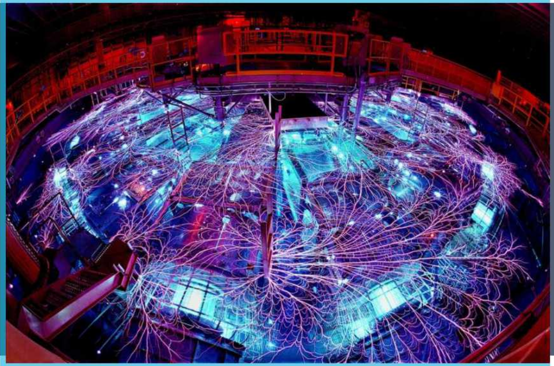
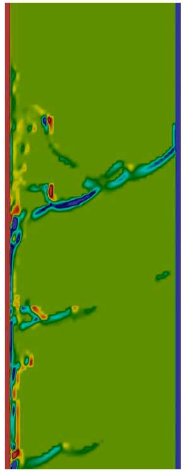
SAND2018-12519C

Power-Flow Modeling using PERSEUS Extended-MHD Simulation Code





PRESENTED BY

Nathaniel D. Hamlin, Charles E. Seyler

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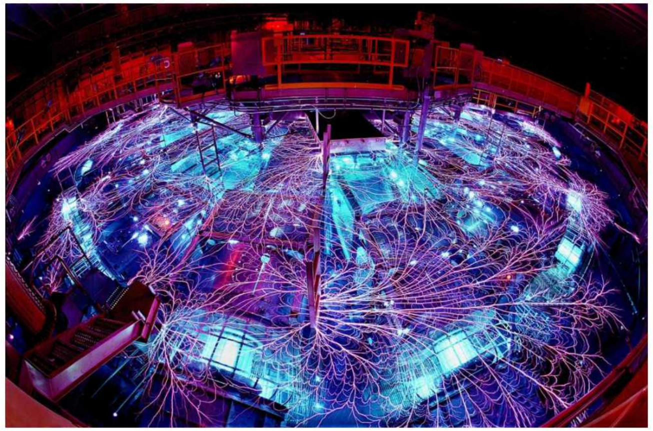
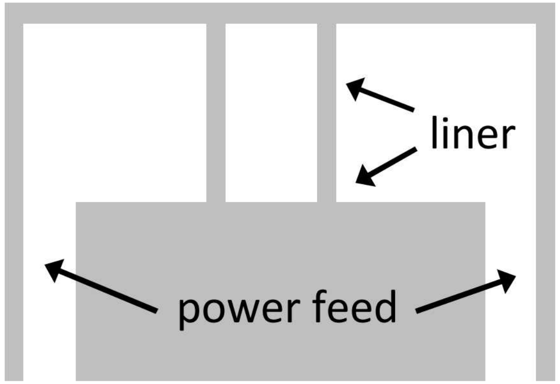
Motivation and outline

Modeling power-flow with high fidelity is of utmost importance for improving the performance of experiments on present and future pulsed power facilities.



- Extended MHD equations - Hall MHD
  - *Need to go beyond resistive MHD.*
- Transmission lines: Hall MHD simulations show complex behavior
- MagLIF: current coupling from feed to liner
- Future direction: Incorporation of non-quasi-neutral, space charge effects

MagLIF



Extended MHD equations add Hall physics to resistive MHD model**

- Maxwell: $\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}, \quad \frac{\partial \boldsymbol{E}}{\partial t} = \mathrm{c}^2(\nabla \times \boldsymbol{B} - \mu_0 \boldsymbol{J})$
- Continuity: $\frac{\partial}{\partial t}(mn) + \nabla \cdot (mn\boldsymbol{v}) = 0$
- Momentum: $\frac{\partial}{\partial t}(mn\boldsymbol{v}) + \nabla \cdot (mn\boldsymbol{v}\boldsymbol{v} + P\boldsymbol{I}) = \boldsymbol{J} \times \boldsymbol{B}$
- Energy: $\frac{\partial \epsilon}{\partial t} + \nabla \cdot [\boldsymbol{v}(\epsilon + P)] = (\boldsymbol{J} \times \boldsymbol{B}) \cdot \boldsymbol{v} + \eta J^2 , \quad \epsilon = \frac{1}{2} mnv^2 + \frac{P}{\Gamma - 1} + \epsilon_{ionization}$
- Extended-MHD Generalized Ohm's Law:

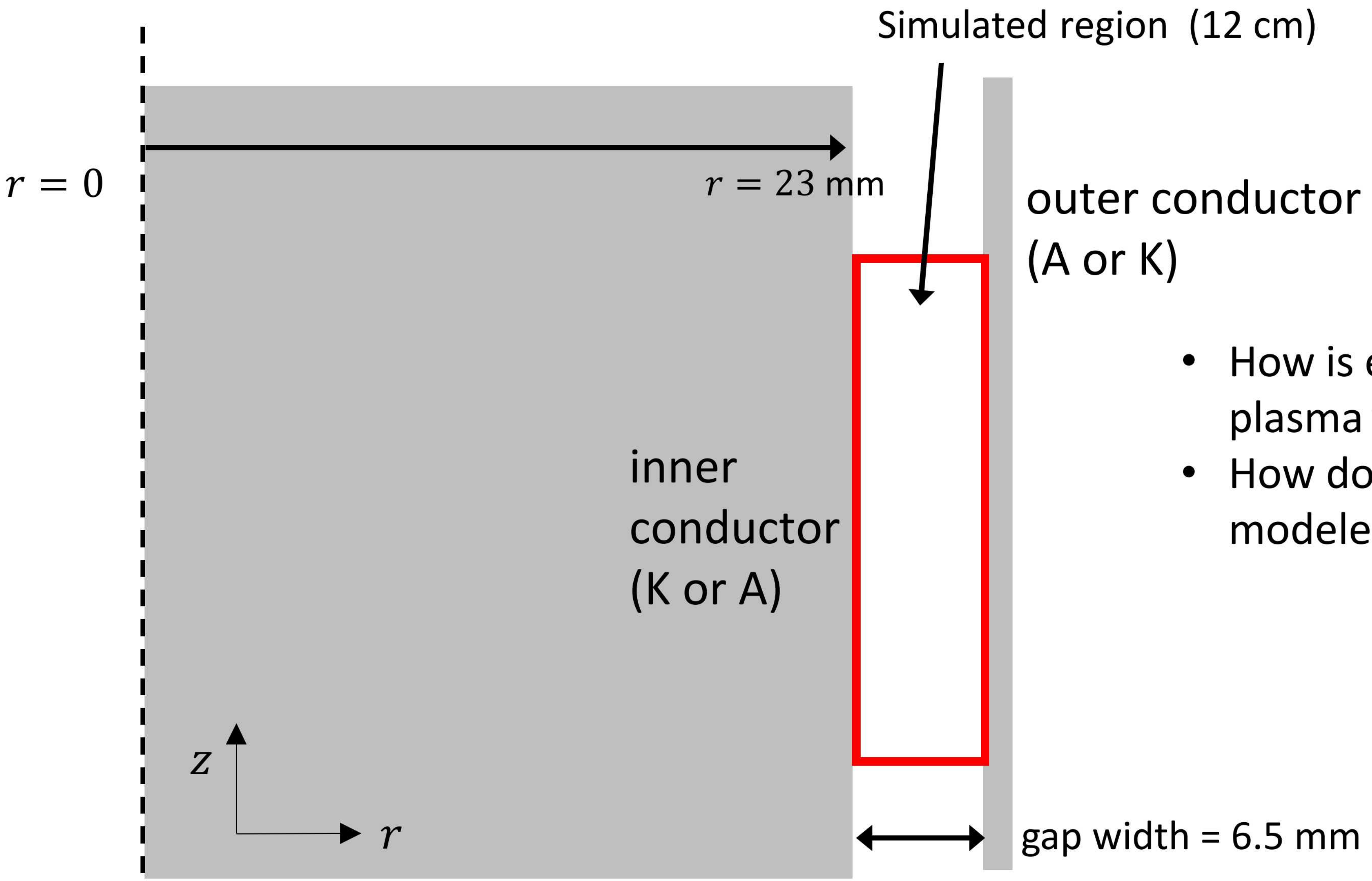
*** Until recently, the overwhelming majority of fluid simulations of pulsed-power problems employed an MHD theory.*

$$\frac{m_e}{n_e e^2} \frac{\partial \boldsymbol{J}}{\partial t} \sim \boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} - \frac{\boldsymbol{J}}{n_e e} \times \boldsymbol{B} - \eta \boldsymbol{J}$$

electron inertial term

Hall term

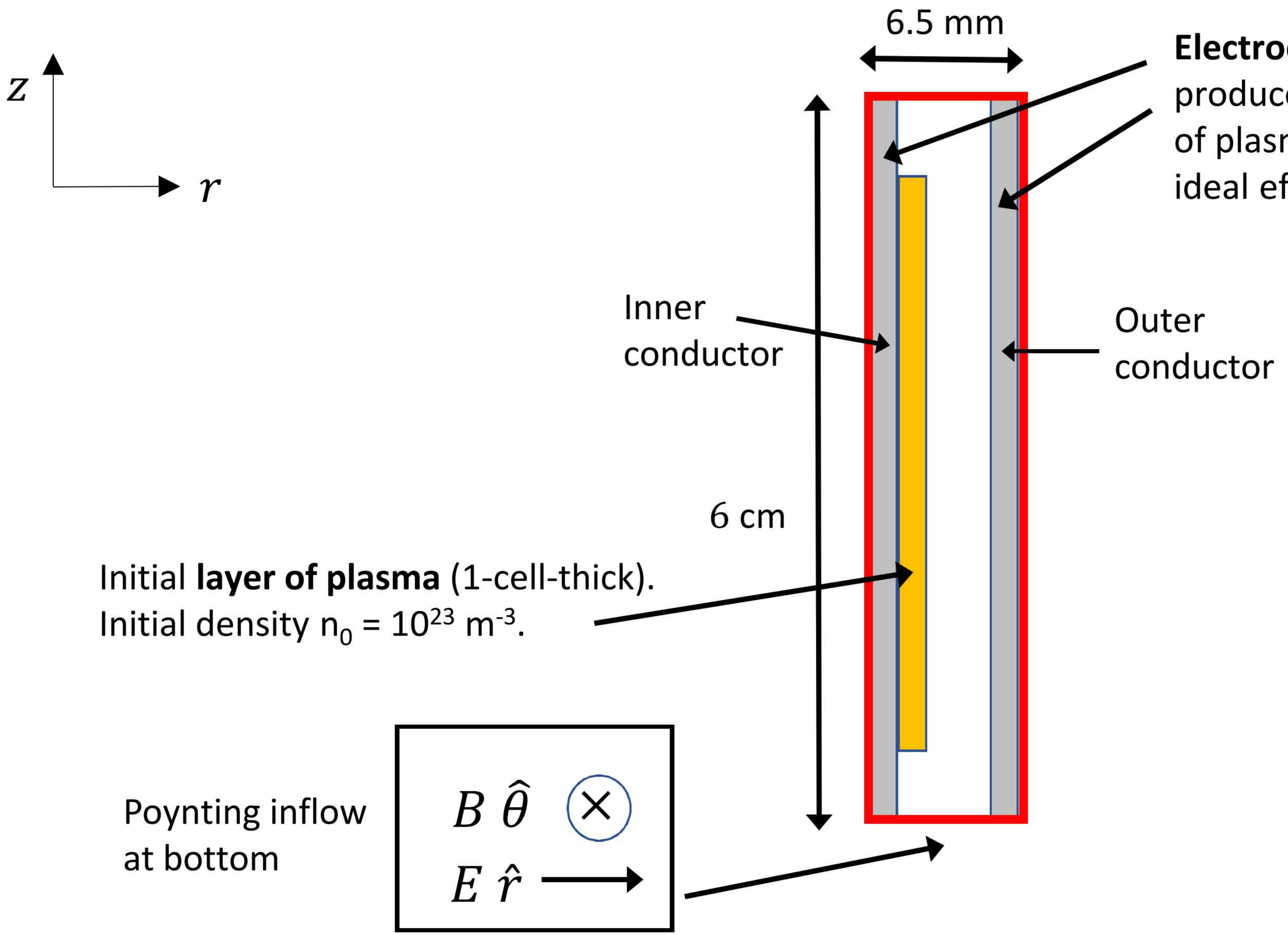
Power flow along coaxial transmission line in axisymmetric cylindrical geometry



