SAND2021-13866C

Sandia National Laboratories

Pulsed power method for determining the electrical conductivities of metals from ambient to HED conditions



Andrew J Porwitzky, Kyle Cochrane, Brian Stoltzfus

APS Division of Plasma Physics Meeting, 10 Nov 2021

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

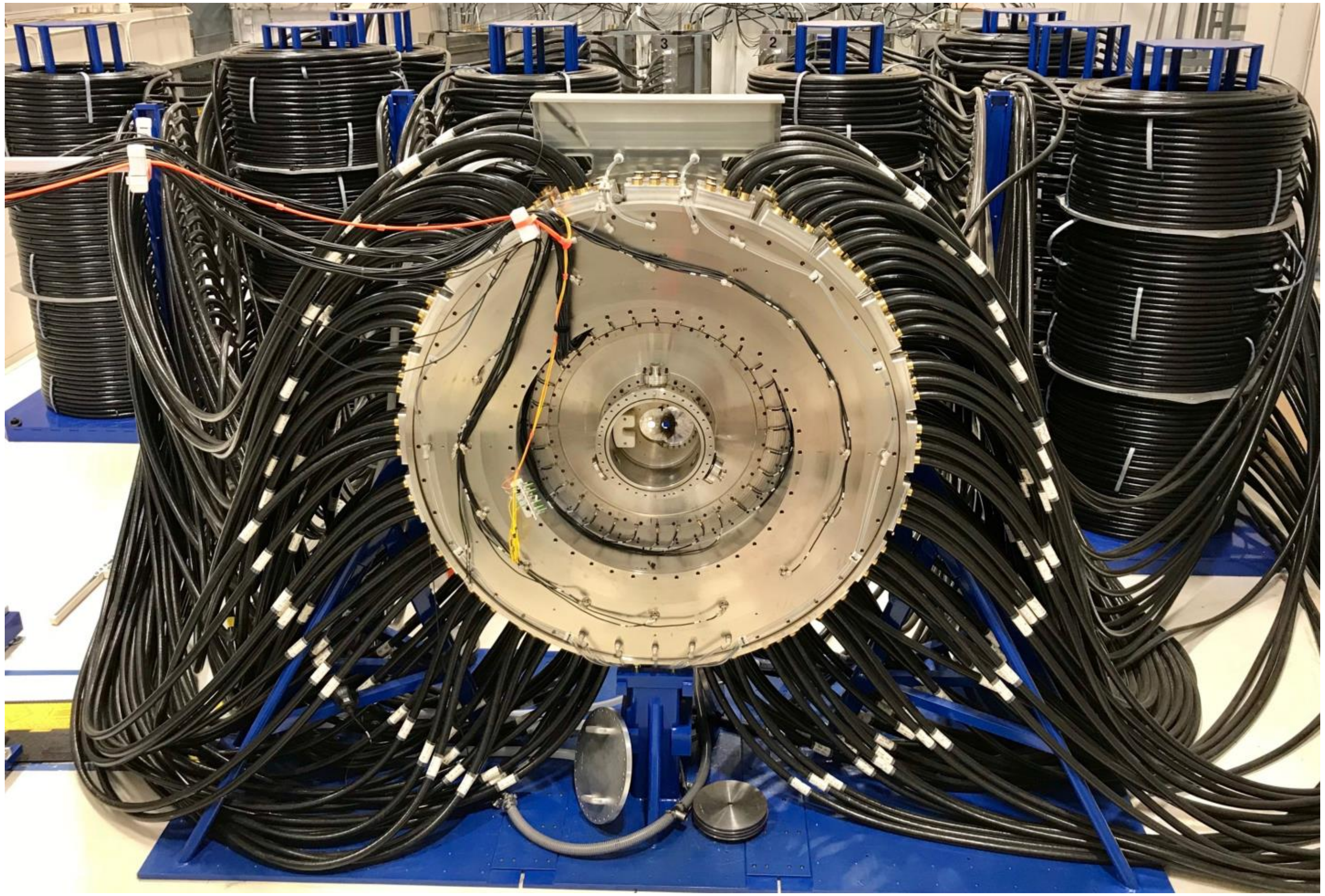
Motivation

- Magnetic Direct Drive (MDD) uses magnetic fields to compress materials to high energy density (HED) states.
- MDD is used in inertial confinement fusion (ICF) and dynamic materials properties (DMP) experiments on the Z Pulse Power Facility.
- Accurate modeling of pulsed power HED experiments requires accurate equation of state (EOS) models for all materials, as well as accurate electrical conductivity (ECON) models for any material carrying MA of current.
- Determining ECON at HED conditions is difficult given the transient nature of these dynamic states.
- Diamond anvil cell (DAC) determination of ECON at elevated pressures is often not done at elevated temperatures consistent with HED experiments.
- **We present refinement of a method previously used on the Z Machine for determining ECON in-situ at HED conditions that has proven successful on the 2 MA Thor pulsed power driver.**

