Chicago Simulation Capabilities for the Inner MITL near the Load

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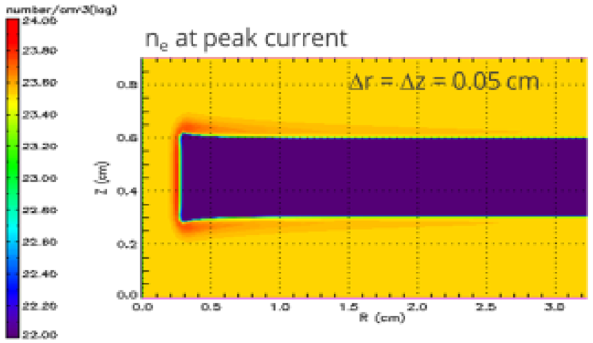

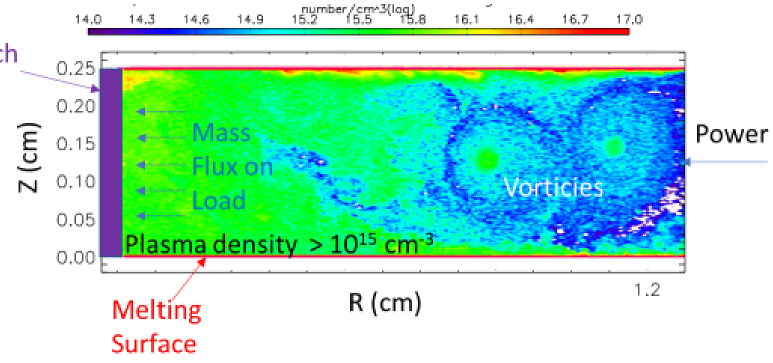

Z Fundamental Science Workshop

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Albuquerque, NM

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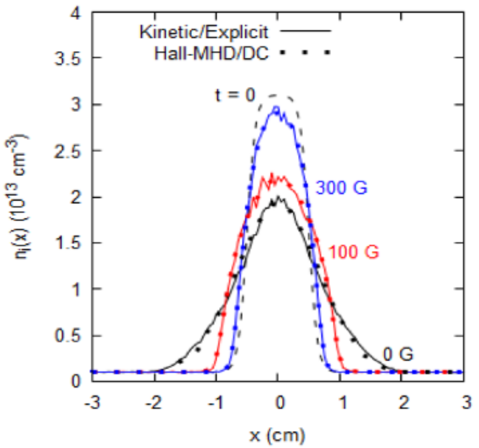
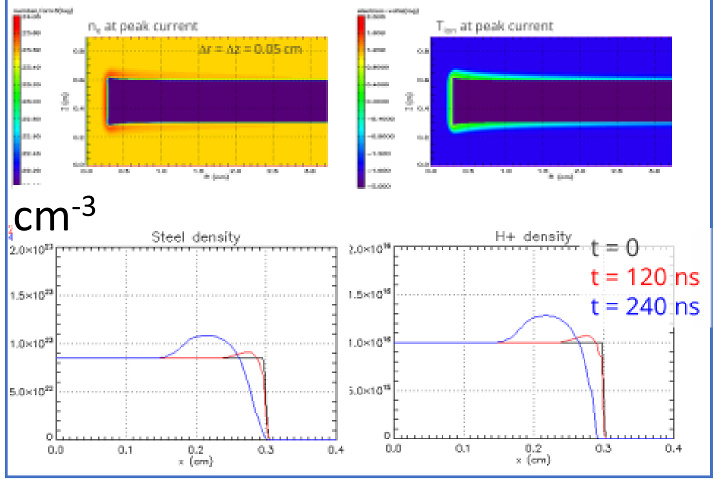
Chicago providing understanding to Power Flow on Z

Magnetized Plasma / Hall MHD

C. Thoma, Comp. Phys. Comm. **261**, 107823 (2021).



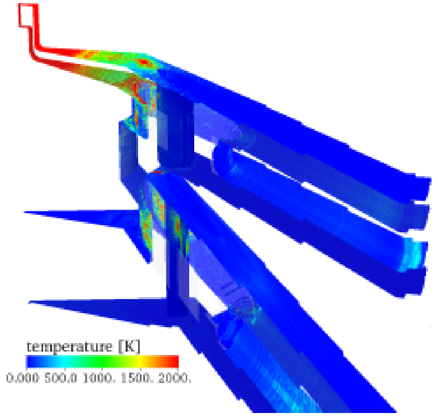
Electrode deformation, multi-ion Hall MHD

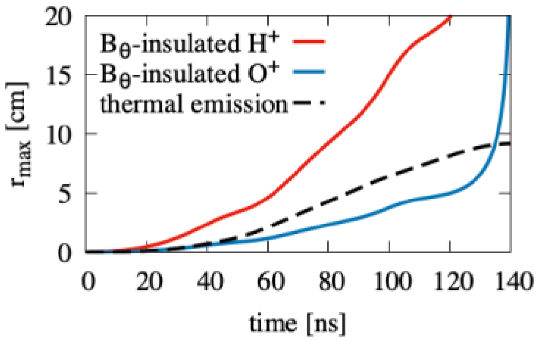


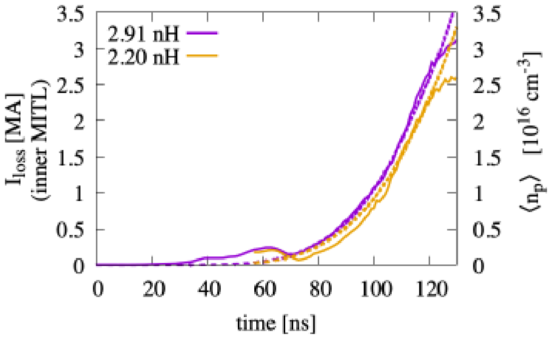
Power flow Validation Exp, Current loss mechanism

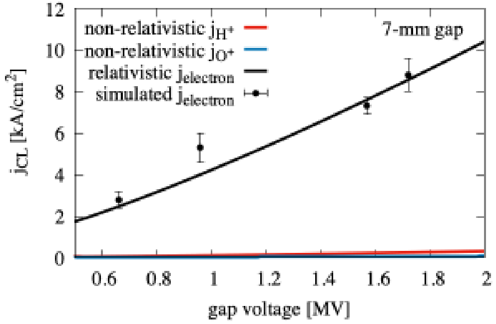
Bennett, Phys. Rev. Acc. and Beams **24**, 060401 (2021).

Current loss scales linearly with mean plasma in Inner MITL confirming **Hall-like transport**.





