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Verification and validation of ALEGRA-MHD with exploding wire data.

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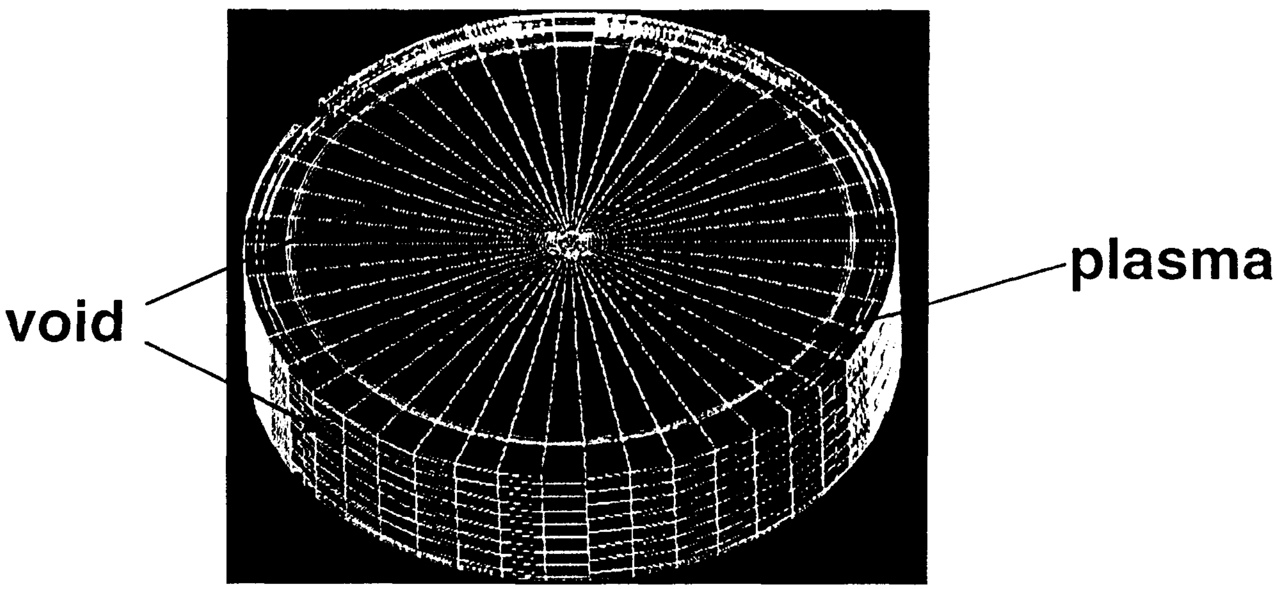
Abstract

One goal of the ALEGRA-MHD project is to develop a 3-D modeling capability for wire array implosions. An important step in this process is to develop, verify and validate the MHD algorithms and related conductivities and EOS databases in one and two dimensions. We report on progress in modeling conductivity measurements of tamped wires [1] and exploding wire experiments [2] to validate ALEGRA. Wire materials studied include aluminum, copper and tungsten, and we report on simulations of both bare wires and wires with insulating coatings. We also report on progress in verifying ALEGRA by comparing with wire initiation simulations using the MACH-2 code that are relevant to modeling Sandia z-pinch experiments.

[1] A.W. DeSilva and J.D. Katsourous, Phys Rev E 57,5945 (1998).
[2] D.B. Sinars, et al, Phys Plasmas 7, 429 (2000).

ALEGRA-MHD is Sandia's parallel, 3D code for MHD

- ALEGRA is an object-oriented code written in C++.
- It is a 2D/3D, parallel, multi-physics Lagrangian finite element code with an Eulerian remap option.
- It handles multiple materials, including void, on unstructured grids and has a variety of radiation options.



Computational details...

- The code is run 2D, R-Z geometry on both Lagrangian and Eulerian grids (up to 10,000 elements) with square zoning and mass-weighted zoning. Effective 1D runs are done in 2D with only one cell in z.

- For comparison to Cornell wire initiation data, the wire sizes and types are 12.7 μm Al and 25 μm Ag, suspended in vacuum.

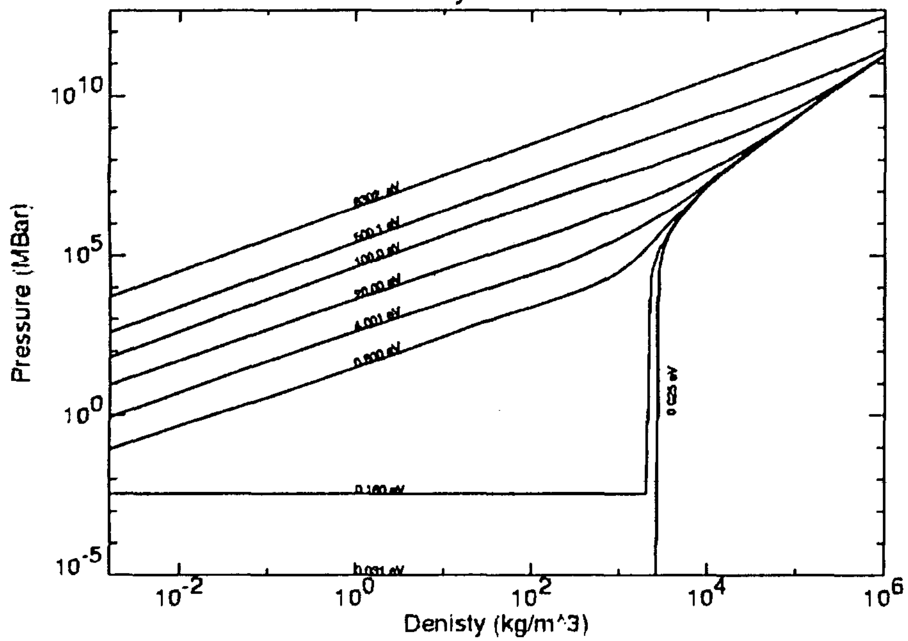
- For comparison to tamped wire explosion data of DeSilva, wire size and type is 100 μm Cu, suspended in water.

- The EOS model is LANL Sesame, the electrical conductivity model is modified Lee-More (Lee-More-Desjarlais), no thermal conduction, and no radiation is modeled.

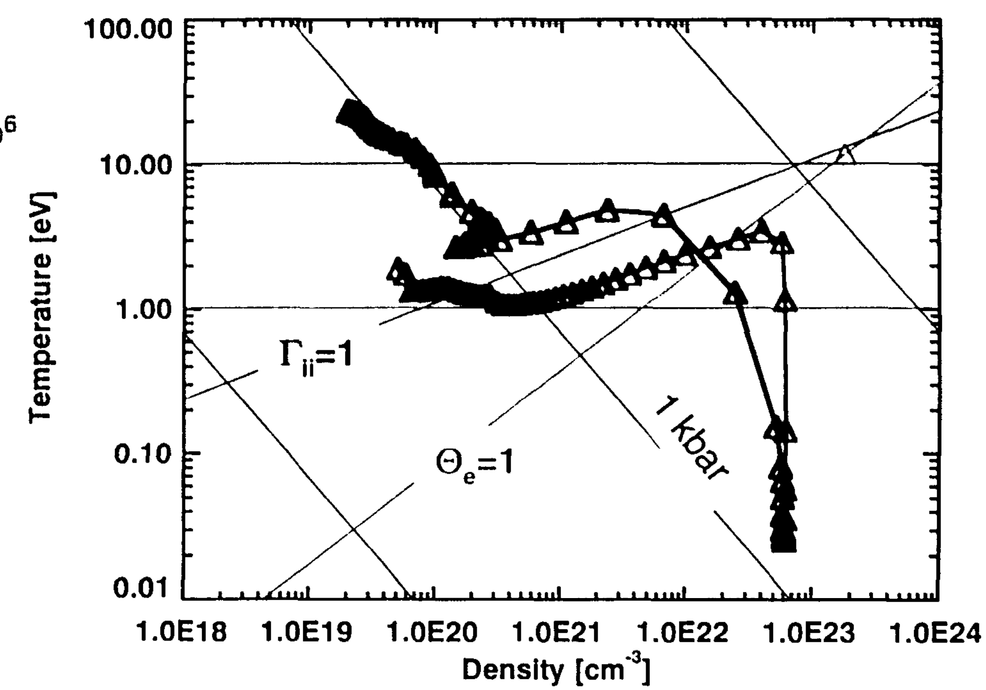
- Calculations conducted in serial take anywhere from a few minutes to an hour

Alegra: LANL Sesame Equation of State model.