"Determining the electrical conductivity of metals using the 2 MA Thor pulsed power driver", Andrew Porwitzky, Kyle R. Cochrane, Brian Stoltzfus, **Rev. Sci. Instrum., 92, 053551, 2021**.

Thor Pulsed Power Driver

- Designed for material science experiments
- 2 MA peak load current
- Sample widths of a few millimeters
- High rep rate (2 experiments/day, minimal staff)
- Low cost (< $10k / experiment)
- Available for academic collaboration with Sandia colleagues
- Thor is capable of accelerating planar fliers 100s of microns thick to > 1 km/s
- If the flyers are thin enough (< 200 microns) then Joule heating can completely vaporize them
- PDV system allows for high fidelity flyer free surface velocity measurements



Methodology

1) 1D MHD modeling is used to determine the drive magnetic field using an optimization algorithm, “thick” experimental velocity, and a known material EOS and ECON.

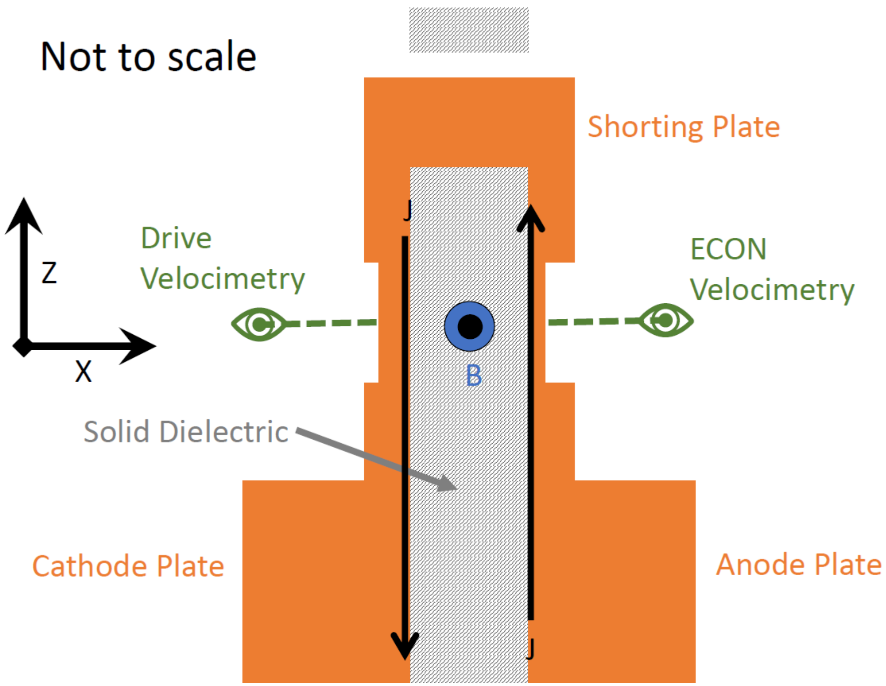
2) The drive magnetic field is applied to a 1D MHD simulation of a flyer thin enough to completely vaporize, and an optimization algorithm finds a local ECON multiplier using the “thin” experimental velocity.

