SAND2013-####C

SAND2013-7611C

International Conference on Lightning & Static Electricity, Seattle, WA, September 18 – 20, 2013

Validation of ALEGRA-MHD to Model Confined Electrical Discharges

Thomas A. Haill, Kenneth M. Williamson,
Raymond Martinez and Jane M. Lehr

Pulsed Power Sciences and
Radiation Sciences Centers
Sandia National Laboratories
Albuquerque, NM

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

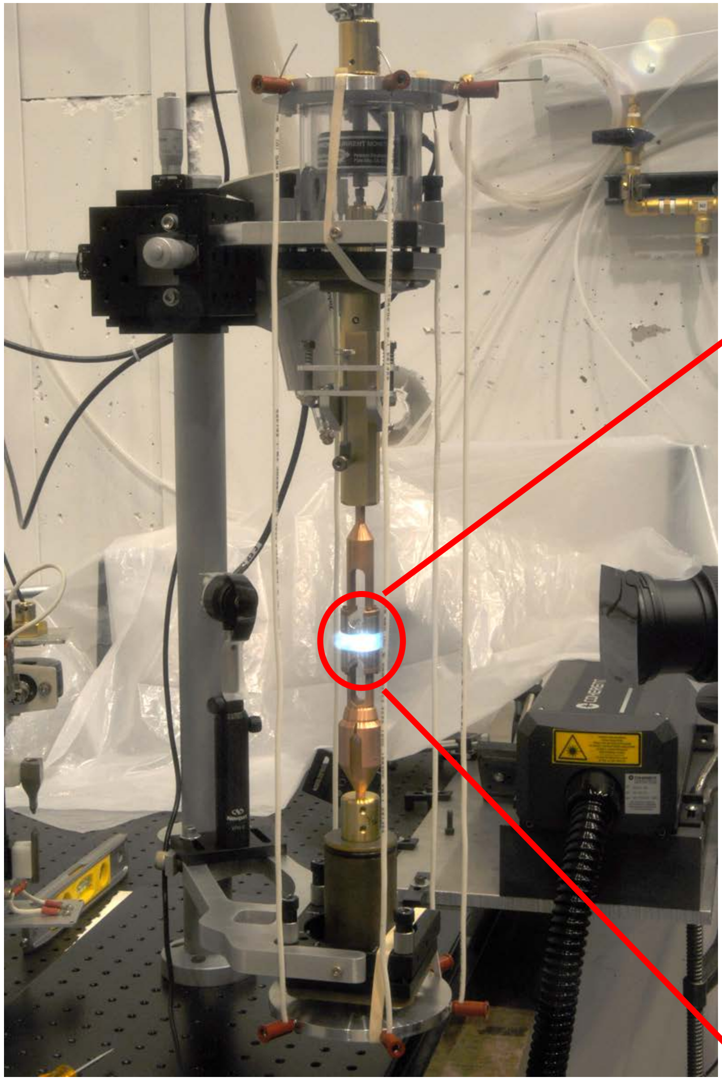
Outline

- **Motivation**
- **Experimental approach**
  - Velonex and HILO waveform generators
  - Experimental fixture
- **MHD simulation approach**
  - Description of ALEGRA-MHD
  - General simulation setup
  - Thevenin equivalent circuit model of waveform generator
- **Experimental and simulation results**
  - Wire burst in air
  - Wire burst in alternate materials (water, epoxy, PMMA)
- **Summary**
- **Acknowledgments**

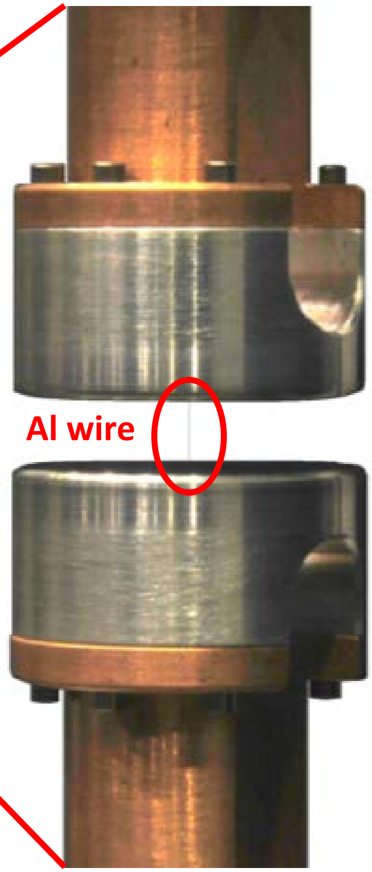
Our motivation is to predict the electrical and thermal characteristics of short arcs in confined gaps

- **Transient currents of several thousands of Amperes can penetrate sealed metallic compound joints**
  - Causing thermal transients, shock waves, changes of state, etc.
  - Resulting in spalling, delamination, burn through, etc.
- **Our approach is a multi-step effort**
- **Perform experiments in confined gaps**
  - Start with wider gaps and transition to narrower gaps
  - Start with simpler experiments such as wire burst in air or water
  - Transition to more complex experiments with alternate materials (epoxies and sealants)
  - Eventually eliminate the wire to study direct breakdown of materials
- **Validate ALEGRA-MHD simulations**
  - Assess sufficiency of the physical models
  - Develop material models for unknown materials
  - Explain features seen in experiments
  - Develop a predictive capability

The experimental configuration consists of two parallel metal electrodes separated by a small gap



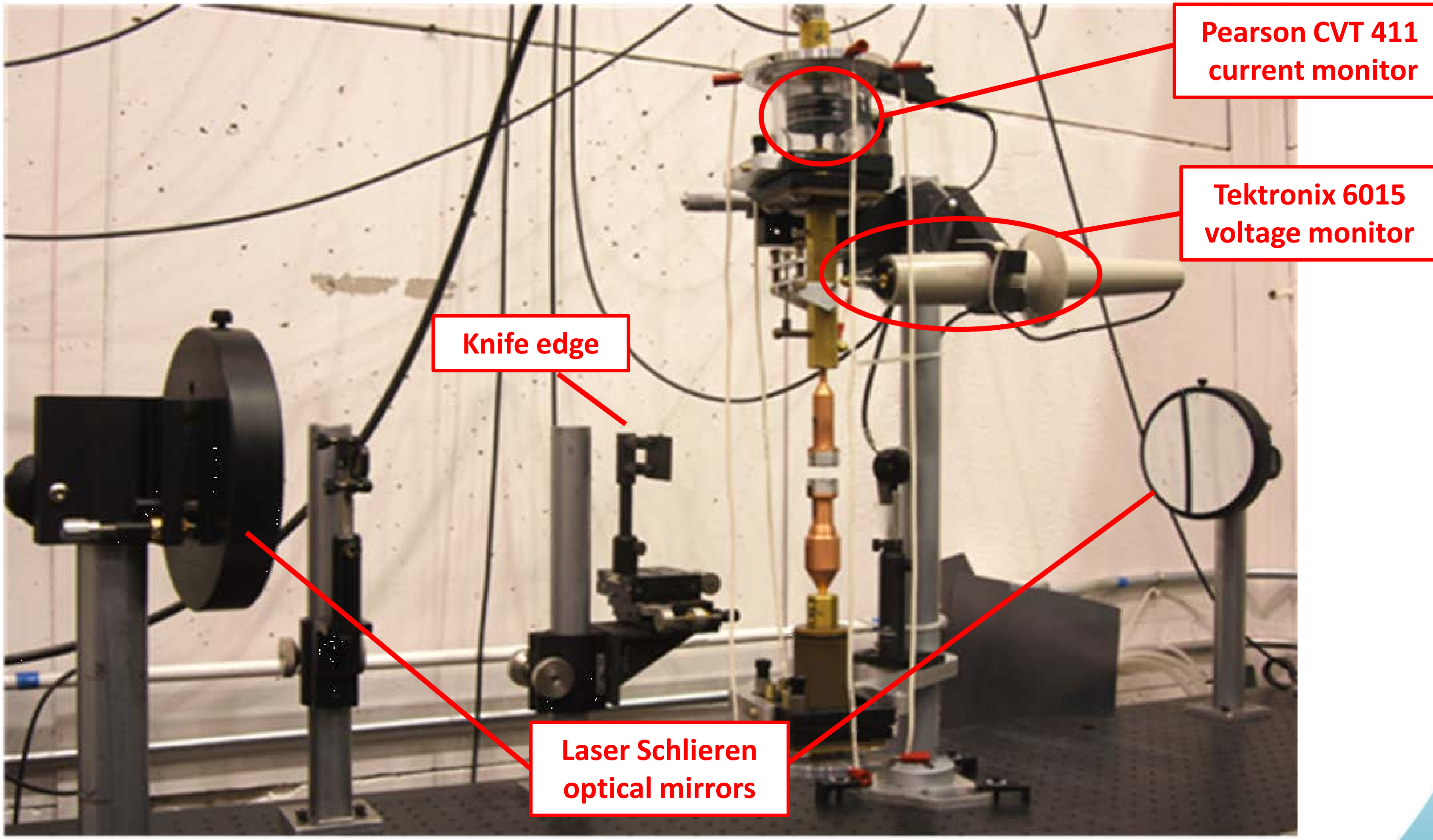
- ~ 100-μm diameter aluminum wire between pair of parallel 1-inch diameter aluminum electrodes
- Driven by Velonex 590 or HILO PG 24-2500 waveform generator