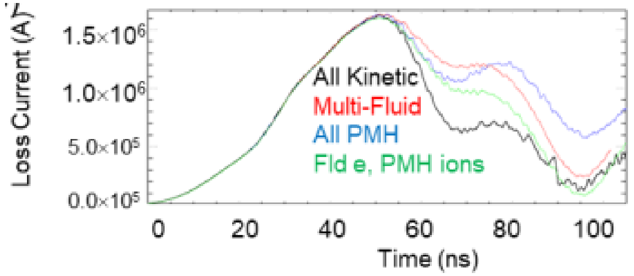




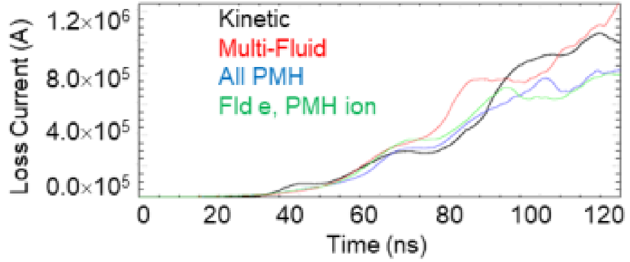
Cross Benchmarking of Kinetic, Fluid, Hybrid Techniques

Welch, Phys. Rev. AB **23**, 110401 (2020).

Convolute Losses



Inner MITL Losses



Current Loss Saturation with Surface Water Inventory

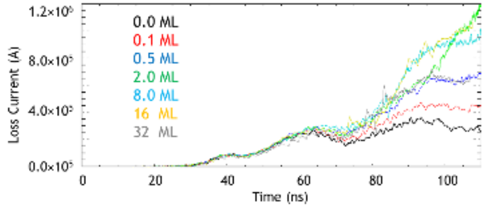
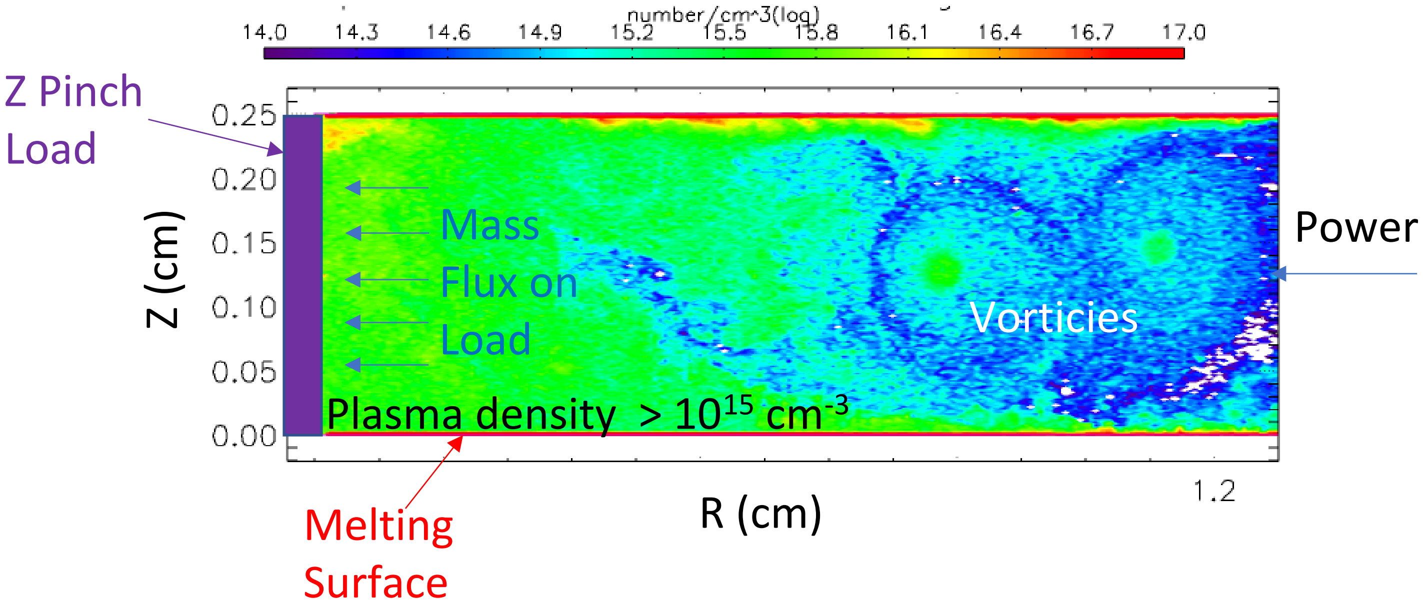


Figure 1. The current lost between the 10-cm radius boundary and just upstream of the can is plotted got several water inventories.

We need a more accurate description of electrodes to understand power delivery and load interactions.

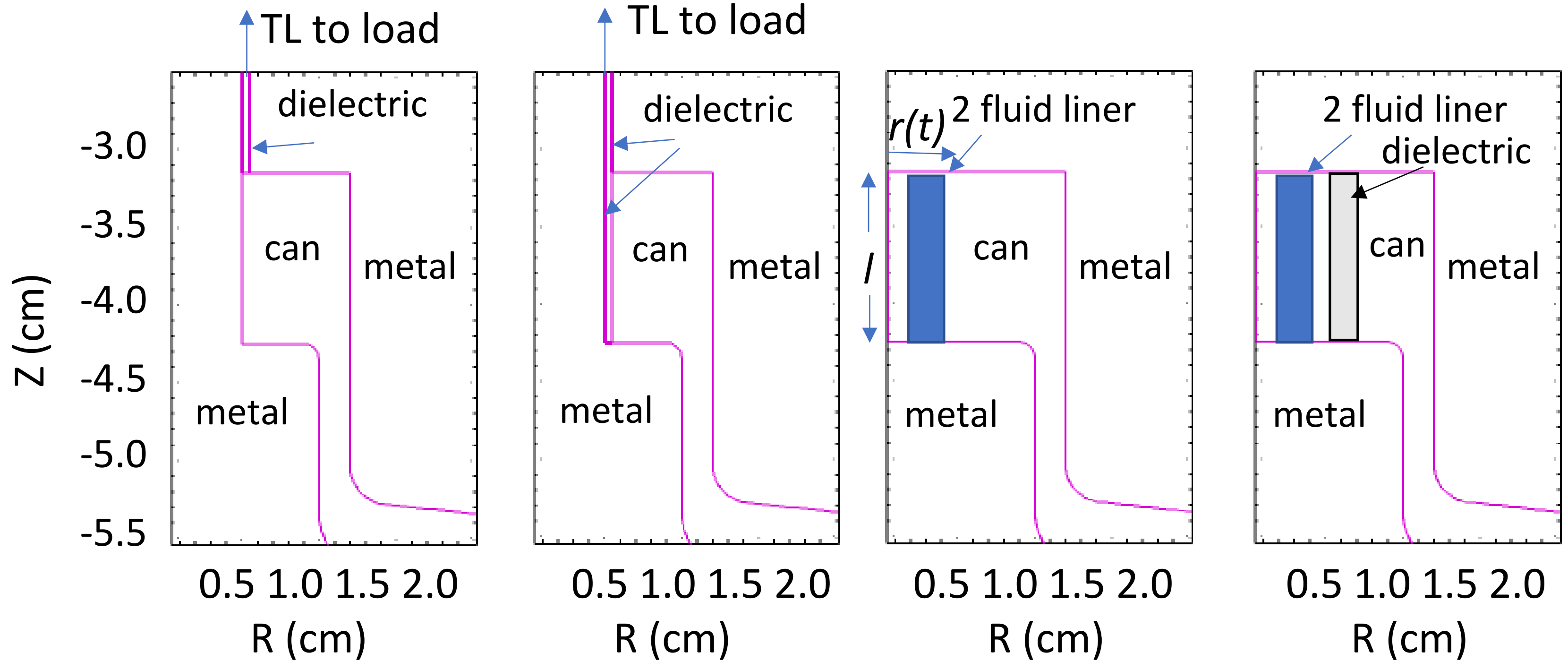
- Surfaces within 4 cm radius heat to beyond melt within a Z pulse.
- Power delivery and plasma interaction with the load can be a limiting factor on performance.
- Plasma drift in and pile up near load from larger radius.
- Electrode material can mingle with contaminant plasmas near the load.
- More important as currents rise -> Znext.



