MHD Analysis of Lithium motion in DiMES

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Outline

- **New 2D calculations of lithium motion with plasma momentum flux effect in slot DiMES sample holder geometry**
- **3D HIMAG simulation of Li motion in slot DiMES sample holder geometry**
- **3D HIMAG simulation of GaInSn motion in table-top benchmark experiments**

2D Lithium motion model with plasma momentum flux effect

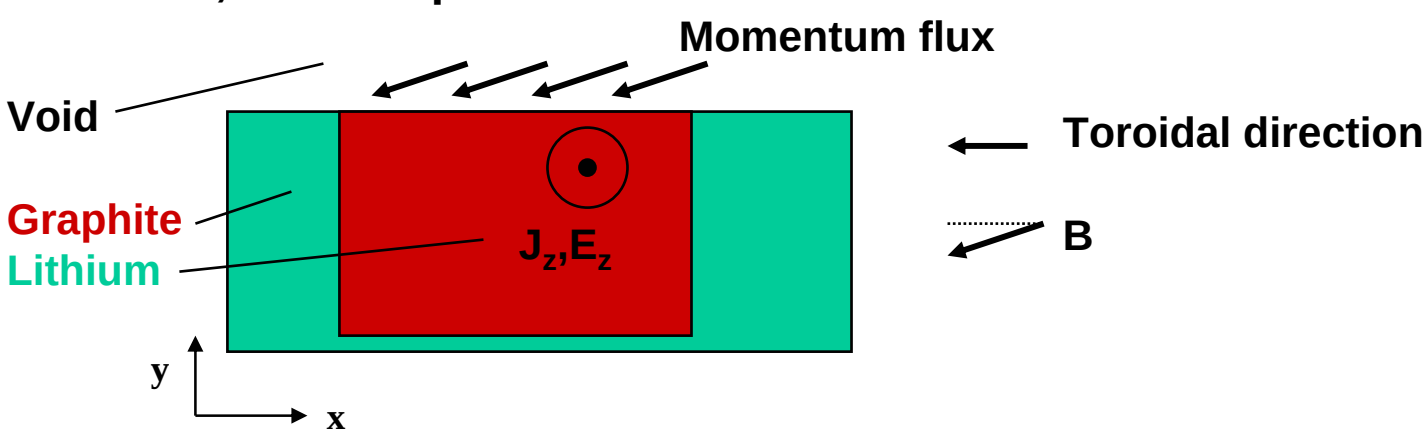
- 2D Free Surface Flow Model – **motion and field in xy-plane produce current in z-direction, VOF free surface tracking**

$$\underbrace{\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla\cdot\tau + \vec{g}}_{Navier-Stokes} + \underbrace{\frac{1}{\rho} j_z \hat{z}\times\vec{B}_a}_{MHD} + \underbrace{\frac{1}{\rho}\left(\vec{F}_s + \vec{F}_P\right)}_{\substack{Surface\ Tension\ + \\ Momentum\ Flux}}$$

$$j_z = \sigma\left(E_z + \vec{u}\times\vec{B}_a\right), \quad \oiint j_z dS = 0$$

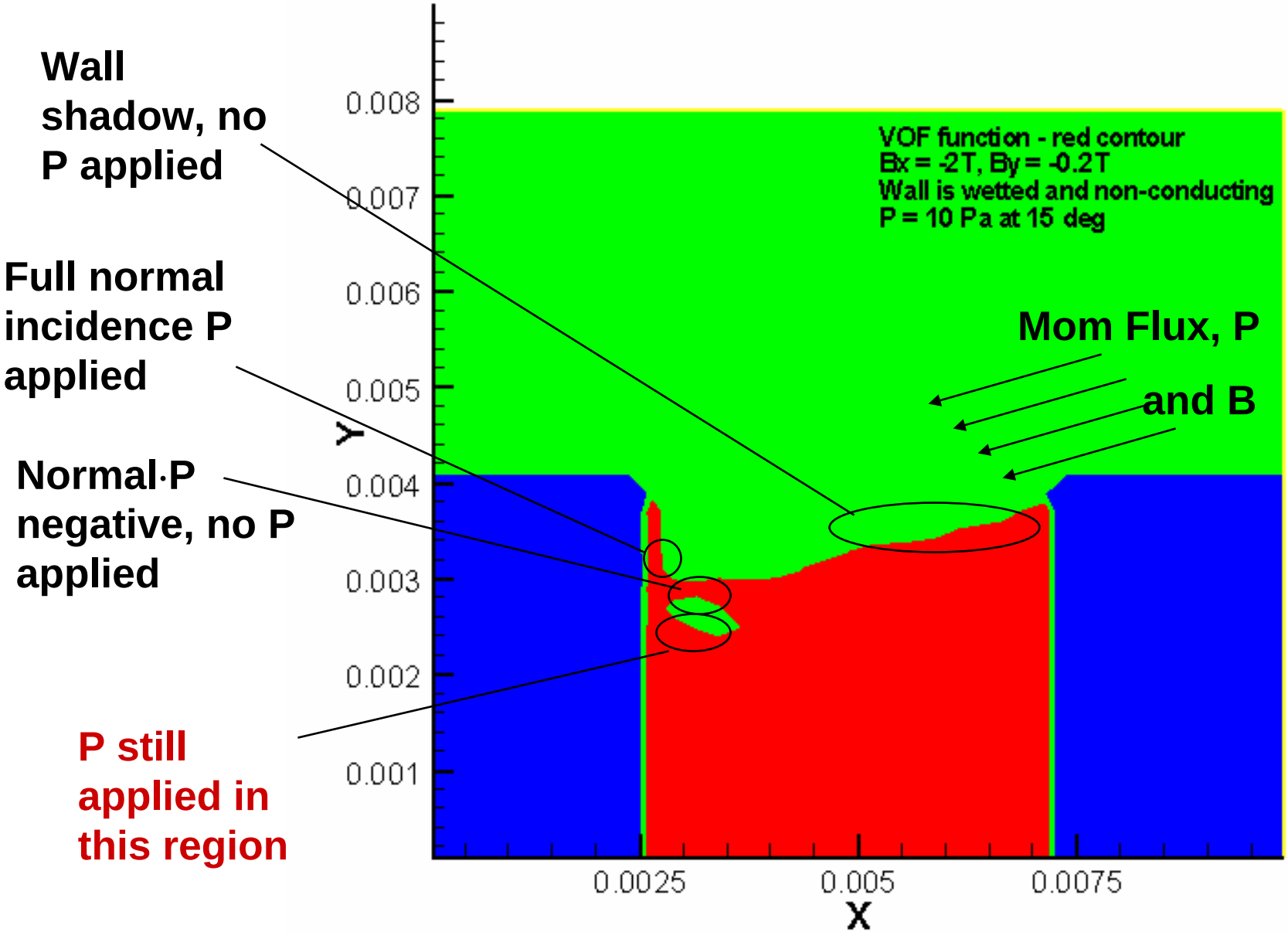
$$\frac{\partial F}{\partial t} + (\vec{u}\cdot\nabla)F = 0, \quad \nabla\cdot\vec{u} = 0$$

- **Graphite can be treated with electrical and wetting properties of the void, or the liquid**



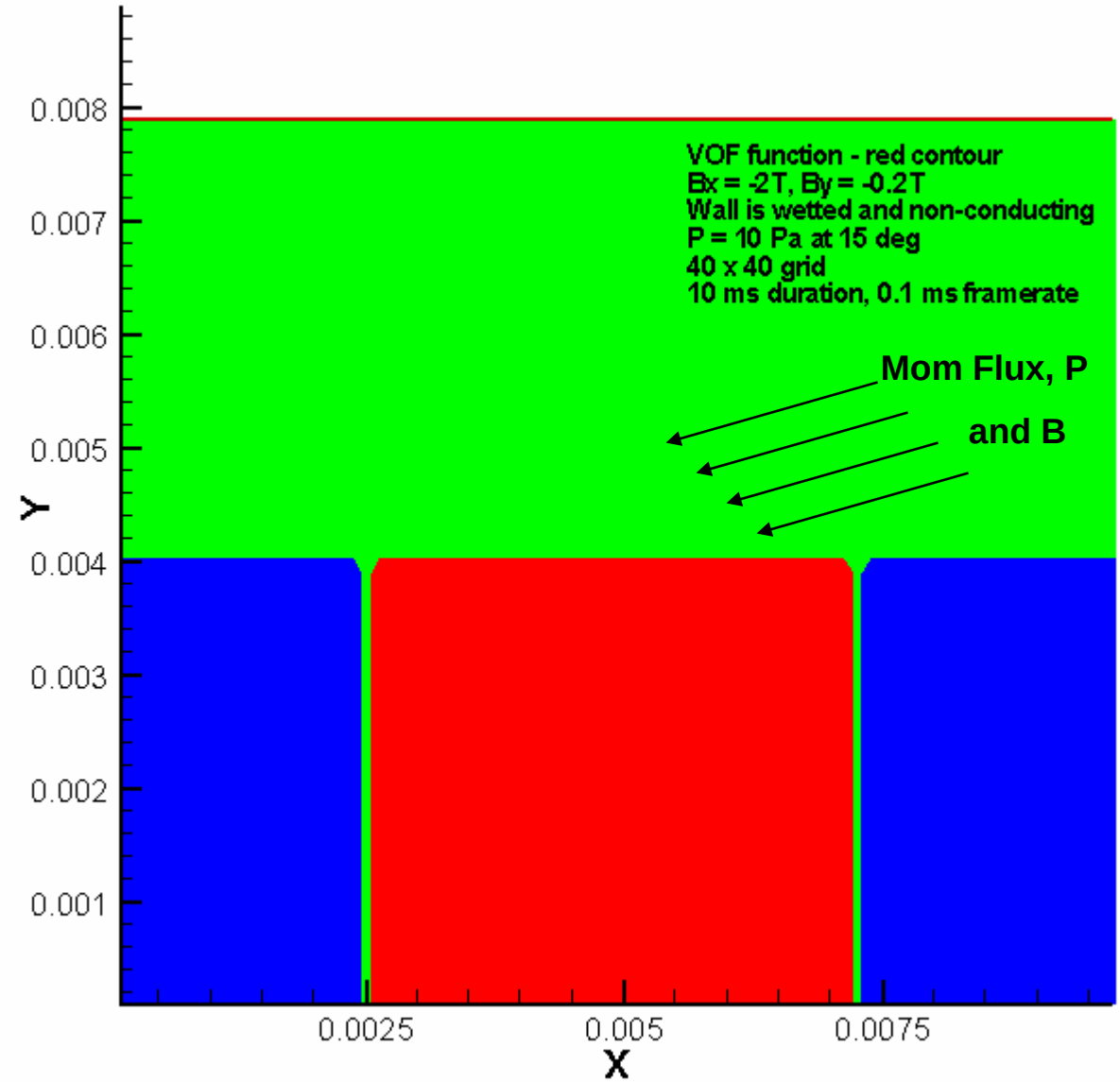
Momentum flux model

- **Momentum flux model, $P = V_D N_D (M_D V_D)$**
  - $N_D \approx 2 \times 10^{19}$ m^{-3}, $V_D \approx 40$ km/s, $M_D \approx 3.34 \times 10^{-27}$ kg/D
  - $P \approx 100$ N/m^2 or Pascal
  - For comparison, ρgh of 1 mm Li is 4.8 Pa
- **Exploring a range of P = 1-100 Pa at different angles on incidence.**
- **Momentum flux applied like surface tension**
  - volume force applied over depth ~1 cell size at free surface
  - magnitude multiplied by $\ell(\hat{n} \cdot \hat{P})$ in each surface cell to account for orientation of flux to surface normal and interface length
  - P flux not applied to cells in shadow of wall or when $\ell(\hat{n} \cdot \hat{P})$ is negative


Wall shadow, no P applied
Full normal incidence P applied
Normal·P negative, no P applied
P still applied in this region
VOF function - red contour
Bx = -2T, By = -0.2T
Wall is wetted and non-conducting
P = 10 Pa at 15 deg
Mom Flux, P
and B
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
Y
0.0025
0.005
0.0075
X

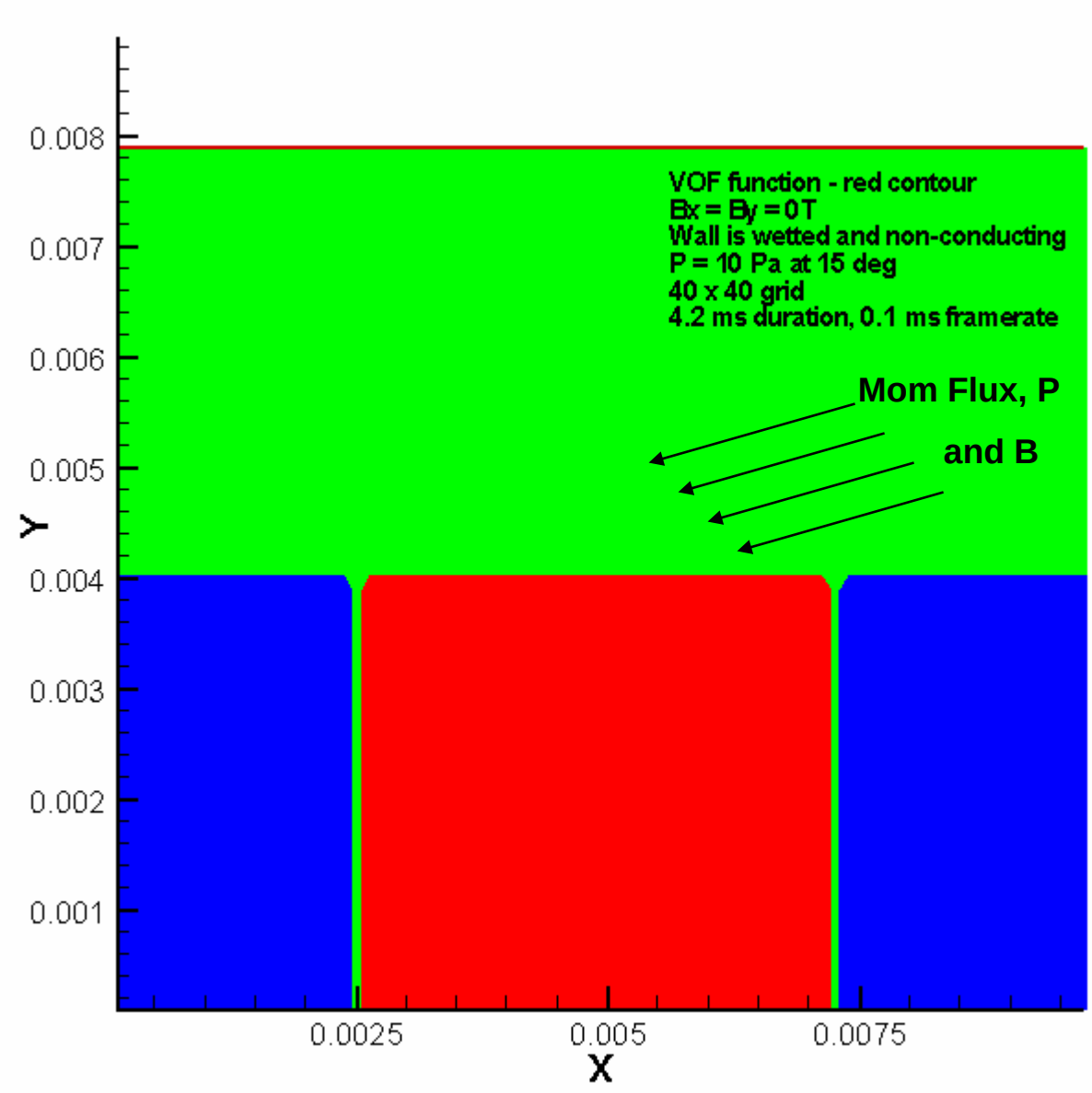
Base Case: P = 10 Pa @ 15° inclination, wetted, with MHD

