SAND2020-7246C

2020 IEEE INTERNATIONAL SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY, SIGNAL & POWER INTEGRITY

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High-Frequency Metal-Oxide Varistor Modeling Response to Early-time Electromagnetic Pulses

Tyler Bowman (tbowma@sandia.gov), Matt Halligan, Rodrigo Llanes

EMP-Resilient Grid
Assess-Optimize-Innovate

Exceptional service in the national interest

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Presenter Bio

Tyler Bowman

- Postdoctoral Appointee at Sandia National Laboratories – Electrical Science and Experiments since 2018.
  - Design and execution of experiments for EMP resilience of electric power systems equipment and other experiment development.
- BS EE in 2012, MS EE in 2014, and Ph.D of EE in 2018 from University of Arkansas with work on experimental Terahertz imaging and spectroscopy.
- IEEE member for 7 years.

Acknowledgements

- This work made possible under Sandia National Laboratories Lab-Directed Research and Development project #209239: EMP-Resilient Electric Grid for National Security.

- Modeling Support
  - Salvatore Campione
  - Richard Schiek
- Experimental Support
  - Alfred Baughman
  - James Taylor
- Technical Review
  - Steve Glover
- LDRD Project Lead
  - Ross Guttromson

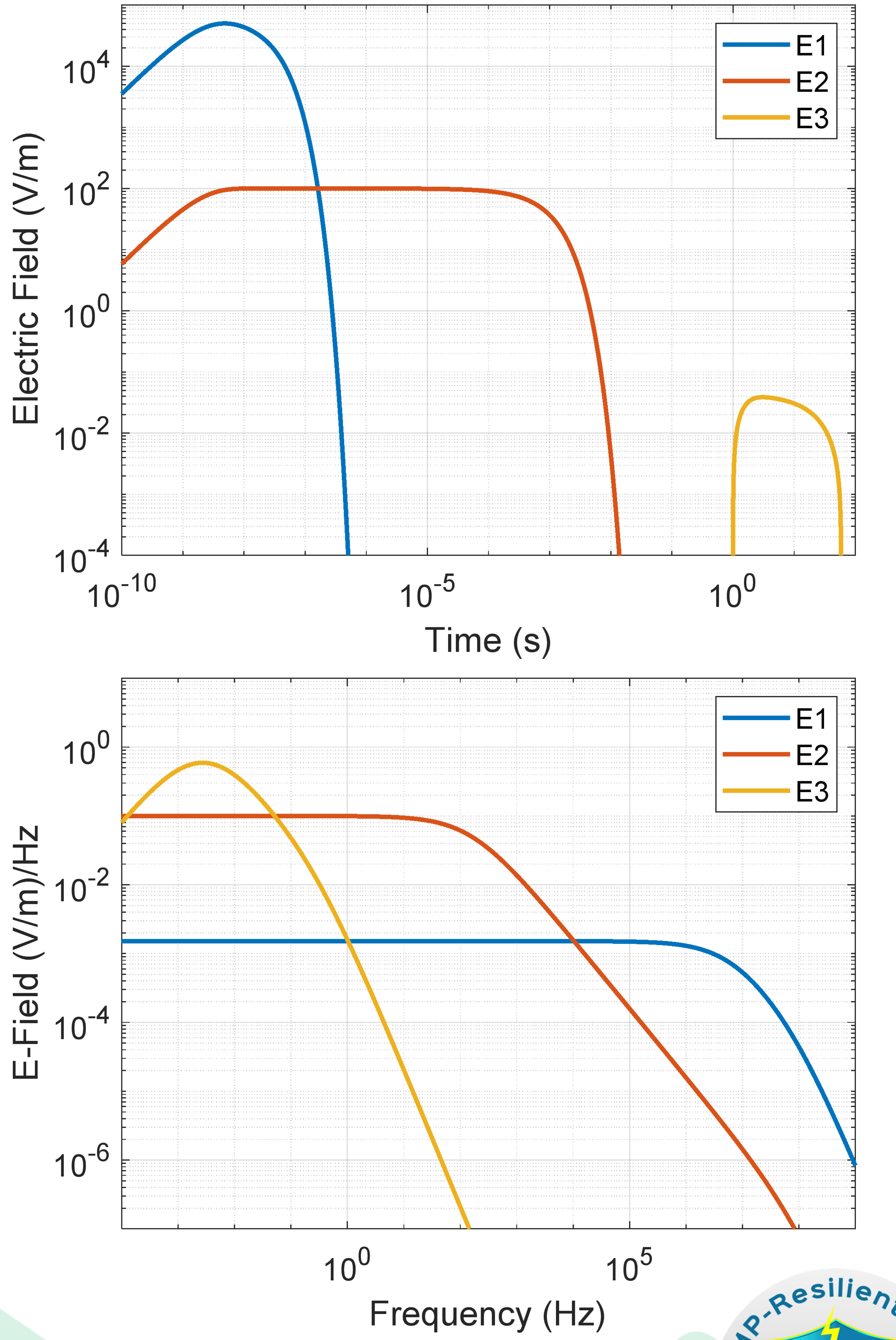
Background

- High-altitude electromagnetic pulses (HEMP) pose an unknown threat for the electric grid

- EMP-Resilient Grid program at Sandia focused on three core thrusts:
  1. Vulnerability Assessment and Model Generation
  2. Materials and Device Innovation
  3. Optimal Resilience Strategies

- Primary efforts are focused on early-time (E1) HEMP due to strong electric field transients

IEC 61000-2-9 Radiated HEMP Definitions



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EMP-Resilient Grid
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Lightning Surge Arrester Experimental Motivation

- Primary interest: HEMP impact on transformer
- Typical interface includes lightning surge arrester
- Neglecting impacts of nearby substation devices
- Motivating research questions:
  - Do lightning surge arresters offer protection against HEMP?
    - Response time?
    - Arrester survivability?

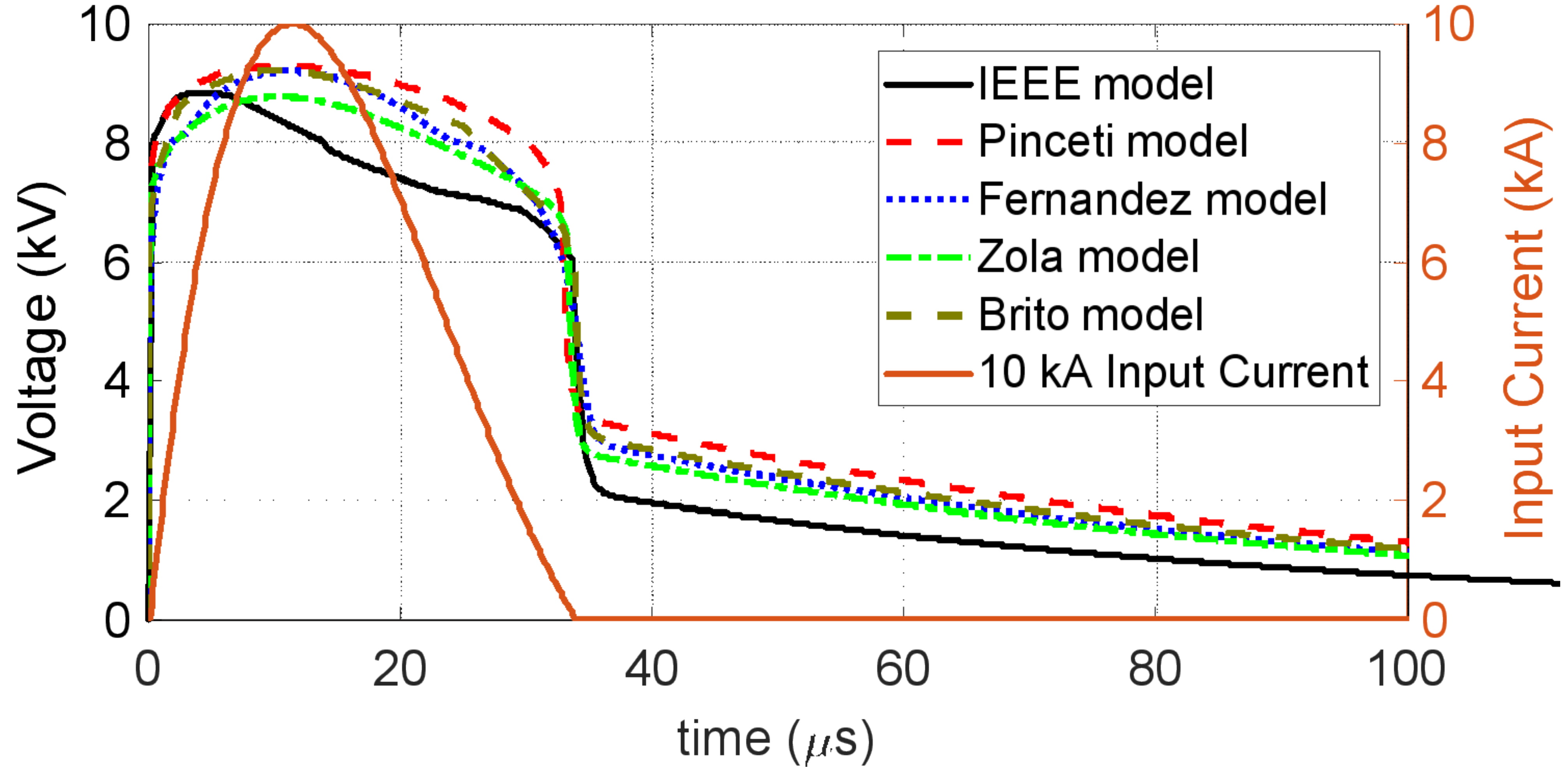
Literature Model Response to Lightning / E1

- Several arrester models optimized in literature for lightning response
- Significant variations when E1-like pulse is applied

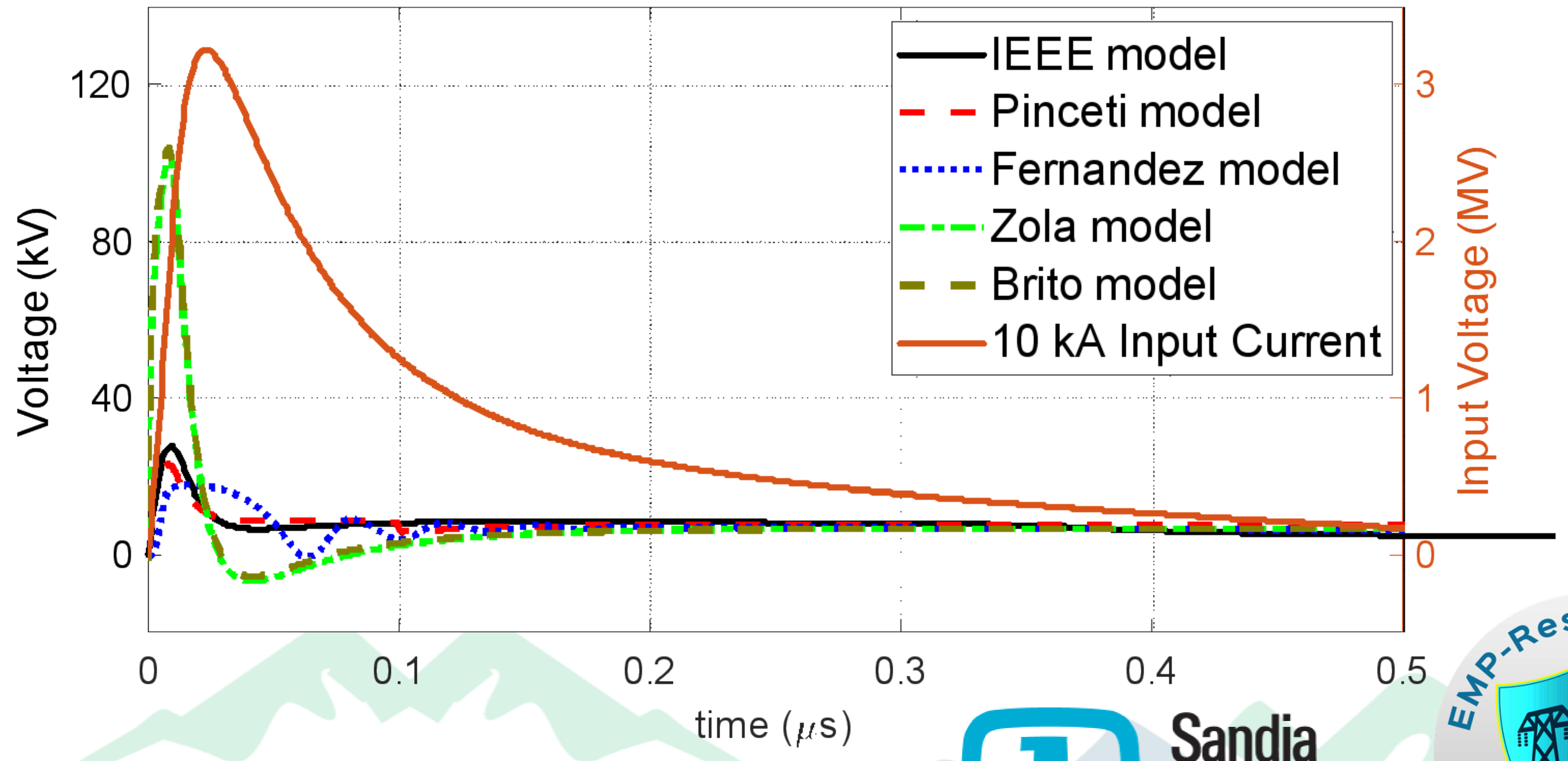
Validated circuit model needed for scalable assessment of arrester response to HEMP

- IEEE WG 3.4.11, *IEEE Trans. Power Deliv.* **7**(1), 302-309, 1992.
- P. Pinceti *et al*, *IEEE Trans. Power Deliv.* **14**(2), 393-398, 1999.
- F. Fernández *et al*, "Metal-oxide surge arrester model for fast transient simulations," Proc. IPST 2001.
- J. G. Zola, *IEEE Trans. Comput.-Aided Design Integr. Circuits Syst.* **23**(10), 1491-1494, 2004.
- V. S. Brito *et al*, *IEEE Trans. Power Deliv.* **33**(1), 102-109, 2018.

10 kA, 8/20 pulse circuit response (combination wave)



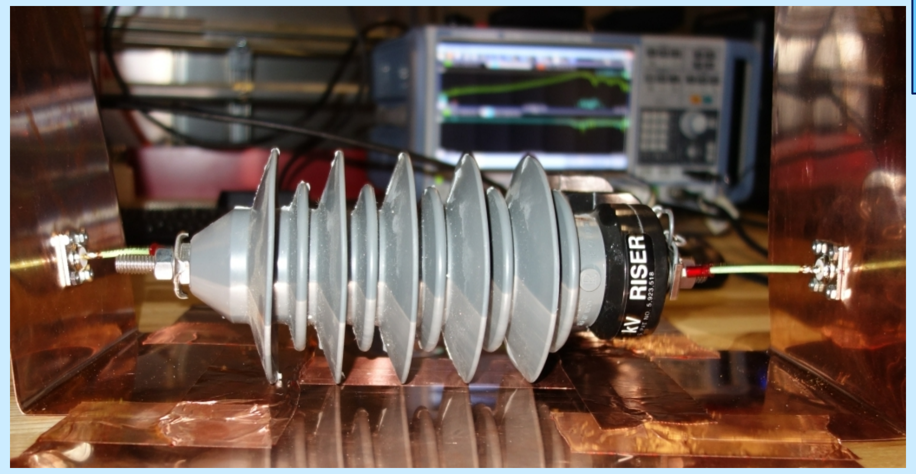
E1-like voltage wave response (5 km coupled wave)



Roadmap of Arrester Work

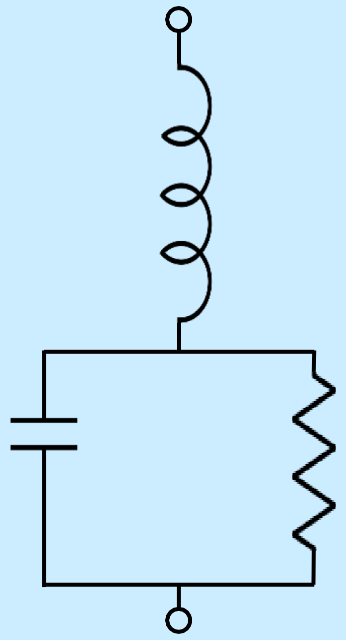
Distribution Arrester Measurement:

- Bias dependent impedance
- I-V curve tracing
- Pulsed characterization



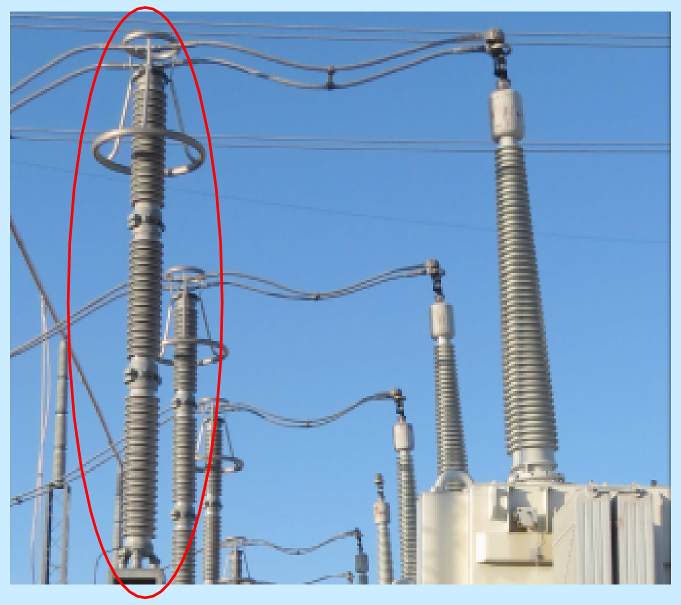
Scalable SPICE Circuit Model:

- Estimations from manufacturer data
- Critical HEMP response parameters
- Failure mode analysis

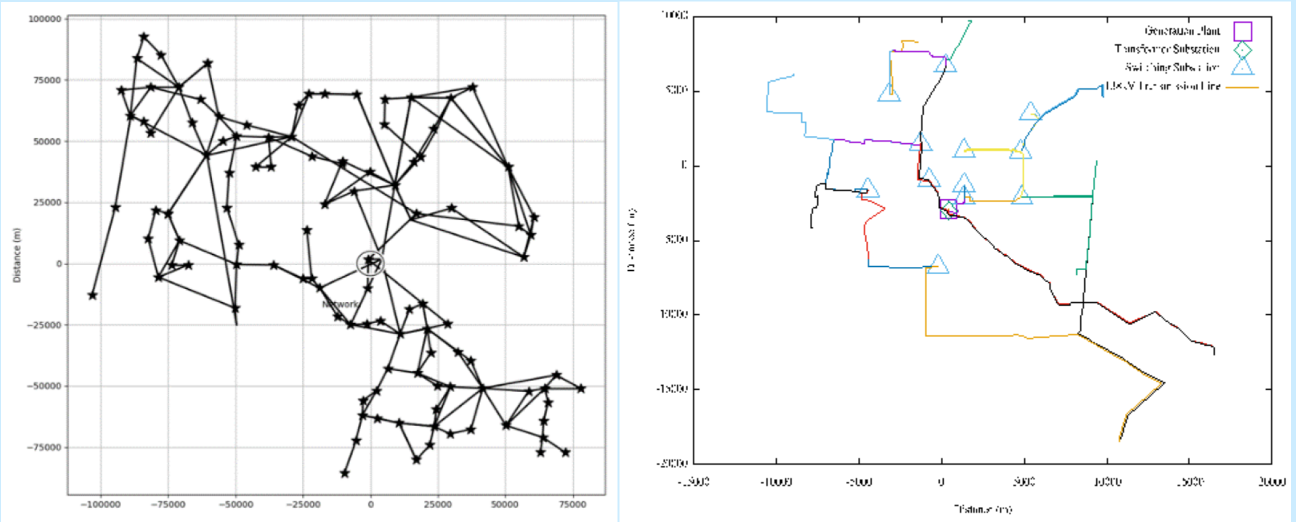


Transmission Arrester Model(s):

- Anticipated arrester response under HEMP with simple load
- Validation of XYCE compatibility



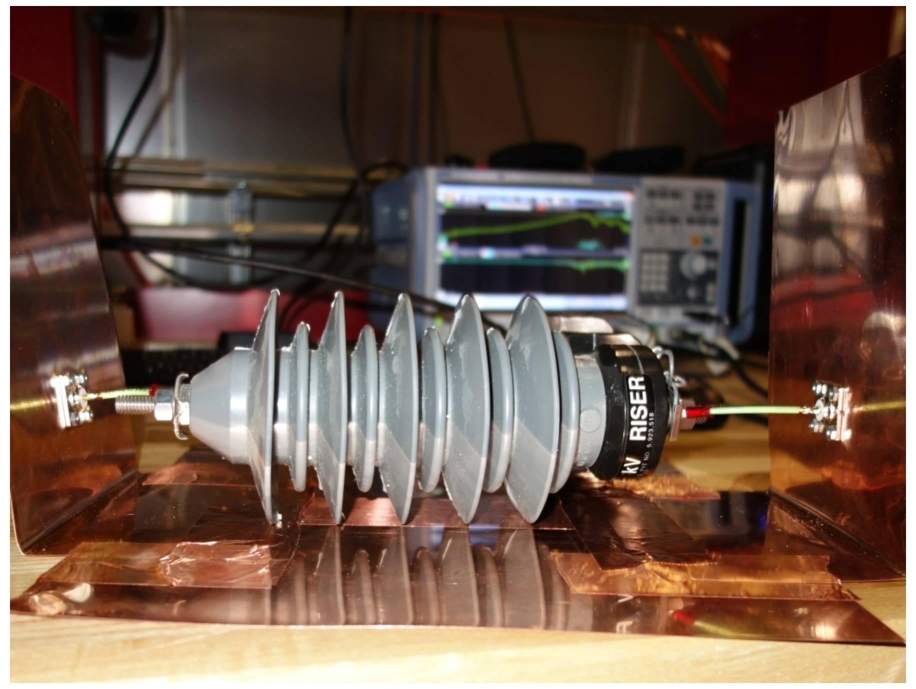
Integration into Coupling and Grid Simulations



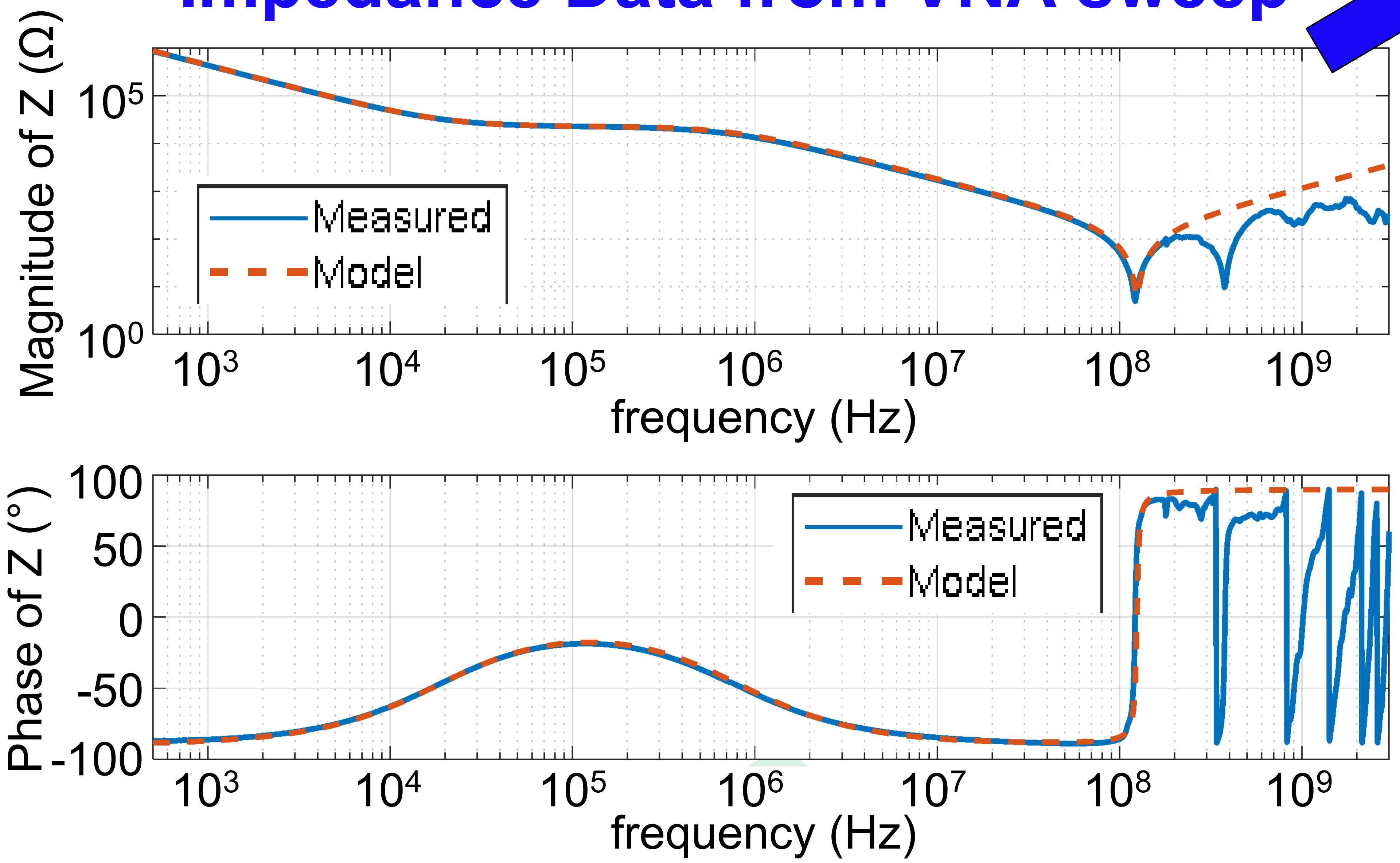
Generation of Basic Arrester Model

- Basic high frequency RLC behavior characterized by VNA sweep

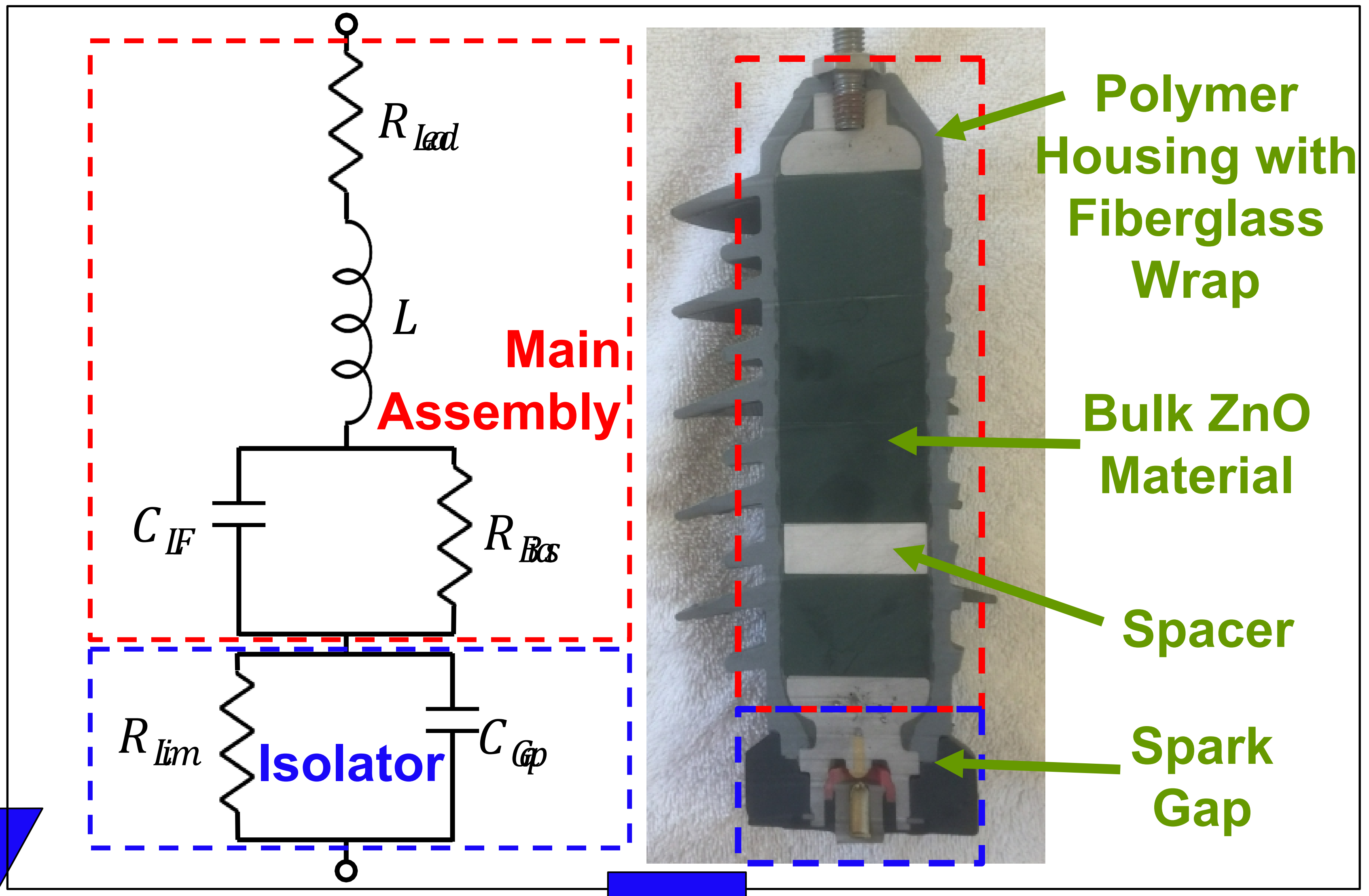
- Critical components identified for scalable, general use circuit model

