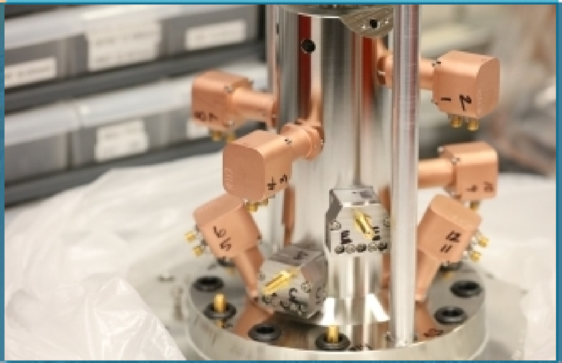
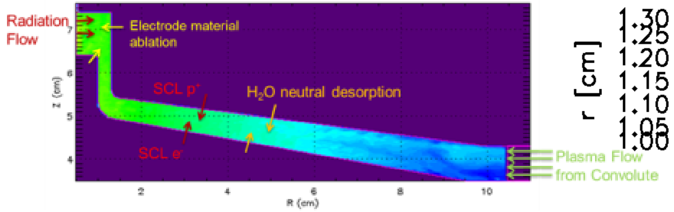
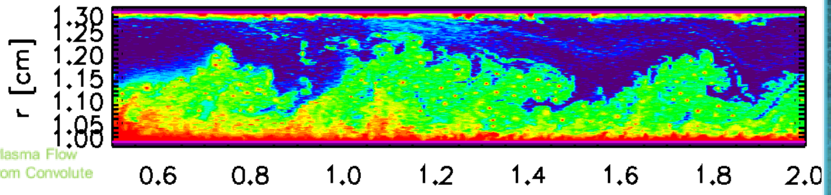
SAND2024-15733C

The electrode plasma conditions in multi-MA transmission lines







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T. Avila, C. De La Cruz, B. Hutsel,
A. Porwitzky, A. Romero, D.R. Welch

Fusion Energy and Pulsed Power Workshop 2024
San Diego, CA
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SAND2024-15733C

Understanding electrode plasma dynamics (in the current adders, in the final feed, and near the ICF load) will help realize a pulsed-power fusion energy system.

In pulsed power, electrode plasmas have long been associated with reduced driver efficiency.
By understanding their generation and transport physics, we can improve designs on current and future systems.

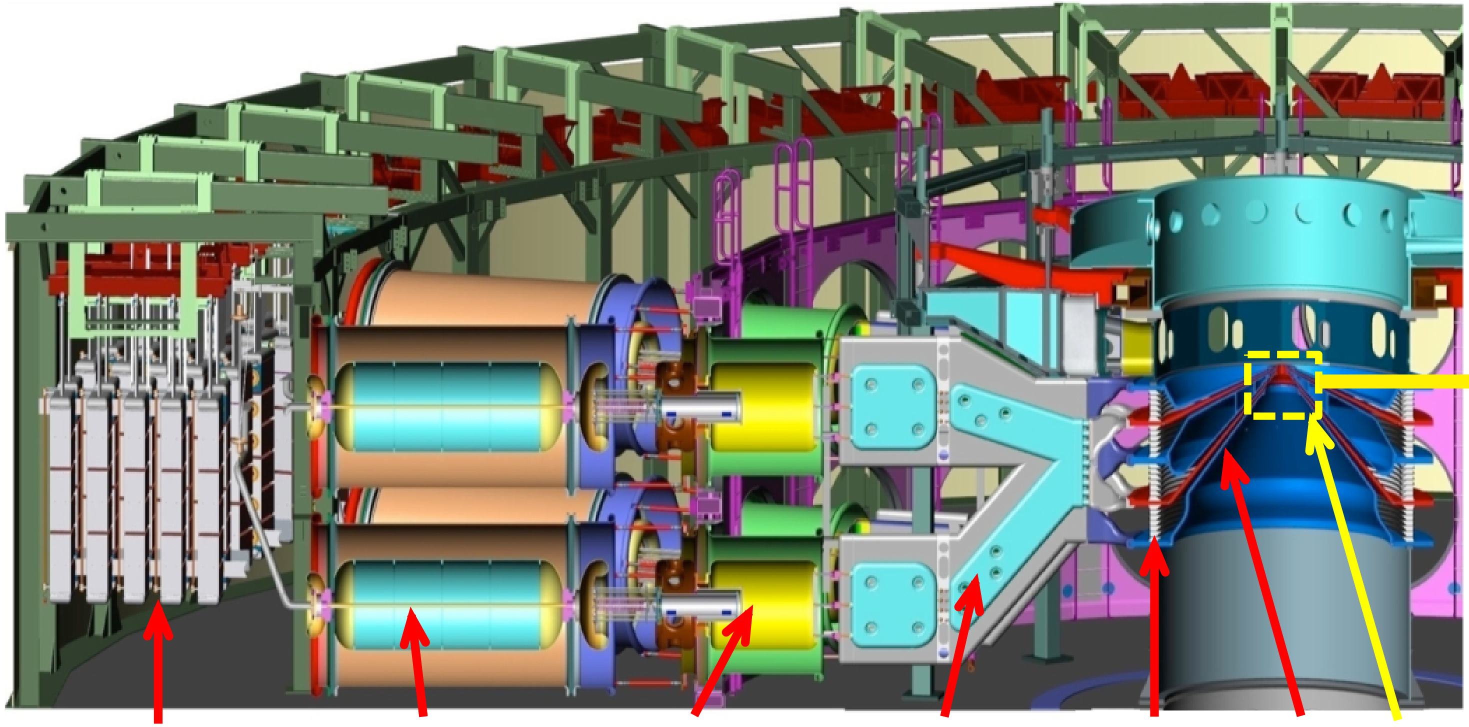
While kinetic codes can capture this physics, casting some mechanisms in MHD terms helps clarify and point to mitigation strategies.

Notable progress:

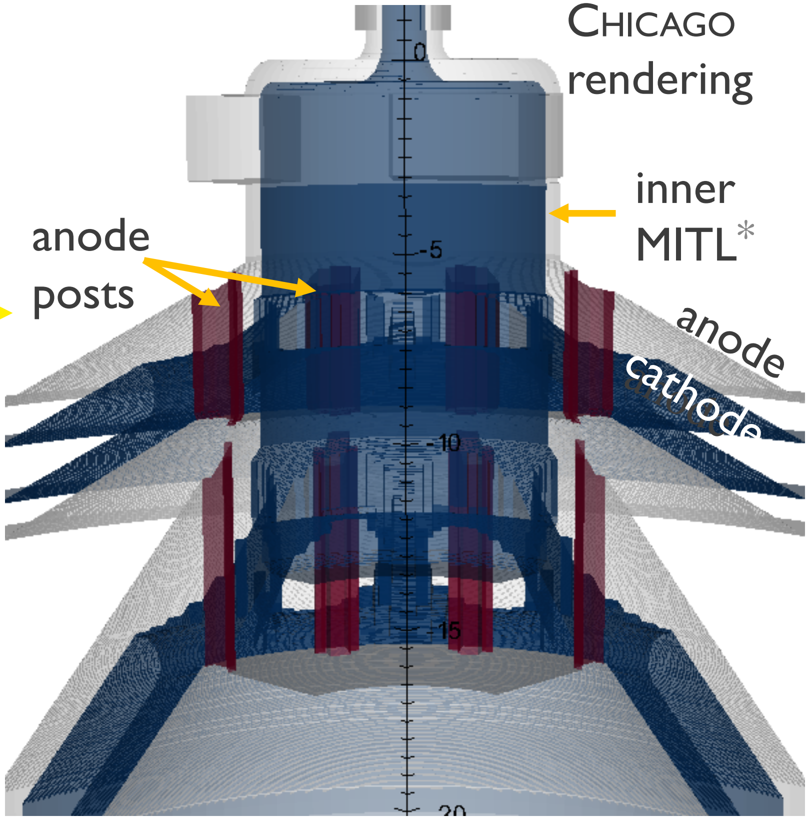
- Hybrid approach to electrode modeling (MHD, kinetic) to understand melt transition near a load [Phys. Rev. Accel. Beams 26 040401 (2023)]
- Plasma sheath instability studies by Vogman, Hammer, and Welch
- Hall-conductivity related transport (validated predictions of current loss)

Electrode plasmas are a concern when current densities are measured in MA/cm.

Using Sandia National Laboratories' Z Machine as an exemplar



2D and 3D models include charged-particle emission and surface contaminant desorption.

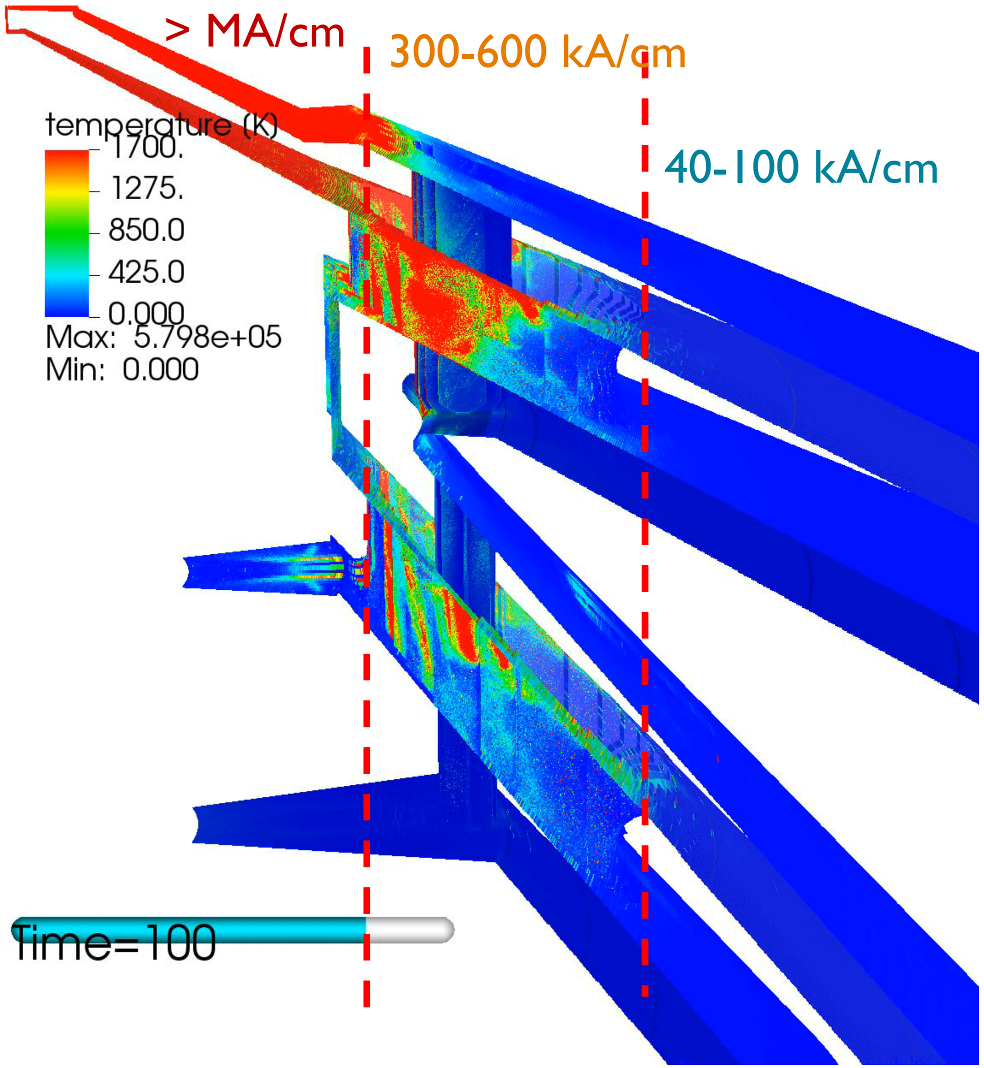


Phys. Rev. Accel. Beams 22, 120401 (2019)
Phys. Rev. Accel. Beams 23, 110401 (2020)
Phys. Rev. Accel. Beams 24, 060401 (2021)

*Magnetically Insulated Transmission Line

In an ICF driver, the inner MITL is engineered to generate plasmas.