- **Top layer of liquid is removed by momentum flux**
- **Wetting causes Li to creep up the wall where it is more easily pushed out of the slot**



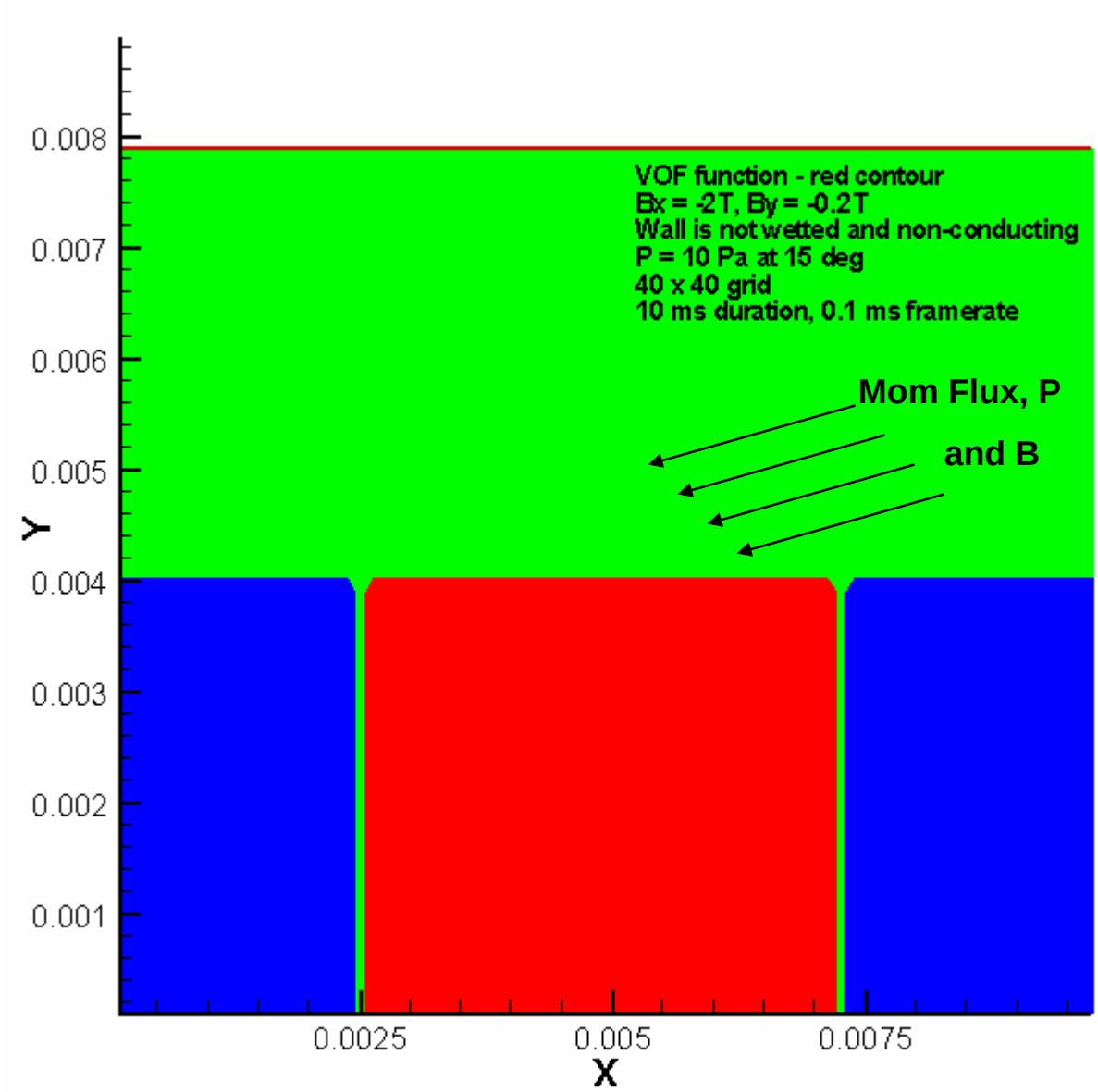
P = 10 Pa @ 15° inclination with no MHD forces

- **MHD acts to suppress fluctuations – removal much more violent**



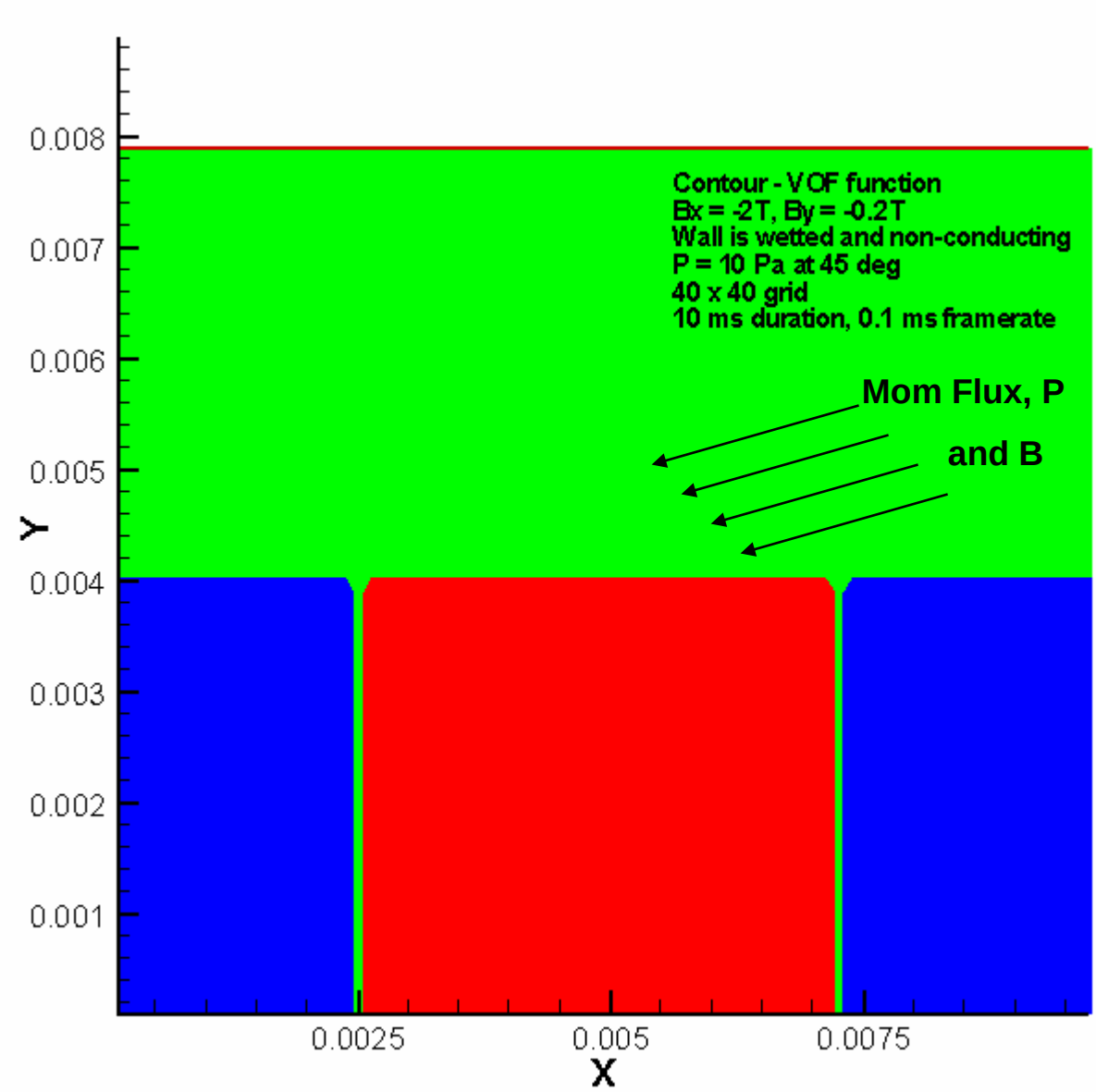
P = 10 Pa @ 15° inclination with non-wetted walls

- **Less liquid removed since tendency at walls is to curve <u>away</u> from momentum flux**



P = 10 @ 45° inclination

- **Effect pushes deeper into Li, but liquid loss about the same**



Observations on Momentum Flux Calculations

- **MHD forces due to liquid motion tend to calm the flow and prevent material loss**
- **Wetting seems to cause more liquid loss since liquid creeps up side and presents normal incidence surface.**
- **Wall conductivity doesn't have much effect since large volume of quasi-static Li provides good return path anyway.**
- **P=1 still removes top liquid layer but startup is slower.**
- **P=100 is much more violent with more droplets.**

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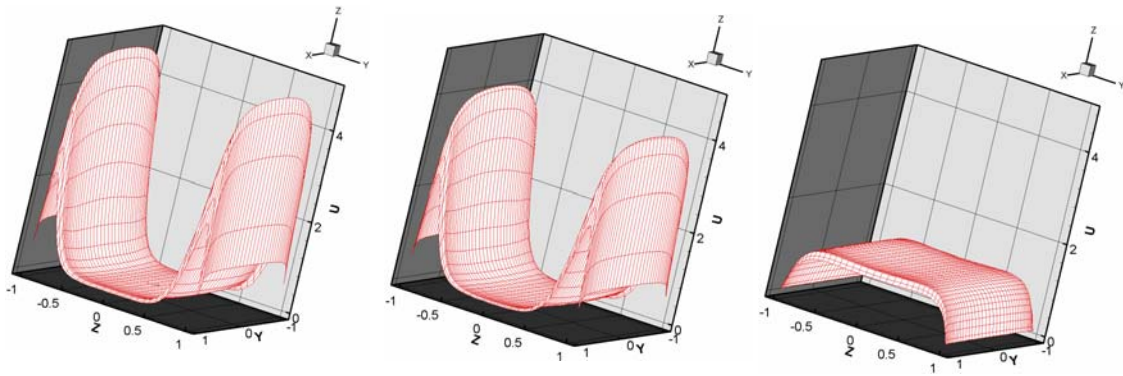
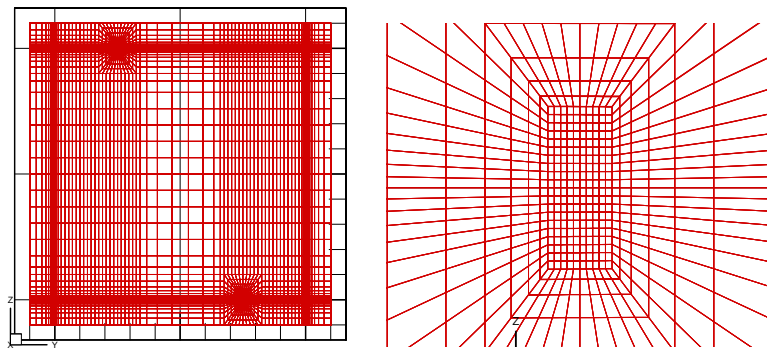
HIMAG

HyPerComp **I**ncompressible **M**HD solver for **A**rbitrary **G**eometry

- **3-D LM-MHD finite volume solver**
- **Unstructured mesh for complex geometry and resolution of small features**
- **Electric potential formulation with non-isotropic conductivity**
- **Level set free surface formulation**



Ha = 200, N = 1000, Velocity profiles at various downstream locations following the steep magnetic field gradient at x = 0.