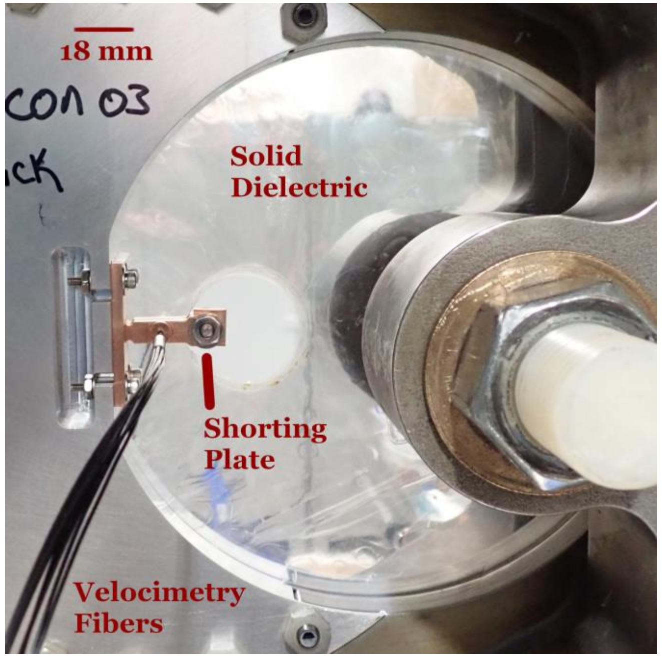
3) The modified ECON is used to re-optimize for the drive magnetic field.

4) Iterative process continues until neither the drive magnetic field nor ECON multiplier changes.

5) The locally modified ECON is used as a guide to adjust the Lee-More-Desjarlais model isotherms and construct a new consistent ECON. Confirmatory simulations are run.

How do we demonstrate that this method is sensitive to electrical conductivity changes and is convergent?



