resistor @ IEC Device

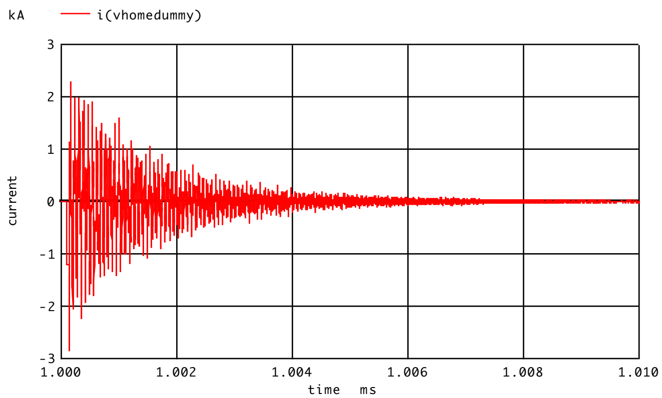
← High-Voltage Power Supply Current →

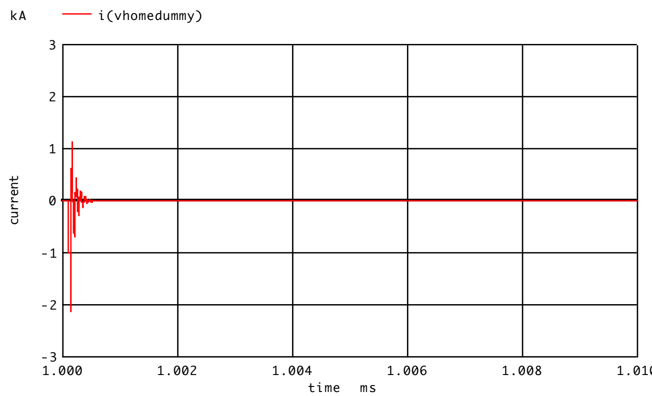


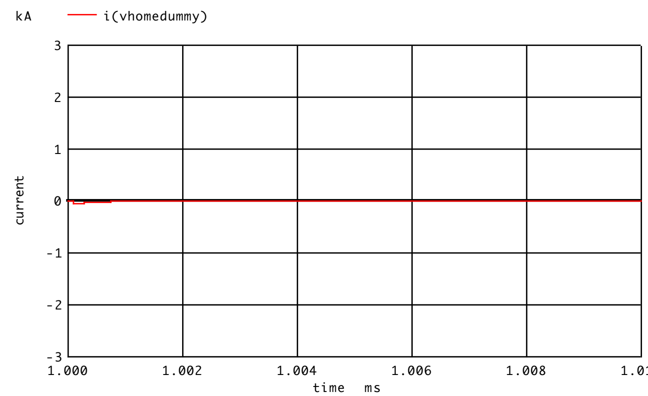




← IEC Device Current →







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Questions to be considered:

- Are micro-arcs an essential part of the conditioning process?
- If so, is it possible to have *excessive* arc suppression?

Switch Status:

- Components to test resistance-based arc mitigation are on hand.

- Components to test power supply shut-down time alterations are also on hand.

- Additional tests of the switch will be conducted this Fall.

Primary Lesson Learned from this Experience:

When designing high-voltage systems (especially over 100 kV), since:

→ keeping electric field intensities within tolerable ranges requires physically larger conductors, and

→ larger conductive surfaces will enhance the parasitic capacitance between conductive surfaces,

→ **The enhanced parasitic capacitances, though still small, can have substantial effects at these higher voltages, even in DC systems!**

Acknowledgements

Grainger and Greatbatch Foundations
for their support of this research groups efforts

Dr. Charles D. H. Williams, University of Exeter, UK
for advice concerning MacSpice simulations