3-D unstructured mesh for channel flow with insulator crack, Crack size / Duct size = 1 / 100, Number of cells = 3639060, Number of cells over one crack = 10

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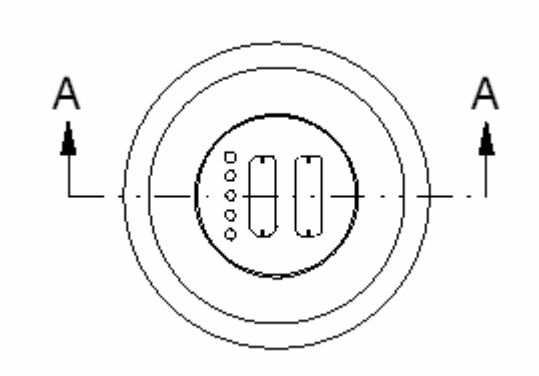
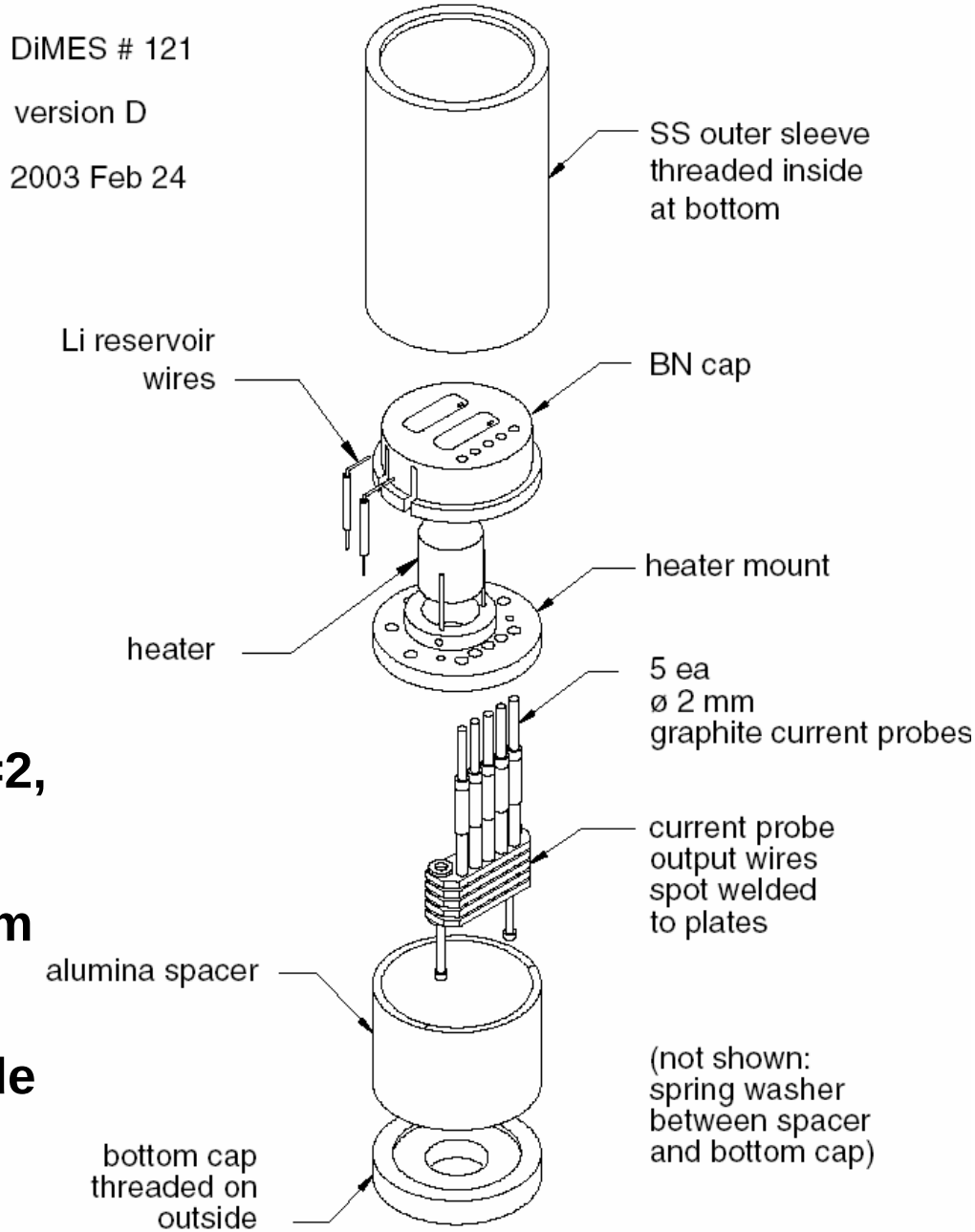
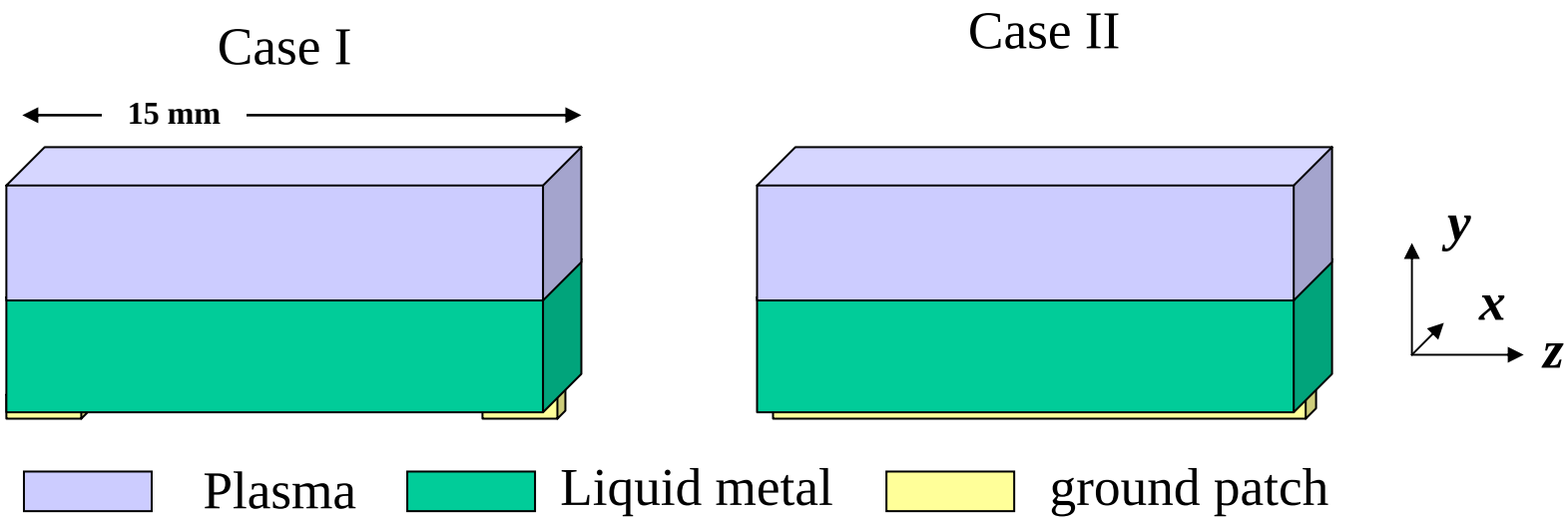
Geometry of DiMES Lithium Probe

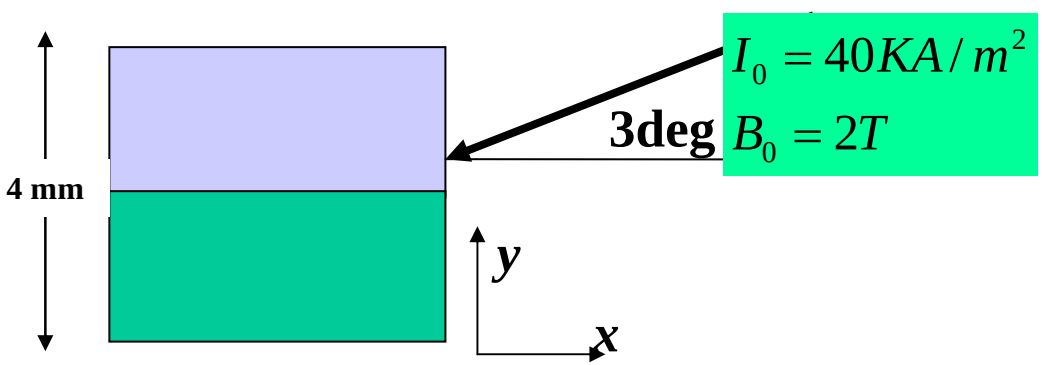




- **3-D with applied current and magnetic field: J=40KA/m2, B=2, angle=3degree**
- **Computational size: 4x5x15 mm (41x41x61)**
- **Grounding arrangement include two patches with sizes 0.5x0.5mm2 distributed on the bottom wall**

Geometry of DIMES Lithium Slot





Lithium Properties:

$$\rho = 485 kg/m^3$$

$$\upsilon = 8.5\times10^{-7} m^2/s$$

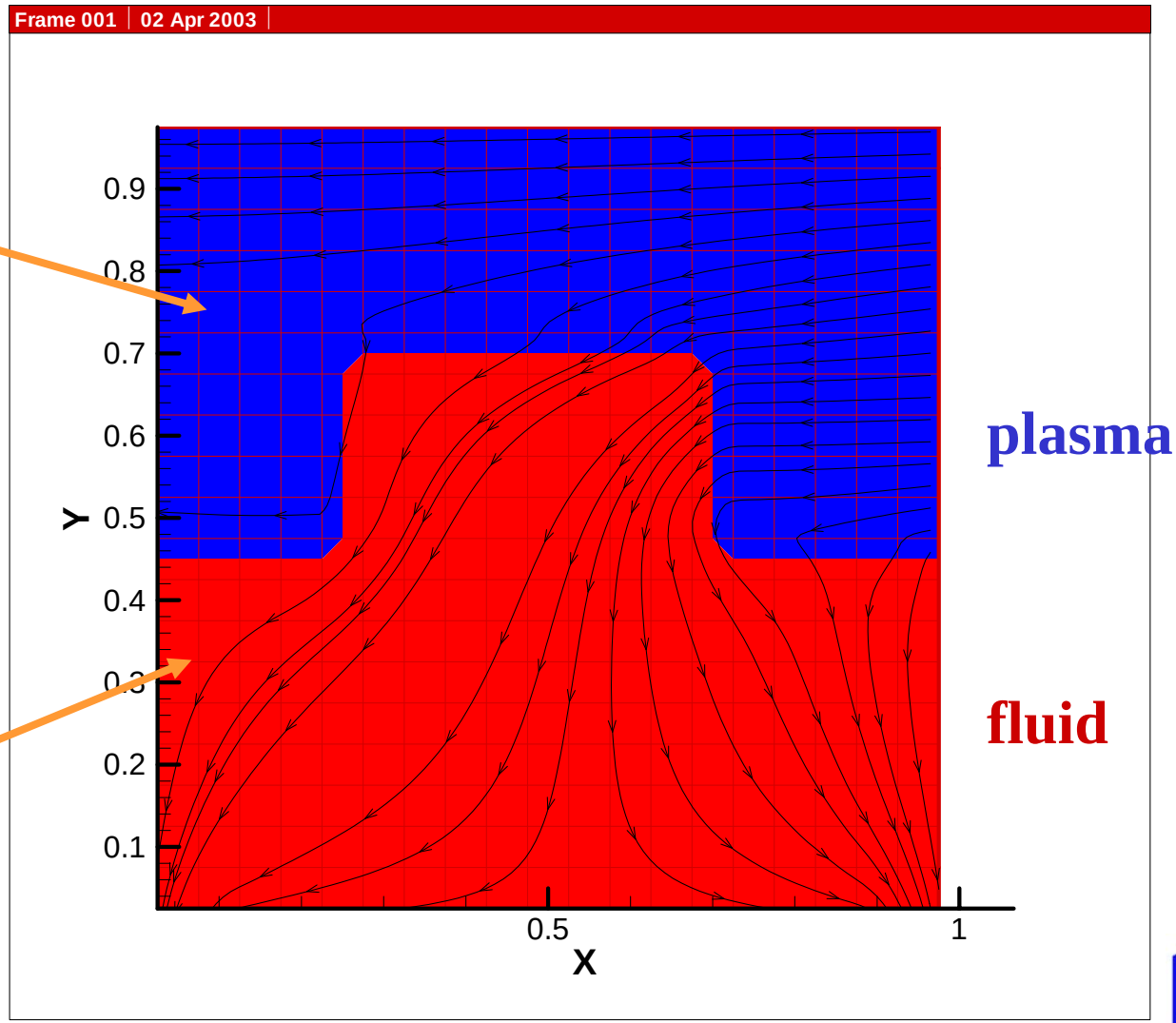
$$\sigma = 2.8\times10^{6} (mOhm)^{-1}$$

$$\sigma_s = 0.35 N/m$$

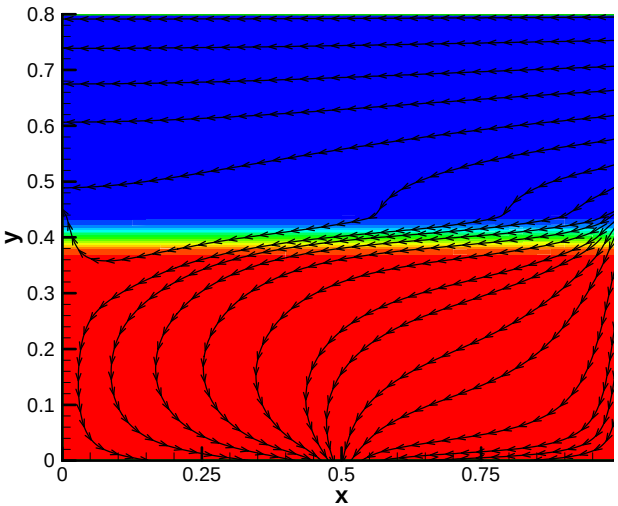
Modification of electric potential formulation force current flow || to B

$$\left.\begin{aligned} j_x &= -\sigma_p \cos\theta \frac{\partial \phi}{\partial x} \\ j_y &= -\sigma_p \sin\theta \frac{\partial \phi}{\partial y} \\ j_z &= 0 \end{aligned}\right\}$$