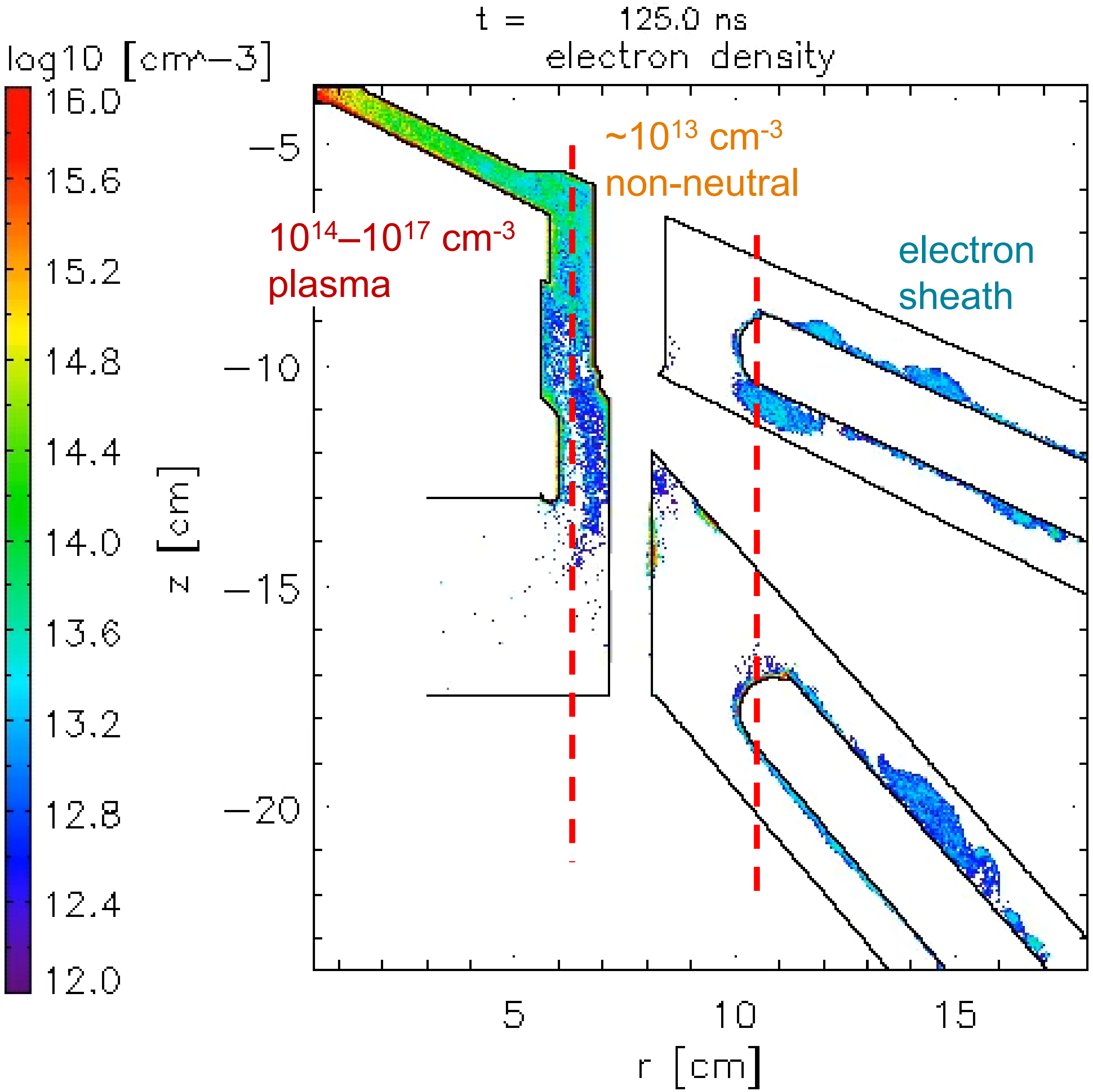
Simulated surface temperatures from Joule and particle dE/dx heating.



- The outer MITLs reach 40-100 kA/cm.
  - negligible temperatures rise (~25 K)
  - Child-Langmuir electron emission
  - losses prior to electron insulation
- The current adder region
  - Child-Langmuir electron/ion emission
  - denser plasmas on hot spots
- The inner MITL exceeds 1 MA/cm.
  - dominated by Joule heating and
  - **magnetic confinement**

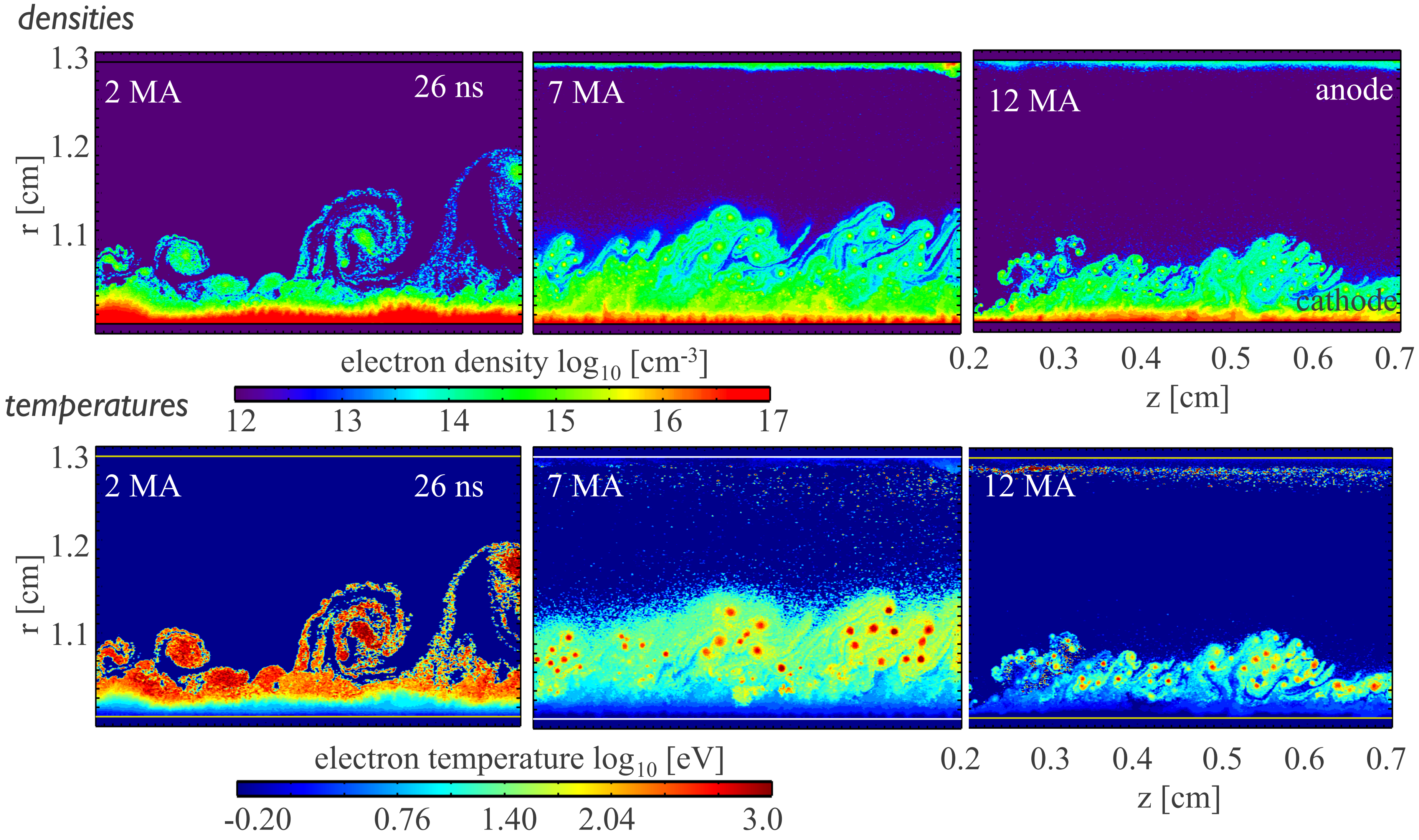
The inner MITL plasma density is impacted by the upstream sheath currents.

- The drifting particles help transport inner MITL surface plasmas into the gap against the confining magnetic field.
- This highlights the importance of the study of surface plasma instabilities (Vogman, Welch)



Kinetic models of surface breakdown (MC-PIC) illustrate magnetic confinement and formation of two plasma populations.

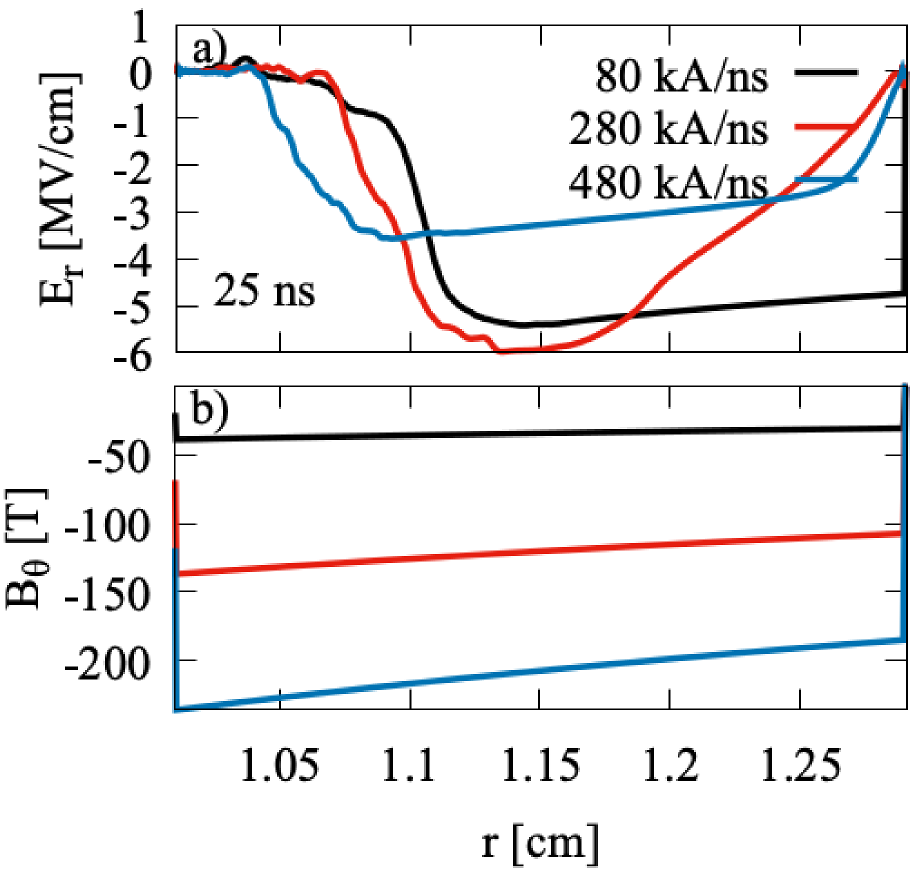
- A cooler, denser surface layer and a hotter, tenuous gap plasma
- The density in the gap is somewhat independent from the surface density.
- The plasma sheath layer gains kinetic energy from the E field.