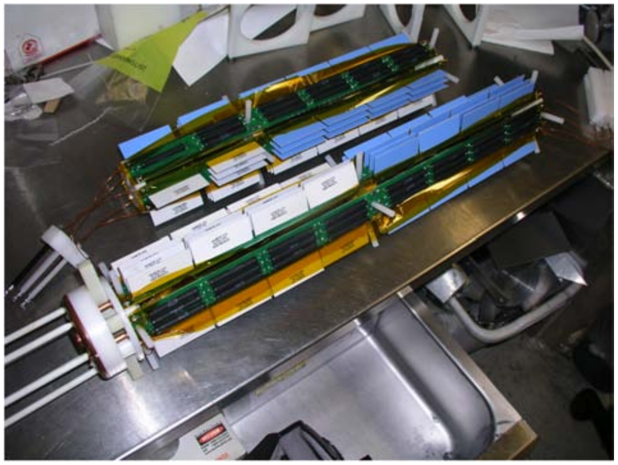
Dr. Jim Davis, UW – Madison
for assistance with translations into Japanese
英日翻訳:ウィスコンシン大学工学部のジェームス・デーヴィス教授

Questions?

Backup / Background / Additional Slides

Switch Manufacturing (from 2011 workshop)

Manufacturing – Internal Components



Series Resistor Strings

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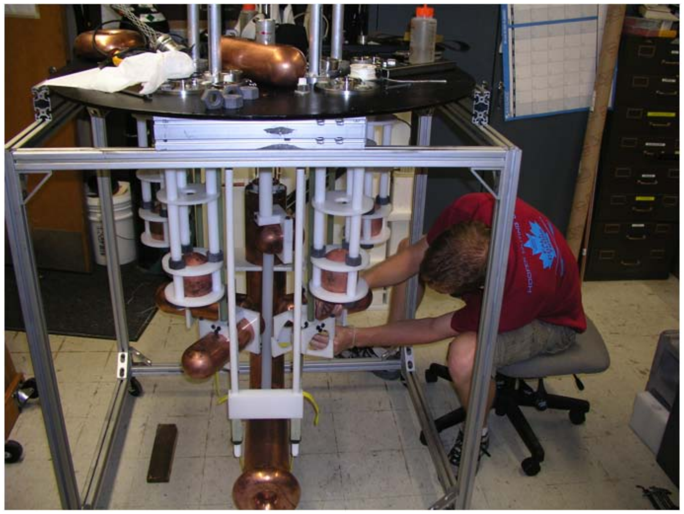
Electrodes (5 types)

Support components
(and electrodes)

>



Manufacturing – External Components (Tank)

Tank Body Volume
~ 1200 L

Removing scale

<

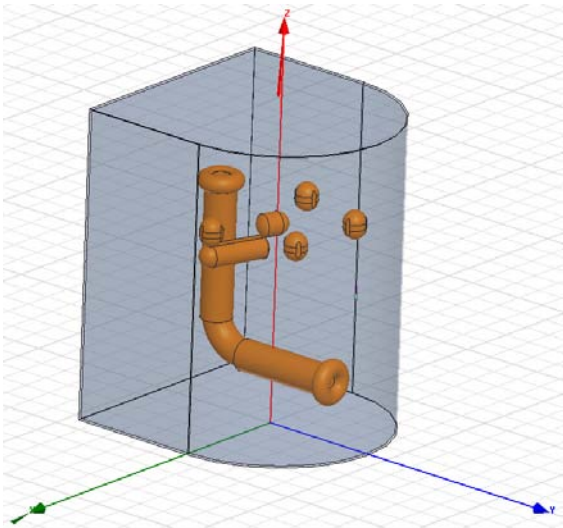
Leak Checking
(note red dye)