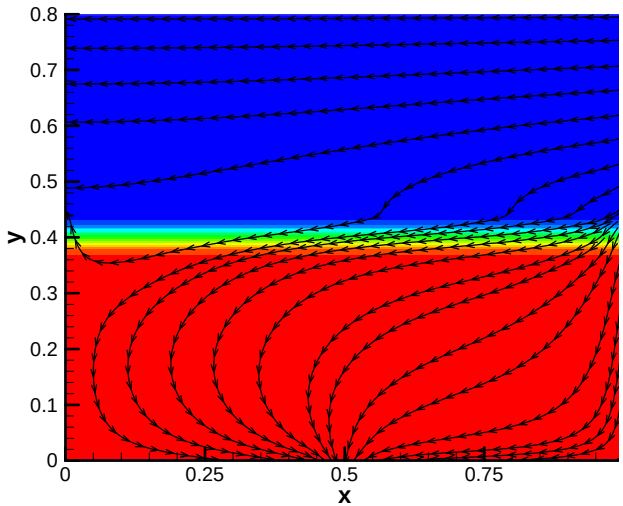
$$\left.\begin{aligned} j_x &= -\sigma_{LM} \frac{\partial \phi}{\partial x} \\ j_y &= -\sigma_{LM} \frac{\partial \phi}{\partial y} \\ j_z &= -\sigma_{LM} \frac{\partial \phi}{\partial z} \end{aligned}\right\}$$



Center Grounding Strip: Density Contour and Current Streamlines



Z=0.1



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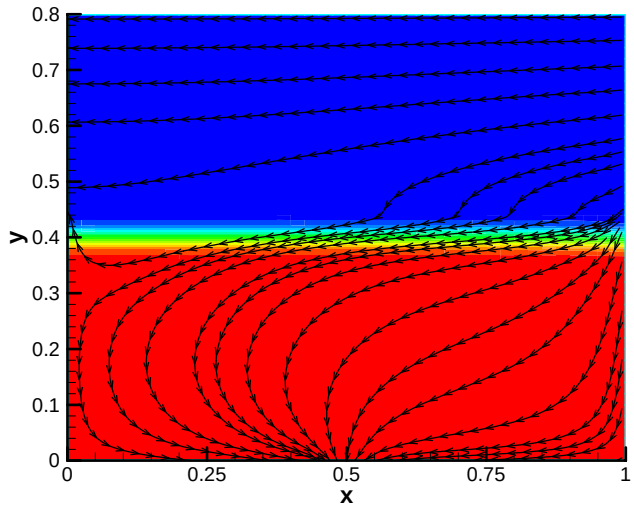

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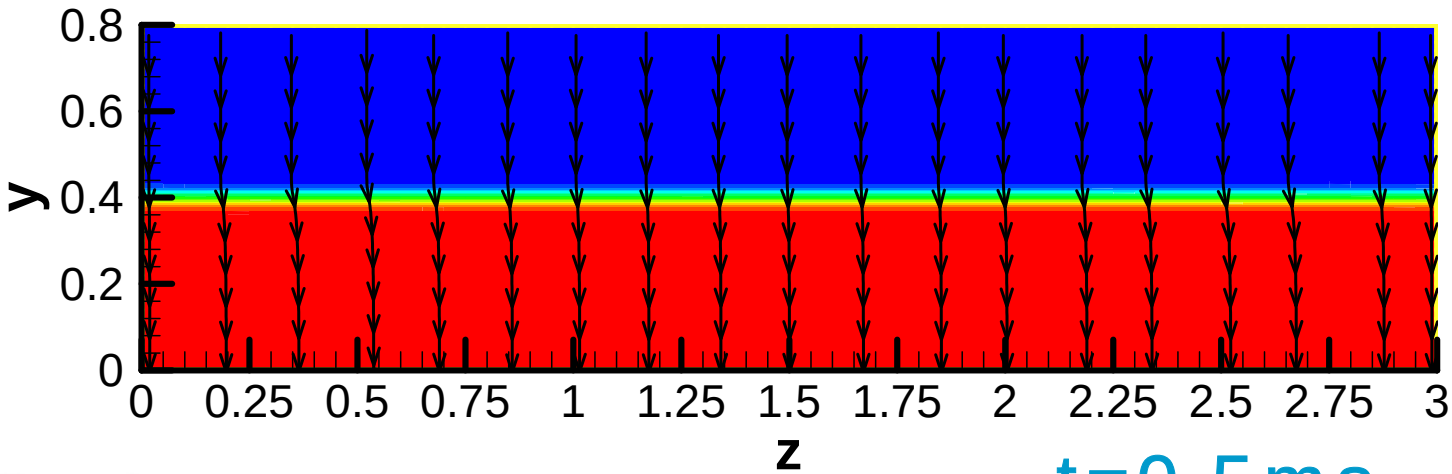

X=0.5

t=0.5ms

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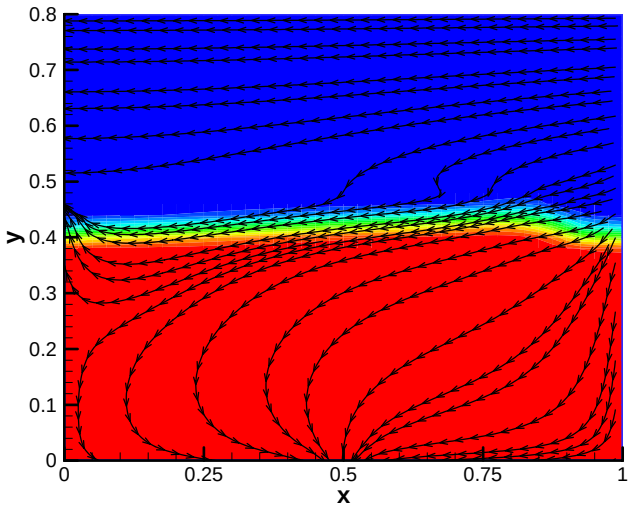
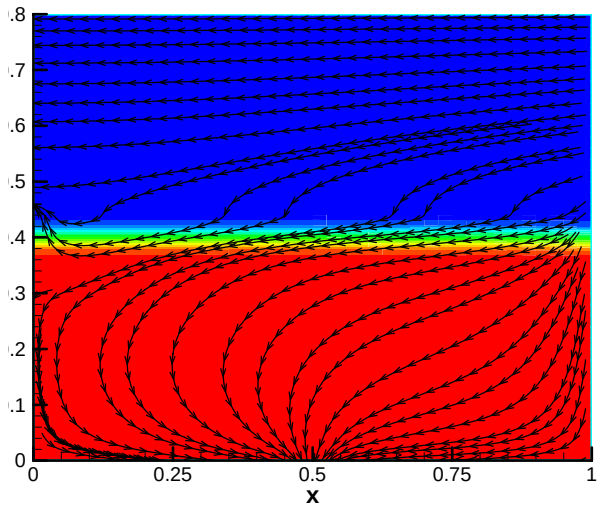
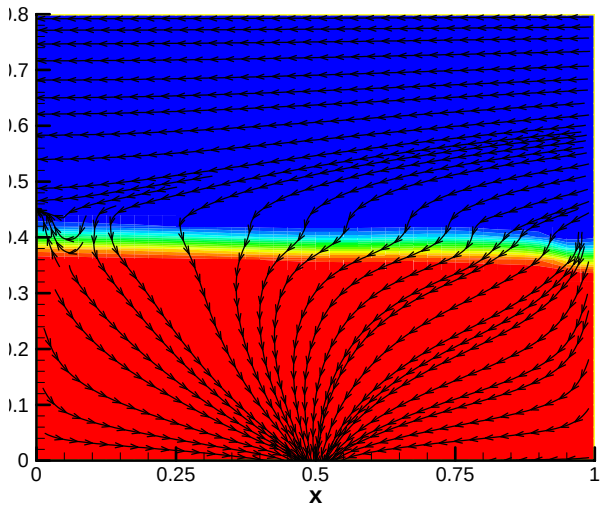
Center Grounding Strip: Density Contour and Current Streamlines



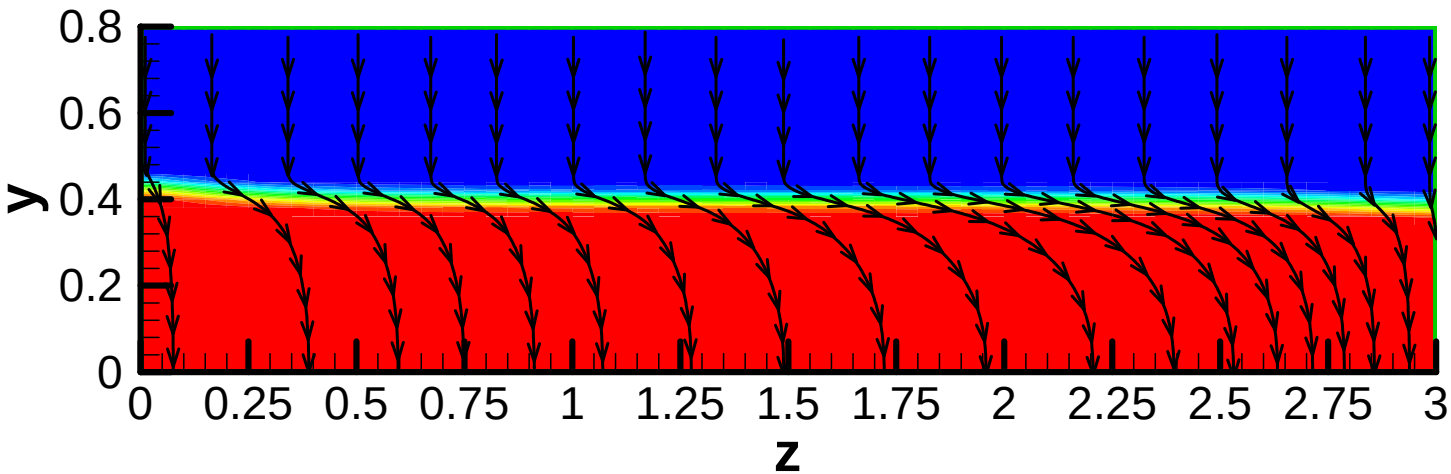
Z=0.1



Z=1.5



Z=3.0



X=0.5

t=11.3ms

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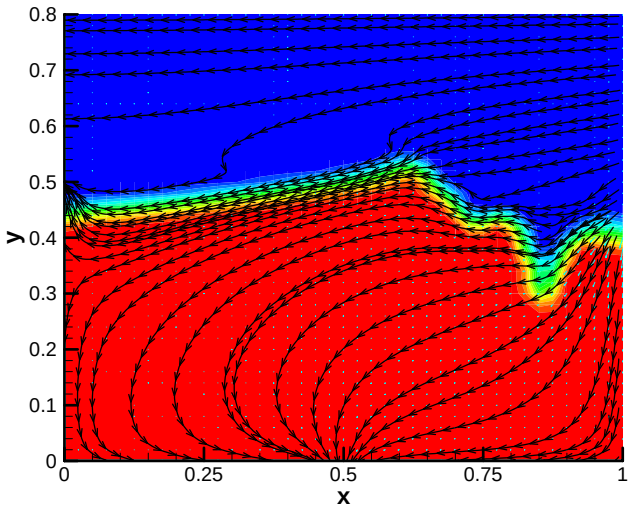
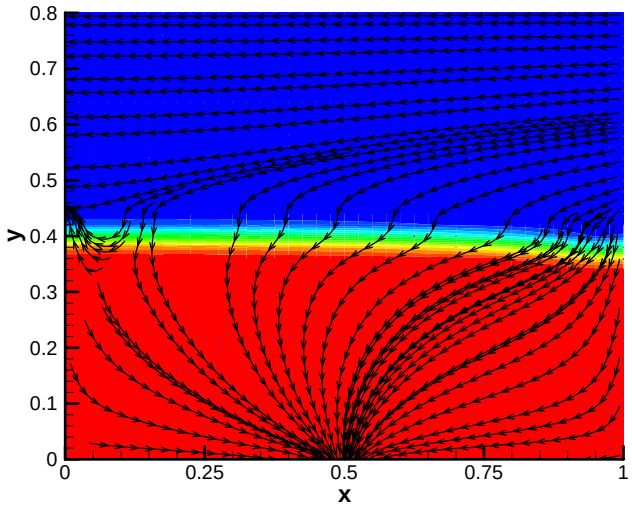
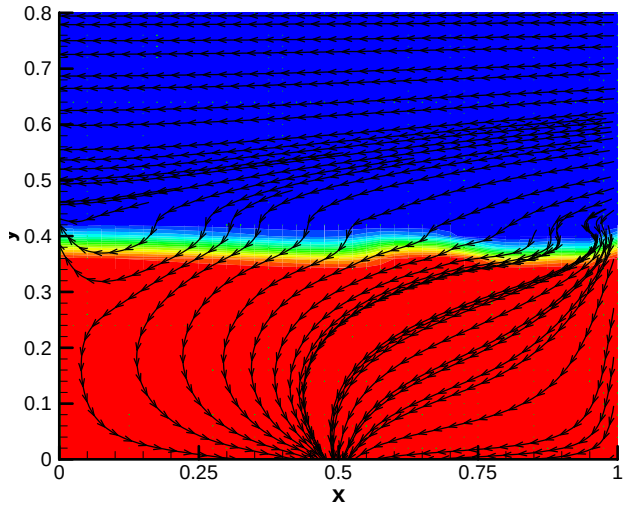
Density Contour and current streamlines for a long grounding patch