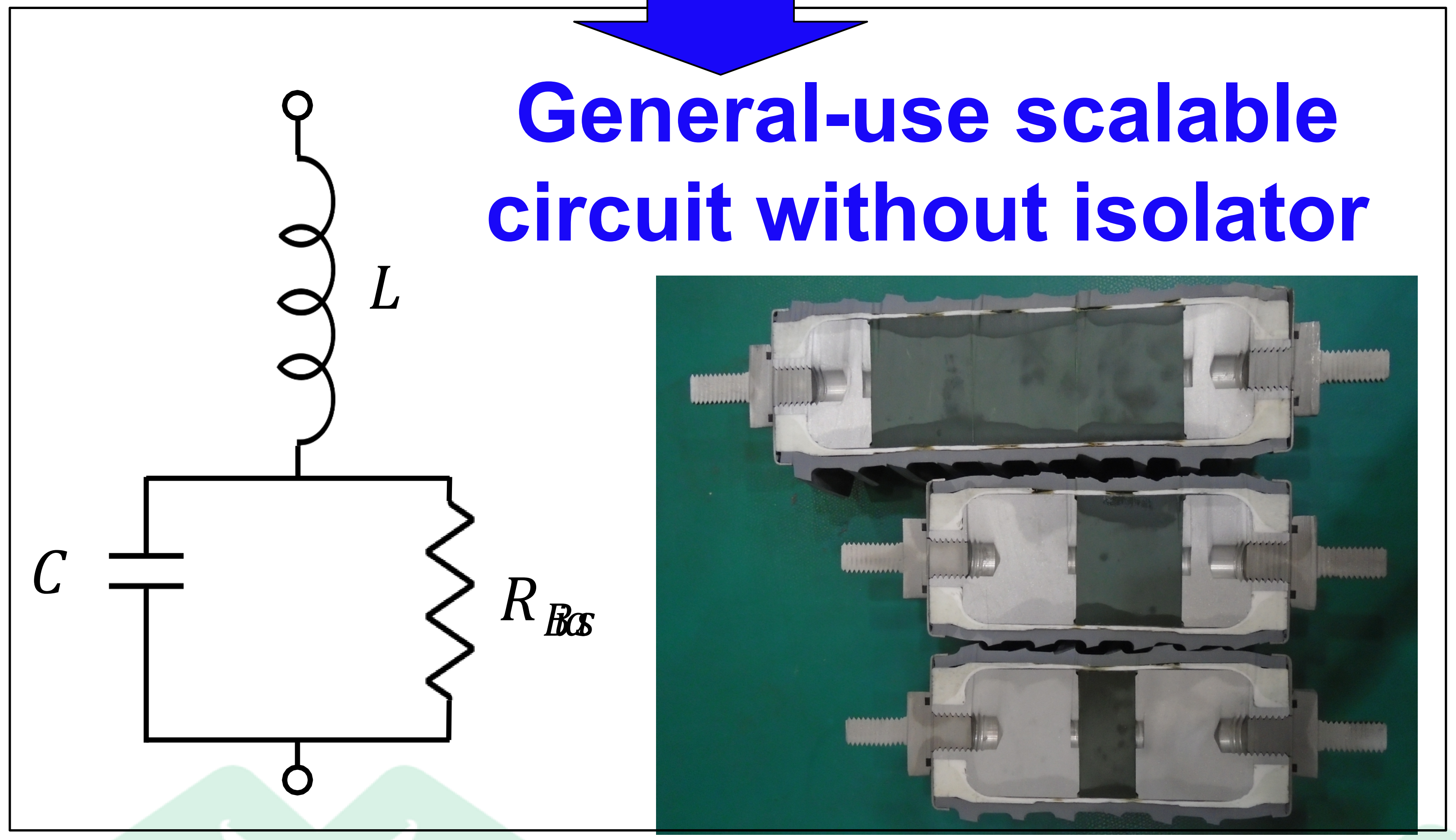


Impedance Data from VNA sweep



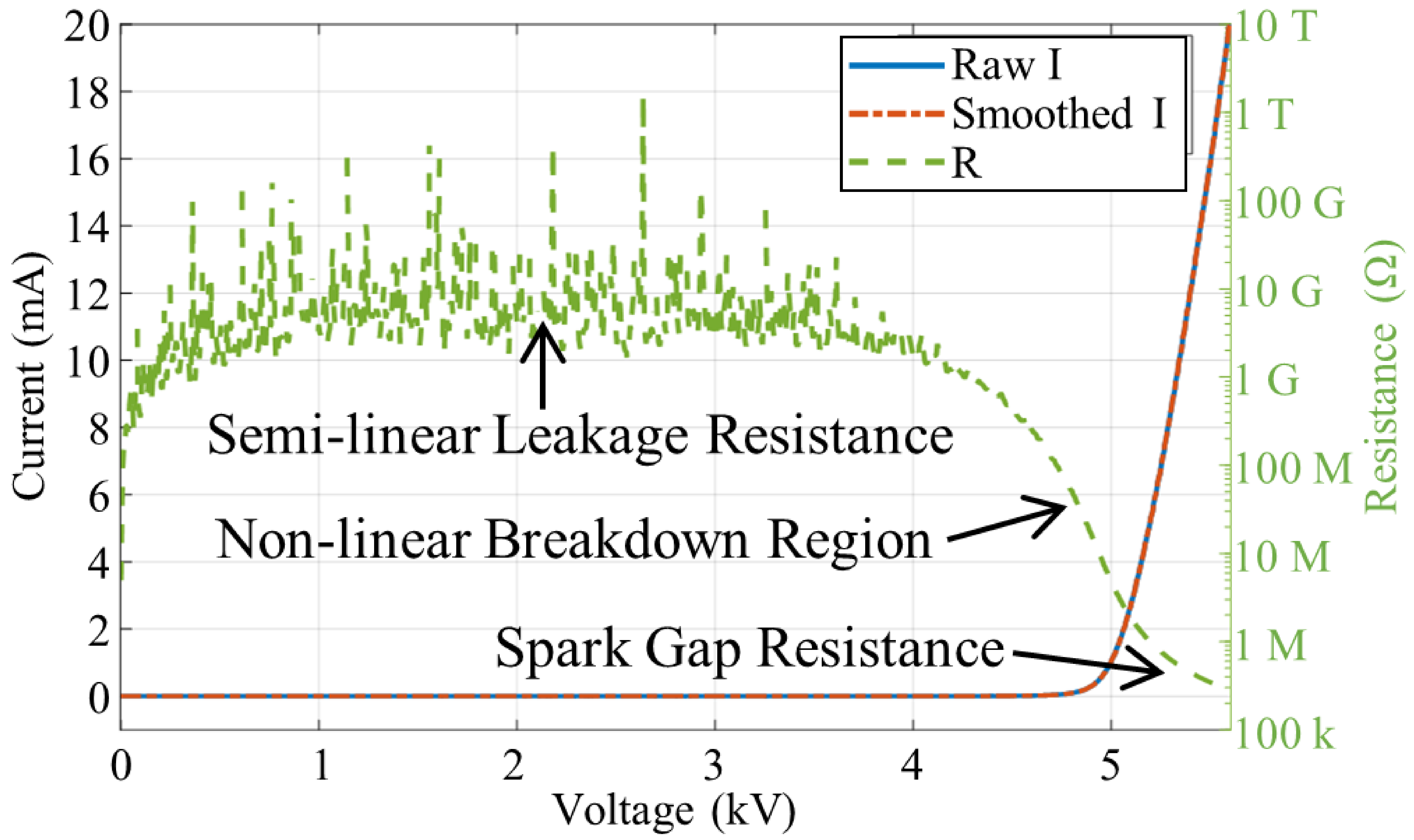
Circuit with separate isolator

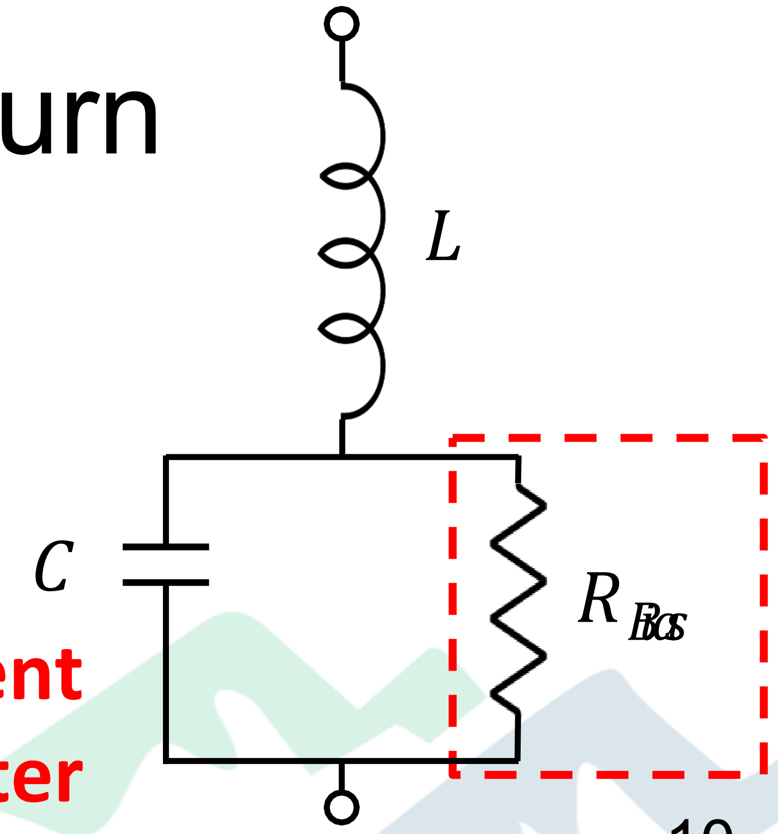




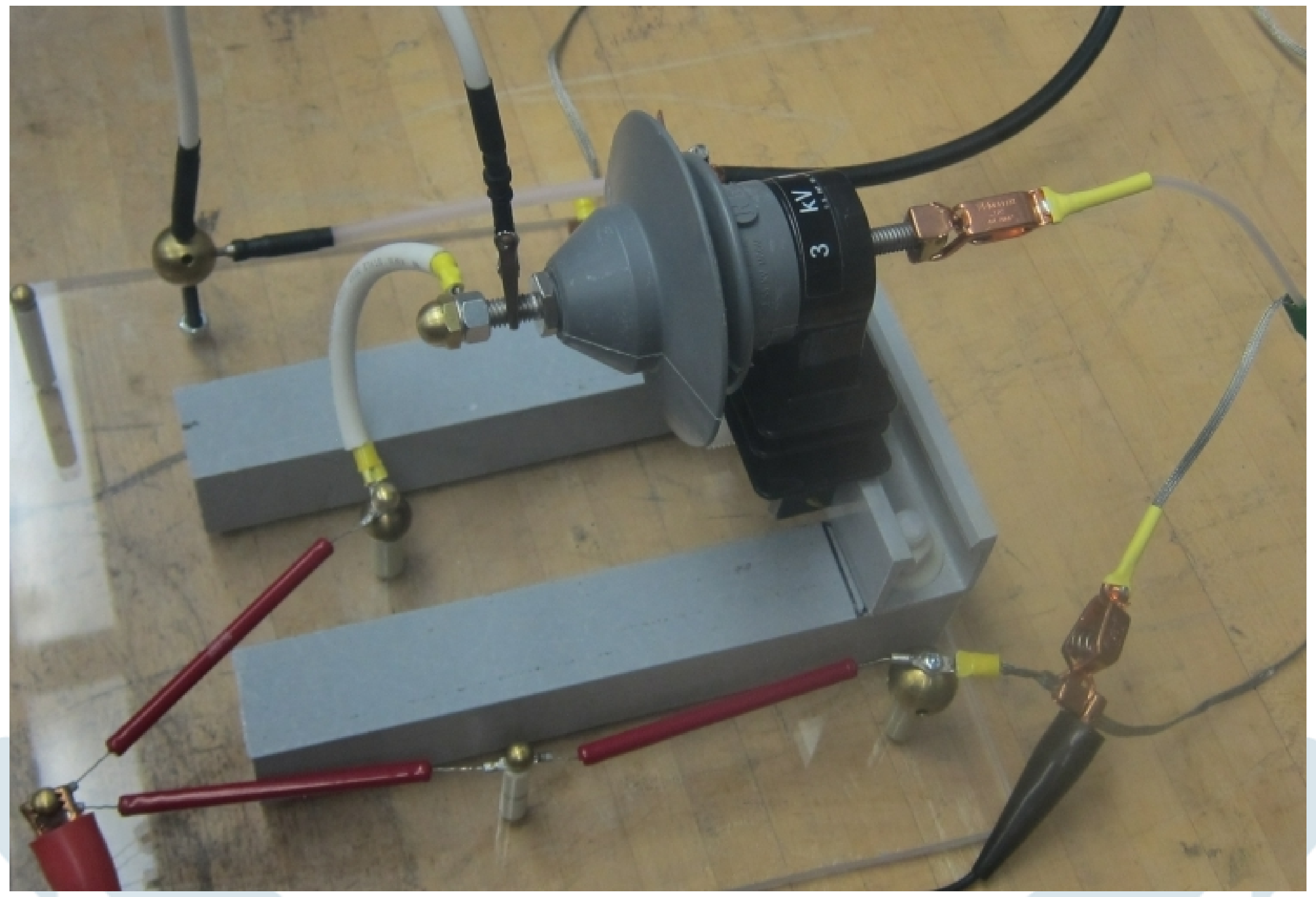
Non-linear Resistance Measurements

- I-V curve trace measurements up to 20 mA
  - Pulsed to avoid overheating
- Resistance approximately linear at low voltage
- Strong nonlinearity in resistance at increased voltages
  - Testing did not reach upturn behavior of MOVs