Ion+Electron Pressure vs Density for Aluminum in Lanl Sesame Ta

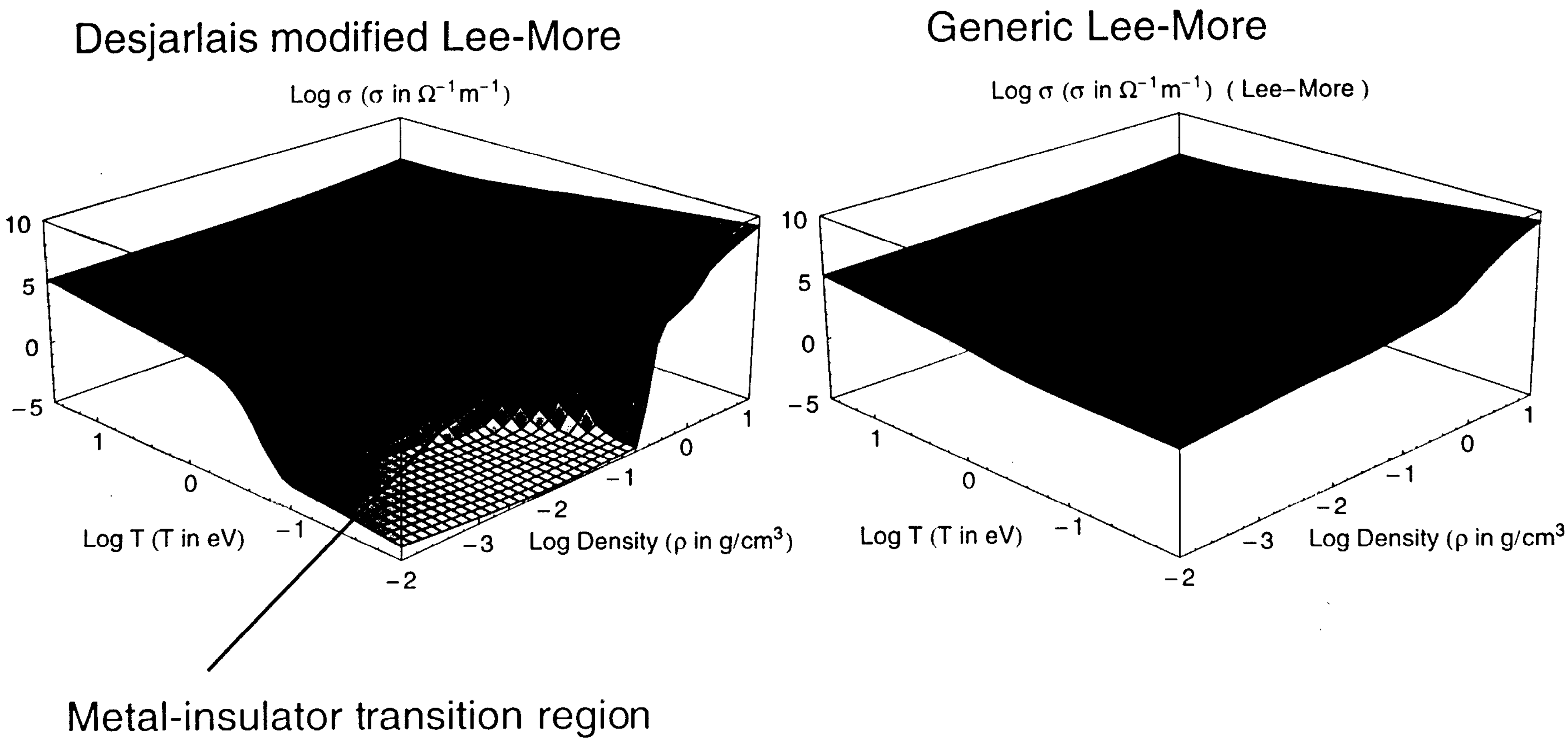


Pressure vs. density at constant temperature



The corona and core of an aluminum wire plasma evolve from a coupled to a classical state

Alegra: Conductivity model based on modified Lee-More which better captures the metal-insulator region

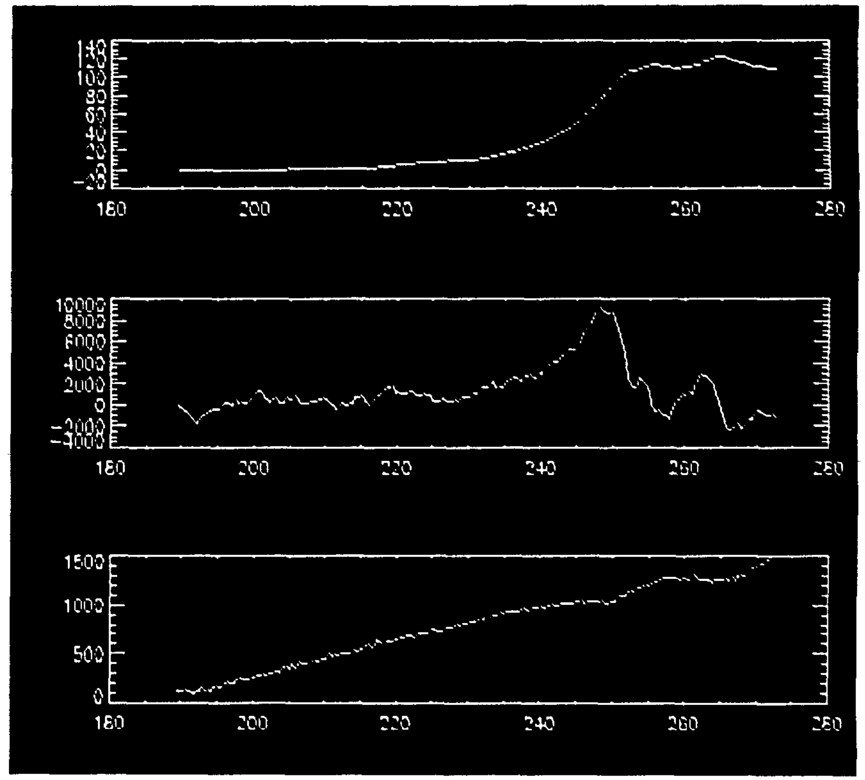


Cornell wire initiation data: Impedance characteristics.

Wire dimensions: 12.7 µm diameter Al and 25 µm diameter Ag, 1 cm long. Exploded in vacuum.

Current and voltage drive: 500 amps, 15 kV, 50-100 ns pulse.

Experimental observations: Wires heat resistively as the current and voltage rise. The deposited ohmic energy causes the wire to explode. A voltage collapse occurs at peak voltages ~ 10 kV (after ~ 40-70 ns). This is most likely due to low density corona formation outside the main wire core.



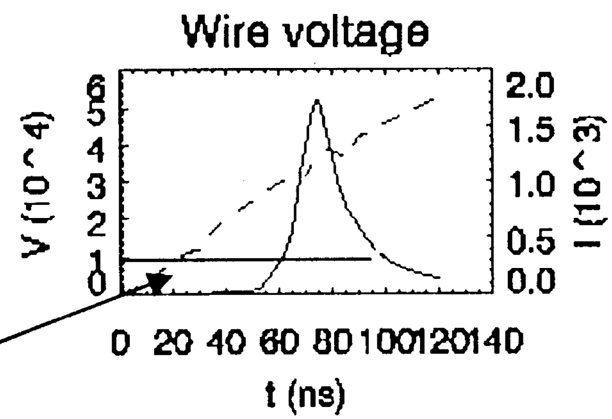
Energy, Voltage, Current trace from 25 µm Ag

References: D.B. Sinars et. al, Phys. of Plasmas, **7**, 429 (2000)
D.B. Sinars et. al, Phys. of Plasmas, **7**, 1555 (2000)

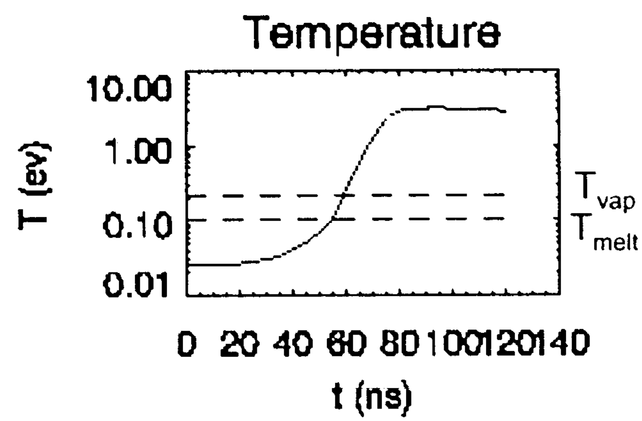
Silver wire simulation results: Voltage collapse occurs during wire expansion.

Lagrangian point diagnostic, radial position includes 95% of mass.

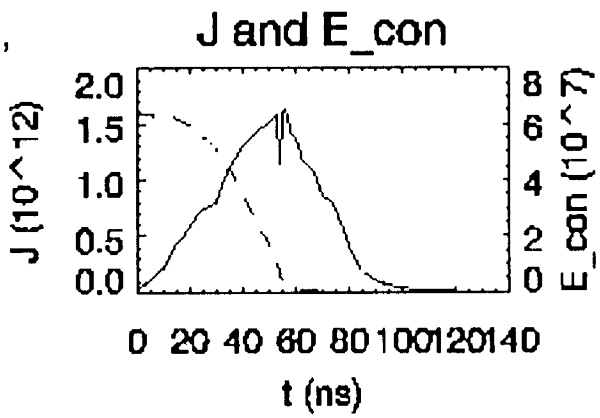
$$V = \int \frac{j}{\sigma}\, dl$$

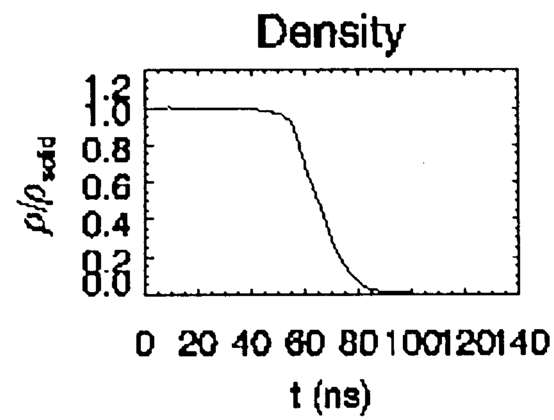


Expt. measured peak voltage



Voltage rise occurs during falling conductivity near melt, collapse occurs during wire expansion.