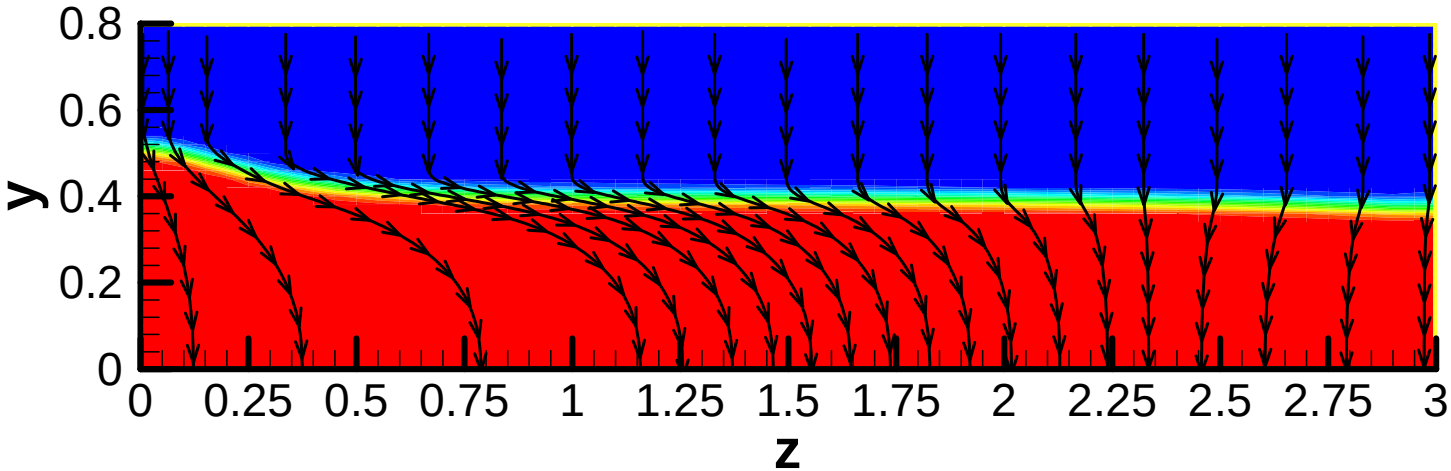
Z=0.1



Z=1.5



Z=3.0



X=0.5

at t=22.5ms

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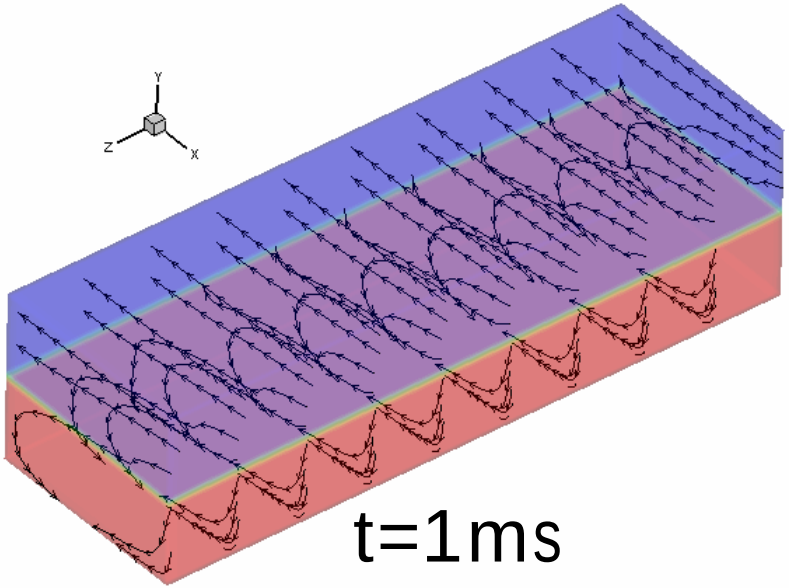
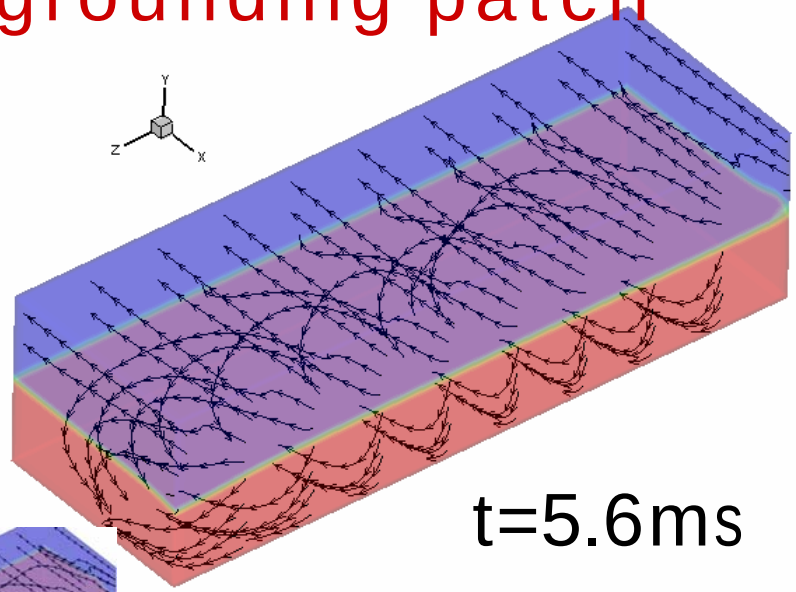
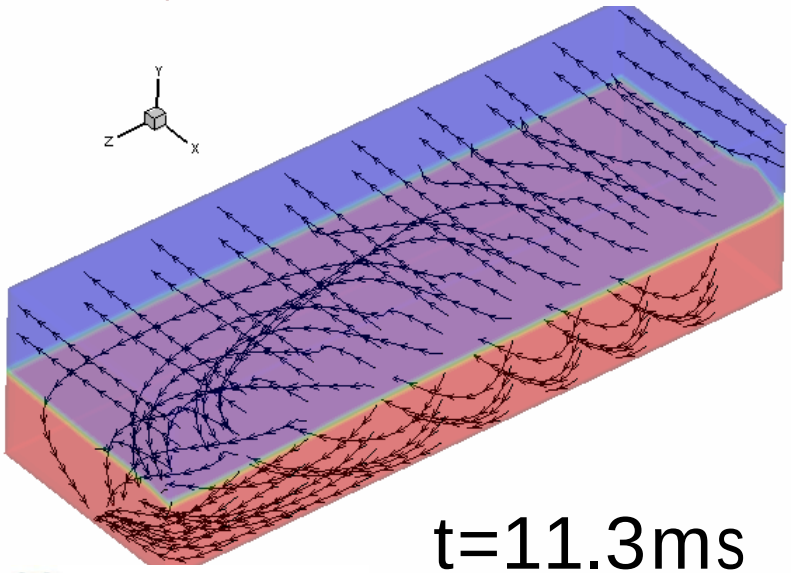
3-D Density Contour and current Streamline for a long grounding patch



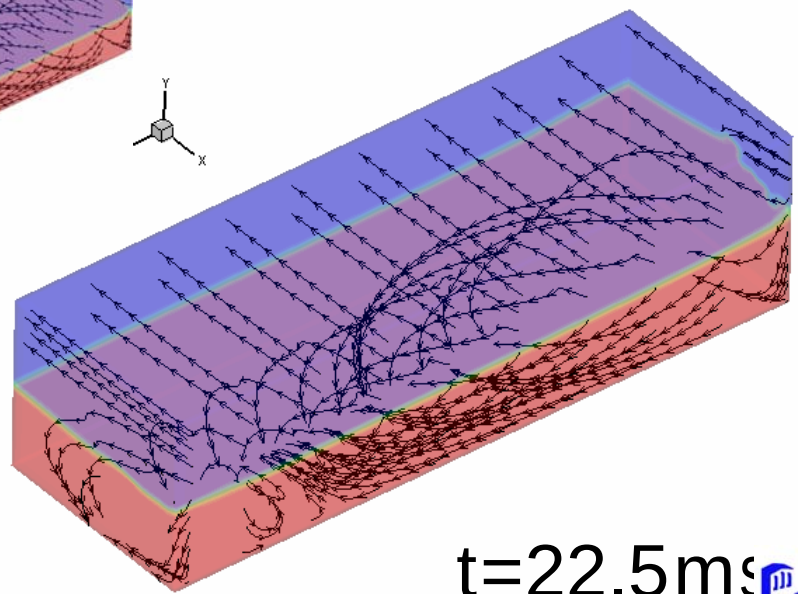
t=1ms



t=5.6ms



t=11.3ms



t=22.5ms

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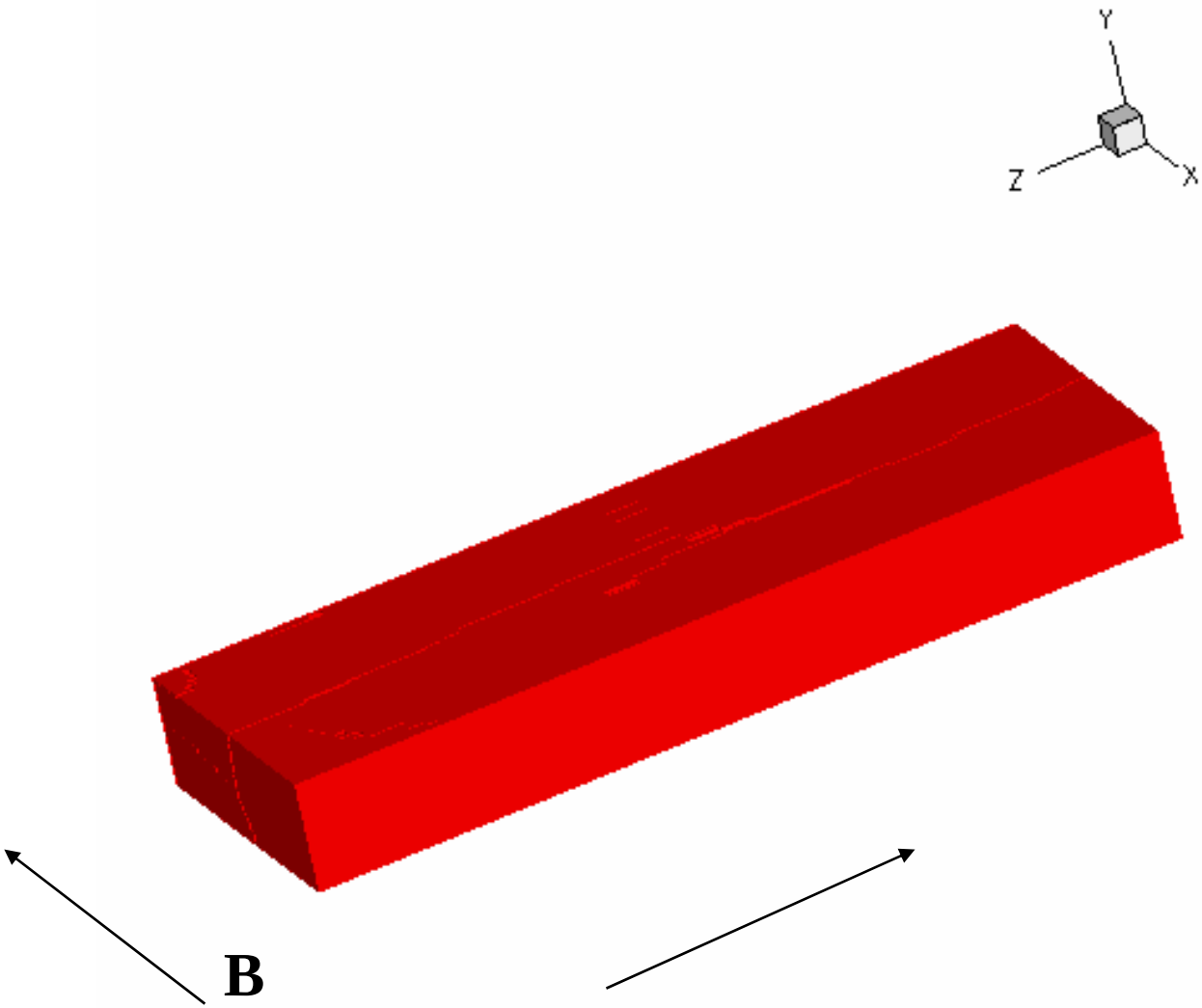
3D interface evolution from 0.5-30 ms with long grounding strip



Inboard direction

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Observations on 3D HIMAG simulations

- **Unverified simulations show the inboard fluid motion onto the main tiles.**
- **Simulations of Li motion with two grounding patches have less relative motion than complete bottom surface grounding**
- **4 mm deep slot case should still be run with main tile lip to observe motion of sloshed material.**

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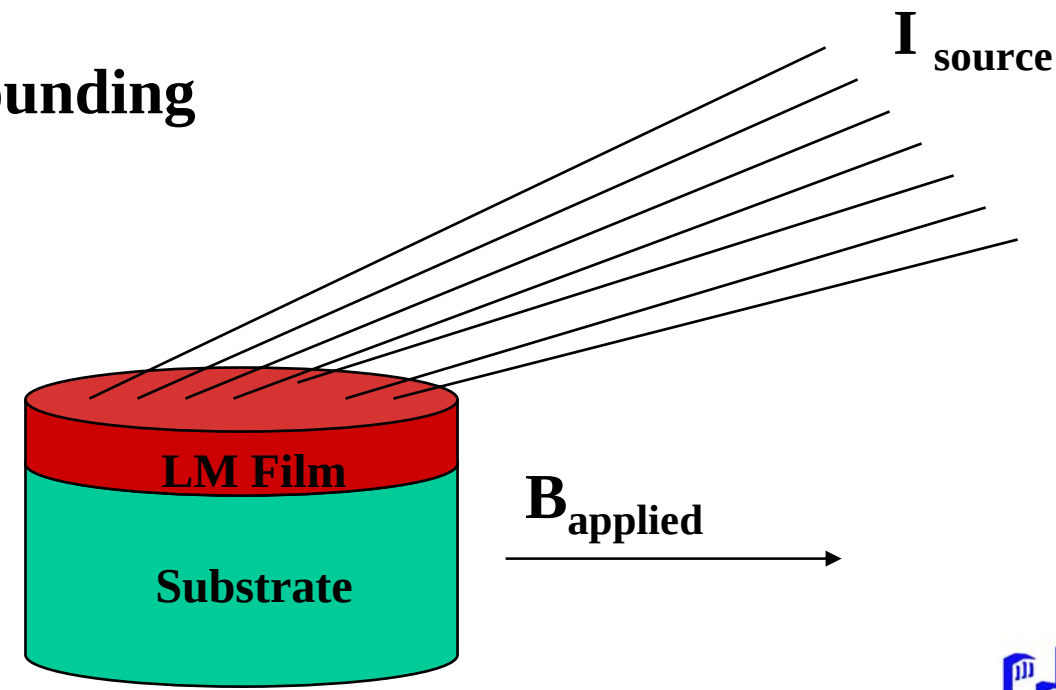
Possible Experiment for DiMES Simulation