Phys. Rev. Accel. Beams 26 040401 (2023)

Kinetic models of electrode plasma formation illustrate the unique space they occupy.

E and B from the kinetic breakdown study



- The **B**-field heats the electrodes while restraining v_{drift}.
- Because **B** rapidly diffuses through the plasma, the plasma is not carrying current and the particles are not Ohmically heated.

$$1/\mu\sigma_? \leftarrow 10^5 - 10^8 \ m^2/s$$

- The denser plasma near the electrode surface excludes **E**. (The collisionless skin depth at 10^{17} cm^{-3} = 16.8 μm and ω_{pe}~10^{13}/s.)

B_θ rapidly penetrates while the electrode potentials are advected by the plasmas. Plasma expansion is against a highly confining B_θ.

The mechanisms that assist plasma transport include instabilities, charge exchange, and the Hall conductivity.

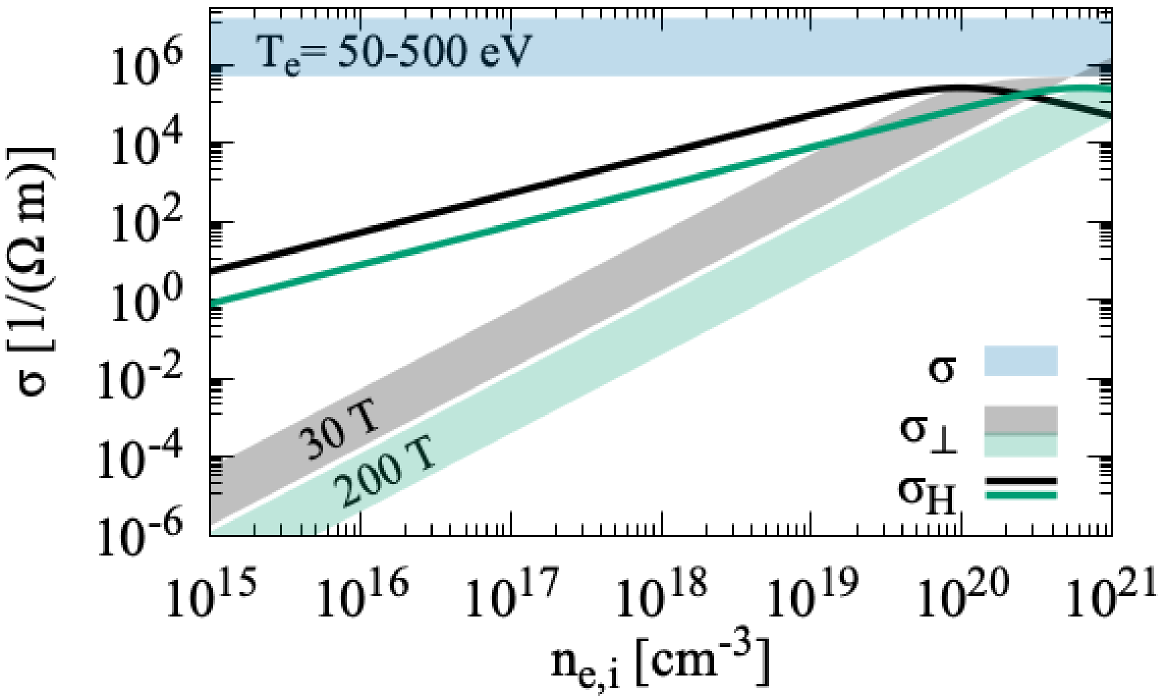
In electrode plasma formation, $\omega_c/\nu_c = 10^3\text{-}10^7$

To understand (kinetic) transport and cross gap currents, we use the generalized Ohm's law fluid description.

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

Absent a mechanism to generate 10^{20} cm^{-3}, there is an abrupt jump in conductivity between the surface plasma and the electrode.

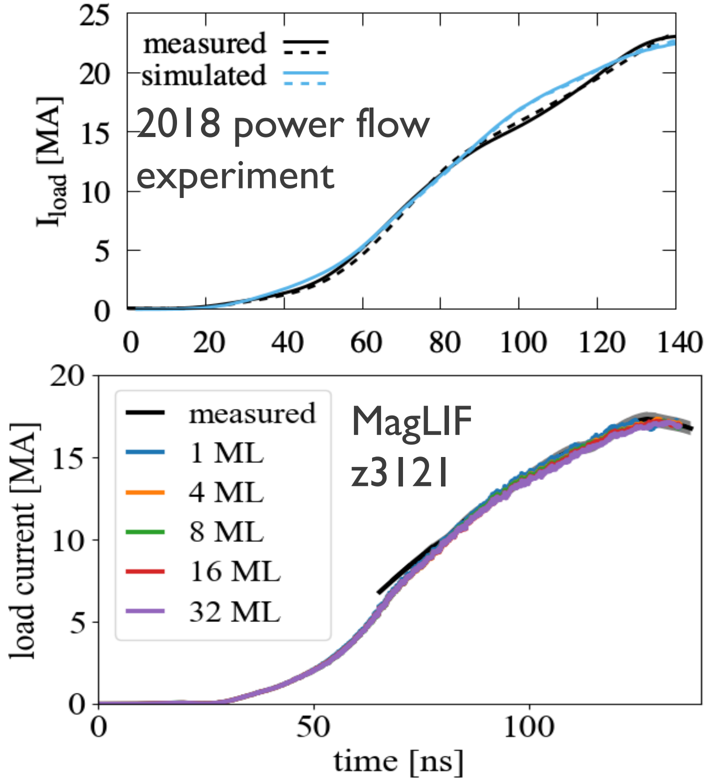
We confirmed the impact of the Hall conductivity experimentally.

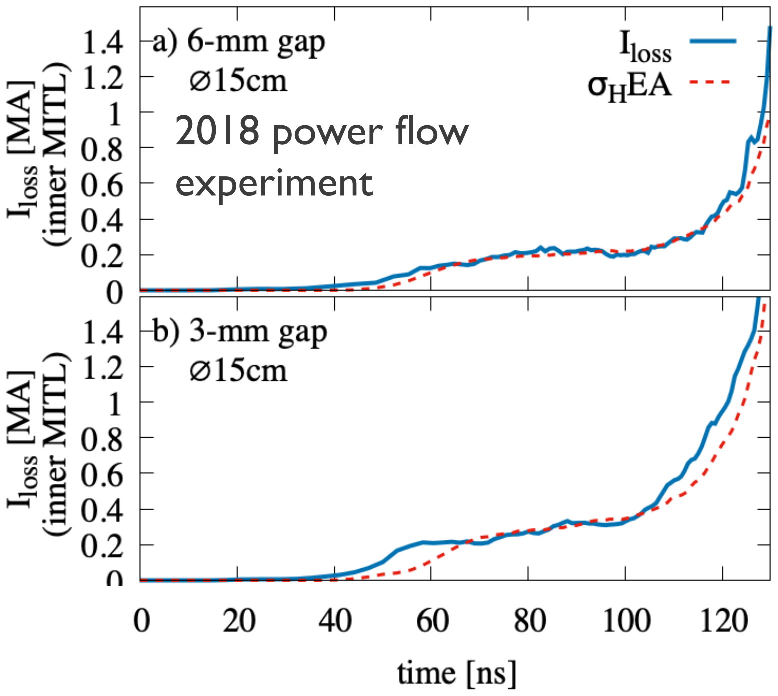


$$\sigma = \frac{ne^2}{m\nu_c} \qquad \sigma_H = \sigma_\perp \frac{\omega_c}{\nu_c}$$

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

There is almost always good agreement between the Chicago kinetic models and measured current loss on Z.





The simulated loss mechanism accords with Z performance:

- ubiquitous but not catastrophic
- increases with inductive E
- suitable for low-density plasmas

We previously determined that a calculated Hall-term current ($\sigma_H(t)E(t)A$) agrees with the loss current. It still needed to be distinguished from competing mechanisms.

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

Two experiments were predicted to distinguish Hall-conductivity losses from enhanced-ion currents and plasma streamers.

enhanced ion current*:

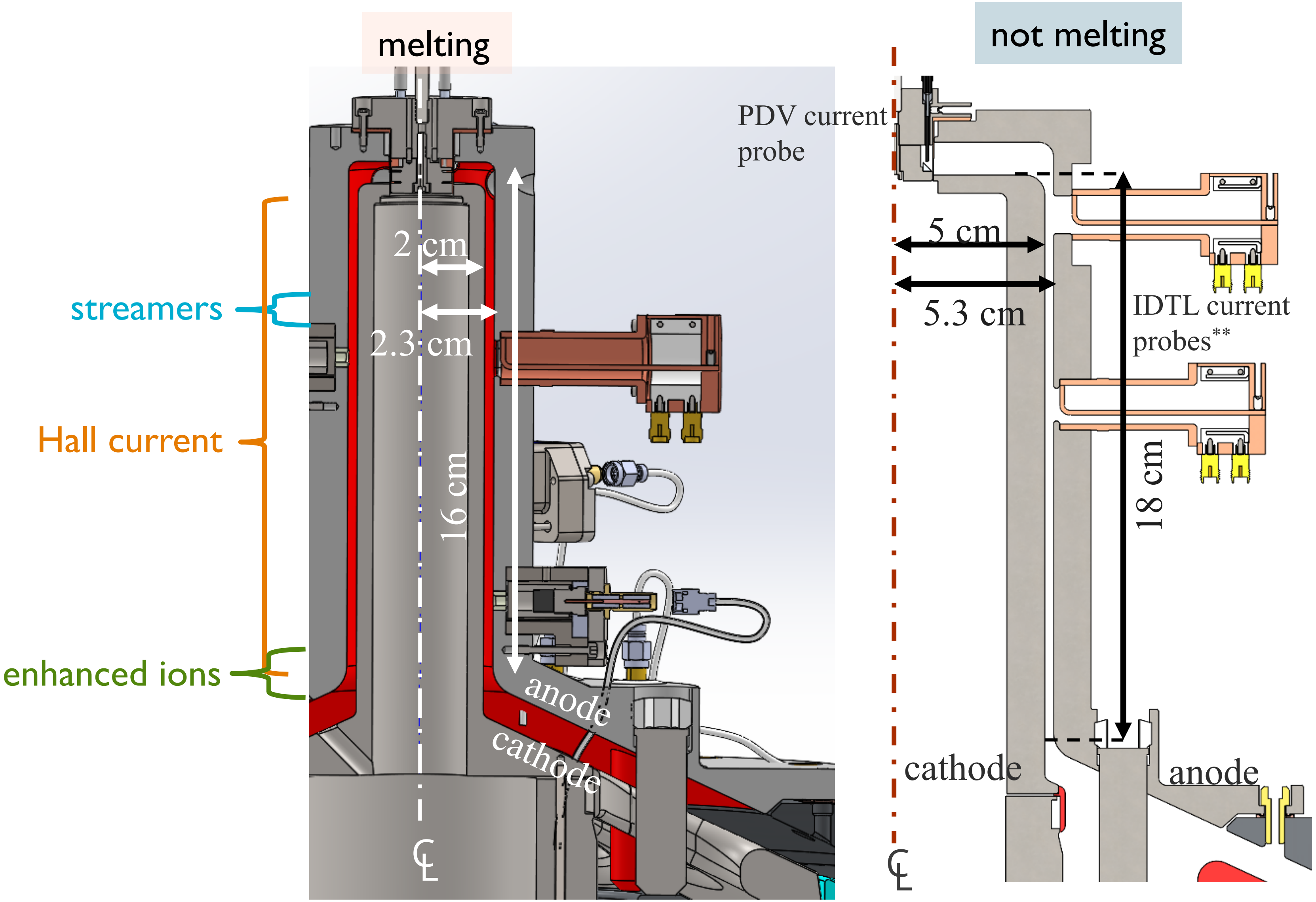
The particle current entering the inner MITL is dominated by electrons. The negative space-charge draws more positive ions from the anode than the applied field alone. These ions cross the gap. (~1 MA at the convolute)

streamers:

High-density plasma in a small volume. (concentrated loss)

Hall current:

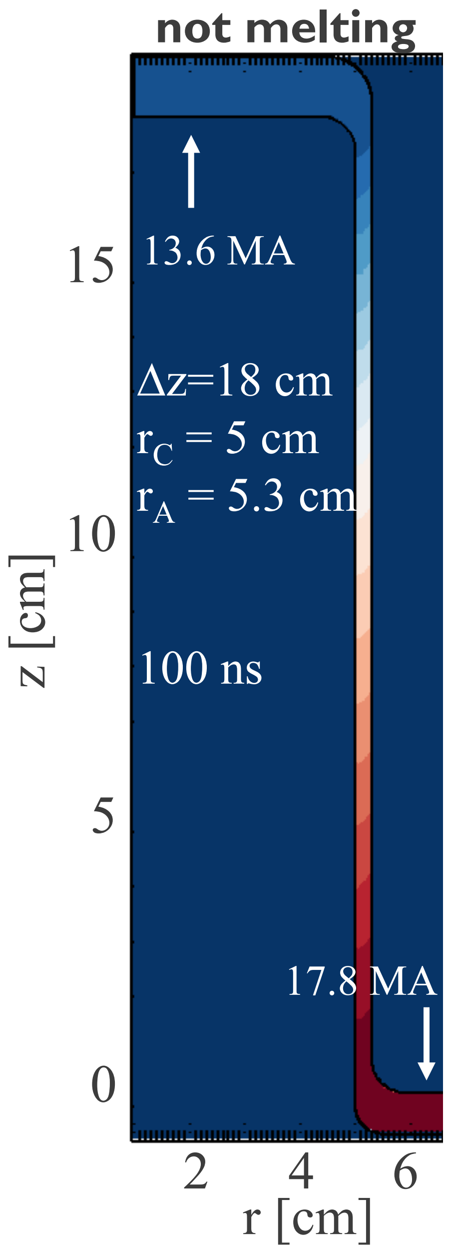
Large-area loss in low-density plasma theoretically possible based on off-diagonal conductivity tensor elements. (extended area loss, ~9 MA)

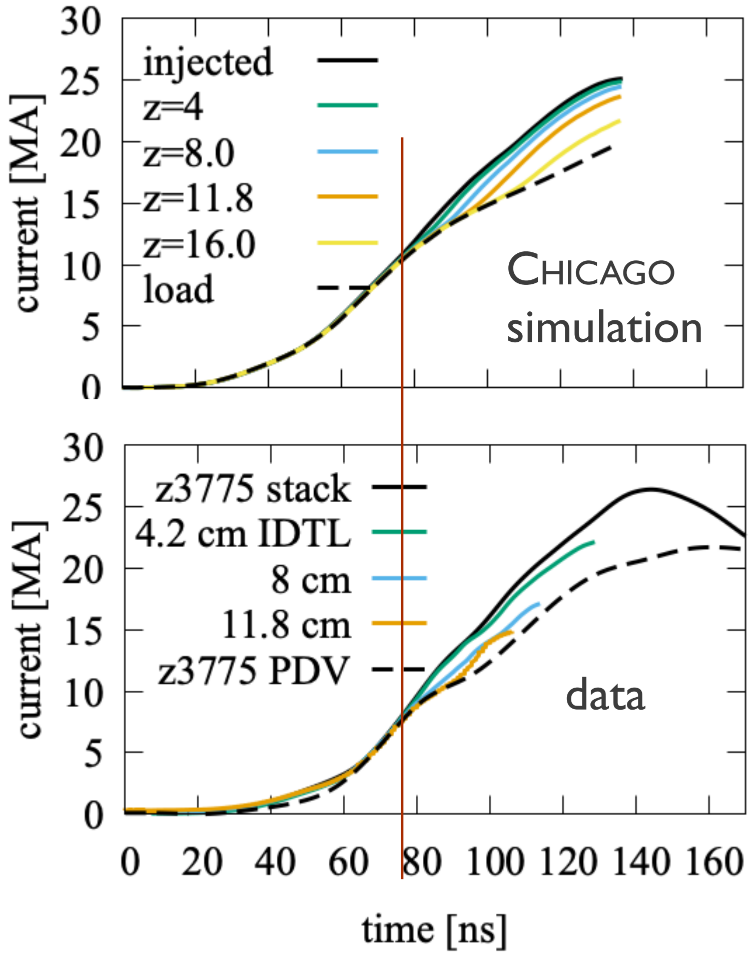


*Waisman, et al. Phys. Rev. Accel. Beams 22, 030402 (2019)

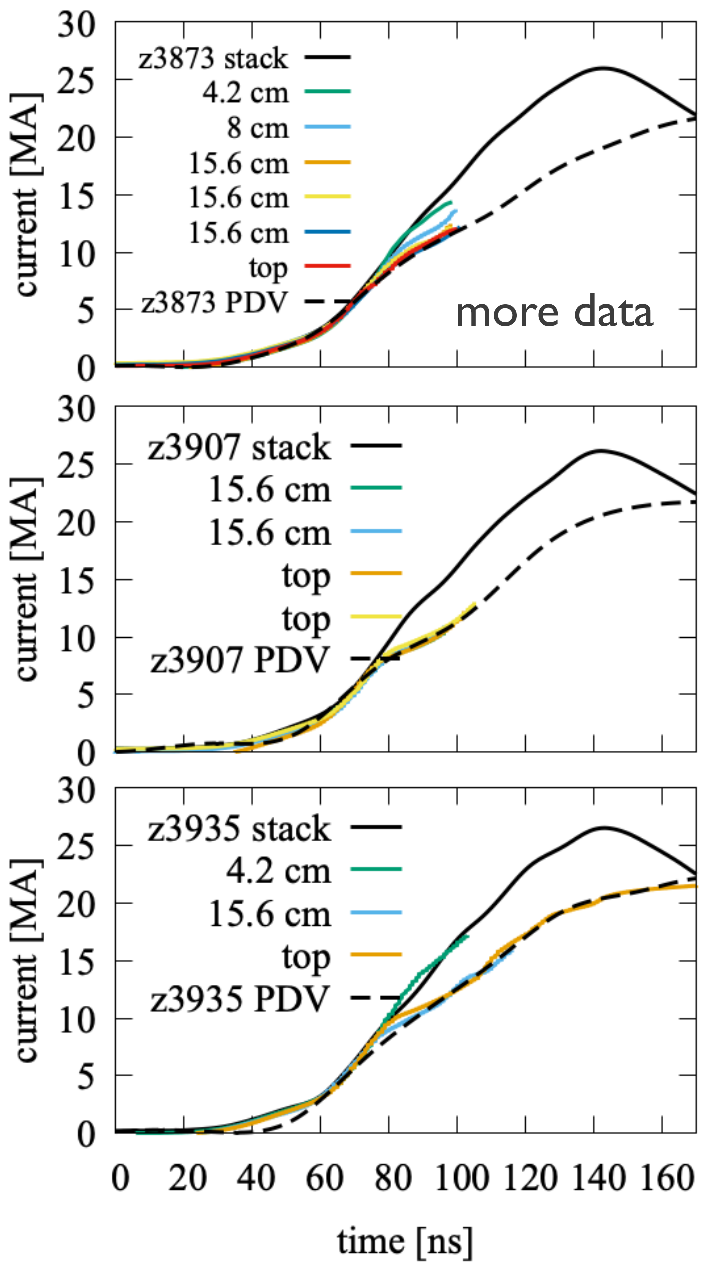
**Myers, et al. RSI 92, 03 (2021)

Kinetic simulations predicted current decreasing along the length of the MITL.