Simulation of region near the load requires:

- Inclusion of dynamic load inductance.
- Characterization of plasmas impinging on the load (Mass Flux Source).
- Improvements in electrode modeling.

Several methods studied for including liner dynamics in “Power Flow” simulations.



Snow Plow Model: **JxB** inward force from a current applied to liner:

$$\rho \frac{dv}{dt} = J \times B,$$

Radius and velocity advanced from

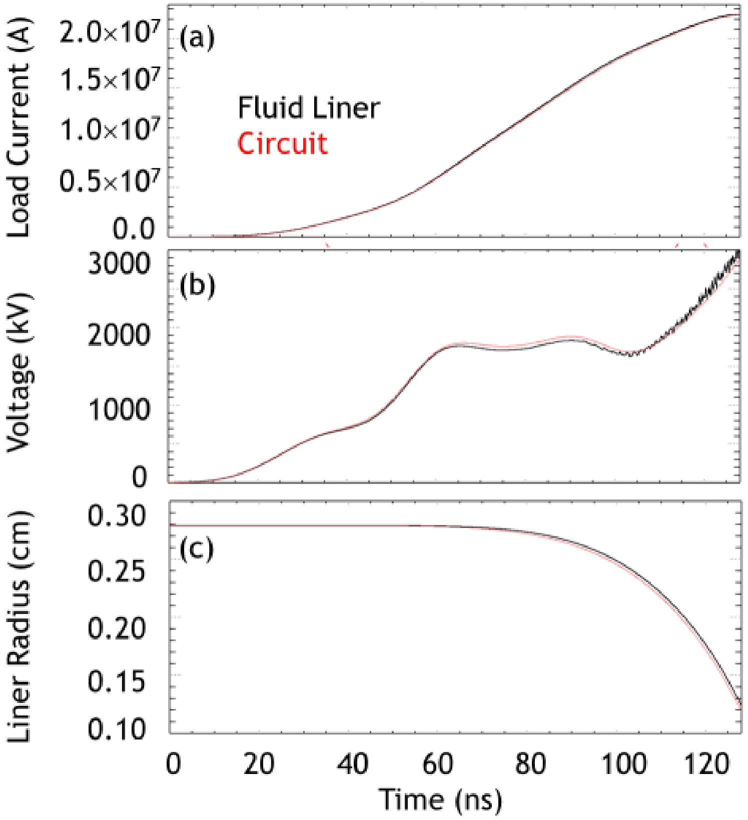
$$\frac{dr}{dt} = v_r,$$

$$\frac{dv_r}{dt} = -\frac{I^2 l}{mr},$$

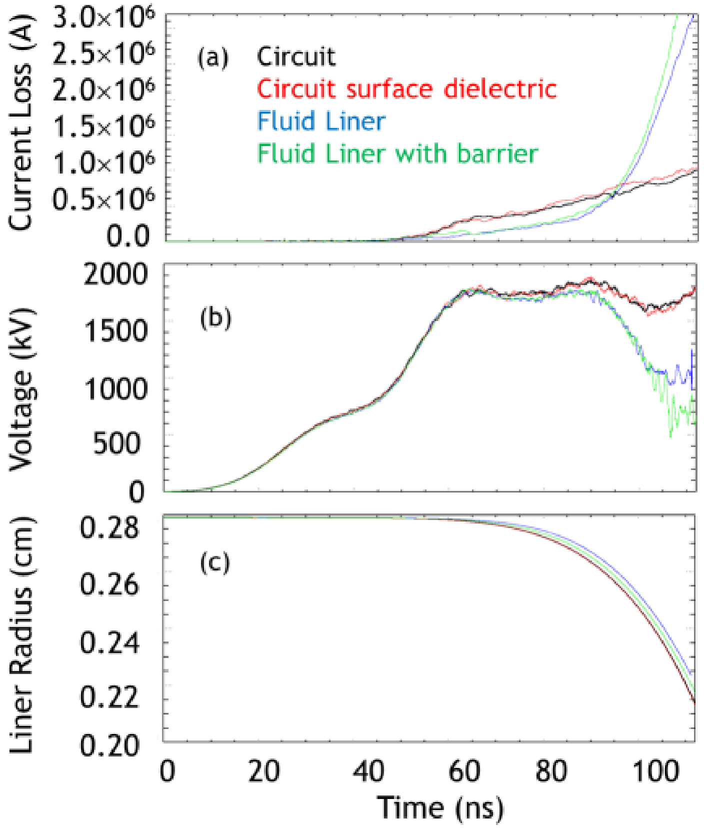
When used as a circuit element or to determine the liner’s effect on inductance

Snow plow model is used advance load circuit element or radial EOM for the Fluid Liner. Fast fluid model mainly used as a conductive medium to exclude *B* field.

Test without plasma benchmarks verifies Circuit and Fluid liner models; Fluid more accurate.