- **Simulate flux tubes with 3D thin wire array**
- **Independently control length/voltage off wires**
- **Control substrate grounding**
- **Pulse magnetic field or voltage and observe metal motion with fast cameras**

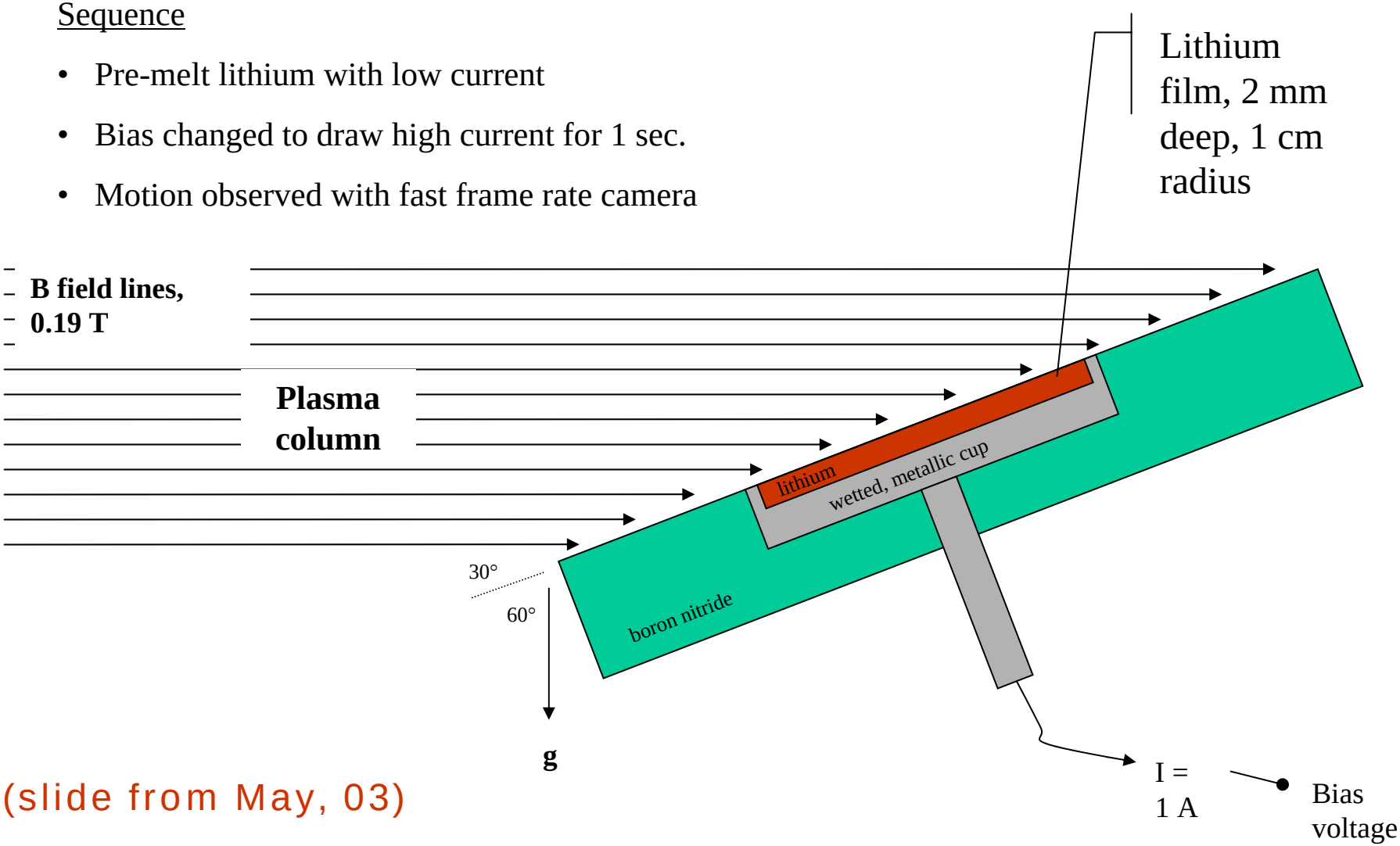


(slide from Nov, 02)

Li motion test in PISCES

Sequence

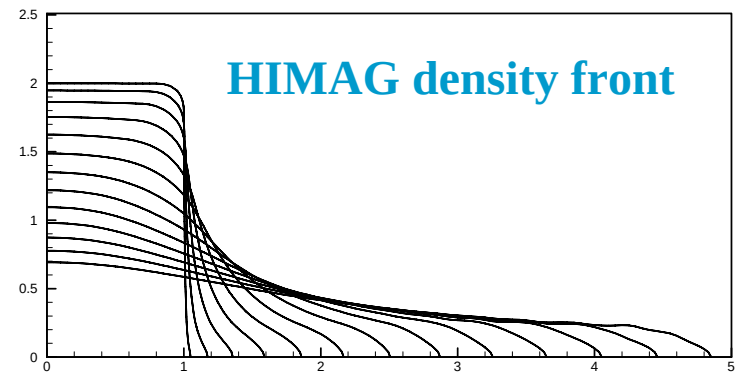
- Pre-melt lithium with low current
- Bias changed to draw high current for 1 sec.
- Motion observed with fast frame rate camera

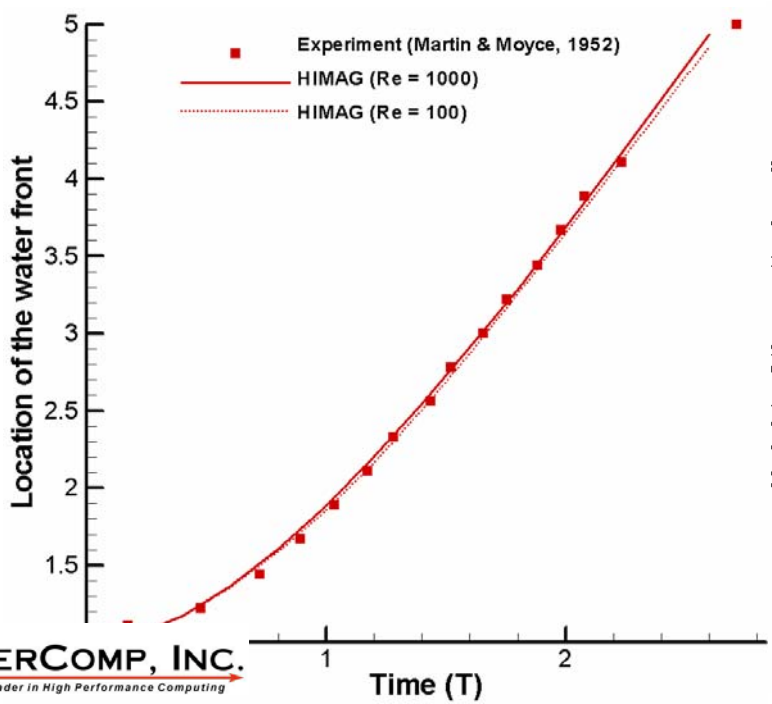


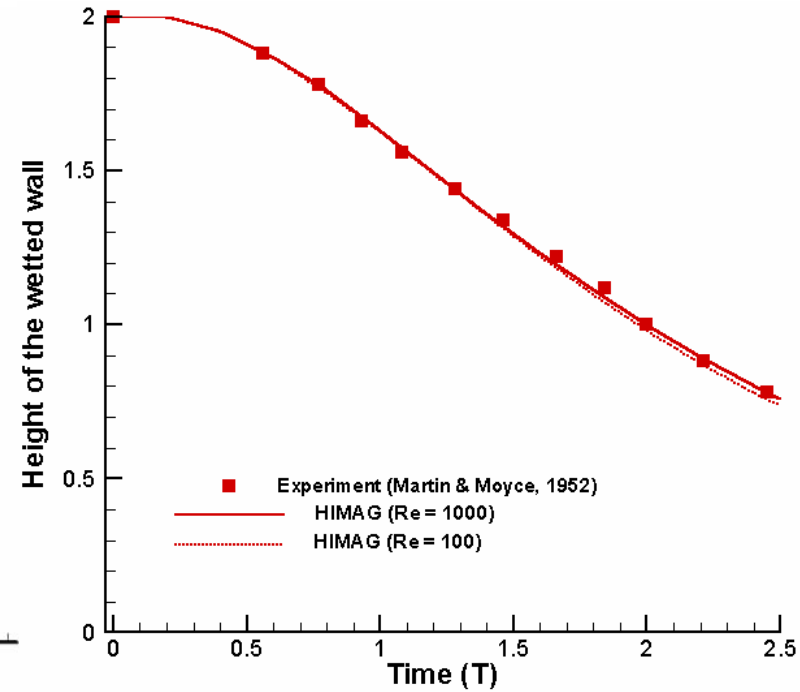
(slide from May, 03)

Validation against an unsteady free surface problem – Broken Dam

Considering repeating this classic experiment with LM and vertical magnetic field







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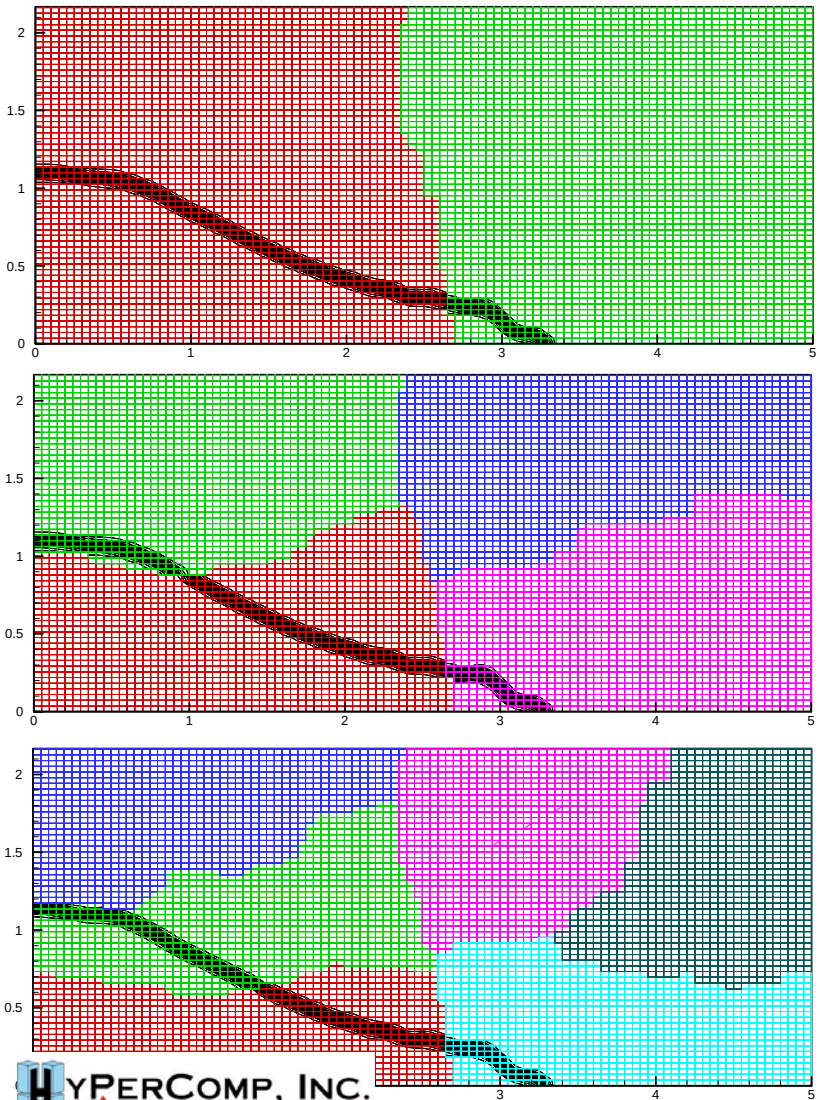
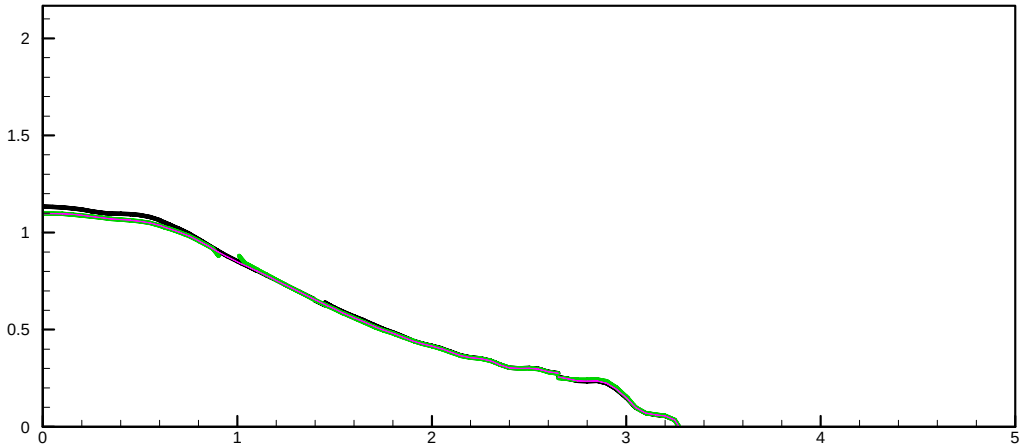
Multiple processors validation on Non-MHD broken dam problem





Interface Position at t=1.8 for the broken dam problem of Martin & Moyce (1952)

Black line: using 6 processors
Green line: using 4 processors
Pink line: using 2 processors