Current reaches 20 MA in 100 ns

- How is energy coupling affected by plasma from electrode surfaces?
- How does Hall physics affect the modeled energy losses?

Simulations are initialized with a thin plasma layer to study the time-evolution of electrode plasmas



Electrodes (in gray) are static; do not produce plasma. This allows explicit control of plasma initialization and eliminates non-ideal effects from solid-to-plasma transition.

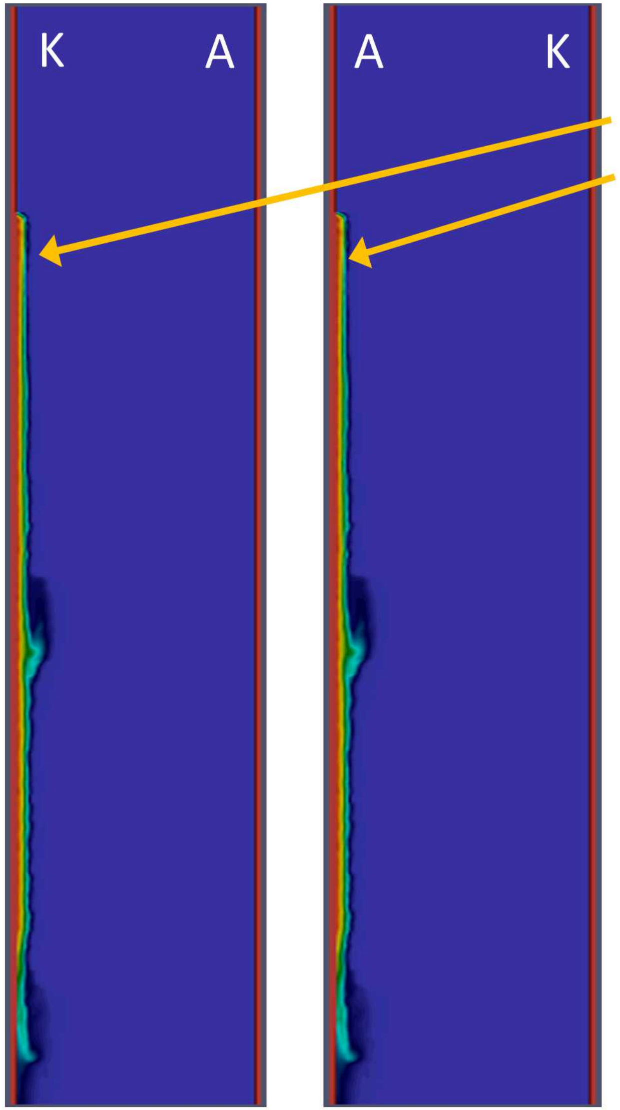
- Gap width ~ 6.5 mm
- Inner radius R ~ 23 mm
- 52x960 cells spanning 0.65 x 12 cm
- $\Delta x = 125\ \mu$m

- Current follows a sine-squared temporal profile that increases to 20 MA over a 100-ns rise time, and then remains at 20 MA.