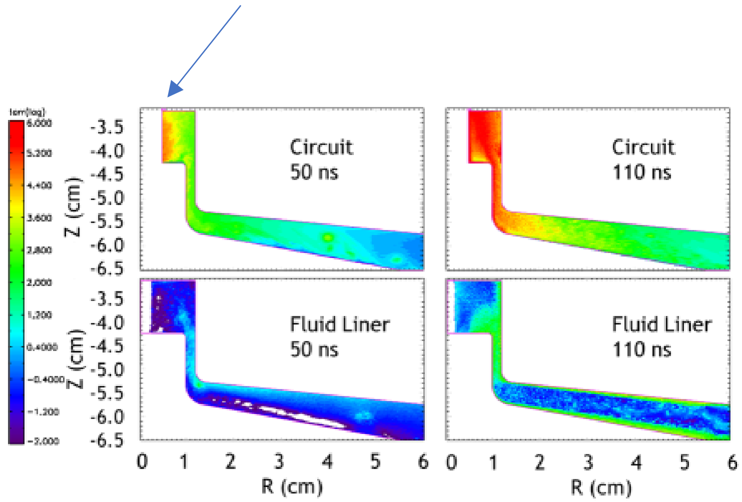


No Plasma Simulation



Full Plasma Simulation

Plasma drift past Circuit TL opening samples non physical field and is heated.



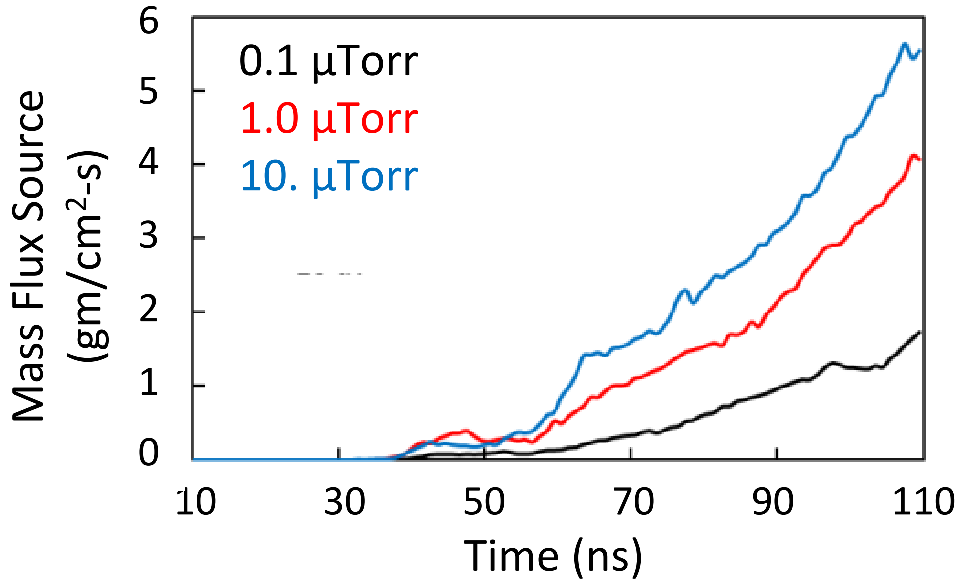
Plasma with Fluid liner remains cooler.

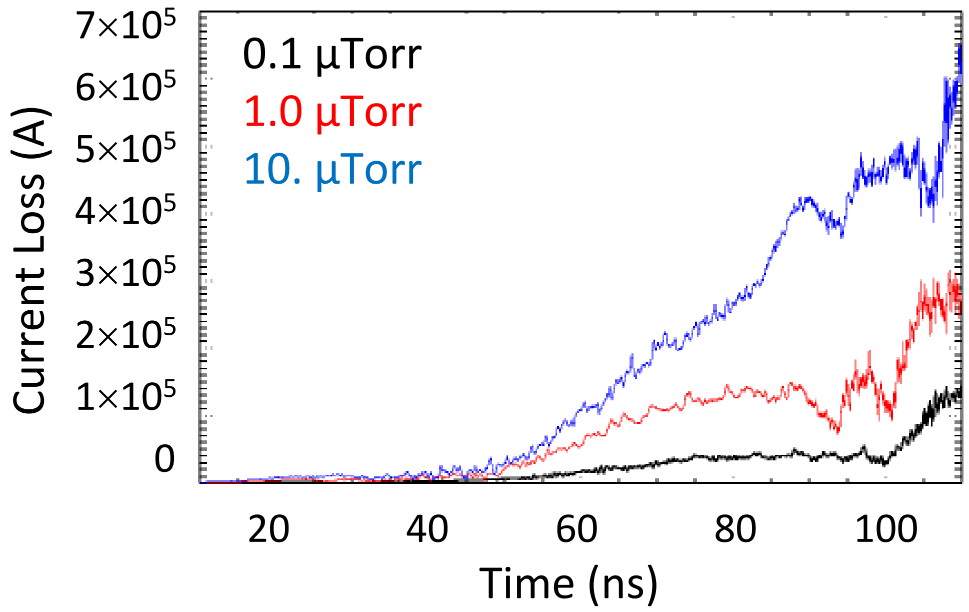
Interaction with TL boundary adversely affects plasma flow via heating. Fluid model is more accurate.

Power Flow plasmas can impact the liner implosion and its simulation in several ways.

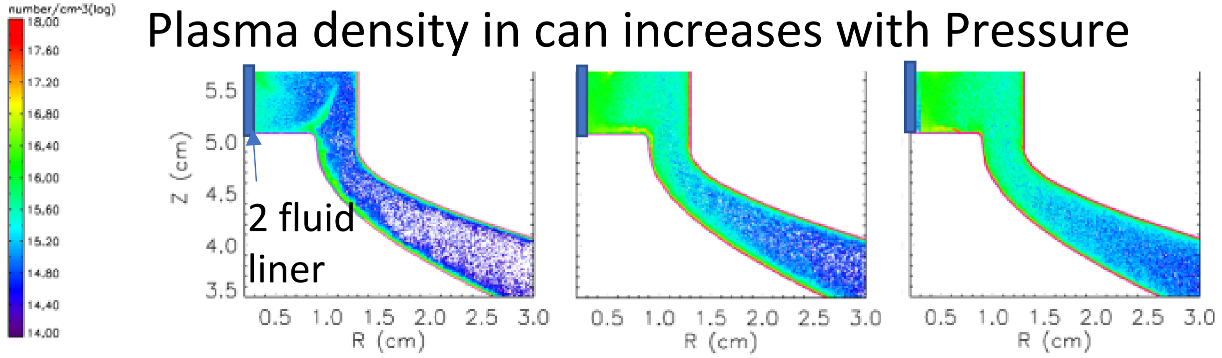
- The hot material can conduct current.
- The plasmas can heat the liner due to energetic impacts.
- Characterization of the Mass Flux Source for fluid simulations of the liner can improve the fluid simulation fidelity by replacing the arbitrary density floors used in MHD codes.
- Chicago and the LLNL fluid code ARIES have been connected to add MFS from Chicago into the fluid code and detailed fluid motion and inductance evolution back to Chicago.