Domain decomposition and computed result on 2,4,6 processors on the left

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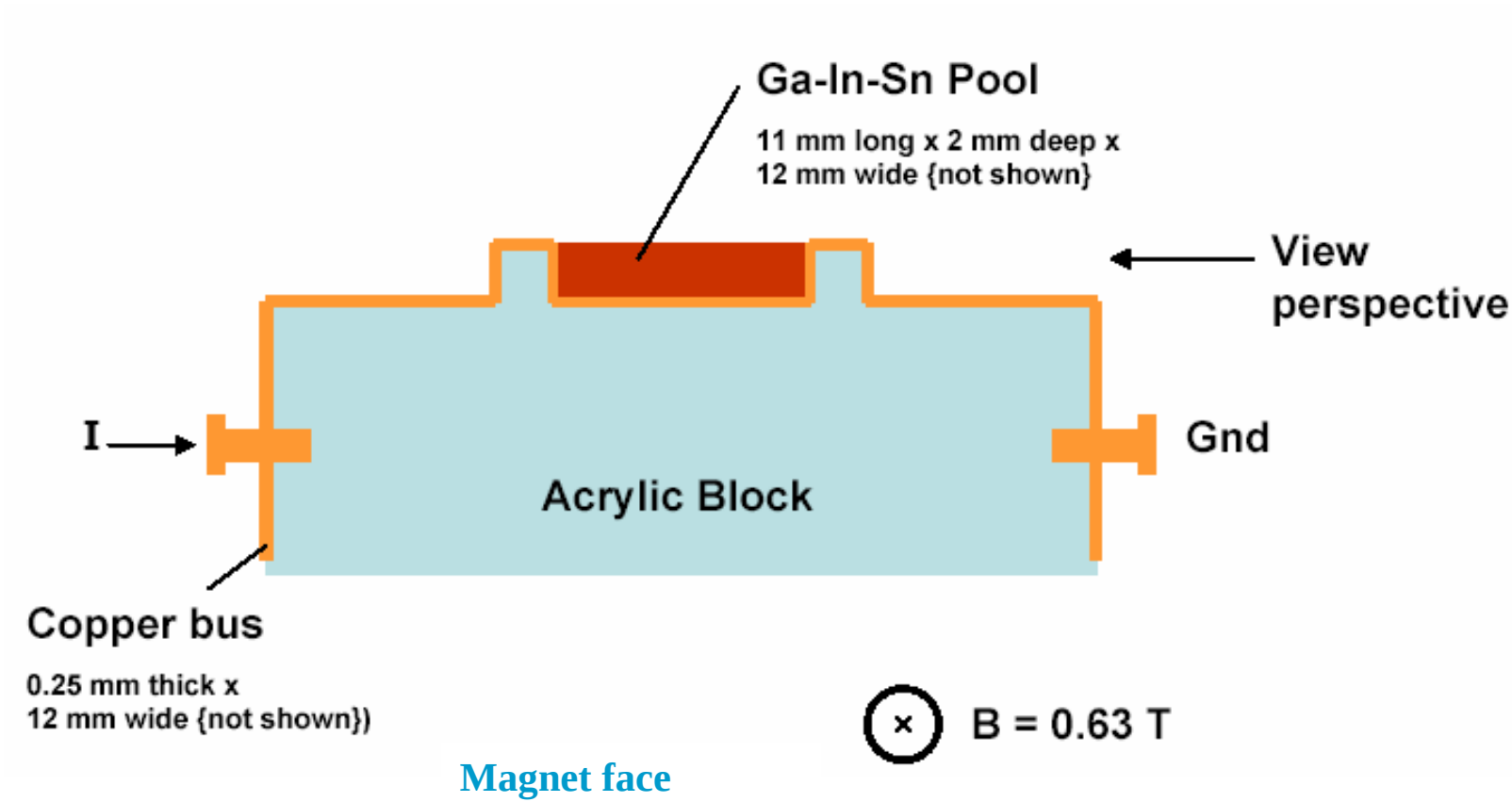
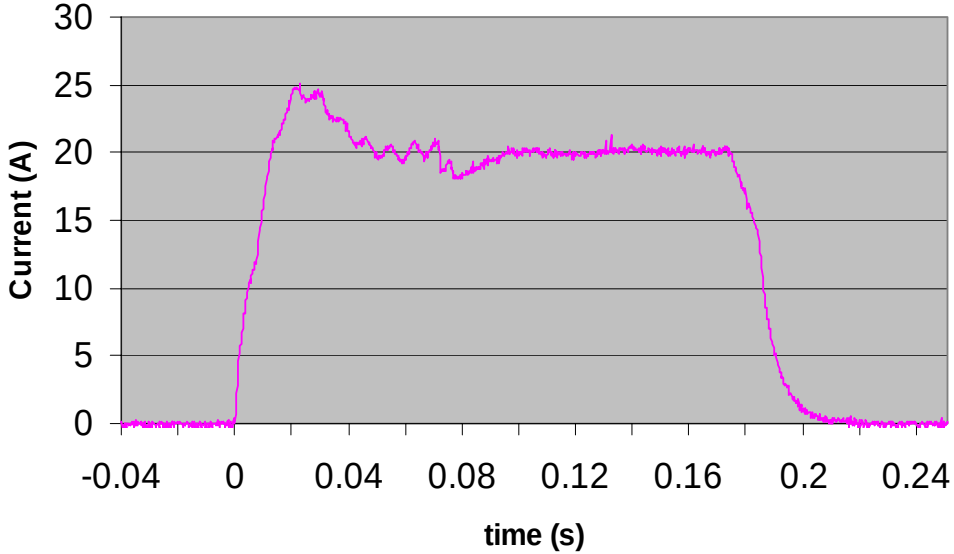
Tabletop Benchmark Experiment For HIMAG validation

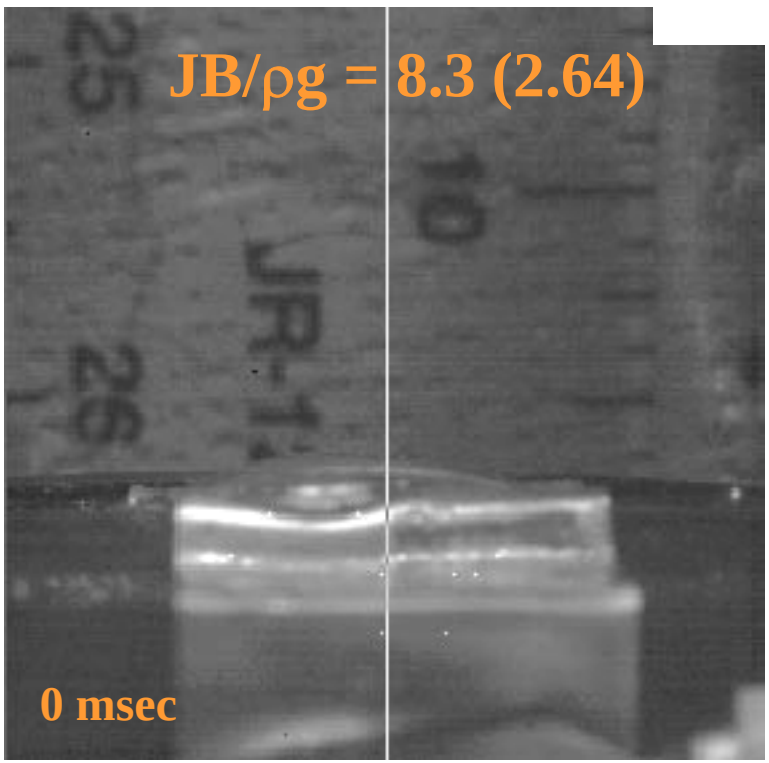


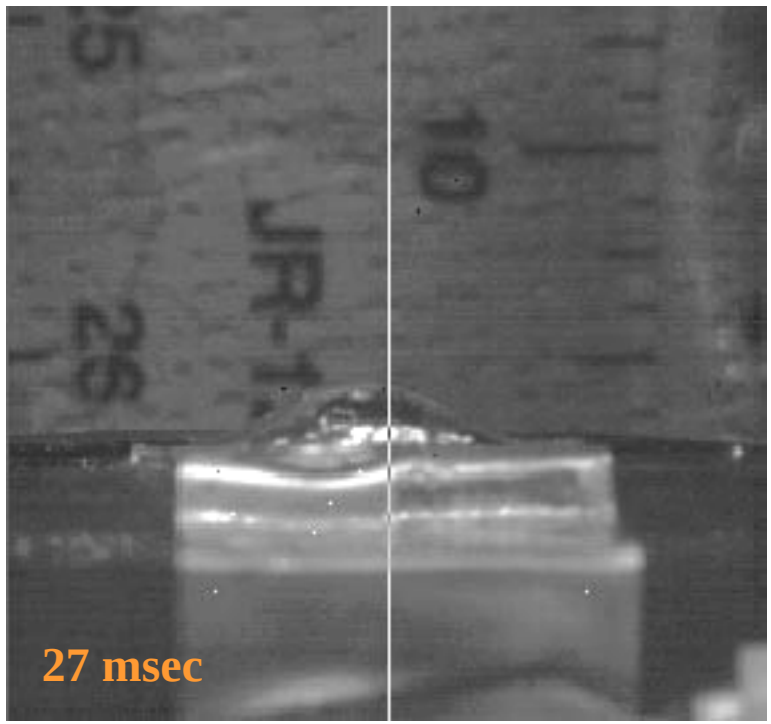
20 Amp Case

- **LM bulges upward during current rise, then sits ~stationary until end of current pulse**



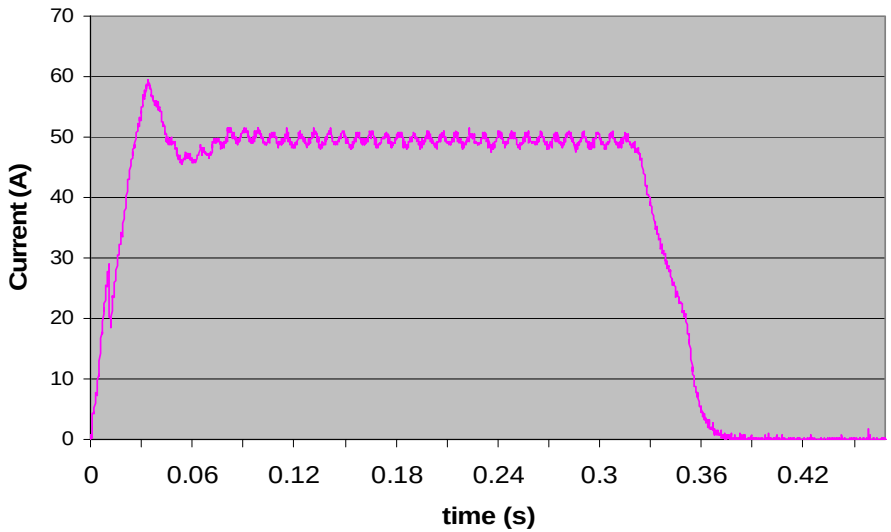
B →



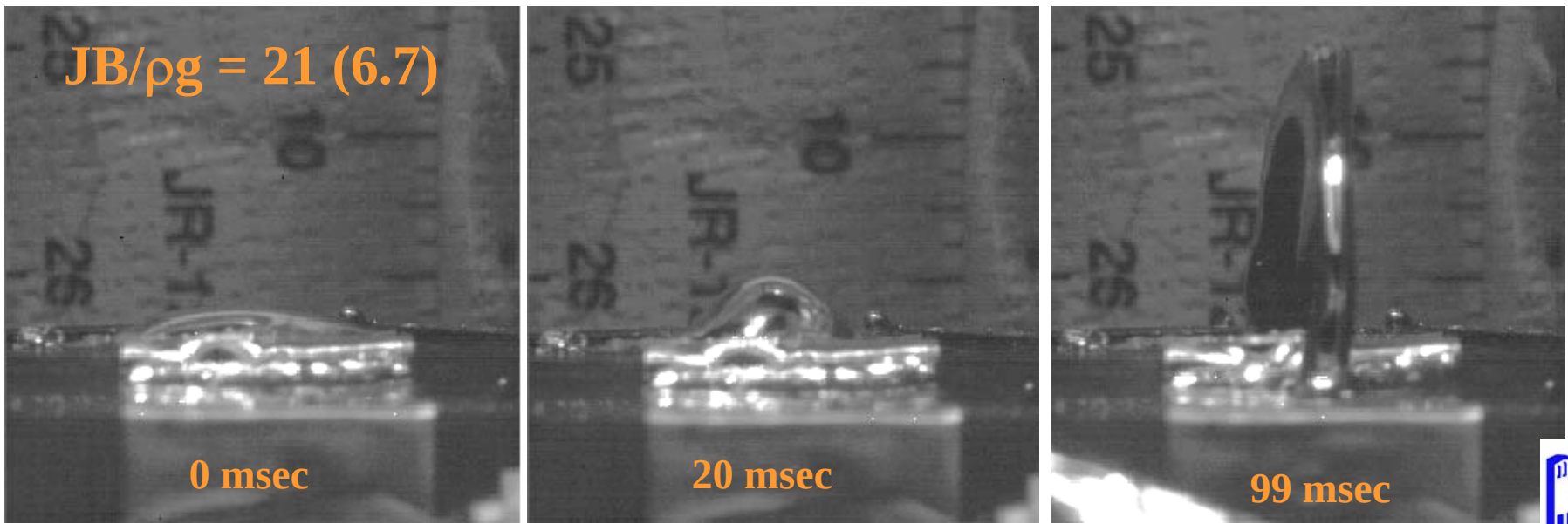


50 Amp Case

- **LM bulges upward during current rise and initial flattop**
- **Flat LM disk forms and dances around during entire current pulse**