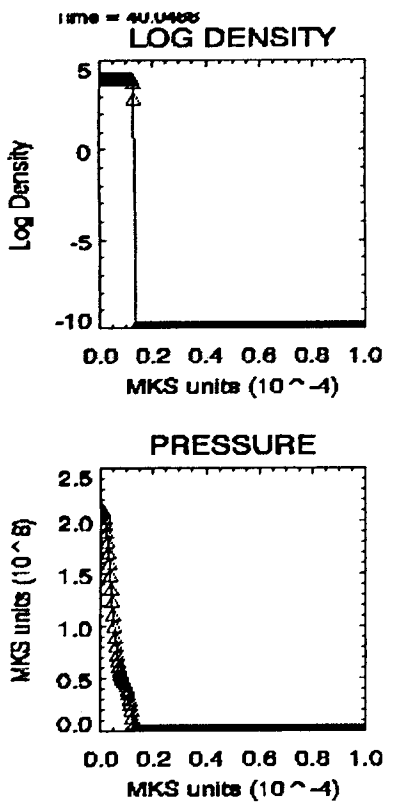




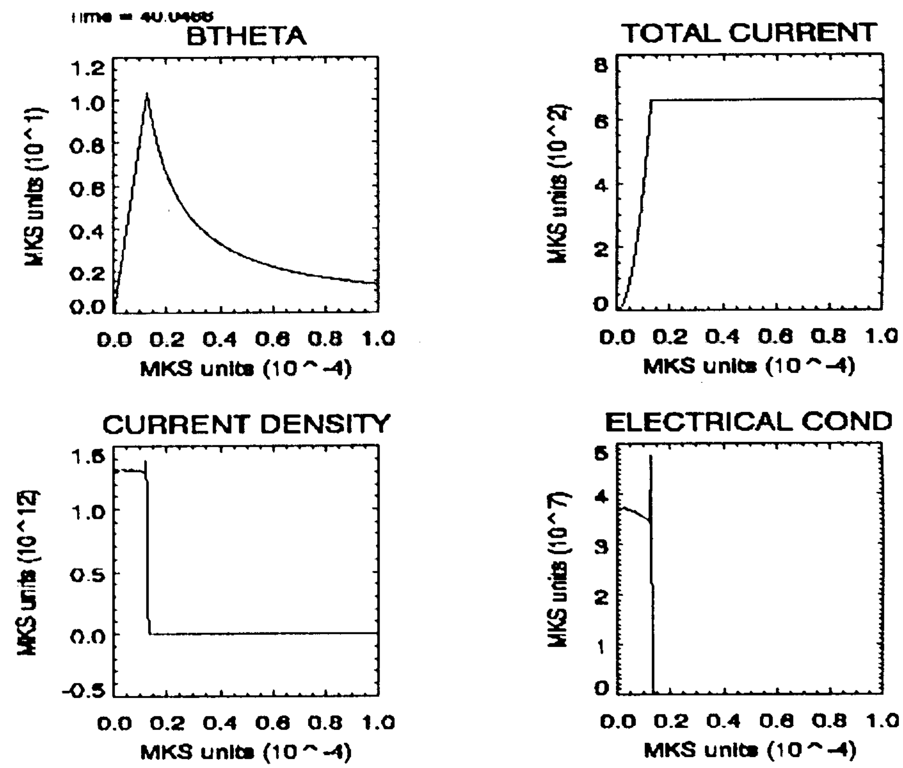
Timing consistent with Cornell data, but max. voltage is 5 times too large. Also voltage fall is too slow (20 ns vs. 3 ns in expt.)

Silver results cont: Early evolution t=40 ns

Hydrodynamic variables.



Magnetic variables.

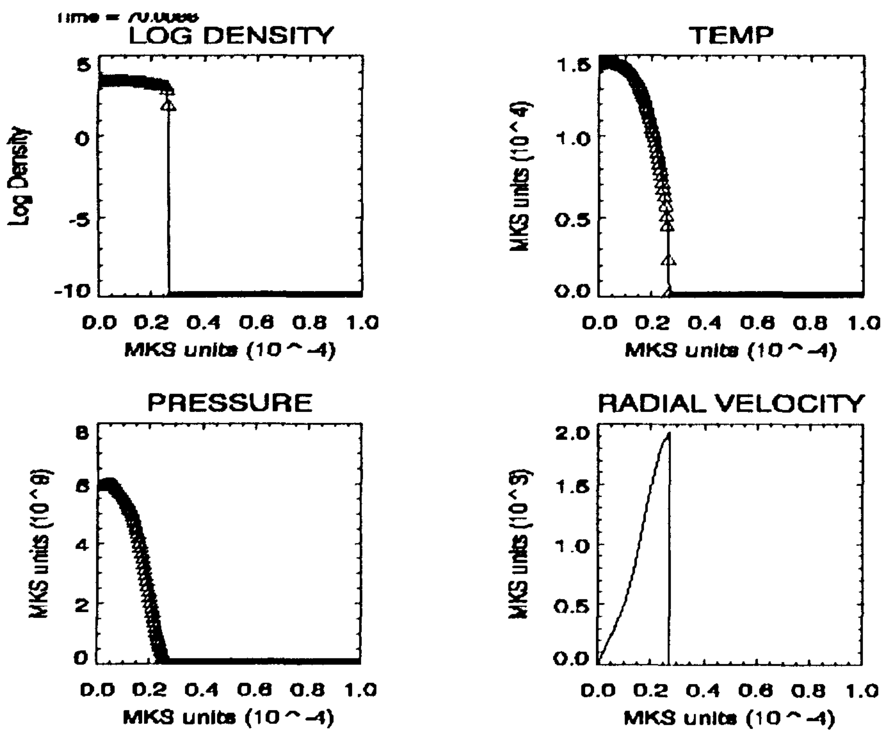


Core heats slowly with minimal expansion. Current is fully diffused through the wire

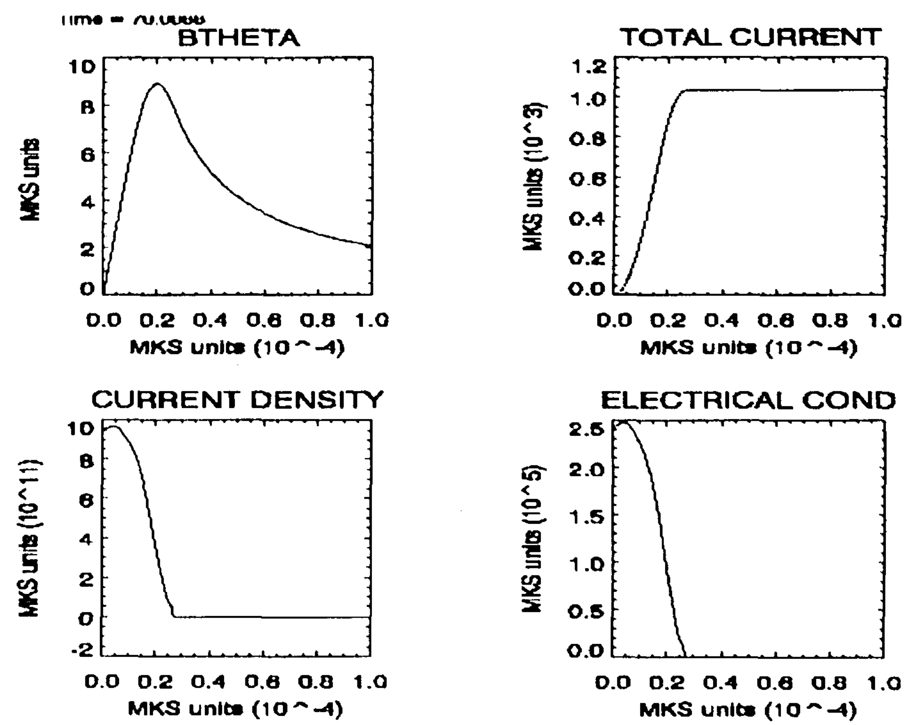
$\tau = 2\pi\sigma r_b^2/c^2 \cong 2$ ns

Silver results cont: Later evolution t=70 ns

Hydrodynamic variables.