Hall term generates anode-cathode asymmetries

MHD, initialized against **cathode**

MHD, initialized against **anode**

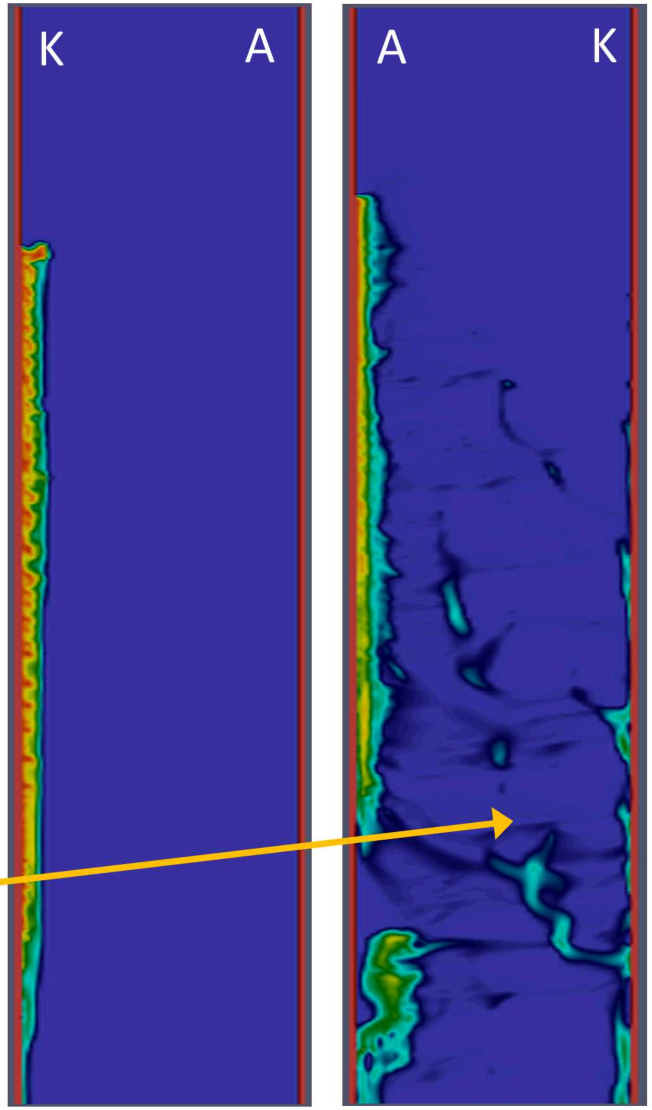


MHD is insensitive to polarity.

Hall MHD shows considerably more blow-off for **anode-initialized** case.

Hall MHD, initialized against **cathode**

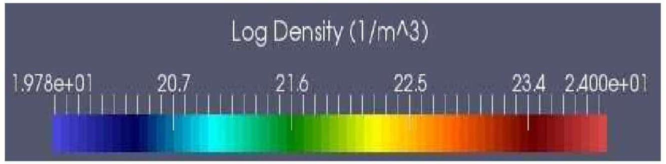
Hall MHD, initialized against **anode**

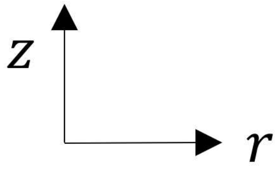


Layer is initialized against the **inner conductor,** on **left.**

$n_{floor} = 10^{-9}\, n_{solid}$

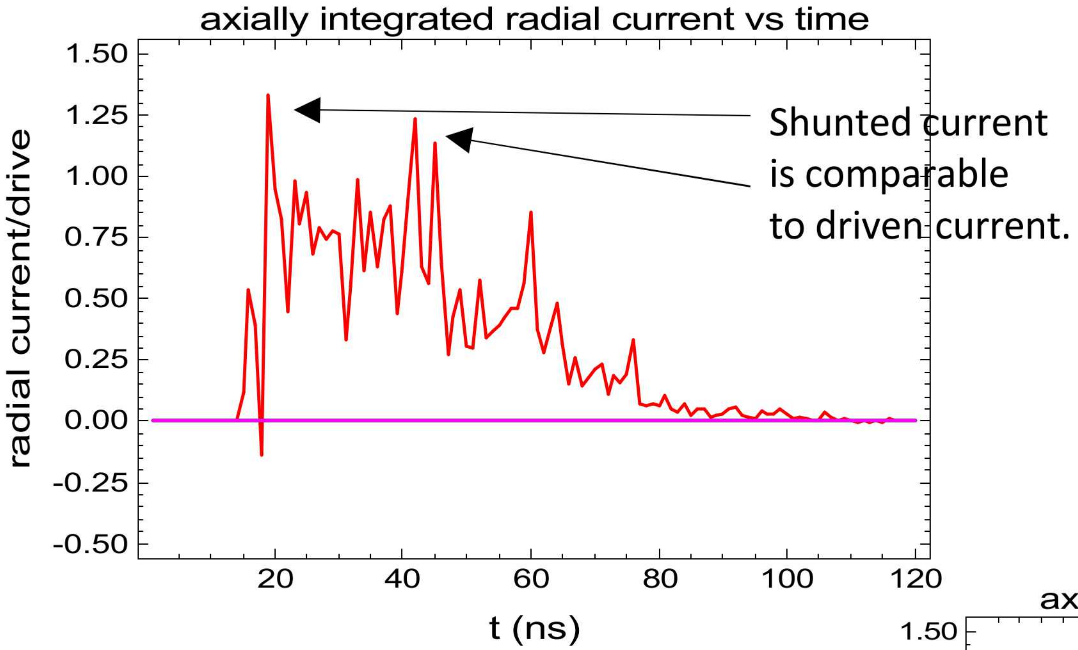
- 6.5 mm gap, 60 ns,
- initial layer density $n_0 = 10^{23}\ m^{-3}$





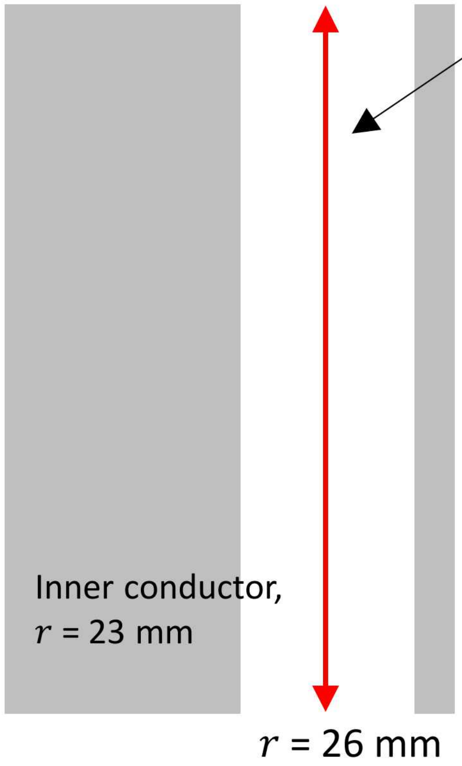
Radial current is shunted from anode - resulting in loss

