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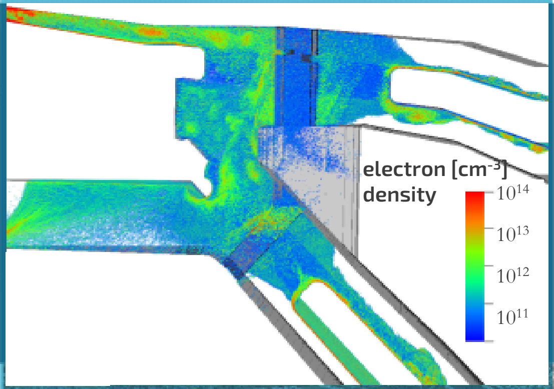
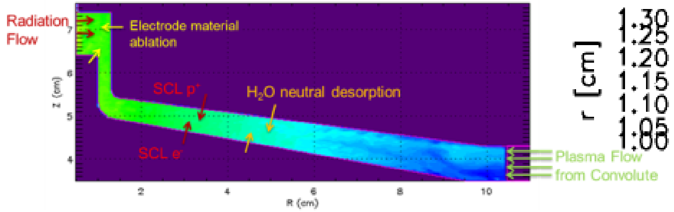
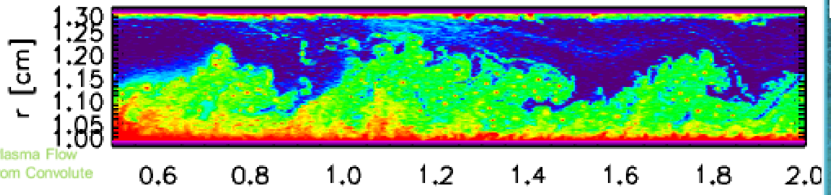


Modeling magnetized transport





N. Bennett, D.R. Welch, and G. Laity

Z Fundamental Sciences Workshop

August 9, 2021

Albuquerque, NM

U.S. DEPARTMENT OF ENERGY NNSA

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Outline

1. Particle transport in highly magnetized systems, such as at the Z accelerator requires consideration of the complete equations of motion.
2. Modeling demonstrates a Hall-term current across the inner transmission line.
3. This modeling may be included in the shot design stage to aid in predicting current delivery to the load.

In multi-MA accelerators, current is inhibited perpendicular to the magnetic field.

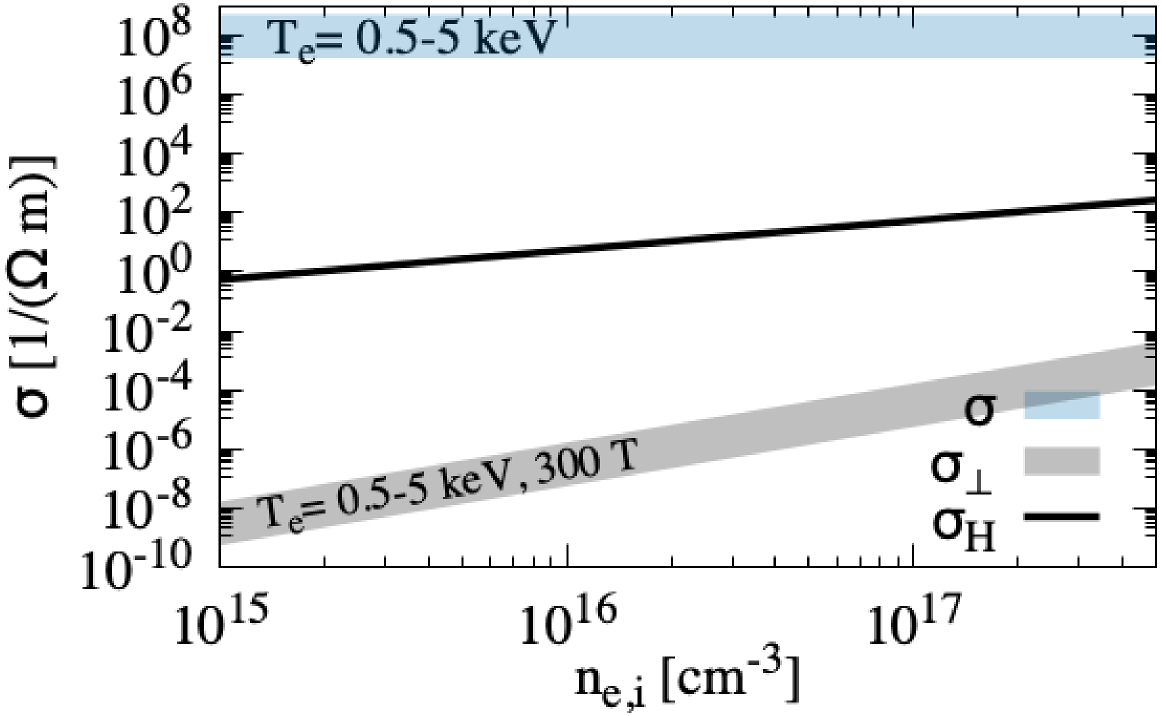
$$\mathbf{j} = \boldsymbol{\sigma} \cdot \left[\mathbf{E} + \mathbf{v} \times \mathbf{B} + \frac{1}{e n_e} \boldsymbol{\nabla}(p_e)\right]$$

