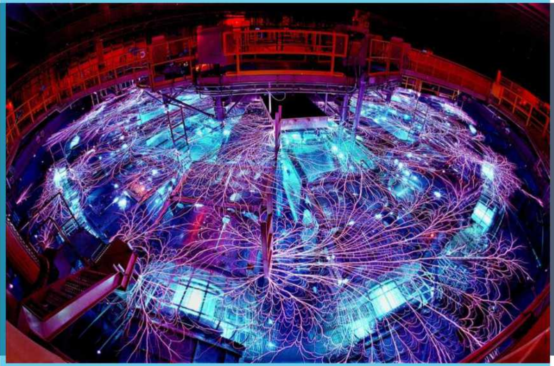
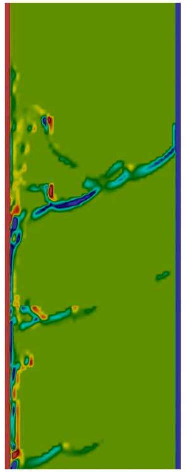
SAND2019-9408C

Power-Flow Modeling using Fluid and PIC Simulation Codes





PRESENTED BY

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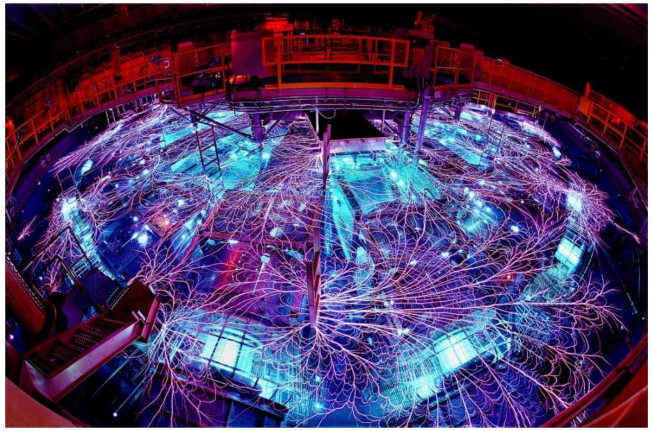
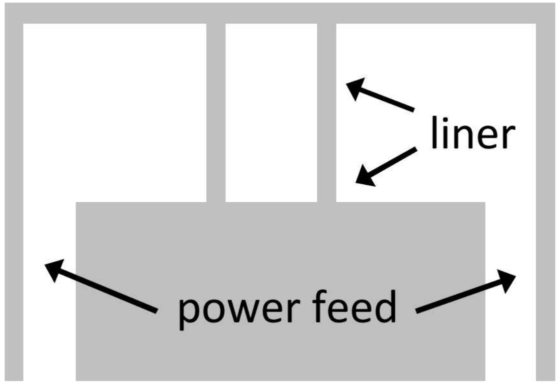
Motivation and outline

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

- PERSEUS, Hall MHD
  - Transmission lines: Hall MHD simulations show complex behavior
- PERSEUS vs HYDRA, Hall MHD
  - Close qualitative agreement for influence of Hall physics on magnetic diffusion into low-density plasma.
- PERSEUS vs EMPIRE-Fluid vs EMPIRE-PIC
  - EMPIRE-Fluid is a fully two-fluid code.
  - Close three-way agreement for 1-D TEM wave interacting with plasma layer.
  - PERSEUS shows damping/diffusion after times approaching 1 ns.



MagLIF



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

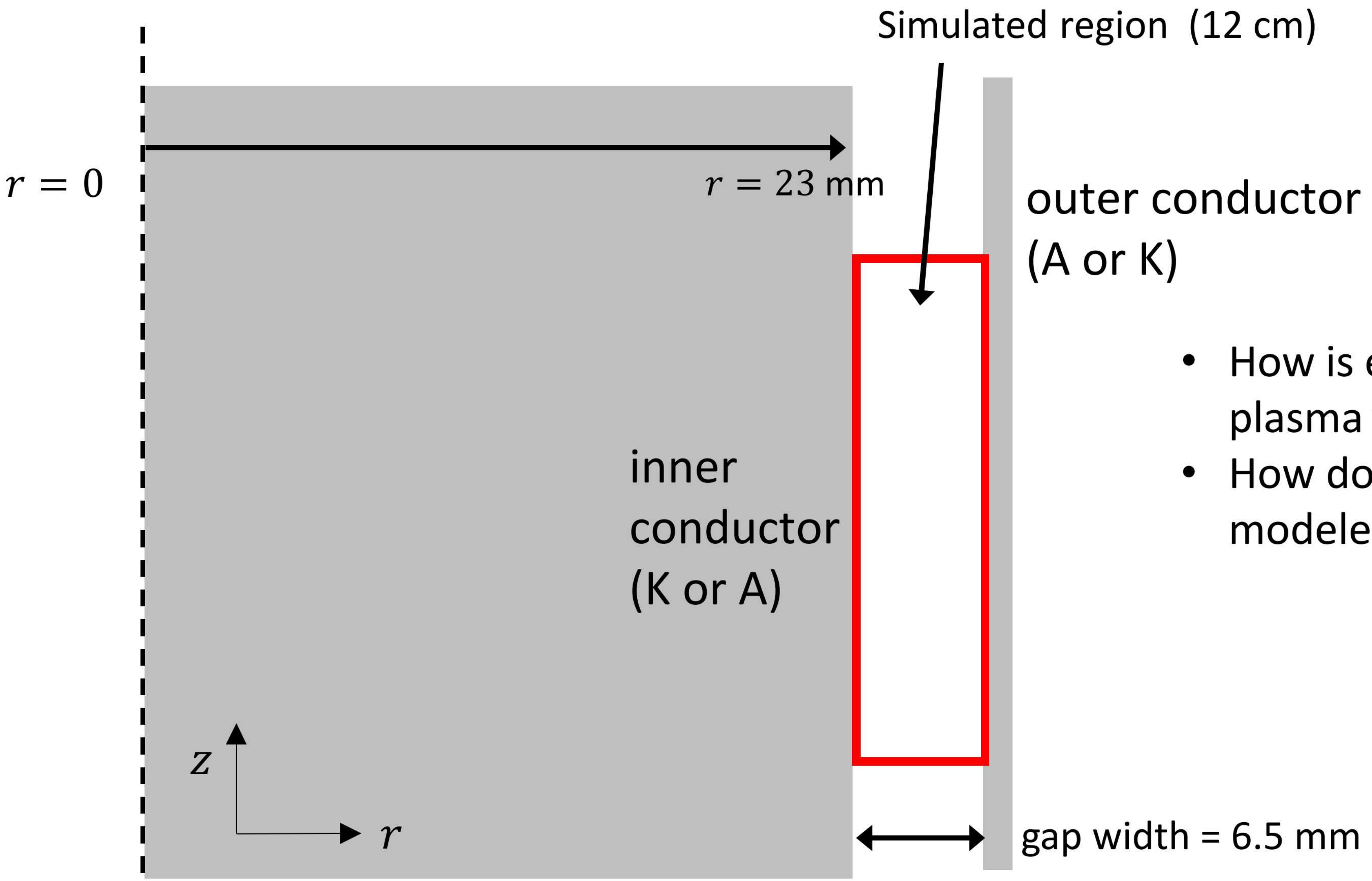
** Until recently, the overwhelming majority of fluid simulations of pulsed-power problems employed an MHD theory.

