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Arc Modeling

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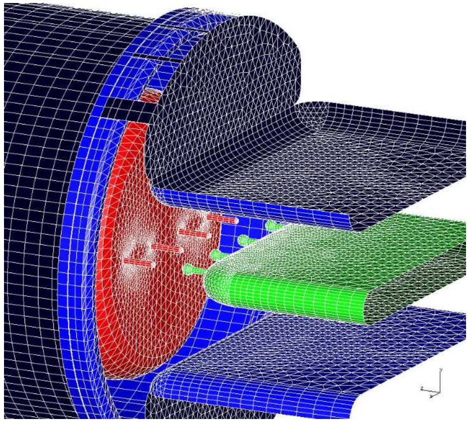
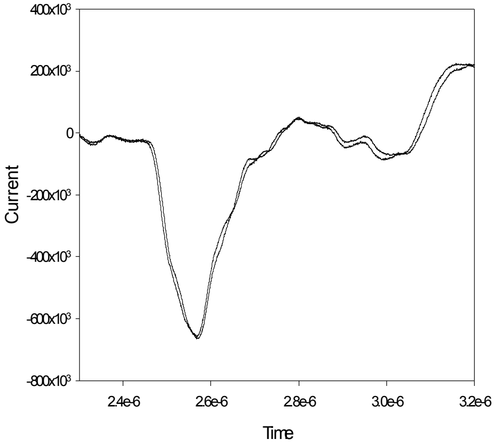
Outline

- Introduction
- Phases of electrical breakdown
- Boeing problem description
- 1D simulations
- Channel physics models
- 0D simulations
- Braginskii model
- Literature review
- Conclusions

Water Breakdown Switches

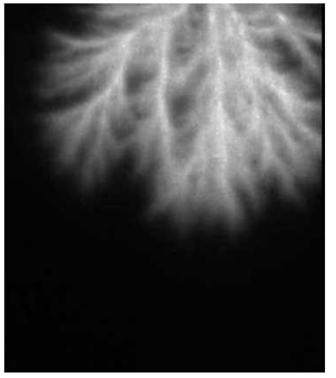
- Geometry

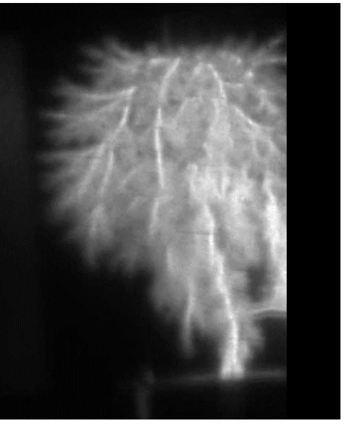




Phases of Breakdown

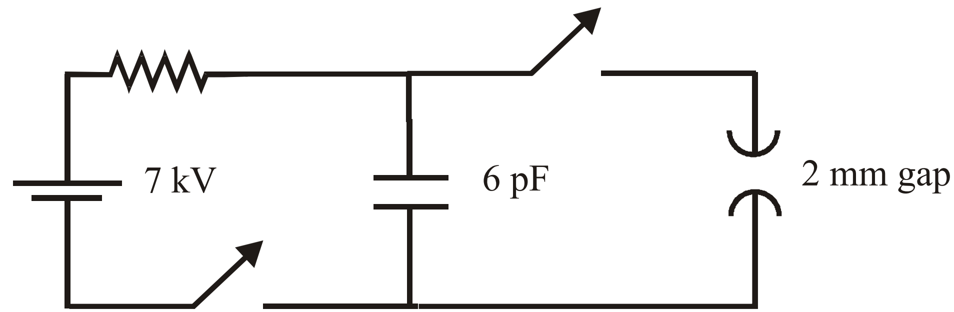
- Early time
  - Avalanche
  - Streamer
- Intermediate time
  - Thermalization
- Late time
  - Channel expansion
  - Channel pinch
  - Steady state arc