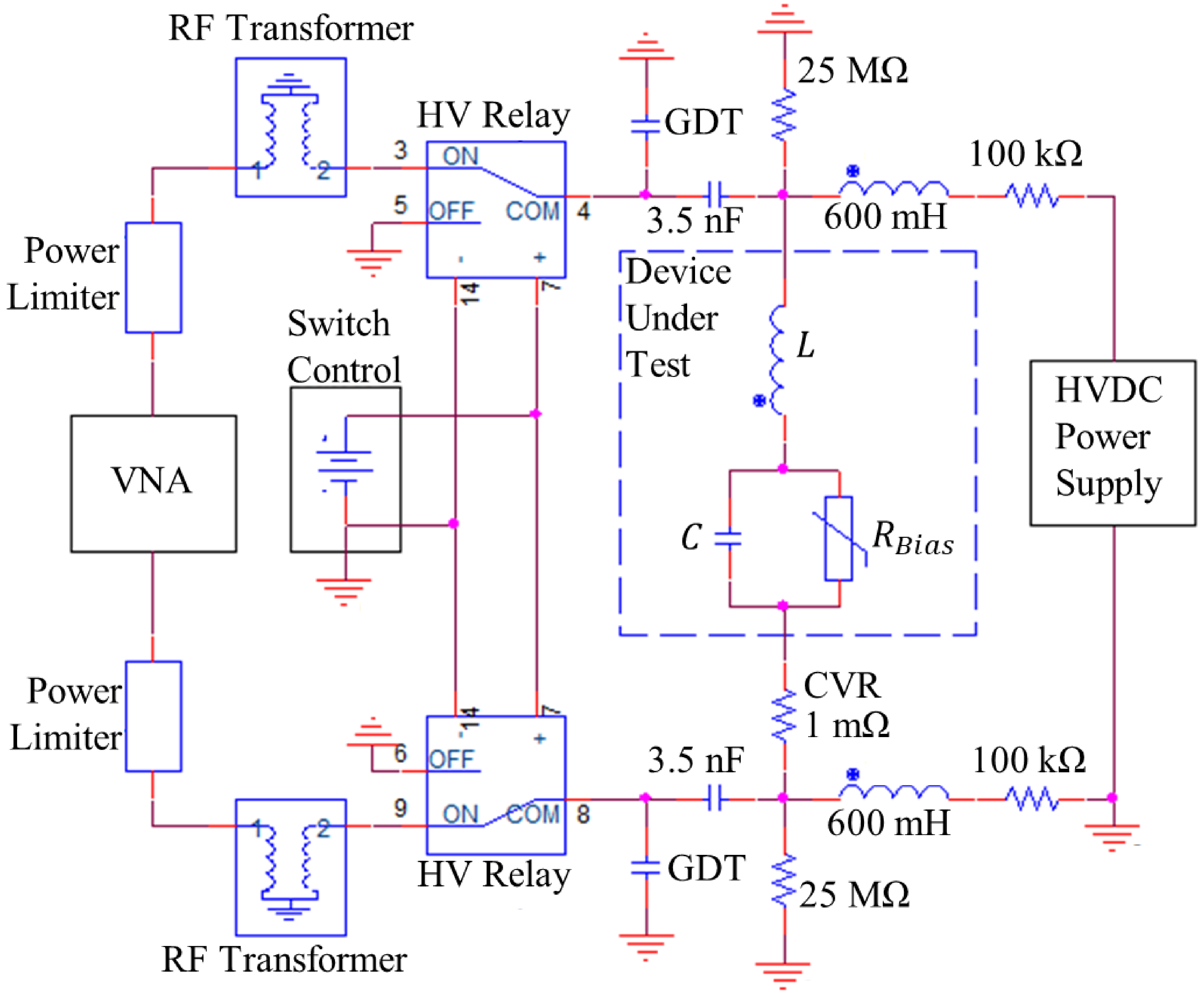


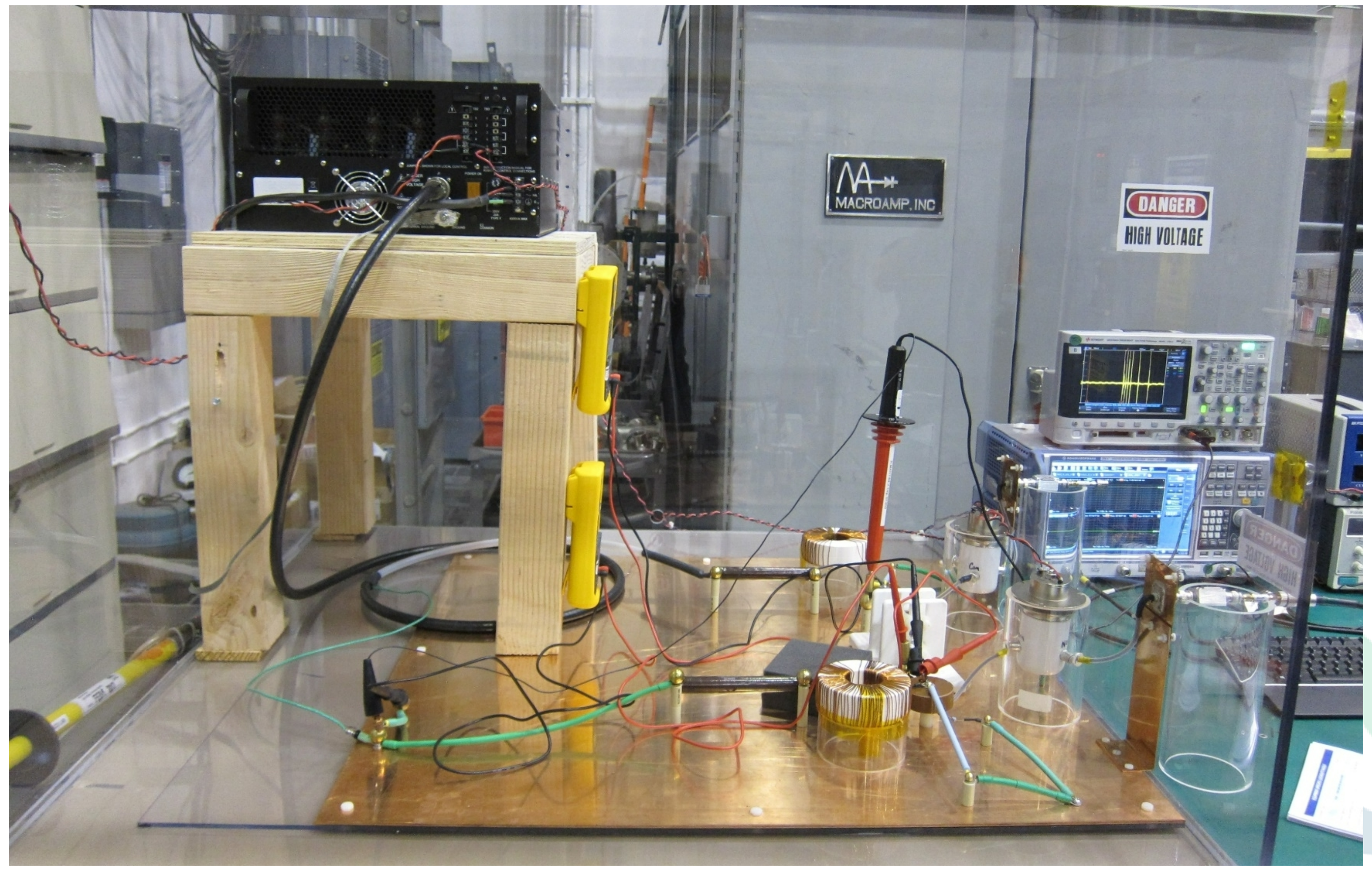
Bias-Dependent Parameter

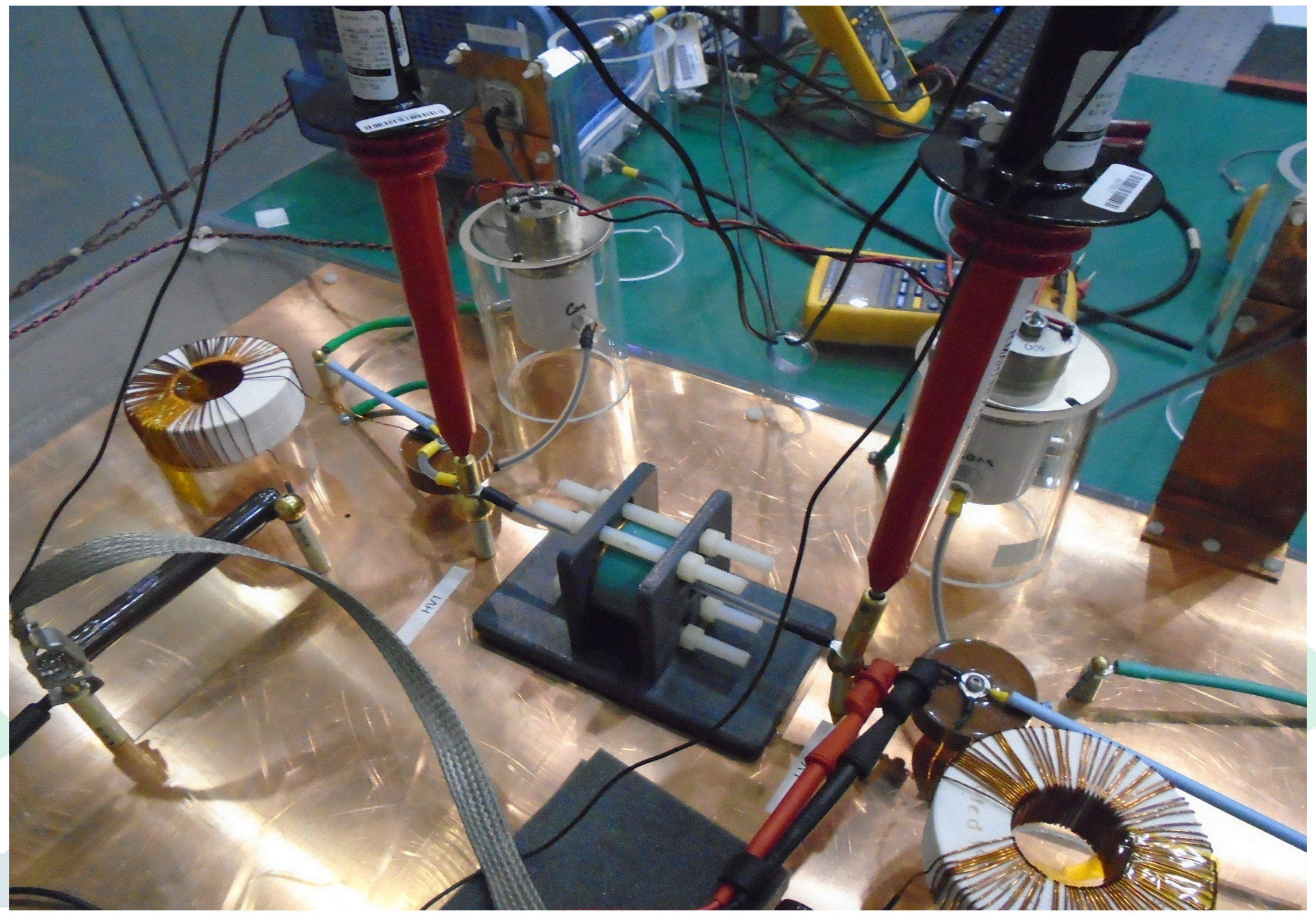


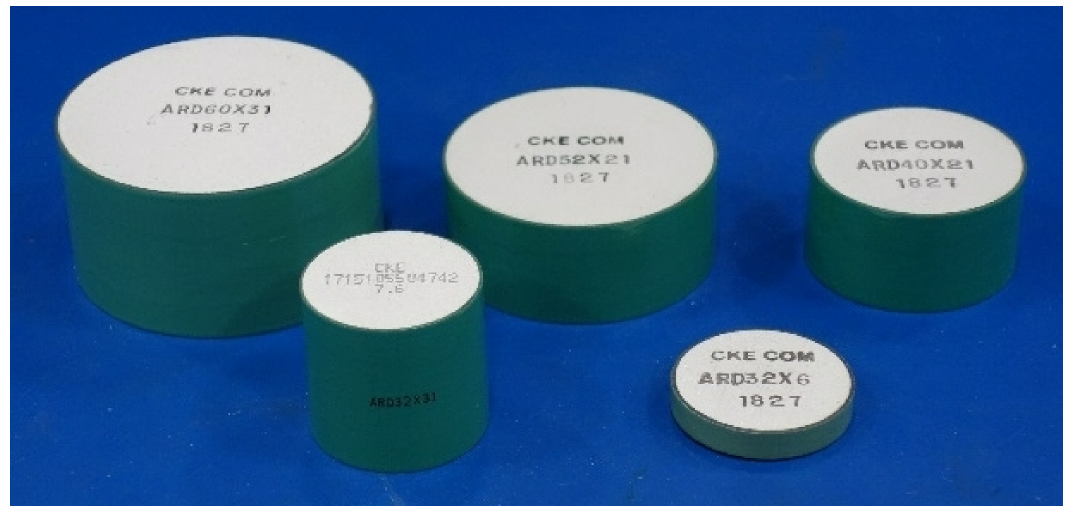
Bias Tee for Non-linear Capacitance Measurement

- Measurement setup with isolated AC and DC loops
  - AC loop measures VNA signal, protected by capacitors
  - DC loop provides high voltage bias, isolated by inductors
  - MOV pucks measured at bias conditions up to 18 kV or 20 mA maximum



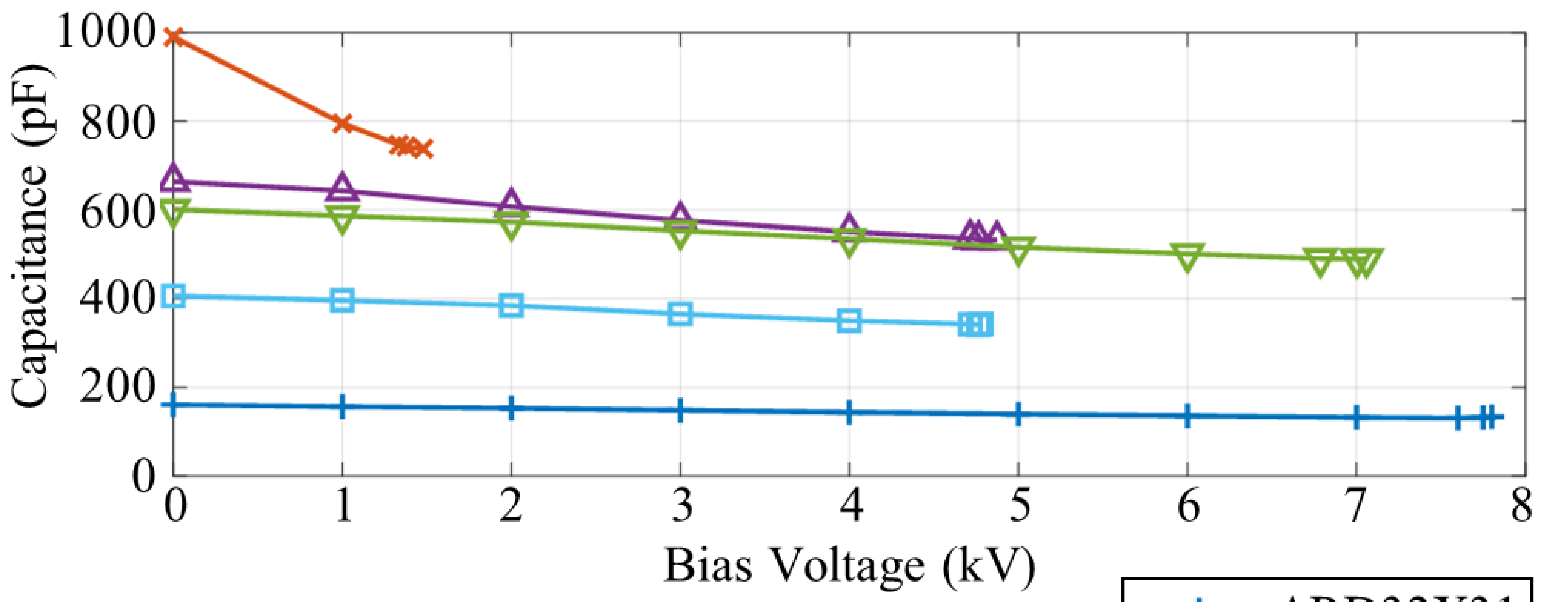


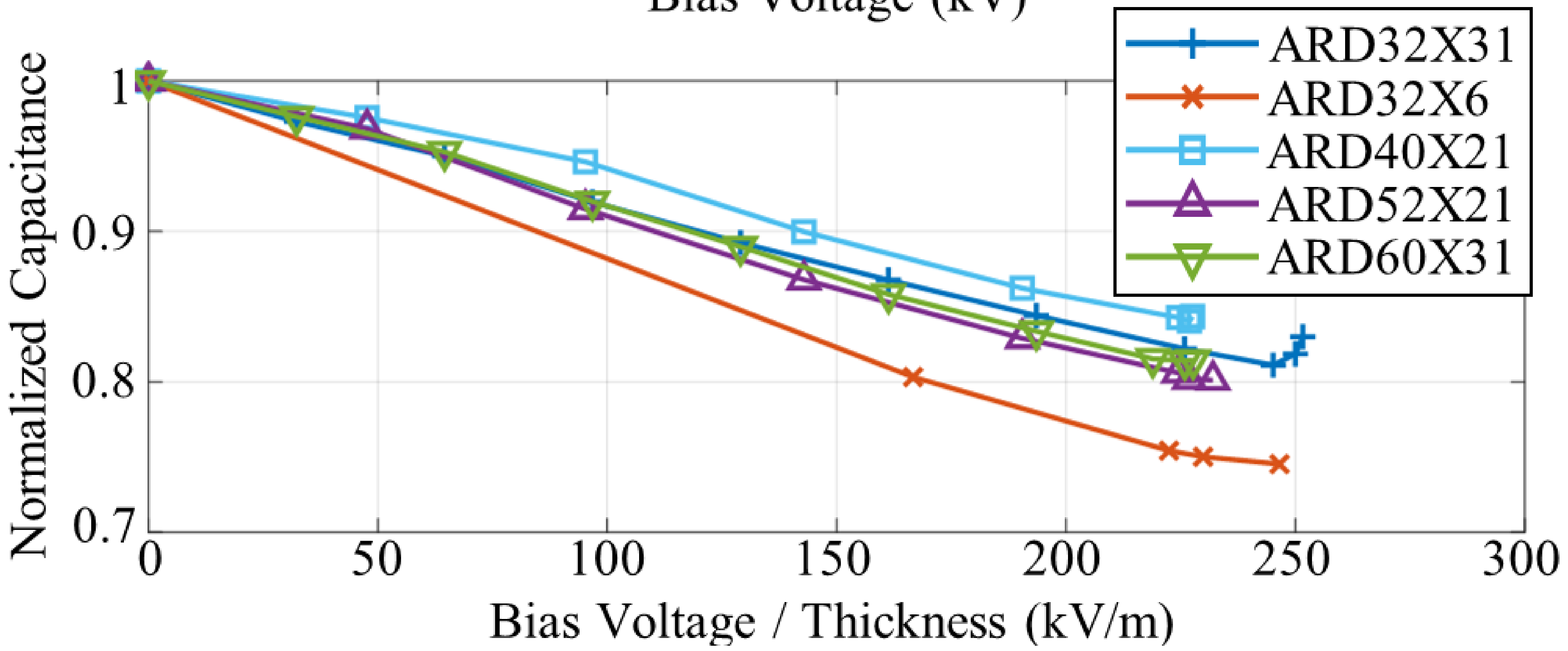


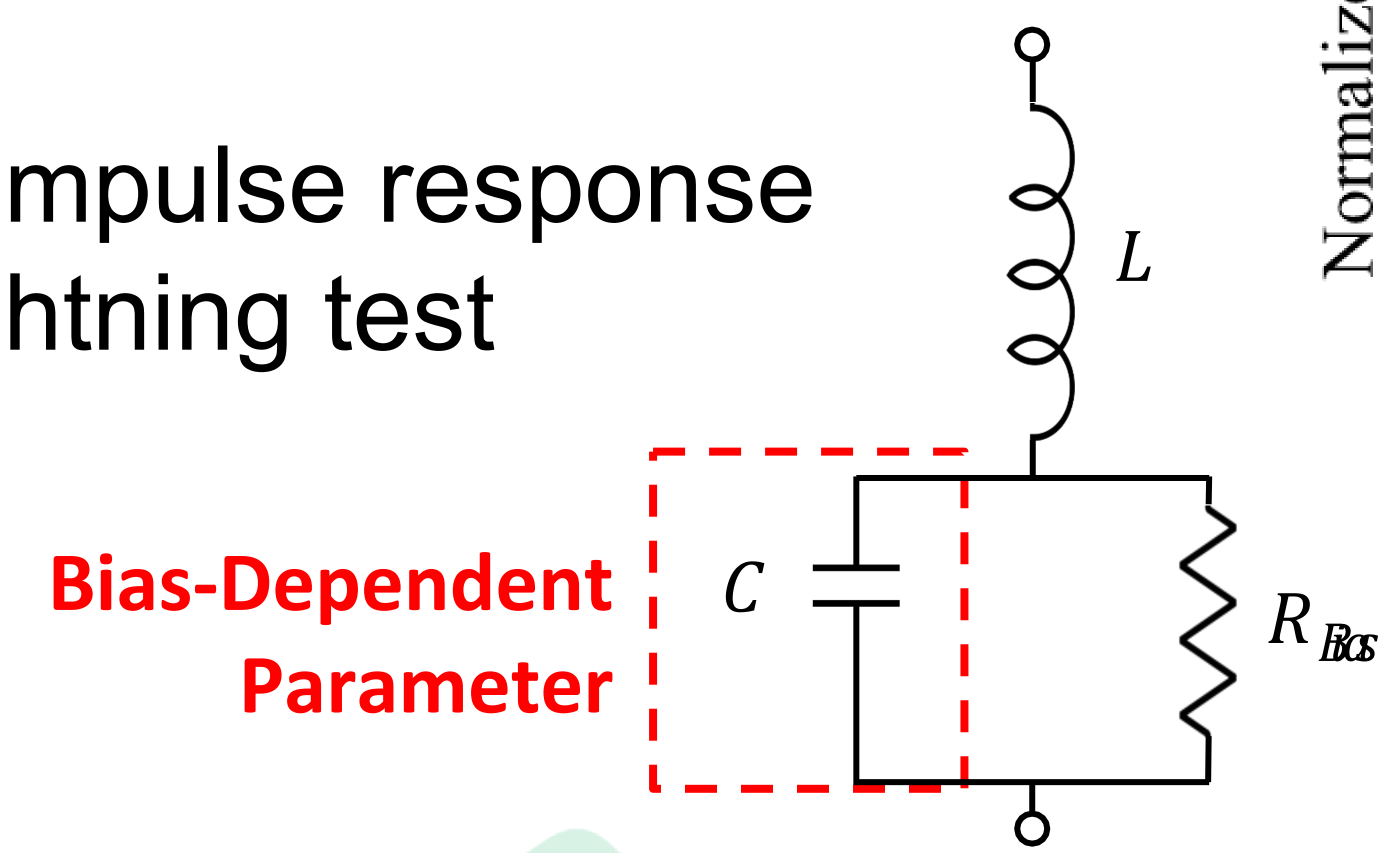


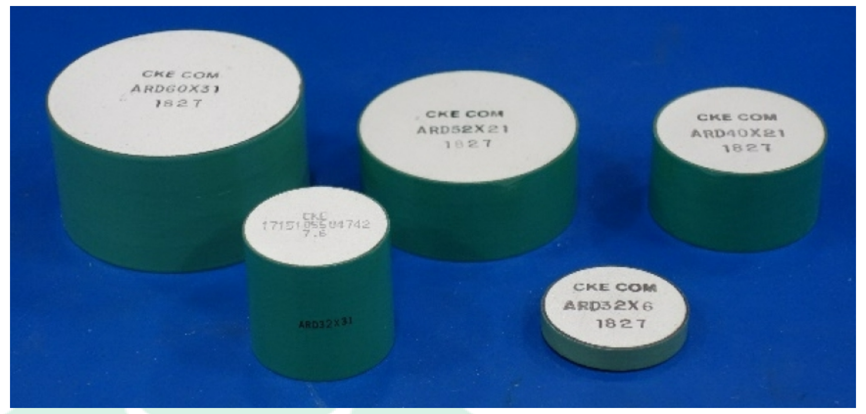
Bias Dependence Measurements of ZnO Pucks

- Capacitance measured using VNA sweeps on bias tee up to 20 mA
  - Diminishing ability to increase voltage as pucks entered breakdown region
- Trend approximately linear when normalized based on puck thickness
- <30% shift in capacitance expected for 10 kA signal
  - No impact on modeled impulse response for E1 HEMP or 8/20 lightning test









Roadmap of Arrester Work

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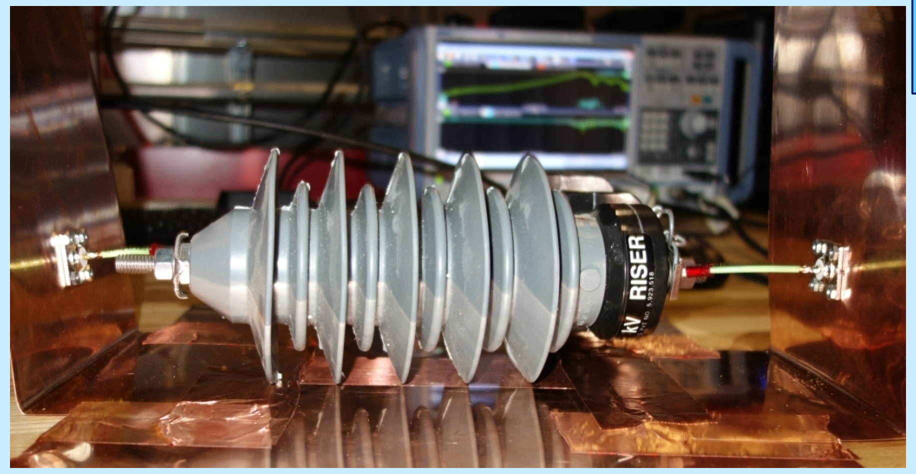
- Pulsed characterization



Scalable SPICE Circuit Model:

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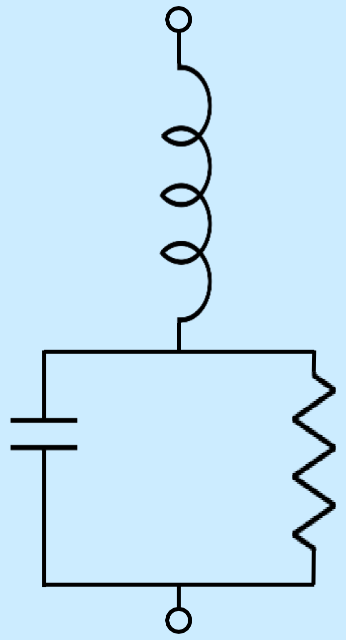

