Progress on Liquid Metal MHD Free Surface Flow Modeling and Experiments

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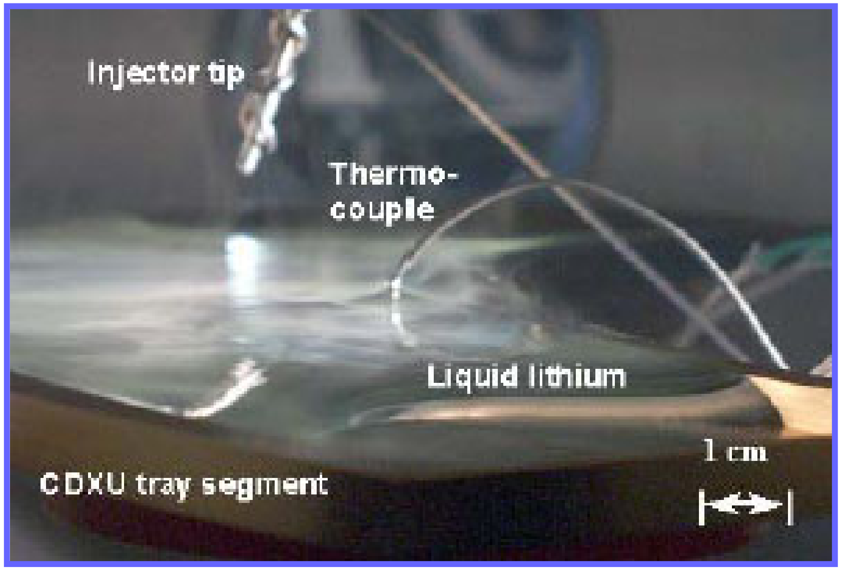
Outline

- Flowing free surface lithium module in NSTX
- HIMAG code and MTOR facility
- Simulations of Lithium jet flow in LIMITS and NSTX fields
- Simulations of Lithium motion in DiMES sample holder
- Ga-alloy film flow simulations and MTOR experiments – M. Narula, poster
- Future work

Both experimental and theoretical physicists are interested in the effects of liquid lithium on plasma performance

- TFTR experiments with injected Li droplets demonstrated the best confinement and highest power shots of the entire TFTR lifetime
- CDX-U experiments with liquid lithium showed incredibly clean plasmas (low impurities) for such a small machine – significant interest of university programs



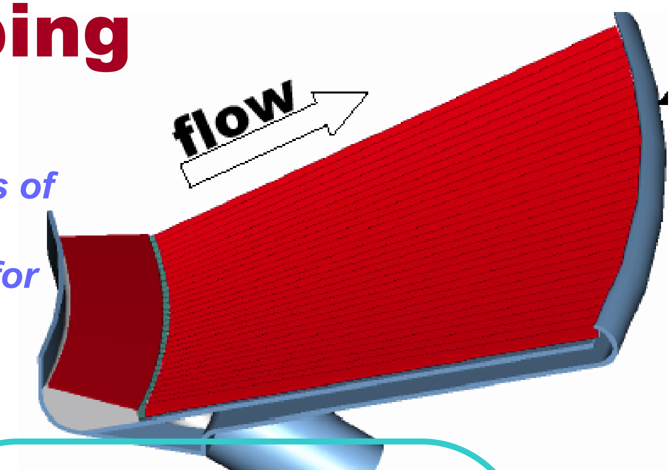
Li layer spreading on tray segment in the CDX-U ST experiment at PPPL

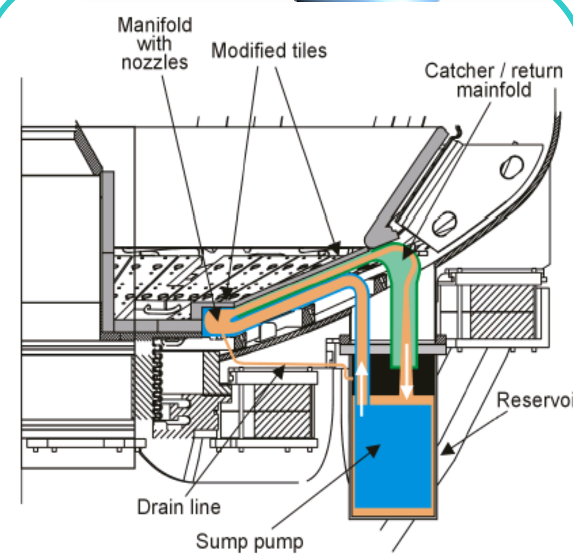
- Special sessions with many papers presented at recent APS-DPP and Sherwood Theory meetings on the use of Li to achieve low recycling plasma edge conditions and improve various stability conditions.

A flowing lithium divertor experiment is considered for NSTX at PPPL to aid in particle pumping

- Next stage of NSTX needs a better mechanism to control particles and impurities –an experimental flowing lithium module in place of cryo-pumping is being considered
- Flowing Lithium Module
  - Stage 1: lithium pellets
  - Stage 2: thin stagnant liquid Li test
  - Stage 3: flowing lithium for improved plasma performance
  - Stage 4: flowing lithium for heat removal for long pulse operation

Sketches of Li flow module for NSTX

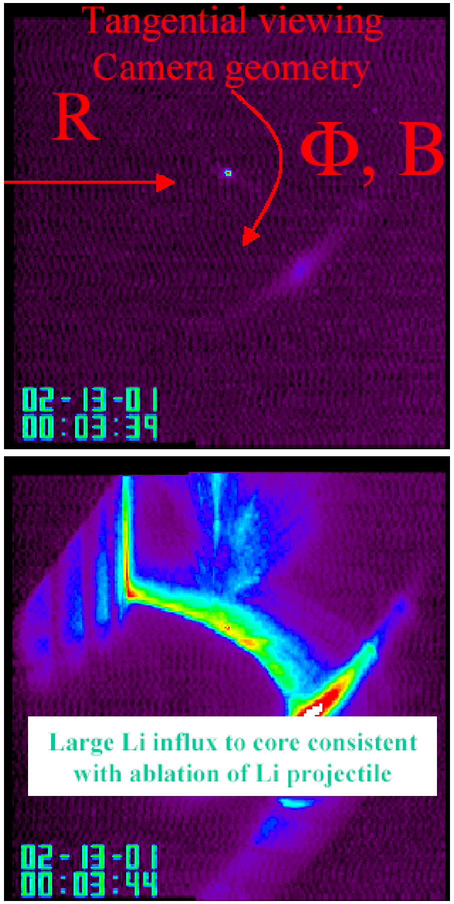




The concept: NSTX Lithium Free Surface Module (ORNL)

Main concern identified by NSTX for flowing Li divertor experiment is the control of free surface MHD flow

- NSTX magnetic fields have strong variations in strength and direction along the lower outboard divertor region
- NSTX is a pulsed device with ~5 sec toroidal field and ~2 sec plasma current flat
- Contact with plasma can result in halo and thermoelectric currents closing through the liquid lithium
- Complex geometry, electrically conducting flow formers, collectors, spill catchers, *etc.* need to be designed and accurately modeled and tested.



Lithium pulled into DIII-D plasma by plasma current driven MHD forces

Combined numerical and experimental effort needed to understand and develop predictive capability for NSTX flowing Lithium module

- Numerical modeling and high-speed parallel computation
  - **HIMAG 3D** free surface MHD code developed in collaboration with Computational Fluid Dynamics (CFD) research specialists from outside fusion
- Small laboratory experiments
  - **MTOR** (***Magnetic Torus***) facility built mostly by students with recycled equipment from MIT, PPPL and Russia is a unique facility for studying free surface liquid metal MHD flows

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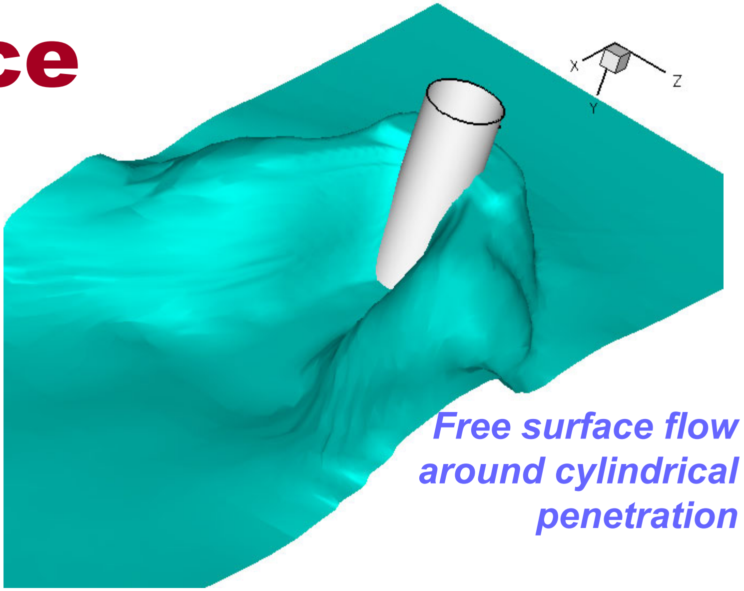
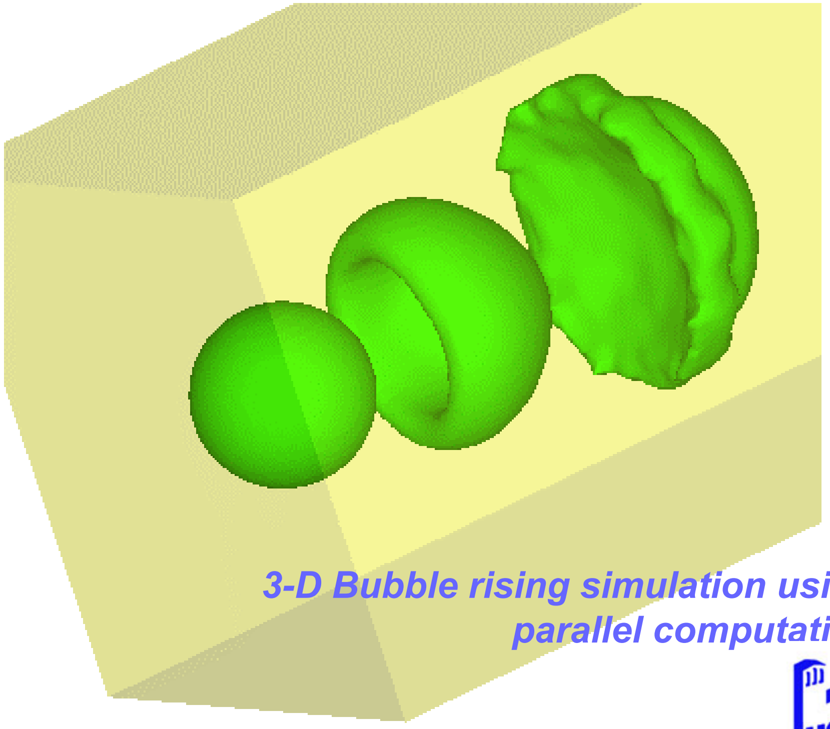
The HIMAG Free Surface MHD Code

- Three dimensional CFD solver
- Finite Volume - Projection
- Unstructured mesh formulation for complex geometry
- Level-Set Free Surface Model
- Electric Potential MHD formulation in multiple materials
- Parallel solution algorithm for large problems
- See Morley, Special APEX issue of FED, 2004



Free surface flow around cylindrical penetration



3-D Bubble rising simulation using parallel computation

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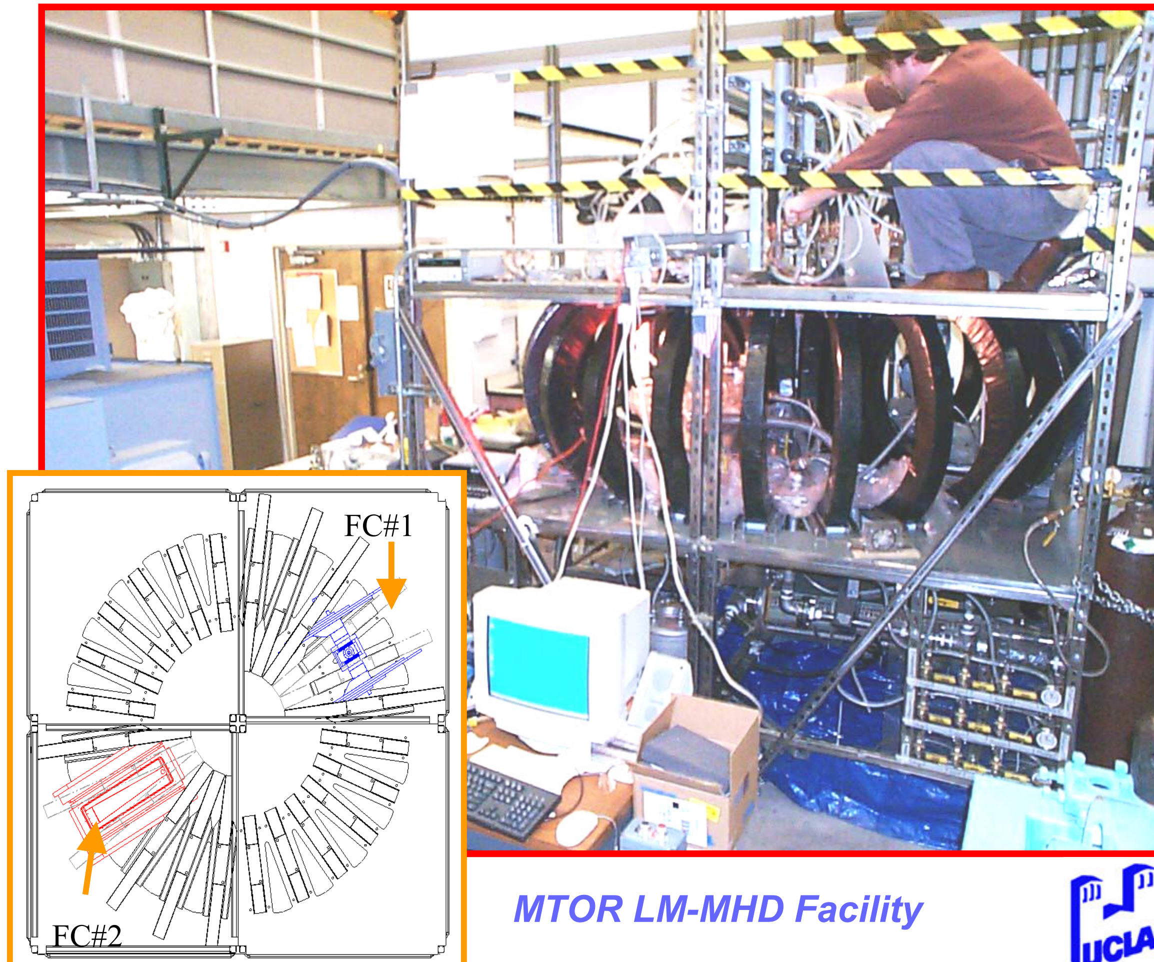
UCLA tokamak field simulator MTOR used for basic flow physics and Li-module simulation experiments

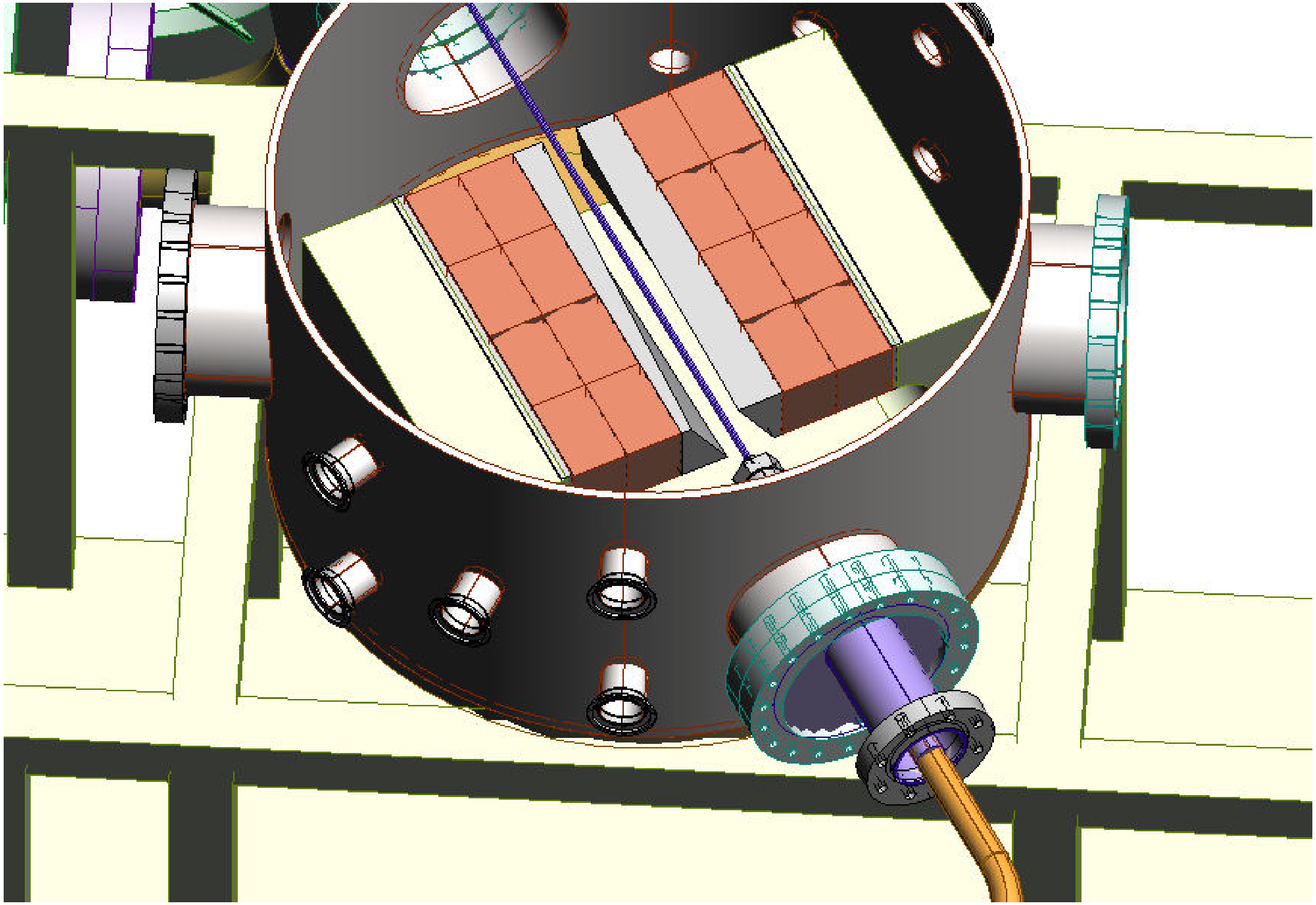
- Large magnetic volume and similar field to NSTX outboard divertor
- Higher field smaller volume regions for higher MHD interaction experiments
- 30 liter gallium alloy flowloop
- See Ying, Special APEX issue of *FED*, 2004