Velonex 590
I ≤ 4.5 kA
V ≤ 3 kV

HILO PG 24-2500
I ≤ 0.2 – 12 kA
V ≤ 0.5 – 24 kV

The experimental configuration is well diagnosed



- **Voltage and current is measured at waveform generator and at the load**
- **Wire burst is recorded by laser Schlieren imaging diagnostic and Andor ICCD gated camera**

The 3D/2D ALEGRA-MHD multi-material ALE code simulates the confined electrical discharges

Hydrodynamics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$$

$$\rho \left(\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla \right) \vec{V} \right) = -\nabla \cdot \tilde{P} + \left[\rho_q \vec{E} \right] + \vec{J} \times \vec{B}$$

$$\rho \left(\frac{\partial e}{\partial t} + \left(\vec{V} \cdot \nabla \right) e \right) = -\tilde{P} : \nabla \vec{V} + \eta \left(\vec{J} \cdot \vec{J} \right) - \nabla \cdot \vec{Q} - \int \sigma_a \left(4\pi B_\nu - cE_\nu \right) d\nu$$

Magnetics

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J} + \left[\tfrac{\partial \vec{D}}{\partial t} \right]$$

$$\nabla \cdot \vec{B} = 0$$

$$\left[\nabla \cdot \vec{D} = \rho_q \right]$$

$$\eta \vec{J} = \vec{E} + \vec{V} \times \vec{B}$$

$$\vec{B} = \mu \vec{H} \qquad \left[\vec{D} = \varepsilon \vec{E} \right]$$

Conduction

$$\vec{Q} = -k \nabla T$$

$$\rho C_V \frac{\partial T}{\partial t} = \nabla \cdot (\vec{Q}) = -\nabla \cdot (k \nabla T)$$

Radiation

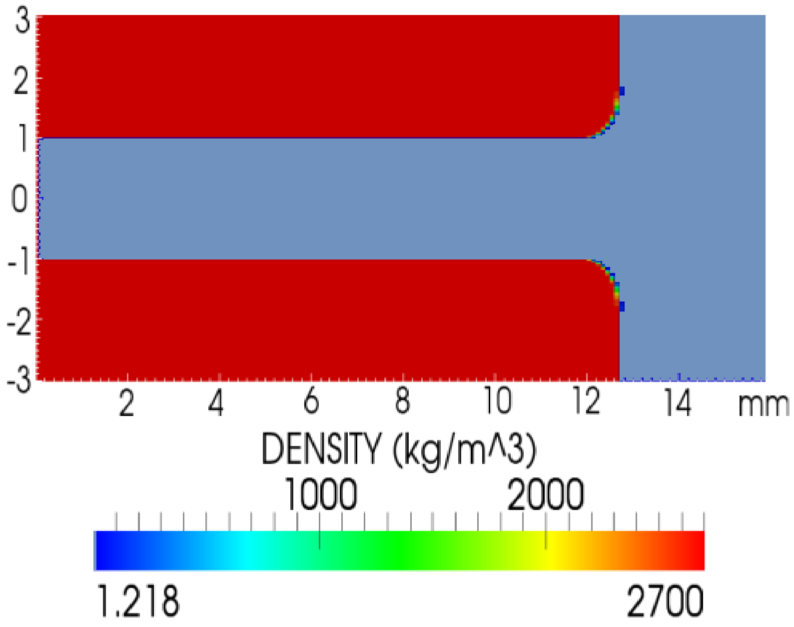
$$\frac{1}{c} \frac{\partial I_\nu}{\partial t} = -\hat{n} \cdot \nabla I_\nu + \sigma_a \left(B_\nu - I_\nu \right)$$

$$cE_\nu = \int_{4\pi} I_\nu d\Omega$$

Robinson, et al., ALEGRA: An Arbitrary Lagrangian-Eulerian Multimaterial, Multiphysics Code, Proceedings of the 46th AIAA Aerospace Science Meeting and Exhibit, AIAA 2008-1235.

Confined electrical discharges are modeled in 2D RZ cylindrically symmetric geometry

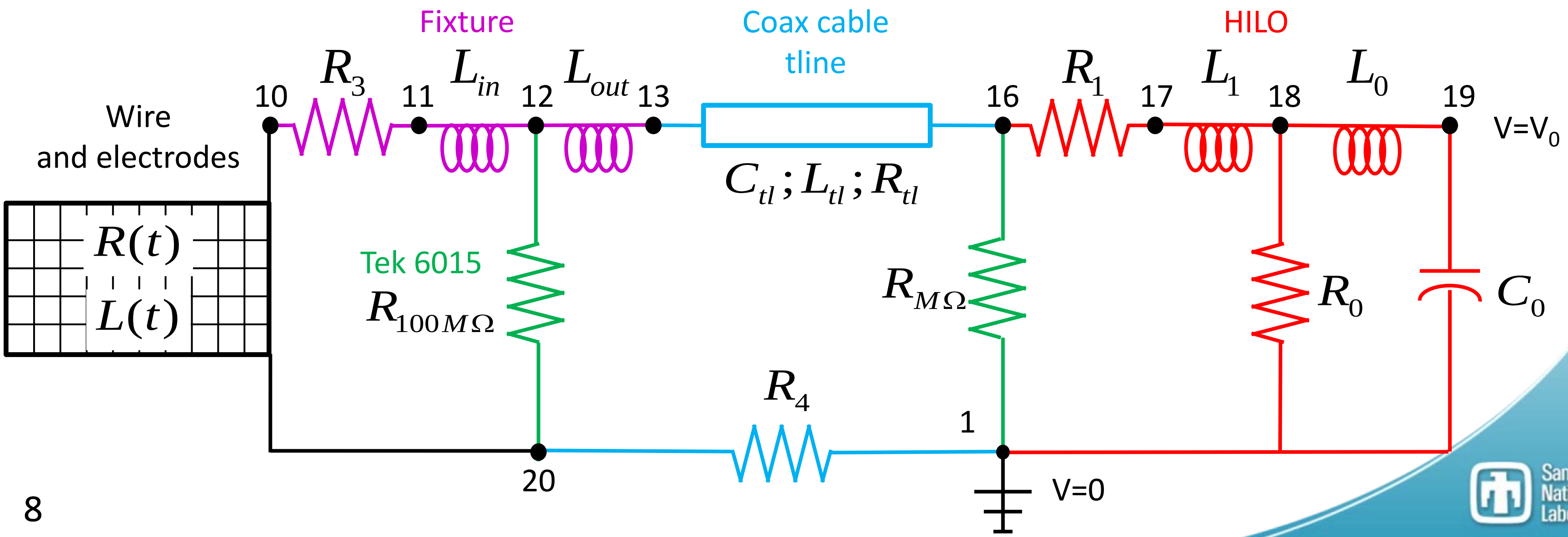
- **Initial conditions**
  - **All materials initialized to standard ambient temperature and pressure**
    - **1 atmosphere pressure**
    - **25°C**
- **Hydrodynamic BCs**
  - **No displacement on axis**
  - **1 atmosphere on other boundaries**
- **Magnetic BCs**
  - **Zero magnetic field on axis**
  - **Outer boundary:** $B_\theta\left(R,t\right)=\mu_0 I\left(t\right)/2\pi R$
  - **Current density normal to top/bottom (tangent E field is zero)**
- **Thermal BCs**
  - **No heat flux through all boundaries**
- **No radiation transport modeled**