effective **E** in the ion inertial frame

for $\mathbf{B} = B\hat{\theta}$

$$\boldsymbol{\sigma} = \frac{e^2 n_e}{m_e \nu_c} \begin{pmatrix} \frac{1}{1+\omega_c^2/\nu_c^2} & 0 & \frac{-\omega_c/\nu_c}{1+\omega_c^2/\nu_c^2} \\ 0 & 1 & 0 \\ \frac{\omega_c/\nu_c}{1+\omega_c^2/\nu_c^2} & 0 & \frac{1}{1+\omega_c^2/\nu_c^2} \end{pmatrix}$$

Elements of the conductivity tensor differ by orders of magnitude at 300 T.



S. I. Braginskii, in Reviews of Plasma Physics, Vol. 1, (1965)
Boyd and Sanderson, “The Physics of Plasmas,” Cambridge 2003.

When the diagonal elements are insufficient, look at the off-diagonal.

$$\sigma = \frac{ne^2}{m\nu_c}$$

$$\sigma_\perp = \frac{\sigma}{1 + \frac{\omega_c^2}{\nu_c^2}}$$

$$\sigma_H = \sigma_\perp \frac{\omega_c}{\nu_c}$$

$$\mathbf{j} = \sigma \mathbf{E'}_\parallel + \sigma_\perp \mathbf{E'}_\perp + \sigma_H (\mathbf{b} \times \mathbf{E'}_\perp)$$

- $\sigma \mathbf{E'}_\parallel$: not relevant
- $\sigma_\perp \mathbf{E'}_\perp$: not happening
- $\sigma_H (\mathbf{b} \times \mathbf{E'}_\perp)$: possible with sufficient n_e, E, and area

Considering all off-diagonal elements in the derivation of the diffusion coefficients yields a similar Hall diffusion.*