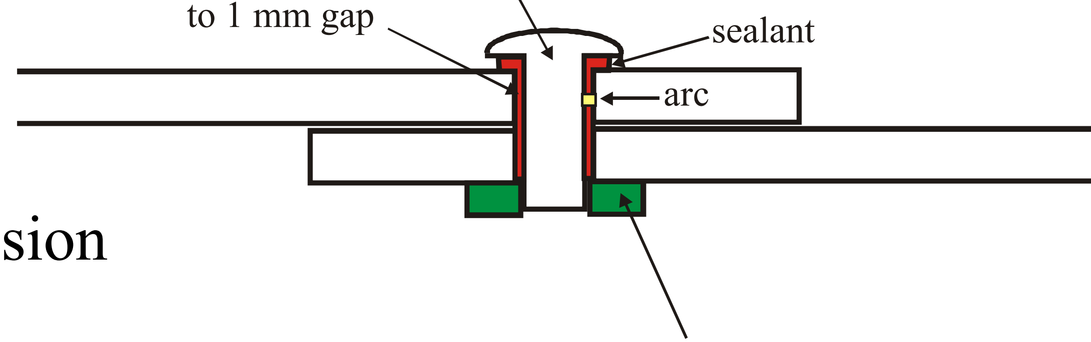




Two Problems

- Problem 1--Hydrocarbon ignition experiment





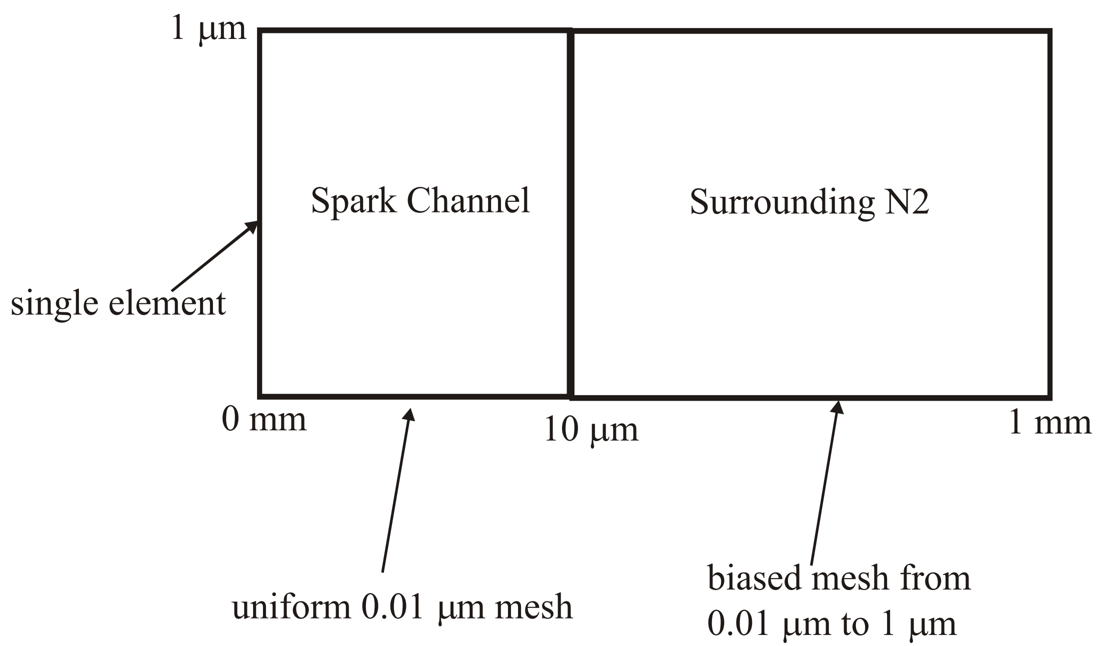
•Problem 2 – electrode erosion

Problem 1 Strategy

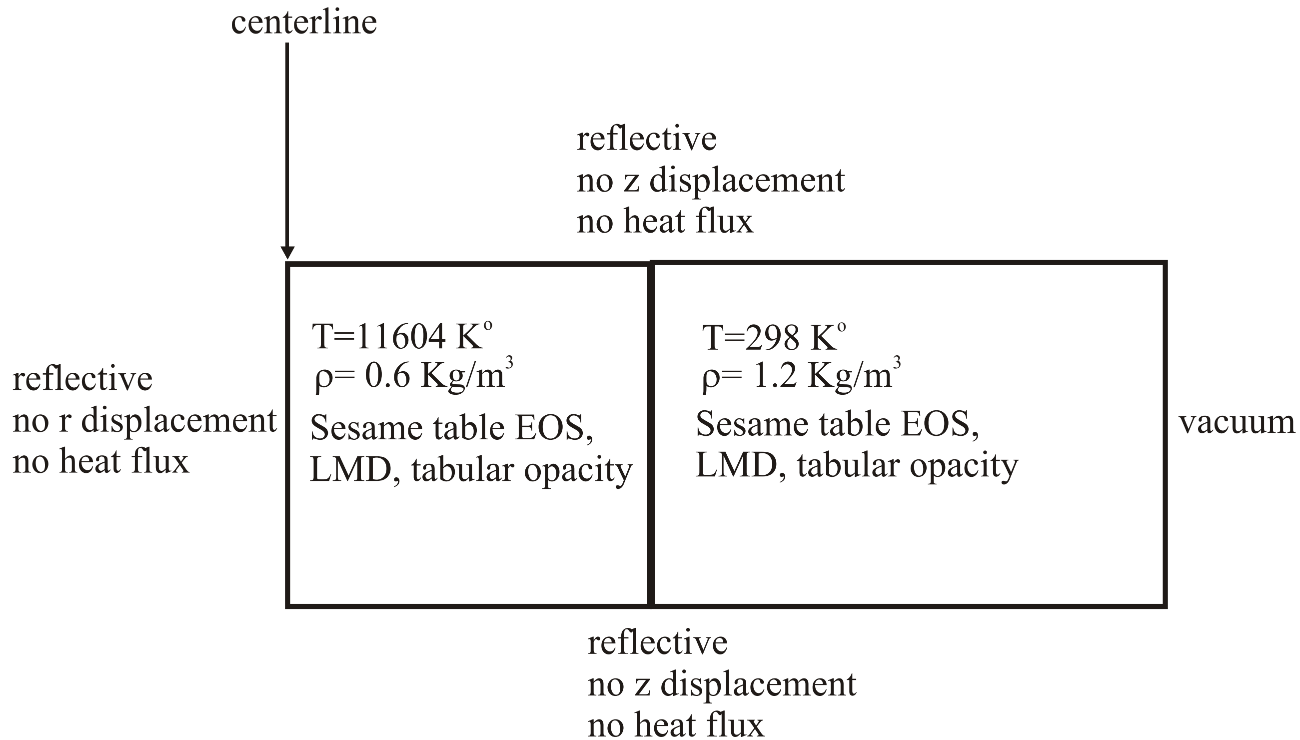
- Run 1d simulation to scope problem
- Extract minimal set of physics
- Incorporate physics into a 0d code
- See if 0d simulation matches 1d simulation

1D Simulations - Alegra

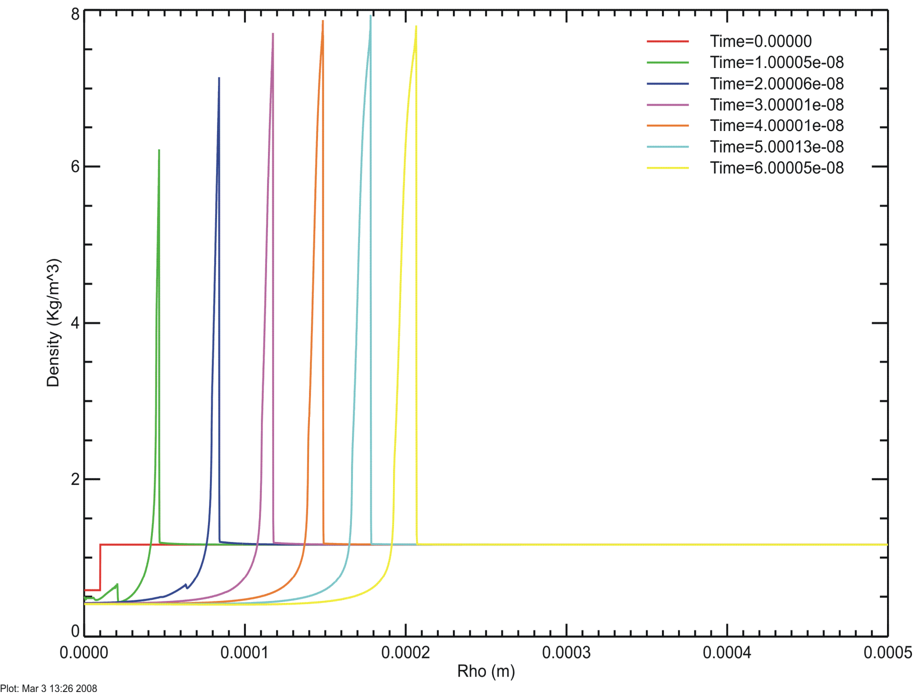
- Hydrodynamic Arbitrary Lagrangian-Eulerian code, with radiation, conduction, electromagnetics
- 2000 – 4000 elements, 200 hours run time (500 ns)