2D RZ ALEGRA-MHD simulation setup for air in 2 mm gap

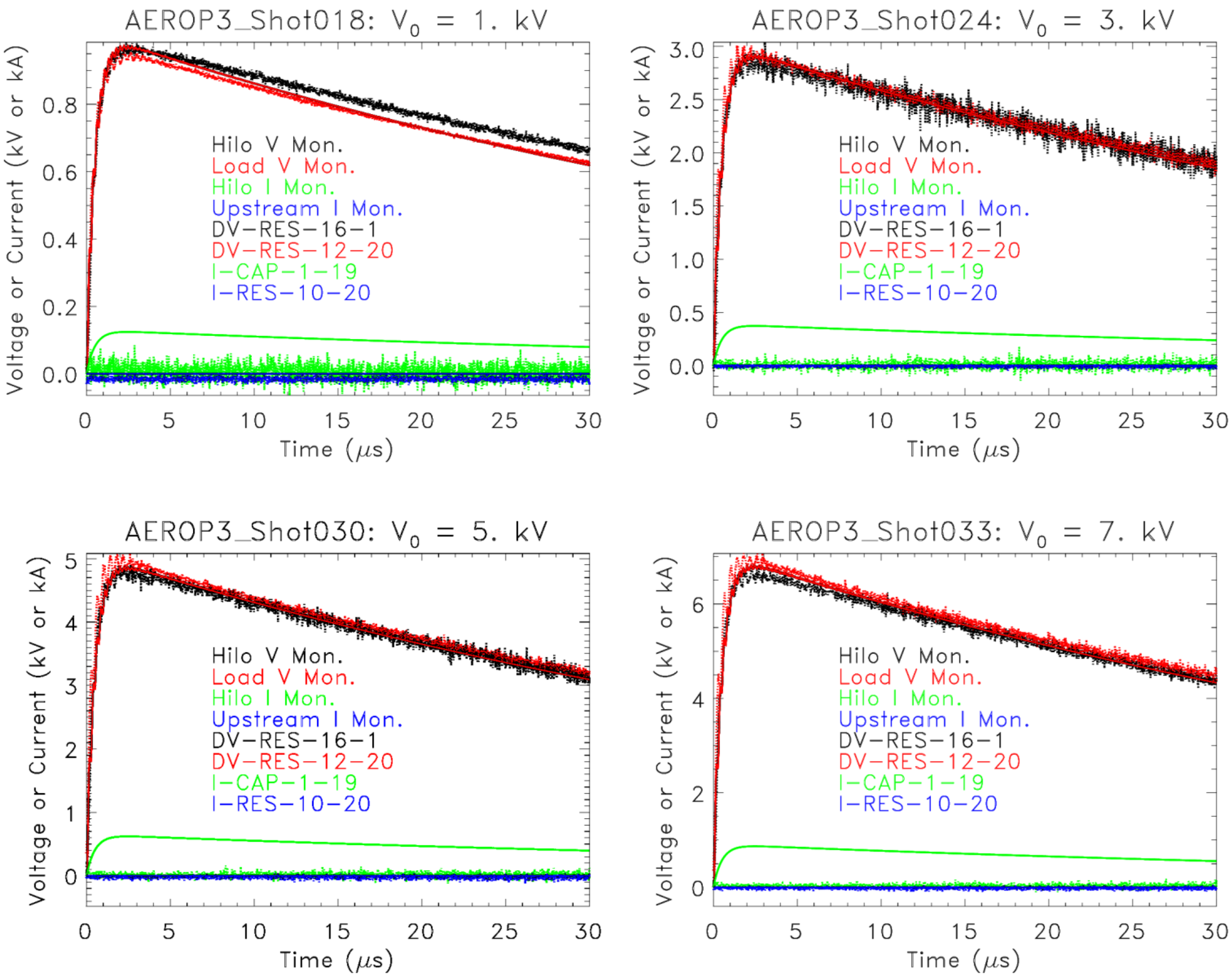
HILO circuit model for ALEGRA MHD simulations

- **HILO pulser is more complicated than a simple RLC model**
  - **HILO model based on information from E. Pohlner (HILO Test GmbH, Karlsruhe, Germany)**
  - **Capacitor (C_0) charged to initial voltage (V_0)**
  - **Internal inductance (L_0) and resistive shunt (R_0) needed to model open circuit tests**
  - **Output current measured through output inductance (L_1) and resistance (R_1)**
  - **Output voltage measured across resistor ($R_{M\Omega}$)**
- **Coax cable connecting pulser to experiment is a transmission line**
  - **Cause of high frequency (0.5 μs) oscillation in open circuit voltage**
- **Need to distinguish fixture and load components**
  - **Fixture inductance divided to test sensitivity of Tek 6015 voltage probe to inductance**
  - **Tek 6015 voltage probe ($R_{100M\Omega}$) apparently measures only resistive voltage drop**



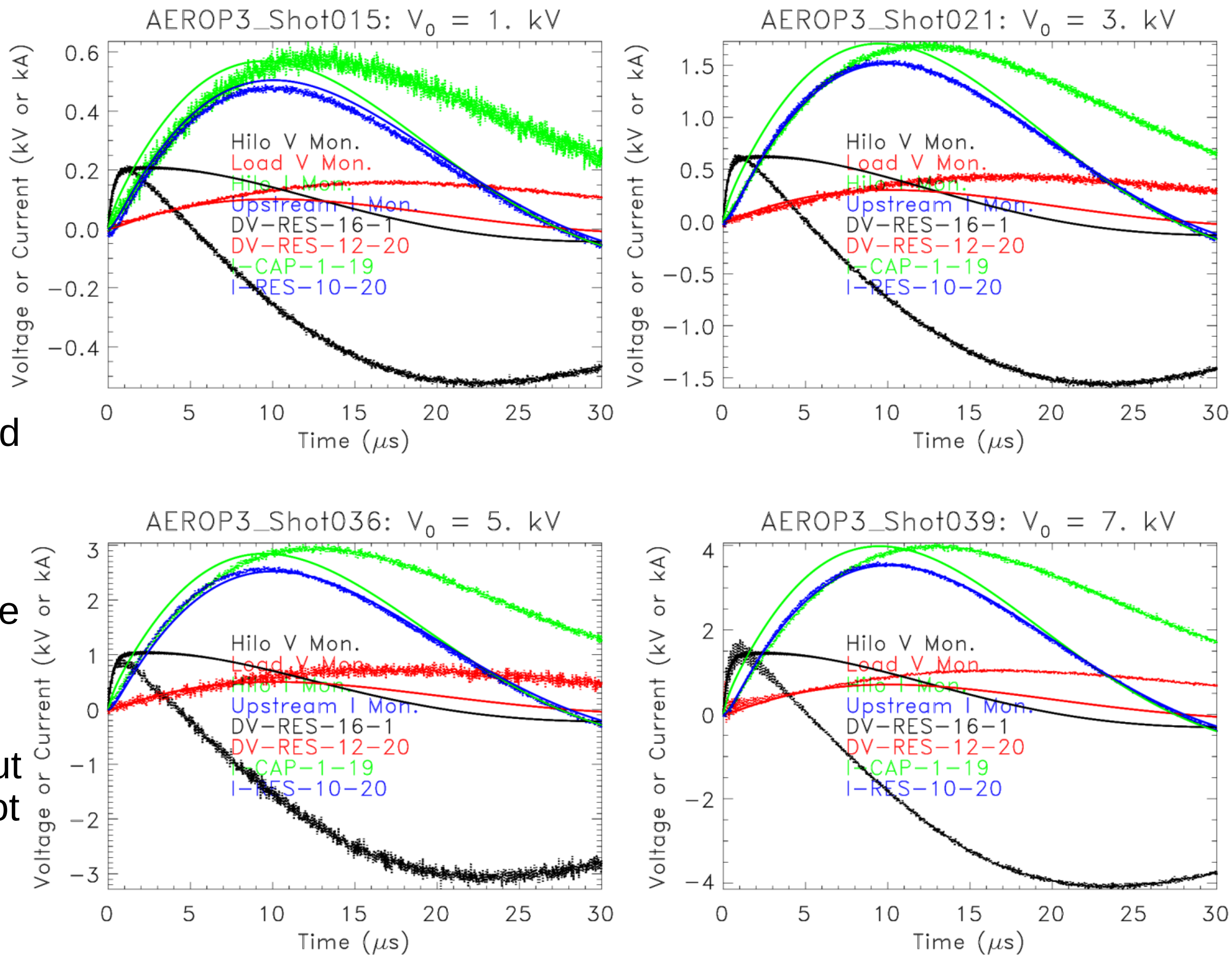
Validated HILO circuit model matches open circuit tests at 4 charge voltages from 1 to 7 kV

- 4 voltages agree
  - o HILO V monitor
  - o Load V monitor
  - o DV-RES-16-1
  - o DV-RES-12-20
- Negligible current output by HILO or seen at load
- Current from capacitor shown for comparison
- High frequency oscillation in voltage pulse verifies transmission line model for coax cable