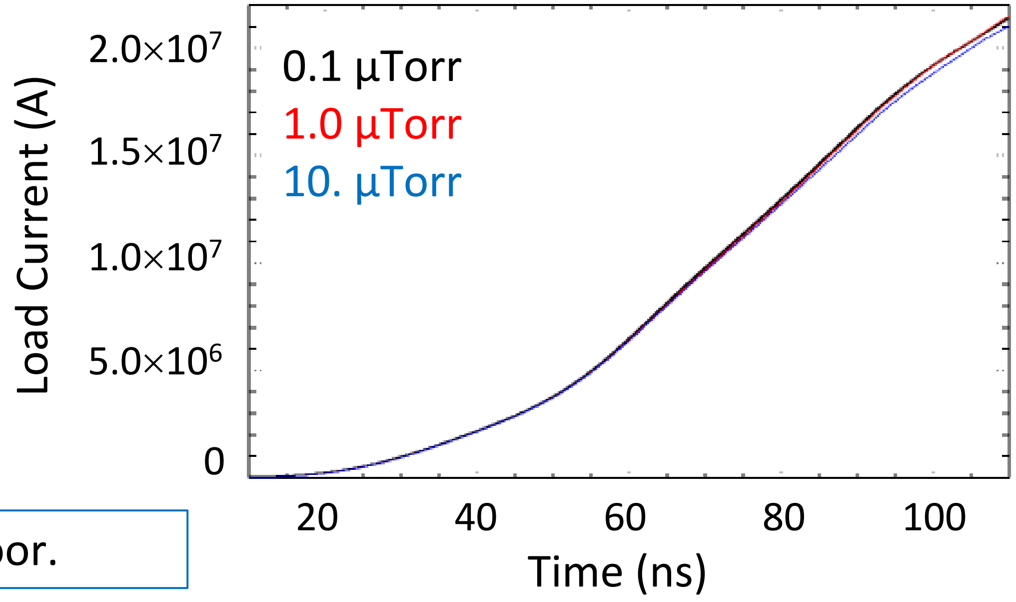
With a fluid liner, the Mass Flux Source and Current loss both scale with vacuum pressure indicating benefits to improved vacuum on Z.





Plasma density in can increases with Pressure





Plasma flux from convolute increased with contaminant inventory. Used 4-mm, 0.058 µgm liner mass.

The MFS can now be share with fluid code removing density floor.

Electrode simulation improved with Substrate Model using 3 coupled diffusion equations.

- 1D Diffusion model for magnetic field (B), temperature (T), and H number density (rho).
- Temperature dependent coefficients where available for Stainless Steel.
- Substrate attached to surface cell in simulation: energy in, mass out from desorption and metal ablation.

Magnetic Field B (G)

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial x}\left(\kappa_B \frac{\partial B}{\partial x}\right)$$

Magnetic diffusivity

$$\kappa_B = \frac{c^2}{4\pi\sigma} \quad \left(\frac{\text{cm}^2}{s}\right)$$

$\sigma(\text{s}^{-1})$ is electrical conductivity.

In general temperature dependent.

Temperature (K)

$$mc_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa_T \frac{\partial T}{\partial x}\right) \qquad \text{diffusion}$$

$$+\frac{\kappa_B}{4\pi}\left(\frac{\partial B}{\partial x}\right)^2 \qquad \text{Joule heating}$$

$$+E_{\text{dep}} \qquad \text{Particle energy deposition}$$

$$\left(-\varepsilon\alpha T^4\right)/\Delta x \qquad \text{surface cell radiation}$$

m, mass density (g/cc)

c_m, specific heat per unit mass (erg/g/K)

κ_T, thermal conductivity (erg/cm/s/K)

ε, surface emissivity (dimensionless)

α, Stefan-Boltzmann constant $(\text{erg/cm}^2/s/K^4)$

Δx, (substrate) cell size (cm)

Hydrogen number density ρ (/cc)

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial x}\left(D_H \frac{\partial \rho}{\partial x}\right) \qquad \text{diffusion}$$

$$\left(-\text{Fluxout}/\Delta\text{x}\right)^2 \qquad \text{H flux from surface}$$

Placeholder model for H flux

$$\text{Fluxout} = (\rho\delta)\nu \exp\left[-E_{\text{bind}}/k_B T\right]$$

δ is the lattice constant so $(\rho\delta)$ approximates a surface density (cm^{-2})

D_H, H diffusivity in SS304 (cm^2/s)

ν (s^{-1})

E_{bind} (erg)

k_B, Boltzmann constant (erg/K)

Explicit solution with subcycling fast and robust

1D Verification Test of Chicago Solution compared with Knoepfel Formula

Linear ramp (time t_o) in B at surface

Constant σ

Analytic solution for B (Knoepfel, Magnetic fields)

Analytic solution

$$B(x,t) = B_o\left(\frac{t}{t_o}\right)\left[(1+2w^2)erfc(w) - \frac{2}{\sqrt{\pi}}we^{-w^2}\right]$$

$$w = \frac{x}{2\sqrt{\kappa_B t}}$$

$x =$ distance into substrate

Magnetic Field B (G)

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial x}\left(\kappa_B \frac{\partial B}{\partial x}\right)$$

Magnetic diffusivity

$$\kappa_B = \frac{c^2}{4\pi\sigma} \quad \left(\frac{\text{cm}^2}{s}\right)$$

$\sigma(\text{s}^{-1})$ is electrical conductivity.

In general temperature dependent.

$B_o = 10^6$ G, $t_o = 10^{-7}$ s

$\sigma \equiv 9\times 10^{15}\ \text{s}^{-1} \rightarrow \kappa_B = 7.96\times 10^3\ \text{cm}^2/s$

FTCS Solution (with constant κ_B)

Grid: i full grid ($i=1$ eq surface), j half-cell positions

B defined at grid points.

All other quantities at cell centers.

Constant σ

$$B_1^n = B_o\left(\frac{t^n}{t_o}\right)$$

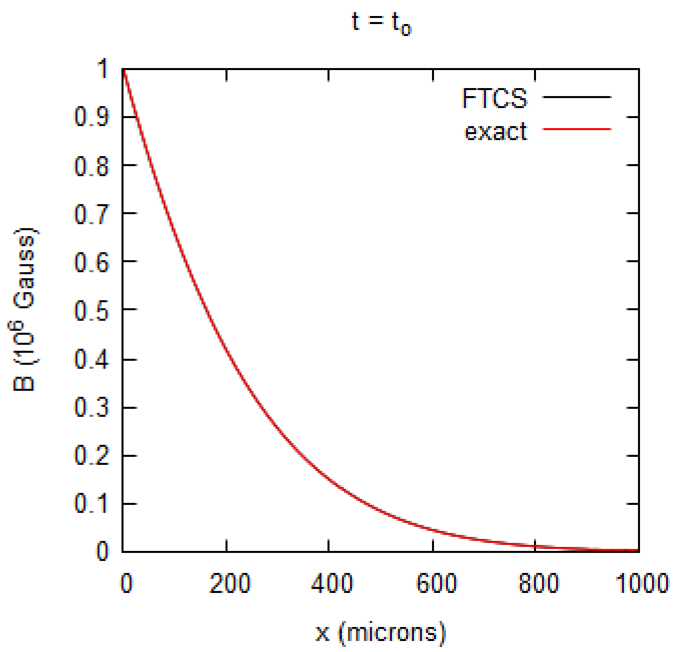
$$\frac{B_i^{n+1} - B_i^n}{\Delta t} = \kappa_B \frac{B_{i+1}^n - 2B_i^n + B_{i-1}^n}{\Delta x^2}$$