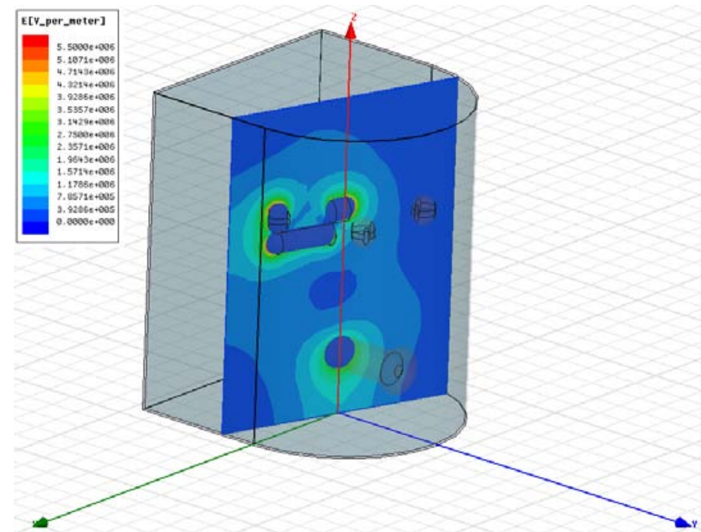
<

Plasma Cutting
Slot into Lid

Design & Construction methodology

Design/Redesign Concept





Simulation (MAXWELL -3D)

Construct

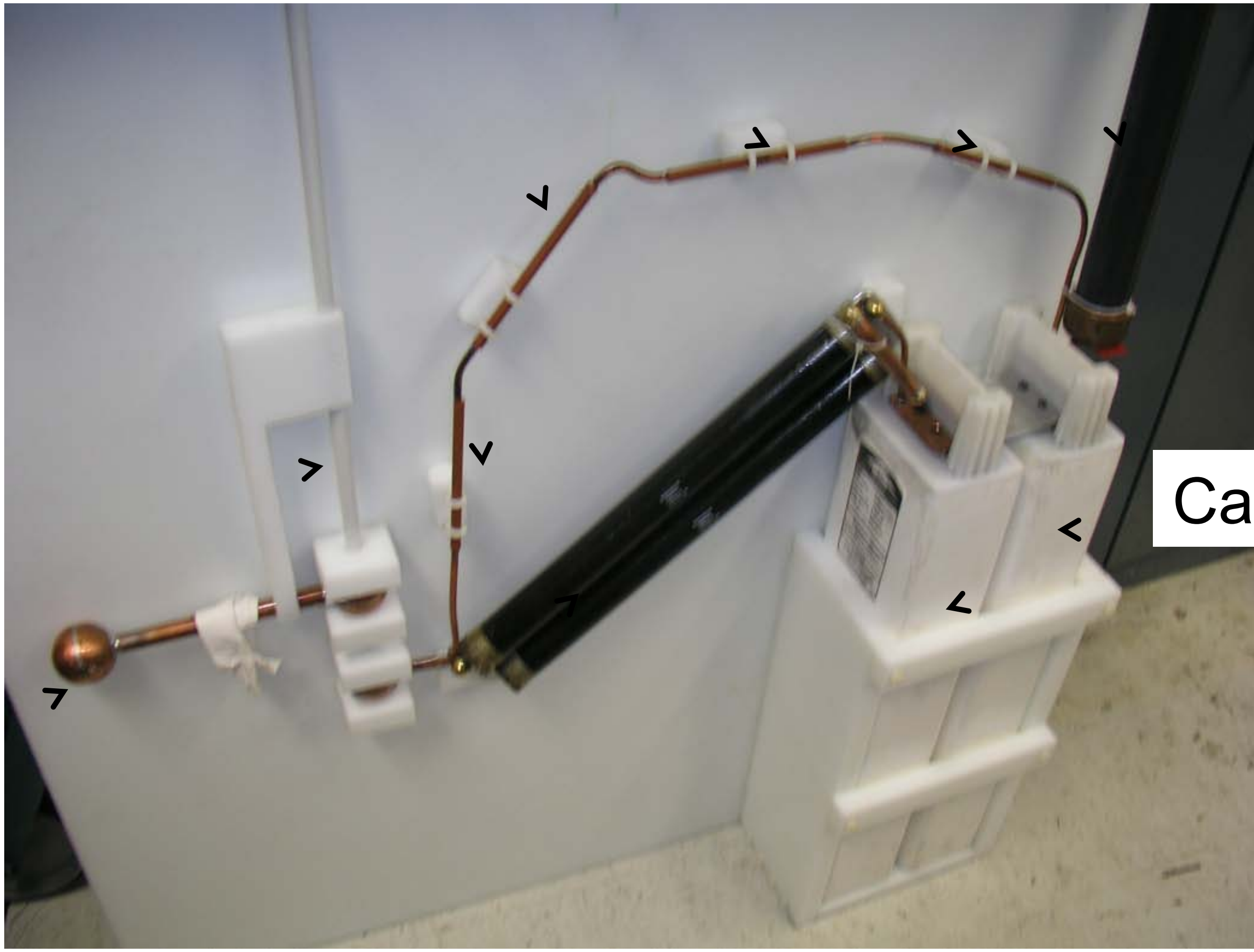
Test

Modify

Implementation: Pulsing

"Bleed-Down" Resistor (4 X 20 MΩ) Current Sense Res. (2 Ω)