- 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: $\frac{\partial \epsilon}{\partial t} + \nabla \cdot [\boldsymbol{v}(\epsilon + P)] = (\boldsymbol{J} \times \boldsymbol{B}) \cdot \boldsymbol{v} + \eta J^2 \;, \quad \epsilon = \frac{1}{2} mnv^2 + \frac{P}{\Gamma - 1}$
- Extended-MHD Generalized Ohm's Law:

$$0 = \boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B} - \frac{\boldsymbol{J}}{n_e e} \times \boldsymbol{B} - \eta \boldsymbol{J}$$

- Large **Hall term** relative to **dynamo term**: small ion inertial length relative to spatial scales, i.e. low-density plasma.
- Large **Hall term** relative to **resistive term**: strongly magnetized plasma (electron gyrofrequency large relative to collision frequency).

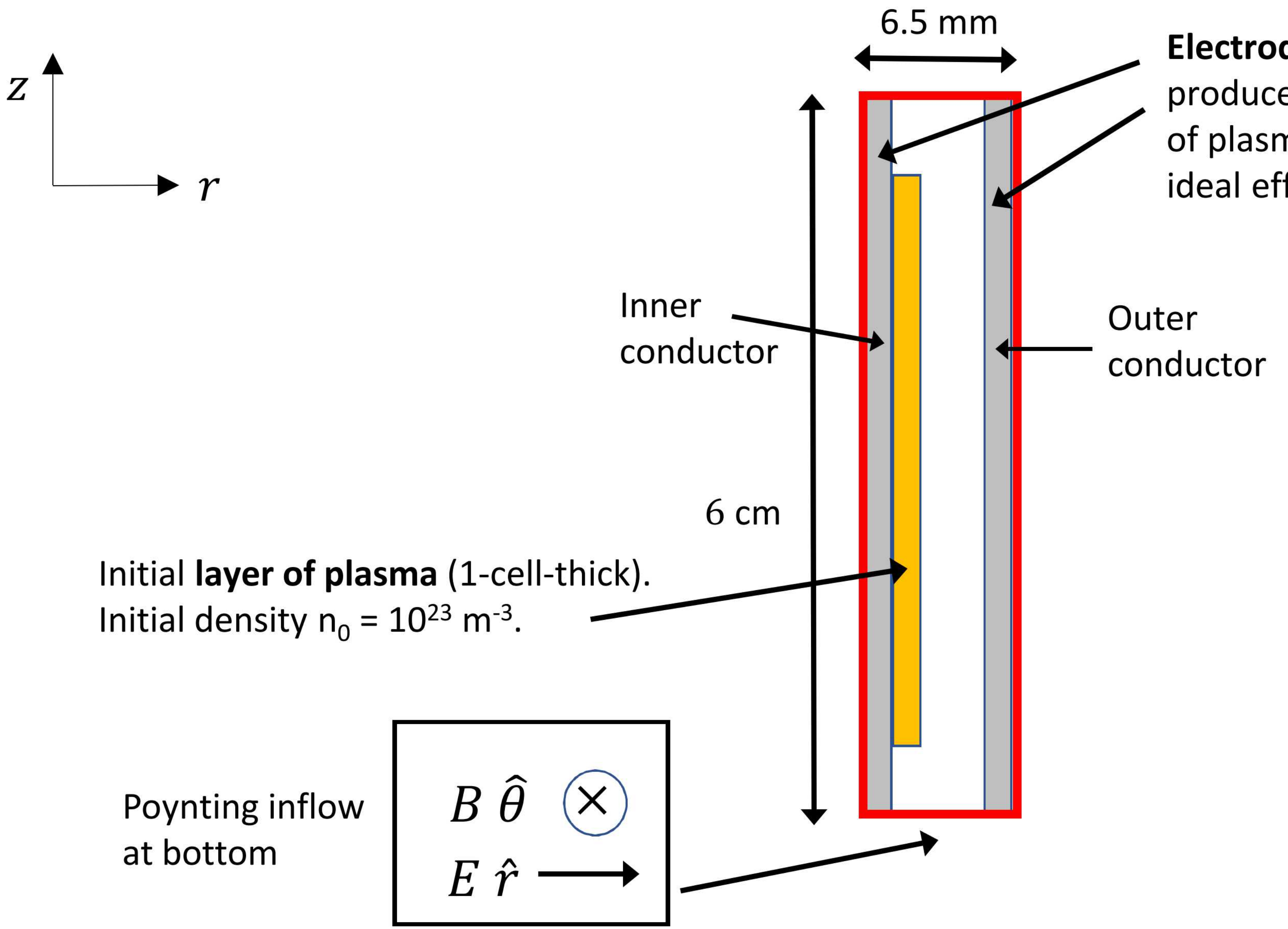
PERSEUS: Power flow along coaxial transmission line in axisymmetric cylindrical geometry



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?

PERSEUS: 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.