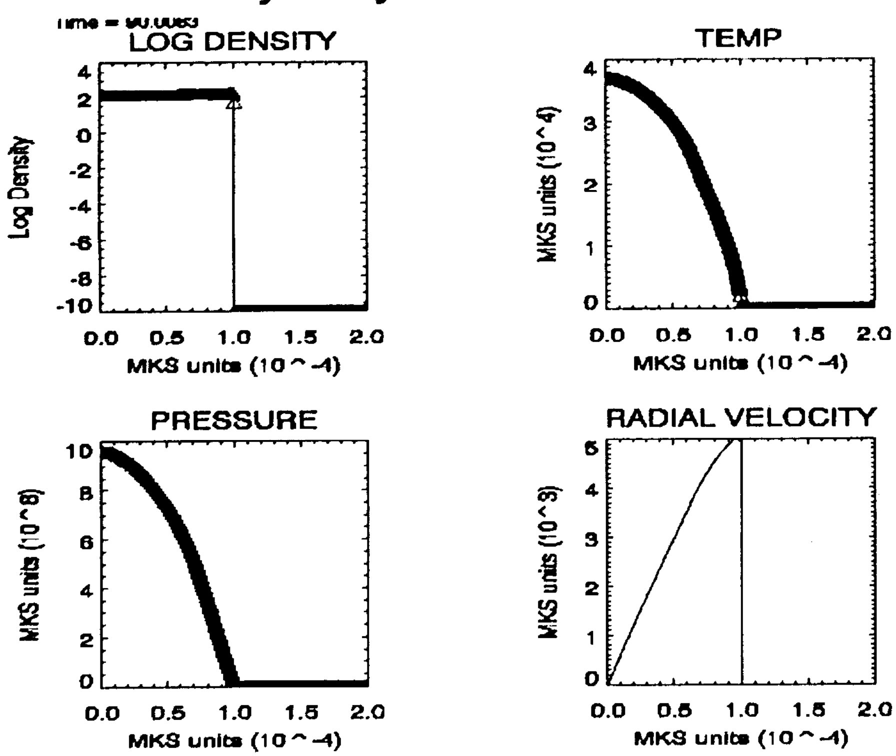
Magnetic variables.



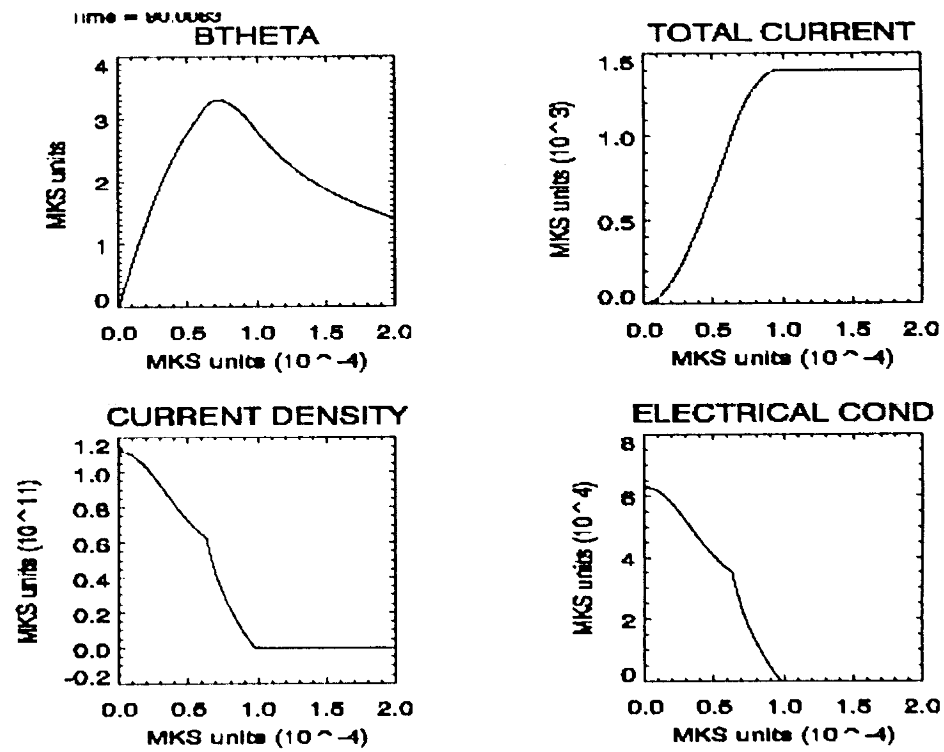
$$\tau = 2\pi\sigma r_b^2/c^2 \cong 0.1 \text{ ns}$$

Silver results cont: Later evolution t=90 ns

Hydrodynamic variables.



Magnetic variables.



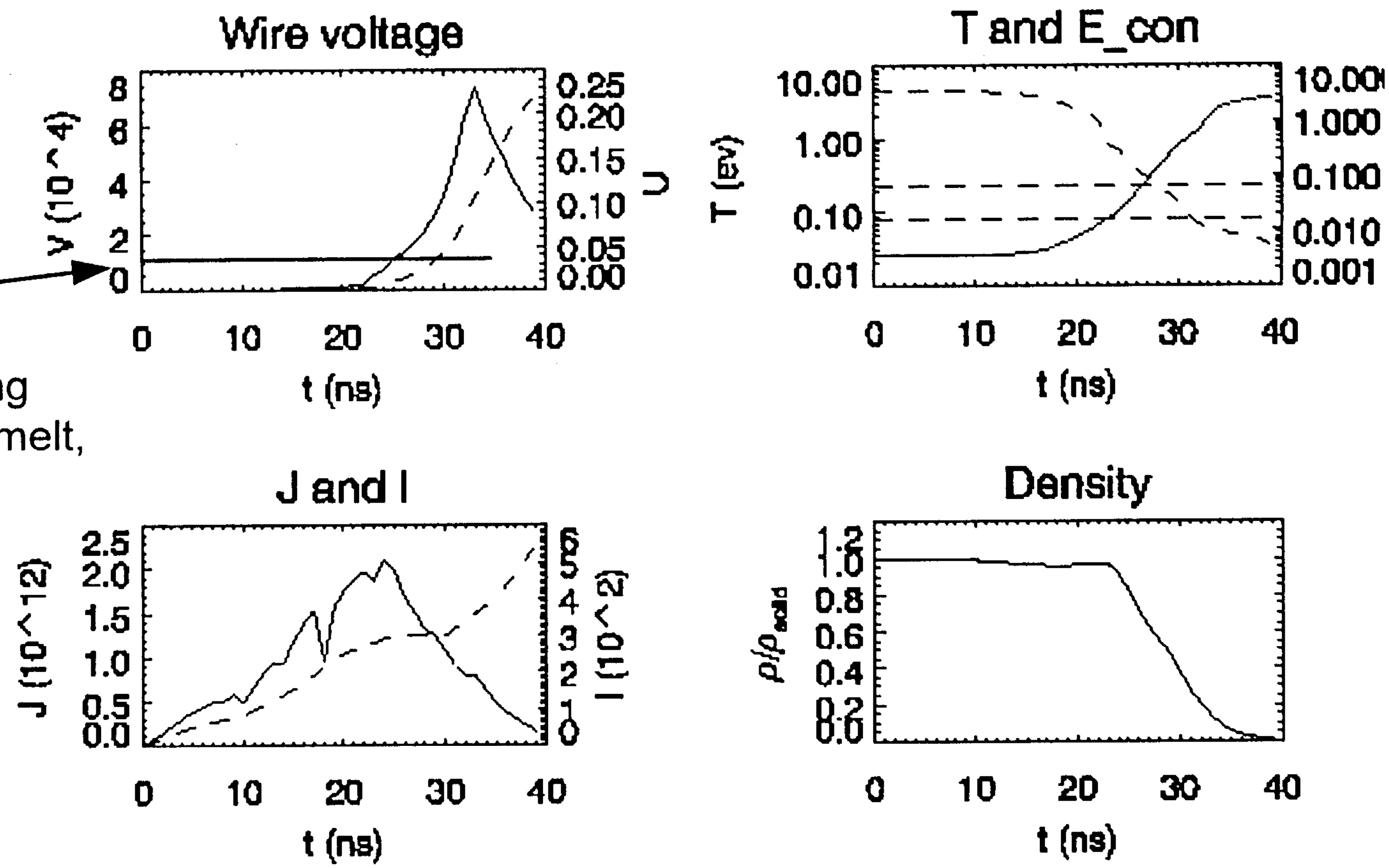
No indication of corona formation

$\beta = 8\pi nkT/B^2 \sim 100$

Al wire results:

Lagrangian point diagnostic, radial position includes 50% of mass.