$$D_\parallel = \frac{k_B T}{m\nu_c}$$

$$D_\perp = \frac{k_B T}{m\nu_c (1 + \frac{\omega_c^2}{\nu_c^2})}$$

$$D_H = \frac{k_B T \omega_c}{m\nu_c^2 (1 + \frac{\omega_c^2}{\nu_c^2})}$$

$$\simeq \frac{k_B T}{m\omega_c} = \frac{k_B T}{eB}$$

Bohm diffusion

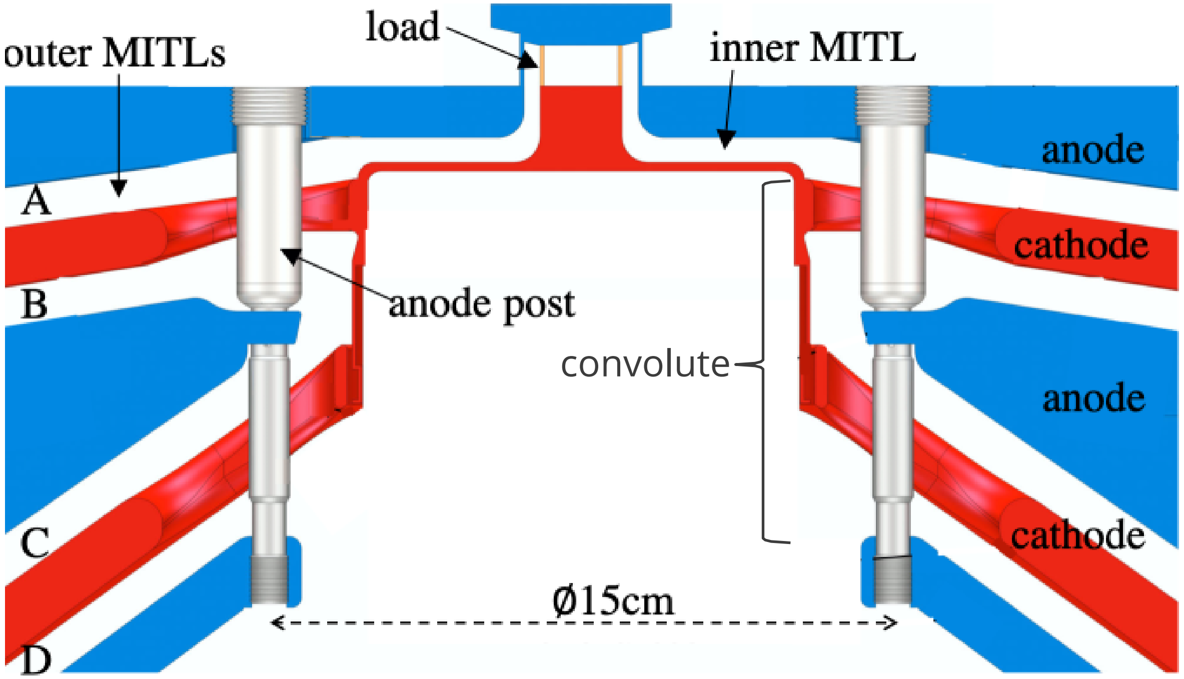
*Bennett, et al. Phys. Rev. Accel. Beams 24, 060401 (2021)

On Z, measurable current is diverted from the load ("I_{loss}").

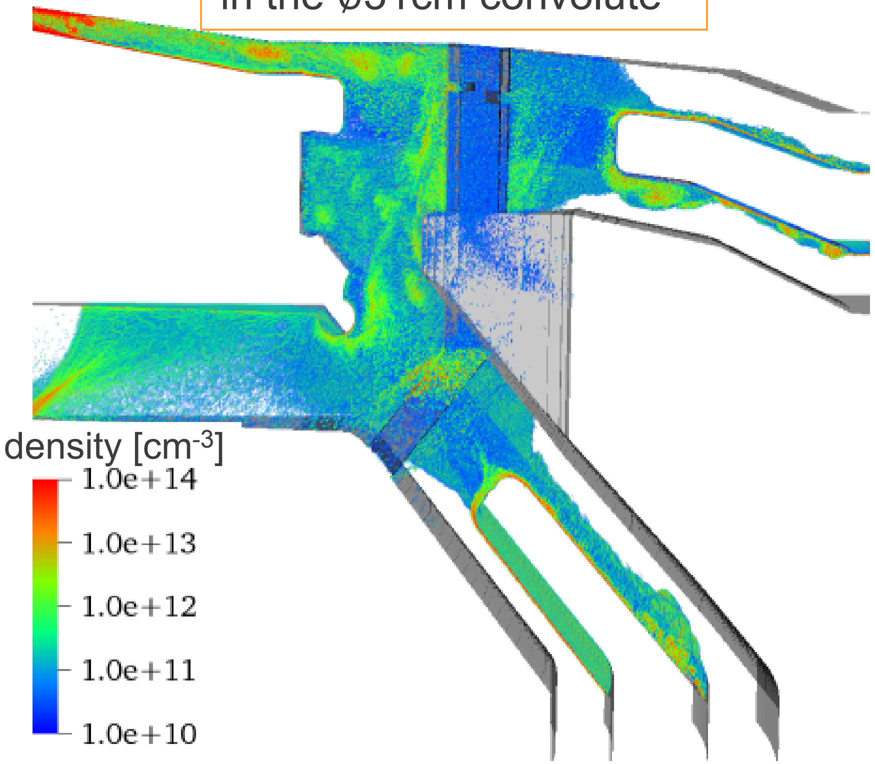
Characteristics of loss current:

- ubiquitous, although ranges from 10^5 to 10^6 A
- may be distributed between the current-adder region and the inner MITL
- not large enough to prevent the z-pinch
- not collisional! $\omega_c/\nu_c > 10^4$

Z Accelerator: current adder to the load

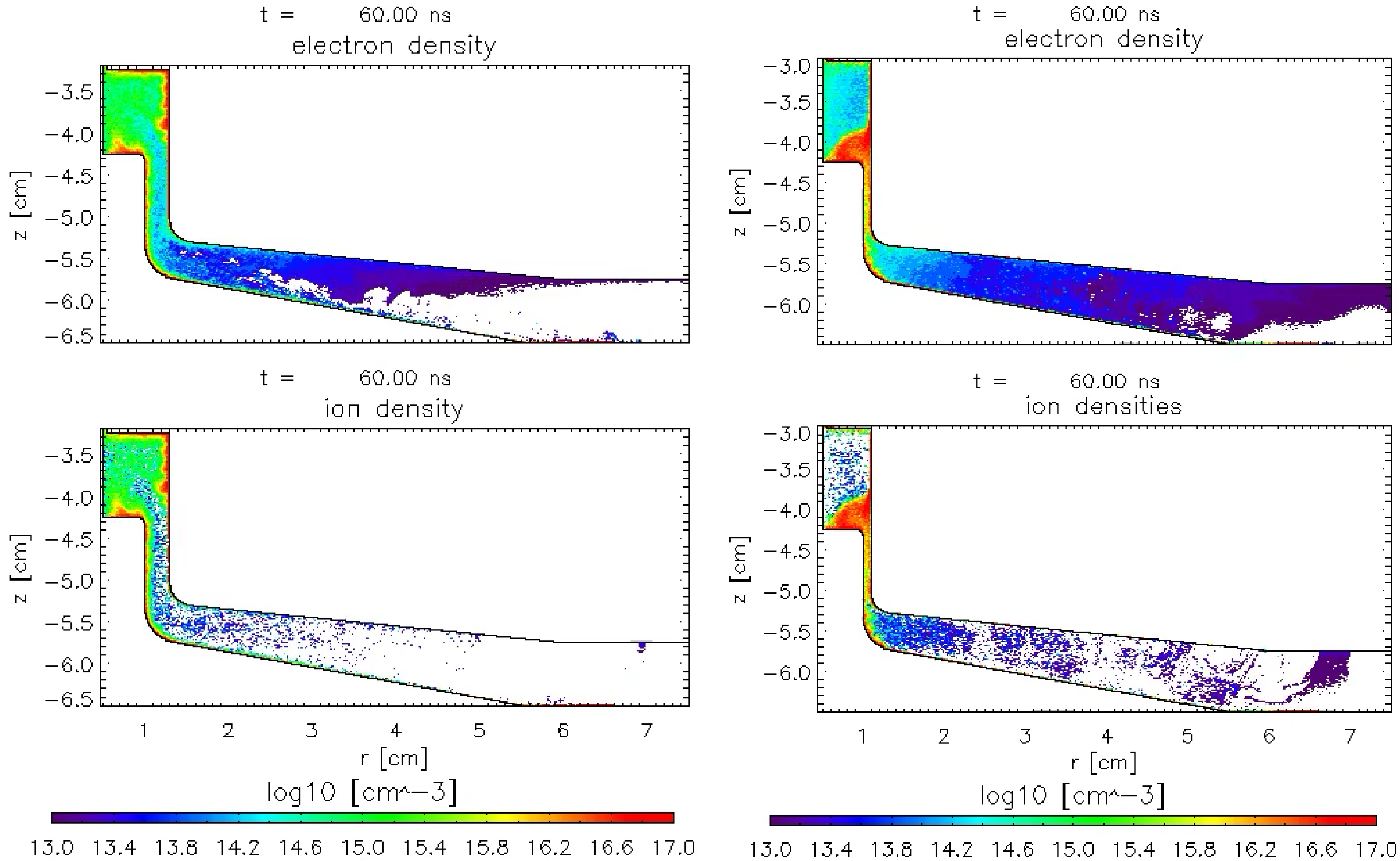


electron density at 80 ns in the Ø31cm convolute



Current loss occurs in models of the inner MITL and convolute only when plasma formation is included.