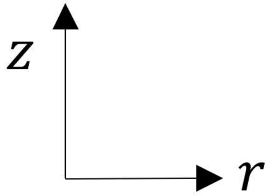
Blue: Hall MHD, cathode layer
Red: Hall MHD, anode layer
Green: MHD, cathode layer
Magenta: MHD, anode layer



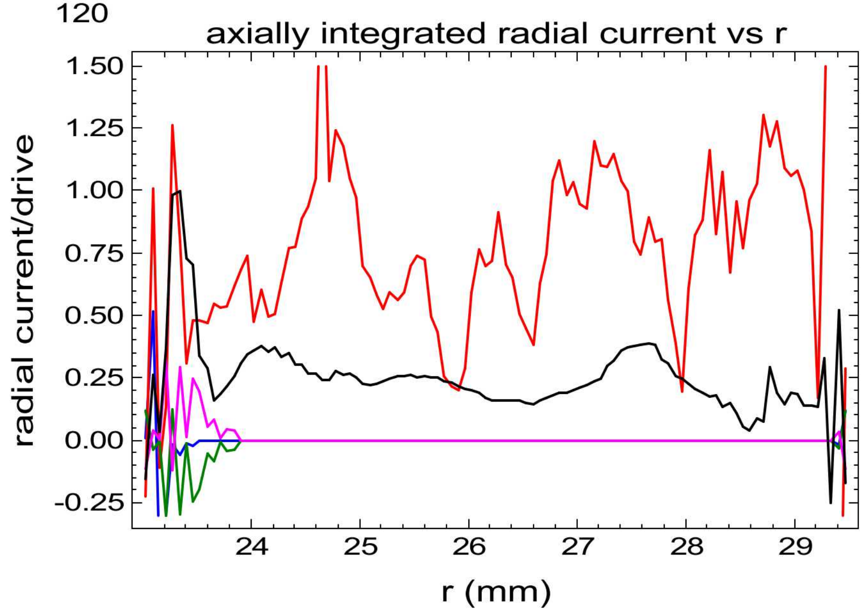
r = 26 mm

Integrate J_r along 12-cm domain length in z.





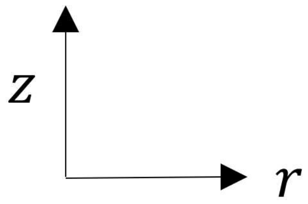
Black curve:
Hall MHD, anode layer, 75 ns



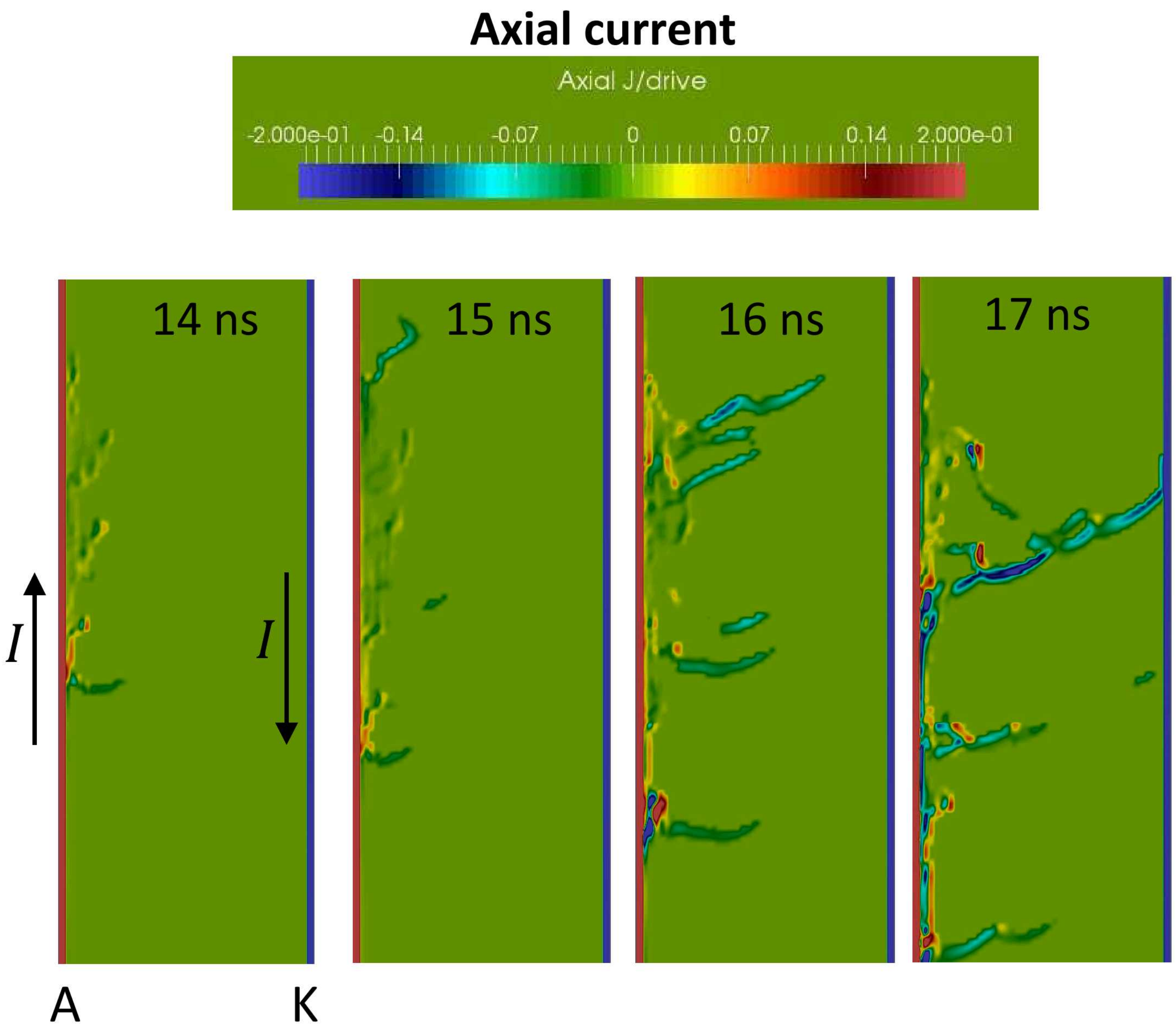
t = 30 ns (colors); 75 ns (black)