Expt. measured peak voltage

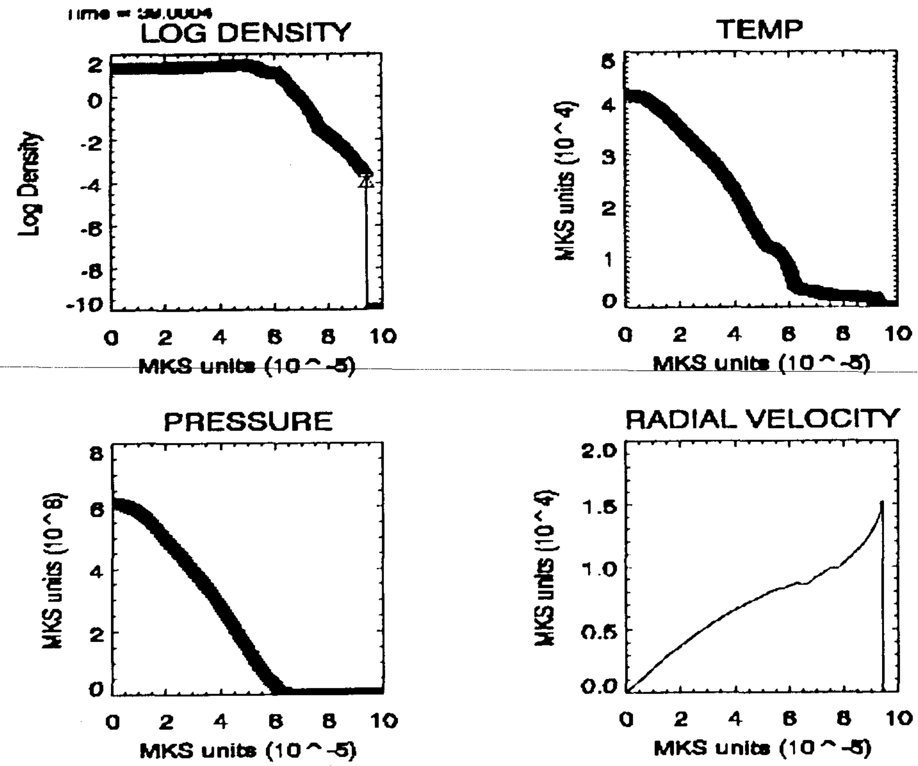


Voltage rise occurs during falling conductivity near melt, collapse occurs during expansion.

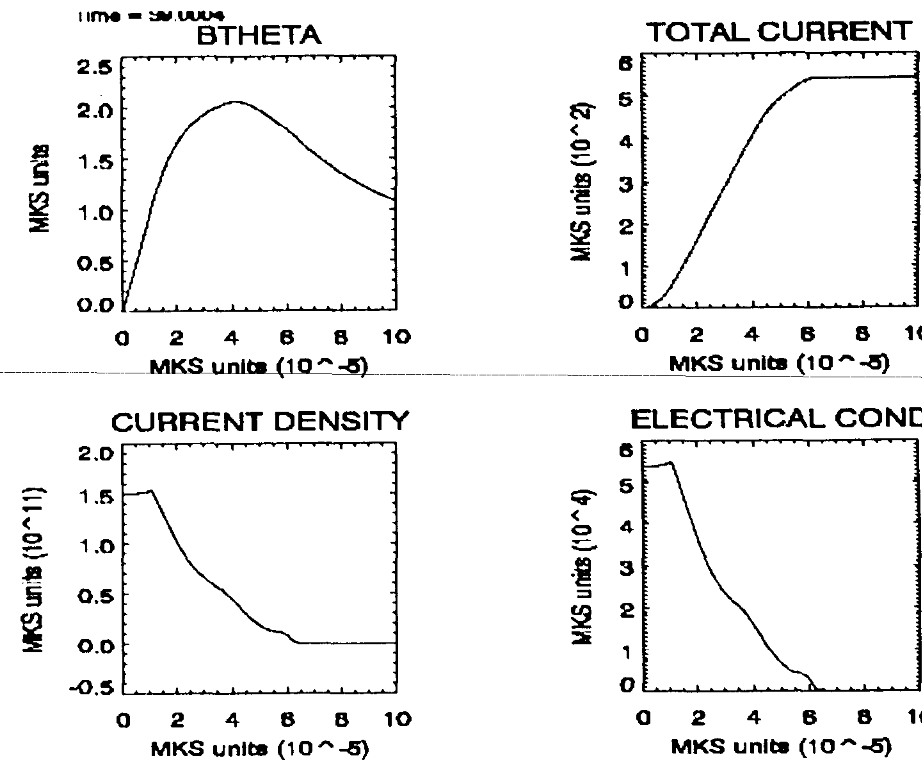
Total ohmic energy deposited ~ 230 mJ, compared to 30 mJ deposited in expt.

Al results cont: After voltage collapse t=40 ns

Hydrodynamic variables.



Magnetic variables.



No indication of corona formation

Al wire trajectory in the ρ,T phase space

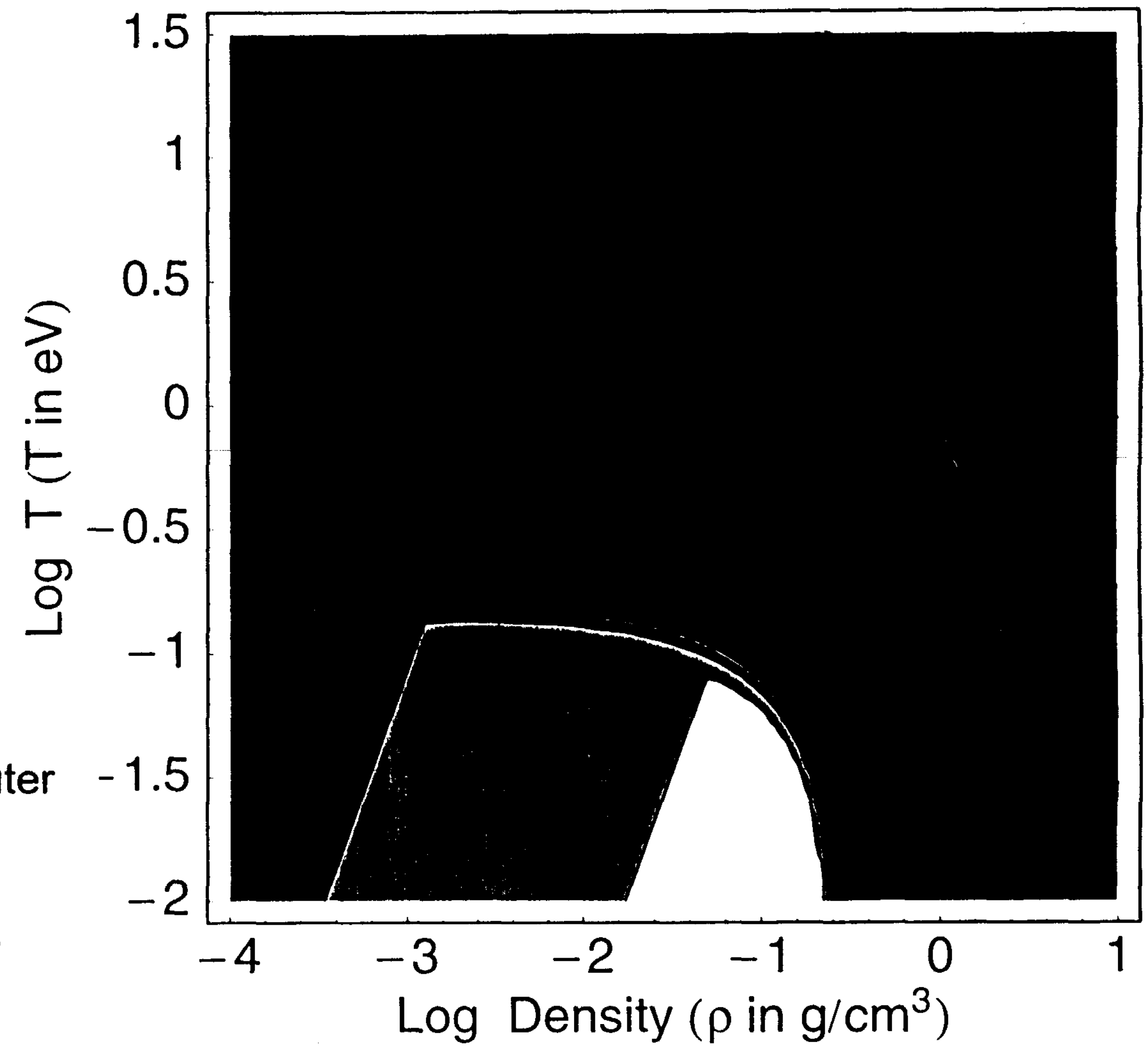
Contours of constant conductivity in the ρ,T phase space for Al.

Lagrangian trajectories of the core (black) and outer edge (green) of an Al wire are shown superimposed.

The initial (cold, solid) conductivity is ~3.4×10^{17} s^{-1}.

Late time conductivity ~10^{14} s^{-1}.

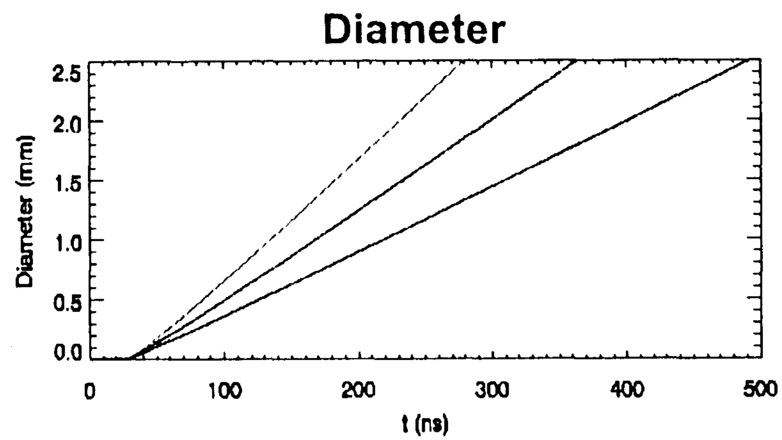
For a corona to form one expects the outer edge (green) to follow a trajectory which stays outside the core (black) trajectory. Changes to EOS models may allow this.