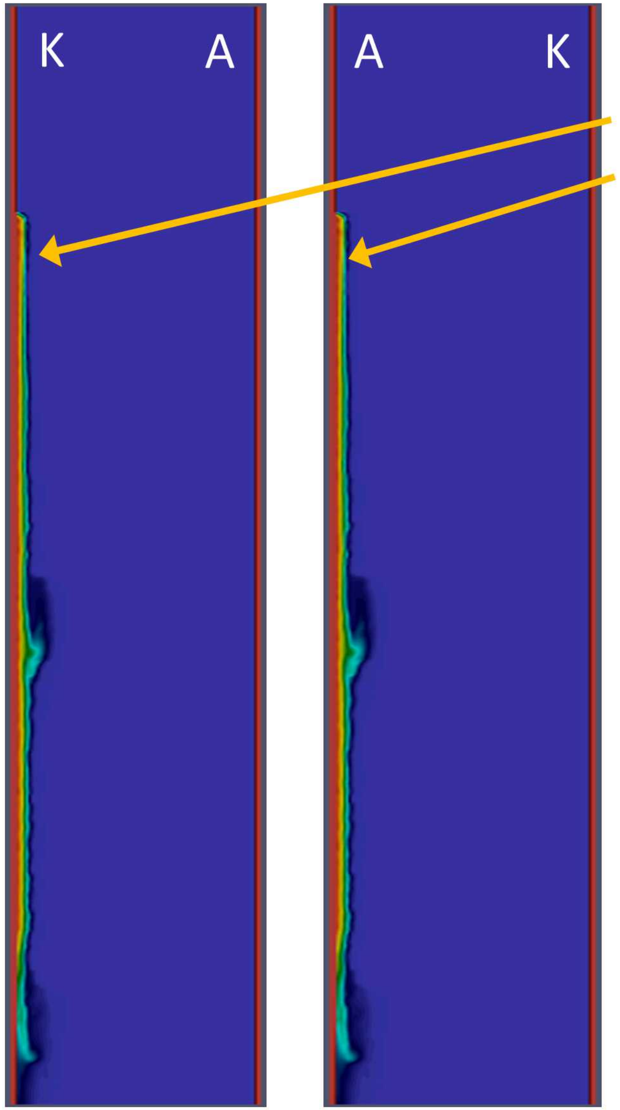
- Gap width ~ 6.5 mm
- Inner radius R ~ 23 mm
- 52x960 cells spanning 0.65 x 12 cm
- $\Delta x = 125\ \mu$m

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

PERSEUS: Hall term generates anode-cathode asymmetries

MHD, initialized against **cathode**

MHD, initialized against **anode**

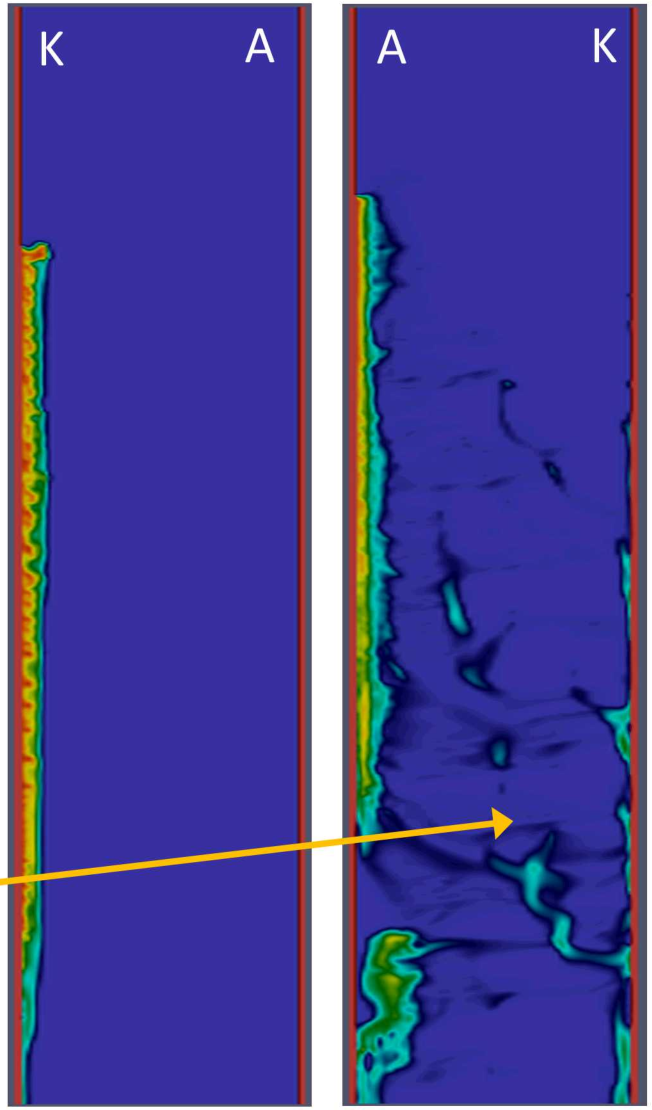


MHD is insensitive to polarity.