Swing Arm Control Rod



Capacitors

Swing Arm

Discharge Resistor (2 kΩ)

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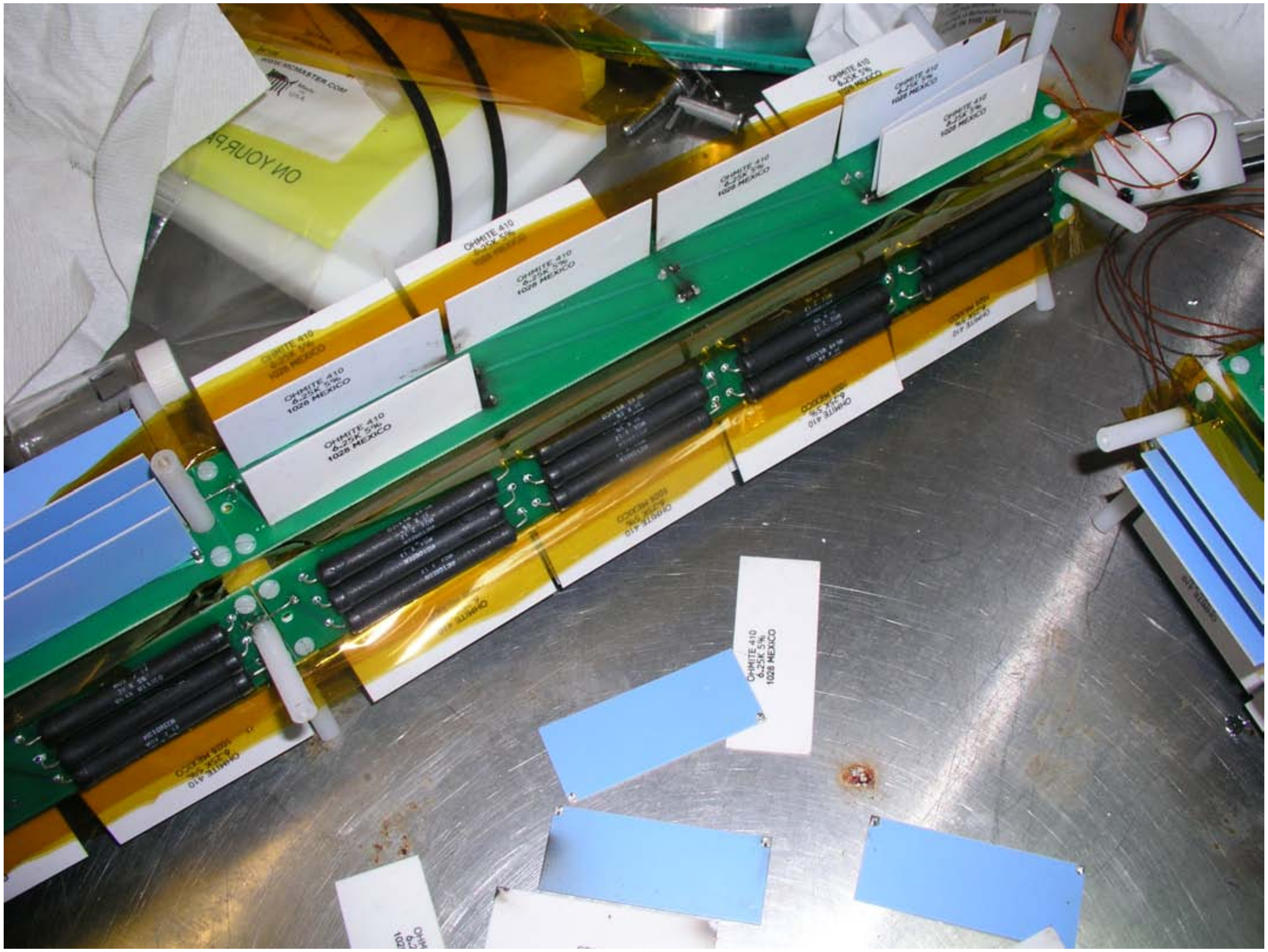
Testing and Assembly
(from 2008 Workshop)