- Plasma that is insulated from crossing the gap without Hall, drifts downstream and increases the local density closer to the can.
- If gap-spanning plasma carries enough j in a small region, it may jxB downstream.



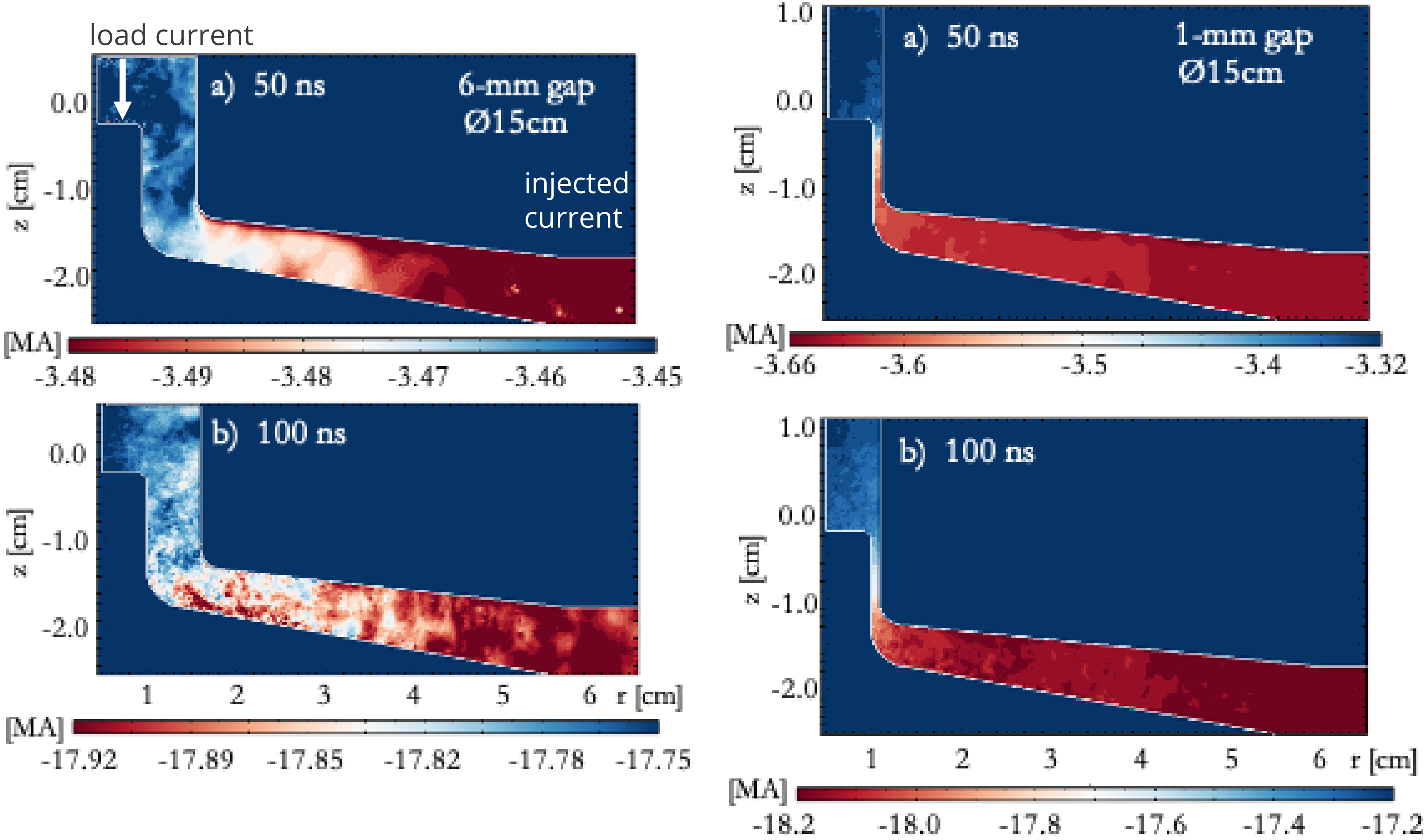
*Bennett, et al. Phys. Rev. Accel. Beams 24, 060401 (2021)

Current loss occurs where plasma accumulates.

Simulated Iloss is the difference between the injected and load currents.