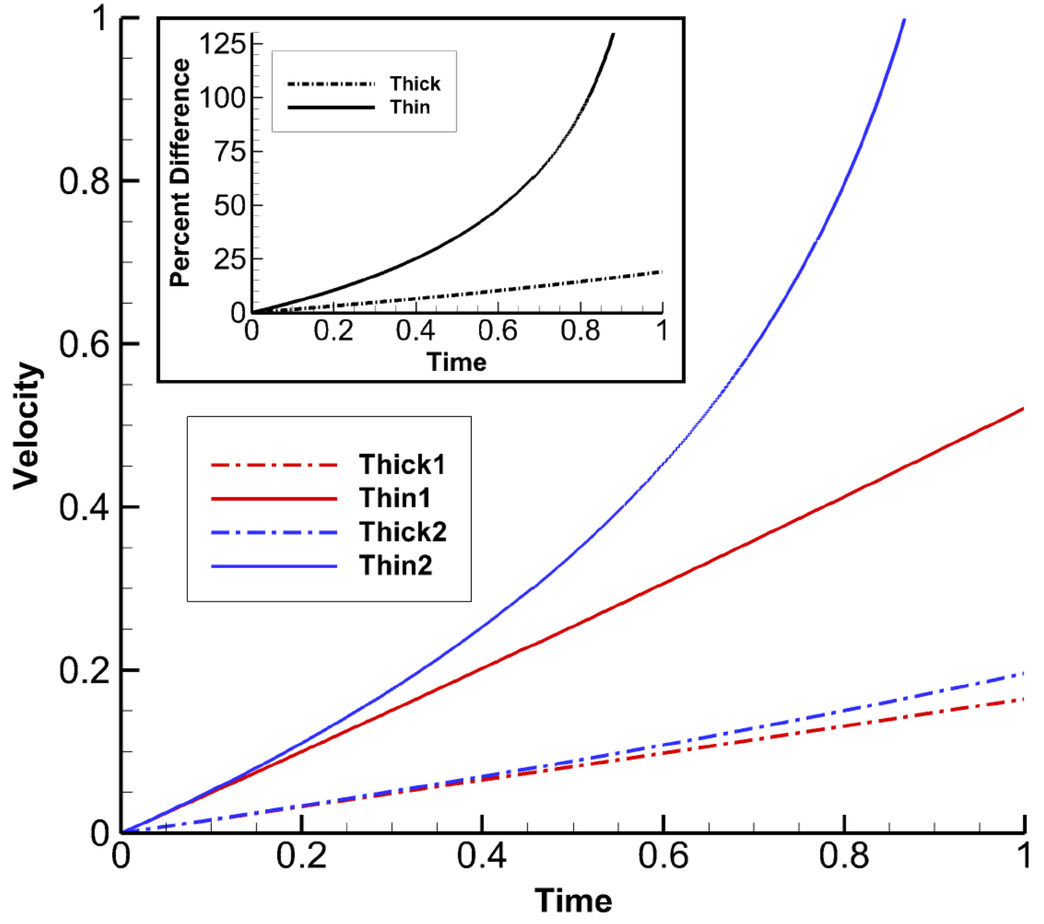


Simplified model provides insight

- Our analysis uses resistive MHD with realistic material models, but a simplified model can build intuition.
- Joule heating vaporizes flyer material, while JxB forces accelerate the remaining flyer mass.
- To zero order, this process resembles rocket propulsion.
- Tsiolkovsky's 1903 "rocket equation" can be modified to represent our problem.
  - rocket mass → time varying thickness of the flyer
  - propulsion force → force from magnetic pressure
  - propellent mass flow rate → vaporization rate of the flyer, $m_R \sim 1/\sigma$
  - assume constant σ and constant force from magnetic drive

$$v(t) = v_c - \frac{F}{m_R}\ln(m_o - m_R t)$$

- Define two sets of flyers:
  - Pair 1: $m_R = 1$; $\sigma = \sigma_o$
  - Pair 2: $m_R = 10$; $\sigma = 0.1\sigma_o$