Testing: Resistor Assembly

Initial Testing Failure: Internal Arc (corrected later)

Testing: Resistor Assembly



Initial Testing Failure: Insufficient Cooling (later corrected)

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Final Assembly

Installation of the pulsed system in the switch tank >

Photo of main switch assembly being lowered into switch tank <

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Testing Results Summary:

- OK: The resistor string assemblies, as modified, can withstand the anticipated voltages and currents that are expected in regular operation.

- OK: The resistor string assemblies, when immersed in oil, will not exceed their temperature limits.

- OK: The assembled switch has been tested to 100 kV DC in air, which implies that it will likely be able to work at 300 kV DC when immersed in oil.

- FAIL: When an IEC devices is connected through the new switch, arcing within the device occurs at 60 kV DC. **This does not occur when the device is connected via the present resistor barrel.**

Why are these "micro-arcs" in our IEC devices not seen when we use our present (designed for 200 kV DC) resistor barrel?

Present Resistor Barrel – internal components exposed

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Fault Analysis Slides
(new for 2012)

It is our "working assumption" that some electrical characteristic of the present resistor barrel prevents these arcs.

We are attempting to determine what this characteristic is in order that we might incorporate it into the new switch

Analytic procedure (in progress):

1. Make measurements of overall impedance characteristics, i.e., |Z| at various frequencies

2. Attempt to fit the observed characteristics with a lumped parameter model

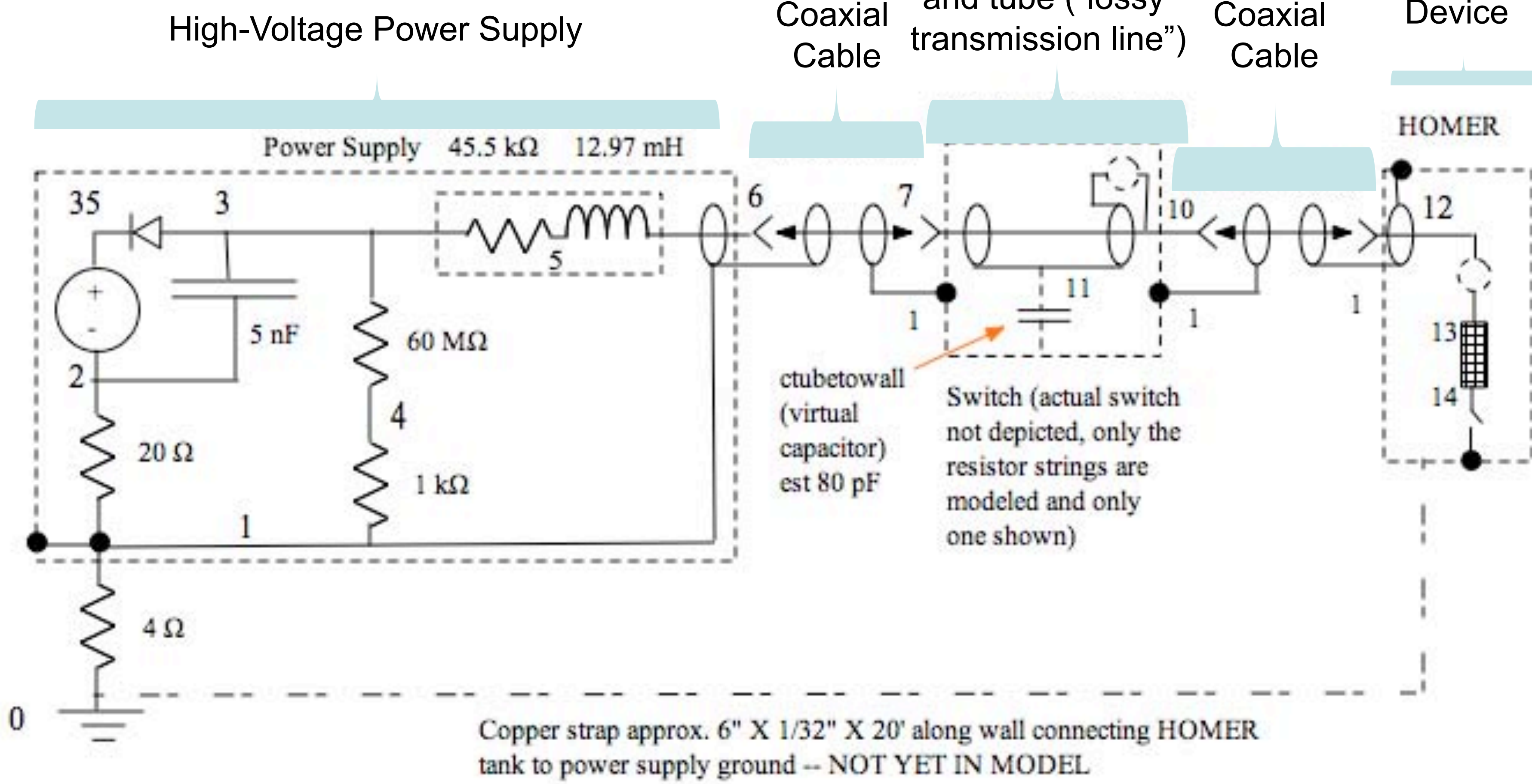
3. If unsuccessful, adjust the model and attempt a fit again.