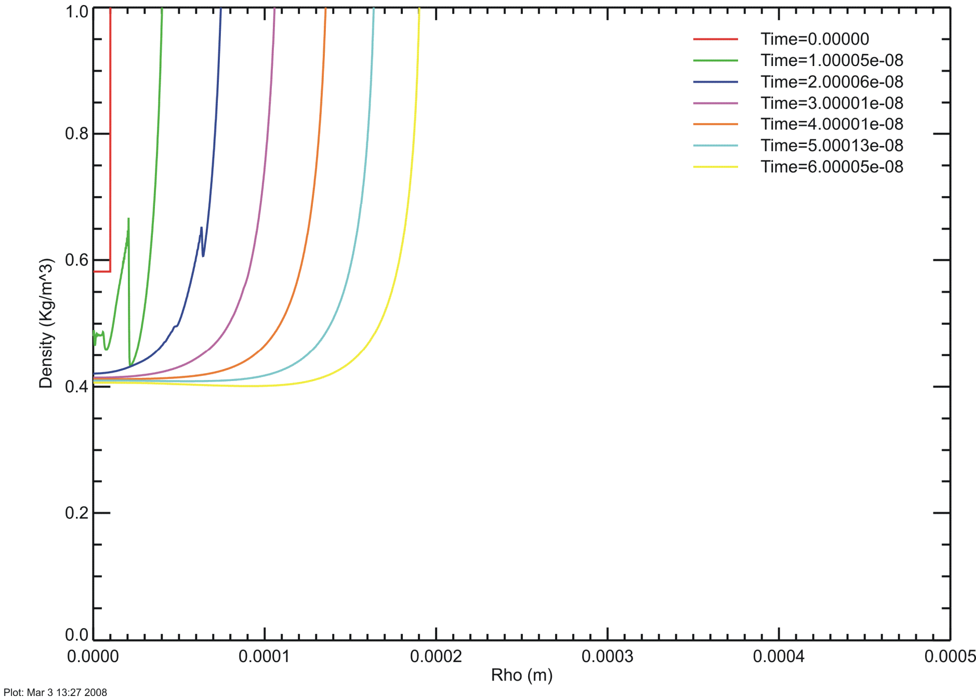


Alegra Simulation – N2



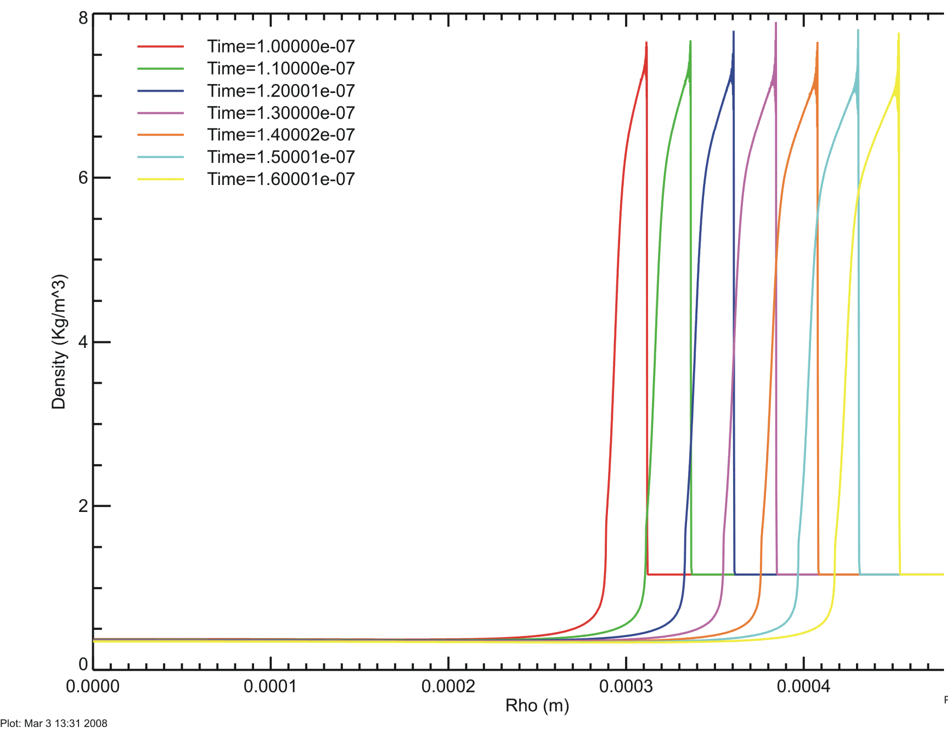
N2 Density 1.8 μs risetime 20KA



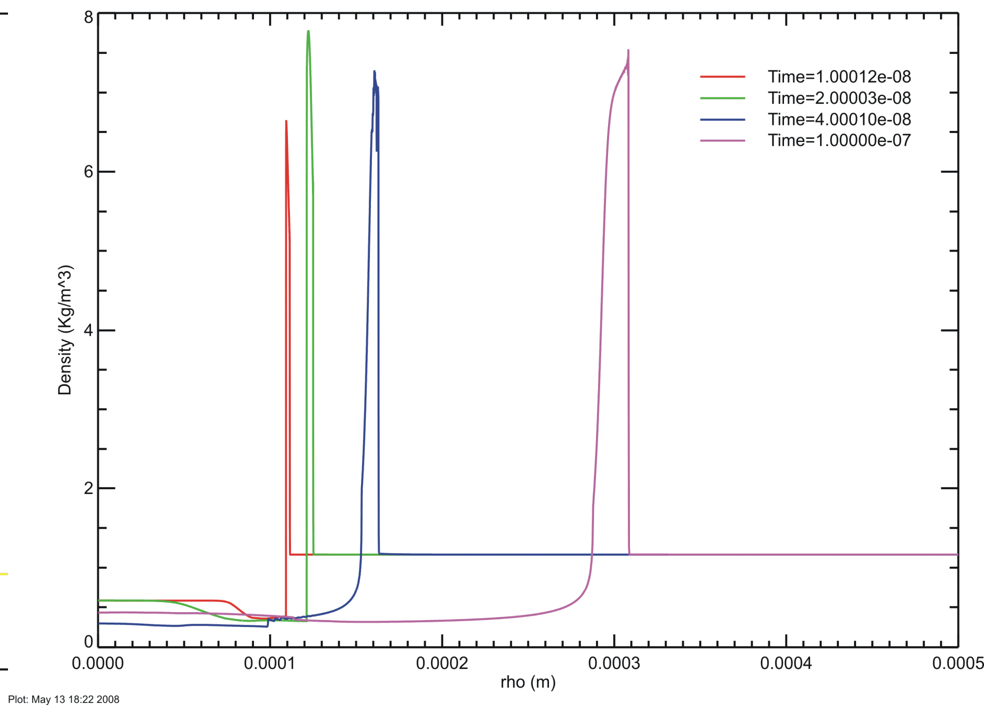


N2 Density

- Proportionally higher than water (30% versus 2%)
- Constant density, where water falls



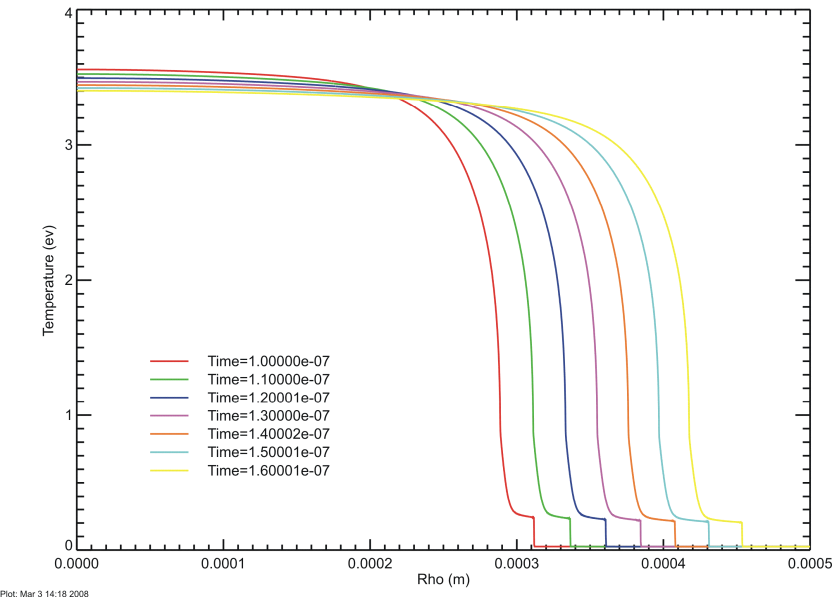
Initial radius = 10 μm

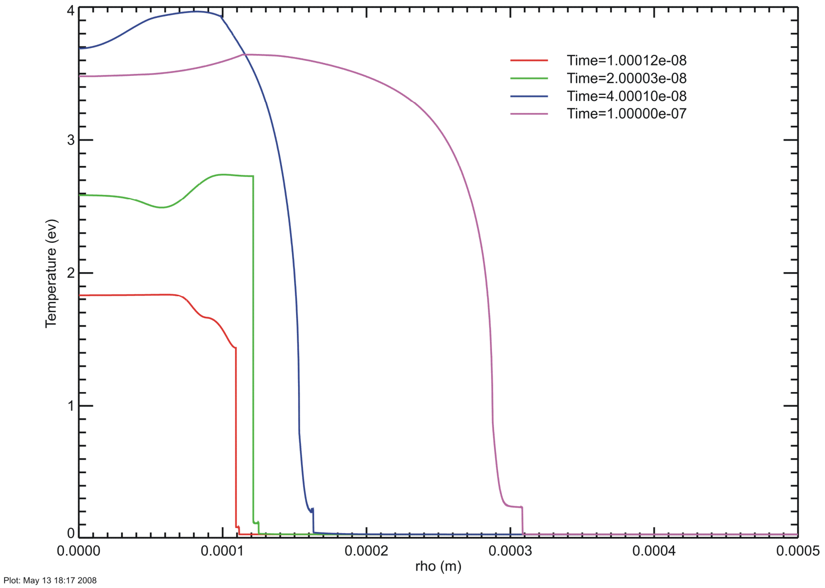


Initial radius = 100 μm

N2 Temperature

Lower than water (3 ev rather than 40 ev)