MTOR LM-MHD Facility

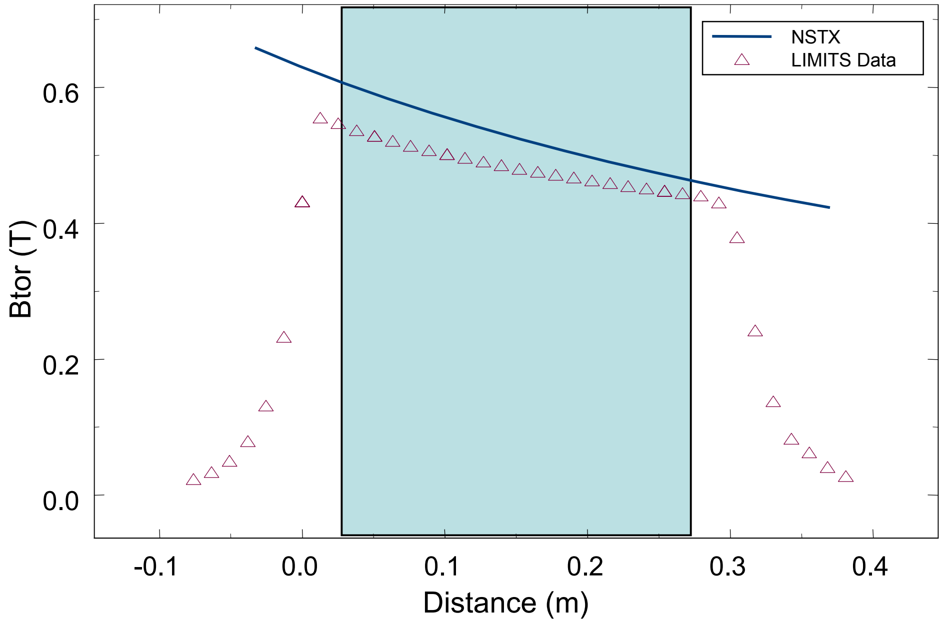
UCLA

Lithium flow in LIMITS is from weak to strong field (outboard to inboard in NSTX)



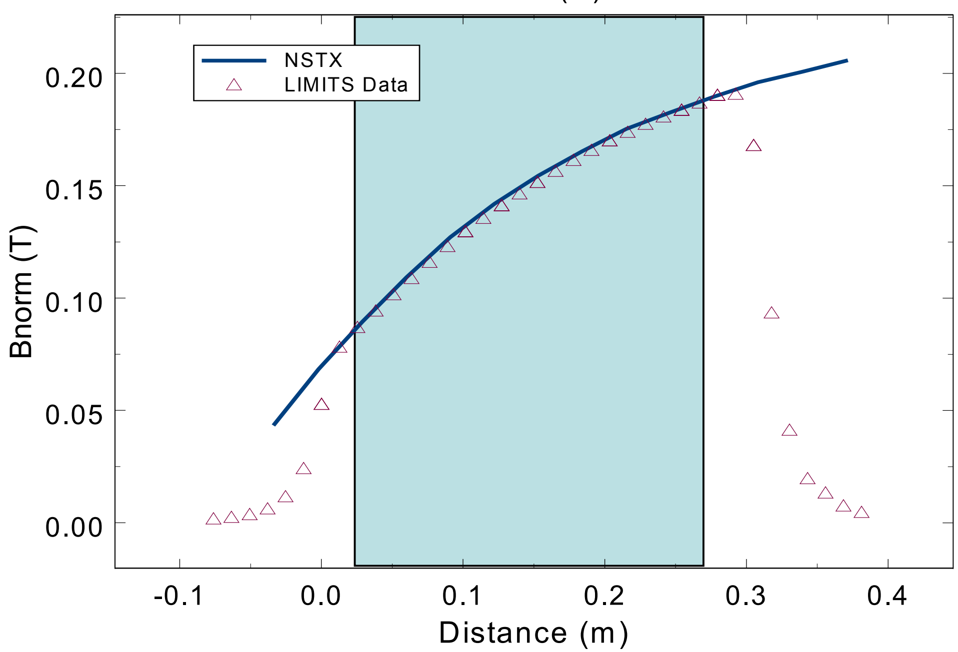
See Tanaka, Special APEX issue of *FED*, 2004

LIMITS Field Configuration



Comparison of the desired toroidal (horizontal) field in NSTX with the measured field in the LIMITS magnet

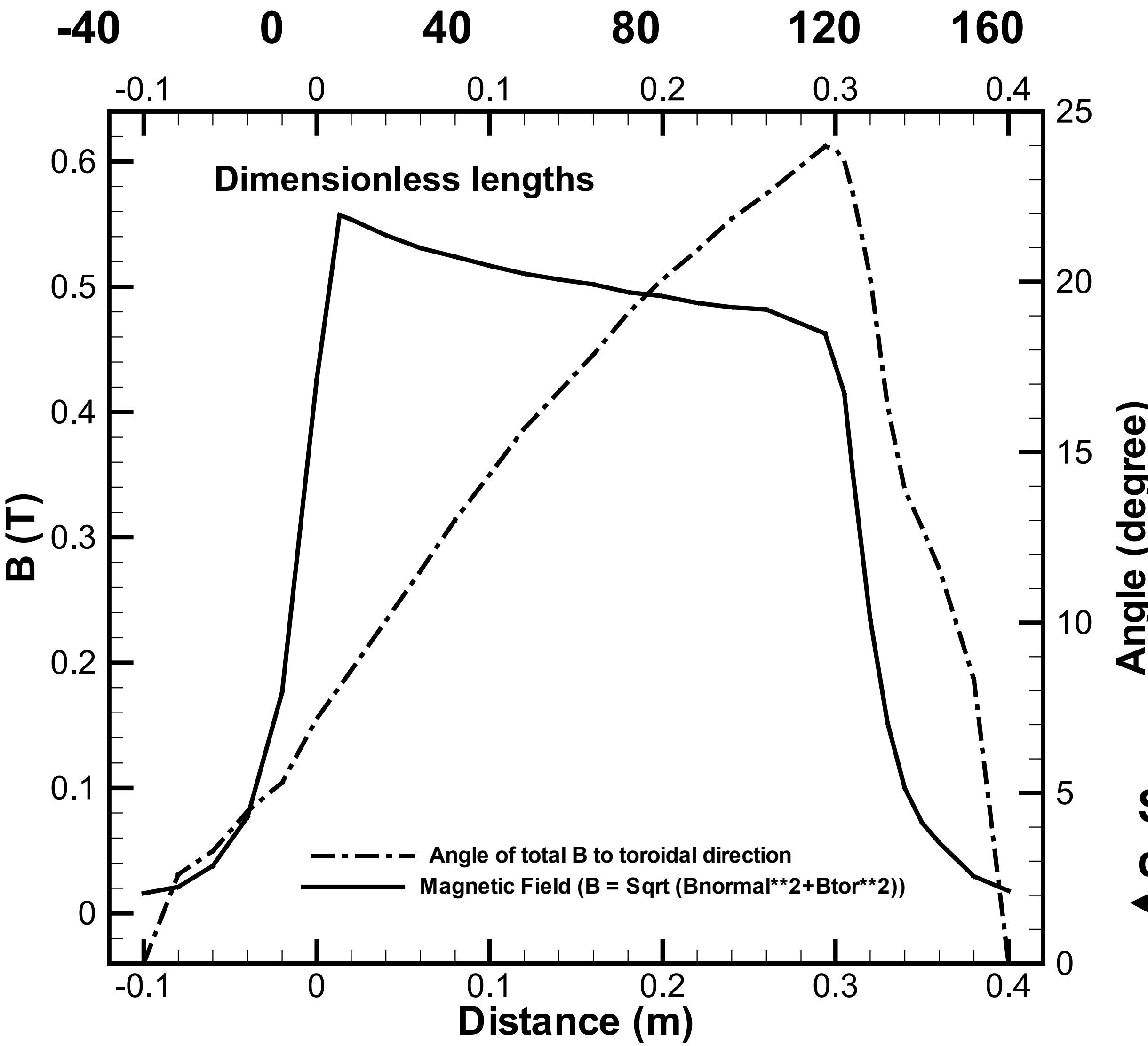
NSTX simulation region



Comparison of the vertical field in NSTX with the measured vertical field in the LIMITS magnet.

LIMITS Field Configuration as a function of distance –

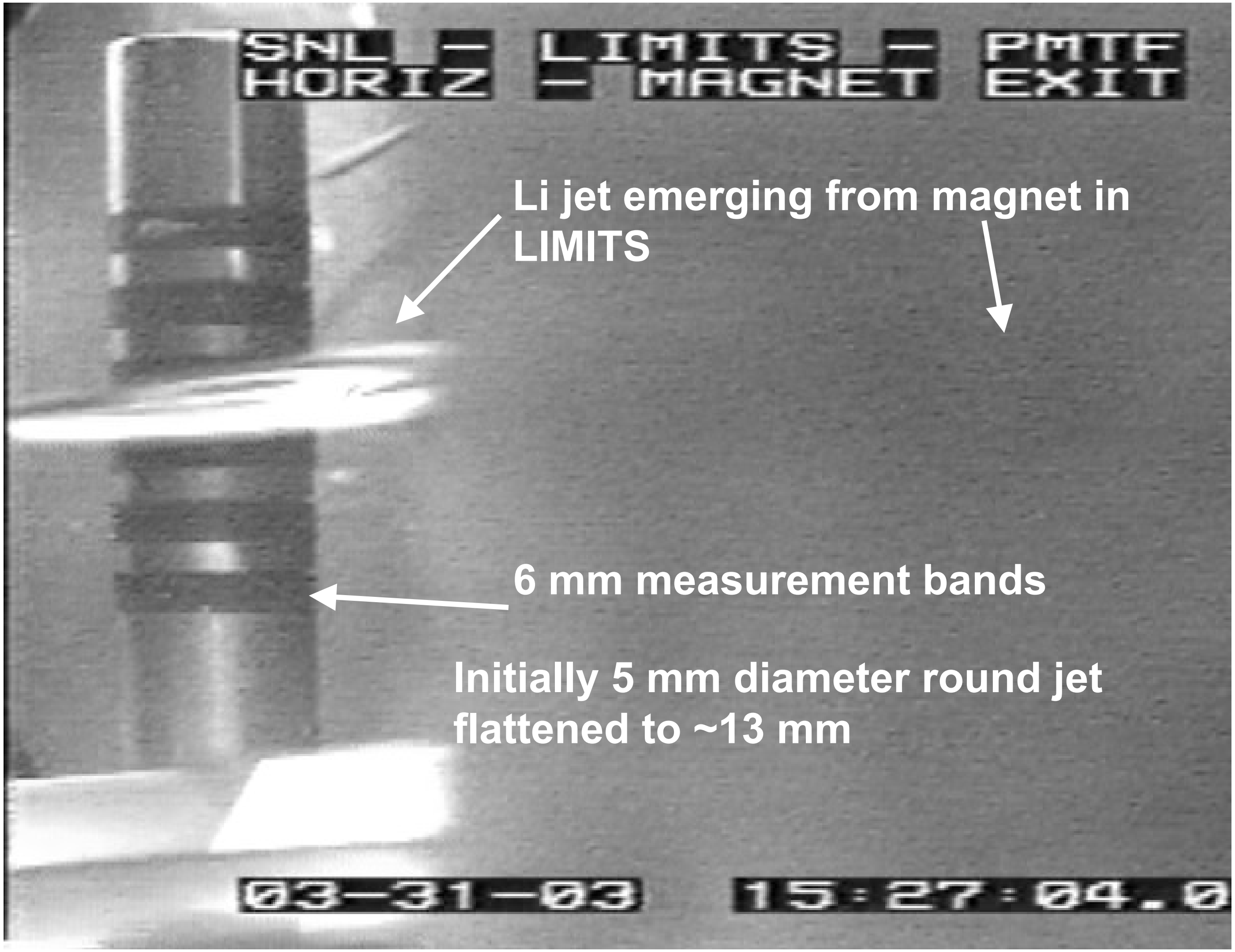
Magnitude gradient and change in field direction by ~25 degree



NSTX flow direction

SNL flow direction

LIMITS Jet flattened as it emerges from the magnet gap



JET Calculation Using HIMAG

5 mm diameter round 200C lithium jet

Inlet velocity = 10m/s

Lithium Properties

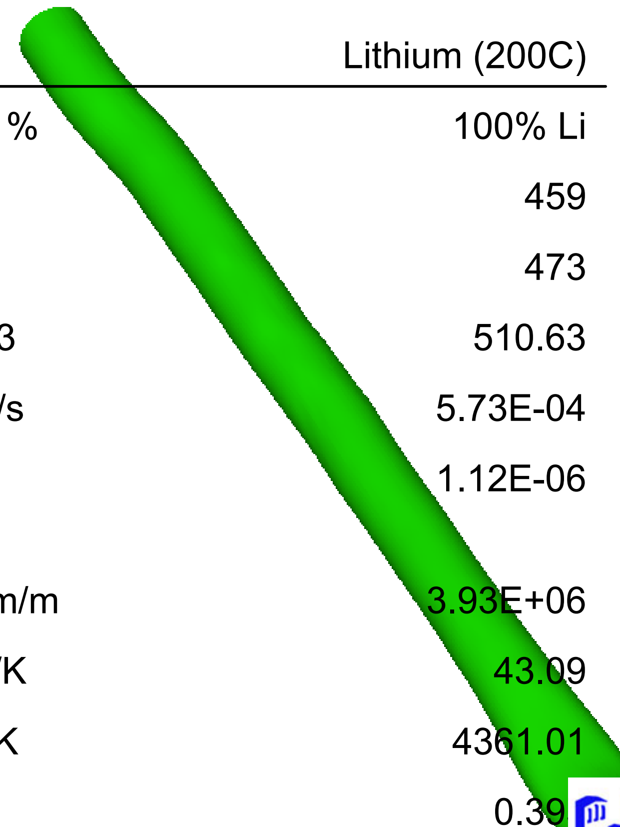
Characteristic scales:
Velocity = 10m/s
Magnetic field = 1T
Length = 2.5mm

Re=22000
Ha=207.04
We=323.18
Fr=4077.5

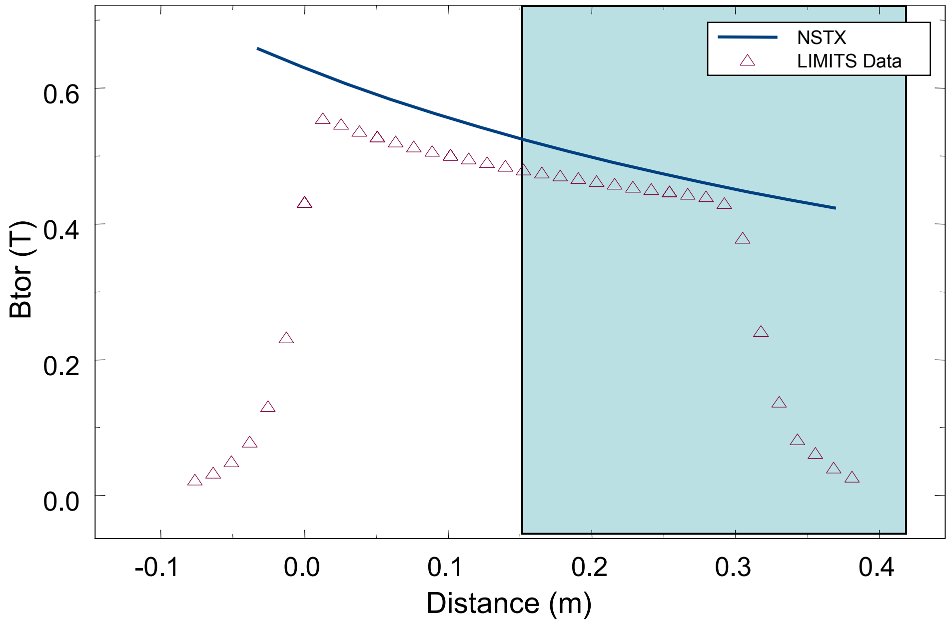
Re=1000

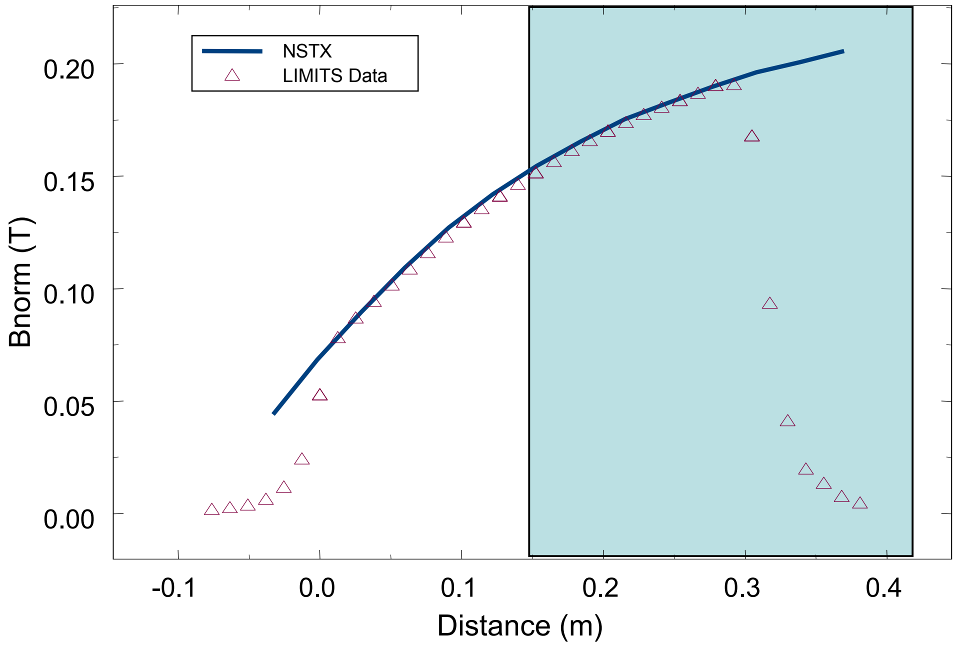
1:3:3

Properties		Lithium (200C)
Composition	Mole %	100% Li
Melting Point, Tm	K	459
Operating Point, T	K	473
Density, rho	kg/m3	510.63
Dynamic Viscosity, mu	kg/m/s	5.73E-04
Kinematic Viscosity, nu	m2/s	1.12E-06
Electrical Conductivity, sig	1/ohm/m	3.93E+06
Thermal Conductivity, k	W/m/K	43.09
Heat Capacity, Cp	J/kg/K	4361.01
Surface Tension, gam	N/m	0.39