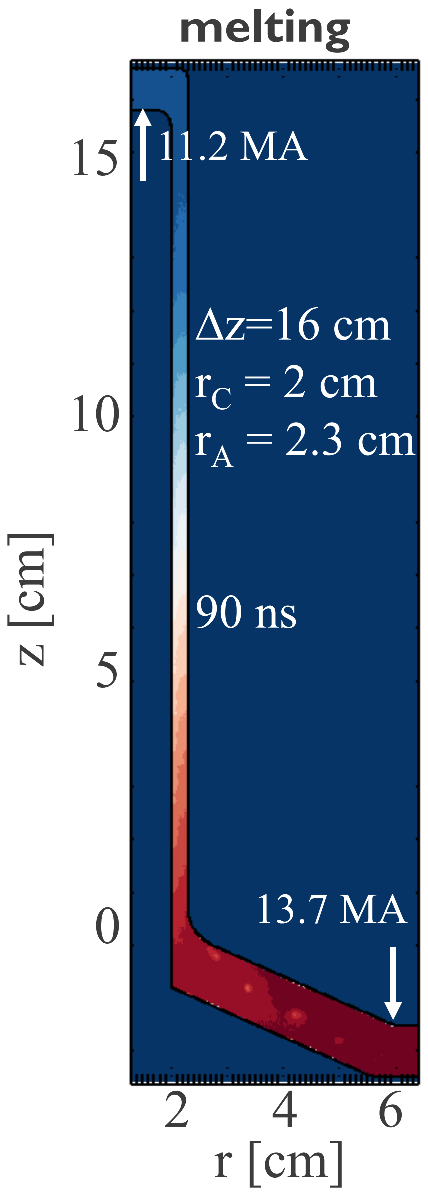


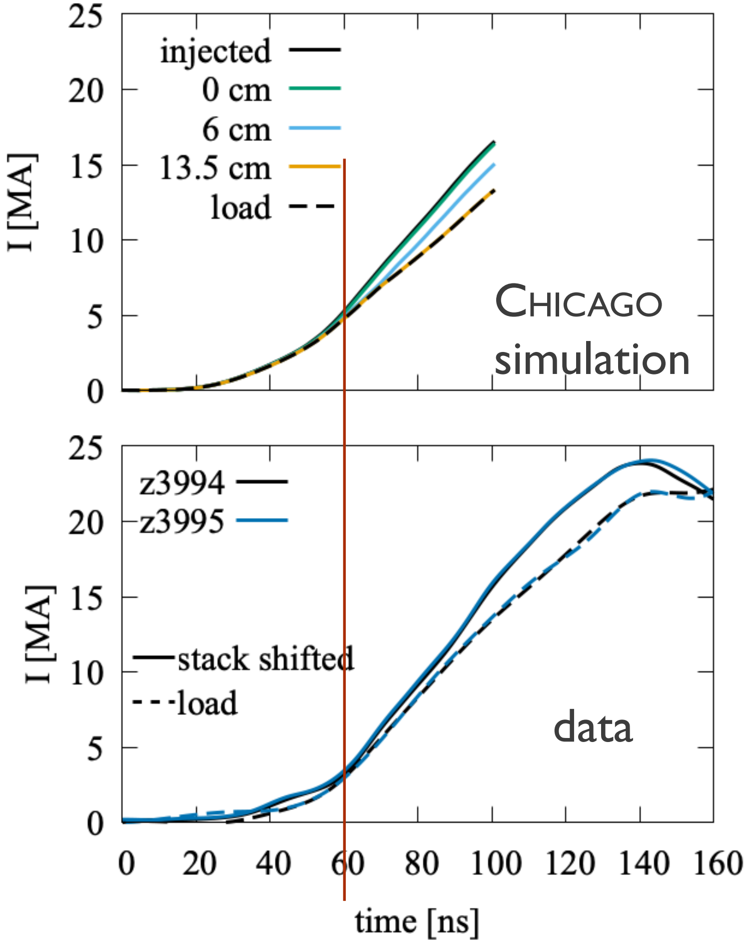


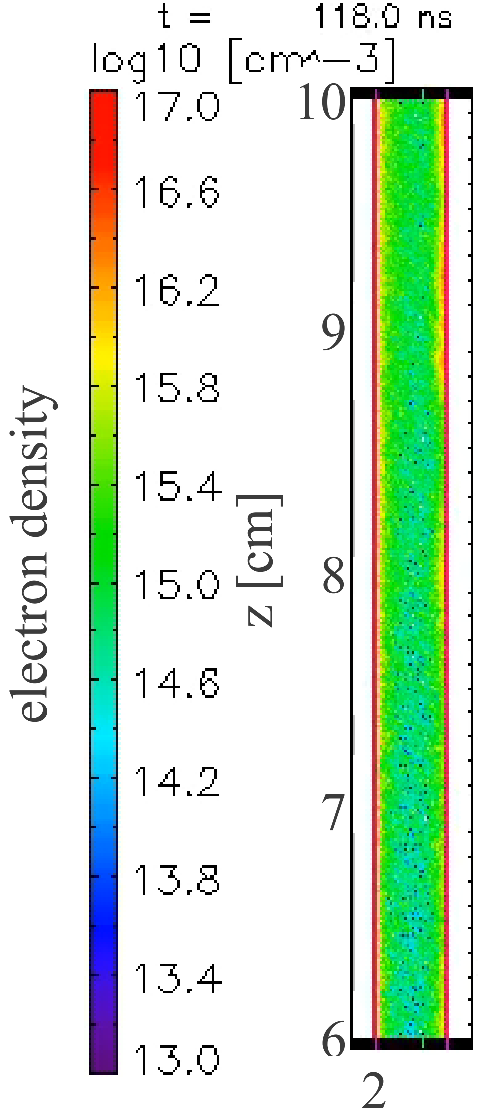
Simulated current loss agrees in onset and magnitude.



Even within the melt radius, simulations predicted current decreasing along the length of the MITL, with loss appearing earlier.



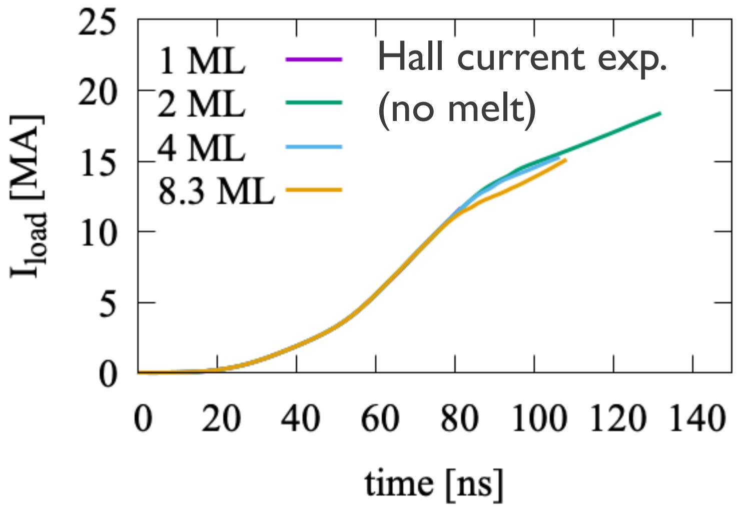


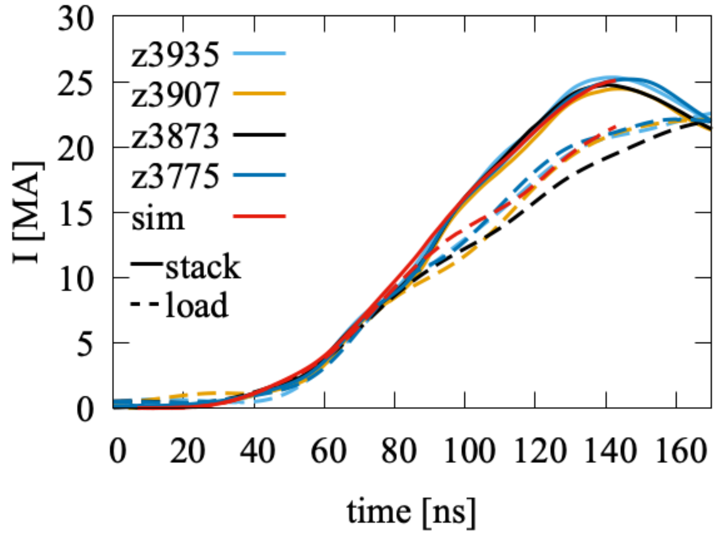


Simulated current loss agrees in onset and magnitude.

Conclusions

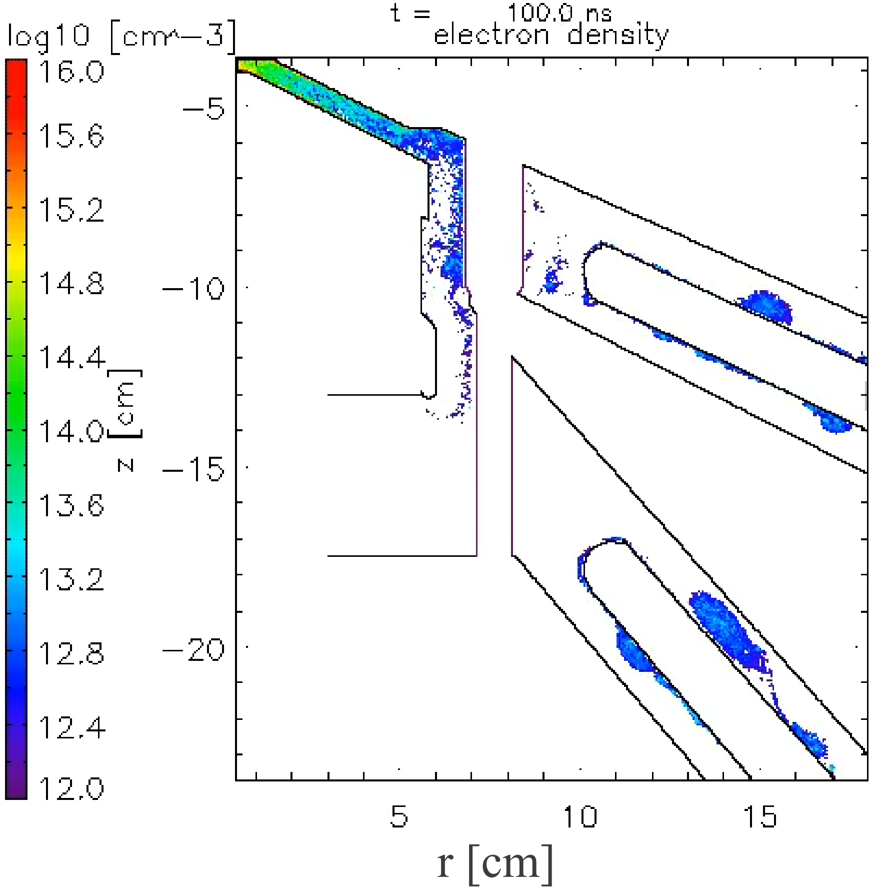
- The plasma evolves via:
    - the rising local magnetic field increases the local electrode surface temperature
    - thermal desorption of neutral contaminants from the electrode surface
    - contaminants rapidly ionize forming a $10^{15} - 10^{18}$ cm^{-3} plasma
    - effectively resistive while weakly collisional because it is created within, and rapidly penetrated by, strong magnetic fields
    - the expected contamination inventory limits the plasma density prior to melt
- Experiments on Z verified current loss via the Hall conductivity in the generalized Ohm's law.
    - The current loss agrees with Hall loss in distribution, turn-on time, and magnitude.
    - Results were not consistent with streamers or enhanced ion losses.
    - This mechanism accords with Z performance:
        - ubiquitous but not catastrophic
        - increases with inductive E
        - suitable for low-density plasmas

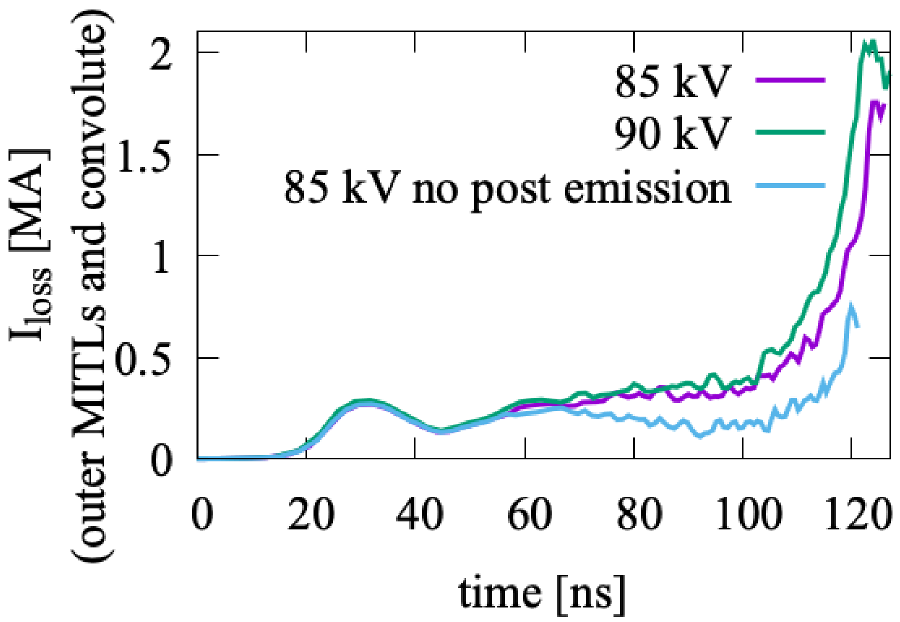




backup slides

Extending this theory to plasma losses in the adder region, we find electron sheaths help increase plasma densities in the gap.