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- Anticipated arrester response under HEMP with simple load
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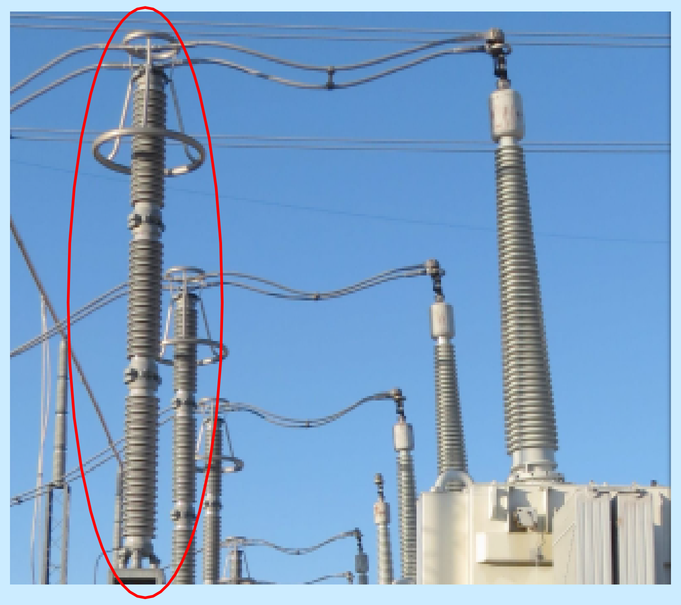
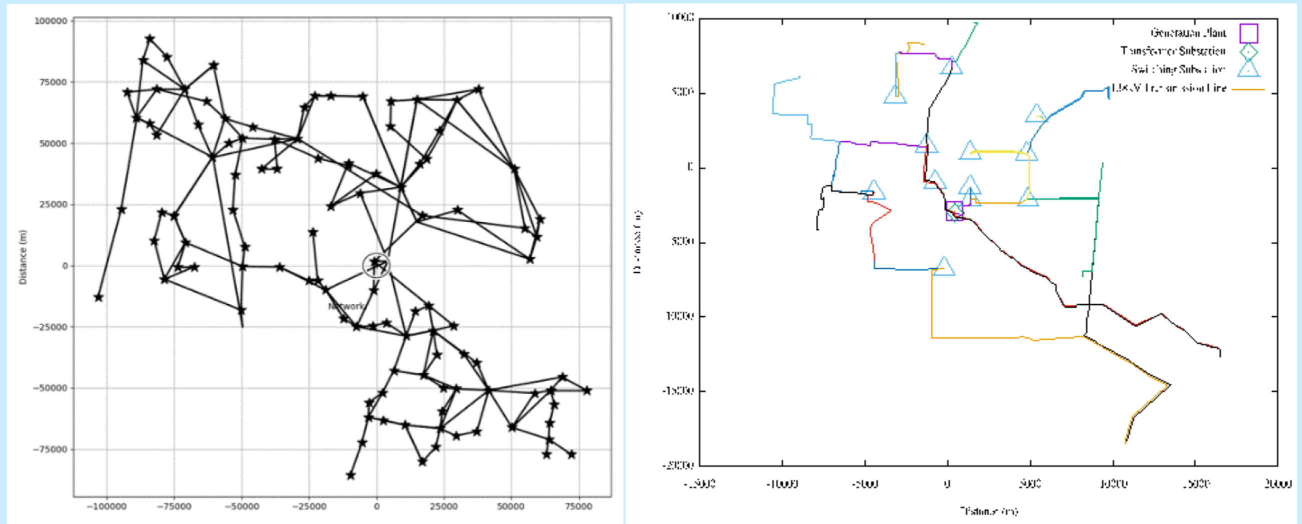
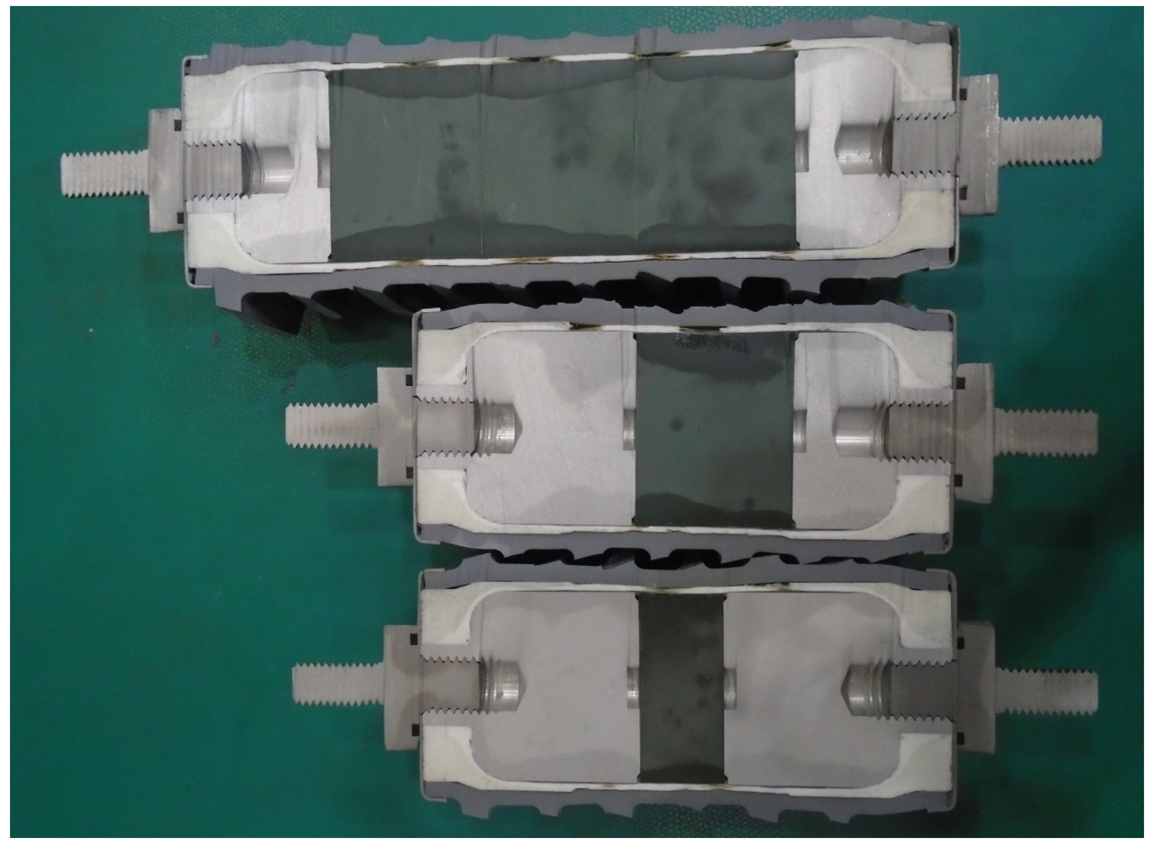


Integration into Coupling and Grid Simulations



Scalable Arrester Model Considerations

- Isolators not considered for general model
- Non-linear resistance should be implementable as SPICE function
- Capacitance ideally based on ZnO dimensions
  - Non-linear capacitance negligible
  - Can account for ESR with 0.01 dissipation factor



Siemens data points used to approximate ZnO dimensions:

$$length_{ZnO} = \frac{V_{10}(r_{ZnO})^{0.2844}}{1.3 \times 10^5}$$

V. Hinrichsen, *Metal-Oxide Surge Arresters in High-Voltage Power Systems*, 3rd edition handbook from Siemens, 2011.

Parameter Estimations for Arrester Model

- Arrester model estimations developed from measurements
  - R_{Bias}: modified 4PL regression equation to match three regions
    - Low-mid frequency: measured data or MOV dimensions
    - High frequency: manufacturer data
  - L: 1 nH/mm (rule-of-thumb) total arrester length
  - C: MOV dimensions and mean measured $\varepsilon_r = 755$

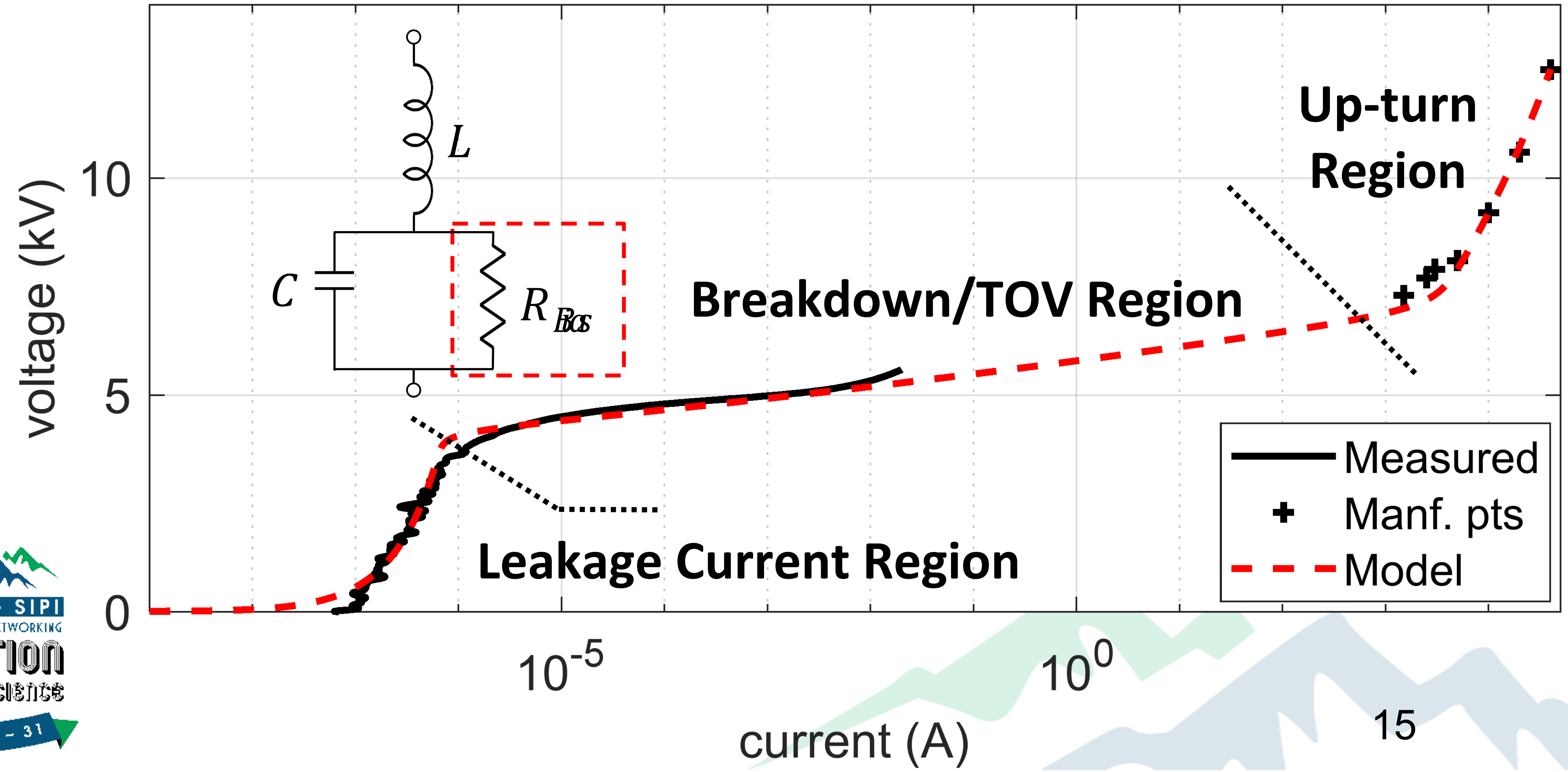
$$I = \frac{V}{\dfrac{a}{1+\left(\dfrac{V}{c}\right)^{b}} + \dfrac{d}{\left(\dfrac{V}{f}\right)^{e}}}$$

$$a = R_{bias,LF} \qquad d = V_{10}/I_{10}$$

$$b = \frac{\log(a/R_{switch})}{\log(V_{switch}/c)} \qquad e = \frac{\log(d/R_{V_{max}})}{\log(V_{max}/f)}$$

$$c = V_{clamp} \approx \sqrt{2}V_{rated} \qquad f = V_{10}$$

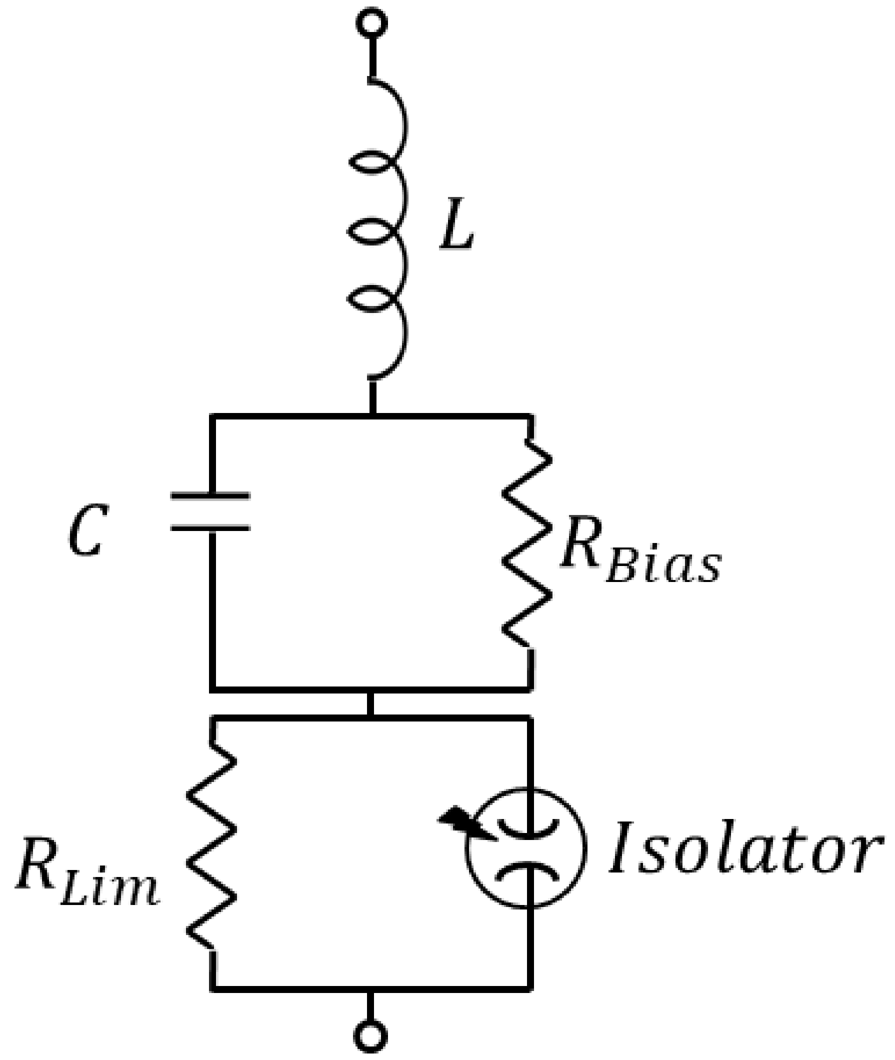
Example 3 kV Arrester I-V Curve for R_{Bias}



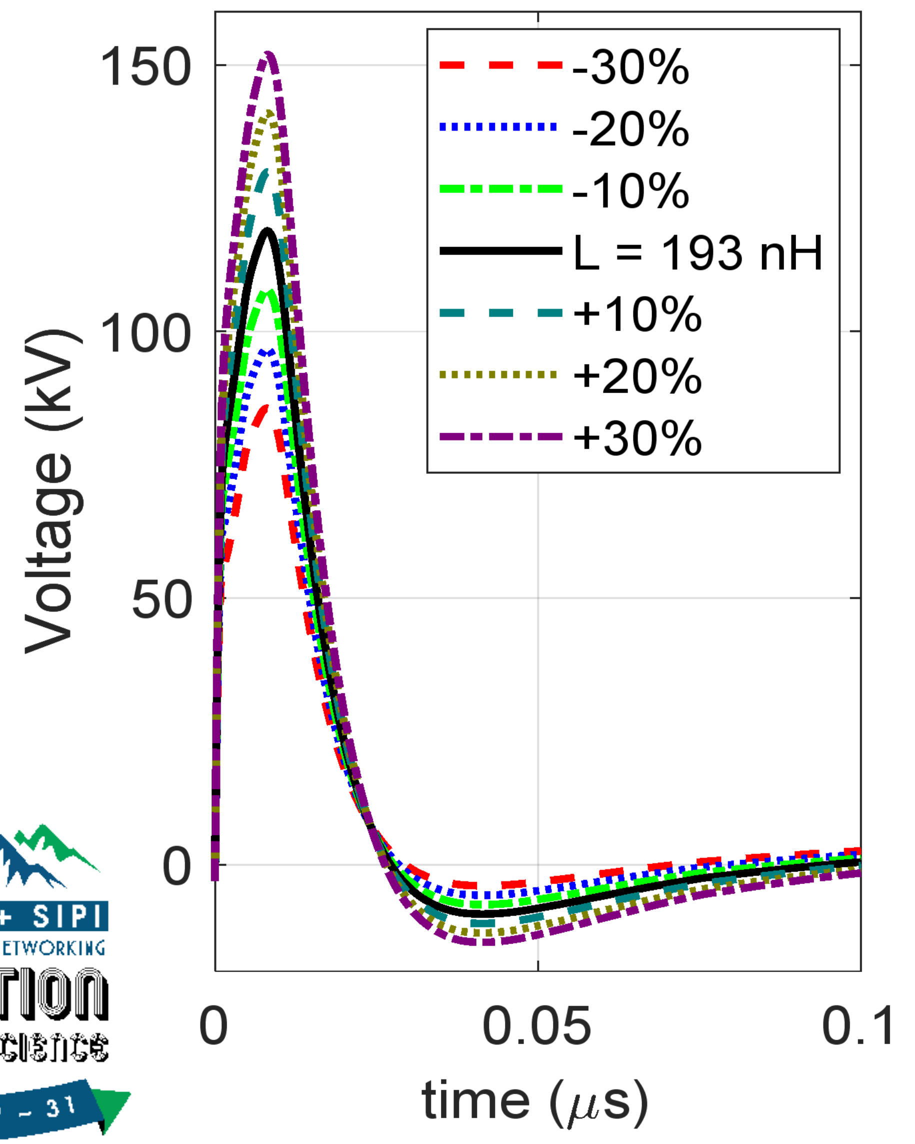
Result is quickly scalable model based only on manufacturer data.