Measurements and analyses led to the discarding of these hypotheses considered to explain the differences in system behavior:

1. Inductance of the resistors in the currently used resistor barrel
   - The resistors in the current barrel are low-inductance
   - Measurements indicated that the resistor barrel did not have high inductive reactance

2. The long resistor path in the new switch caused unexpected transmission-line effects
   - The current that could flow in the resistors could not account for what was seen

Measurements of barrel and switch impedances and other considerations led to the development of this model for the system:



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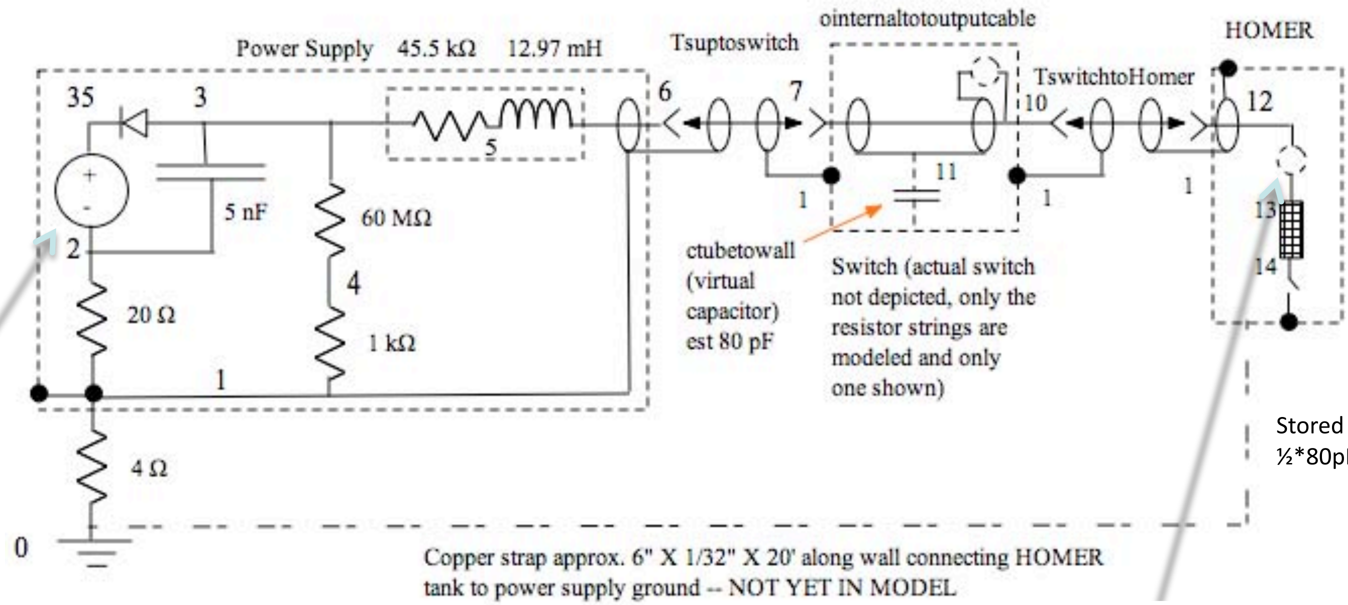
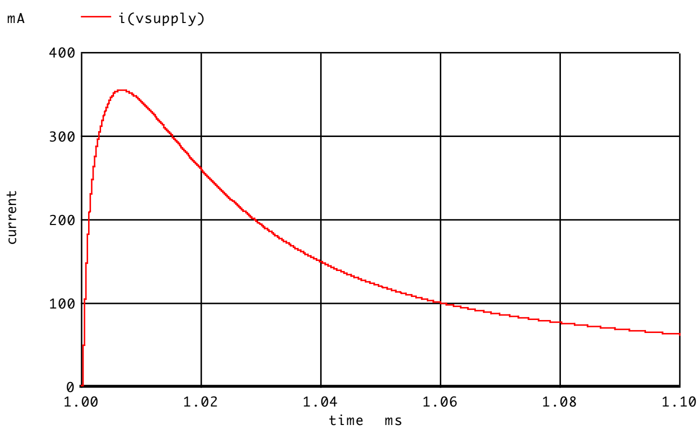
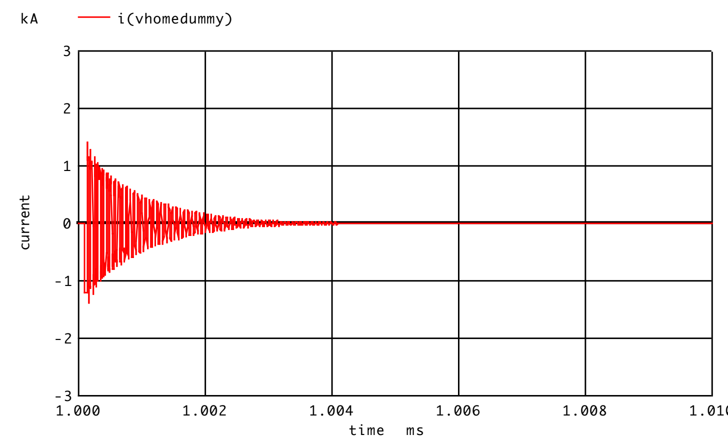
MacSpice Simulation / Distributed RC network for switch string Normal Operating Mode / 0.1Ω resistor for arc / NO Parasitic Cap.

3/2012 RB



Stored Energy in virtual capacitor:
½*80pF*360*10^6 = 0.14J (@60 kV)





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MacSpice Simulation / Distributed RC network for switch string Normal Operating Mode / 0.1Ω resistor for arc