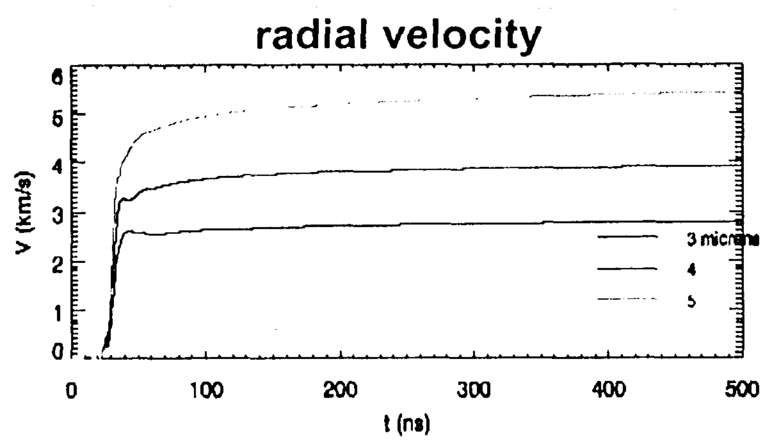


Al results cont: Wire expansion velocities are 4 times larger than experimental observations

Increased expansion consistent with increased joule heating/internal energy calculated prior to voltage collapse

Expt. measured radial velocity = 1 km/s





Each curve represents a lagrangian point with initial condition of 3,4,and 5 microns

Discussion of Cornell data and simulation results:

Breakdown for 12.7 μm Al wires occurs: $V \cong 10$ kV, $I \cong 300$ A, $\rho \cong \rho_{solid}$
The inferred electrical conductivity: $\sigma = j/V \cong I/\pi a^2 V = 2.5 \times 10^4\ (\Omega\text{-cm})^{-1}$

Alegra-MHD suggest that when V = 10 kV: $I \cong 300$ A, $\rho \cong 0.9\rho_{solid}$, $T \cong 0.2$ eV
$\sigma \sim 2.2 \times 10^4\ (\Omega\text{-cm})^{-1}$

$\Rightarrow$ Experimentally observed breakdown occurs near wire vaporization!!

However: Heat of vaporization $\Delta H_{vap} \sim 35$ mJ for Al wires
Electrically energy deposited $E \leq 30$ mJ

$\Rightarrow$ Breakdown occurs before complete wire vaporization!!

In the simulations, wires fully vaporize (never enter the vapor dome), dropping the electrical conductivity rapidly ($\sigma \propto (\rho^{\alpha}/T)$, $\alpha > 2$) and causing the voltage to rise. Different EOS models may keep the wires from fully vaporizing, thus maintaining higher conductivities and lower voltages.

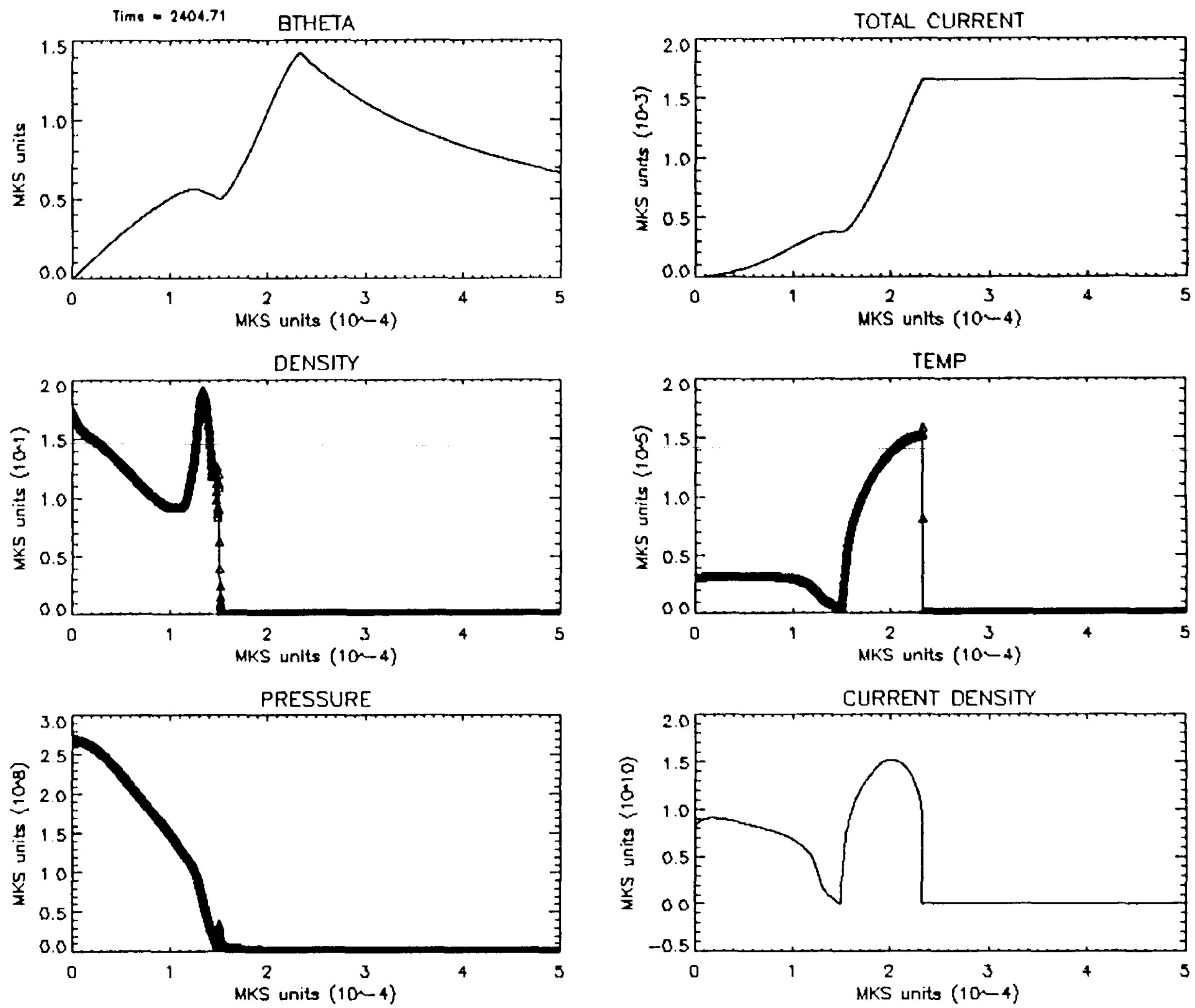
Simulations of wire initiation expansion on Z (shot 293) demonstrate coronal plasma formation

20.4 μm Al wire

Current rise 20 A/ ns (1 kA in 50 ns). This is higher than Cornell expt.

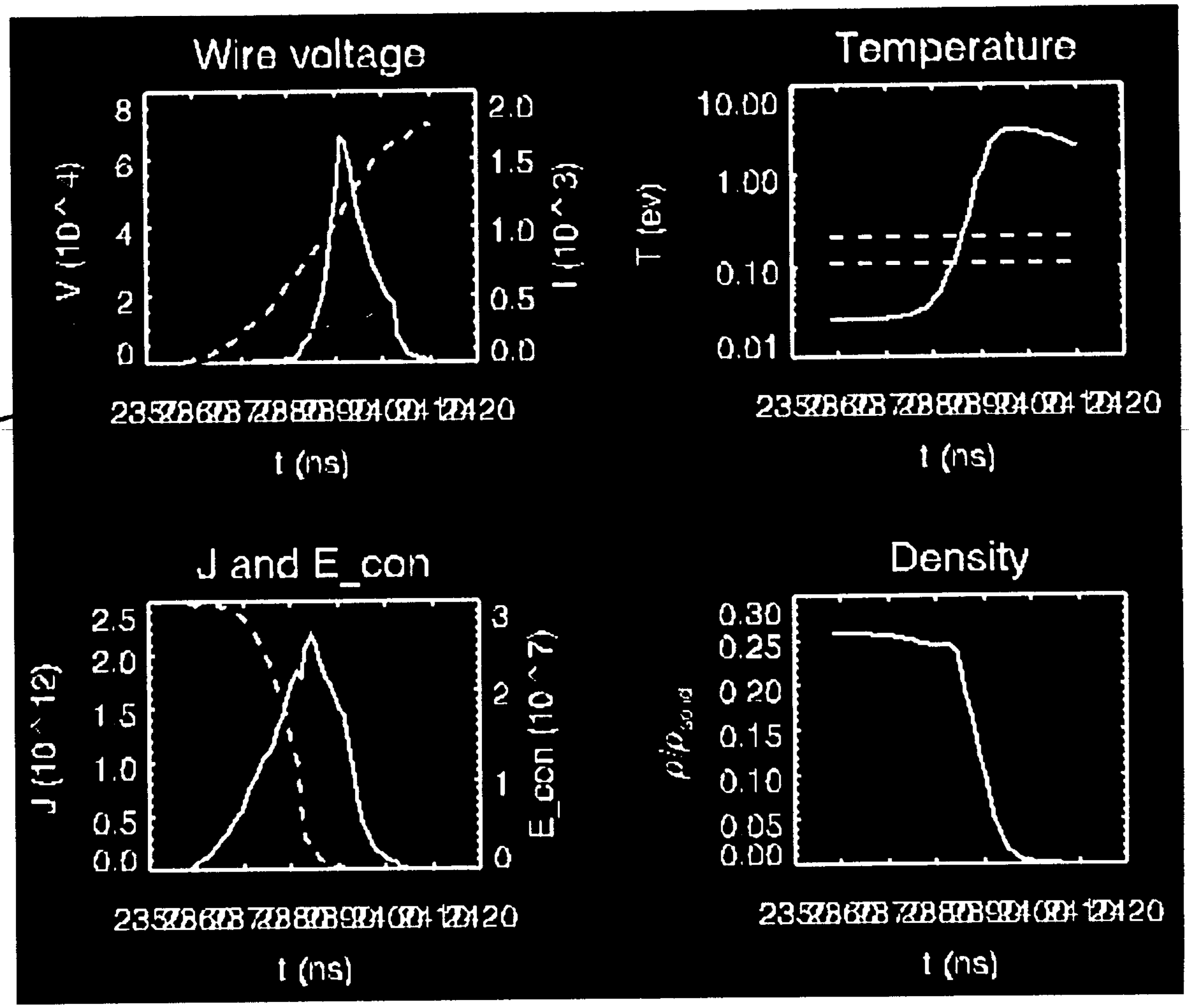
High density ridge on outer edge surrounded by low density/high temp corona.