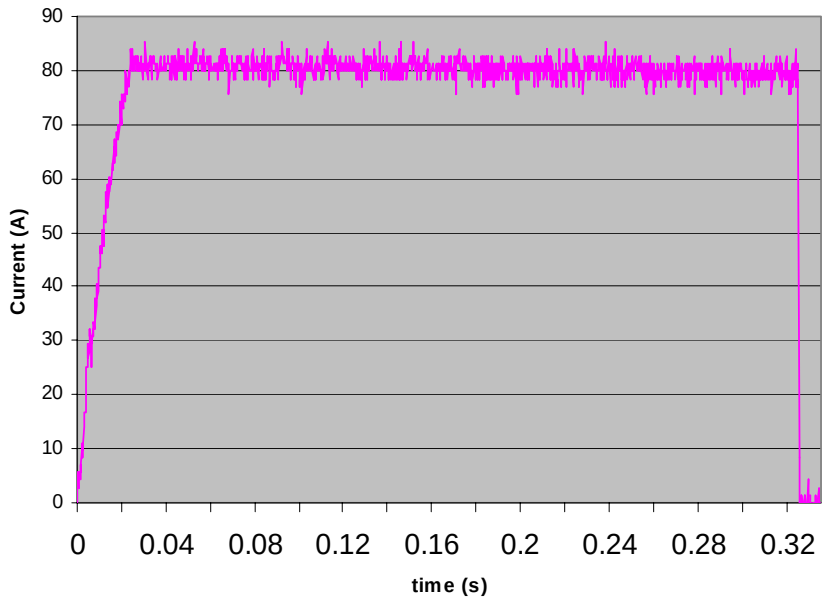


B →

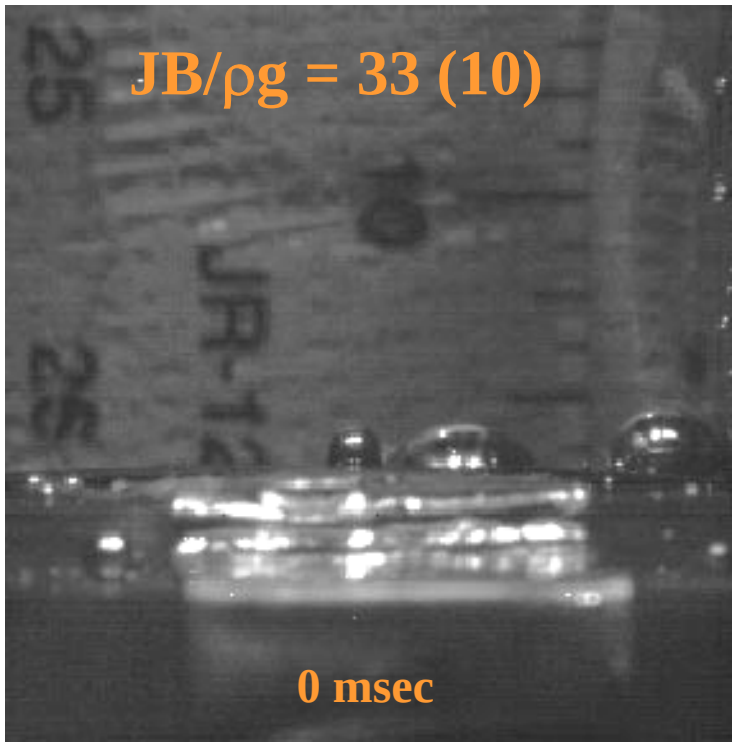


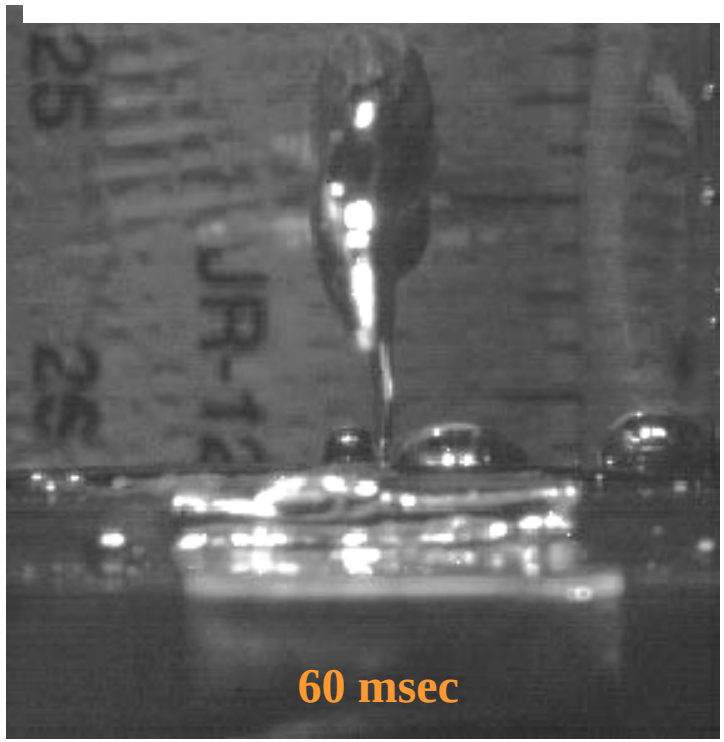
80 A Case

- **LM bulges upward during current rise and continues rising during current flattop**
- **Ejects large droplet (significant portion of total liquid)**

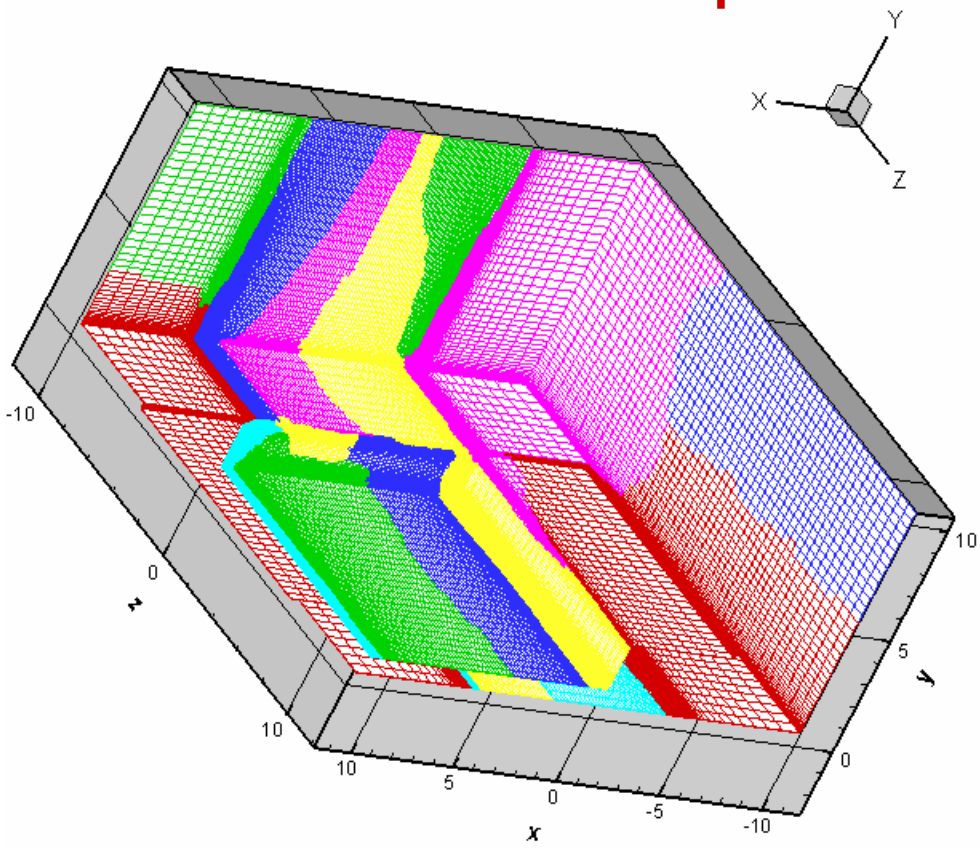


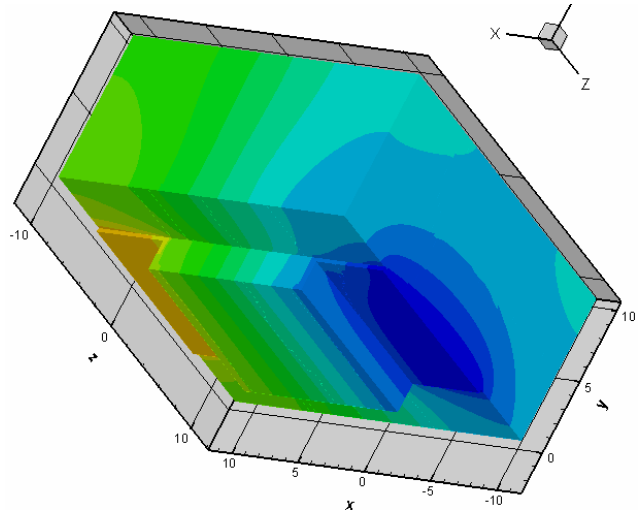
B →

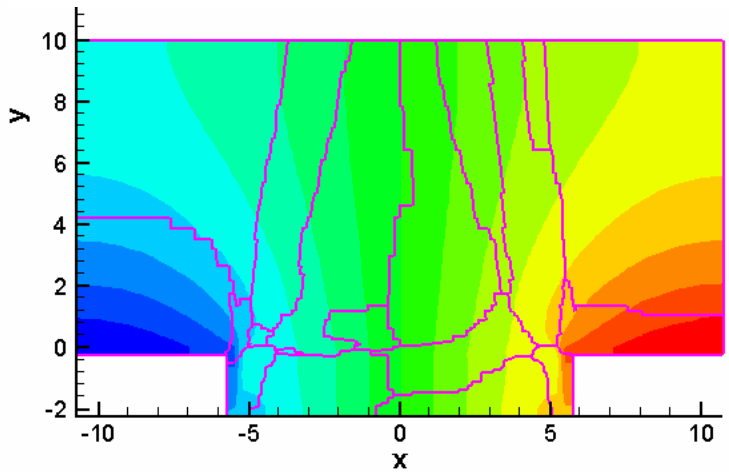




HiMAG Computational mesh







- **Resolving both liquid and solid conductor bus so that current switching is modeled.**
- **16 processors, ~350000 cells**

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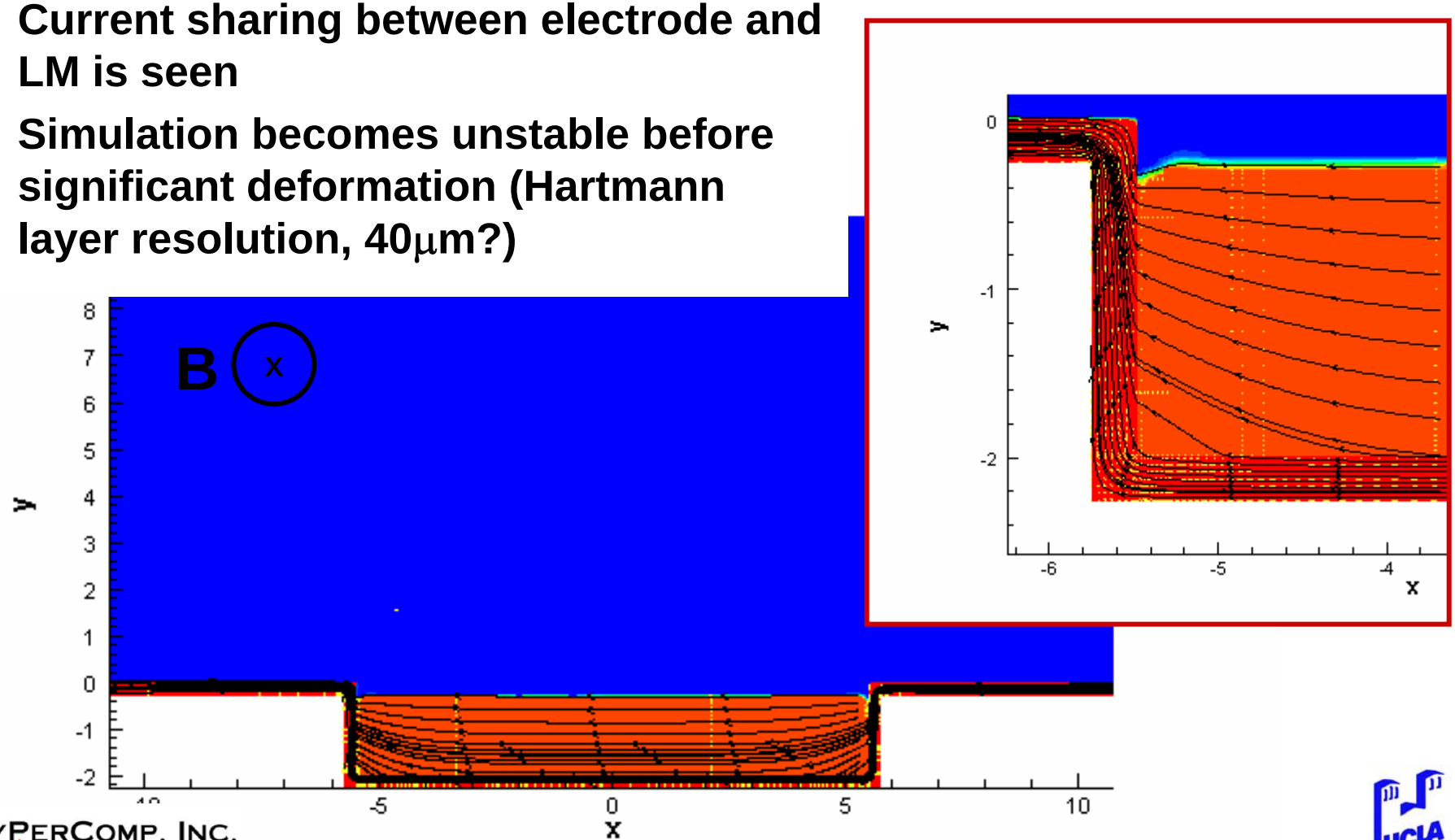
Current Streamline and Level Set Contour for 20 A case at t=0.8ms

- **Current sharing between electrode and LM is seen**
- **Simulation becomes unstable before significant deformation (Hartmann layer resolution, 40μm?)**



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Observations on table top experiment and simulations

- **Small and large deformation experiments show the motion of LM**
- **Wetted surfaces and surface tension seem to play a strong role in holding the liquid down.**
- **Simulations must still be completed and verified on these relatively simple experimental cases before confidence in more complex 3D DiMES slot calculations can be established.**

Future work for DiMES modeling

- **Continue HIMAG development and validation. Debugging, resolution and time step for stability, addition of momentum flux model in 3D, phase change, etc.**
- **Application of HIMAG to tabletop experiment**
- **Performance of LM-MHD broken dam experiment as fundamental benchmark case**
- **Application of models to cases of metallic PFC melt layer motion with MHD.**
- **Suggestions? All are welcome (even if unheeded)…**