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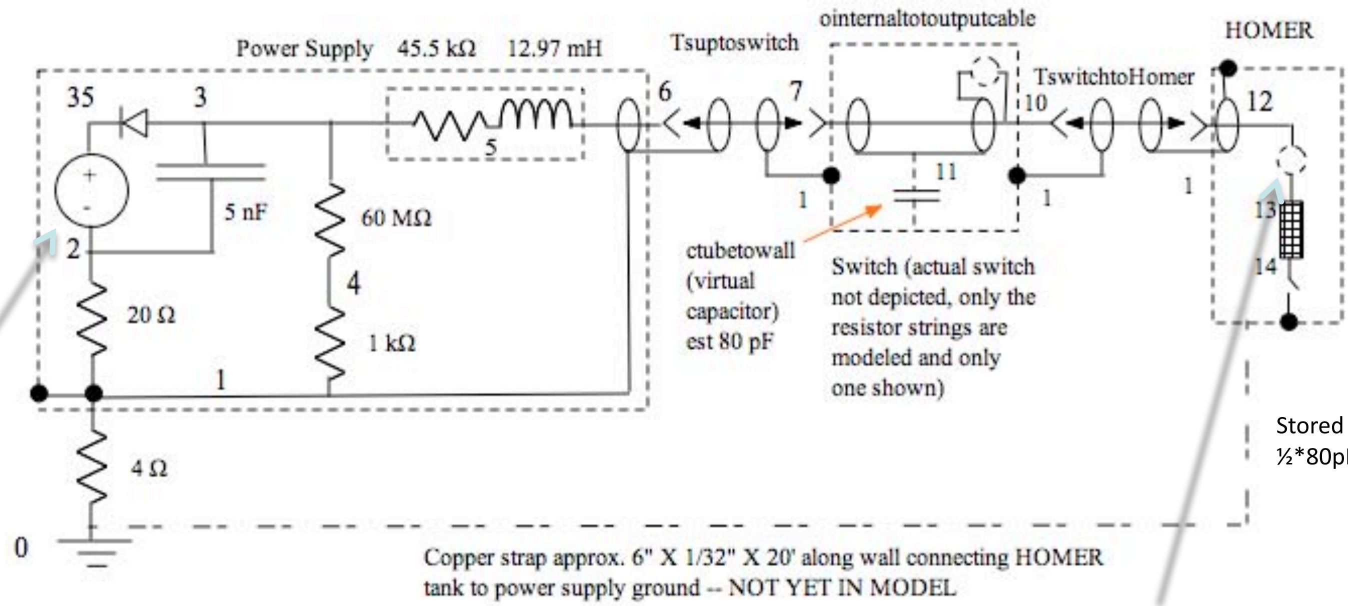

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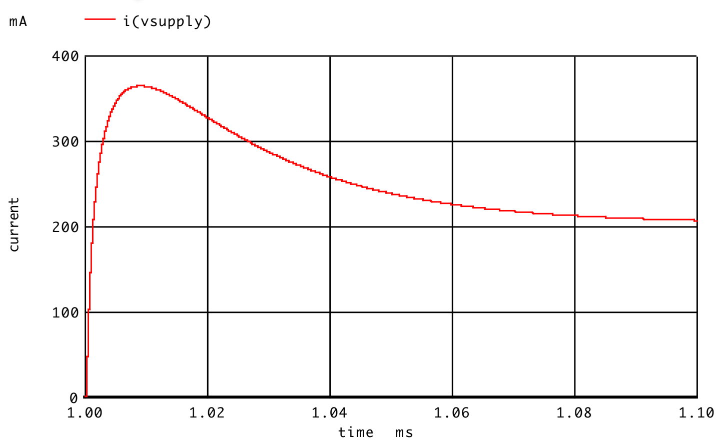

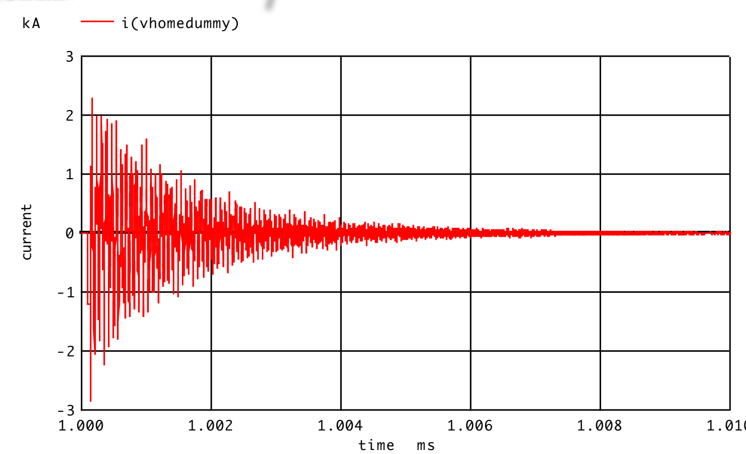

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