LIMITS Exit Field Simulation

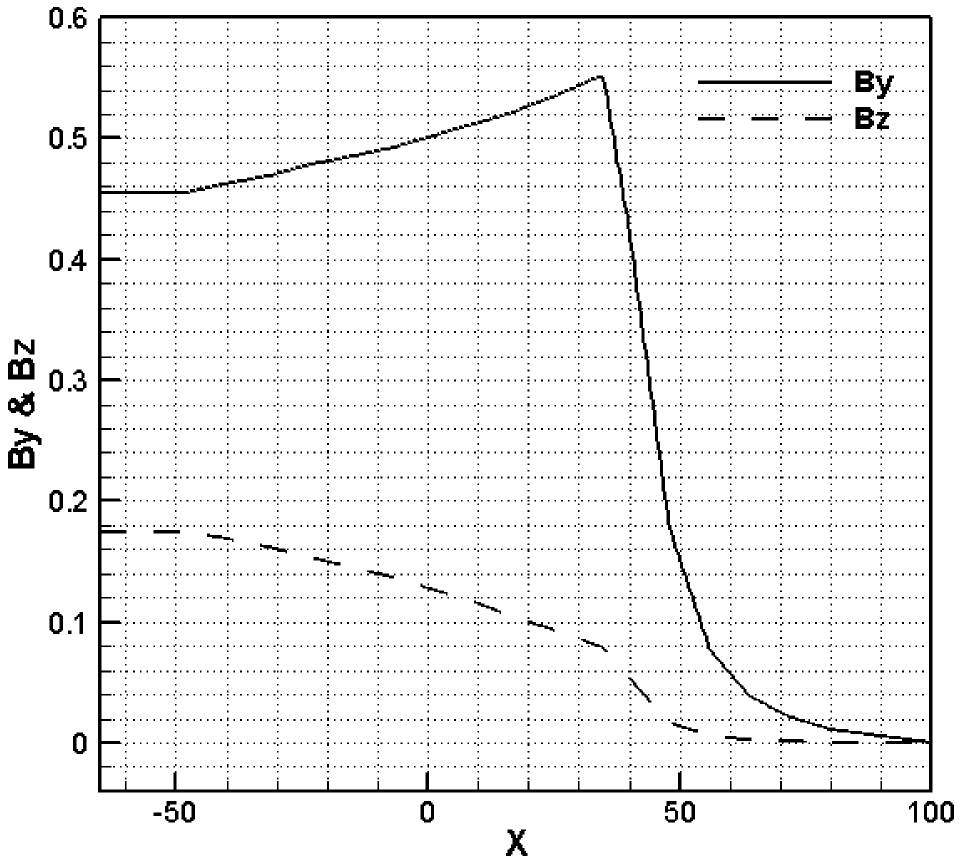




- ❑ Jet flows initiated in the magnet with round cross-section near the field exit region
- ❑ Reduced Re number regions explored, Re=1000 and Re=5000 by varying viscosity, not velocity
- ❑ Different initiation strategies tried (A) abrupt turn-on and (B) gradual turn-on with extra damping

Calculation area
In this presentation

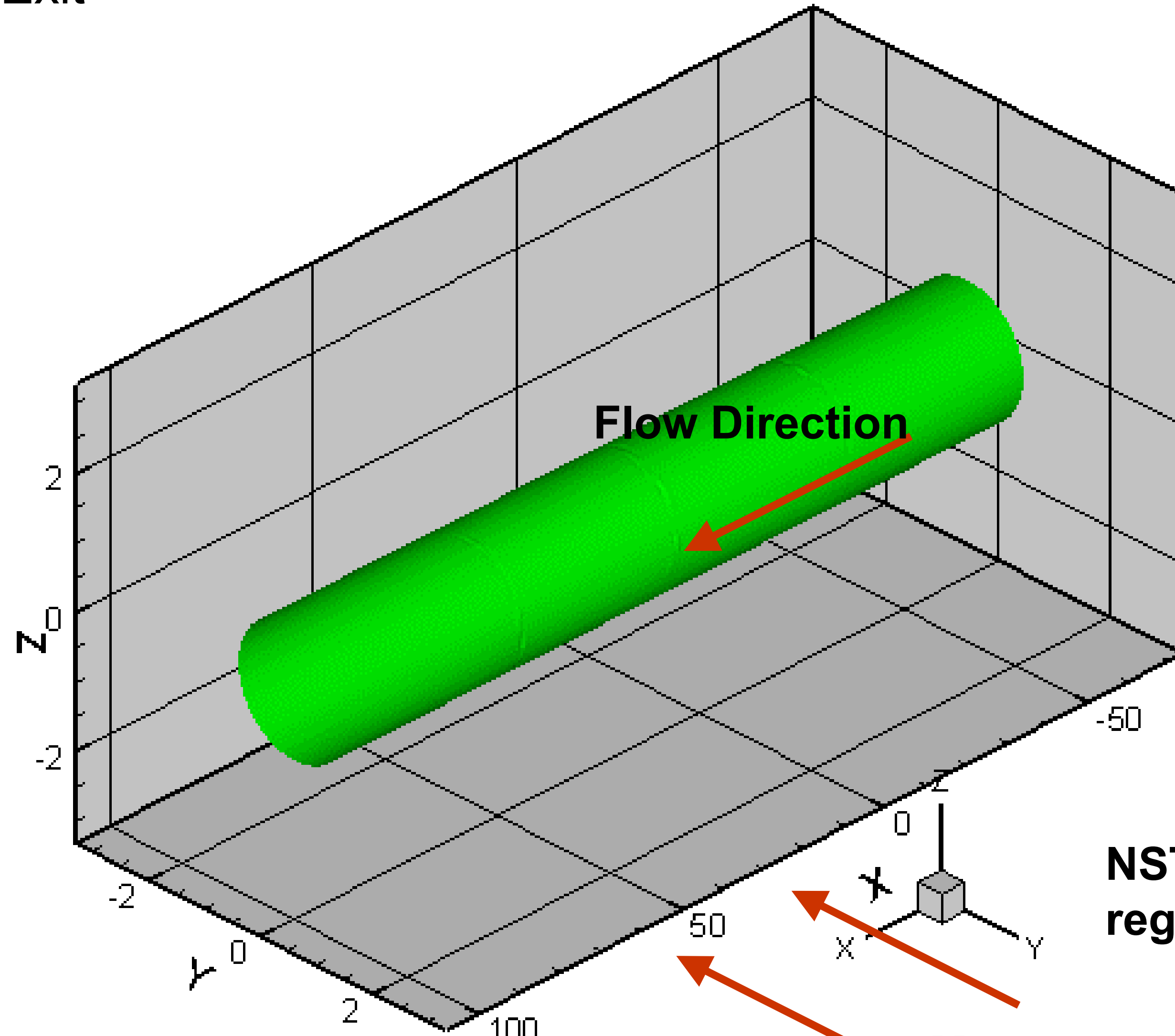
Limits exit field with non-dimensional scale



Limits Magnet Exit

Re=5000

abrupt start



NSTX field region

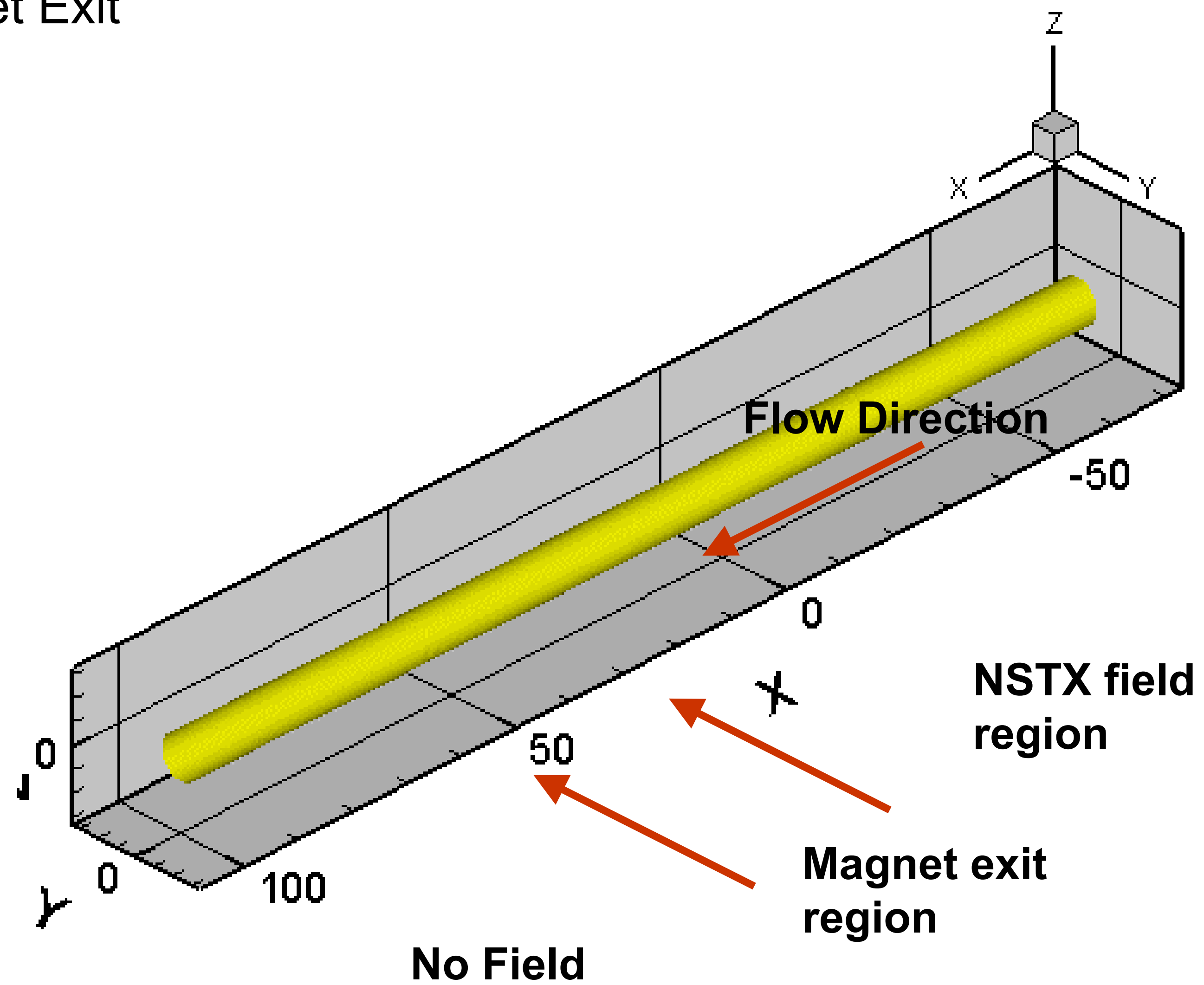
Magnet exit region

No Field

Grid 370x75x75, >2M cells

Magnification1:15:15

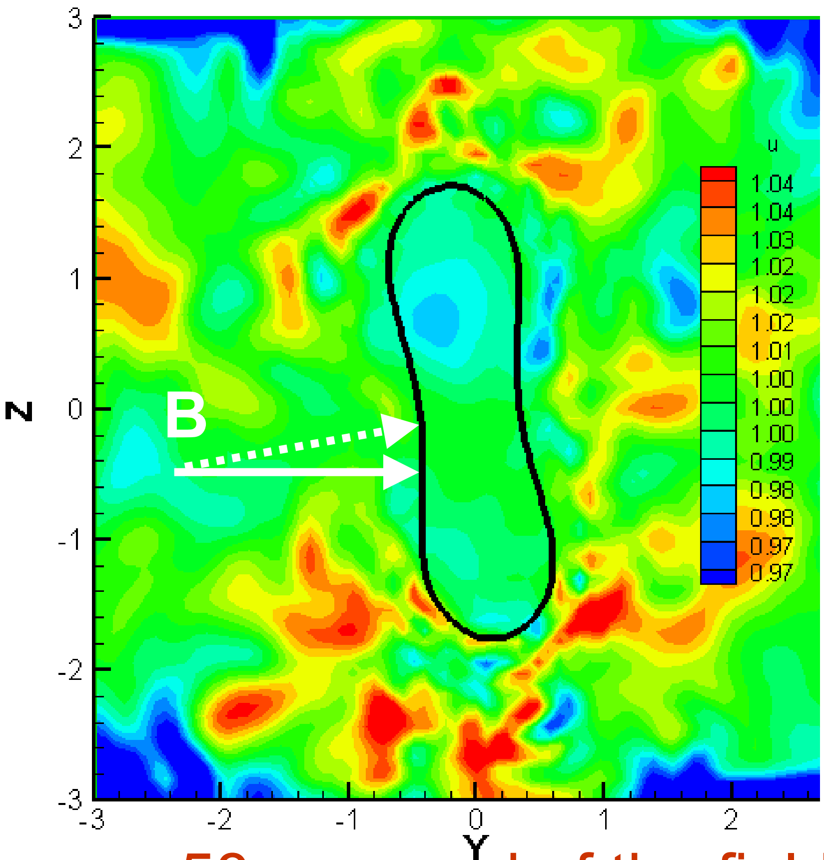
Limits Magnet Exit
Re=5000
Abrupt start

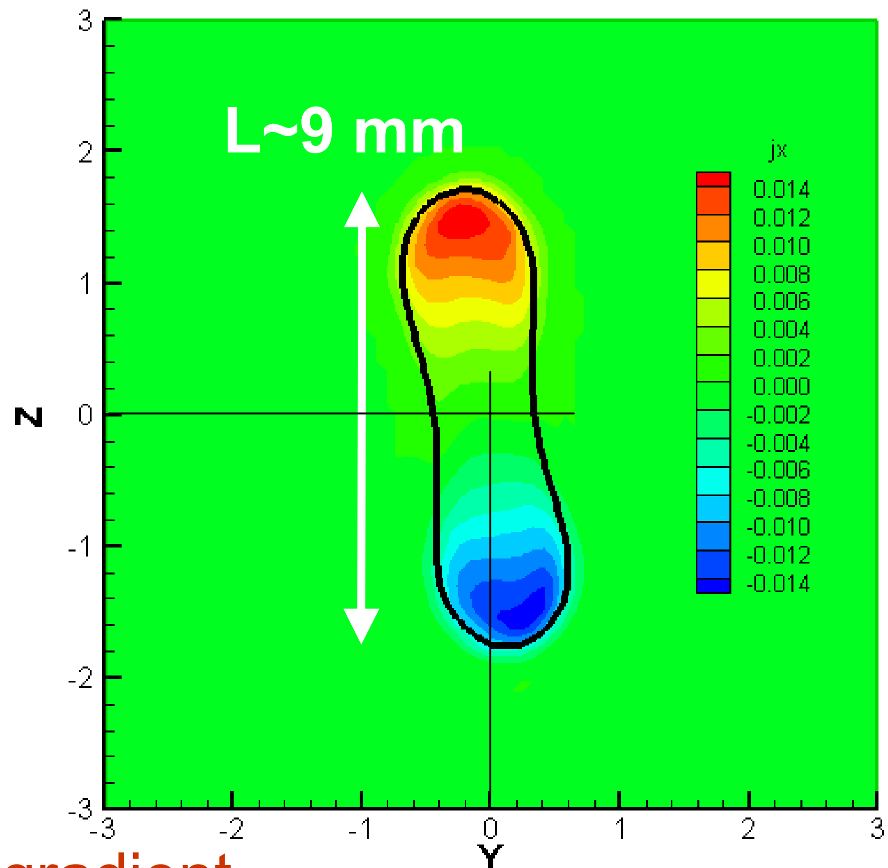


Grid 370x75x75

Magnification1:3:3

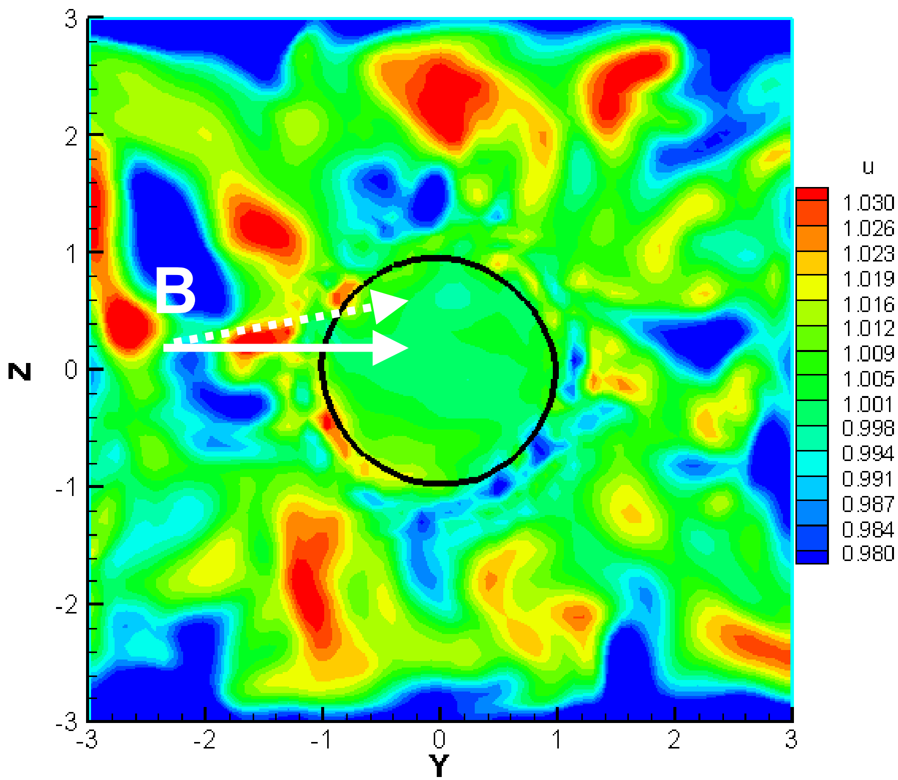
Cross section of maximum deformation less than observed deformation in LIMITS experiment