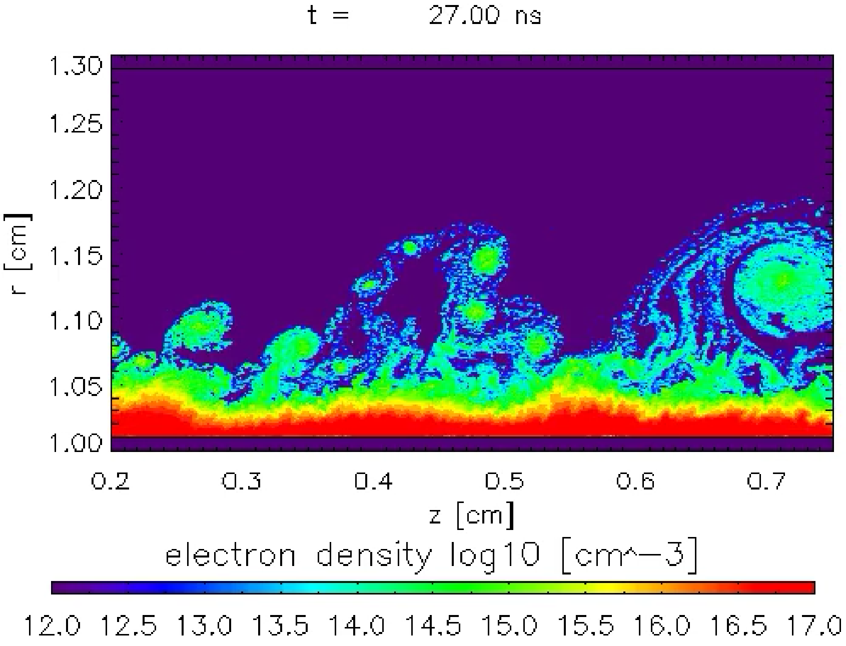




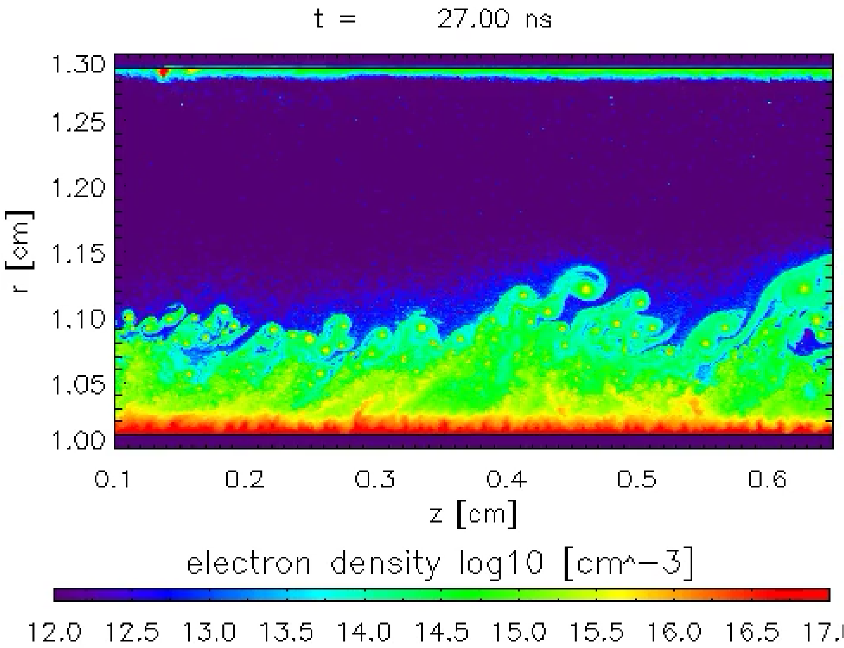
We need to understand instability-driven transport.

Breakdown is modeled for three peak currents: 8, 28, and 48 MA.

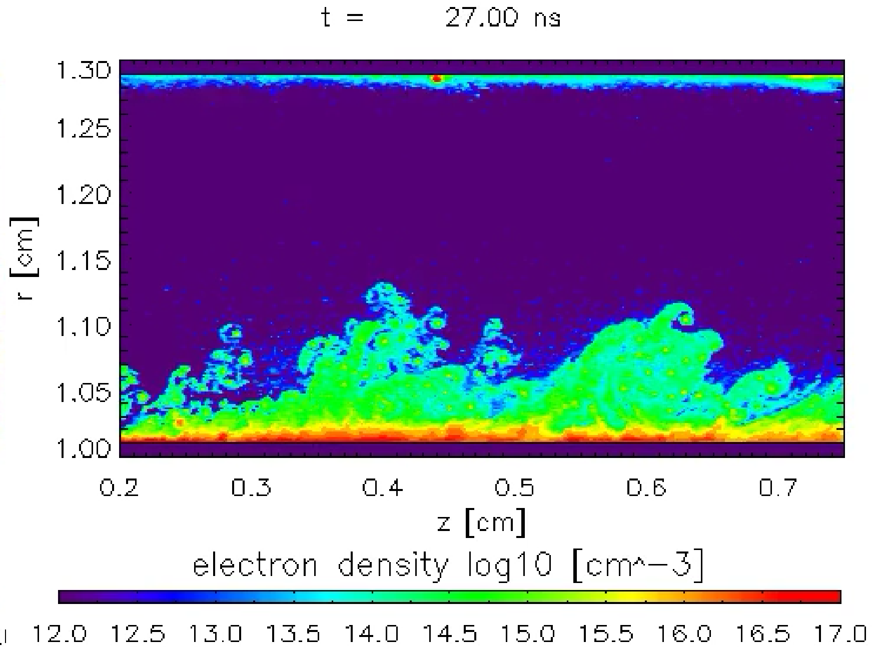
80 kA/ns



280 kA/ns



480 kA/ns



- The plasma formation rate is the confluence of **B,** dn/dt, the ionization rates, and **E**.
- The emission is later for lower peak current, but the transport into the gap is more rapid.
- This is related to plasma diffusion, but complicated by neutral resupply, ionization, charge exchange, and applied **E**.

$$D_{H} = \frac{\omega_c}{\nu_c} D_{\perp} \simeq \frac{k_B T}{m\omega_c} = \frac{k_B T}{eB}$$

The PIC kinetic treatment advances Maxwell's equations and Lorentz force without approximation*. Multi-fluid substitutes pressure for intra-species collisions.

* $F_c(\mathbf{v}_1,\mathbf{v}_2)$ interactions may be approximate.

PIC kinetic equations

$$m_\alpha \frac{d(\gamma_\alpha \mathbf{v}_\alpha)}{dt} = q_\alpha(\mathbf{E} + \mathbf{v}_\alpha \times \mathbf{B}) - \nu_{\alpha\beta} m_\alpha (\mathbf{v}_\alpha - \mathbf{v}_\beta)$$

$$\epsilon\mu \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

electrostatic

$$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon}$$

$$\nabla \cdot \mathbf{B} = 0$$

current and charge densities

$$\mathbf{j} = \sum_\alpha q_\alpha \mathbf{v}_\alpha \delta(\mathbf{r} - \mathbf{r}_0)$$