This effect is captured in kinetic and multi-fluid treatments.

However, kinetic may include additional surface physics that impacts surface plasma formation.

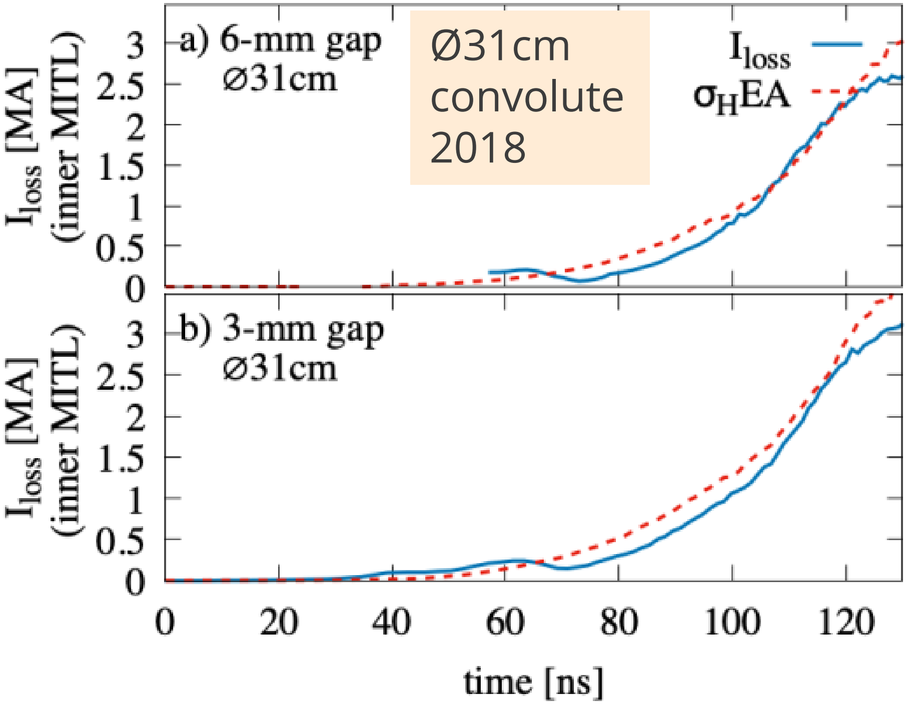


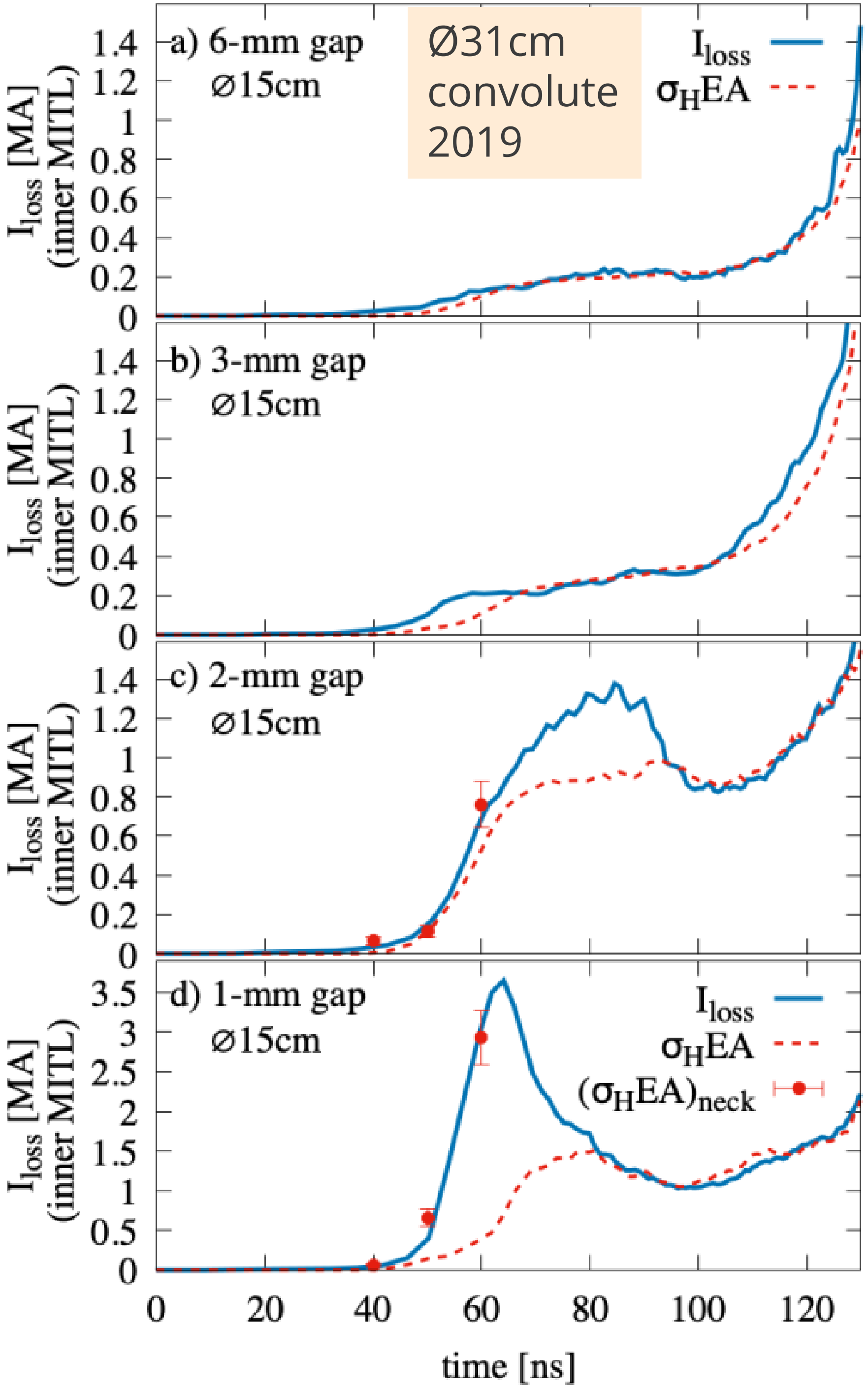
*Bennett, et al. Phys. Rev. Accel. Beams 24, 060401 (2021)

A calculated Hall-term current ($I_{loss}=\sigma_H