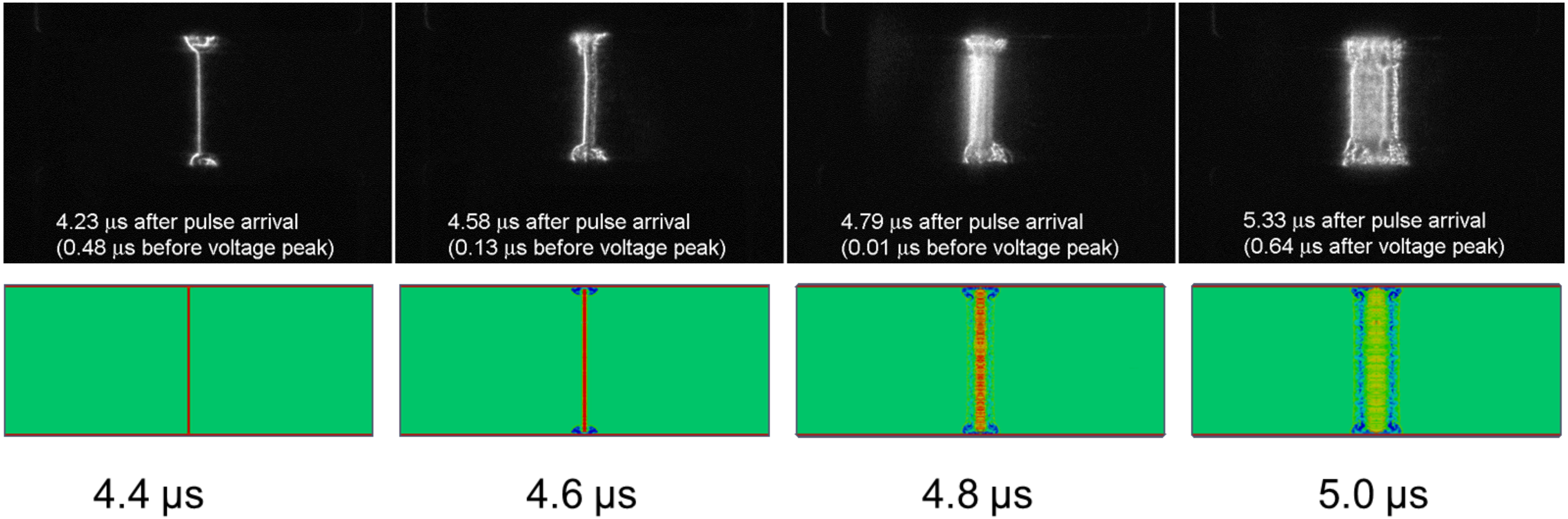


Validated HILO circuit model matches some data for <u>short circuit</u> tests at 4 charge voltages from 1 to 7 kV

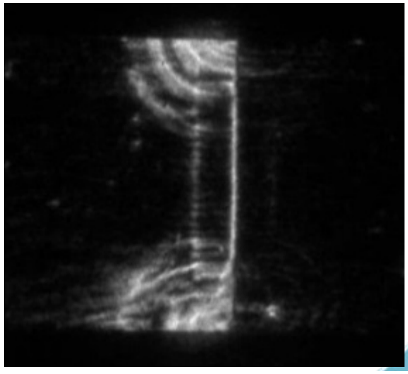
- Load currents agree
  - o Upstream I monitor
  - o I-RES-10-20
- Load voltages agree up to 7-9 μs
  - o Load V monitor
  - o DV-RES-12-20
  - o Tek 6015 does not appear to pickup load inductance
- Capacitor current matches output current amplitude, but not shape
  - o HILO I monitor
  - o I-CAP-1-19
- Initial rise of HILO output voltage matched, but not full waveform
  - o HILO V monitor
  - o DV-RES-16-1



Experiment and simulation of wire burst in air show burst and shock wave emanate from the wire ends

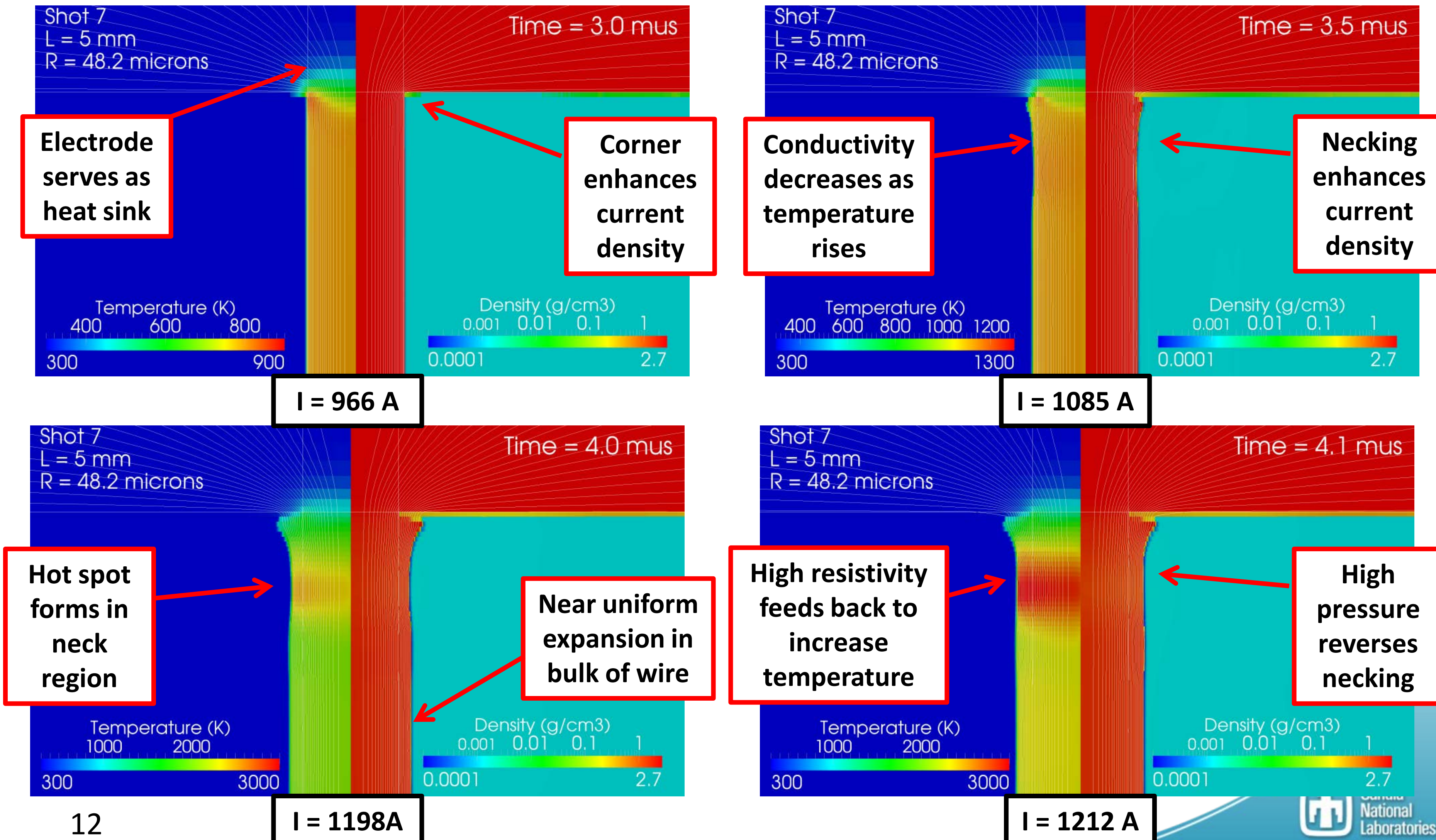


- **This feature not seen or else not reported in other reports of wire burst in vacuum or water**
- **Simulations show feature persists to gaps of 0.3 mm where hemispherical shocks merge immediately**
- **Feature may be important to damage when wire potted in other materials, too**