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

Hall MHD, initialized against **cathode**

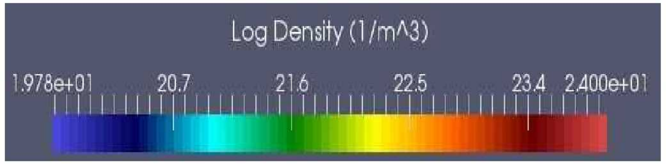
Hall MHD, initialized against **anode**

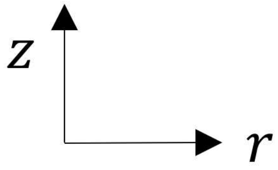


Layer is initialized against the **inner conductor,** on **left.**

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

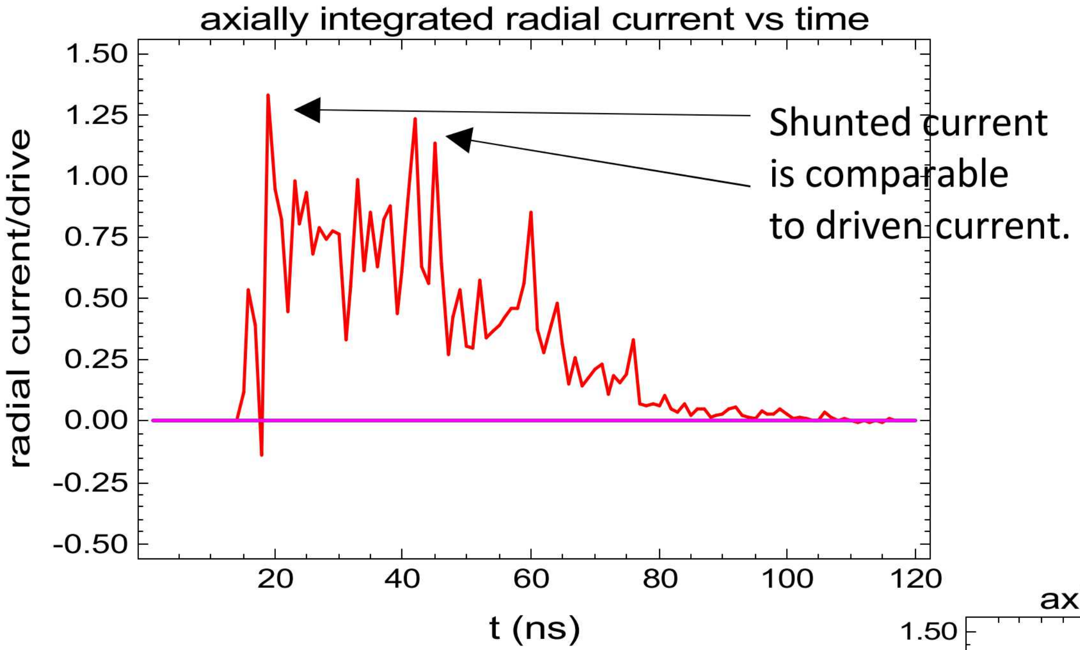
- 6.5 mm gap, 60 ns,
- initial layer density $n_0 = 10^{23}\ m^{-3}$





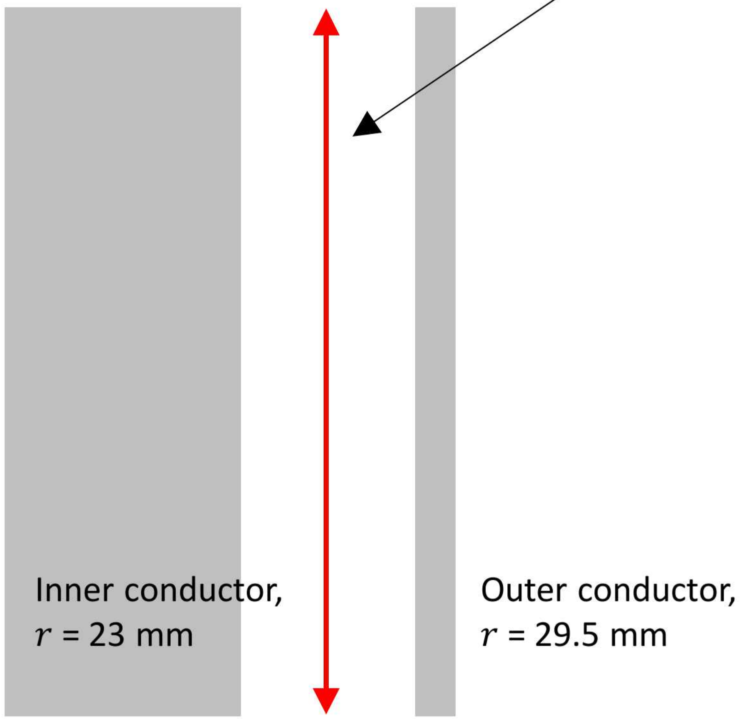
PERSEUS: Radial current is shunted from anode - resulting in loss

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

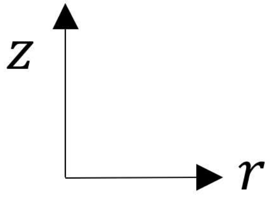


r = 26 mm

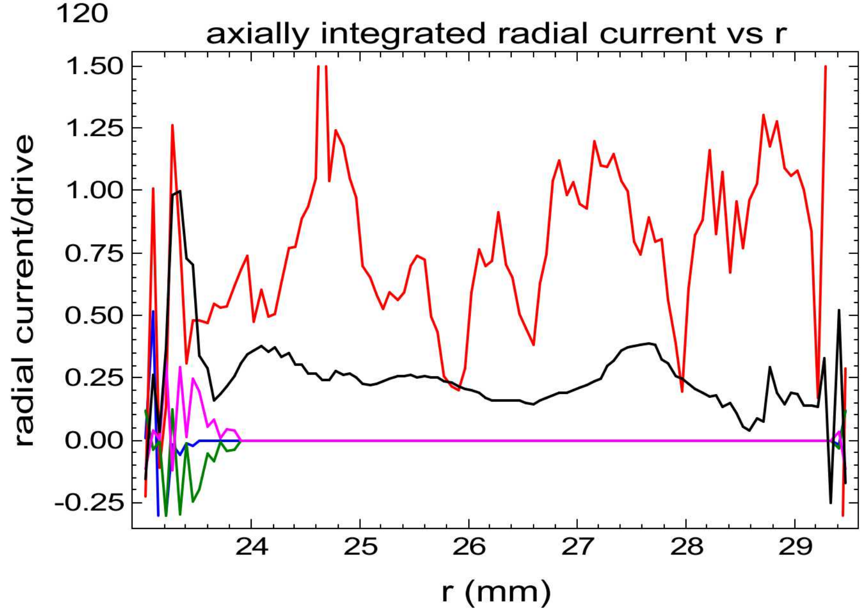
Integrate J_r along 12-cm domain length in z.