EA$) agrees with the current diverted in the inner MITL.

Calculating I_{loss} using values of n_e, B, T_e, and E in the higher plasma region (A).

$$\sigma_H = \frac{ne^2}{m\nu_c}\left(\frac{\frac{\omega_c}{\nu_c}}{1+\frac{\omega_c^2}{\nu_c^2}}\right)$$





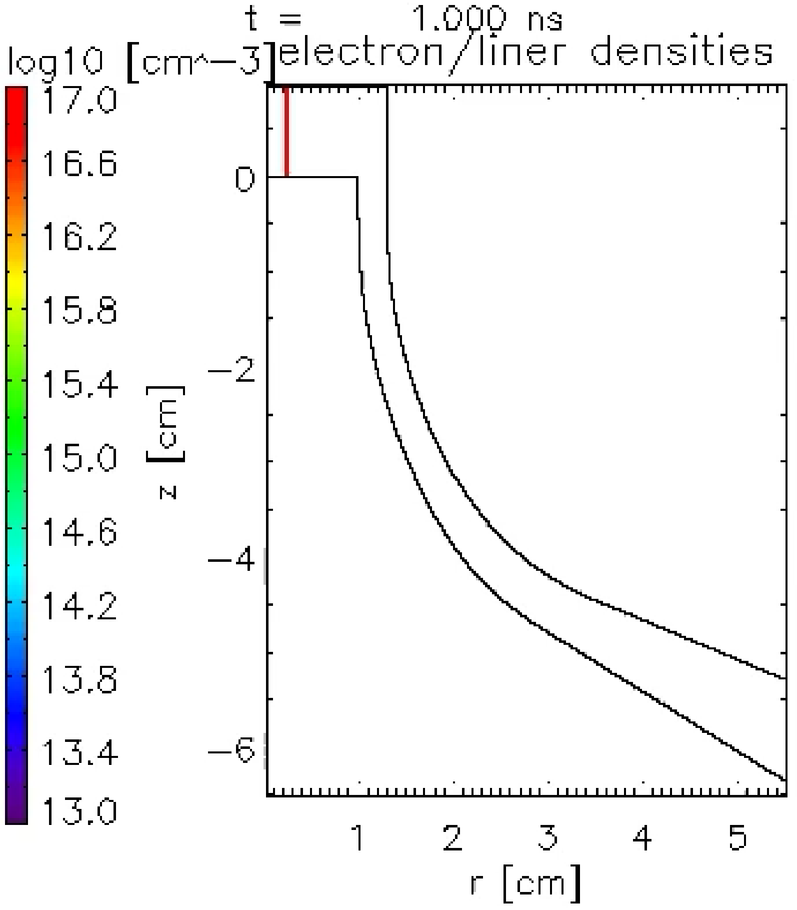
*Bennett, et al. Phys. Rev. Accel. Beams 24, 060401 (2021)