Distribution Arrester Model Response – 3 kV

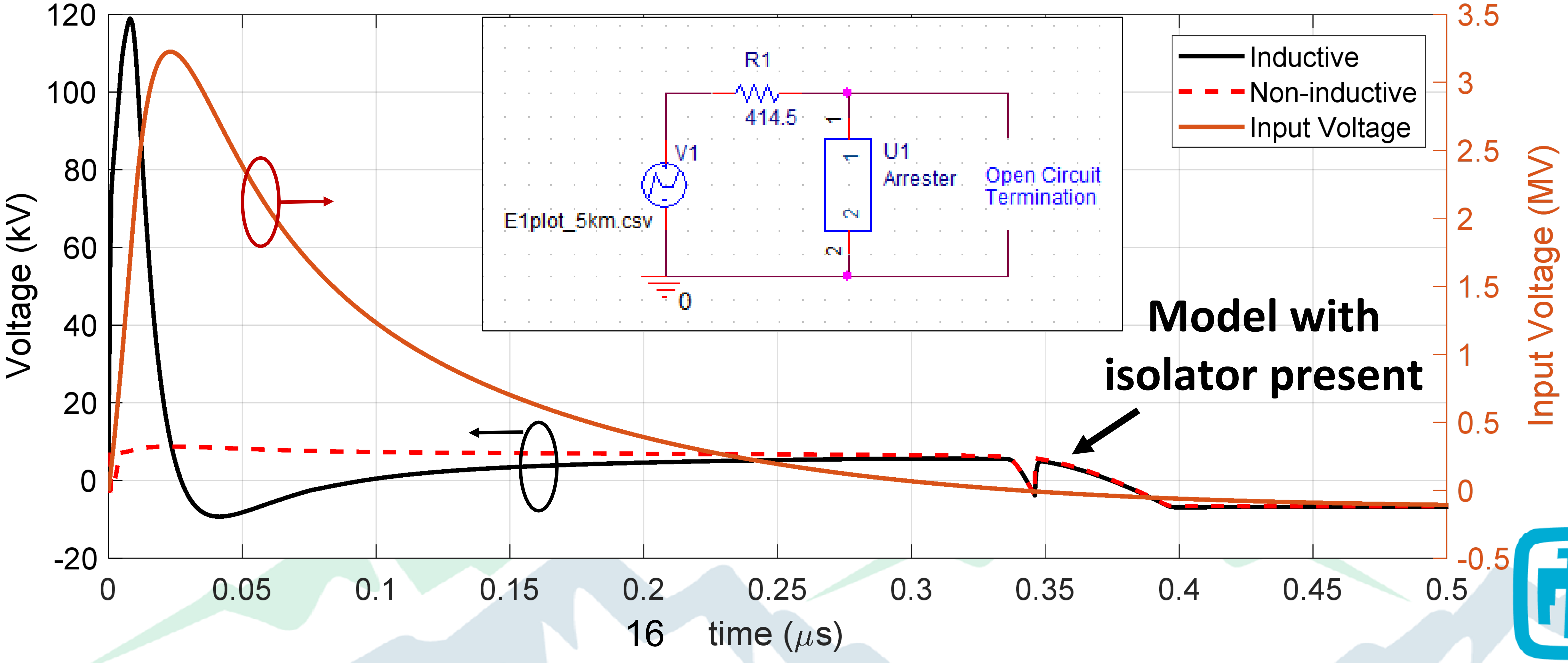
- 3 kV arrester model subjected to E1-like pulse generated in ATLOG
- Primary response due to inductive ‘kick’ causing high overvoltage
- Delay between initial response and proper arrester behavior
  - Clamping time = within 10% of non-inductive simulation
  - Observed clamping time ranges: 130-340 ns



Inductance is primary limiting factor of E1 response.



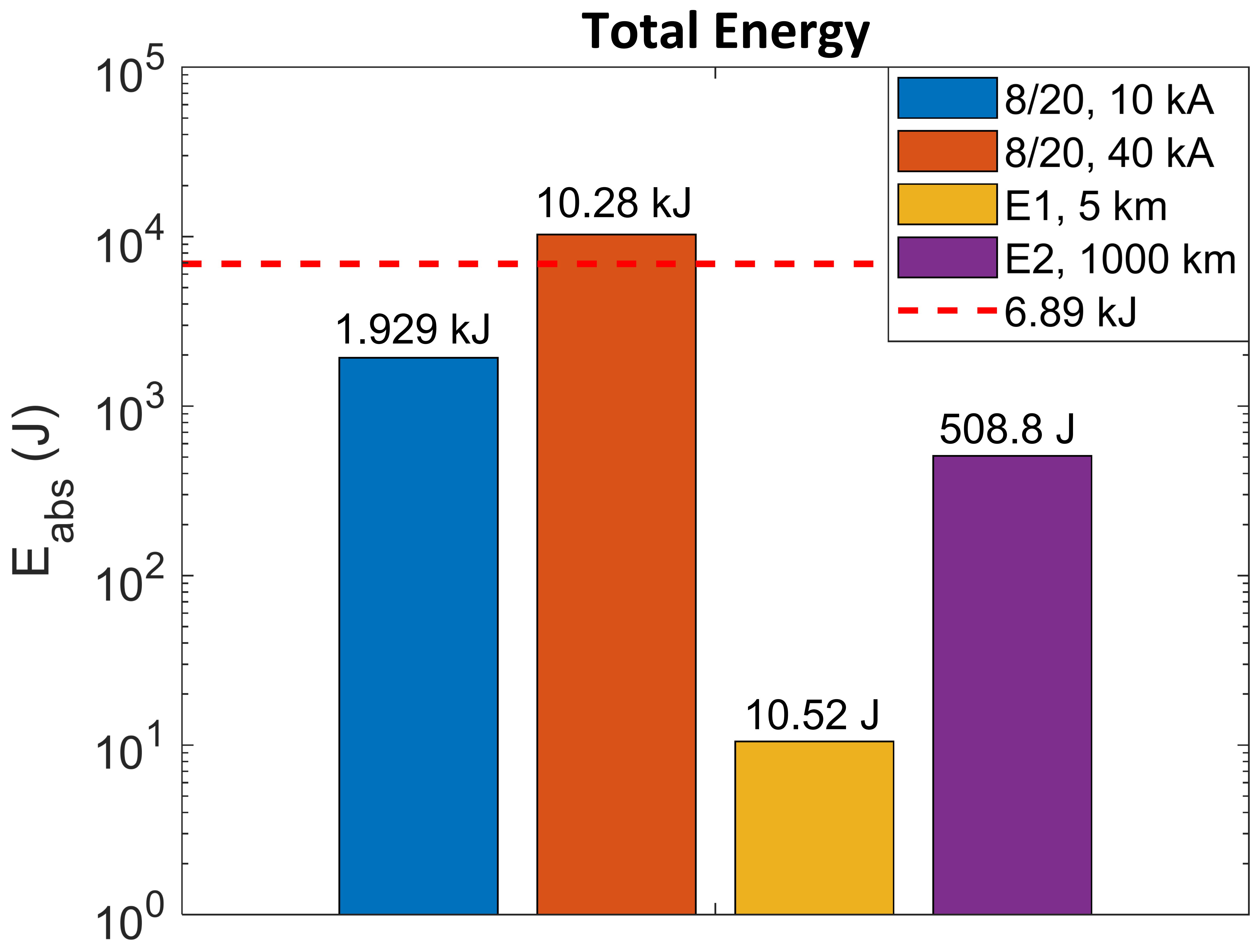
E1-like 3 kV Arrester Simulation on a 5 km Line



Failure Assessment – 3 kV Arrester

Typical arrester failure metric: energy handling

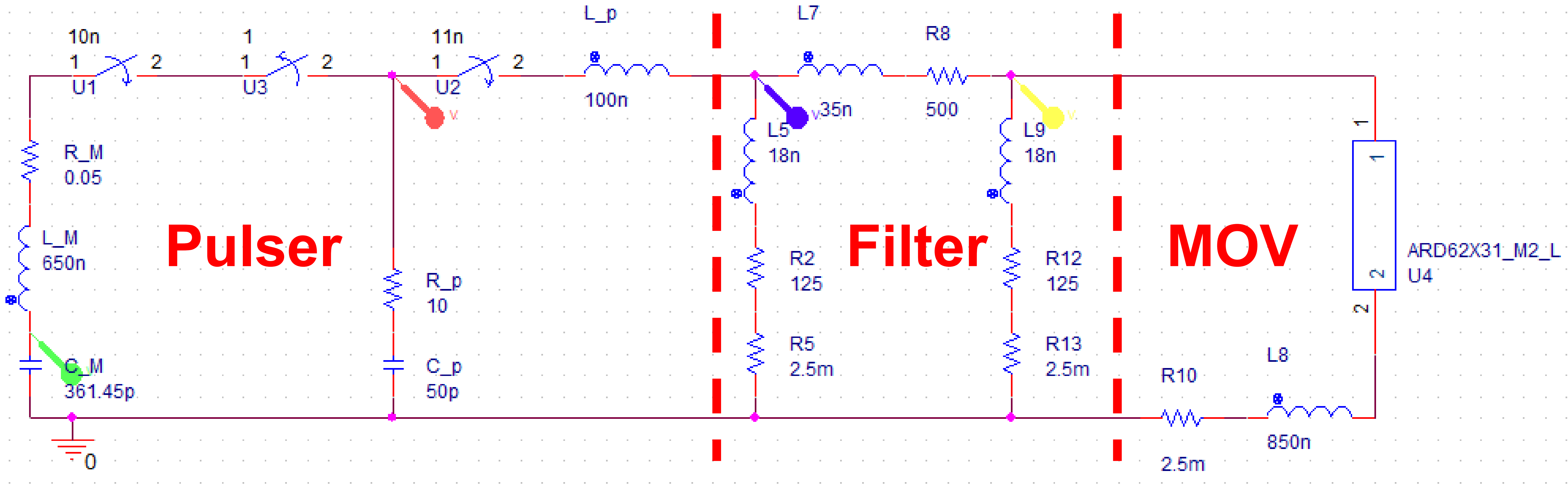
- Arrester rated to 2.7 kJ/kV_{MCOV}, or ~6.89 kJ
- HEMP pulses orders of magnitude below damage threshold
- Potential for damage due to voltage peak
- Unknown how aging effects energy response

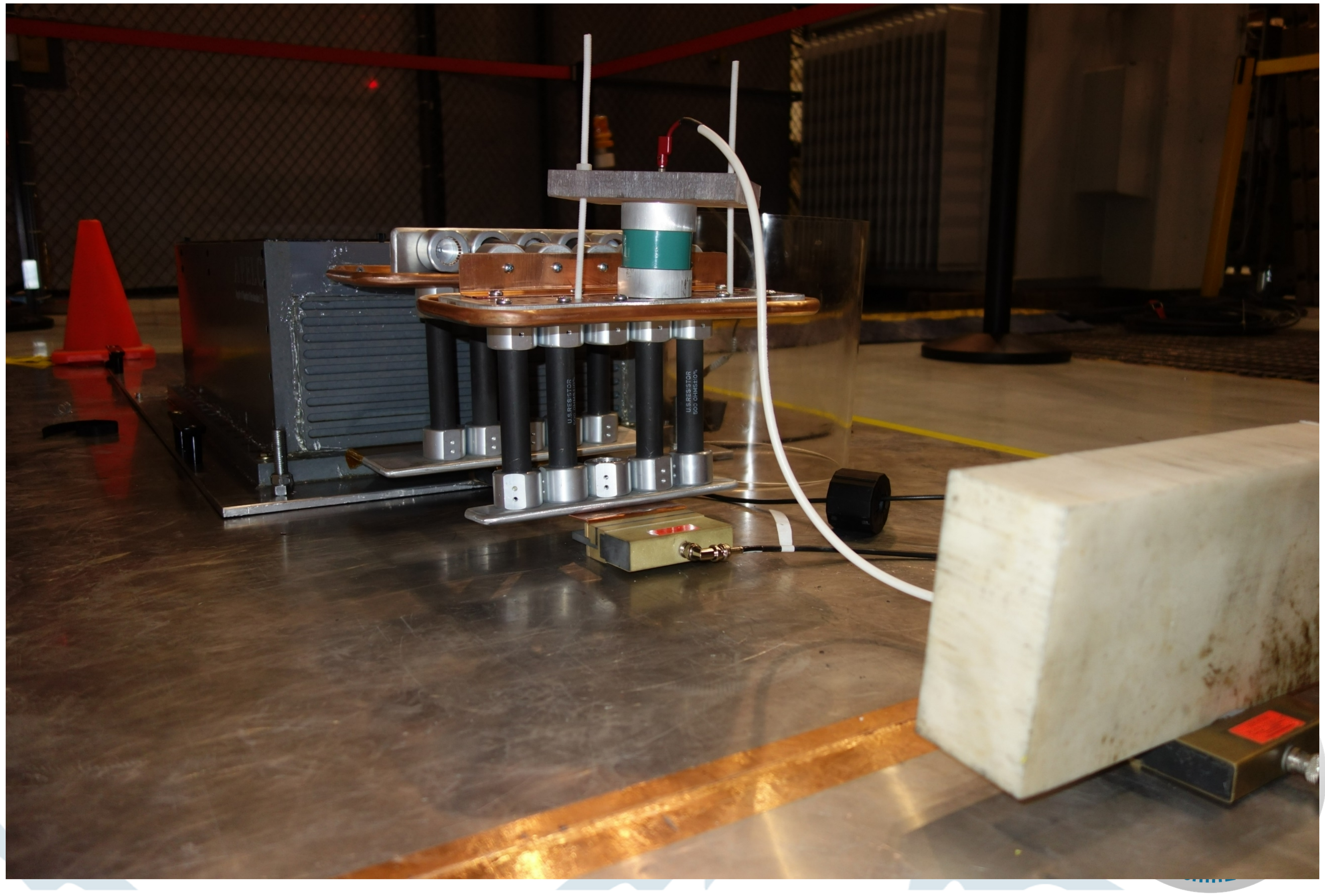


Arresters have negligible chance of failure by normal metrics. Other potential failure modes outside scope of work.