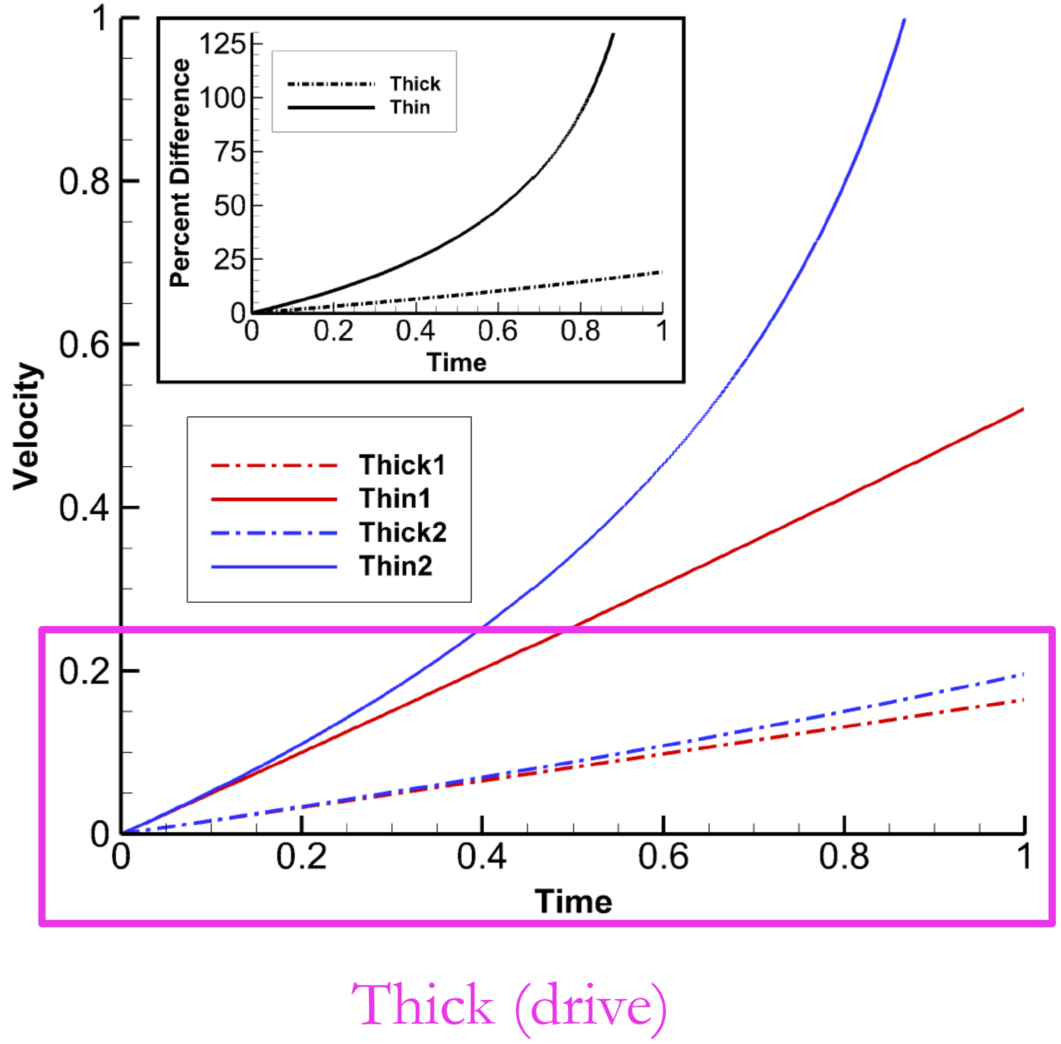


Simplified model provides insight

- Our analysis uses resistive MHD with realistic material models, but a simplified model can build intuition.
- Joule heating vaporizes flyer material, while JxB forces accelerate the remaining flyer mass.
- To zero order, this process resembles rocket propulsion.
- Tsiolkovsky's 1903 "rocket equation" can be modified to represent our problem.
  - rocket mass → time varying thickness of the flyer
  - propulsion force → force from magnetic pressure
  - propellent mass flow rate → vaporization rate of the flyer, $m_R \sim 1/\sigma$
  - assume constant σ and constant force from magnetic drive

$$v(t) = v_c - \frac{F}{m_R}\ln(m_o - m_R t)$$

- Define two sets of flyers:
  - Pair 1: $m_R = 1$; $\sigma = \sigma_o$
  - Pair 2: $m_R = 10$; $\sigma = 0.1\sigma_o$