Anode filaments carry reversed axial current

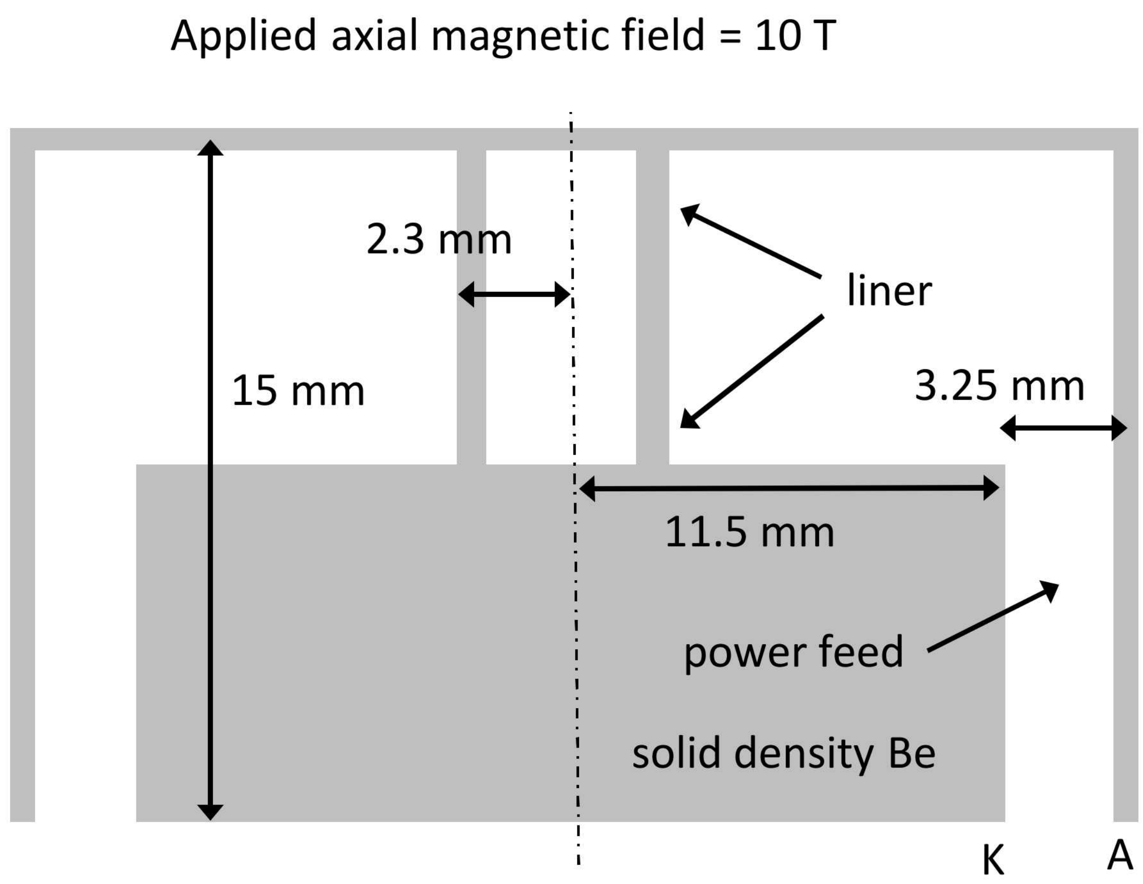
- **Hall MHD**, 6.5 mm gap, 23 mm radius, $n_0 = 10^{23}\ m^{-3}$ layer initialized on **anode (inner conductor)**.
- ExB drift is relevant for the electrons only in the Hall regime.
- This creates current opposite to the power flow direction.
- This plasma current is **opposite** the **anode** current and in the **same direction** as the **cathode** current.
- This results in a repelling of the plasma away from the anode.