MOV Puck Testing with Fast Transients

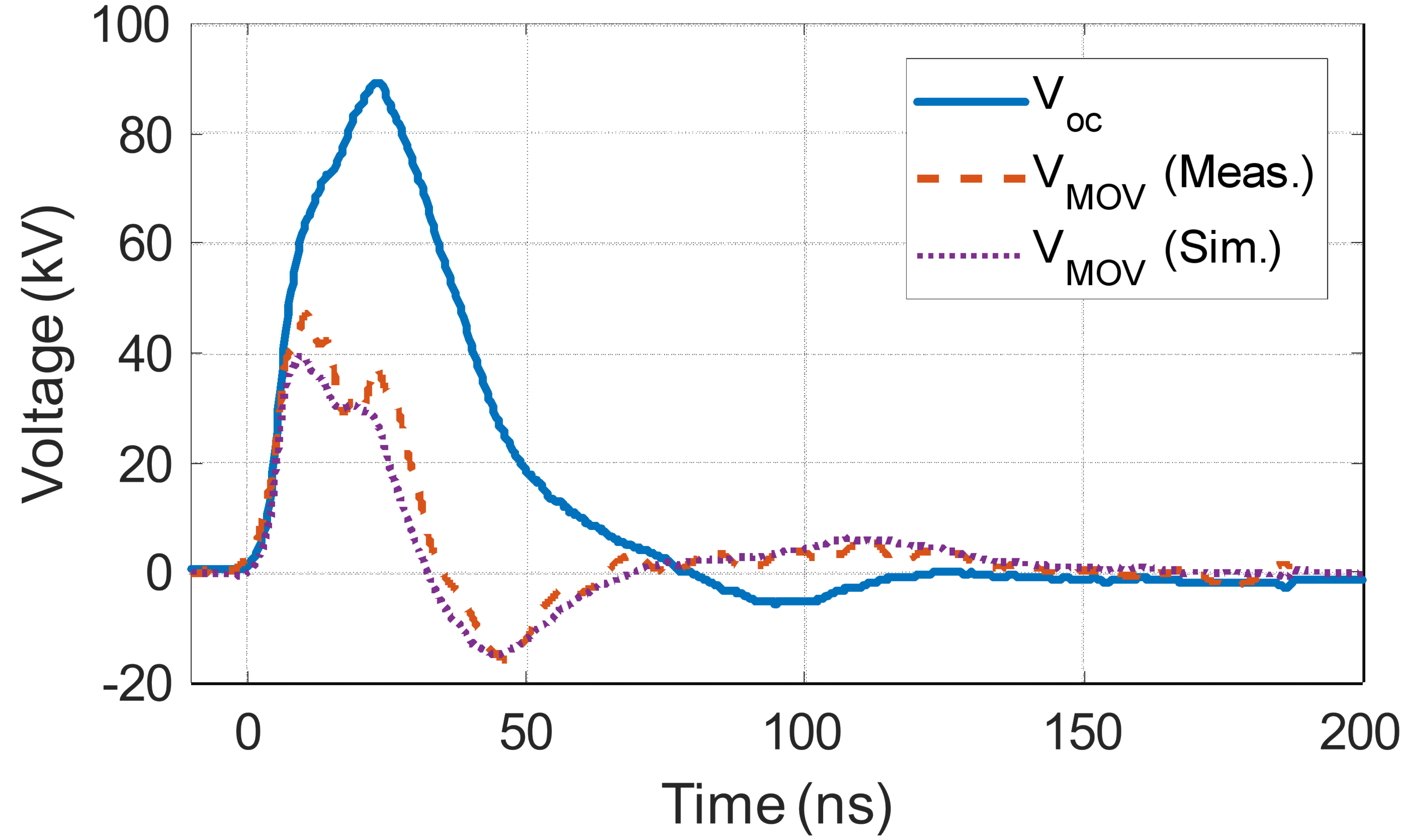
- Fast transient insult test using Marx bank pulser with output filter
  - 13 stage Marx charged to 39.5 kV per stage
- CVRs used to measure current through MOV and voltage at filter output
- Results compared to Spice circuit

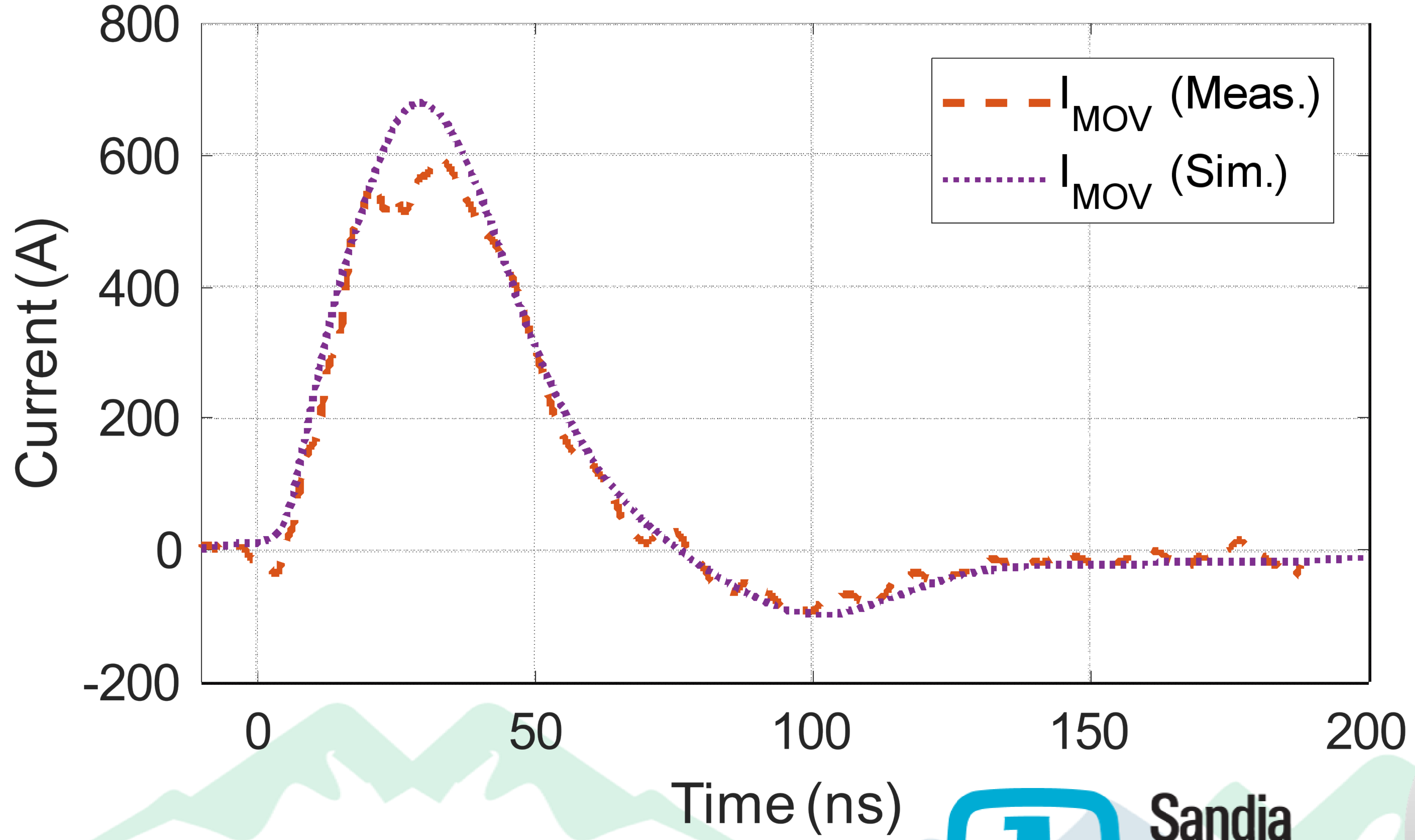




MOV Puck Testing with Fast Transients

- Simulated current and voltage show good alignment to measurements
- Inductive delay prevents immediate clamping (V_{clamp} around 6 kV)
- Inductive peak and rebound last beyond length of signal
- Follow-on needed with reduced inductance





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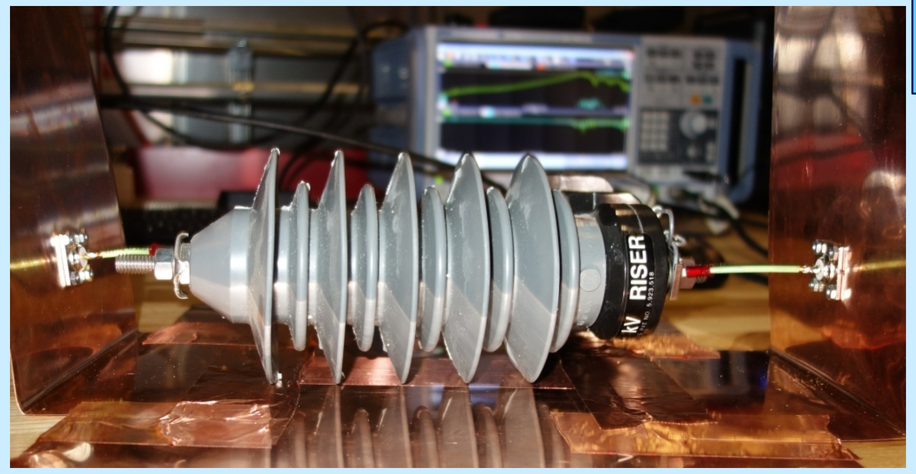

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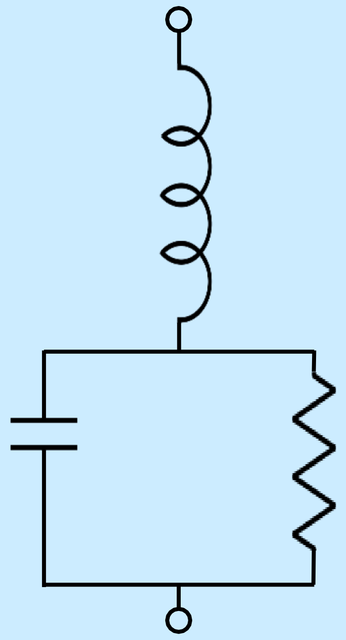

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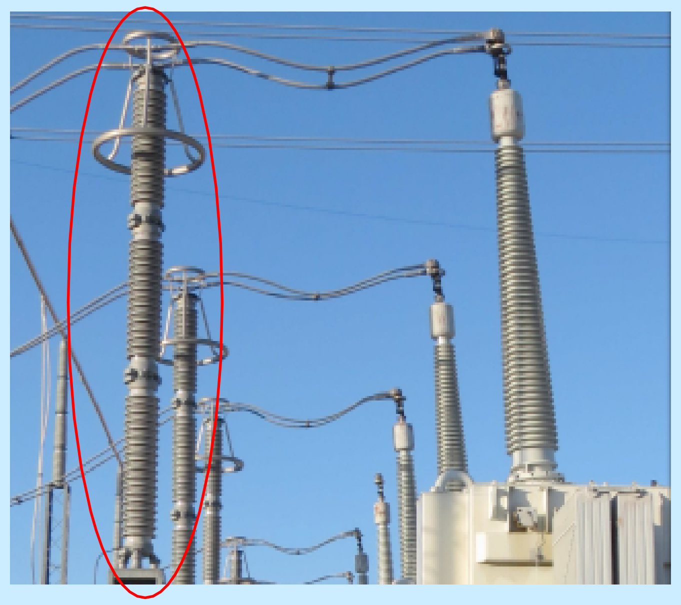

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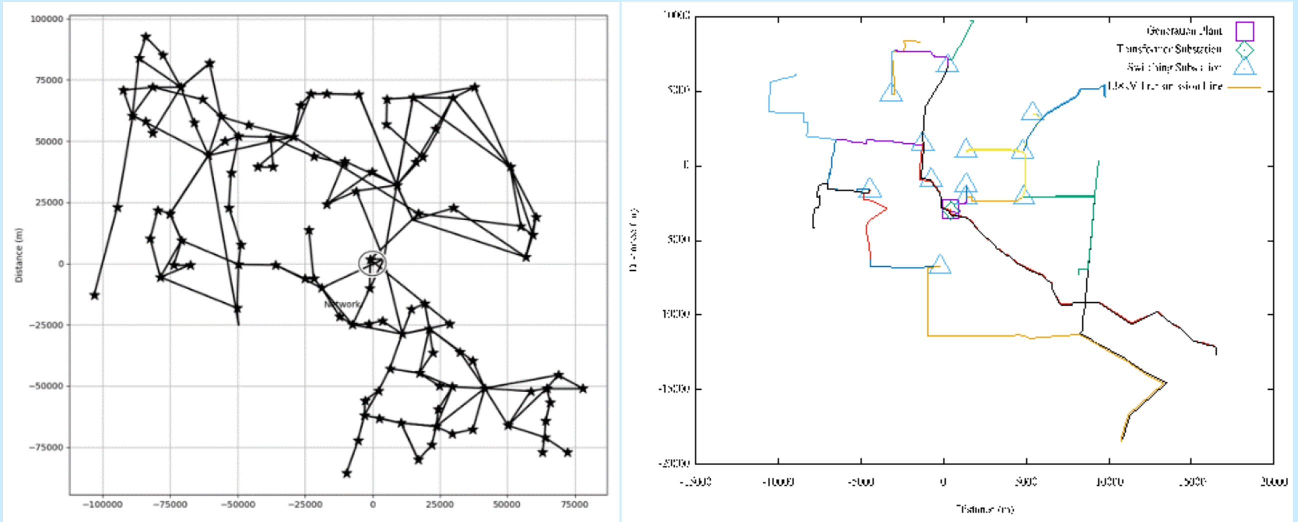
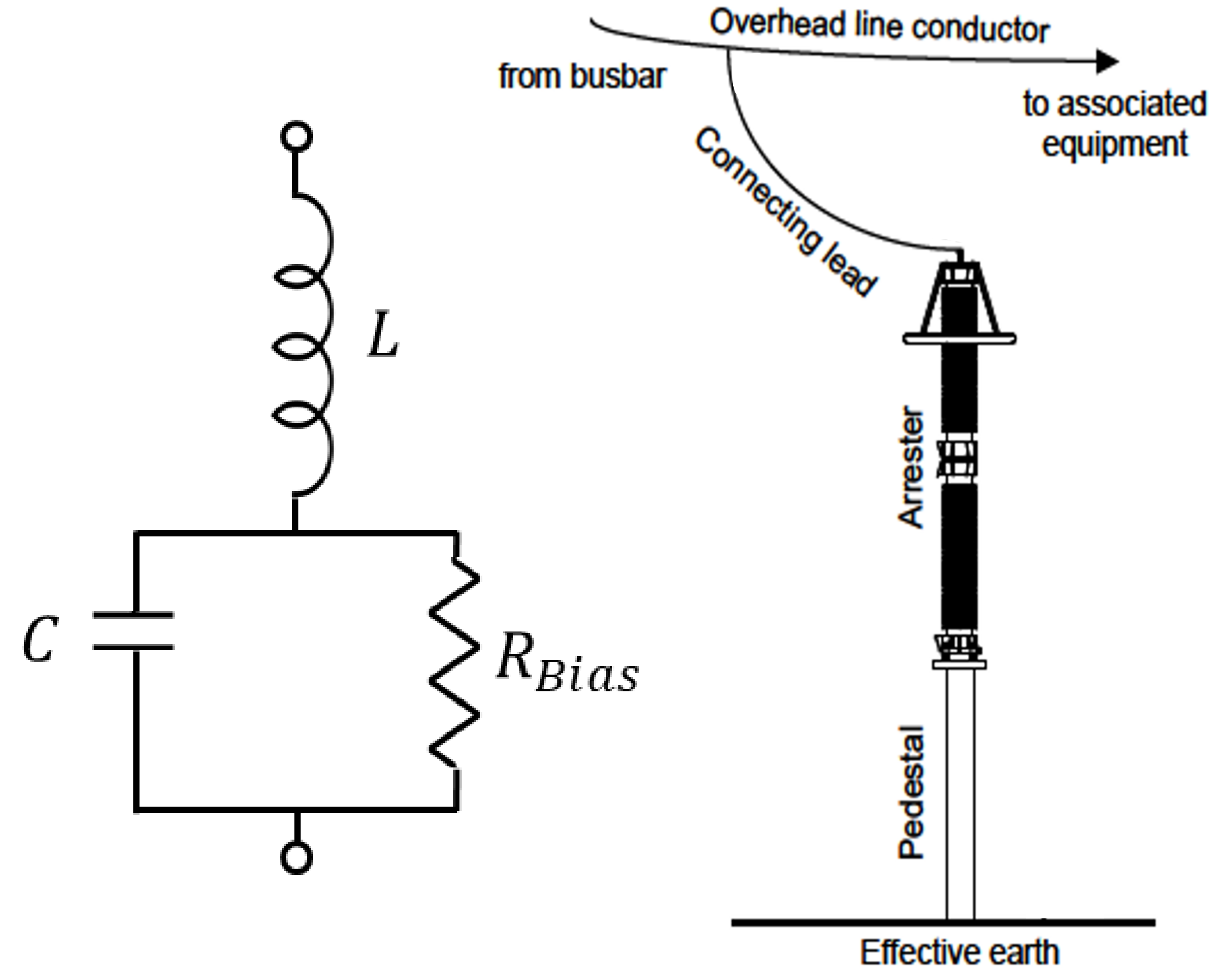


Transmission Arrester Response Modeling – 108 kV

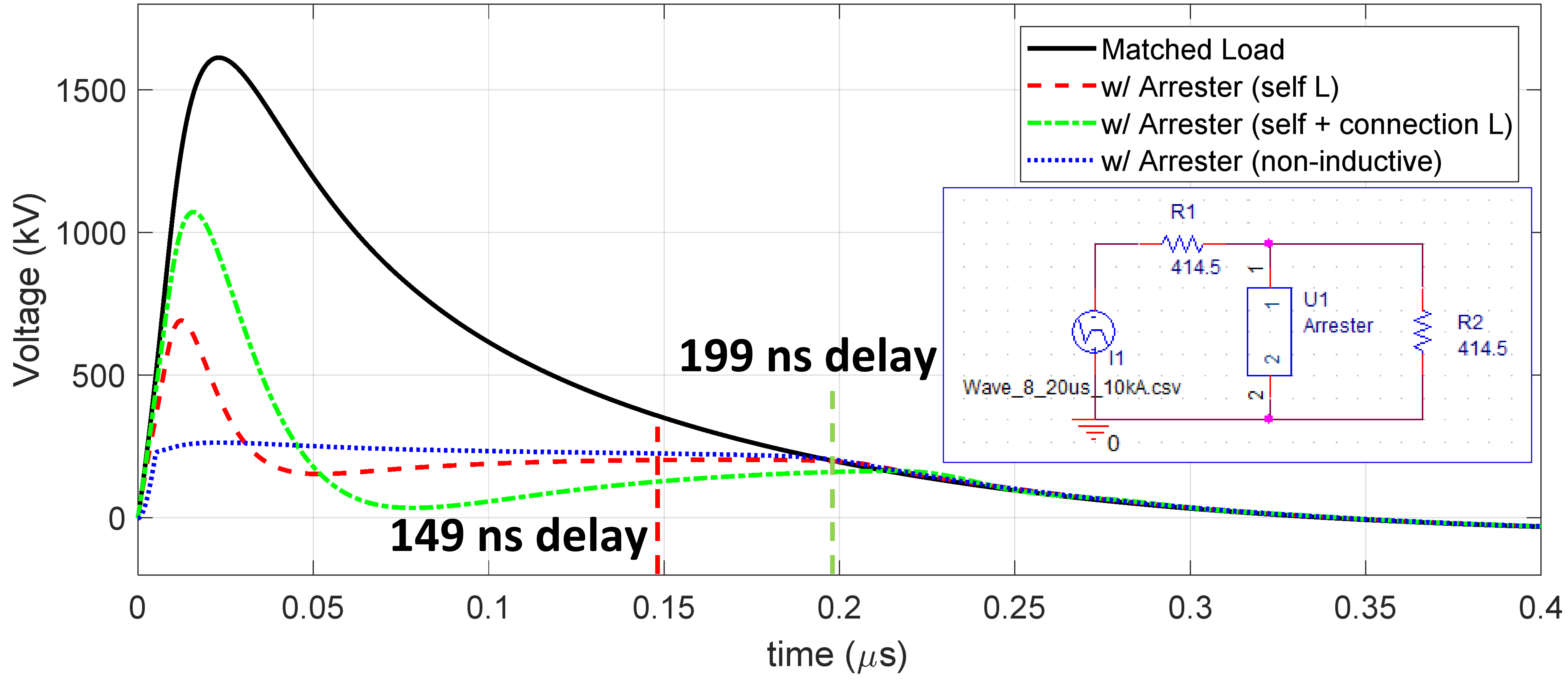
- MacLean ZIP 108 kV Arrester



Volker Hinrichsen, "Metal-Oxide Surge Arresters in High-Voltage Power Systems", 3rd edition handbook from Siemens