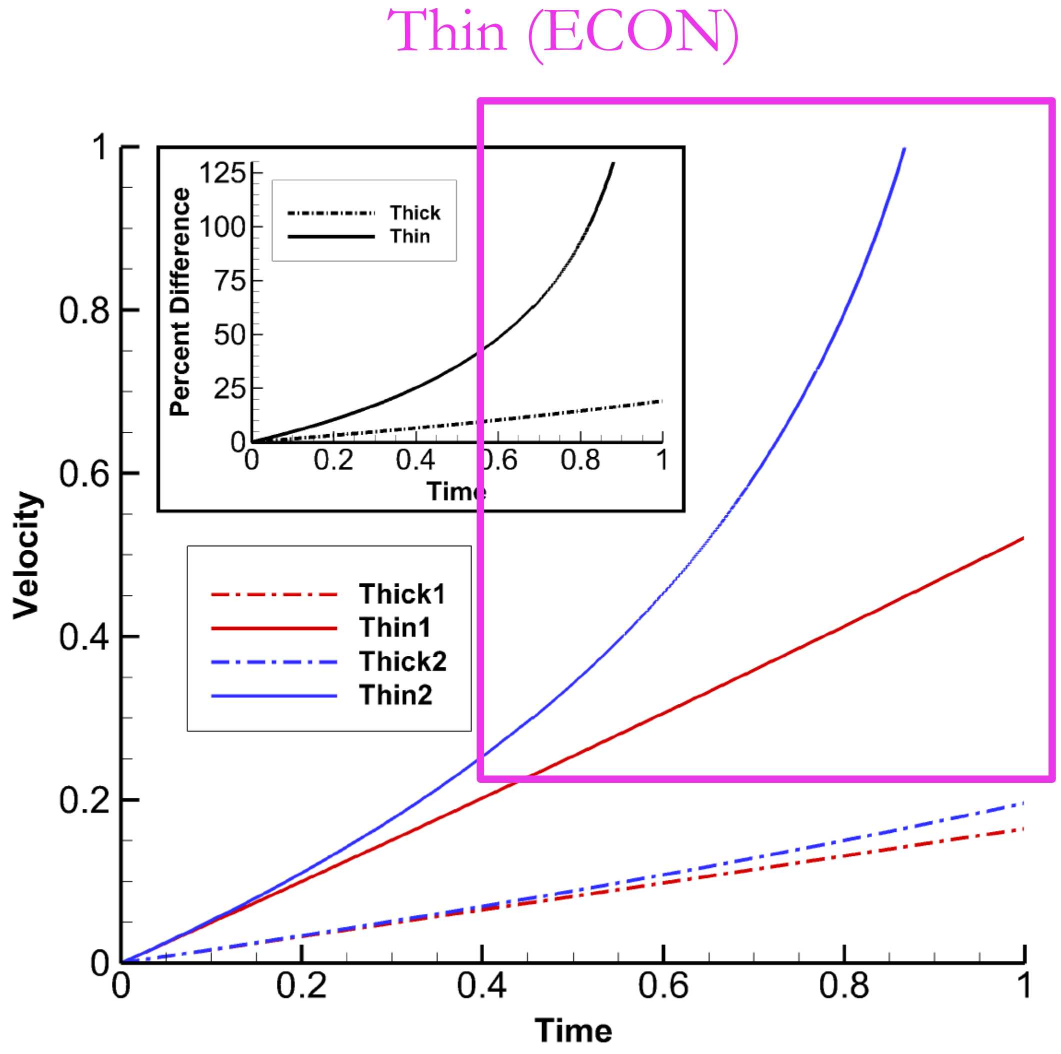


Simplified model provides insight

- Our analysis uses resistive MHD with realistic material models, but a simplified model can build intuition.
- Joule heating vaporizes flyer material, while JxB forces accelerate the remaining flyer mass.
- To zero order, this process resembles rocket propulsion.
- Tsiolkovsky's 1903 "rocket equation" can be modified to represent our problem.
  - rocket mass → time varying thickness of the flyer
  - propulsion force → force from magnetic pressure
  - propellent mass flow rate → vaporization rate of the flyer, $m_R \sim 1/\sigma$
  - assume constant σ and constant force from magnetic drive

$$v(t) = v_c - \frac{F}{m_R}\ln(m_o - m_R t)$$

- Define two sets of flyers:
  - Pair 1: $m_R = 1$; $\sigma = \sigma_o$
  - Pair 2: $m_R = 10$; $\sigma = 0.1\sigma_o$