Current density down by ~ 100 from Cornell Al wire simulations.



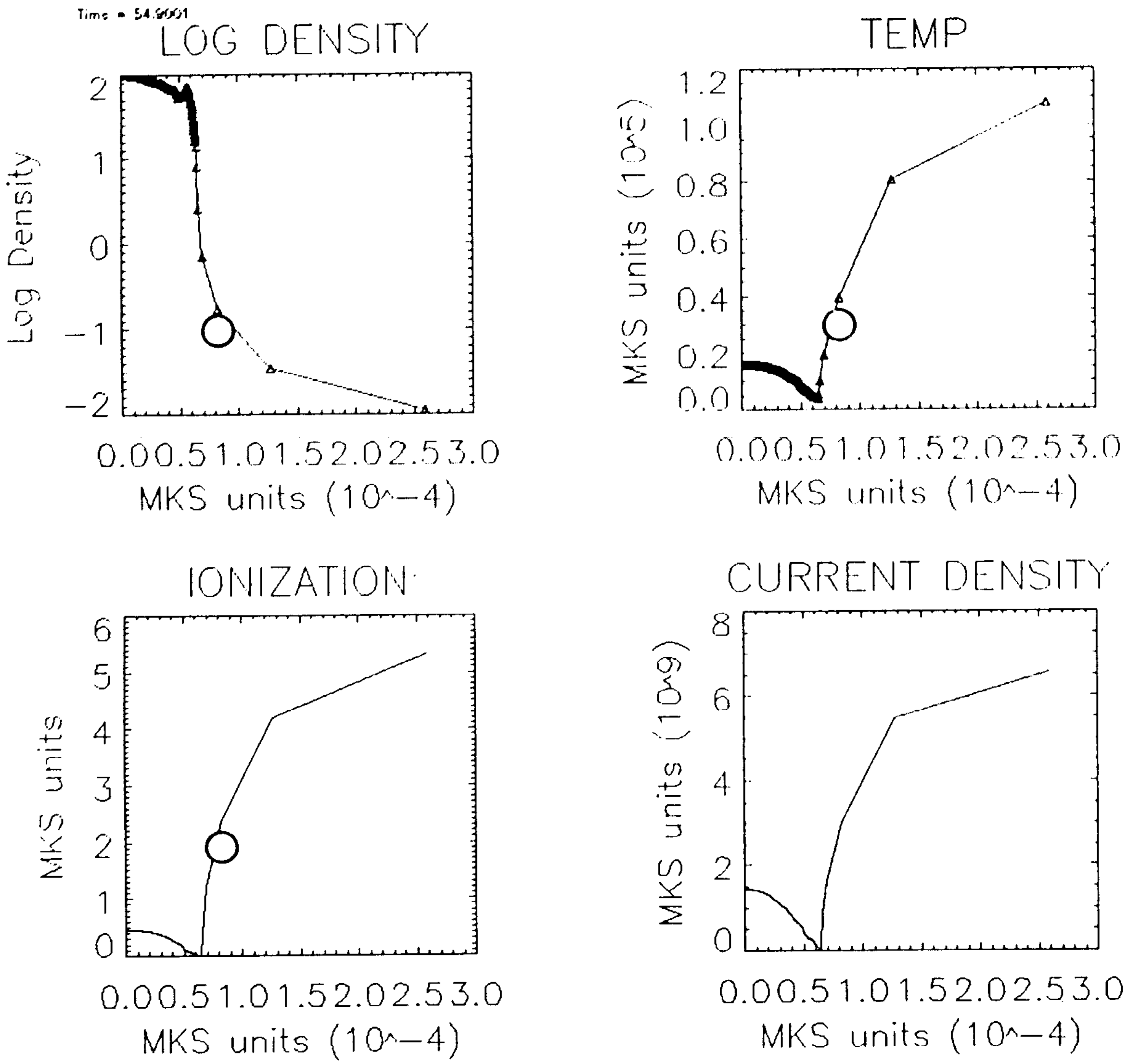
Voltage indicates fast drop late in time, during formation of corona for higher current wires (shot 293).

corona forms after main voltage drop, but prior to very rapid drop later in time.



Simulations of wire initiation on shot 293 are in qualitative agreement with J. Bailey's spectroscopic data

○= Data from J. Bailey



For Z=2 and I=1kA, spectral data gives $n=3.5\times10^{18}/cm^3$ and T= 2-3 eV. This is plotted as red circles.

Analysis of continuum spectra suggests that the core is cooler than calculated in simulation. This is consistent with the expectation that in simulation we deposit more energy (higher voltage) than occurs in expt.

[Y. Maron, private communication]

Comparison with DeSilva tamped wire data

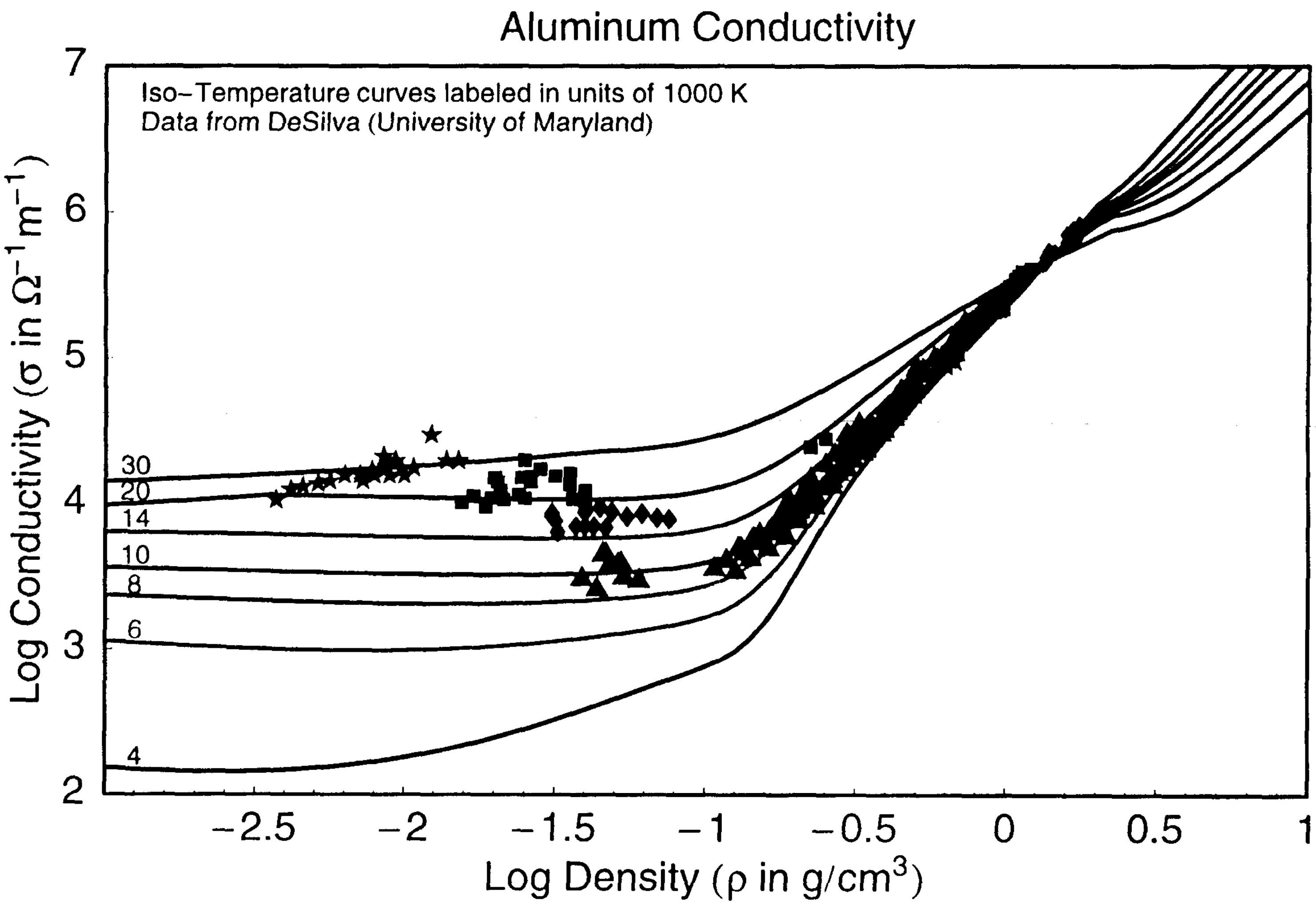
Wire dimensions: 100 μm diameter, 2.6 cm long, Cu exploded in water.