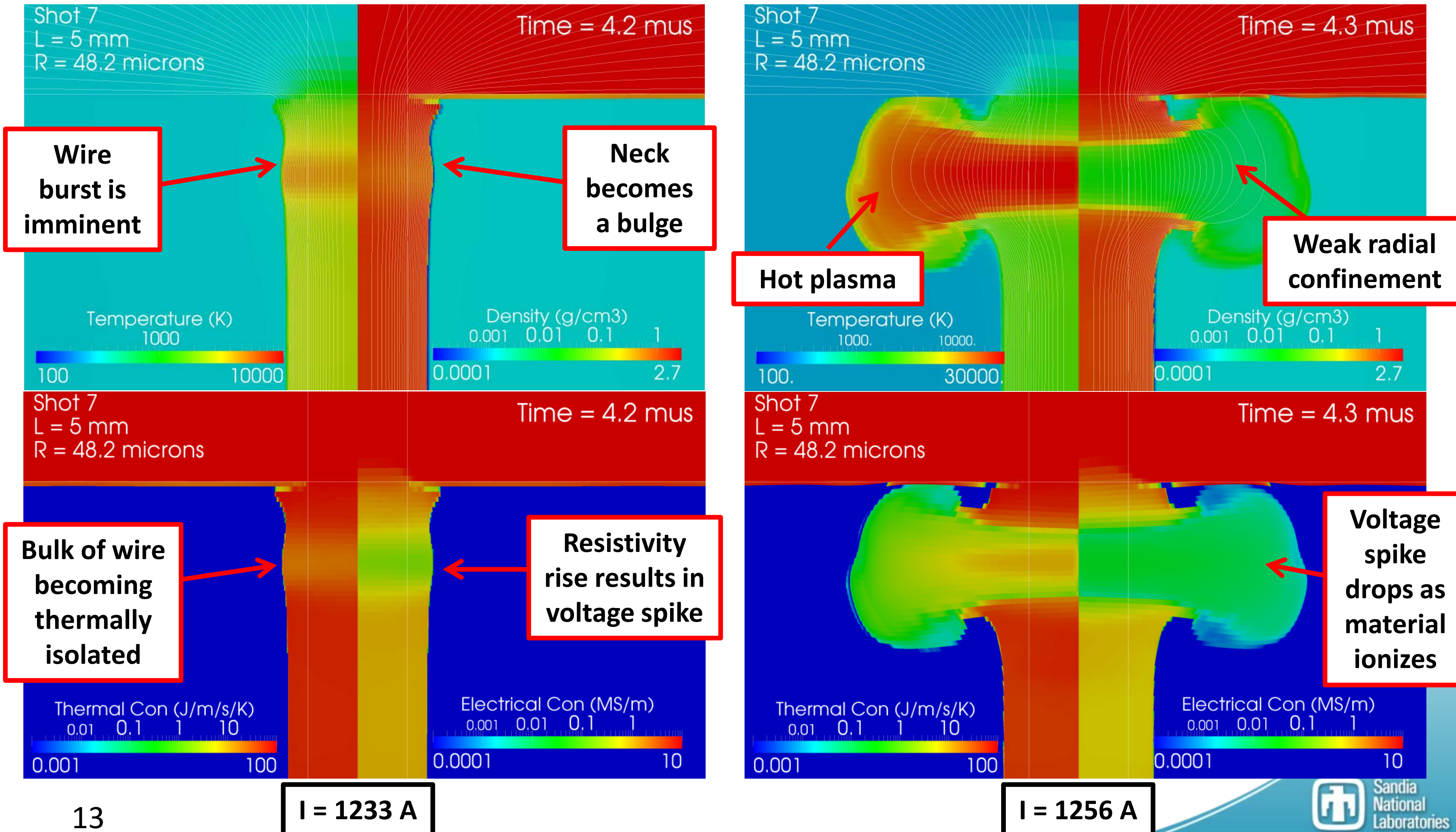


Wire burst in water

Snapshots at 4 early times show formation of a hot region ~1 radius to ~1 diameter off of electrode

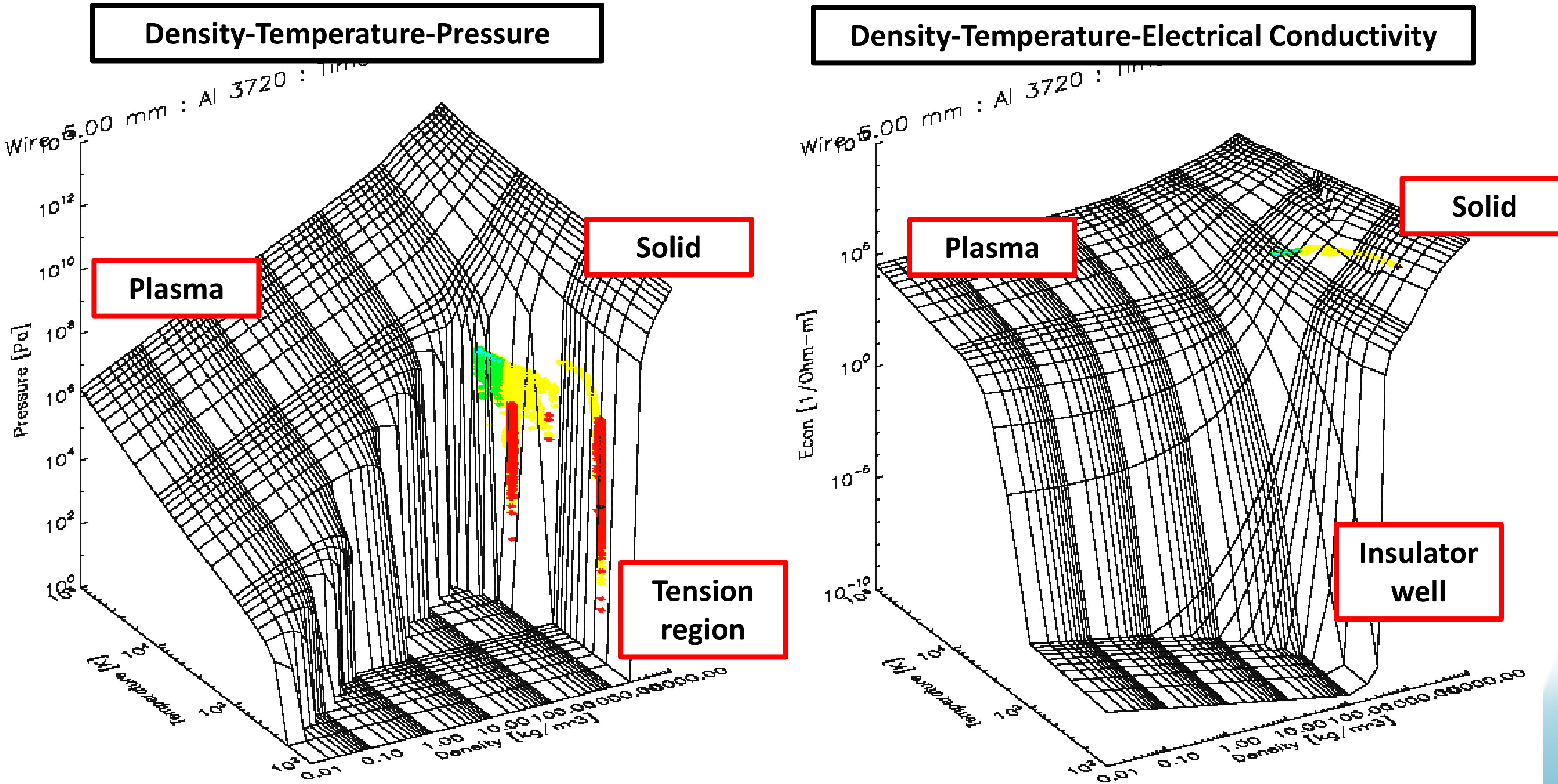


Snapshots at 2 later times show wire burst at hot region ~1 radius to ~1 diameter off of electrode