r = 26 mm



Black curve:
Hall MHD, anode layer, 75 ns

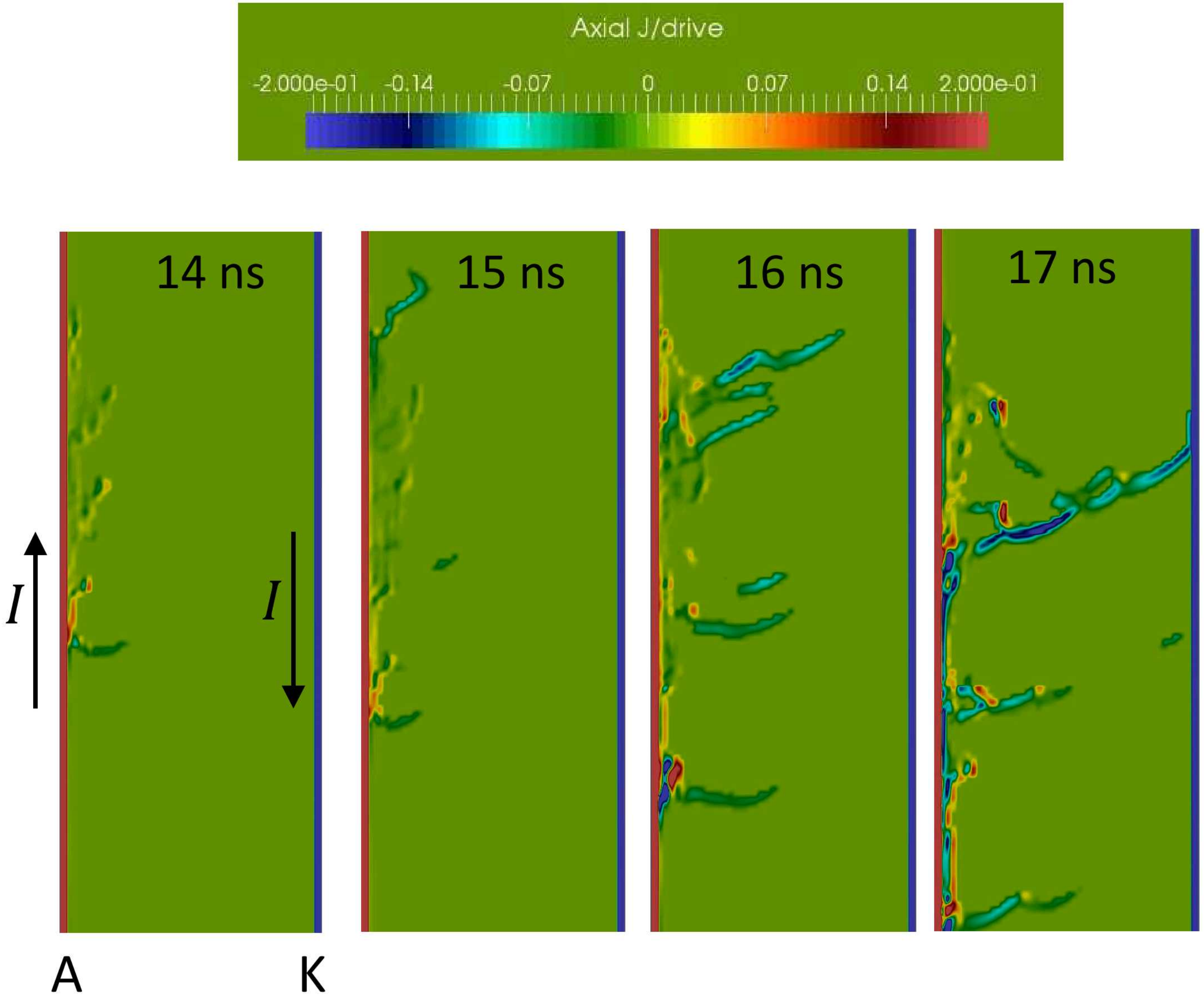


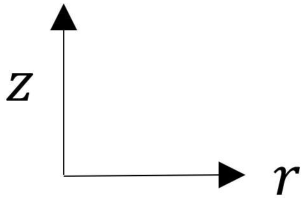
t = 30 ns (colors); 75 ns (black)

PERSEUS: 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.