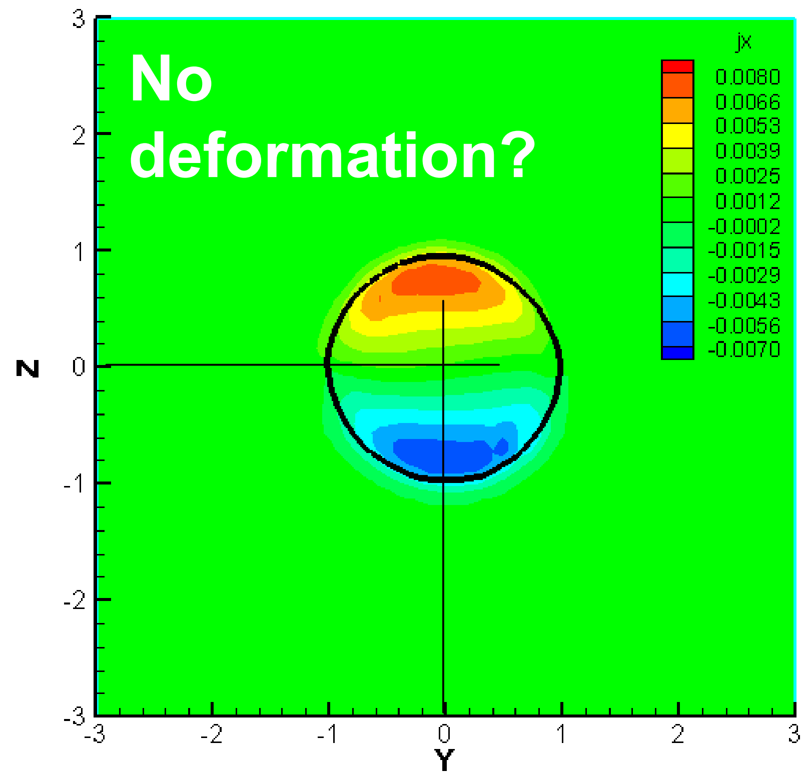




x=58 near end of the field gradient,
t=78 ms greater than 2 flow-thru times

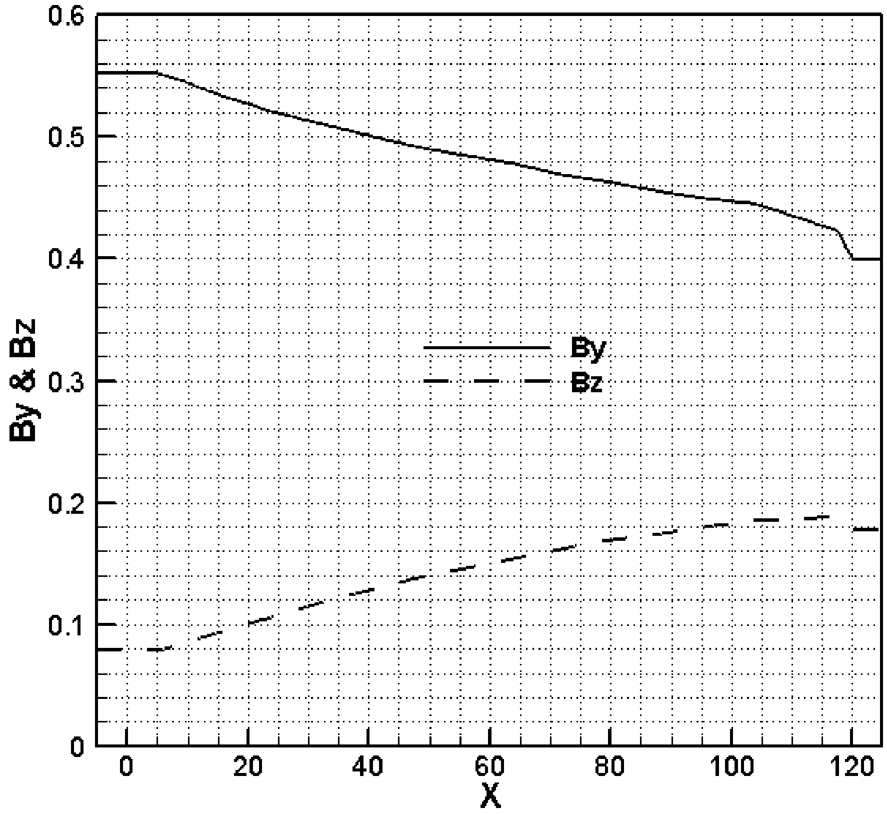
Cross section of maximum deformation compares favorably with observed deformation in LIMITS experiment





x=50 still near end of the field gradient,
t=148 ms greater than 4 flow-thru times

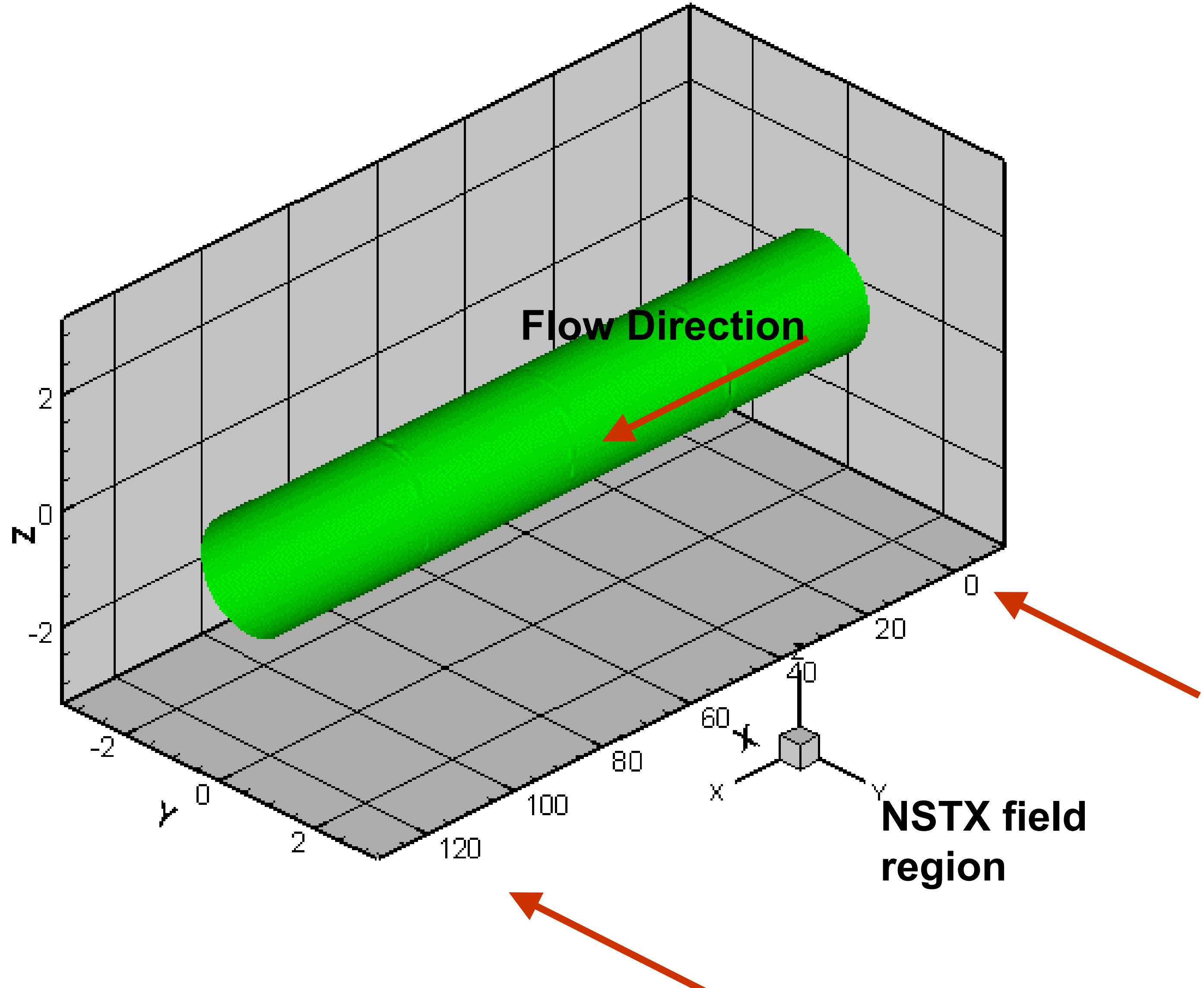
Simulations in NSTX Field – no large gradient regions



NSTX Field Inboard to Outboard

Re=10000

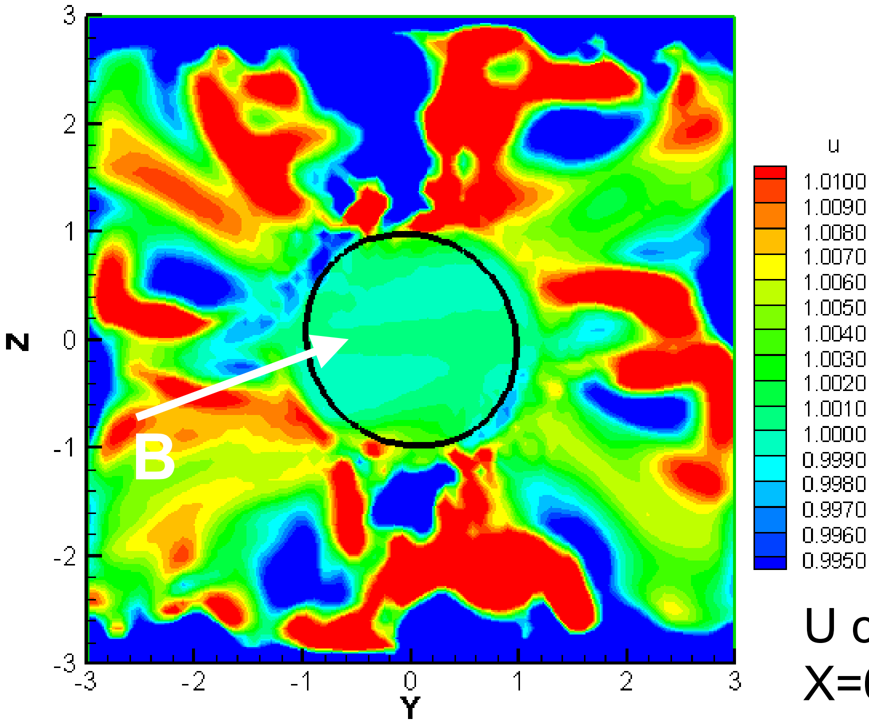
abrupt start



Grid 301x75x75, >1.6M cells
Magnification1:15:15

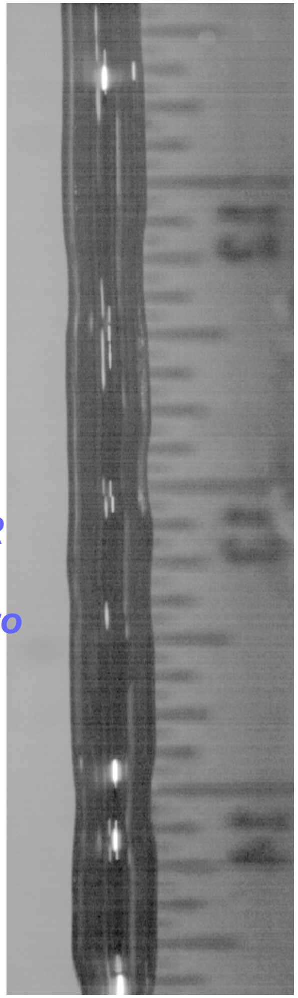
No significant deformation seen in NSTX-like field gradients

- Similar to results from MTOR jet experiments where significant deformation was not observed

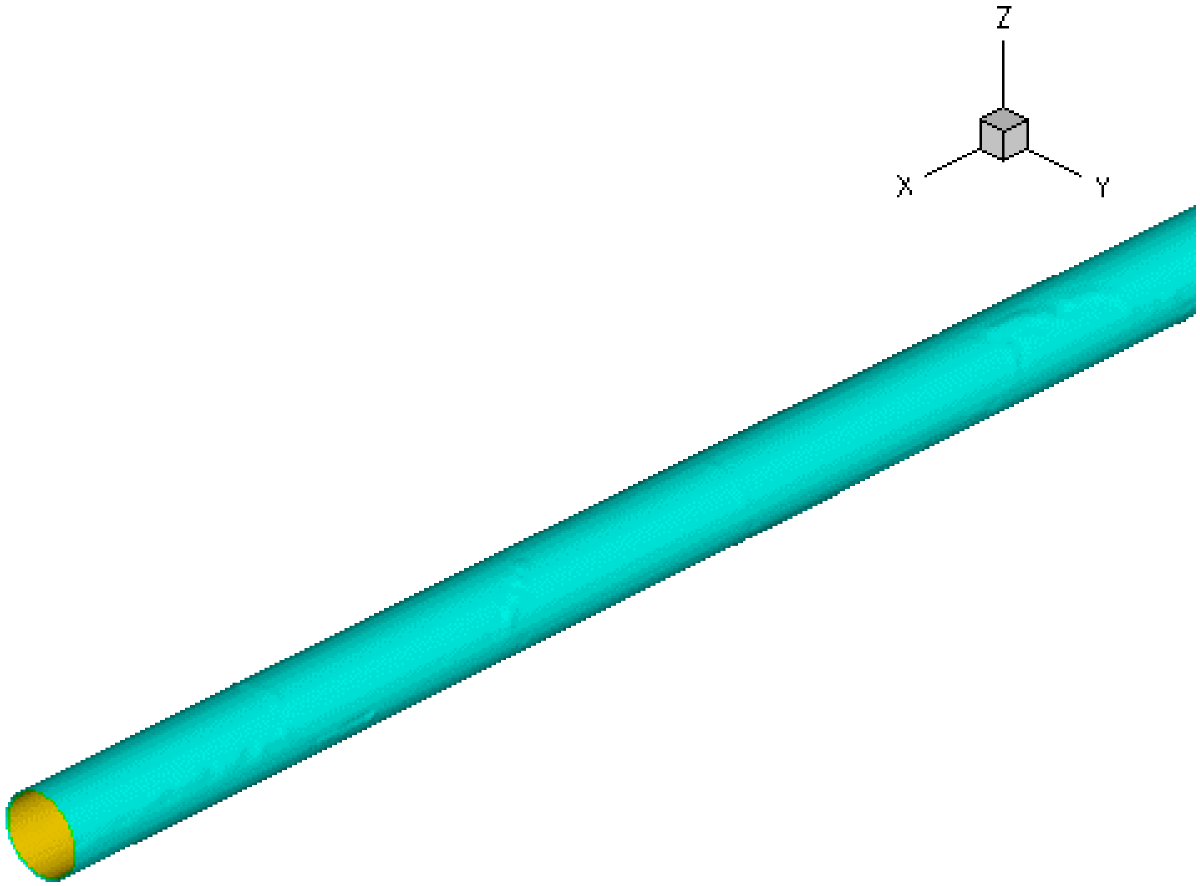


U contour for MHD at X=66 and t=75ms

Ga alloy Jet flows in MTOR under increasing field strength (B varies from .5 to 1.1 T)



Higher resolution needed for full Re=22000 flow, full flow length



Summary of LIMITS jet simulation

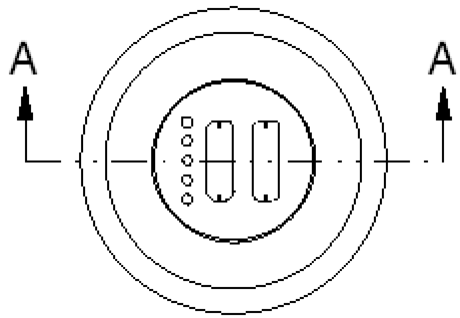
- Large deformation seen in LIMITS comes from magnet inlet and outlet gradient fields.
- Reason for change of state from deformed to almost non-deformed steady state must be investigated
- Initial results for NSTX case with strong-to-weak-field flow direction and jet initiation in the field region shows no significant deformation
- Effects of full Re and conducting nozzles must still be modeled
- Effects of plasma contact must still be modeled