6.5 mm by 16.9 mm



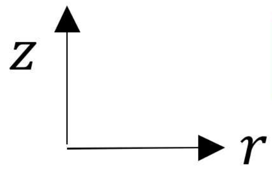
Power coupling in MagLIF: transmission line (feed) is now coupled to a load



Magnetized Liner Inertial Fusion experiment, Sandia National Labs

- Implosion of cylindrical liner driven by Poynting flux with azimuthal magnetic field from power feeds.
- Efficiency ~ (current in liner)/(current in feeds)
- **Hall MHD** vs **MHD**
- **Cathode** vs **anode**-initialized layer
- Azimuthally symmetric cylindrical geometry
- 216x216 cells, 15 mm by 15 mm domain
- Electrodes in feed are static (do not produce plasma)

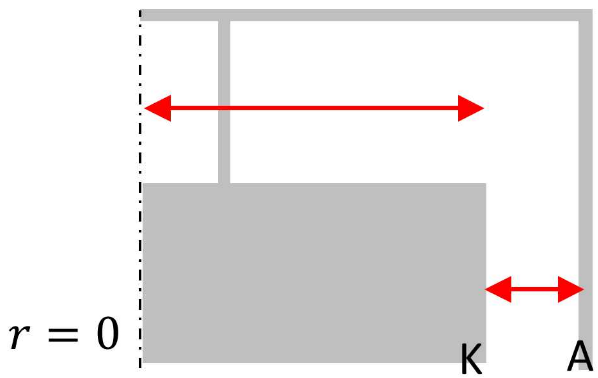
Current coupling onto liner



Biggest delay in coupling is Hall MHD, anode-initialized case.

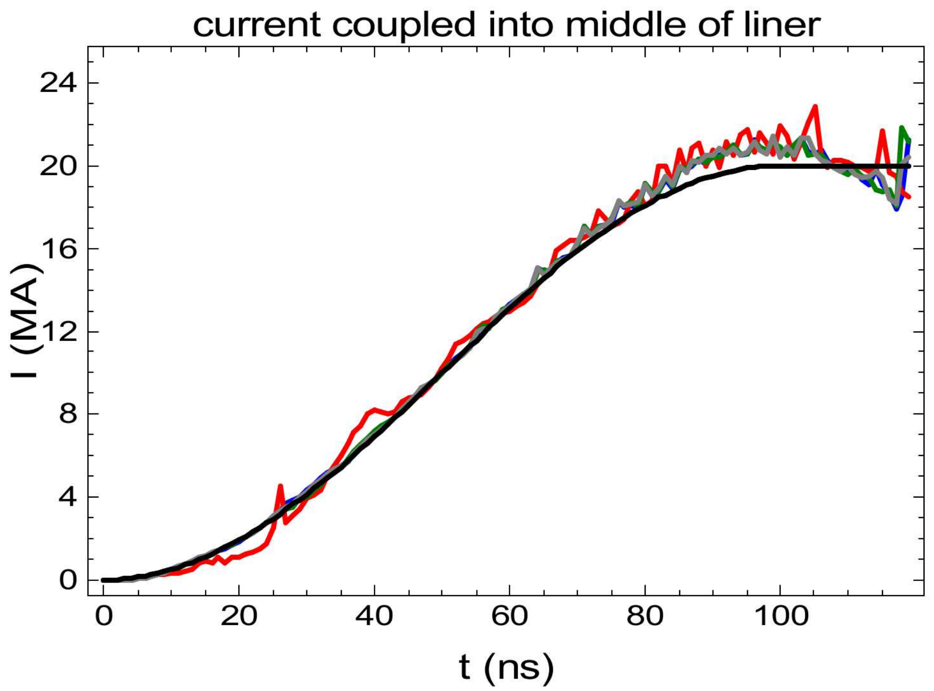
Blue = Hall MHD initialized against cathode
Red = Hall MHD initialized against anode
Green = MHD initialized against cathode
Gray = MHD initialized against anode

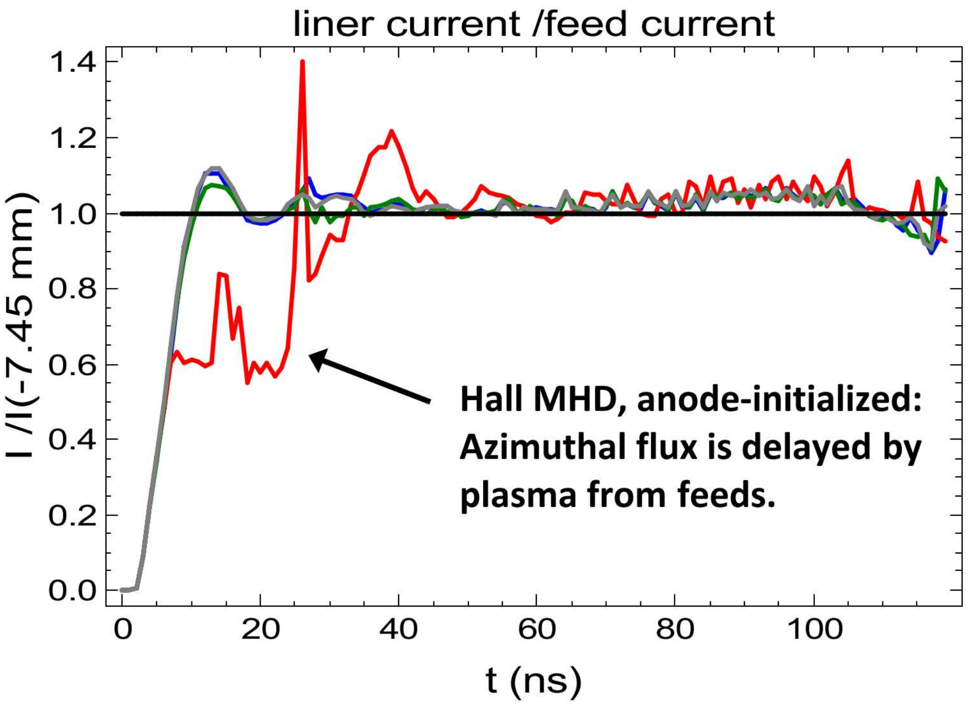
Initial layer density = 10^{25} m^{-3}
n_{floor} = 1.2x10^{20} m^{-3}



Liner current is $\int (J_z < 0)\, 2\pi r dr$ along upper red line.