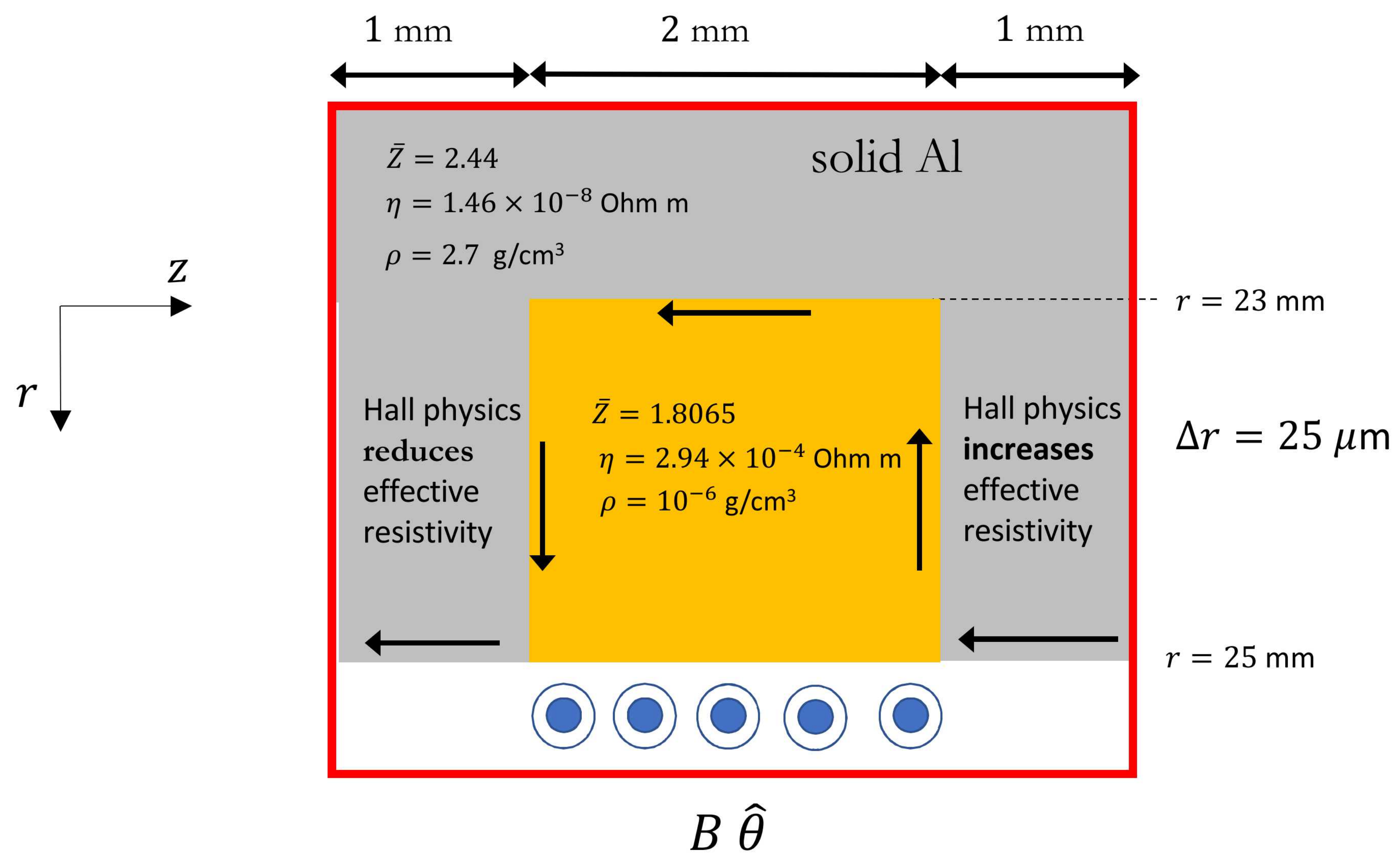
Axial current





6.5 mm by 16.9 mm

PERSEUS vs HYDRA: Magnetic diffusion into low-density plasma



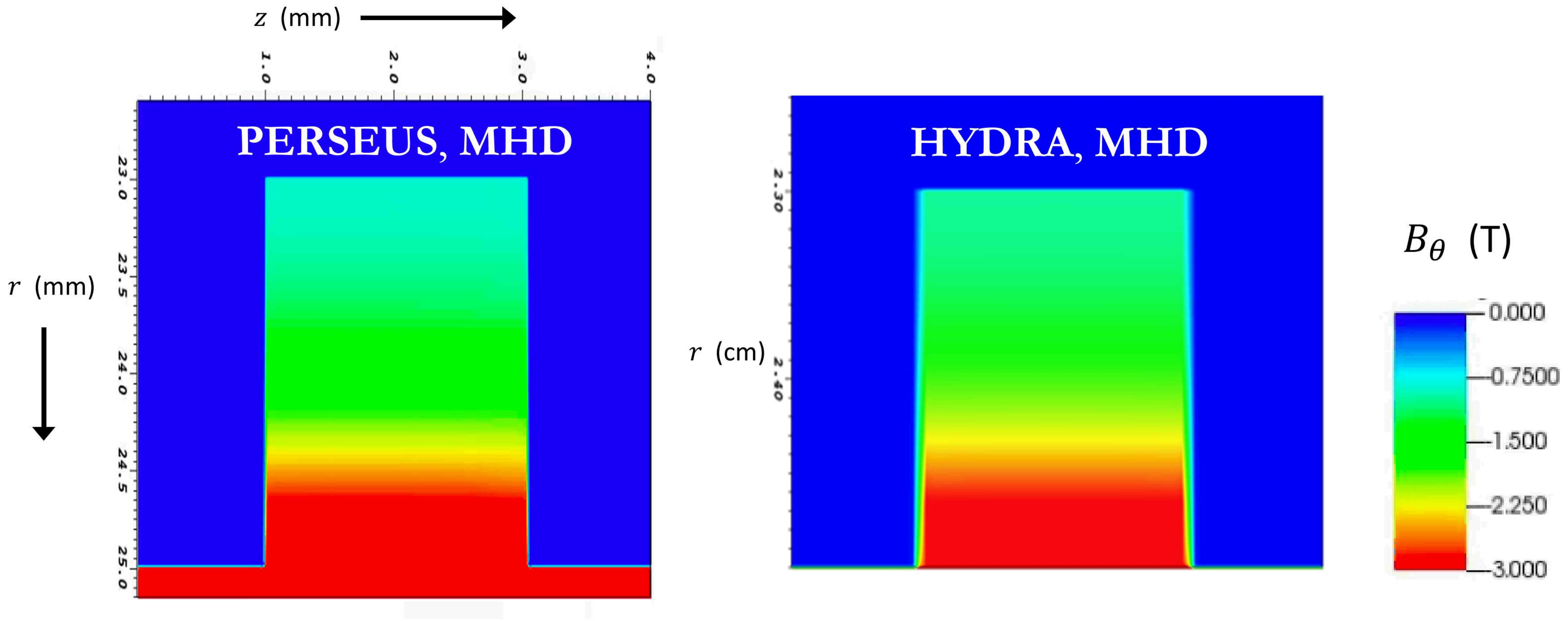
Results are approximately converged for $\Delta r \leq 25\ \mu$m.

PERSEUS vs HYDRA: Influence of Hall term on magnetic diffusion

- Faraday's law with Hall term: $-\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\eta \boldsymbol{J} - \boldsymbol{v} \times \boldsymbol{B} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{ne}\right]$
- Hall term contributes: $\nabla \times \left[\frac{J \times B}{ne}\right] = \frac{1}{ne} \nabla \times (\boldsymbol{J} \times \boldsymbol{B}) - \frac{\boldsymbol{B}}{\boldsymbol{e}}\left[\boldsymbol{\nabla}\left(\frac{\boldsymbol{1}}{\boldsymbol{n}}\right) \cdot \boldsymbol{J}\right]$, $\quad \boldsymbol{J} \cdot \boldsymbol{B} = 0$
- Simplifying assumptions:
  - 2-D axisymmetric system; only J_r, J_z, and B_θ are nonzero.
  - Spatially uniform resistivity and density within each material (vacuum, plasma, electrode).
  - Negligible displacement current.
  - Limited motion of plasma and electrodes.
- Faraday's law with Hall term and simplifying assumptions:
  - $\frac{\partial B_{\boldsymbol{\theta}}}{\partial t} = \eta \nabla^2 B_\theta - \frac{2 B_\theta J_r}{ner} - \frac{B_\theta}{e}\left(\frac{1}{n^2}\frac{\partial n}{\partial r} J_r + \frac{1}{n^2}\frac{\partial n}{\partial z} J_z\right)$