$\Delta x = 5\mu m$

$\Delta t = 0.01$ ns

Stability criterion

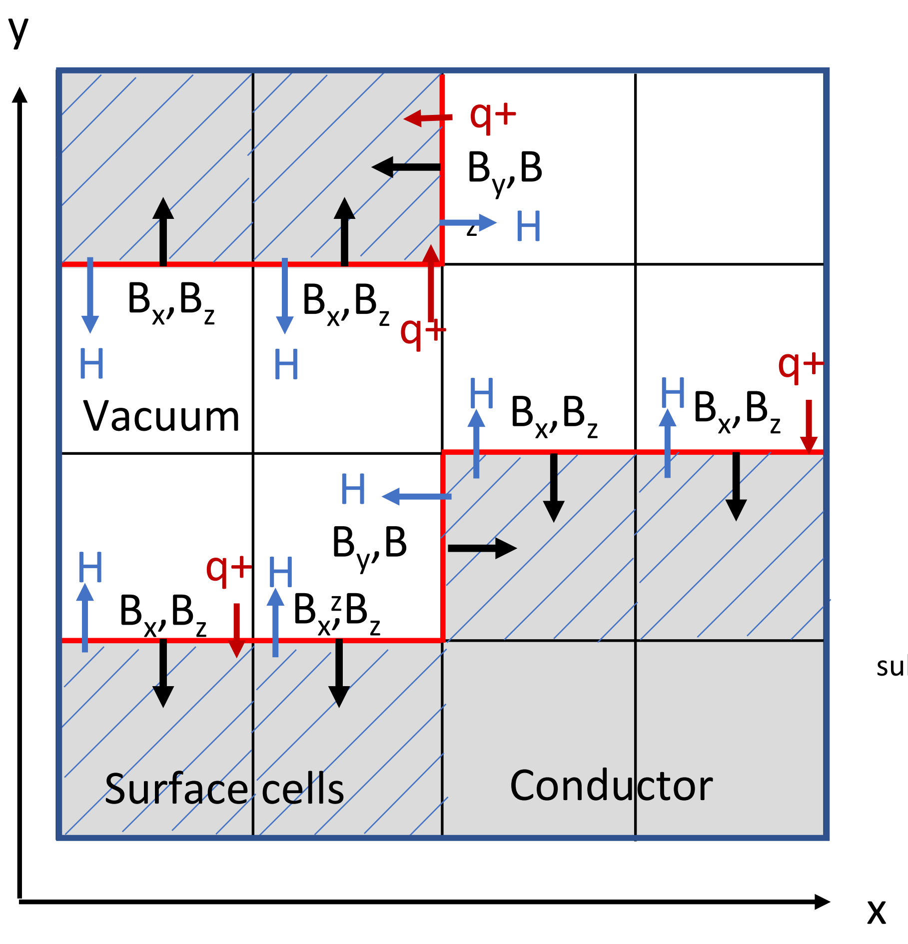
$$\kappa_B \frac{\Delta t}{\Delta x^2}; \quad 0.32 < 0.5$$



Perfect agreement with Knoepfel* analytical formula using constant coefficients.

*H. Knoepfel, Magnetic Fields (John Wiley and Sons, New York, 2000).

Implementation in multiple dimensions



Applied Bz = x [cm] * y[cm] (code units)

Output sub1.dat Shows 8 surface cells, with correct B field at surface center

```
substrate1 ;genoni model
    type 2
    from x y z
    to x y z
    atomic_weight 55.85
    *density 1.0
    *depth 1.0
    resolution 800
    initial_temperature 293.0
    *medium 1
    interval 1
    species 2
    *movie_tag 1
    *movie_fraction 0.1
```

```
#TG Substrate Test: sub_test.chg - Mon Dec 14 17:20:38 2020
#CHG_20200401
# surface cell 0
# axis = 1
# dir = 1
# i j k  = 2 2 0
# B field  = 3.125000e-02

# surface cell 1
# axis = 1
# dir = 1
# i j k  = 3 2 0
# B field  = 9.375000e-02

# surface cell 2
# axis = 0
# dir = -1
# i j k  = 4 3 0
# B field  = 1.875000e-01

# surface cell 3
# axis = 1
# dir = 1
# i j k  = 4 3 0
# B field  = 3.125000e-01

# surface cell 4
# axis = 1
# dir = 1
# i j k  = 5 3 0
# B field  = 4.375000e-01

# surface cell 5
# axis = 1
# dir = -1
# i j k  = 2 5 0
# B field  = 9.375000e-02

# surface cell 6
# axis = 0
# dir = 1
# i j k  = 3 5 0
# B field  = 4.375000e-01

# surface cell 7
# axis = 1
# dir = -1
# i j k  = 3 5 0
# B field  = 2.812500e-01
```

Each Surface cell contains a 1D substrate.

2D Inner MITL with Substrate electrode Fe ablation using high current rise (Znext).