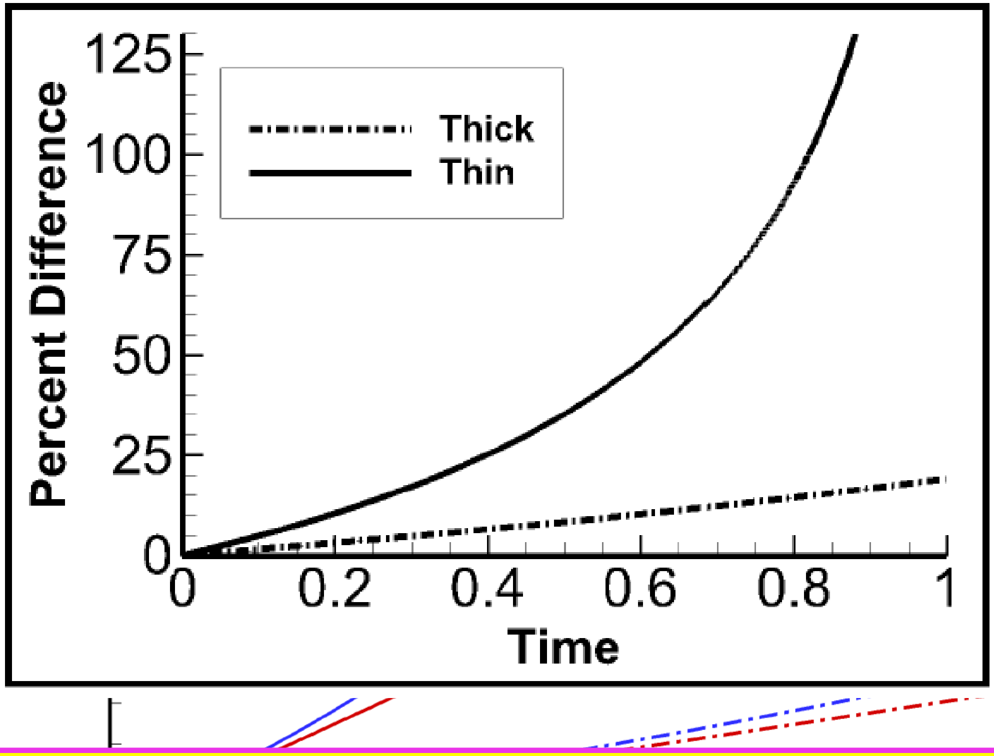


Simplified model provides insight

- Our analysis uses resistive MHD with realistic material models, but a simplified model can build intuition.
- Joule heating vaporizes flyer material, while JxB forces accelerate the remaining flyer mass.
- To zero order, this process resembles rocket propulsion.
- Tsiolkovsky's 1903 "rocket equation" can be modified to represent our problem.
  - rocket mass → time varying thickness of the flyer
  - propulsion force → force from magnetic pressure
  - propellent mass flow rate → vaporization rate of the flyer, $m_R \sim 1/\sigma$
  - assume constant σ and constant force from magnetic drive

$$v(t) = v_c - \frac{F}{m_R}\ln(m_o - m_R t)$$

- Define two sets of flyers:
  - Pair 1: $m_R = 1$; $\sigma = \sigma_o$
  - Pair 2: $m_R = 10$; $\sigma = 0.1\sigma_o$