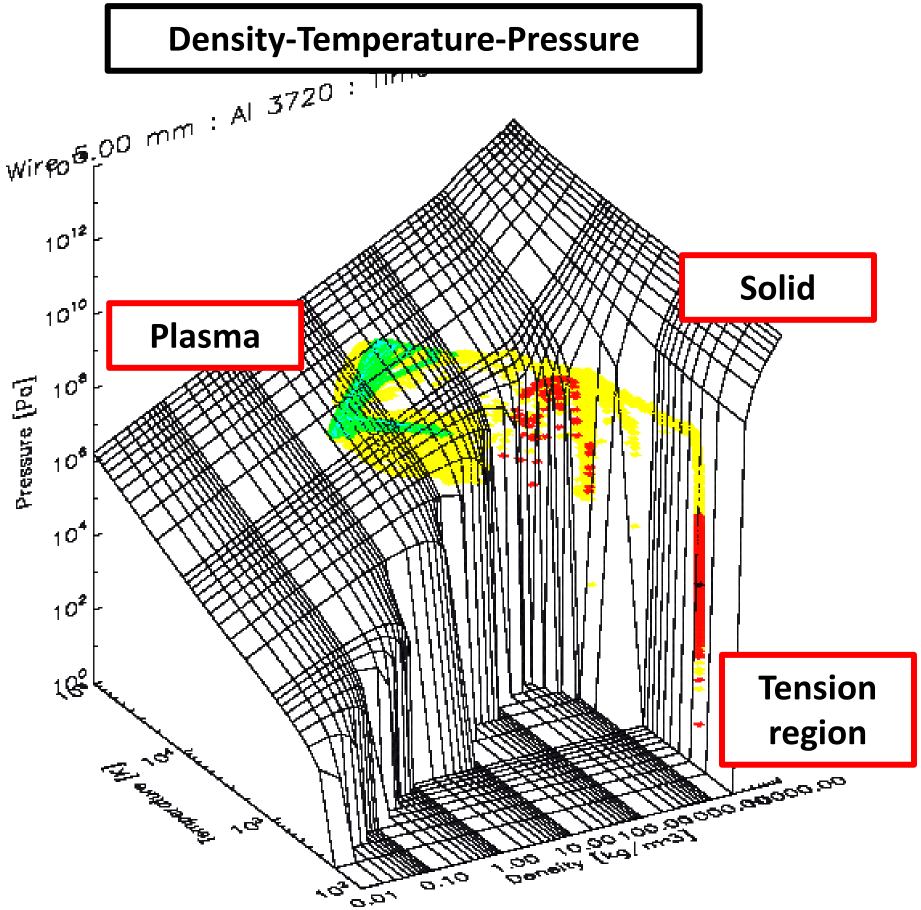
Sandia National Laboratories

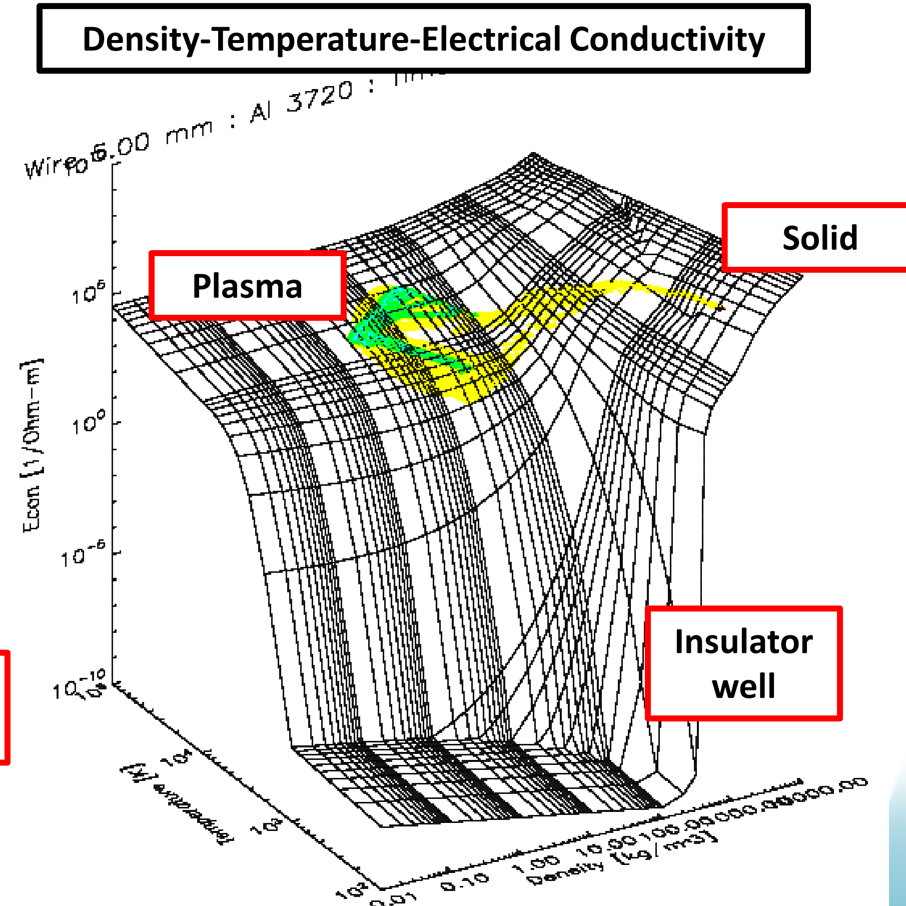
Phase space plots indicate the state of the material at 4.2 μs just before burst



- **(cyan/green) End part of wire near electrodes lead path through phase space**
- **(yellow) Intermediate part of wire follows on path through phase space**
- **(red) Central part of wire follows last on path through phase space**

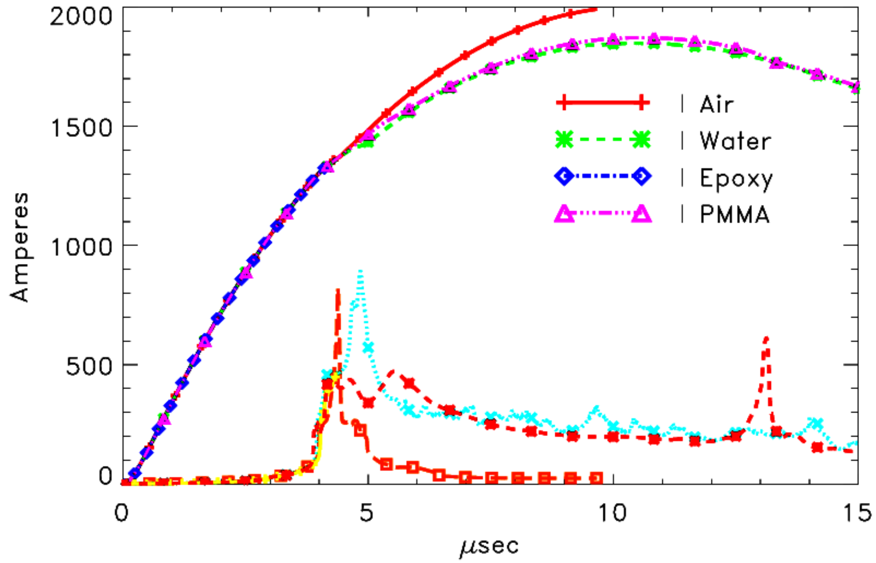
Phase space plots indicate the state of the material at 4.3 μs just after burst

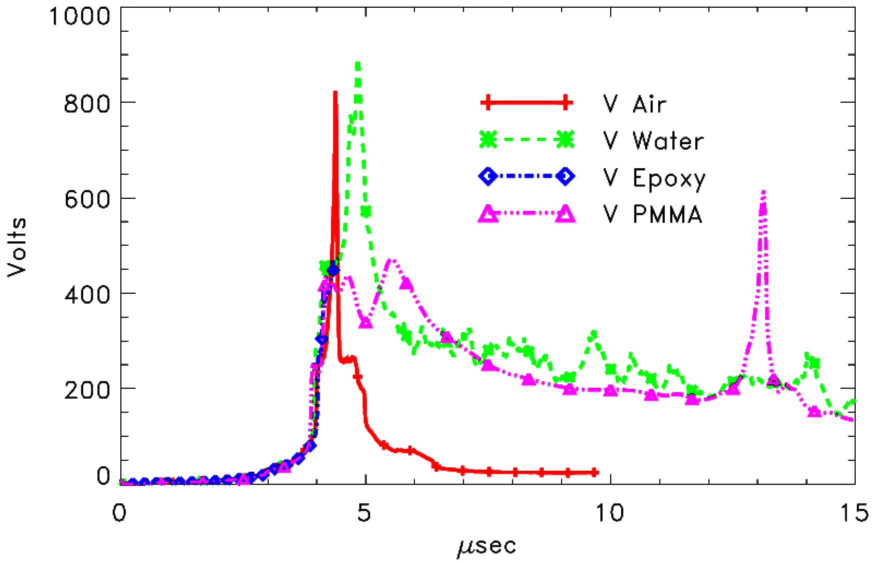




- **(cyan/green) End part of wire near electrodes lead path through phase space**
- **(yellow) Intermediate part of wire follows on path through phase space**
- **(red) Central part of wire follows last on path through phase space**

Confinement by various gap materials (air, water, epoxy, PMMA) exhibit some similarities and some differences

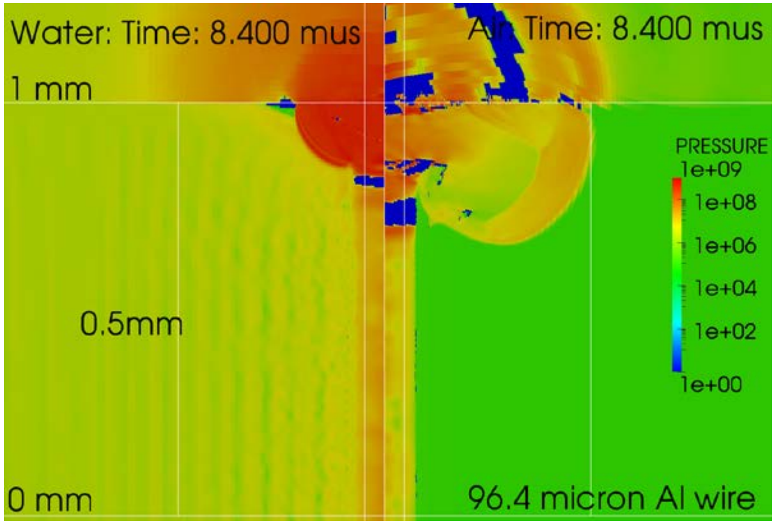


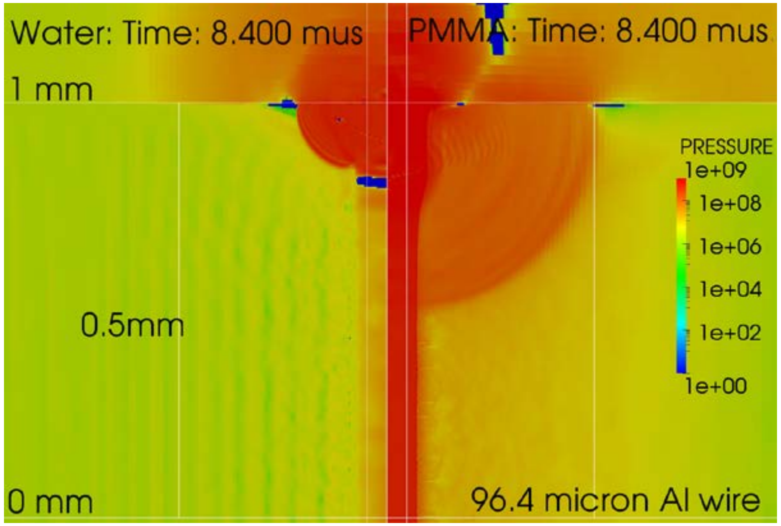


- **Current flow similar up to burst**
- **Current inflection seen at time of burst and voltage spike**
- **Air current higher after burst due to greater ionization**