$$\rho_e = \sum_\alpha q_\alpha \delta(\mathbf{r} - \mathbf{r}_0).$$

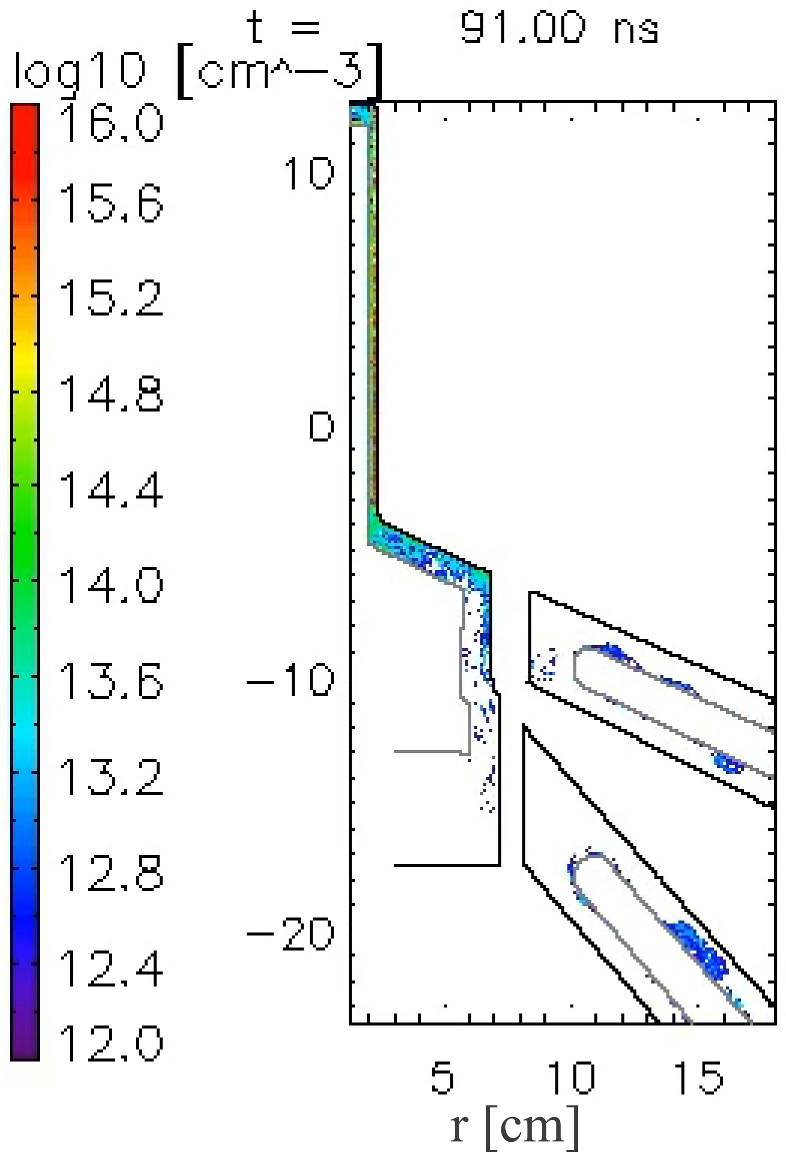
Chicago multi-fluid equations

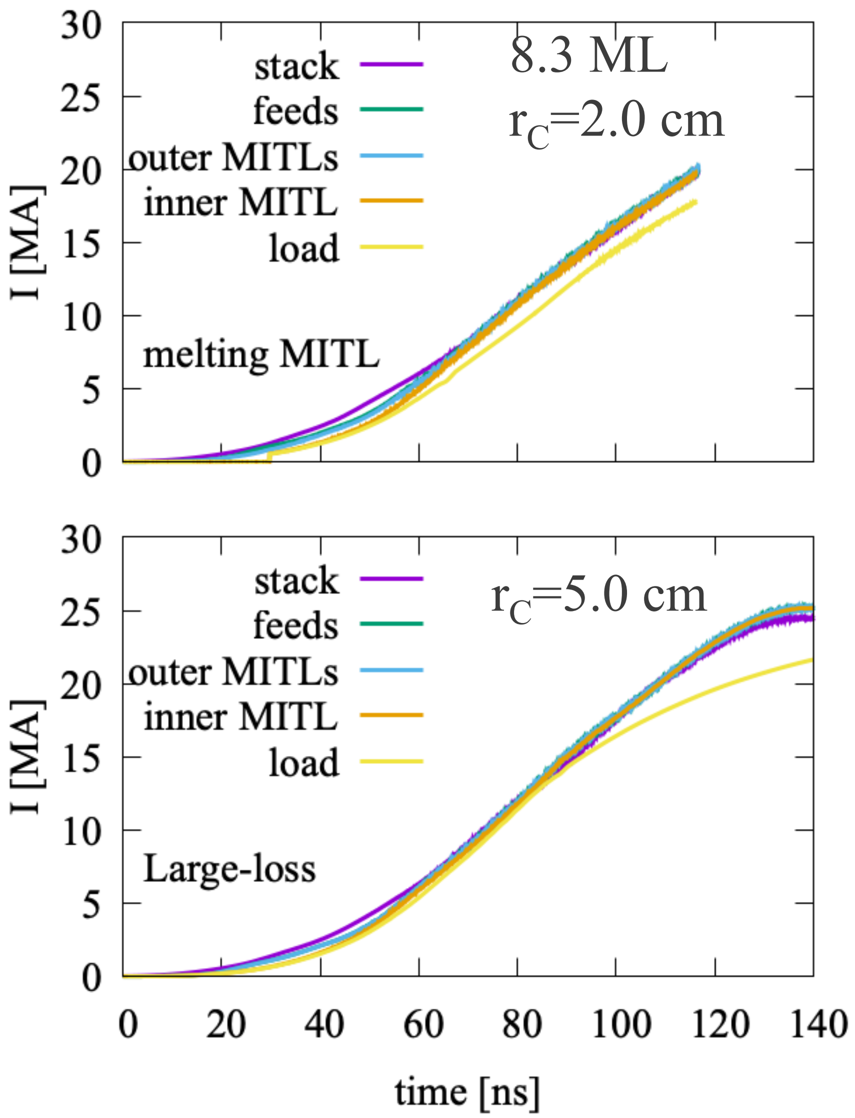
$$m_e \frac{d\gamma \mathbf{v}_e}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{v}_e}{c} \times \mathbf{B}\right) - \frac{\nabla p_e}{n_e} - m_e \nu_{ei}(\mathbf{v}_e - \mathbf{v}_i)$$

$$m_i \frac{d\gamma \mathbf{v}_i}{dt} = e\bar{Z}\left(\mathbf{E} + \frac{\mathbf{v}_i}{c} \times \mathbf{B}\right) - \frac{\nabla p_i}{n_i} - m_i \nu_{ij}(\mathbf{v}_i - \mathbf{v}_j).$$

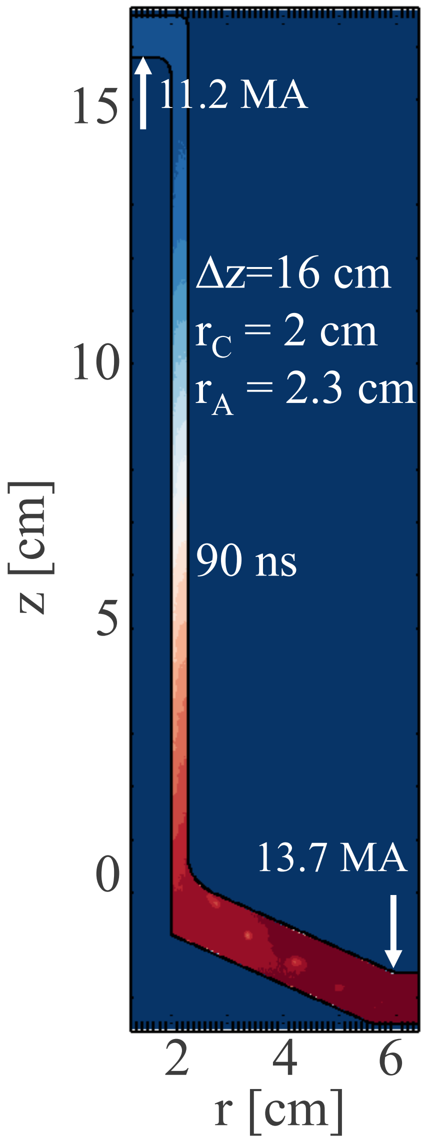
Kinetic and multi-fluid have the same resolution requirements (ω_{ce}).

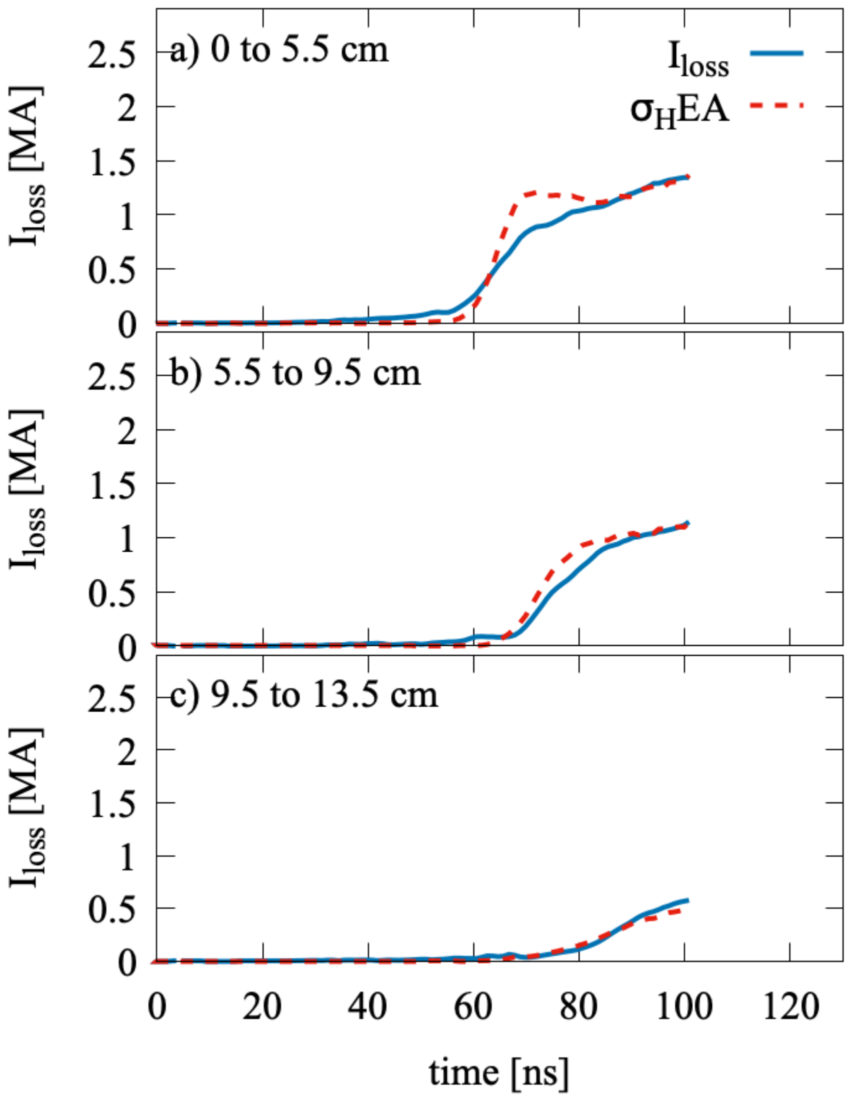
Large-scale, 3D models show the adder region has negligible losses.





The kinetic losses are well-matched to a Hall current.