SS electrode Ablation

0.25 µm substrate resolution

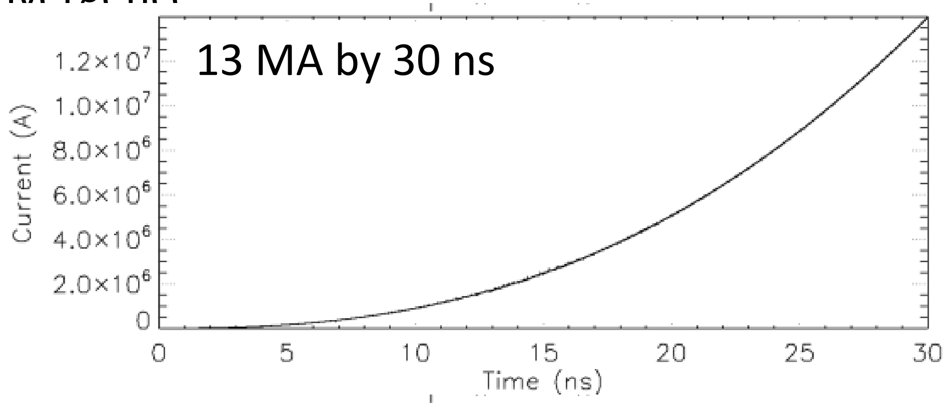
Fe emission in sim at 3000 K

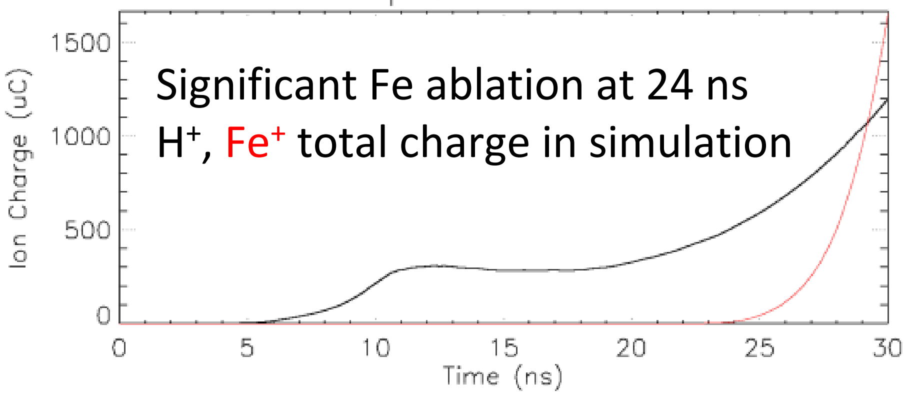
H_2 Contaminant Desorption

1.0 ML on surface, 0.8-eV binding energy

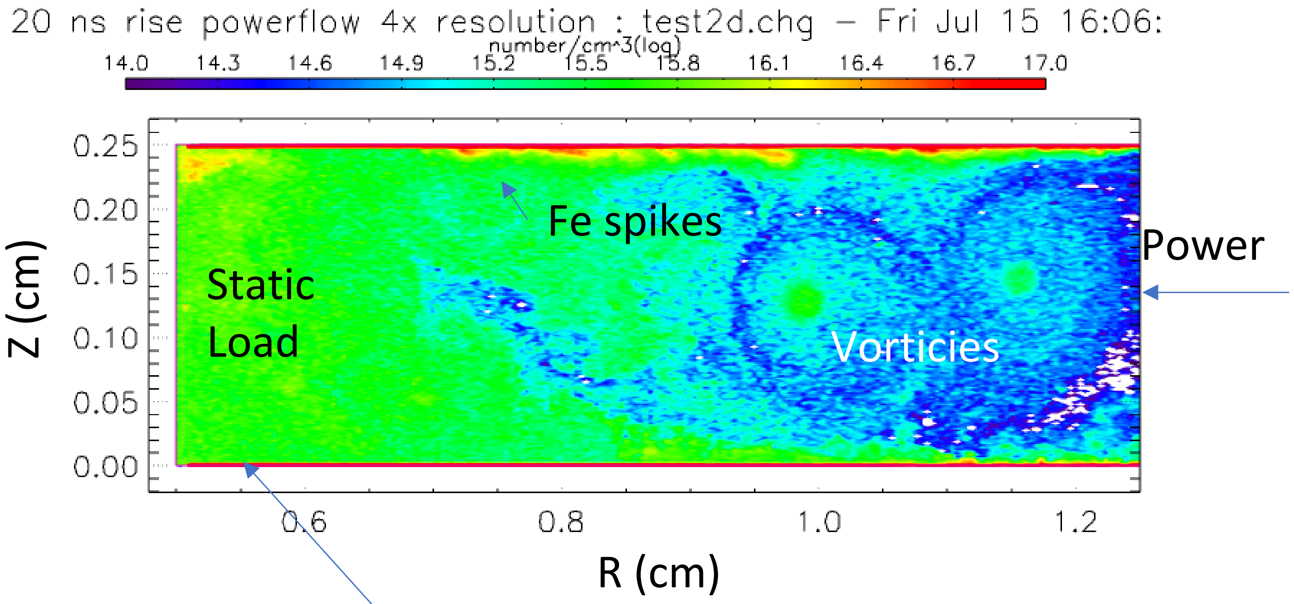
2×10^{20} /cc volume density

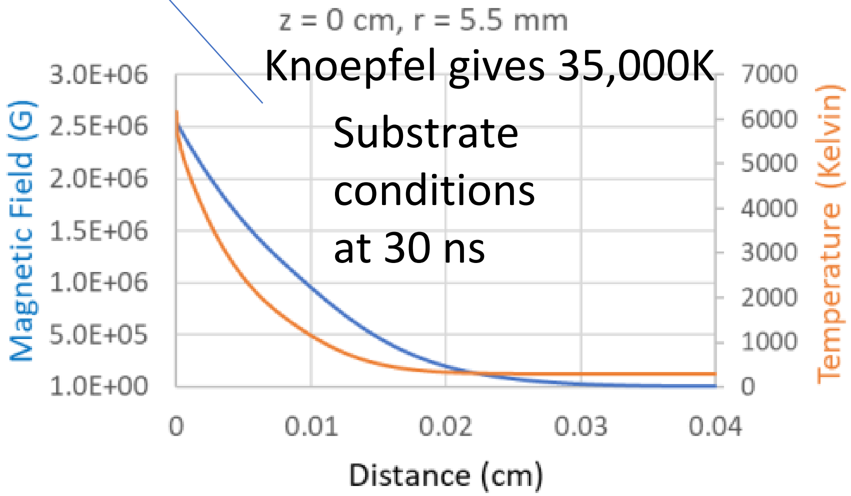
Require 6—12 µm resolution in gap for convergence