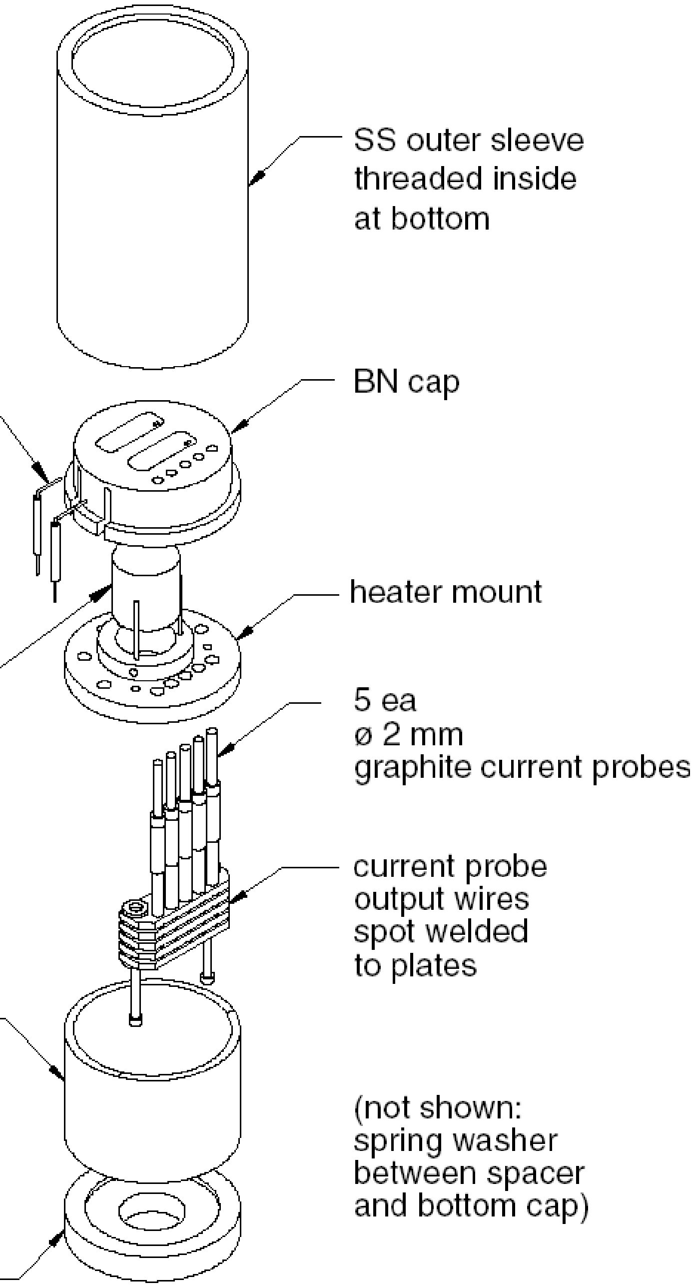
DiMES Slot Geometry Analysis

DiMES # 121

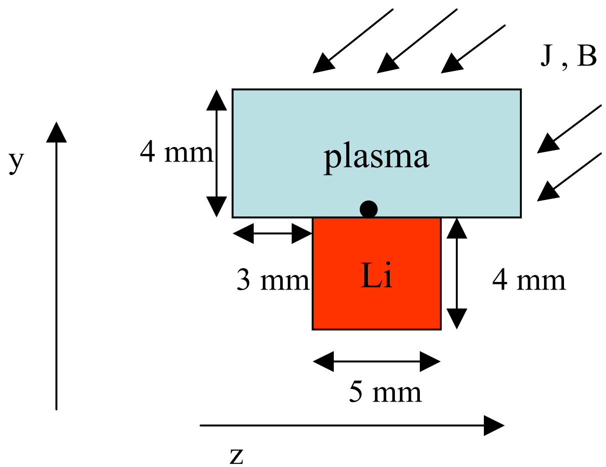
version D

2003 Feb 24

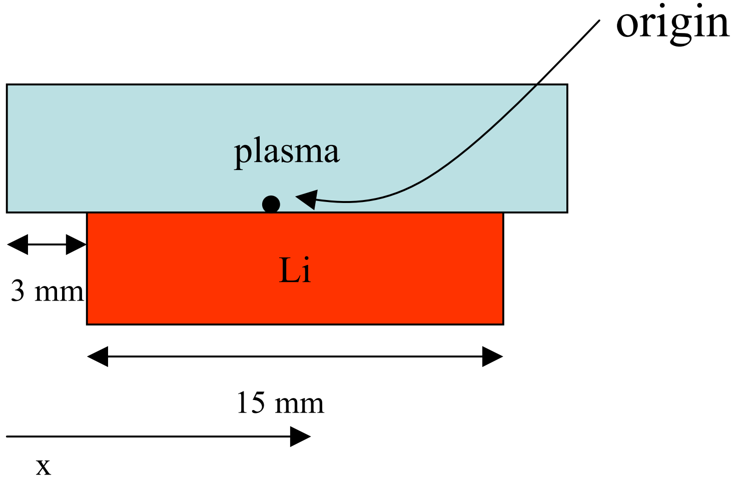




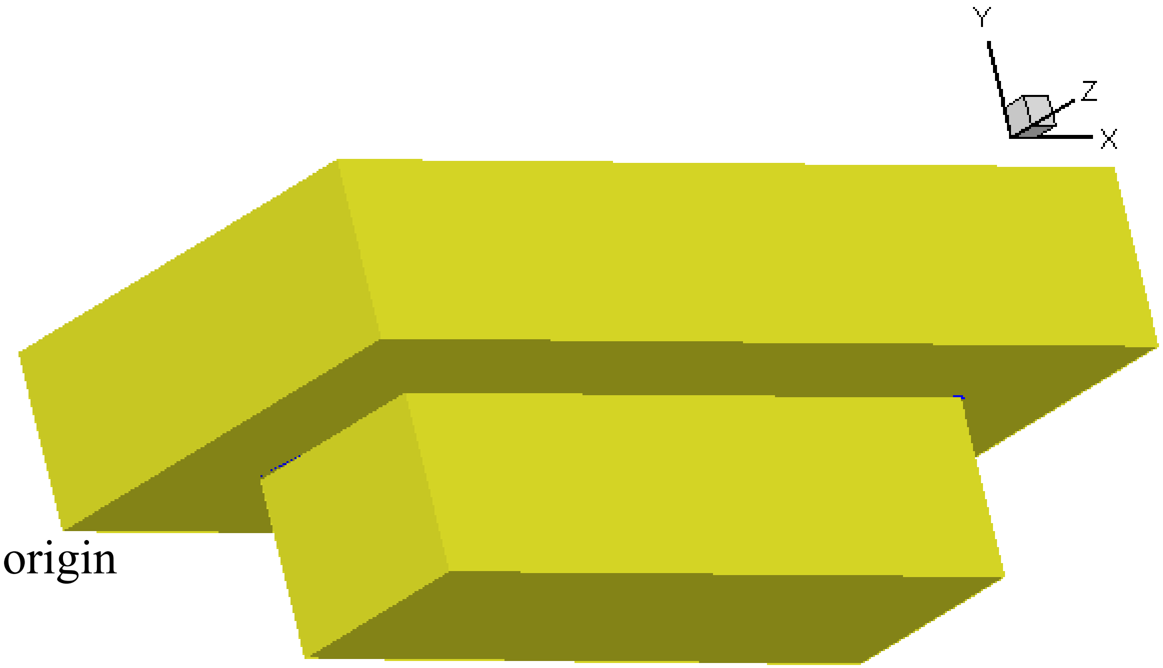
DiMES slot geometry



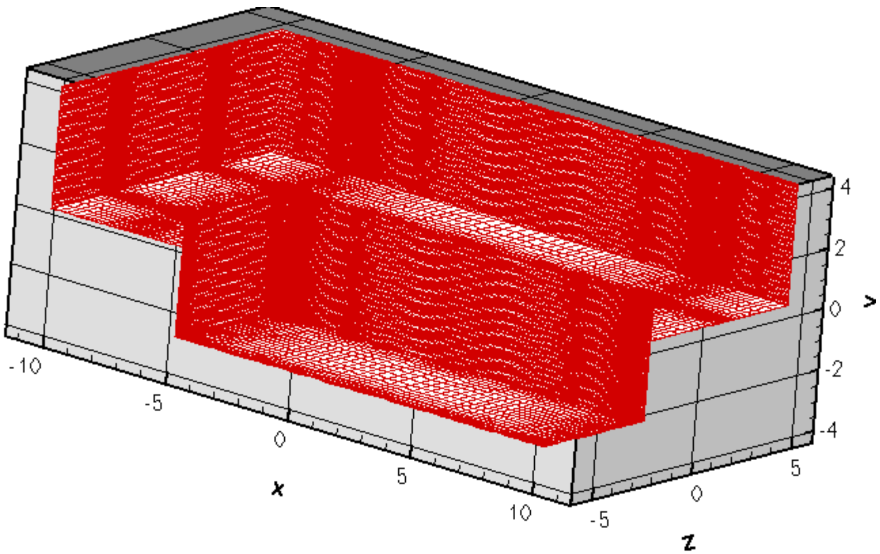
toroidal-vertical view

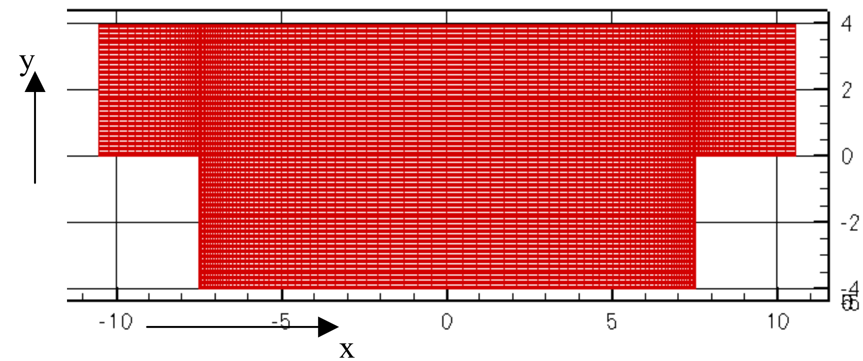


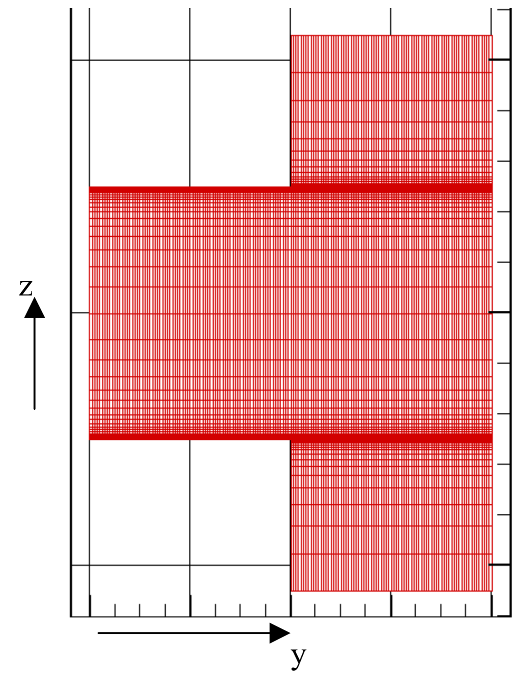
radial-vertical view

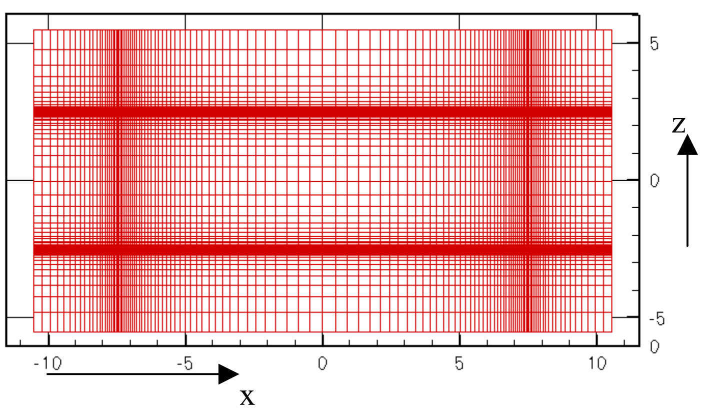


Block Mesh – Hartmann Layers Resolved









Nodes = 1,222,371
cells = 1,184,000

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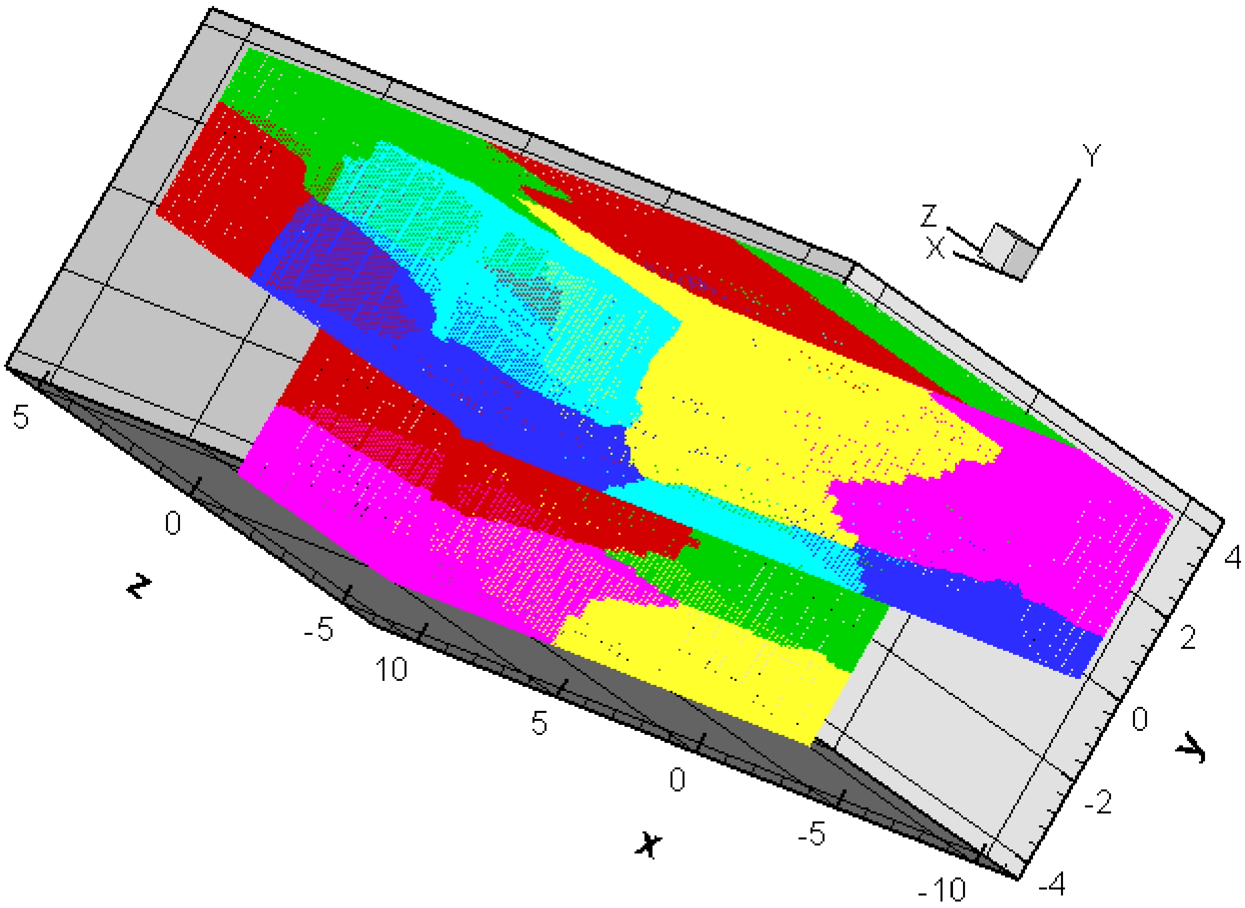
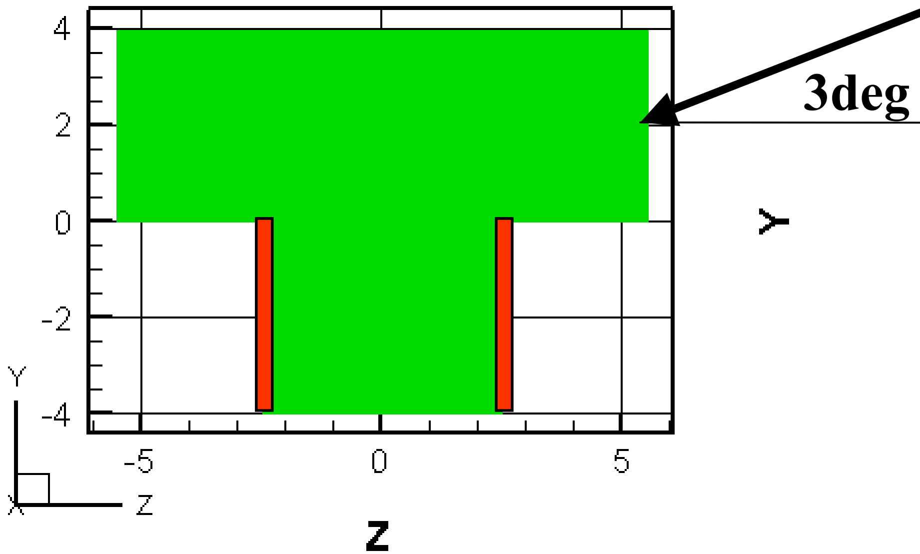
Mesh and its partition to 16 processors



Case I: Grounding side of slot



$I_0 = 40KA/m^2$

$B_0 = 2T$

Lithium Properties:

$\rho = 485kg/m^3$

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

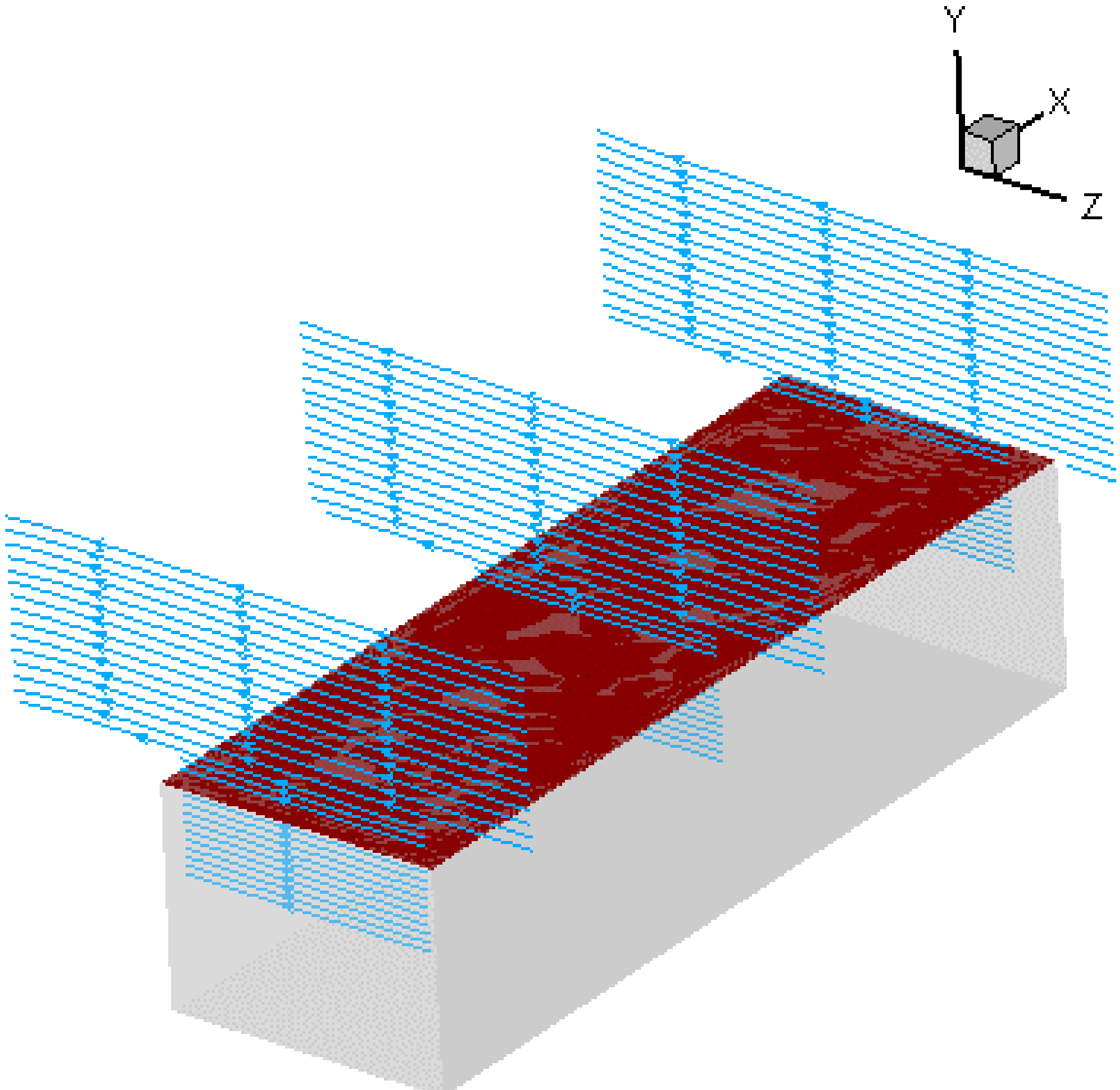
$\sigma = 2.8\times10^{6}(mOhm)^{-1}$

$\sigma_s = 0.35N/m$

- Top and bottom boundaries: insulated wall with $d\phi/dn=0$
- Right top part: applied current boundary condition
- All other boundaries are ground with $\phi = 0$