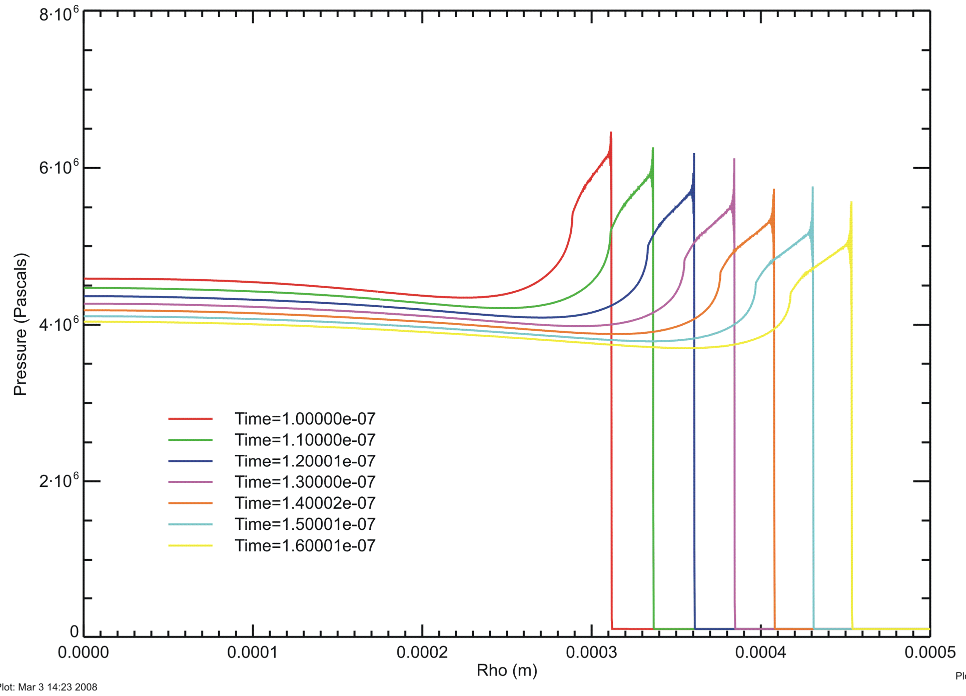


Initial radius = 10 μm

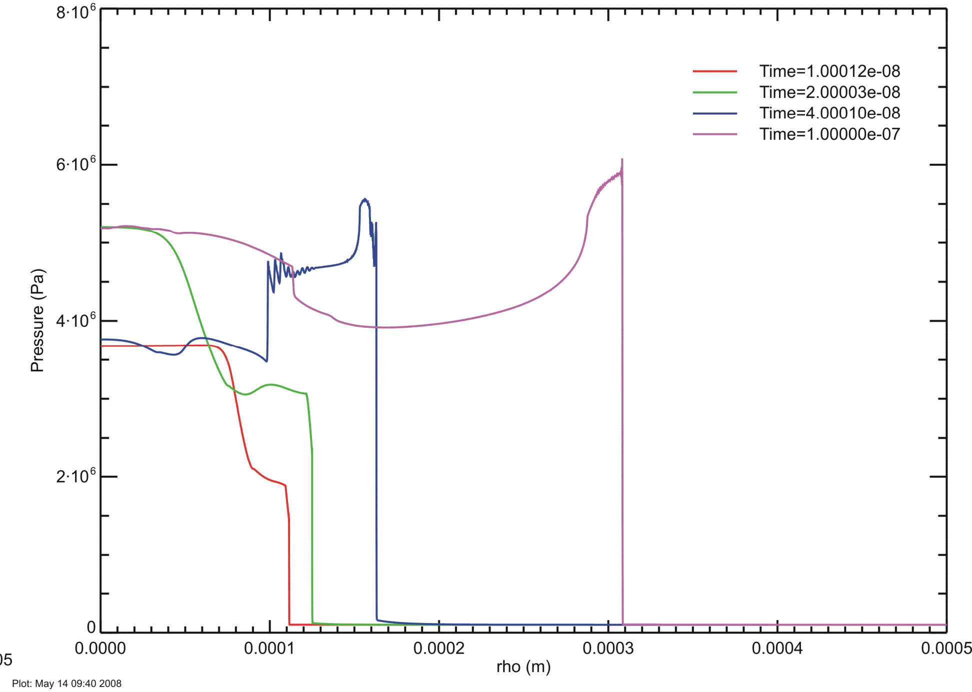
Initial radius = 100 μm

N2 Pressure

No evidence of magnetic pinch, rises at channel boundary



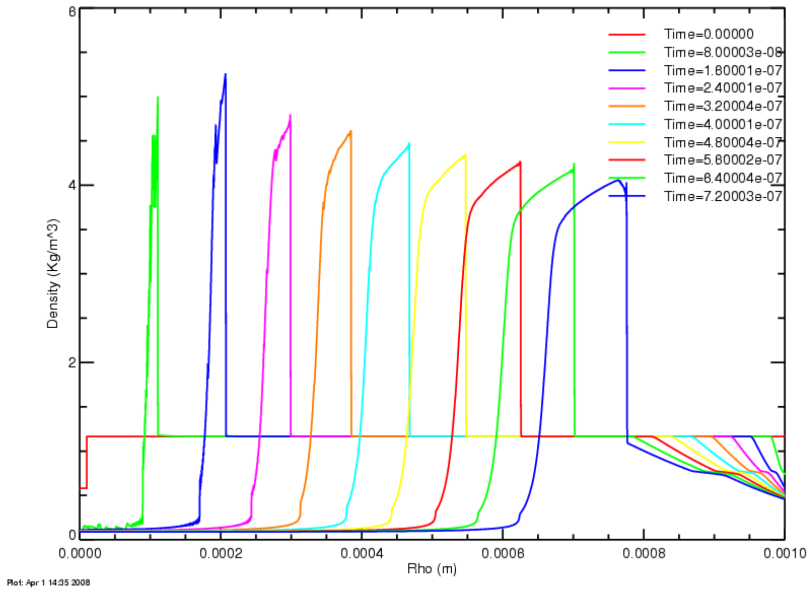
Initial radius = 10 μm

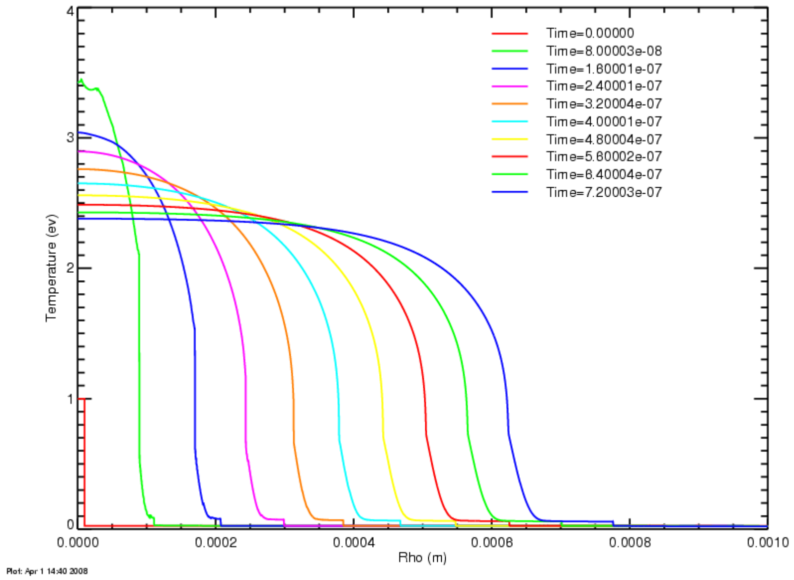


Initial radius = 100 μm

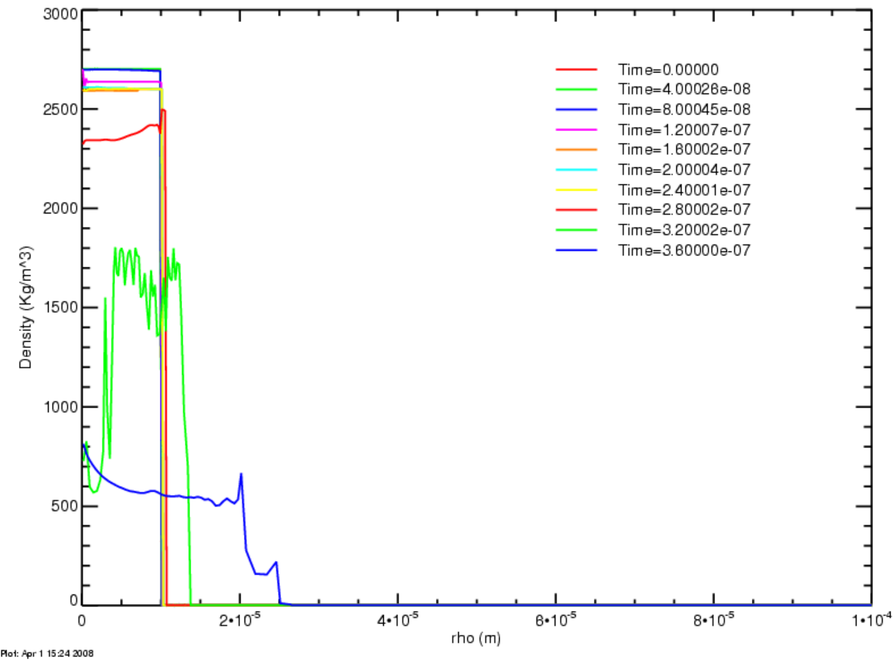
N2 40 μm risetime 10KA (At 720 ns, 500 Amps flow)

Looking if we can reach late time for Problem 2

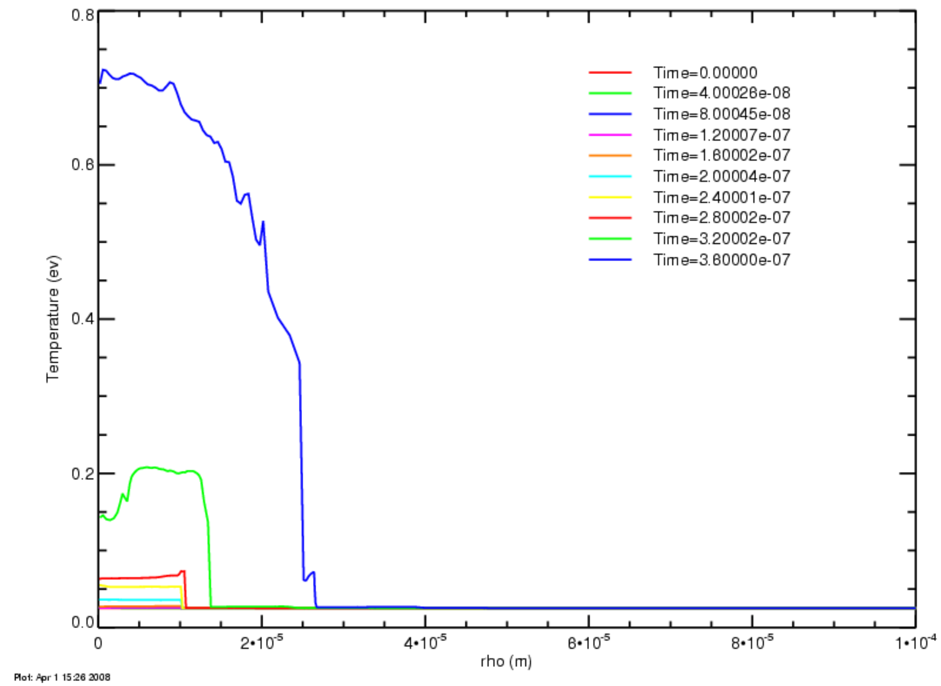




Al 40 μm risetime 10KA (At 380 ns, 270 Amps flow)



Density



Temperature

0D Equations

- Hydrodynamics

energy

$$\frac{\partial}{\partial t}\left(\rho\varepsilon+\frac{1}{2}\rho u^2\right)+\nabla\cdot\left[\rho\underline{u}\left(\varepsilon+p/\rho+\frac{1}{2}u^2\right)\right]=-q$$

$$q=\nabla\cdot\underline{S}+\rho_q\underline{u}\cdot\underline{E}+q_s \quad , \quad -q_s=\underline{J}\cdot\underline{E}$$

mass

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\left(\rho\underline{u}\right)=0$$

momentum

$$\rho\frac{\partial\underline{u}}{\partial t}+\rho\left(\underline{u}\cdot\nabla\right)\underline{u}=-\nabla p+\underline{F}$$

$$\underline{F}=\underline{J}\times\underline{B}+\rho_q\underline{E}$$

Channel

$$U=\int_0^a\rho\varepsilon 2\pi r dr\approx\rho\varepsilon A$$

$$Q_J=I^2/\left[\int_0^a\sigma 2\pi r dr\right]\approx I^2/\left(\sigma A\right)$$