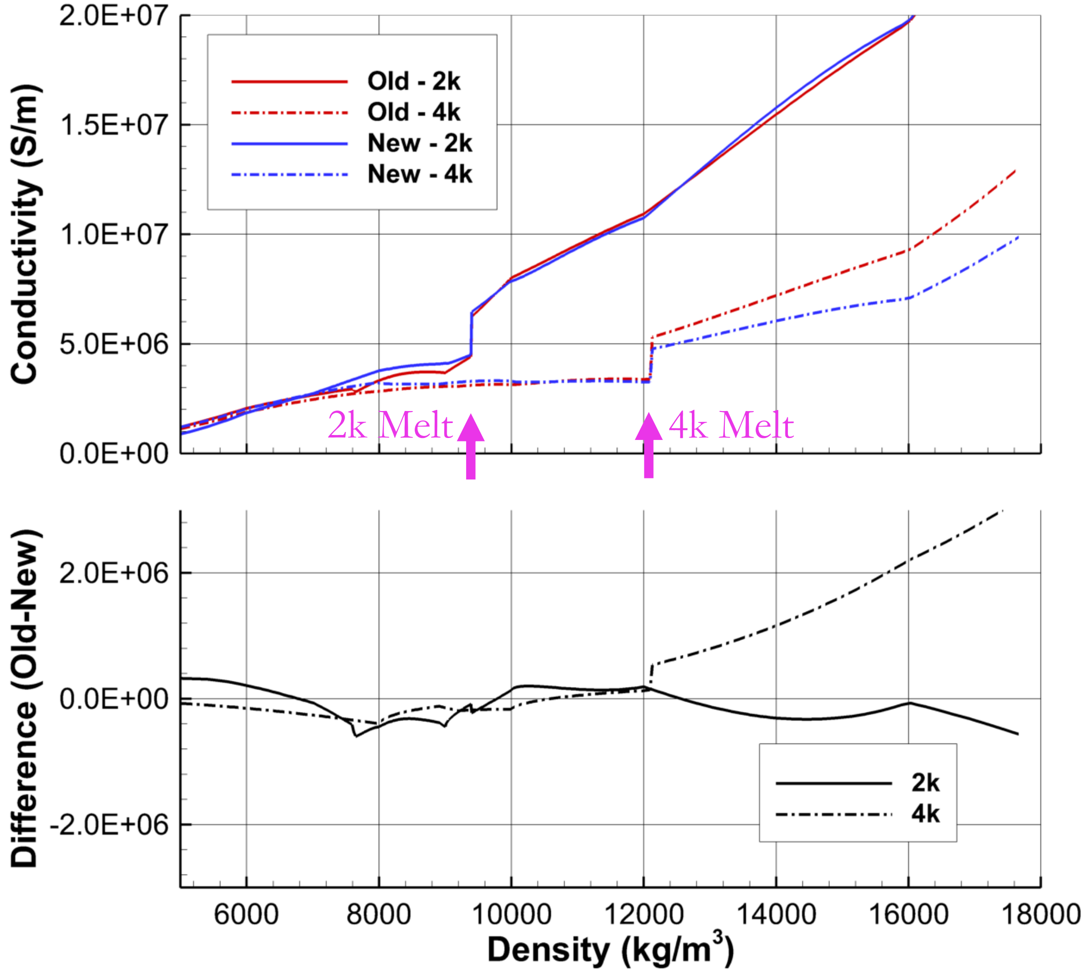
We can determine stable drive magnetic fields from the thick flyers, and infer ECON from the very sensitive thin flyers.

Copper results

- 3 experiments conducted; 1 tuning, 2 tests
- Different current profiles used to test different loading paths
- Prior ("Old") model predicted flyer vaporization earlier than experiment
- Revised ("New") model improves agreement for Thor test experiments *and* existing ICF load current velocimetry experiments
- Primary modifications involved the high temperature (2000 & 4000 K) melt transitions
- The electrical conductivity of the elevated temperature melt transition is not readily accessible to conventional techniques
- **Revised model maintains agreement with existing experimental data used to calibrate the prior model**

Magnitude of modifications indicate this method has order 1% sensitivity to electrical conductivity

Expt.	Thick side (μm)	Thin side (μm)
A	587	192
B	597	256
C	593	173



Conclusion

- The 2 MA Thor facility can be used to infer the electrical conductivity of metals at HED conditions.
- We demonstrated a simple model that explains how vaporizing flyers are highly sensitive to small changes to electrical conductivity, while thicker flyers are insensitive to the same order of changes.
- A retuned Lee-More-Desjarlais electrical conductivity model for copper was developed that preserves agreement with existing experimental data, while improving agreement for a subset of prior HED experiments on Thor and the Z Machine.
- Ongoing work is applying this technique to other metals and alloys.
- Future work will explore advanced statistical techniques and tools for automated construction of electrical conductivity models.

Thank you for your time!

ajporwi@sandia.gov

More Details

"Determining the electrical conductivity of metals using the 2 MA Thor pulsed power driver", Andrew Porwitzky, Kyle R. Cochrane, Brian Stoltzfus, **Rev. Sci. Instrum., 92, 053551, 2021**.