DiMES
Slot

- Side Ground
- 0-12 ms

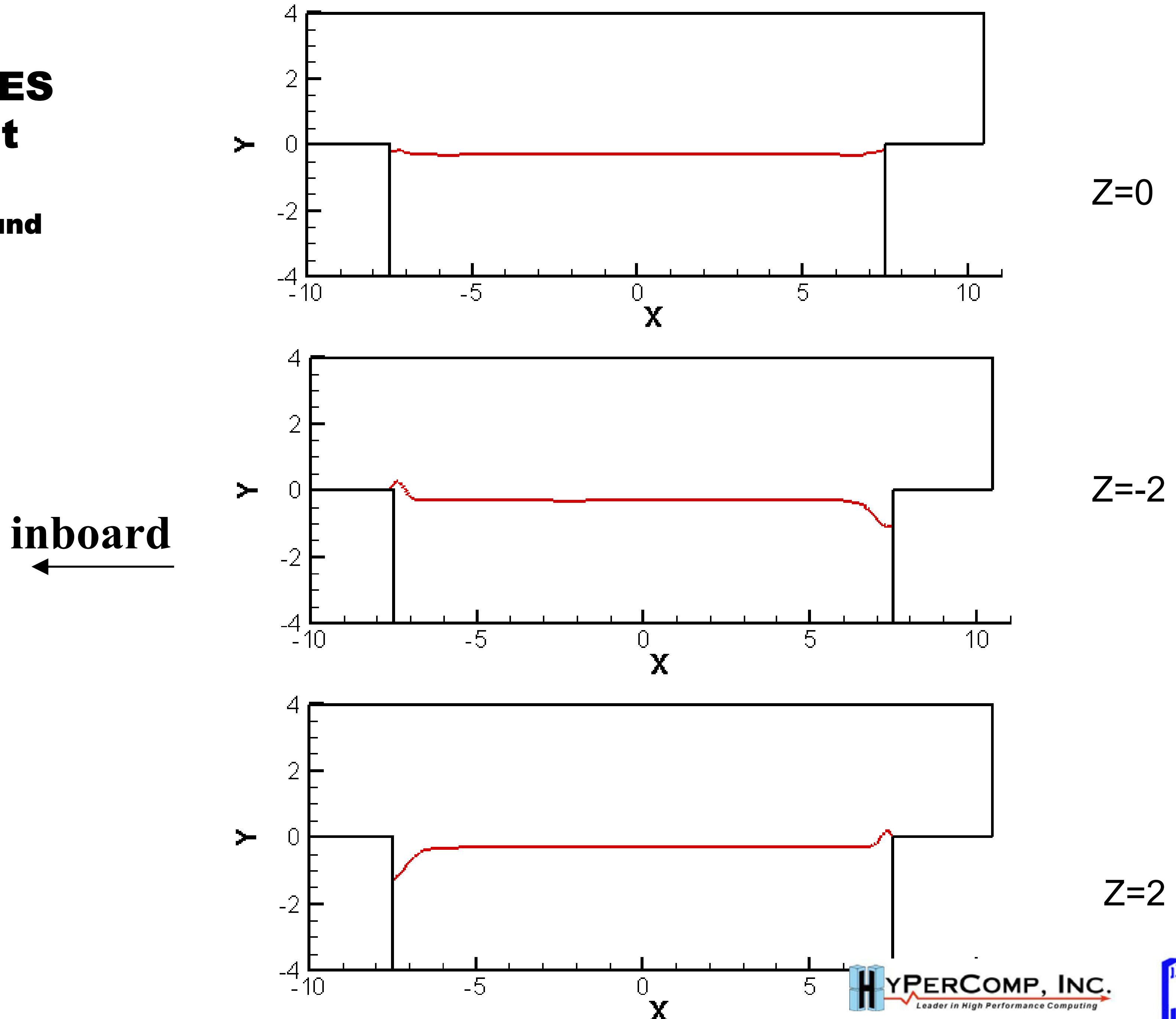


DiMES Slot

- Side Ground
- 0-12 ms

DiMES Slot

- **Side Ground**



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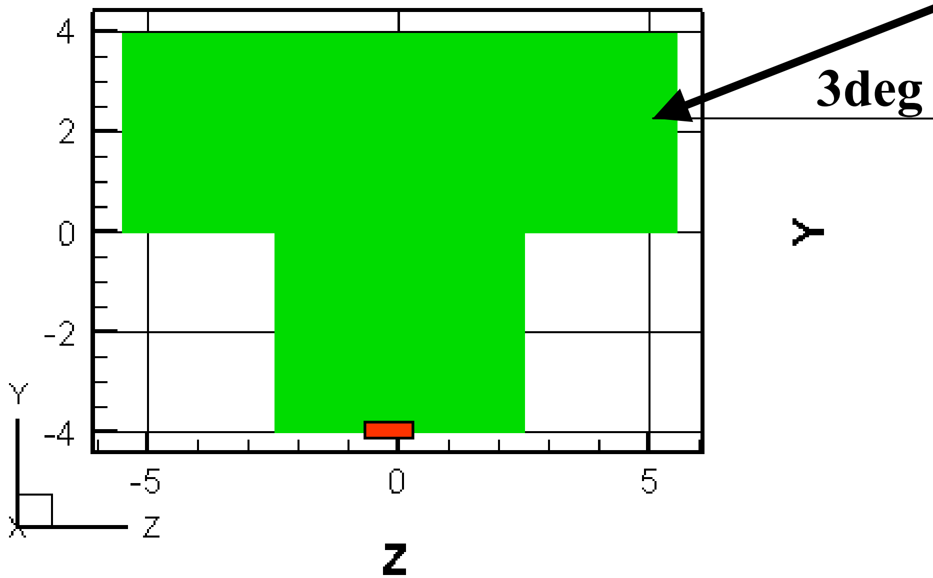
Case II with Bottom Grounding



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$$\sigma = 2.8\times 10^{6} (mOhm)^{-1}$$

$$\sigma_s = 0.35N/m$$

- Right top part: applied current boundary condition
- There is a ground patch located at the central of bottom wall parallel to x axis.
- Left top part: zero electrical potential boundary condition $\phi = 0$, and all other parts are insulated wall with $d\phi/dn = 0$

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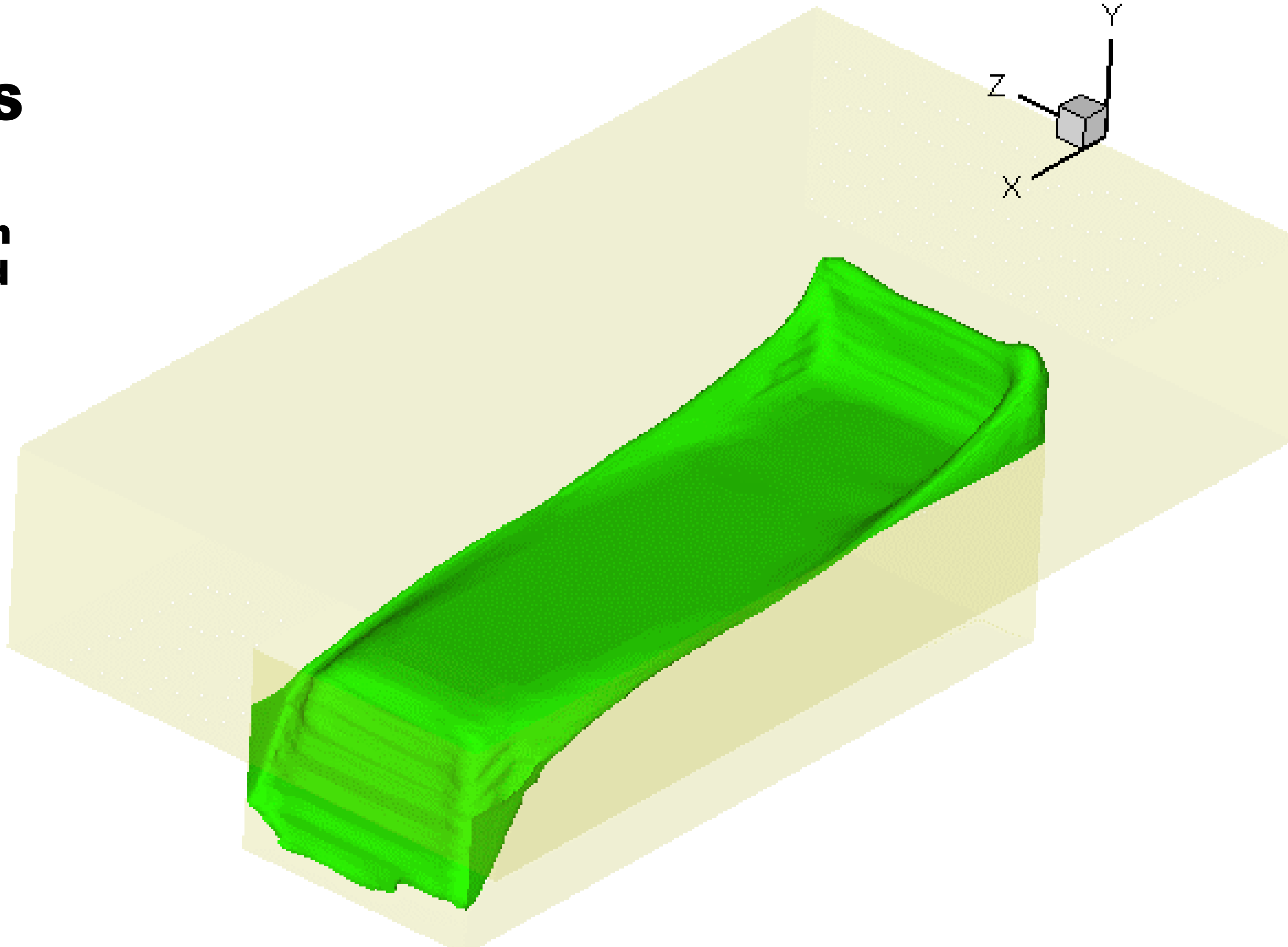
DiMES Slot

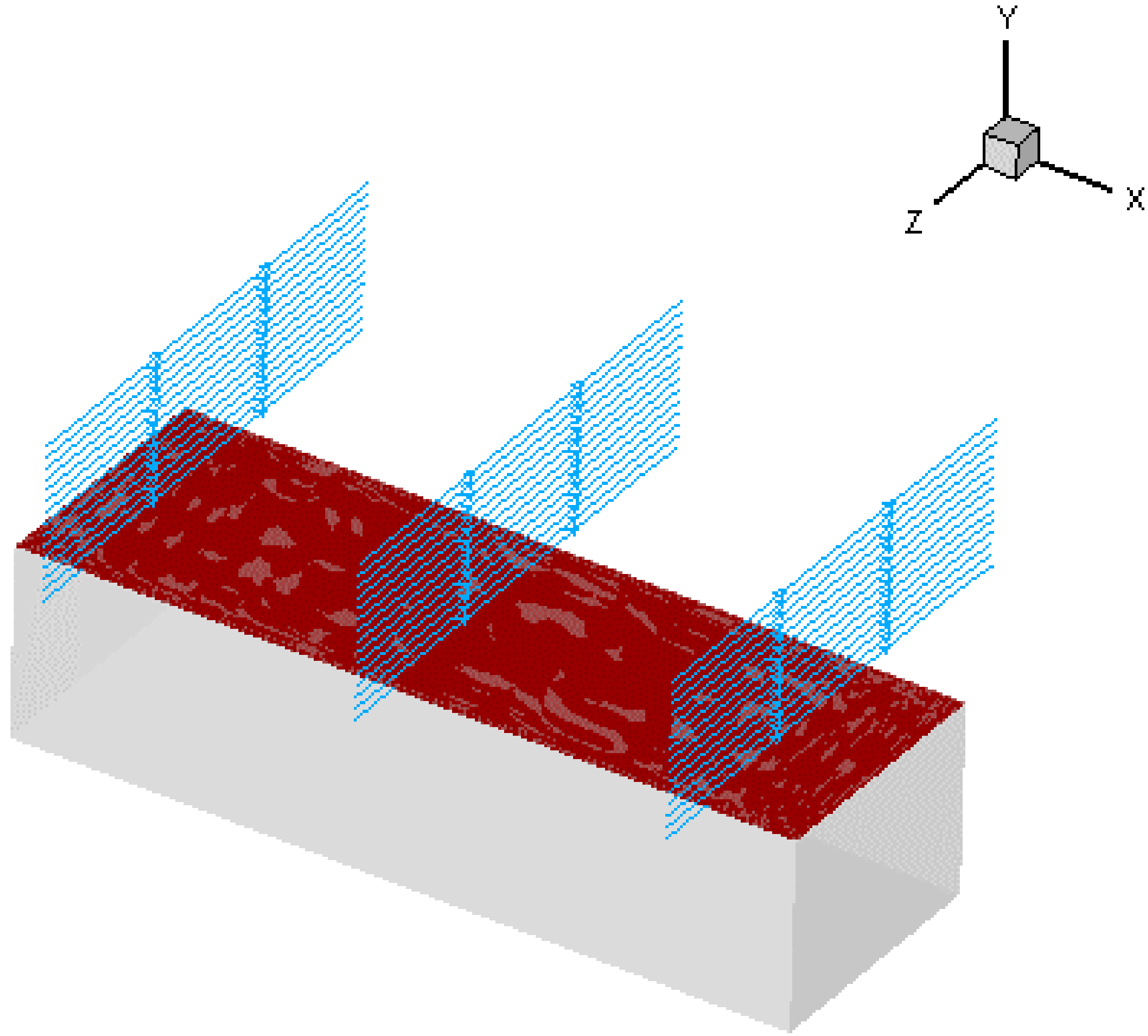
- **Bottom Ground**



Interface shape at t=21ms

DiMES Slot

- Bottom Ground
- 0-21 ms



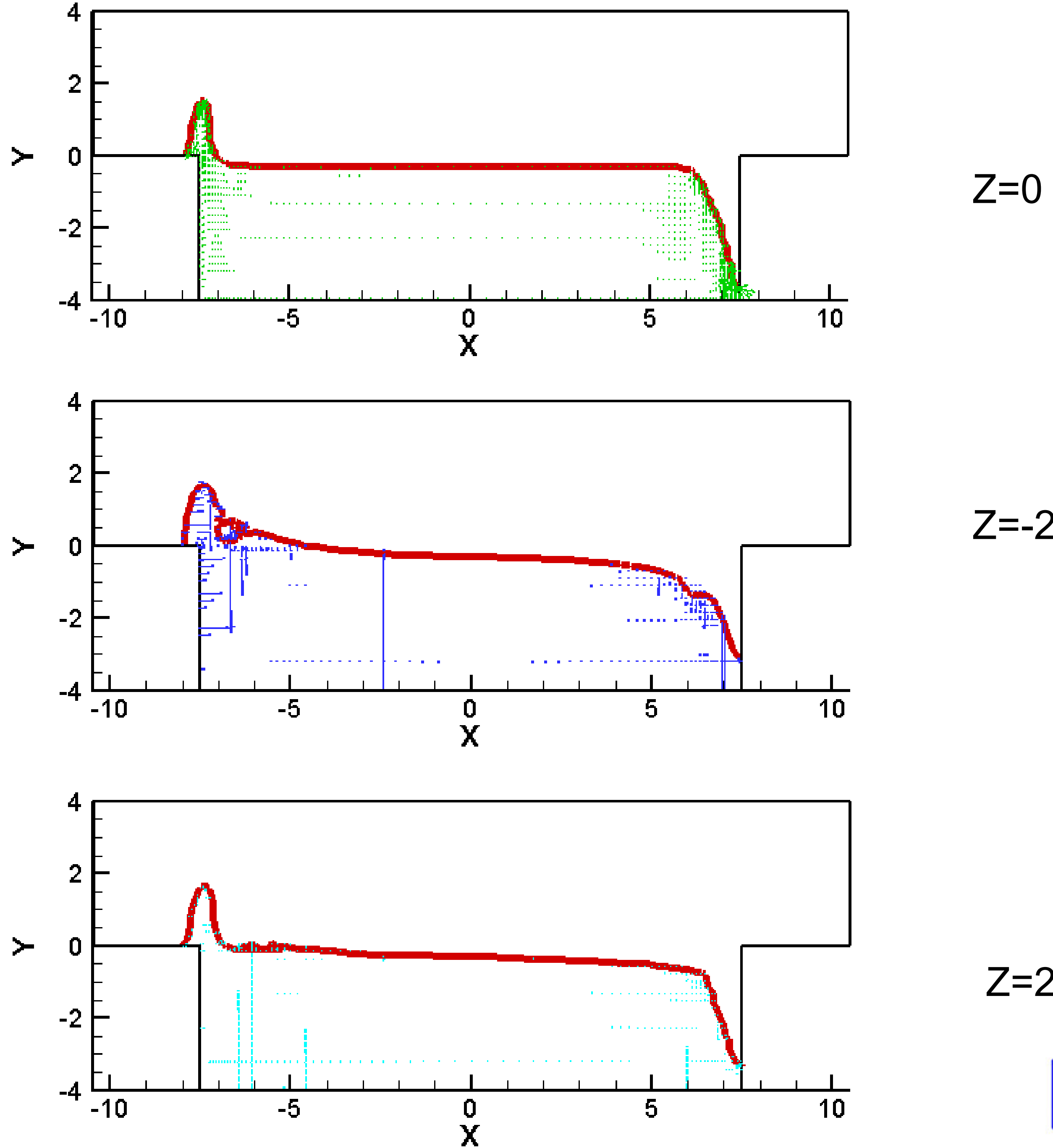
DiMES Slot

- **Bottom Ground**
- **0-21 ms**

DiMES Slot

- **Bottom Ground**

inboard ←



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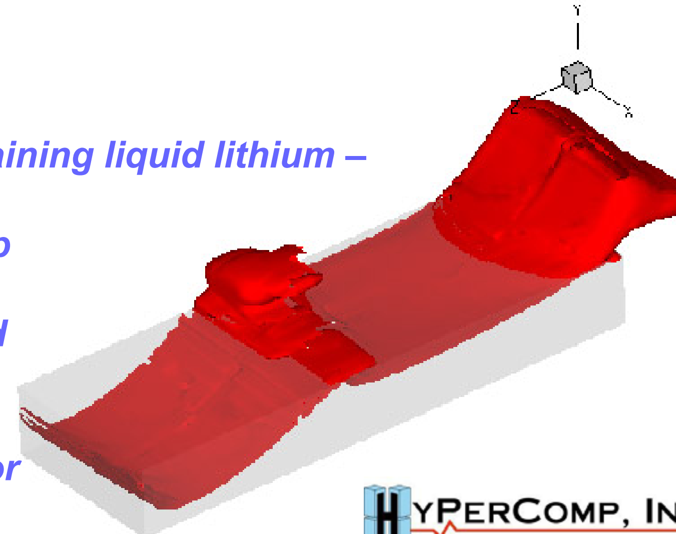
Plasma current model in HIMAG used to simulate Li-DIMES experiments in DIII-D