$$Q_R=2\pi a S_r$$

$$A=\pi a^2$$

$$\frac{dU}{dt}+p\frac{dA}{dt}=Q_J$$

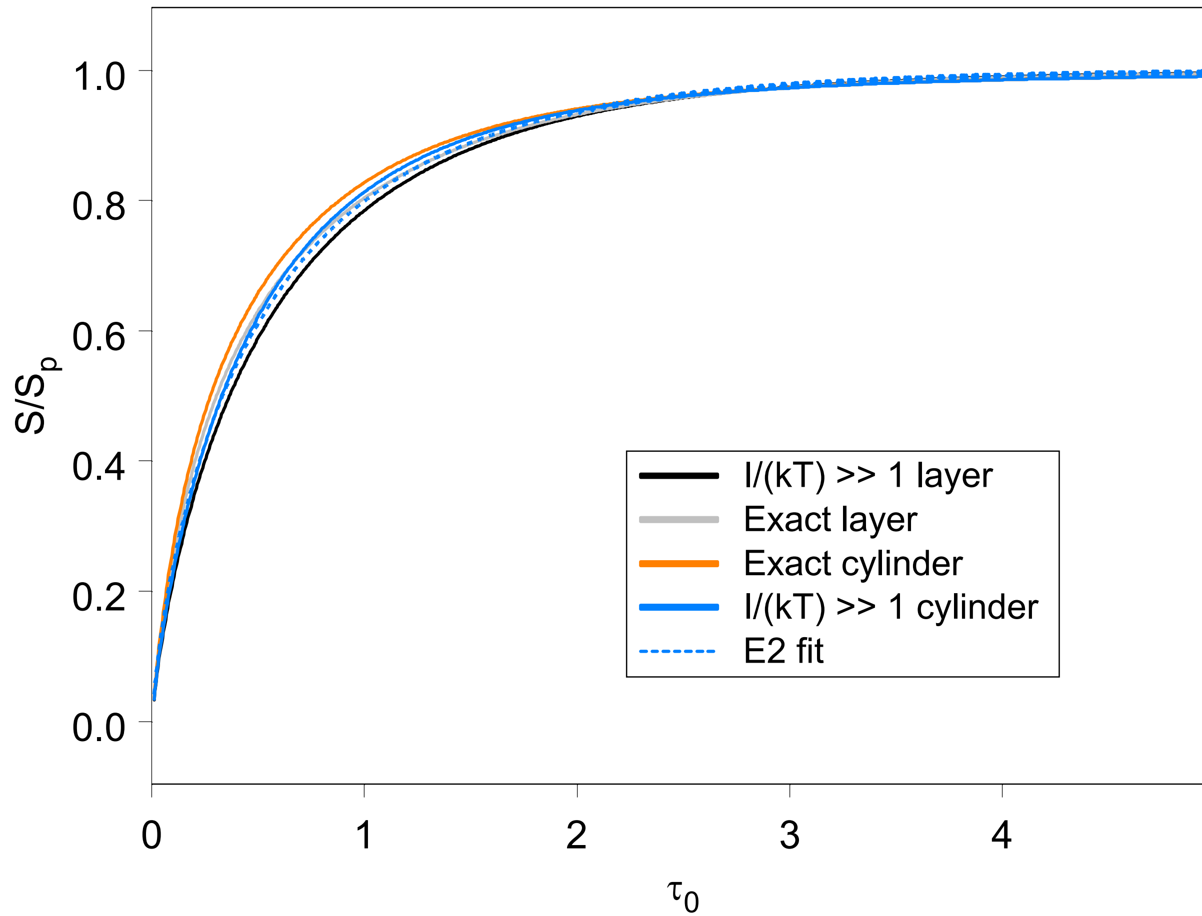
$$\left(\varepsilon+p/\rho\right)\frac{dM}{dt}=Q_R$$

$$p=K_p\rho_0\left(\frac{da}{dt}\right)^2$$

Radiation transitions between black body and transparent

$$Q_r = 2\pi a \frac{S}{S_p} S_p$$

$$S_p = \sigma_{SB} T^4$$



$$Q_{trans} = \pi a^2 2 \times 10^{-46} \frac{\overline{m}^5 n^2}{\sqrt{T}}$$

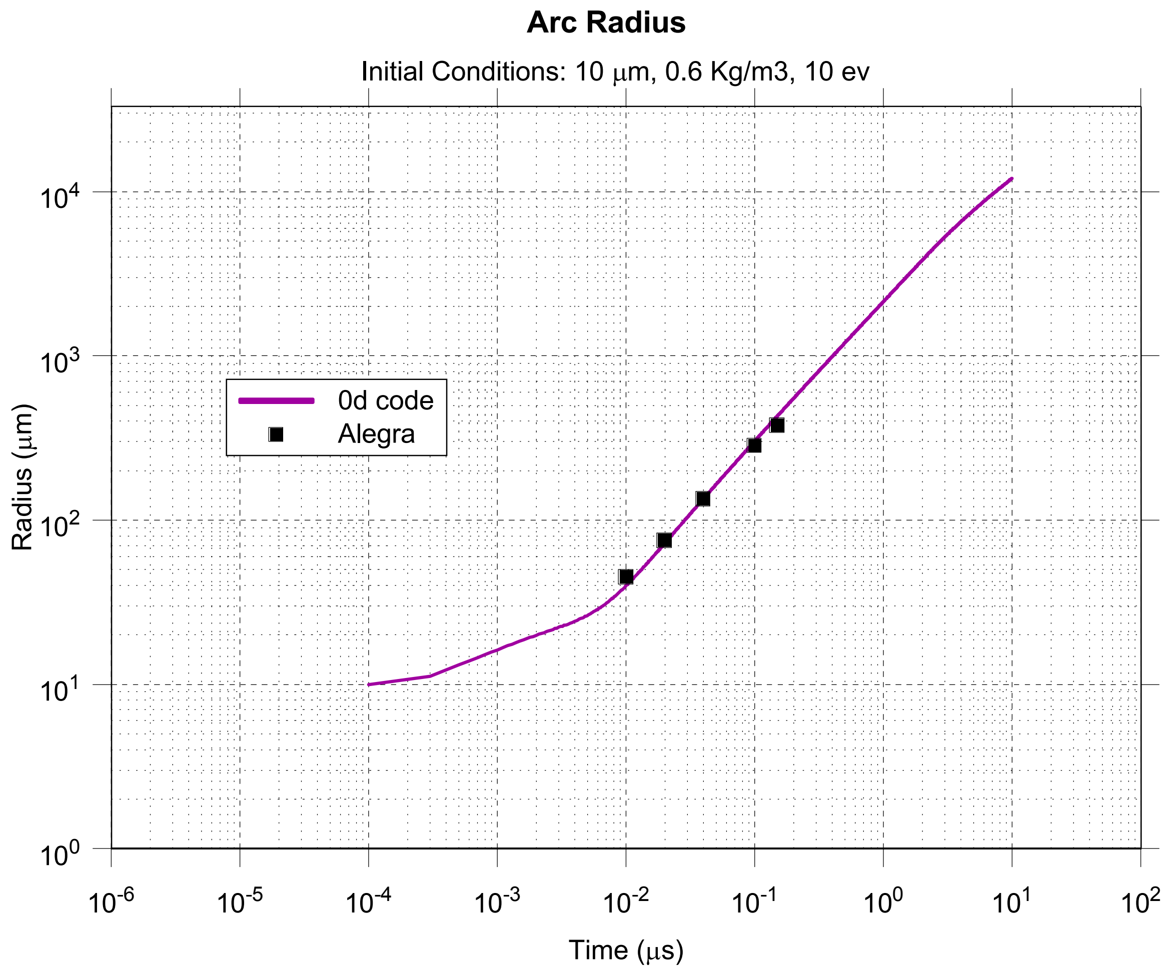
Channel Equations

- Used ideal gas law for equation of state for an average atom of nitrogen and oxygen.