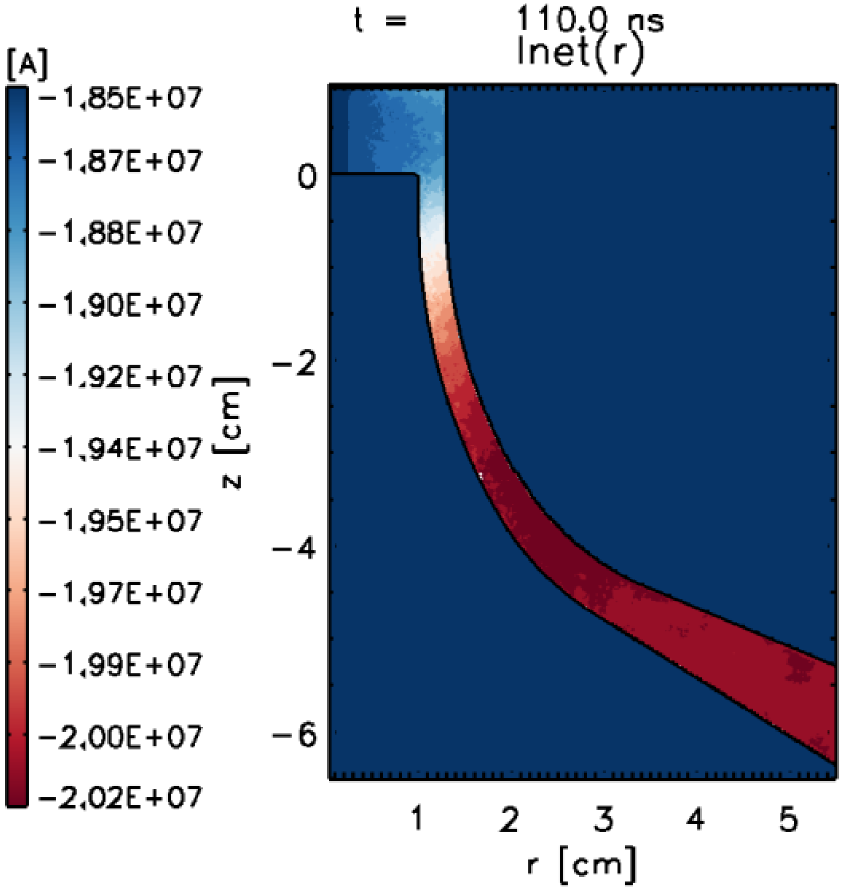
Improvements to simulation run time and load inductance modeling have made power flow simulations valuable tools for Z shot designs.

MagLIF* type geometry without an applied Bz field has current loss co-located with higher n_e and E.

- Multi-fluid simulations provide predictions relatively rapidly. (This depends on the hardware design and the computing resources available.)

- The “moving liner” model is being applied to studies conducted by M. Gomez and D. Zimmer. This provides a robust simulation of the inductive E-filed during implosion.





*Gomez, et al. Phys. Rev. Accel. Beams 20, 010401 (2017)

Current loss in Z may be studied /predicted using kinetic of multi -fluid models that include surface plasma formation.

1. Kinetic modeling includes the complete equations of motion. Multi-fluid should also allow for charge separation and space-charge-generated electric fields.
2. Cross-gap currents can manifest as continued losses over a region of the transmission line. They may also accumulate enough current density to $j\times B$ downstream.
3. Multi-fluid modeling is sufficiently fast to be included in the shot design stage, complementing circuit-model predictions of current delivery to the load. (See N. Bennett, M. Hess, and E. Estatiev.)