- Given plasma current density forced to flow along field lines by imposing anisotropic conductivity
- Self-consistent current density in the Li calculated based on intercepted plasma current and induced current due to lithium motion
- New grounding geometry suggested to GA for reduced motion in new DIII-D experiments

DiMES slot containing liquid lithium –

(right) whole cup grounded liquid is pushed toward inboard with significant loss of Li onto divertor Tiles



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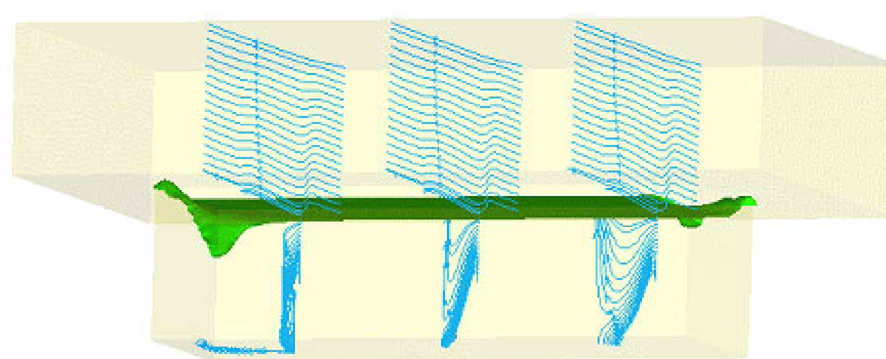
(Below) Only Hartmann walls grounded, minimal motion of the surface



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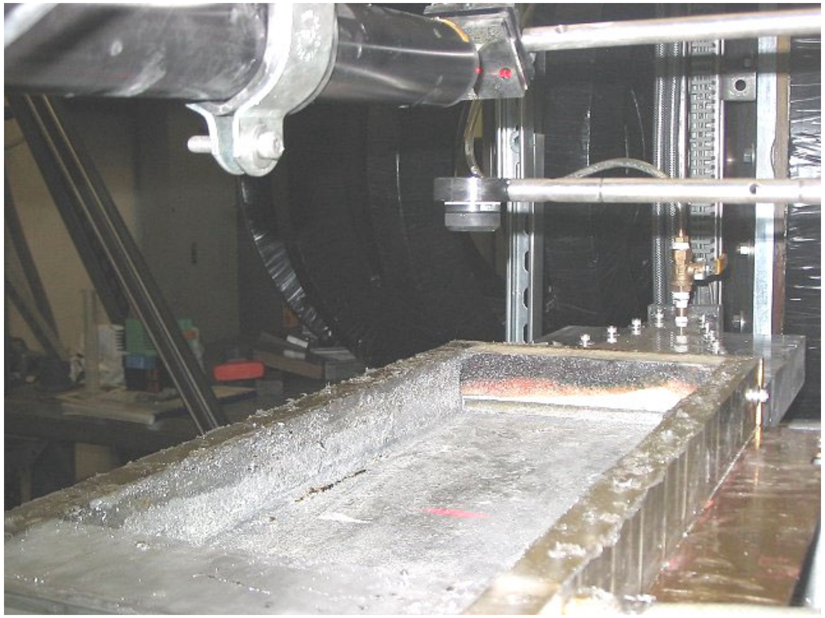
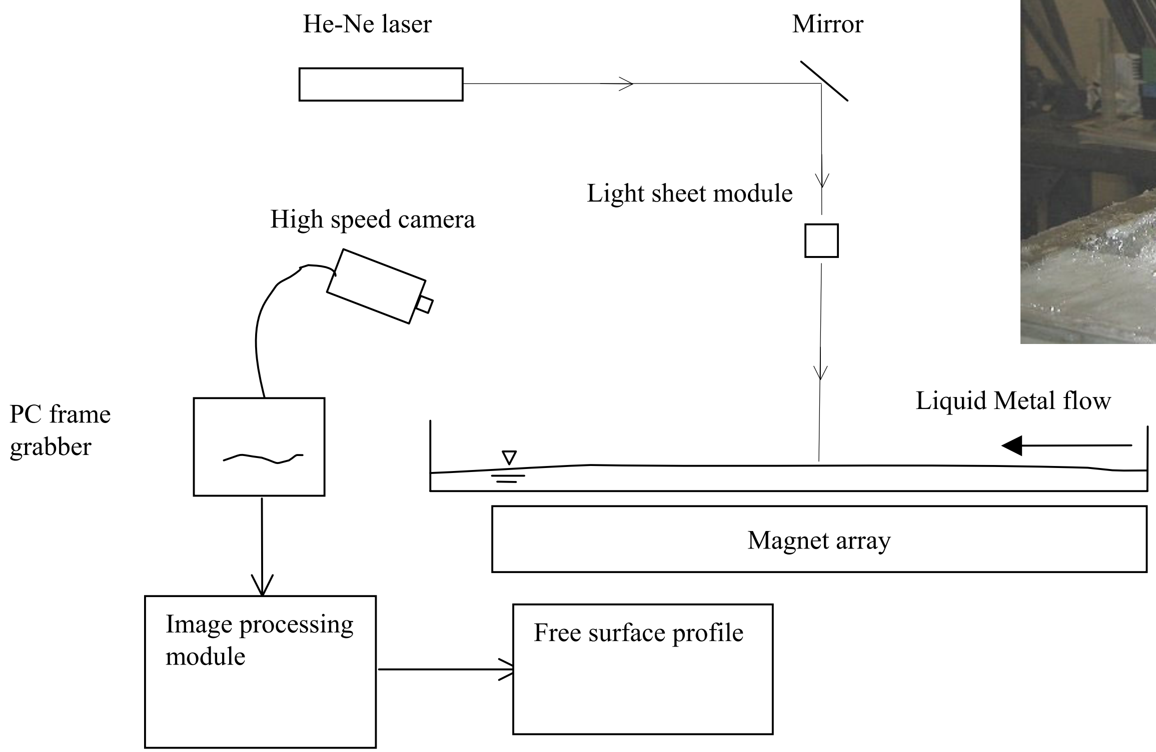
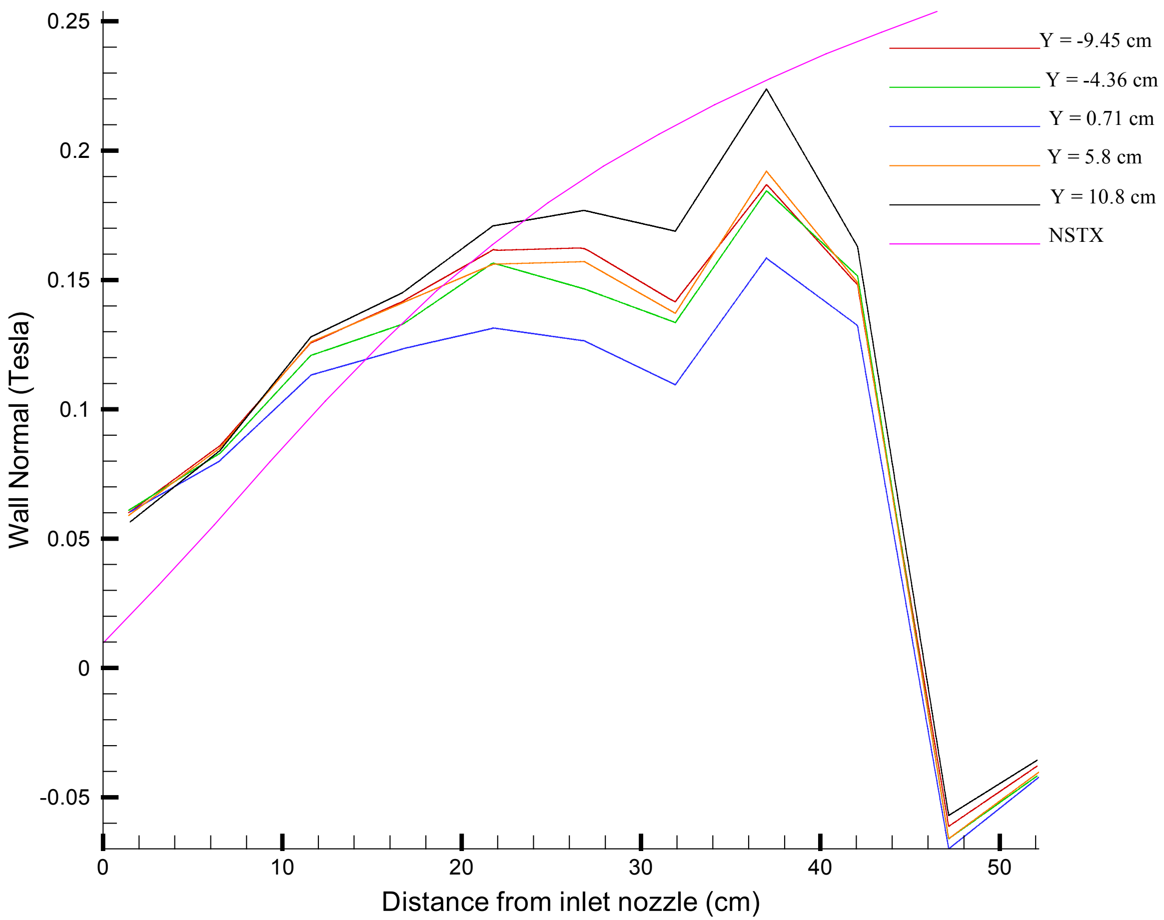
MTOR wide (20cm) LM film flow experiment in a surface normal magnetic field





Applied Magnetic Field

An assortment of permanent magnets placed beneath the test section are use to closely reproduce the scaled NSTX divertor region wall normal magnetic field component

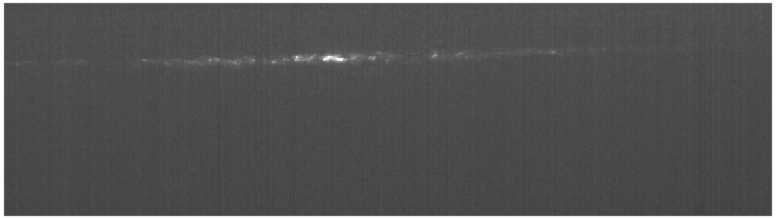


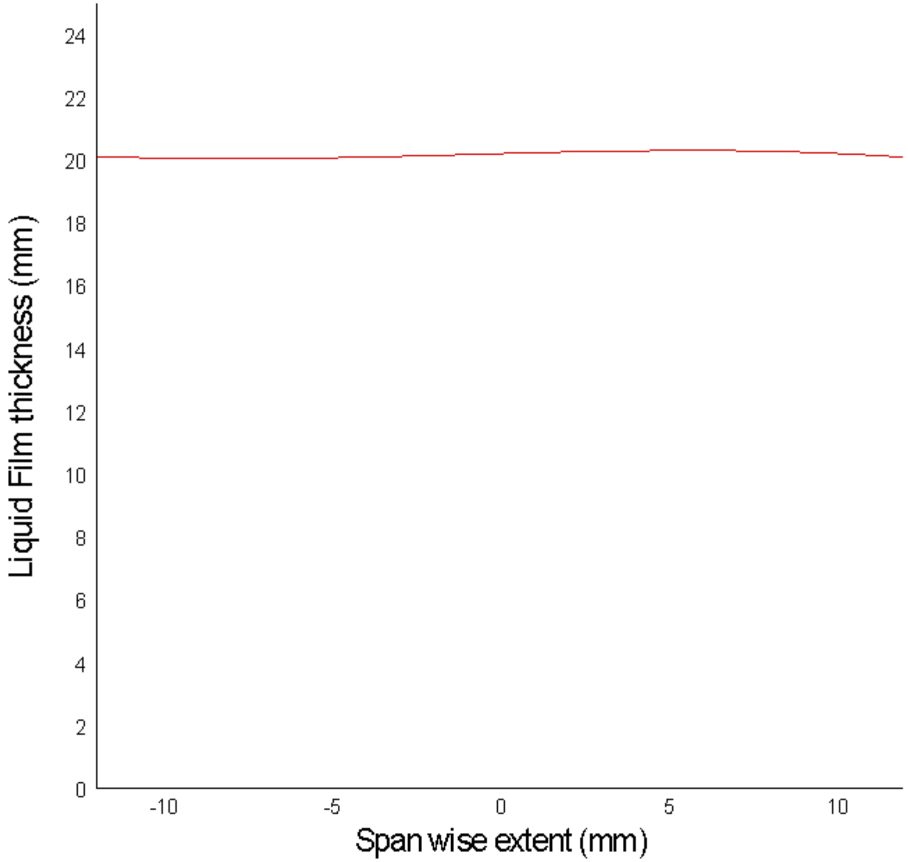
Comparison of the magnetic field produced by the magnet set up to the NSTX divertor region surface normal field component

The stream wise variation of the magnetic field is measured at five different span wise locations. 'Y=0.0' marks the center of the channel

Liquid metal film thickness measurements with scattered laser light sheet

- Liquid metal film thickness, evaluated 16cm downstream at an average inlet velocity of 1.1m/s.
- The location is **downstream** of the hydraulic jump for the current inlet velocity.
- The light beam covers 3 cm width around the channel center.



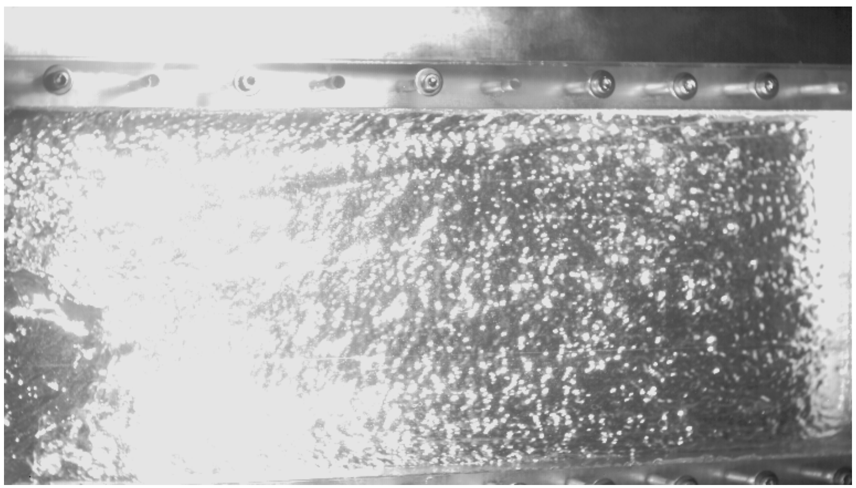


The movie to the right shows 50 frames processed from the one on the left using image processing software.

Initial experimental observations for horizontal LM film flow

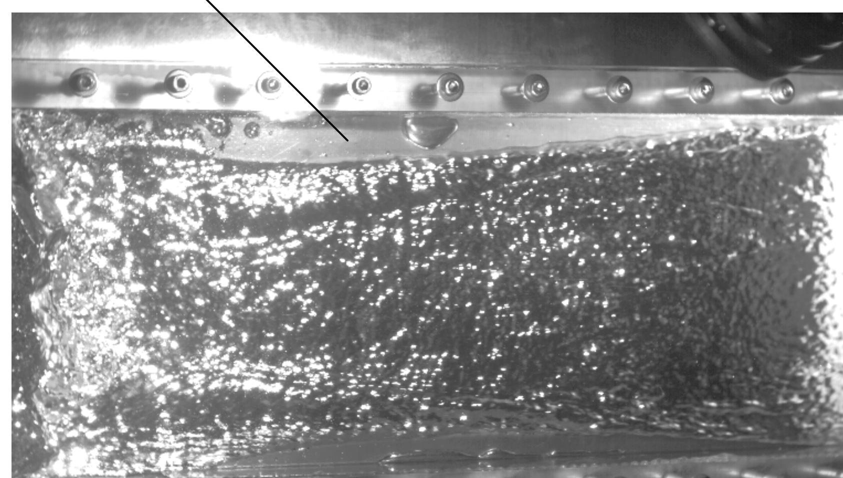
- The flow tends to go through a sudden hydraulic jump, located at a particular downstream location, this dissipates a large amount of flow energy and slows down the liquid.
- The hydraulic jump location moves further downstream as the inlet flow velocity is increased and changes shape in the span wise direction.
- At higher inlet velocities (~2.5 -3.0m/s) the liquid metal tends to get pushed inwards from the side walls of the conducting channel, creating separation zones and bare spots.