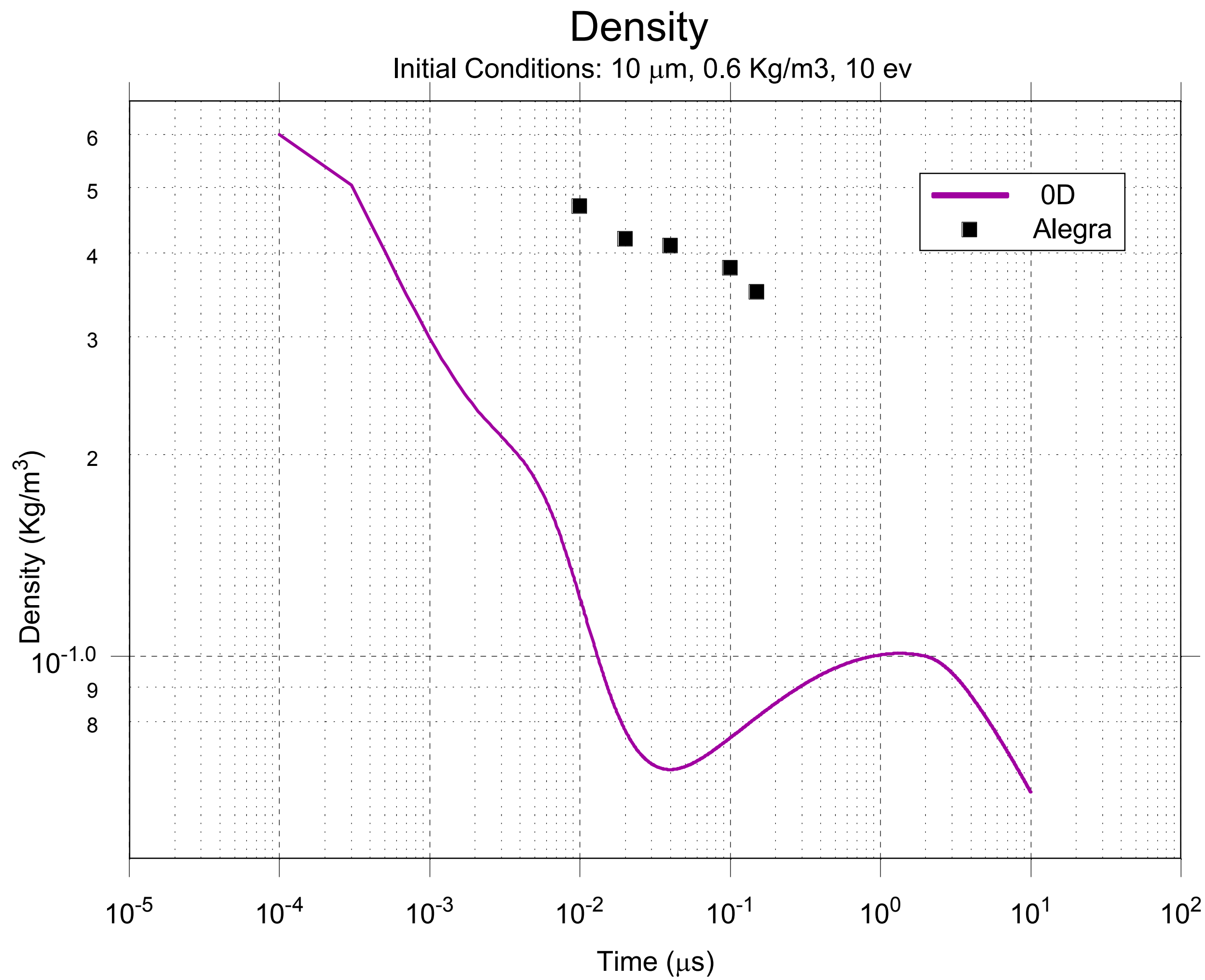
$$p = \left(1+\overline{m}\right)\left(\rho / m_a\right)kT = \left(\gamma - 1\right)\varepsilon\rho$$

- Can find conductivity using Spitzer's formula
  - Need ionization level $\overline{m}$
    - Based on knowledge of average ionization levels
  - Need Coulomb Logarithm
    - Used either Born approximation or WKB method to approximate scattering from a shielded coulomb potential
- Conductivity is relatively constant
  - $\sigma = 3 - 7 \times 10^4\, S/m$ T=1-3 ev and density = 10% to 100% of ambient
- Details are in report