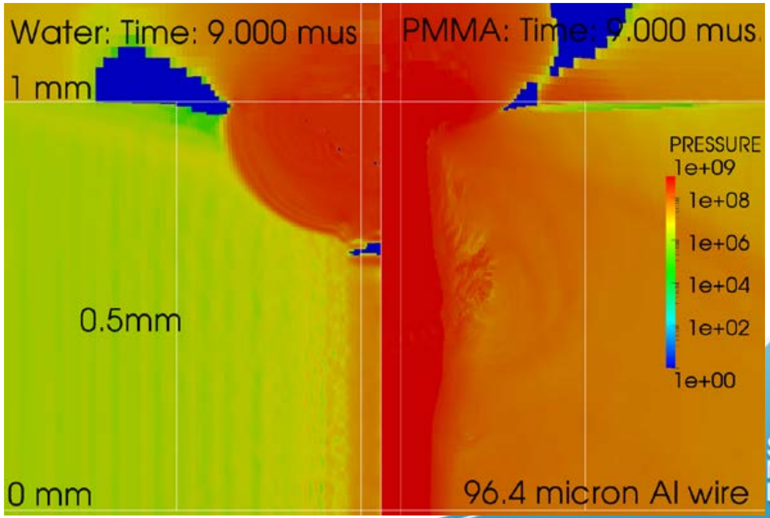
- **Air and water have similar voltage spikes**
- **Water spike later and wider due to slower ionization and greater inertia**
- **PMMA confines wire material keeping conductivity higher and voltage spike much lower**
- **Need better conductivity model for epoxy**

Comparison of water/air and water/PMMA confinement show higher pressure build up with greater confinement





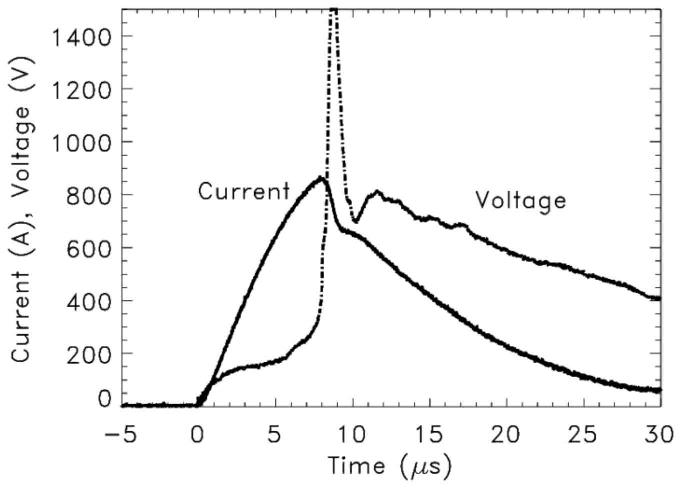
- **Shocks potentially present stronger mechanism for damage than Joule heating of confining material**



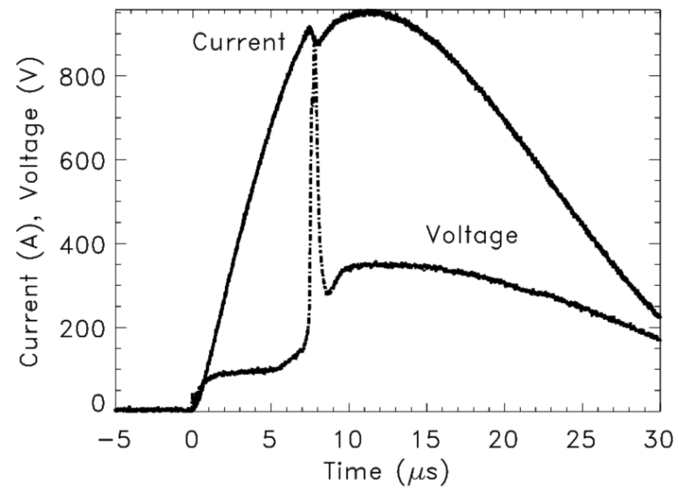
Sandia National Laboratories

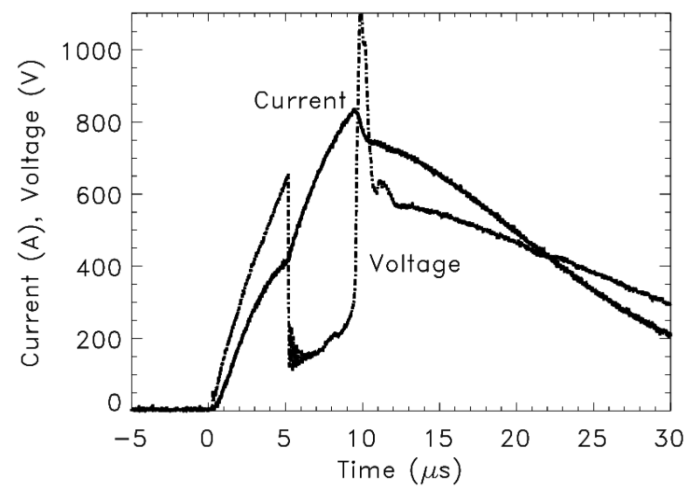
Experimental electrical waveforms when confined by epoxy or PMMA show unexpected variability

Epoxy experimental waveforms



PMMA experimental waveforms





- **Epoxy confinement may show 1, 2 or 3 voltage spikes**
- **PMMA confinement may show 1 or 2 voltage spikes**
- **More work needs to be done to use this data for verification**

Conclusions

- Experiments and simulations quantify the behavior of confined arcs
- Experiments validate many aspects of the simulations
- Thevenin equivalent circuit model has been developed to drive the exploding wire simulations

- Wires first burst near the electrodes when confined by air, water, and PMMA
- Concentrated Joule heating and the strong shocks are two mechanisms by which damage to electrode surfaces can occur
- Indeed minor damage to the electrode surface is observed even at these low voltages and currents
- A quantitative assessment and comparison of the damage is in order for future simulations and experiments

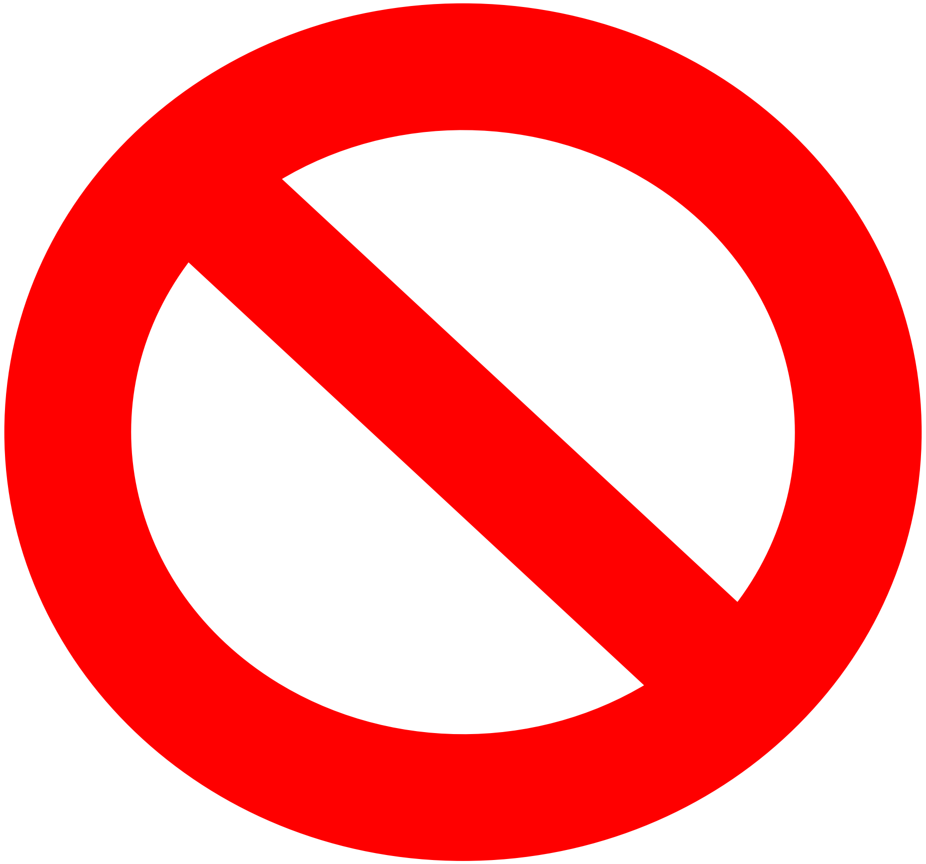
- Simulations and experiments of wire burst confined by alternate materials are still in their early stages
- Initial experiments with alternate potting materials show significant variability
- Such variability needs to be controlled if these experiments are to be used to validate code results
- Discrepancies point to areas where improvements are needed