- Estimated Parameters
  - $L \approx 1.218$ μH
  - $C \approx 16.4$ pF
  - $R_{bias,LF} = 39.7$ GΩ
  - 0.313 m lead
  - 2.69 m pedestal

E1-like 108 kV Arrester Simulation on a 5 km Line



- Some high voltage passes arrester before clamping takes place (exceeds typical insulation level)
- Addition of minimum conductor clearances creates inductive delay beyond width of pulse

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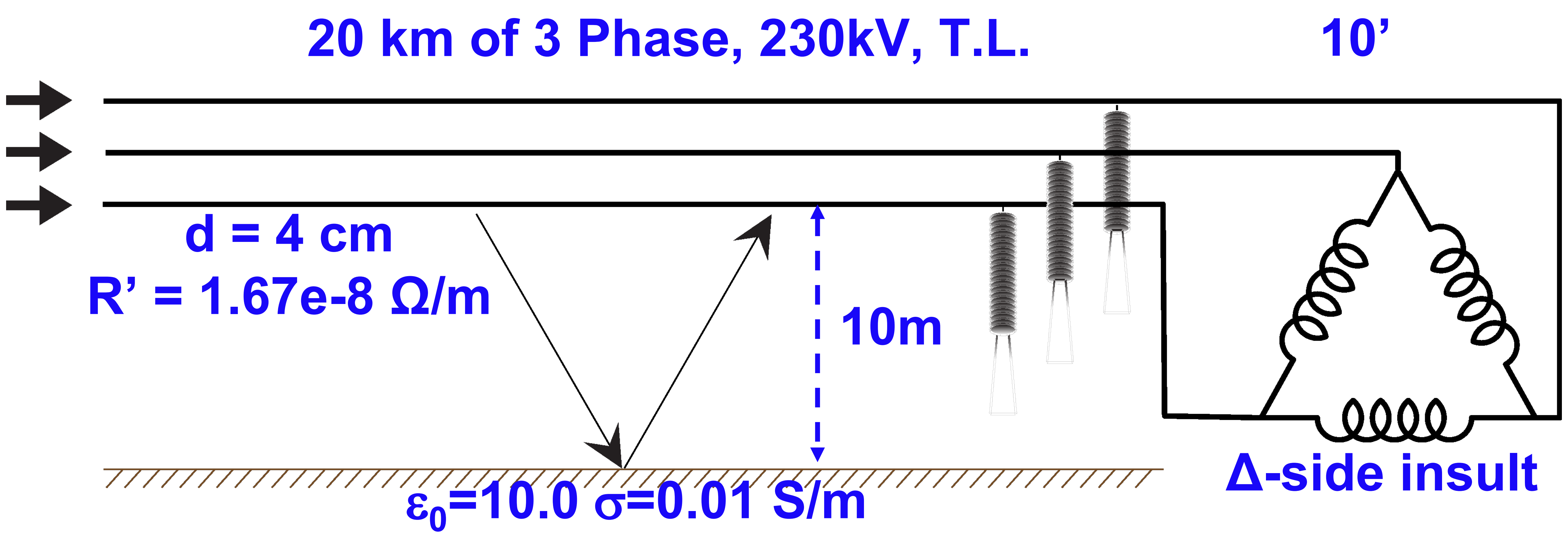
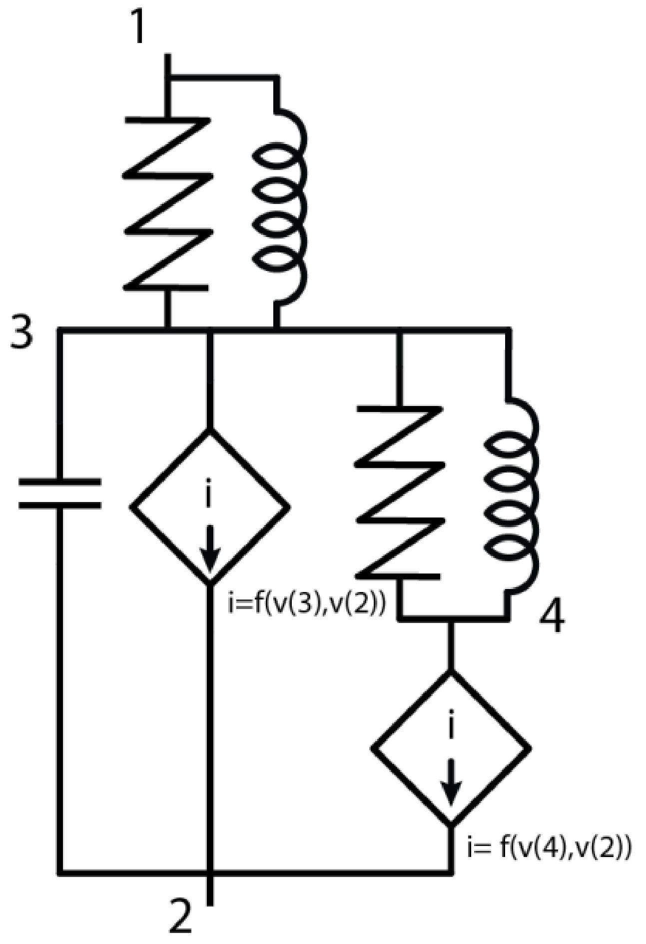
Initial Substation Voltage Simulation (XYCE)

- IEC E1 and E2 HEMP source
- Field incidence angle: 9 degrees



- Multiple lightning arrester models examined:

IEEE Working Group



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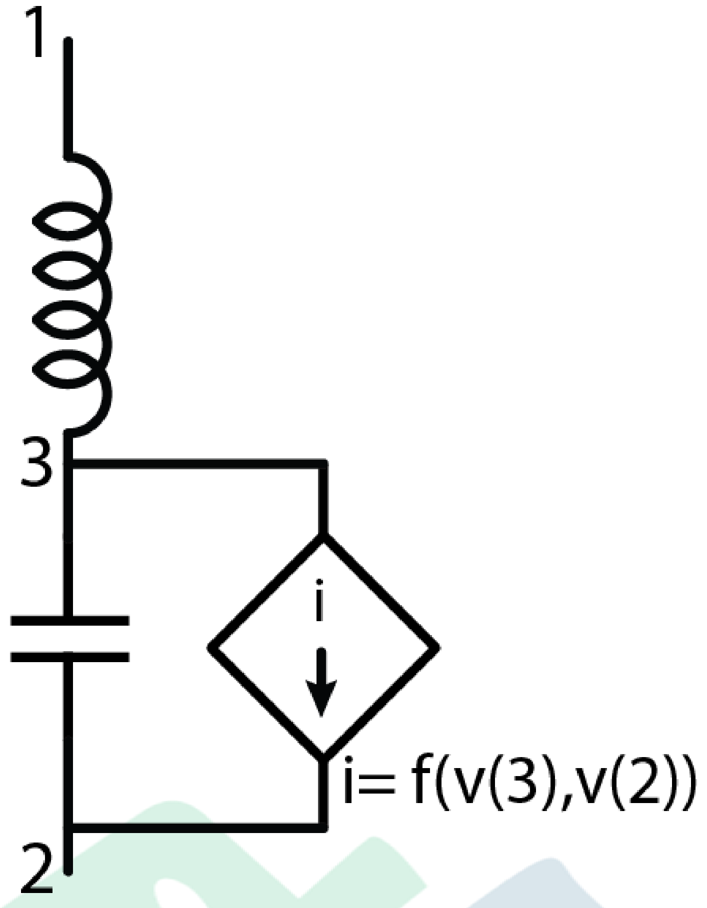
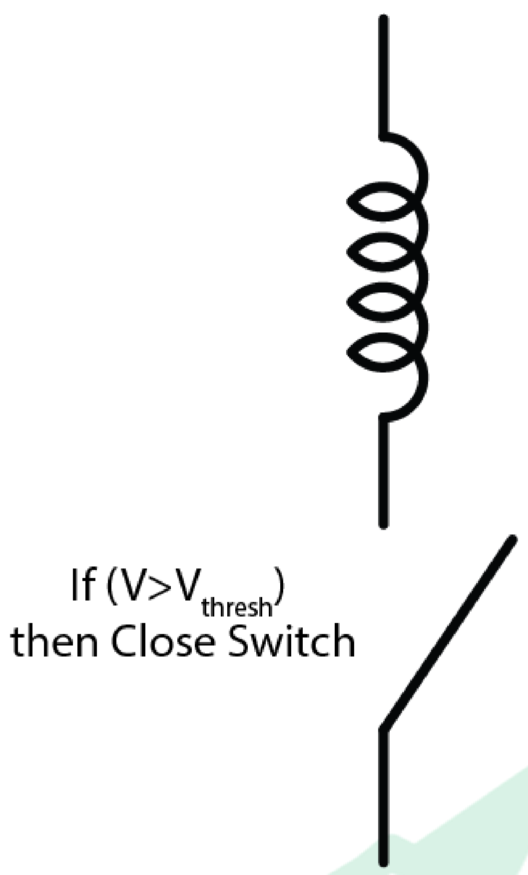


Ideal



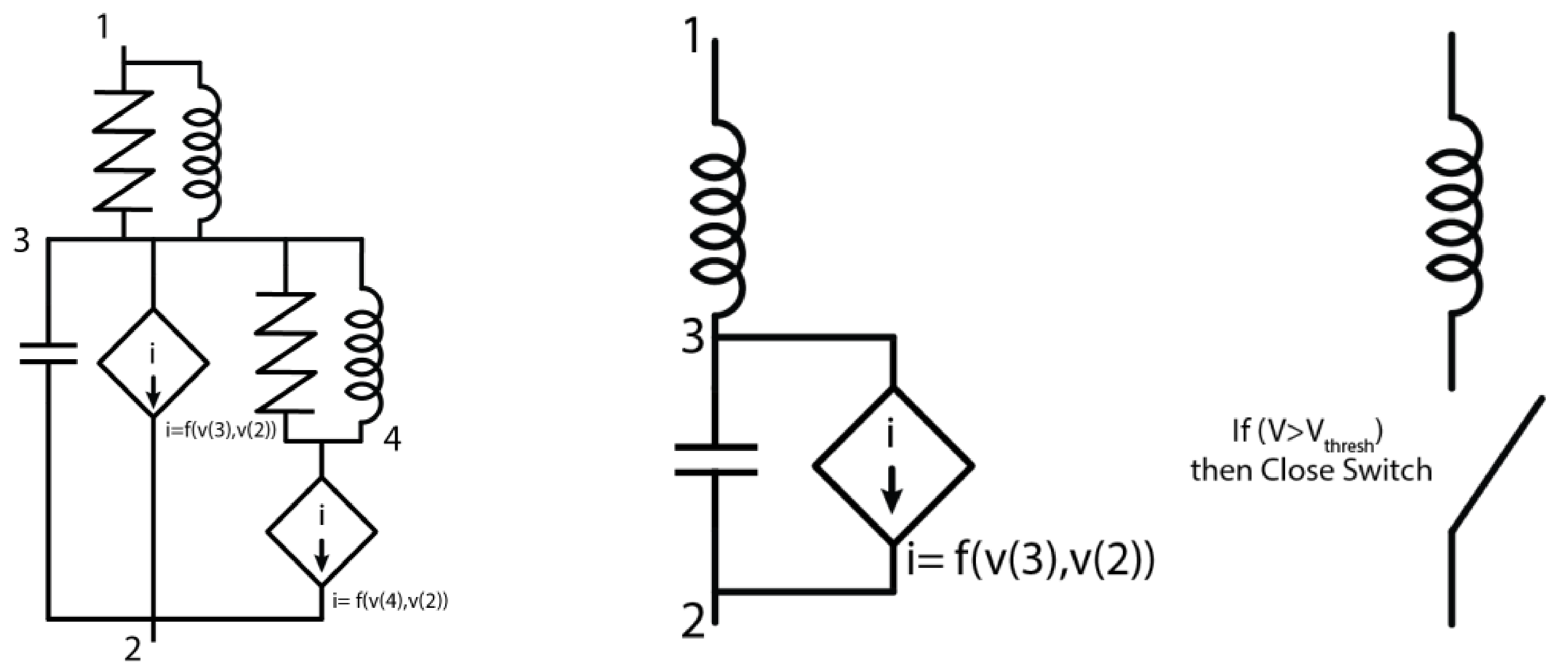
Additional lengths:

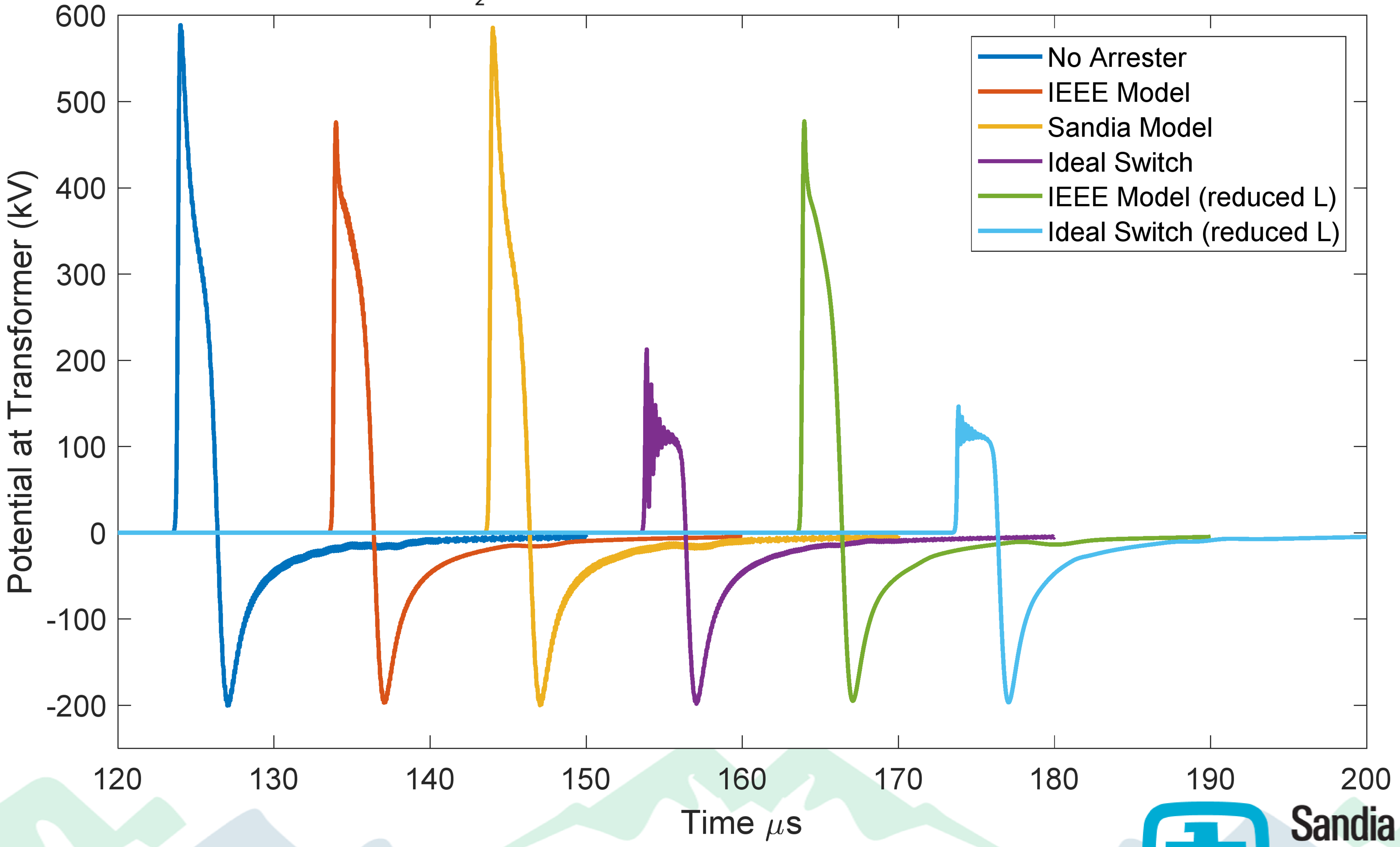
- 187 nH lead
- 2.77 uH pedestal

Ideal model has 1.613 uH internal inductance (same as Sandia).

Initial Substation Voltage Simulation (XYCE)

- Preliminary results show lack of sufficient clamping from arresters
- Greater than anticipated delay requires more investigation





Reduced L:

- Lead: 1.87 nH
  - Order of magnitude
- Pedestal: 0.74 μH
  - Coaxial length approximation

There is a need for HEMP arresters and parasitic inductance handling.

Summary

- Scalable arrester model developed for simulation integration.
- Estimated inductance for arrester is primary limitation of existing technology.
  - Device failure is unlikely for unaged arresters.
- Some final model validation necessary with nanosecond-scale transient testing.

Thank You

(Please contact tbowma@sandia.gov for questions)

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