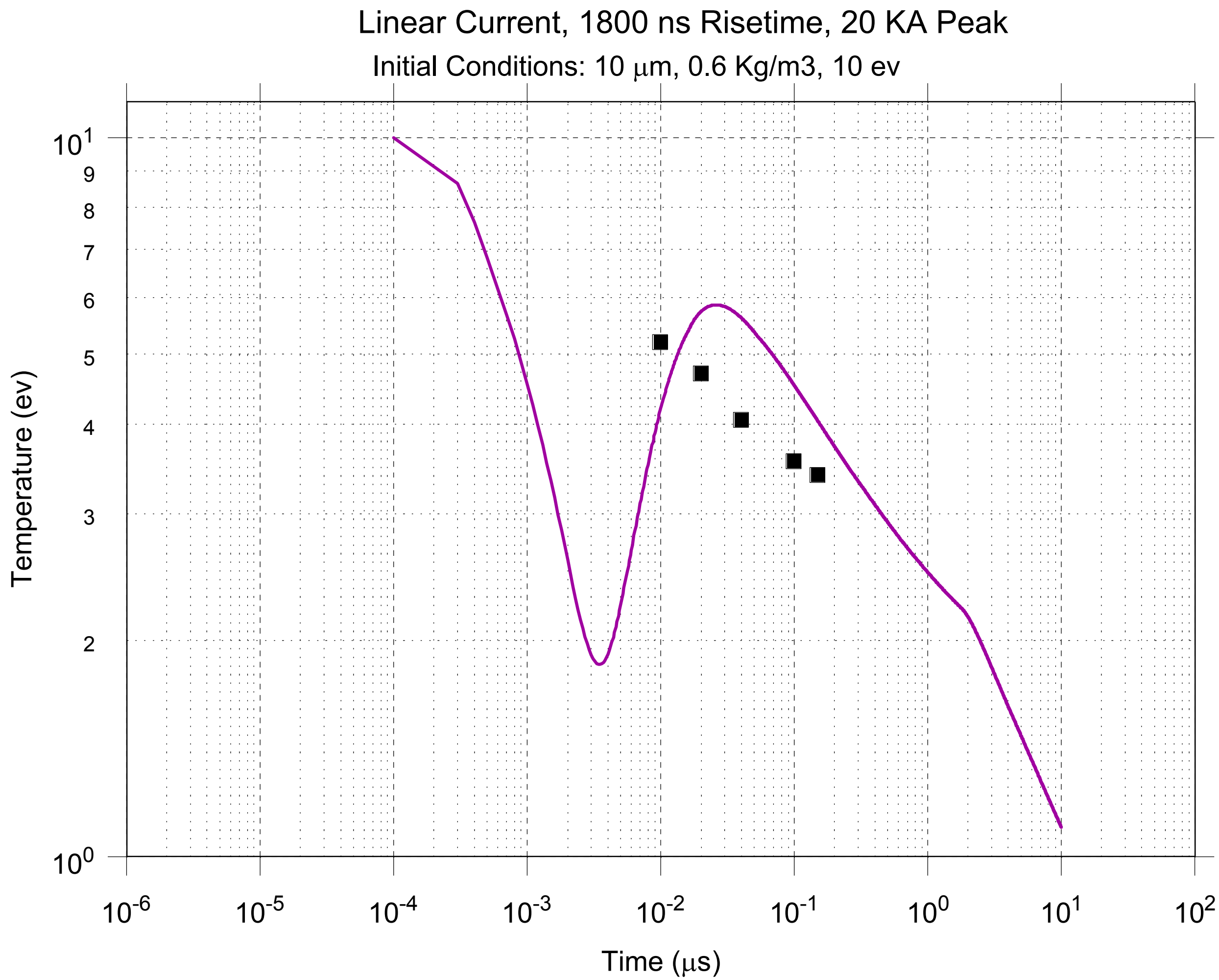
Radius is always predicted well



Other Quantities are Poorly Predicted -- Density

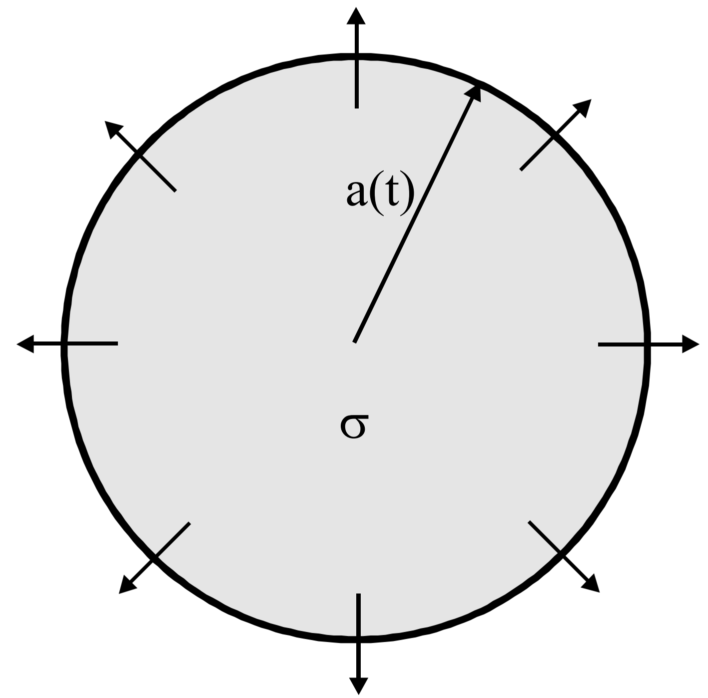


Temperature



Braginskii-Martin Expansion Model

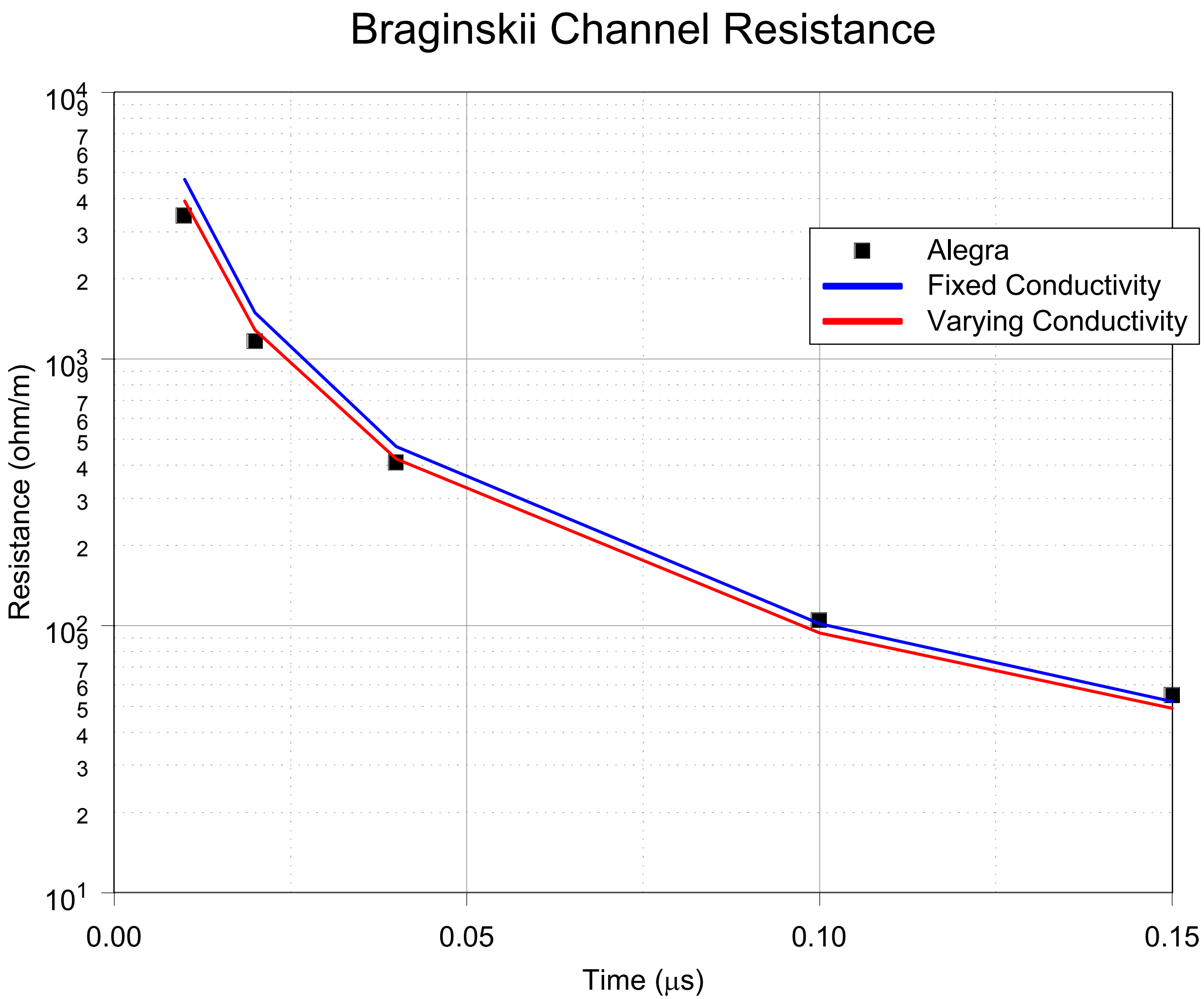
- Use fact that radial expansion is stable and conductivity (T and density) approximately constant



$$R = \ell / \left(\pi a^2 \sigma \right)$$

$$a^2(t) = \left(\frac{4}{\pi^2 \rho_0 \xi \sigma} \right)^{1/3} \int_0^t I^{2/3}(\tau)\, d\tau$$

Resistive Fall



Problem 2 Literature Review

- Problem 2 is in steady state
  - Joule heating balanced by convection and radiation losses
- Welding Literature – Free-burning arc
- Low current (< 30 A)
  - Driven by natural convection
  - Not of interest
- High current (> 30 A)
  - Magnetic pinch near cathode leads to pressure gradient
  - Radiation dominates thermal conduction
  - Is of interest

High Current Arc

- Four conservation equations (steady state)
  - Mass continuity
  - Axial momentum
  - Radial momentum
  - Energy
- Current Continuity and Magnetic Field
- Assumptions – LTE, rotational symmetry, laminar flow
- Simplifications
  - Ramakrishnan – integration of energy and axial momentum
  - Lowke – Analytical expressions for E field and radius
  - Hsu – numerical solution with assumed cathode and anode conditions

Electrodes

- Menhart – effect of anode vapor on arc
  - Radiation and energy balance
- Lago et.al. -- anode and arc affect each other
  - Conservation of energy and current continuity
  - Calculates anode melting without magnetic stirring

Conclusions

- Examined physics of later time air channel expansion
- 1D runs showed
  - Insensitivity to starting conditions
  - Constant channel temperature (2 - 5 ev) and density (0.2 – 0.5 Kg/m**3)
  - Extremely slow
- 0D runs
  - Good prediction of radius
  - Poor prediction of density, pressure and temperature
- Braginskii model
  - Good predictor of radius and resistive fall
  - Simpler to implement
- Literature summary for problem 2