PERSEUS vs HYDRA: Magnetic diffusion in MHD

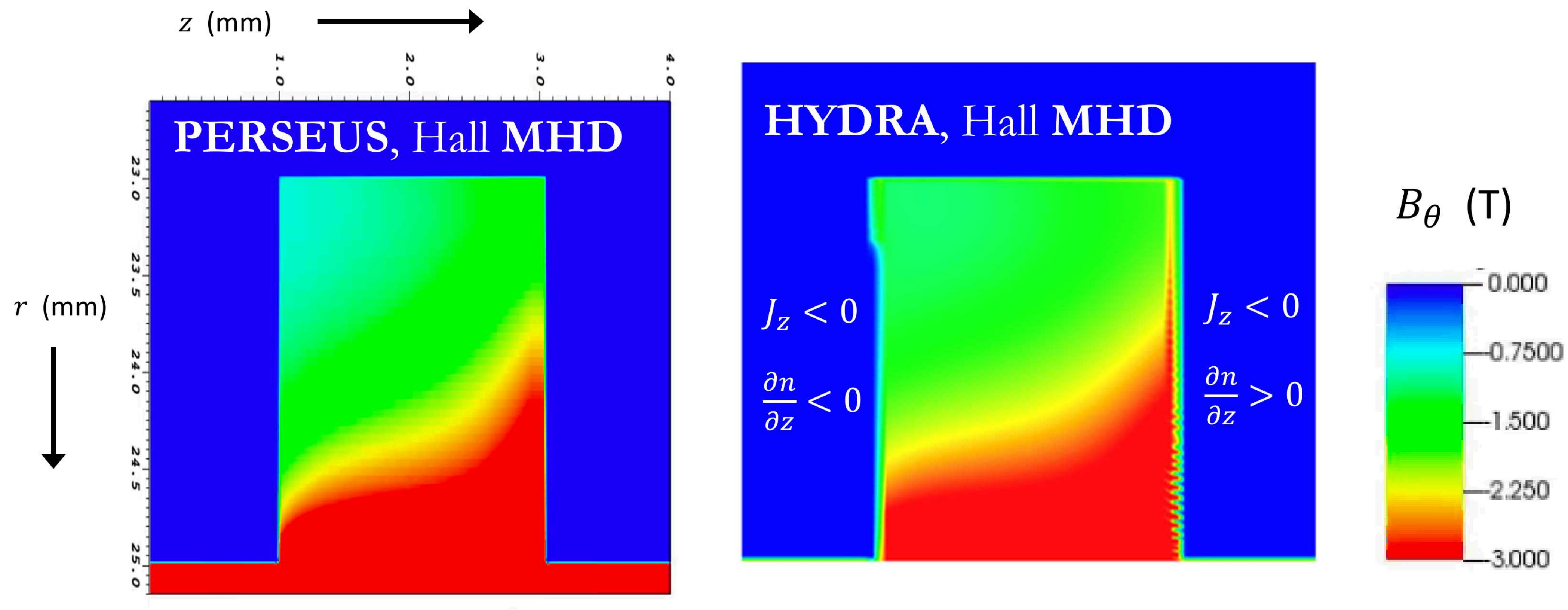
- In **MHD**, PERSEUS and HYDRA show close agreement.
- Axially uniform diffusion in both cases, unaffected by density gradients at boundaries.



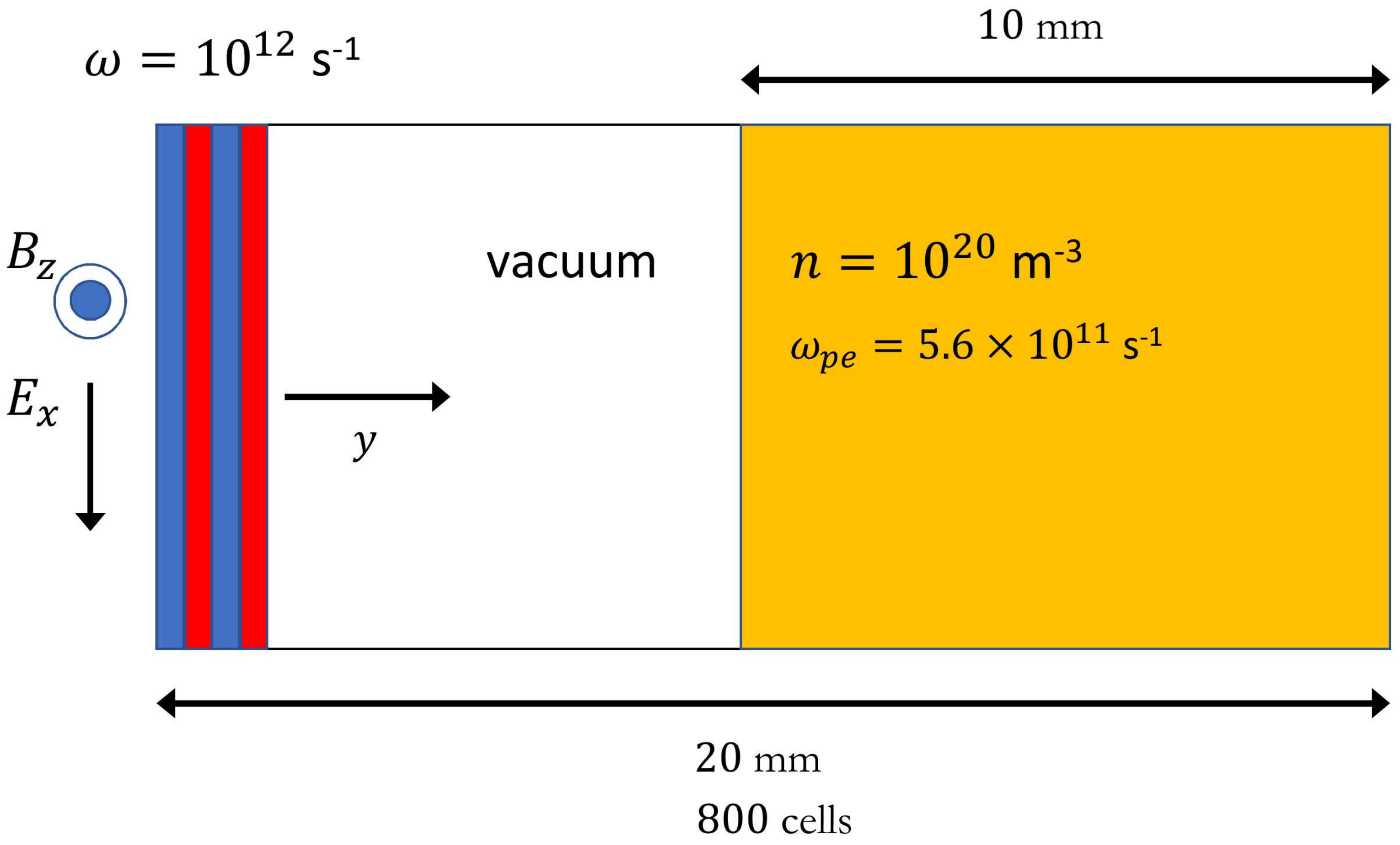
PERSEUS vs HYDRA: Magnetic diffusion in Hall MHD

- In **Hall MHD**, PERSEUS and HYDRA show close qualitative agreement.
- With Hall physics, diffusion rates depend on density gradients at boundaries.