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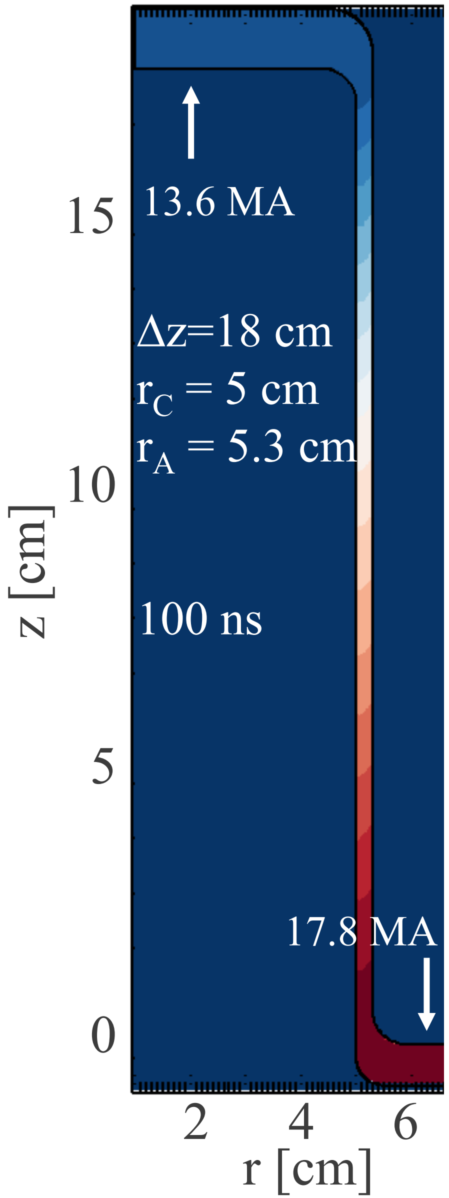
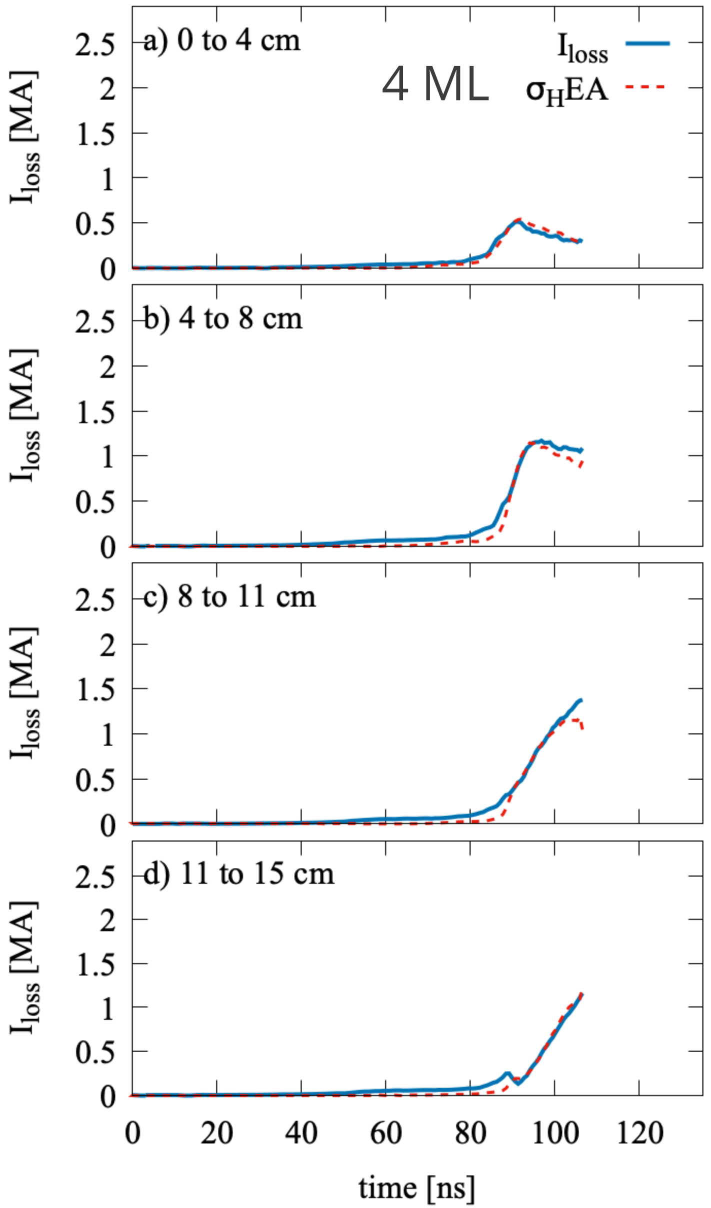


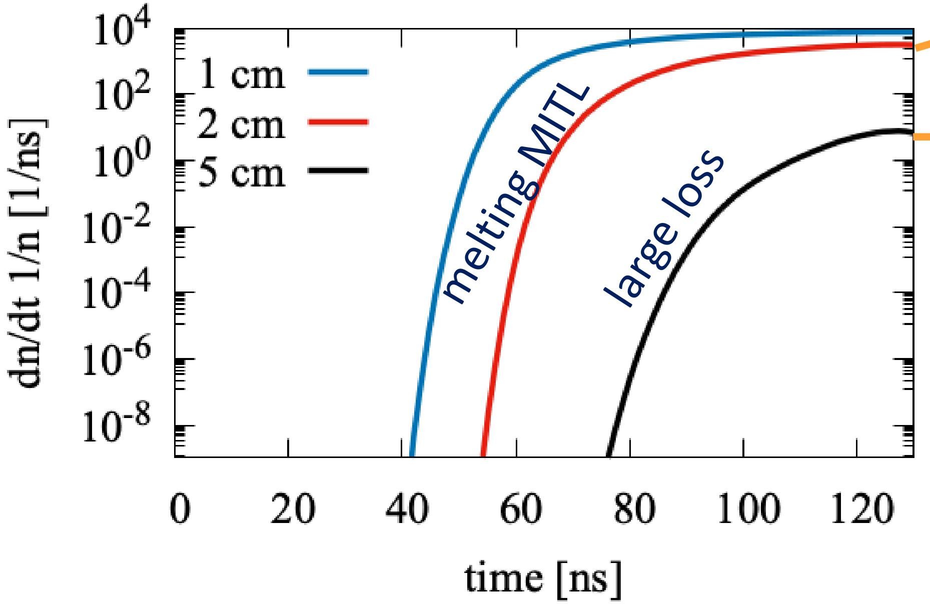


Current loss occurs after the onset of plasma formation, which depends on current density/radius.

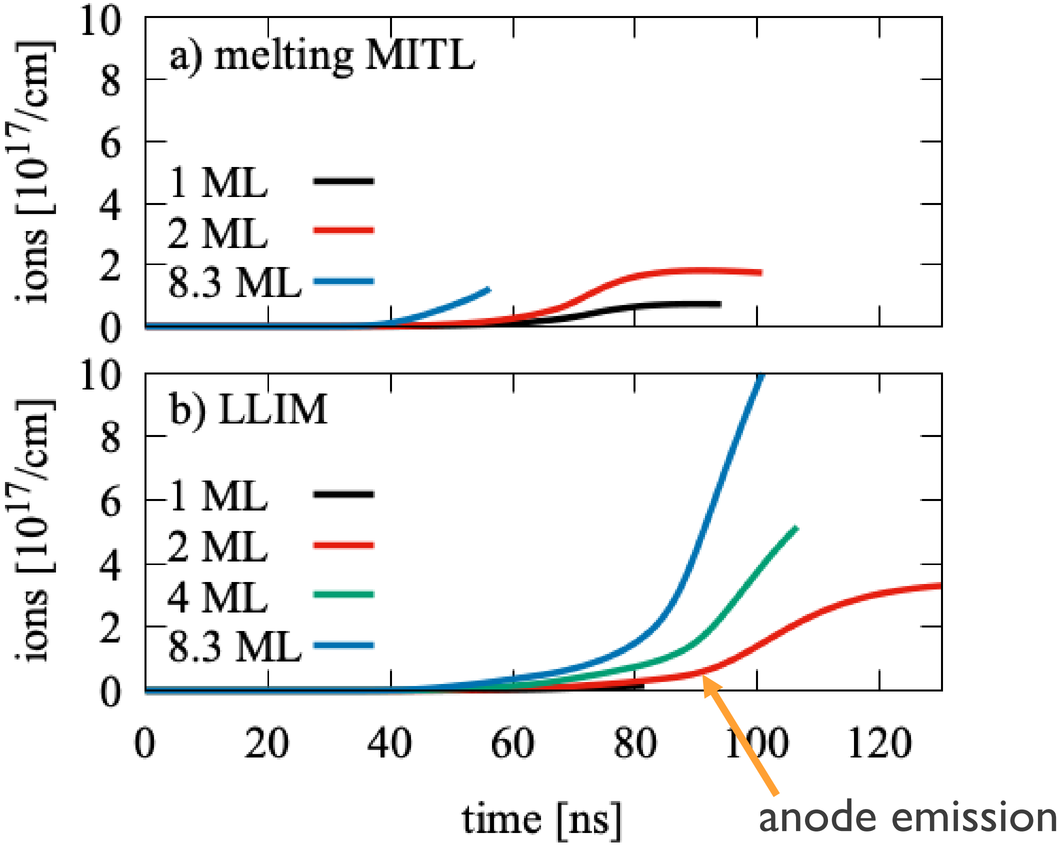
Joule heating $$\Delta T_J(t) \approx \frac{\vartheta \mu_0 H^2(t)}{2c_v}$$

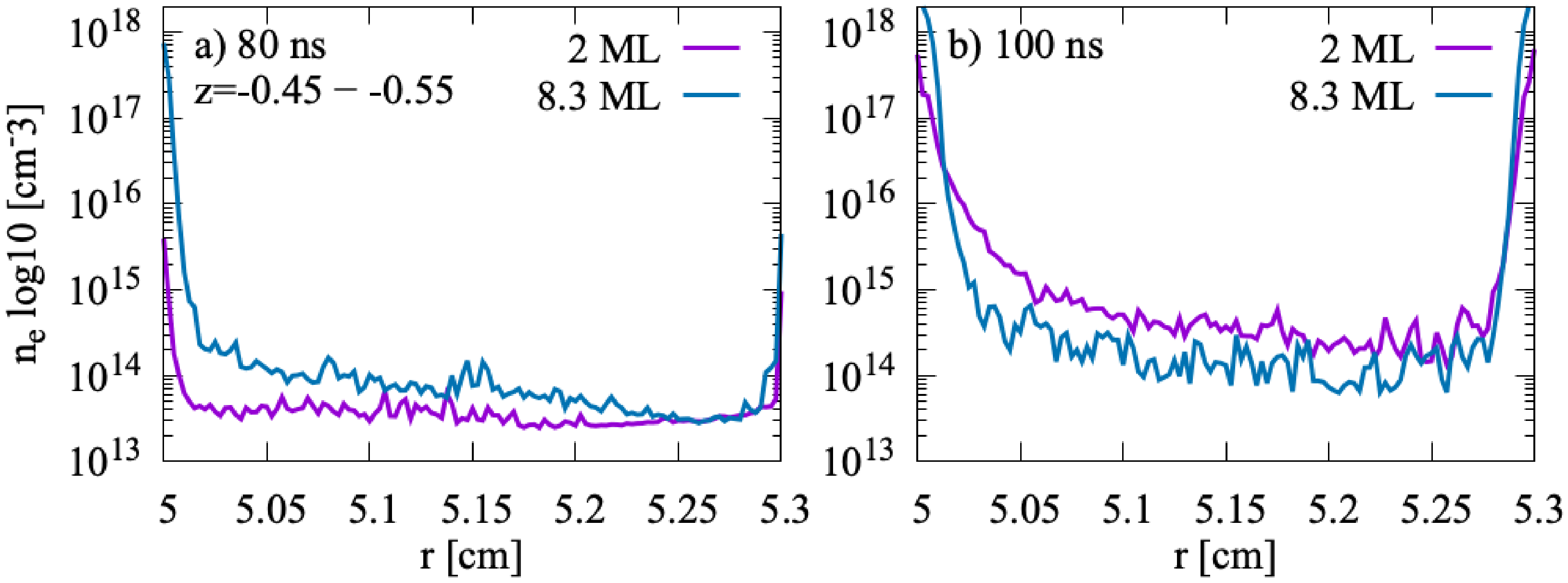
Arrhenius equation $$\frac{dn(t)}{dt} = -\nu_{th} n(t)\, e^{-E'(n)/(k_B T(t))}$$

Temkin isotherm $$E'(n) = E_d\left(1 - \alpha \frac{n(t)}{n_{ML}}\right) \quad [\text{eV}]$$



The desorption eqn translates to a plasma density scaled by inventory and current density.




a) 80 ns
z=-0.45 − -0.55
2 ML
8.3 ML
b) 100 ns
2 ML
8.3 ML
n_e log10 [cm^-3]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
5
5.05
5.1
5.15
5.2
5.25
5.3
r [cm]
r [cm]