Acknowledgements

- **This work is sponsored by the Boeing Company through a Cooperative Research and Development Agreement (CRADA) with Sandia National Laboratories under contract PTS No. 1651.15.05.**
- **I wish to acknowledge present and past:**
  - **Principal experimental investigators:**
    - *Kenneth Williamson and Jane Lehr*
  - **Simulation analysts:**
    - *Thomas Haill, Sophie Chantrenne, and John Neiderhaus*
  - **Experimental technicians:**
    - *Raymond Martinez, and Keith Hodges*
  - **Boeing Company sponsors:**
    - *Arthur Day*
  - **Sandia National Laboratories management:**
    - *Steven Glover, Thomas Mattsson, Mark Kiefer, and Michele Caldwell*

Sandia National Laboratories

Extra viewgraphs



RLC components are ubiquitous in pulser lumped circuit model

$$\frac{q}{C} - L\dot{I} - RI = 0$$

$$\dot{q} = -I$$

$$\ddot{I} + \frac{R}{L}\dot{I} + \frac{1}{LC}I = 0$$

$$I(t) = a \bullet e^{bt}$$

$$b^2 + \frac{R}{L}b + \frac{1}{LC} = 0$$

$$b = -\left(\frac{R}{2L}\right) \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\frac{1}{LC}\right)}$$

- **Case 1: damped oscillatory (short circuit)**

$$\omega_0 = \sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2} \qquad \tau = \frac{2L}{R}$$

$$I(t) = \frac{V_0}{\omega_0 L}\sin(\omega_0 t)\exp(-t/\tau)$$

- **Case 2: critically damped**

$$\omega_0 = 0 \qquad \tau = \frac{2L}{R}$$

$$I(t) = \frac{V_0}{L} \bullet t \bullet \exp(-t/\tau)$$

- **Case 3: overdamped (open circuit)**

$$\omega_0 = \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\frac{1}{LC}\right)} \qquad \tau = \frac{2L}{R}$$

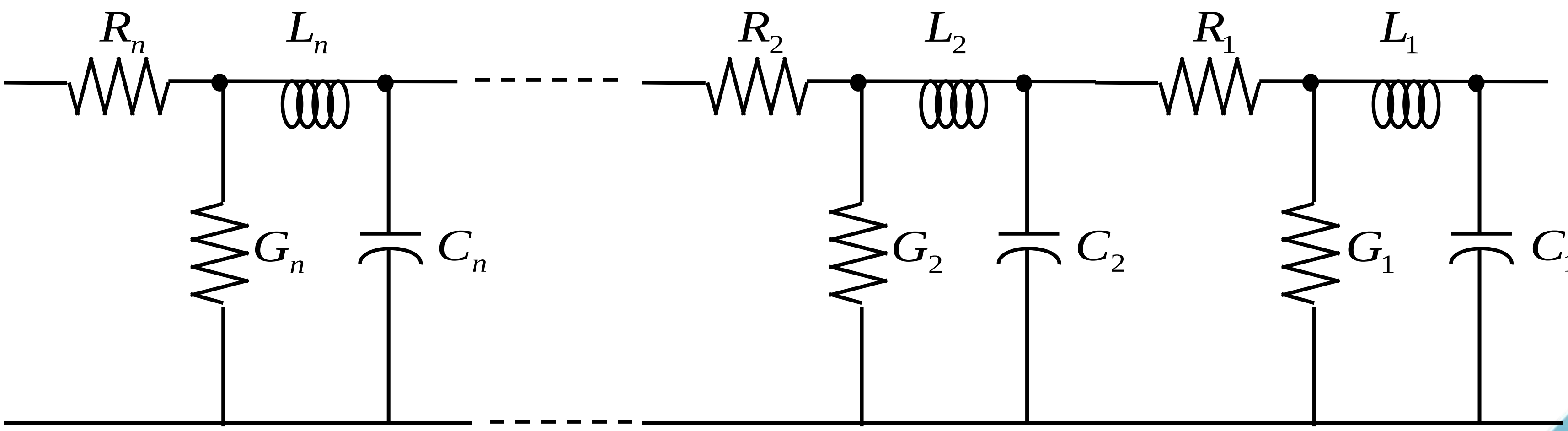
$$I(t) = \frac{V_0}{\omega_0 L}\sinh(\omega_0 t)\exp(-t/\tau)$$

Comparison ALEGRA-MHD circuit model with open and short circuit shots determines model parameters for Velonex waveform generator

		Velonex Setting	V_0 Volts	C_0 μF	L_0 μH	R_0 Ohms
AP1 001	Open	1	1010	9.0	5.0	8.0
AP1 008	Open	1	950	9.0	5.0	8.0
AP1 430	Open	3	2789	9.0	3.0	8.0
AP2 005	Open	3	2789	9.0	3.0	8.0
AP1 078	Short	1	1500	12.6	5.0	8.0
AP1 091	Short	3	3000	12.6	3.0	8.0
AP1 092	Short	3	2250	12.6	3.0	8.0
Coax	Tline			0.383 nF	1.606 μH	47.6 mΩ

Transmission line model

- **Transmission lines are modeled as a set of inductors and resistors in series and a set of capacitors and resistors in parallel**
- **Total length is divided into N segments depending upon desired time resolution**
- **Lossless transmission lines have zero resistance, i.e., inductors and capacitors only**
- **Transmission line model:**



Transmission line properties of a coax cable

- Inductance/length
  - L' = 348.8 nH/m

$$L' = \mu_0 \left\{ \frac{1}{8\pi} + \frac{1}{2\pi} \ln\left(\frac{b}{a}\right) + \frac{1}{2\pi}\left[\frac{1}{\left(1-(b/c)^2\right)^2} \ln\left(\frac{c}{b}\right) - \frac{3-(b/c)^2}{4\left(1-(b/c)^2\right)} \right] \right\}$$

- Capacitance/length
  - C' = 3.309 pH/m

$$C' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{b}{a}\right)}$$

- Impedance
  - Z = 64.52 Ohms

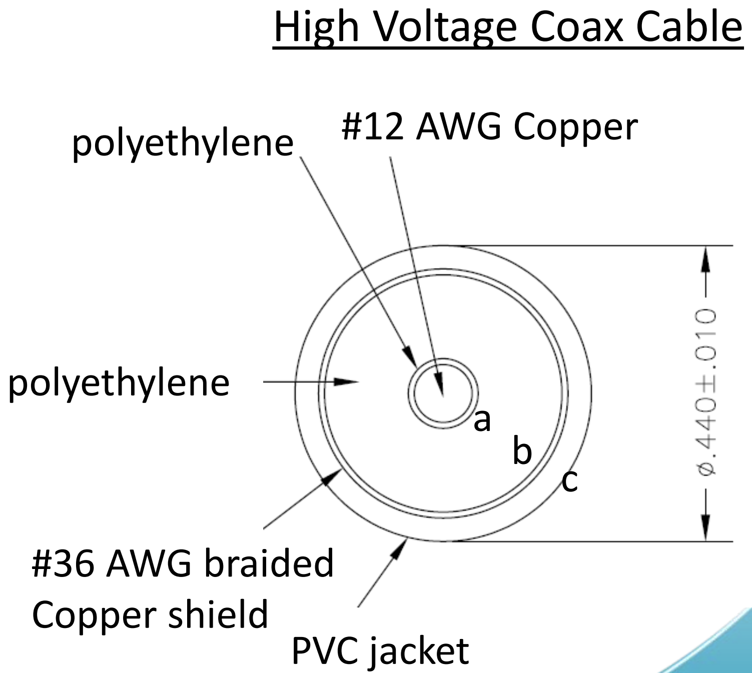
$$Z = \sqrt{\frac{L'}{C'}}$$

- Wave speed
  - v = 1.85e8 m/s

$$v = \frac{1}{\sqrt{L'C'}}$$

- Delay time
  - τ = 24.7 ns

$$\tau = \frac{length}{v}$$



Issues and concerns for short circuit shots

- HILO output current:
  - o Model output current will match model load current
  - o How can these be made different?
  - o How can model capacitor current and output current pulse be made longer?
- HILO output voltage
  - o What caused negative voltage I HILO V monitor to happen so soon?
  - o Why don't measured output voltage and current mimic each other?
- Load (upstream) current monitor (CVT411)
  - o We're good to go here
- Load voltage monitor (Tek 6015)
  - o Simulated load voltage and current mimic one another
  - o What causes measured load voltage to stay higher?
  - o Can circuit model be made to do same?