Current and voltage drive: 30 kA, 20 kV, 2.5 μs pulse.

Experimental observations: Wires heat resistively as the current and voltage rise. The deposited ohmic energy causes the wire to explode. A voltage collapse occurs at peak voltages ~ 20 kV (after ~ 1 μs). This is most likely due to wire core expansion.

Ref: A.W. DeSilva and J.D. Katsourous, Phys Rev E 57,5945 (1998).

Desjarlais' modifications to the Lee-More model provides a good fit to DeSilva's aluminum data

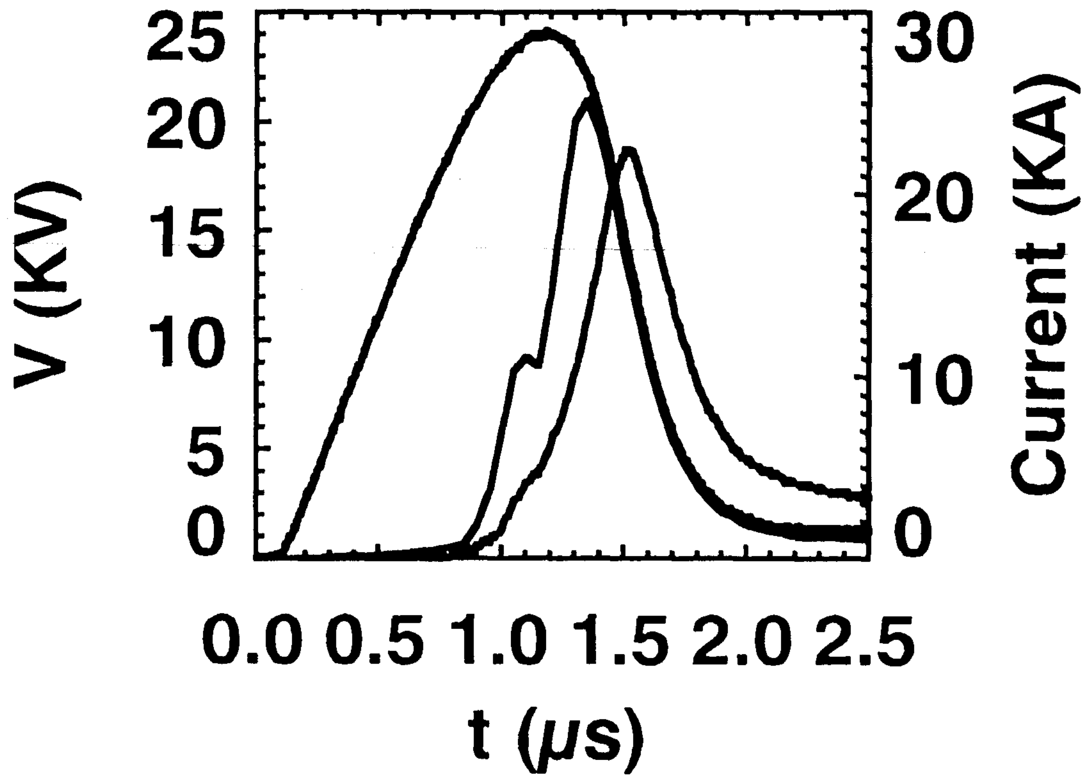


The ALEGRA voltage has about the right maximum and start time, but has a higher slope

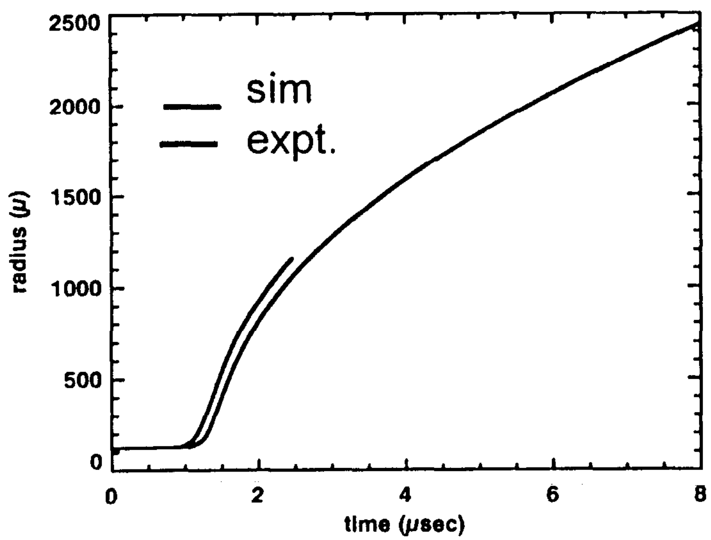
Resistive voltage measured along the wire.

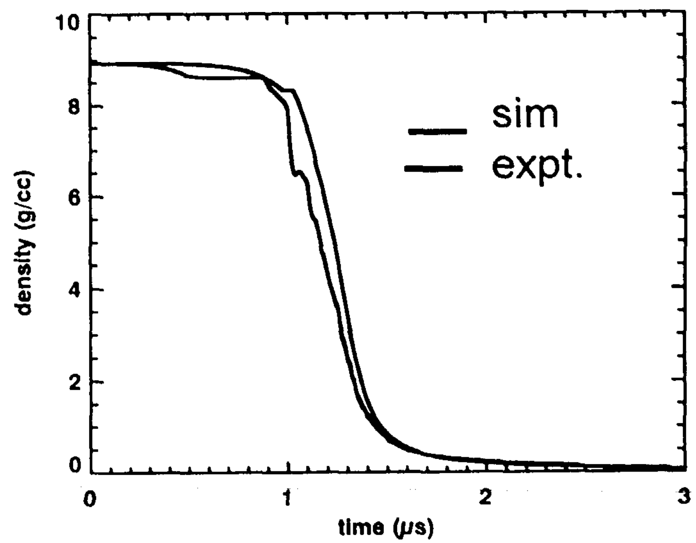
$$V = \int \frac{j}{\sigma}\, dl$$

- Current (expt. & Alegra)
- Voltage (Alegra)
- Voltage (DeSilva expt)



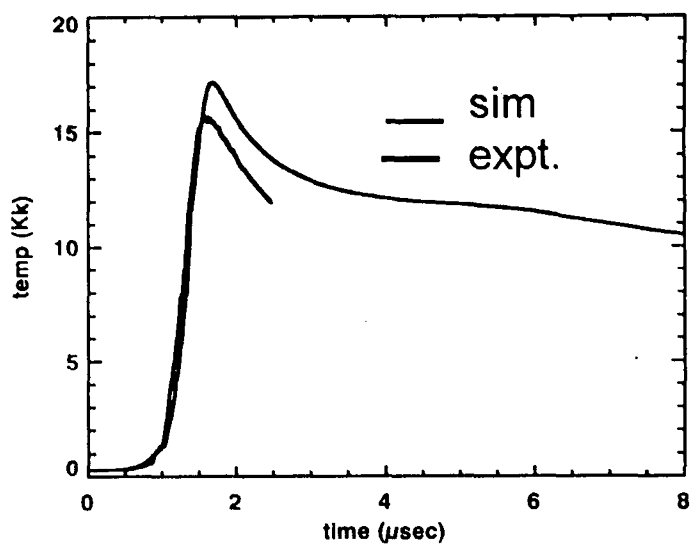
Other variables agree well with experimental measurements.





Experimental measurements/assumptions

Wire core radius is inferred from streak photographs.
Wire density is measured from radius and assuming constant density.
Wire temperature is calculated from plasma radius and measured input energy using LANL Sesame EOS models.



Conclusions

High voltages calculated for wire breakdown in vacuum (compared to the Cornell expt. measurement) are indicative of not forming a low density corona outside the main wire core.

Similar results are observed in Mach 2 simulations (see poster GP066), suggesting need to implement better physics (e.g. EOS) not algorithms.

There is better agreement with tamped wire explosions (compared to the DeSilva expt. measurement). Suggests that modeling in the absence of coronal formation is reasonable.

Can we expect to model coronal formation of wire breakdown in vacuum with a fluid code?

yes......it is demonstrated in high current drive systems (see Z shot 293)
no......if it is a true flash (i.e. kinetic beam electrons).

Better EOS models and resolution may enhance the probability of formation even for the low current drives of the Cornell experiments.