Feed current is $\frac{1}{2}\int |J_z| 2\pi r\, dr$ along lower red line.

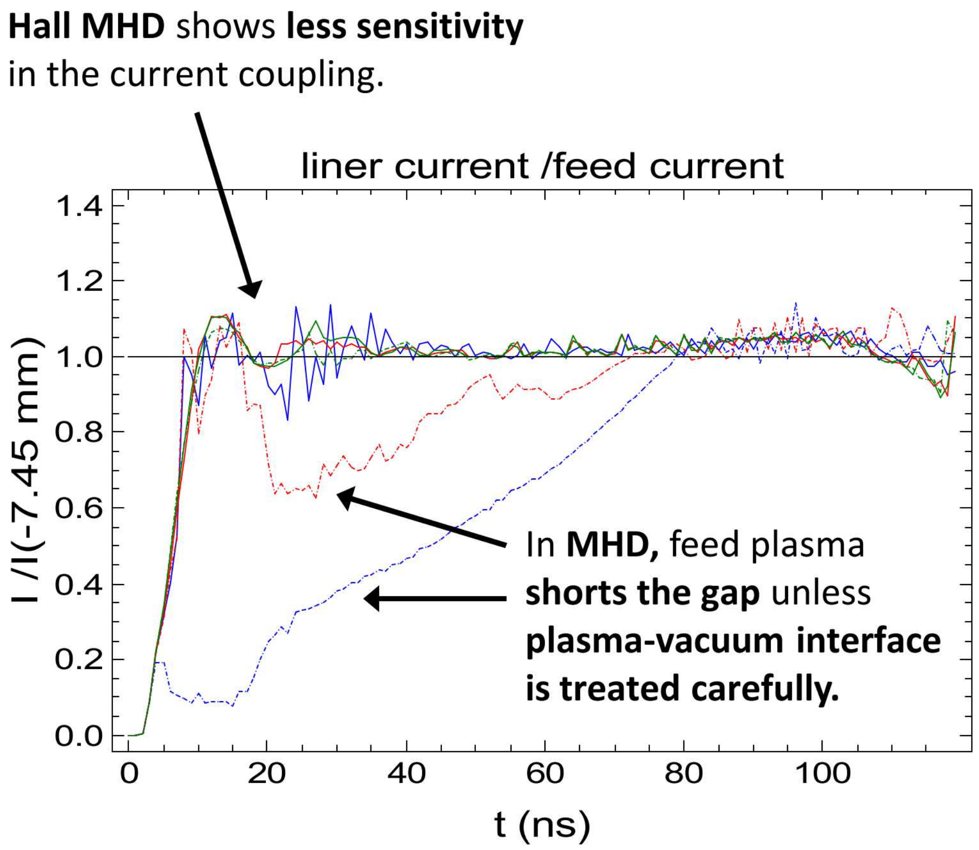




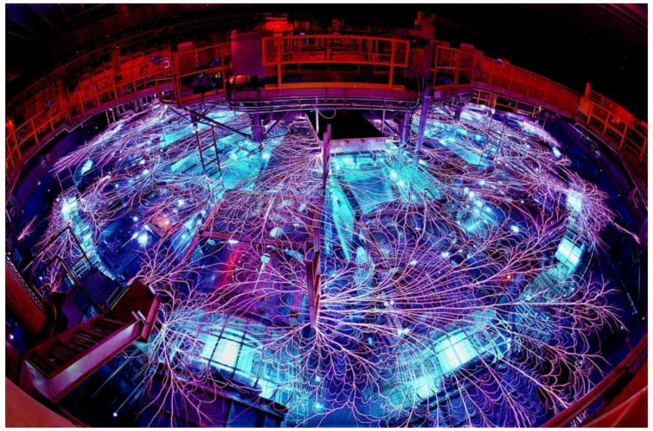
Sensitivity to plasma-vacuum interface

- The transmission line is now coupled to a load.
- Energy coupling to the load (liner) is sensitive to the feed (electrode) plasma dynamics, and therefore to modeling of the vacuum and low-density regions.
- Hall physics shows less sensitivity to this modeling – but the ultimate treatment of the plasma-vacuum interface remains an active area of research.
- It is critical to understand how the results depend on the numerical modeling of the low-density and vacuum regions in any MHD or Hall-MHD simulation.

- Below is for cathode-initialized cases.
- Different colors: slightly different treatments of plasma-vacuum interface.



Conclusions/future directions



Modeling power-flow with high fidelity is of utmost importance for improving the performance of experiments on present and future pulsed power facilities.

- Extended MHD equations - Hall MHD
  - *Resistive MHD has fundamental limitations – need to go beyond*
- Transmission lines: Hall MHD simulations show complex behavior
  - Anode-cathode asymmetries
  - Significant current loss from anode; electron ExB drift causes bridging of gap
- MagLIF: current coupling from feed to liner
  - Strong sensitivity to modeling of low-density and vacuum regions
  - Hall physics significantly improves the modeling of low-density plasmas
- Future directions
  - Incorporation of non-quasi-neutral, space charge effects
  - Modeling of low-density/vacuum regions : Validation of fluid codes against PIC codes and/or experiment
  - T-lines with dynamic electrodes; influence of material properties

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ndhamli@sandia.gov