- Faraday's law with Hall term: $\frac{\partial B_{\boldsymbol{\theta}}}{\partial t} = \frac{\eta}{\mu_0}\nabla^2 B_\theta - \frac{B_\theta}{n^2 e}\frac{\partial n}{\partial z} J_z + \ldots..$



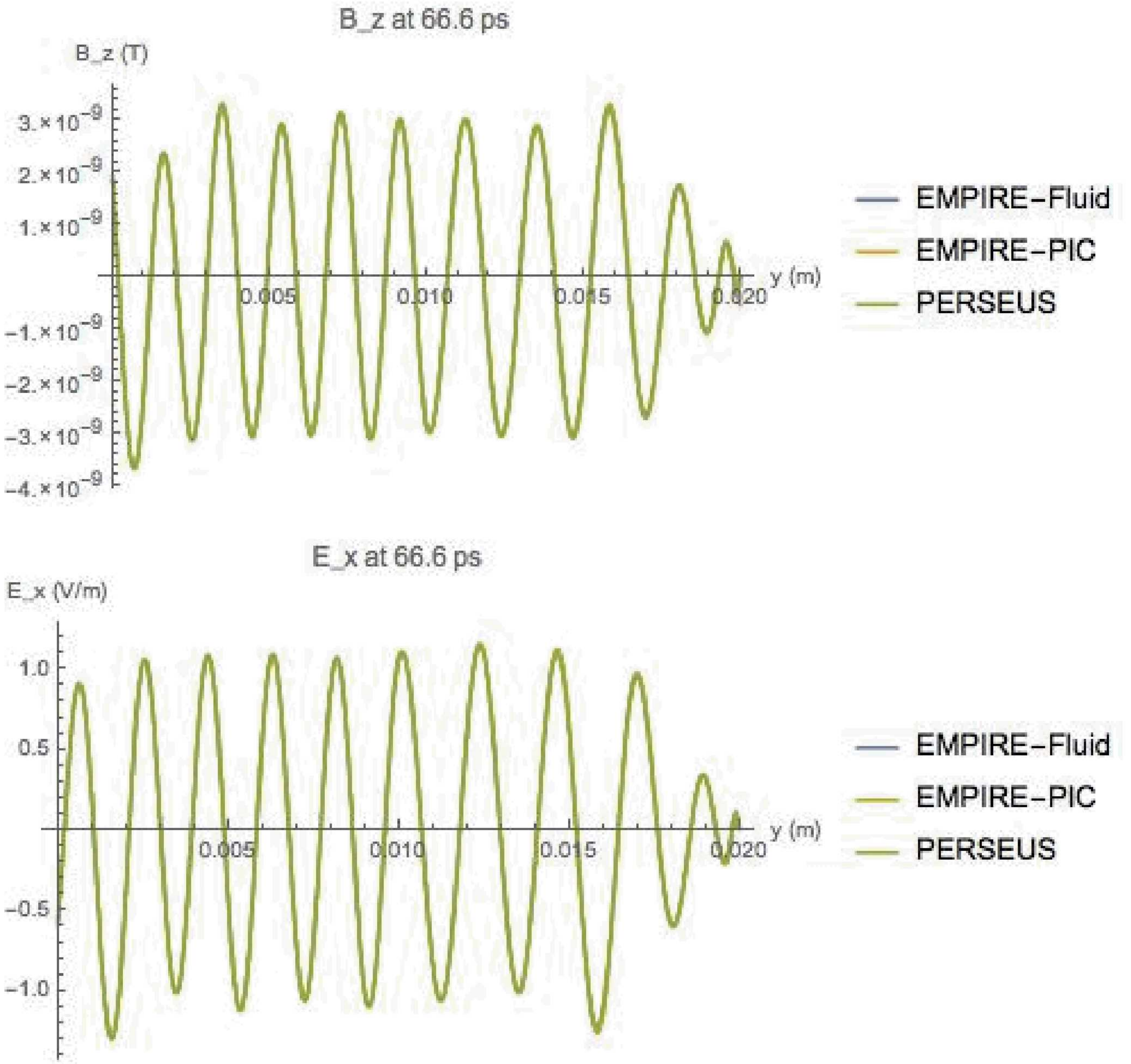
EMPIRE vs PERSEUS: 1-D TEM wave



Small space and time scales: Explicit advance in EMPIRE requires resolving electron space and time scales.

EMPIRE vs PERSEUS: 1-D TEM wave

PERSEUS, EMPIRE-Fluid, and EMPIRE-PIC show close agreement after 66.6 ps.



EMPIRE vs PERSEUS: ICF-relevant MITL modeling

- PERSEUS loses accuracy if > 1,000,000 time integrations are required.
  - Could be mitigated by using a reduced speed of light.
- Even if implicit advance enables stepping over plasma frequency, Courant limiting by physical speed of light can lead to prohibitive computational times.

Conclusions

- PERSEUS, Hall MHD
  - Transmission lines: Hall MHD simulations show plasma blow-off at anode; not seen at cathode.
  - How would this be affected by incorporation of space-charge limiting in a fully two-fluid model?
- PERSEUS vs HYDRA, Hall MHD
  - Close qualitative agreement for influence of Hall physics on magnetic diffusion into low-density plasma.
  - The Hall term models alteration of diffusion rates due to density gradients at plasma boundaries.
- PERSEUS vs EMPIRE-Fluid (two-fluid) vs EMPIRE-PIC
  - Close three-way agreement for 1-D TEM wave interacting with plasma layer.
  - PERSEUS shows damping/diffusion after times approaching 1 ns.

Future directions in MITL flow modeling

- Incorporation of thermal and field desorption models
- Extension of fields to relativistic regime (~ 1 MV)
- Hybridize EMPIRE-fluid and PIC using delta-*f* approach.
- Validation between EMPIRE-Hybrid and Chicago
- 2-D planar/coaxial MITL, then 3-D convolute geometries