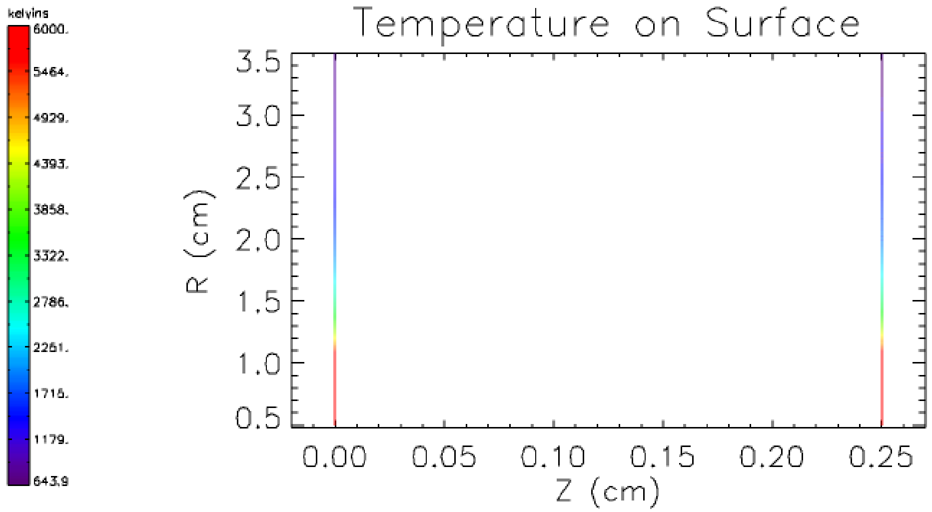


Electron Density

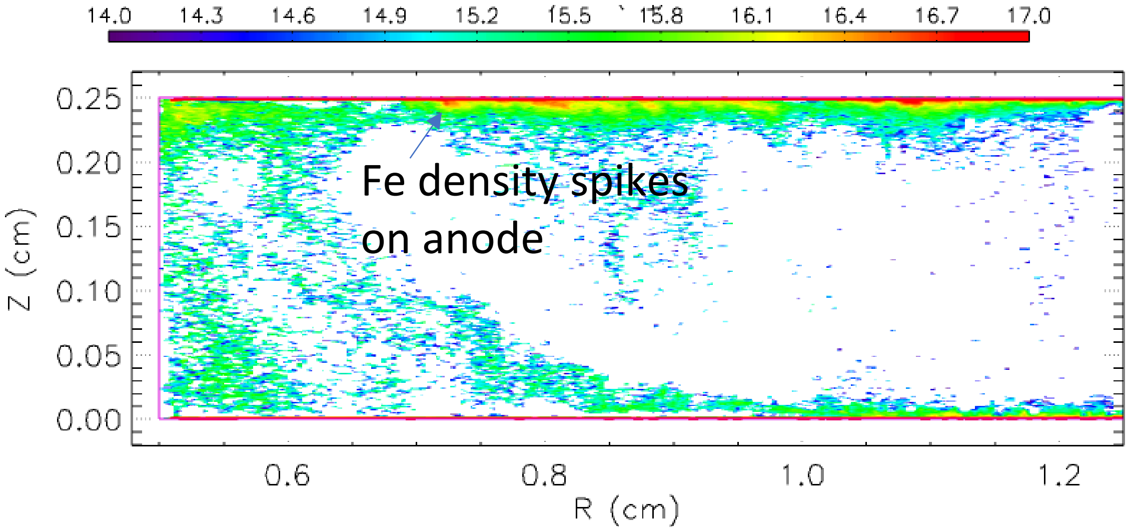




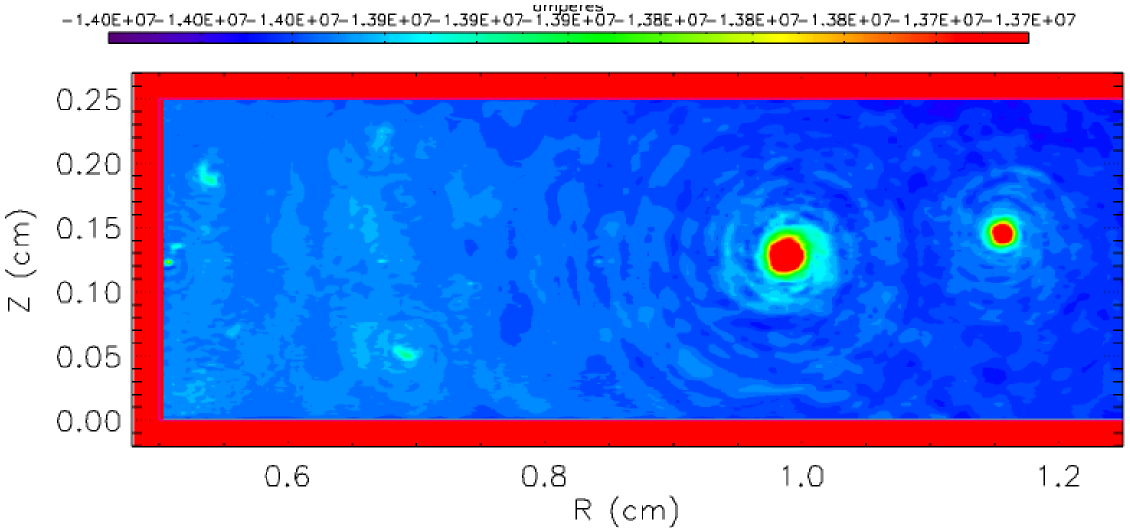
Dense Fe spikes on anode surface, heating in gap by 30 ns.



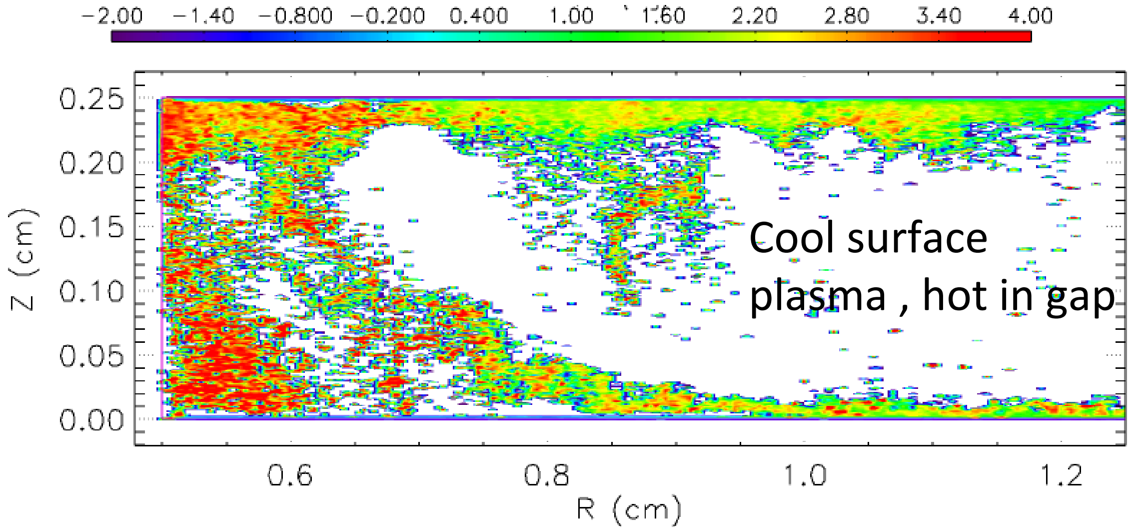
Fe+ density (log N 1/cc)



Enclosed Current (A)



Fe+ Temperature (log T eV)



Given sufficient resolution, we can now simulation electrode desorption and ablation in realistic geometries.

Chicago improved for high current density electrode simulation near load.

- Fluid liner coupled to a snowplow model provides fast, accurate time-dependent inductance.
- We have characterized the MFS and can dynamically couple to the ARIES fluid code.
- Implement a Substrate model with 3 Coupled diffusion equations: Heat, magnetic field and mass to better calculated heating and mass contaminant desorption/metal ablation from electrode.
- *Will enable more realistic modeling of power flow plasma effects on the liner performance.*