Images of 3 m/s inlet flow with and without magnetic field



Flow at inlet velocity of 3.0 m/s without any applied magnetic field

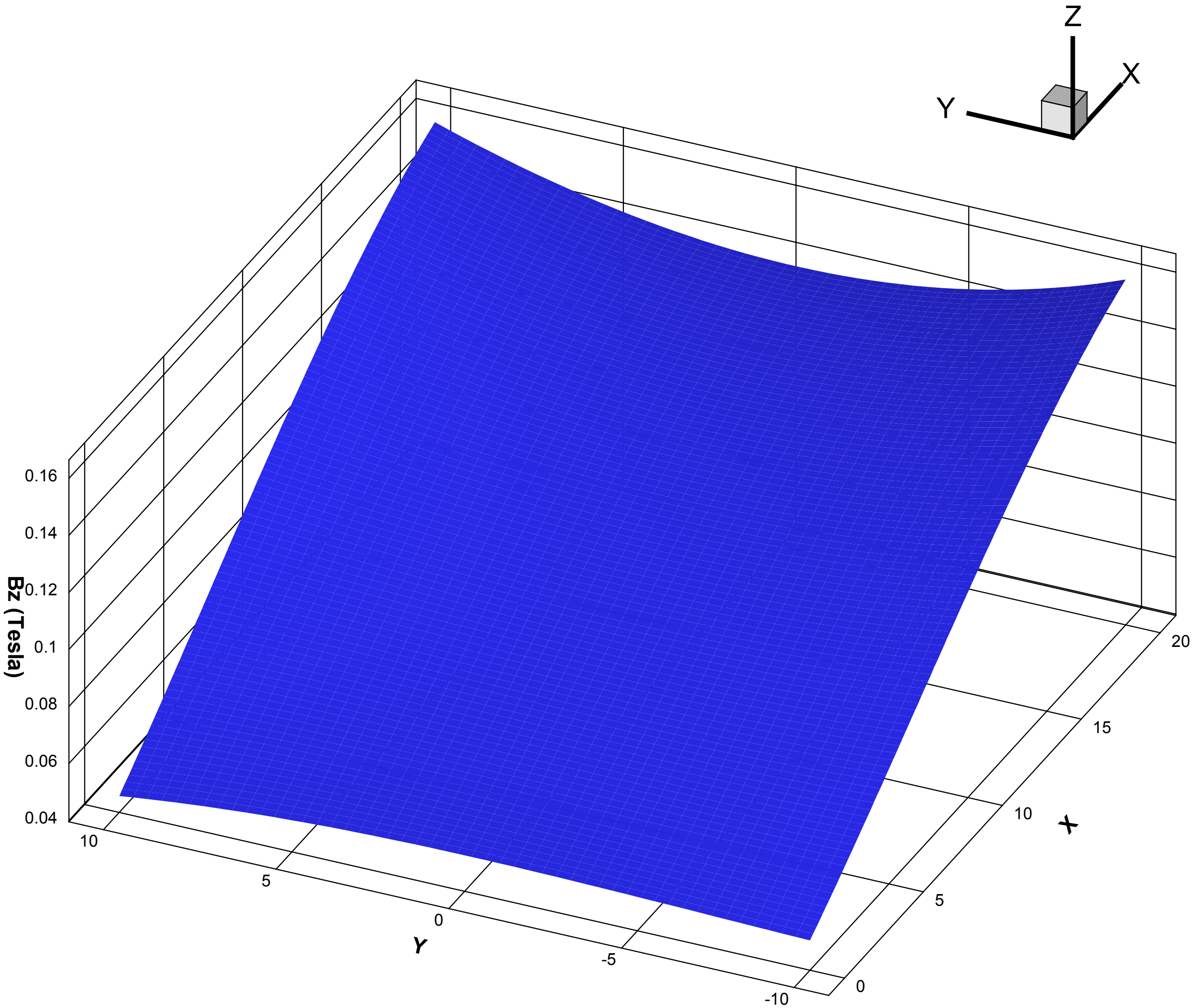
Liquid pulling off from the walls



Flow at inlet velocity of 3.0 m/s with the magnetic field

HIMAG SIMULATION

The surface normal or the 'Z' component of the applied magnetic field



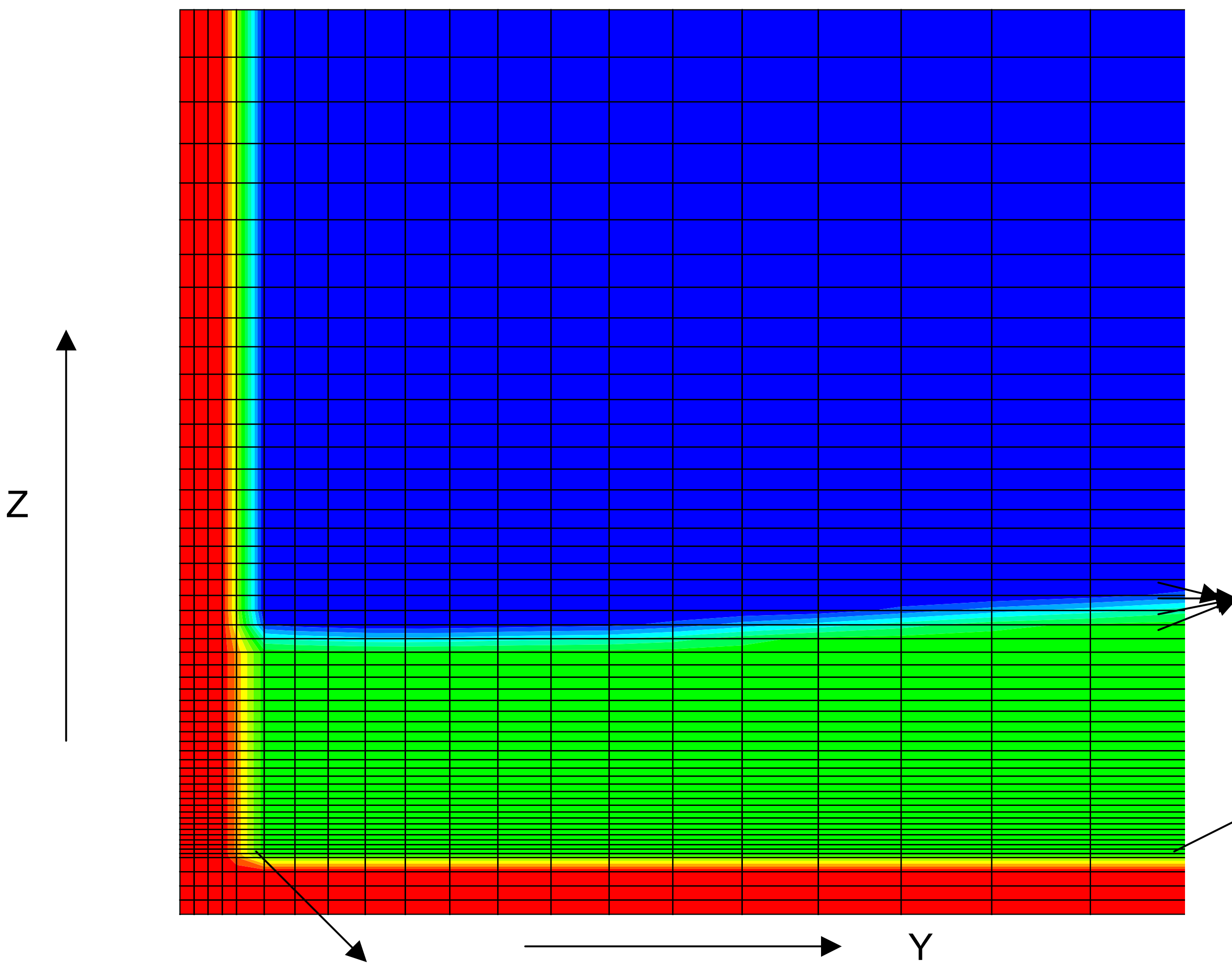
The experimental field measurement data is fitted with a 3rd order polynomial surface

Liquid flows in the positive 'X' direction, 'Y' represents the span with 'Y=0' being the channel center

Y-Z cross section cut at 16cm downstream from the inlet nozzle. The cells are shaded according to density.

The liquid is coming out of the plane. Vertical axis represents thickness and horizontal the span.

Blue represents argon. Green represents liquid gallium and Red represents the stainless steel solid cells.

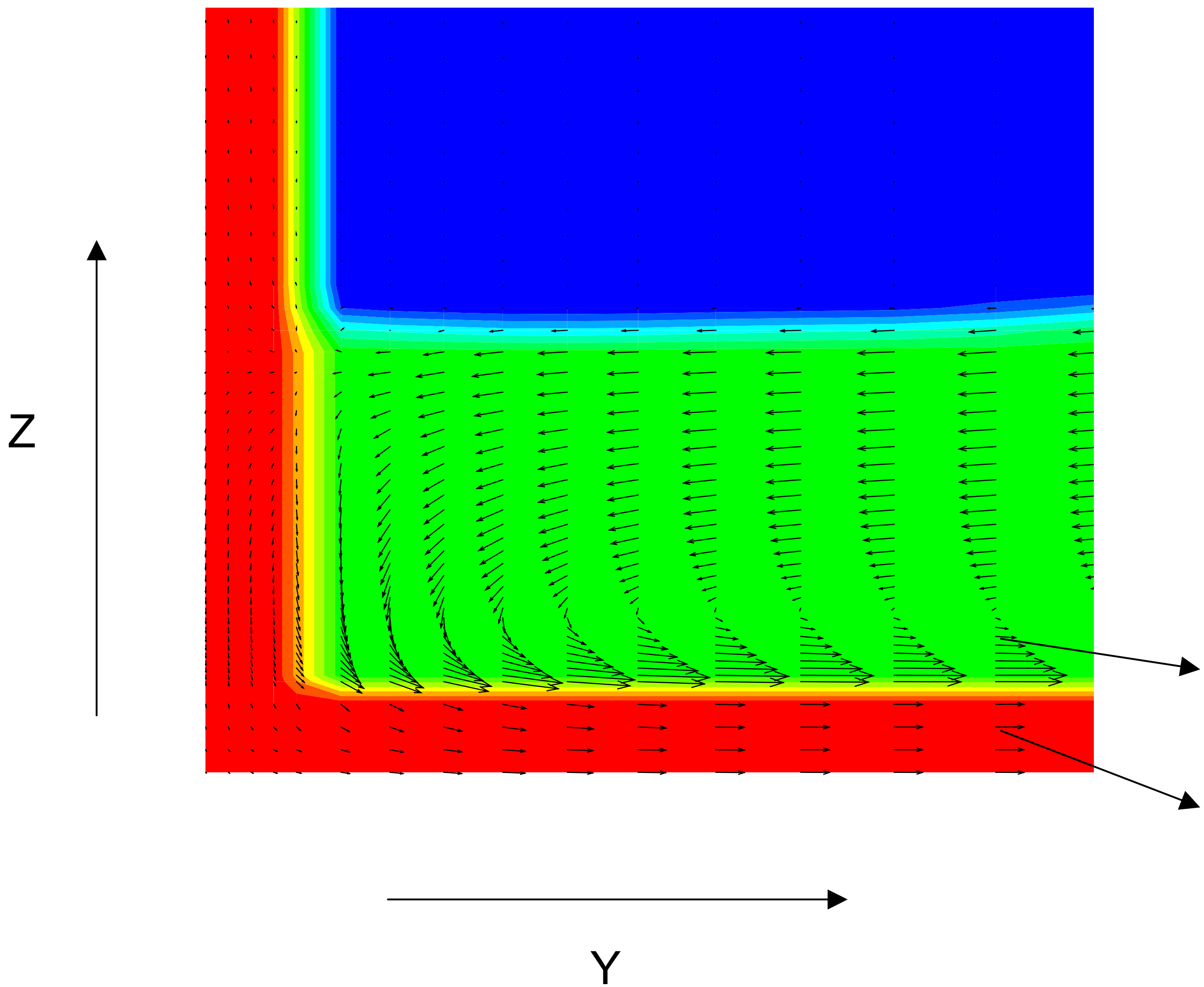


The interface is diffused over four cells by using the heaviside function

Grid stretching to resolve the Hartmann layer which is of the order of 250 micron

Grid stretching near the side walls

Y-Z cross section cut at 16cm downstream from the inlet nozzle. The cells are shaded according to density.



Induced currents in the Y-Z plane. Jy is the strongest induced current component.

The liquid is coming out of the plane. Vertical axis represents thickness and horizontal the span.

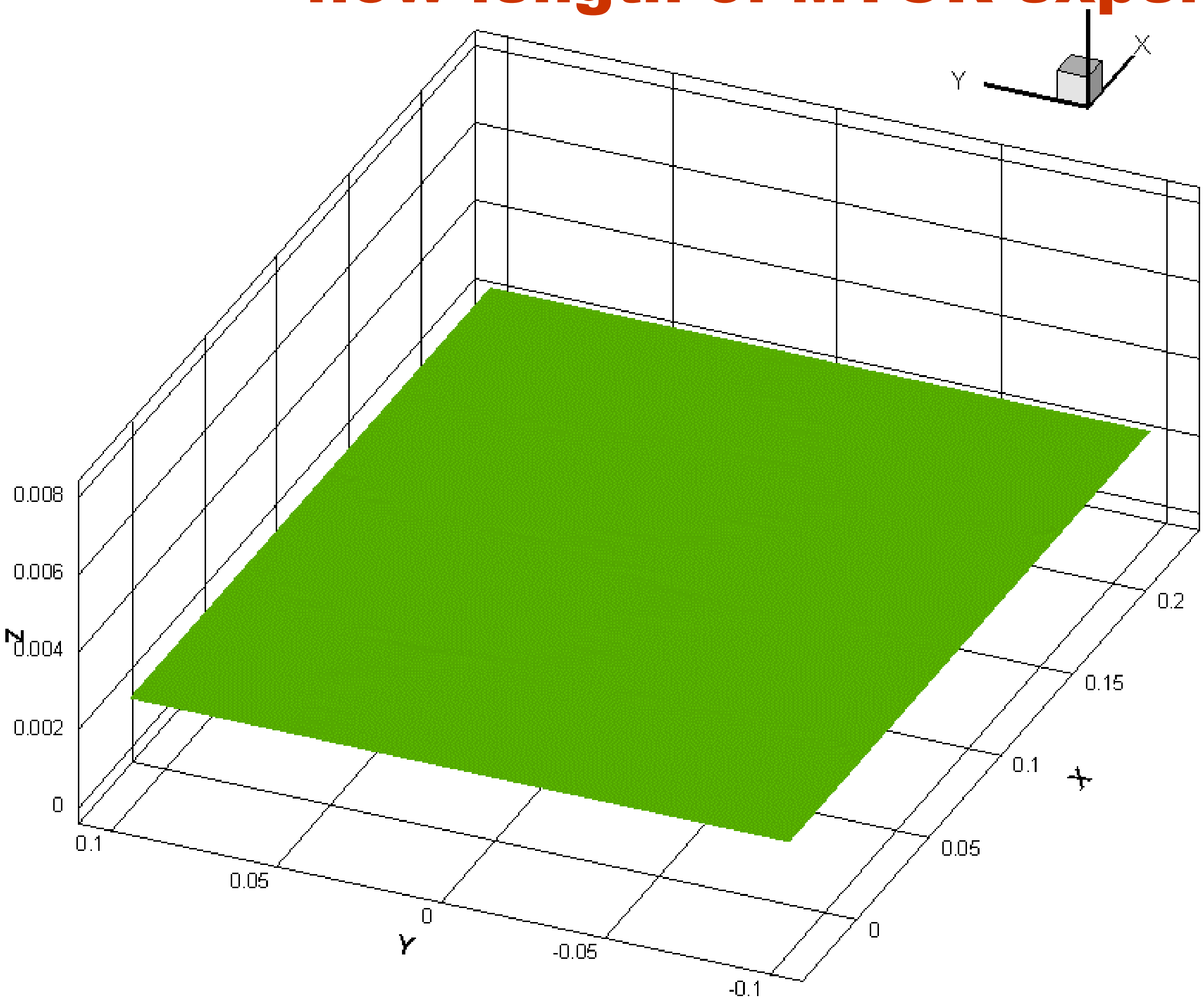
The magnetic field points in the positive ‘Z’ direction.

Electrical conductivity of gallium is three times that of stainless steel.

Return current path through the Hartmann layer

Return current path through the conducting bottom solid

HIMAG SIMULATION of first 20 cm flow length of MTOR experiment



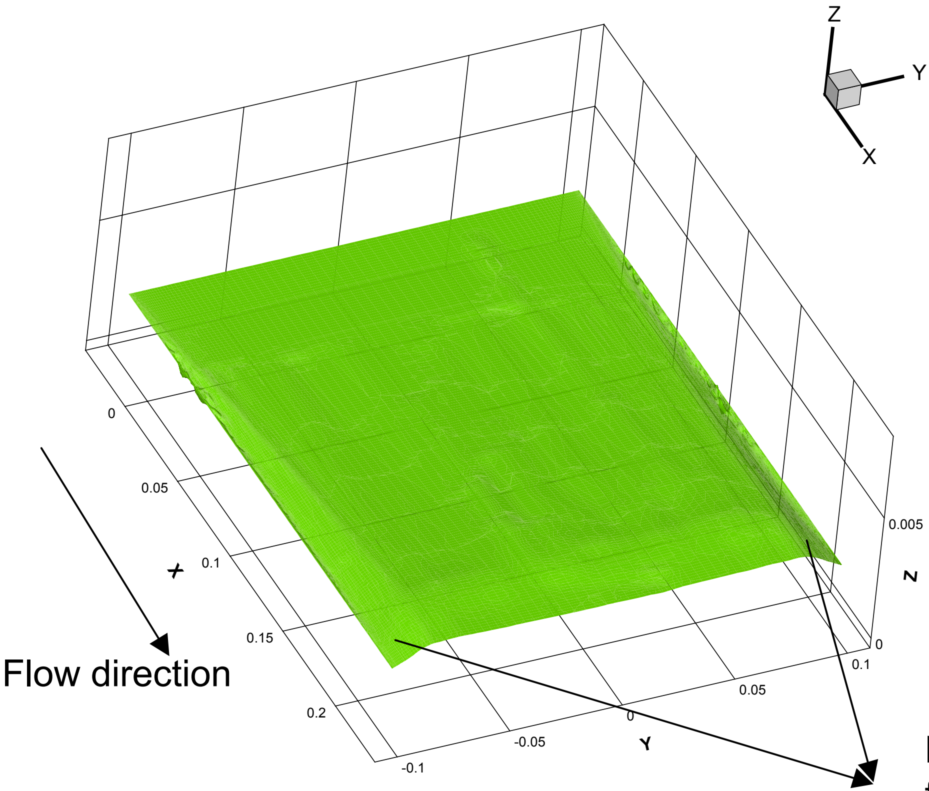
Animation showing the liquid metal free surface flowing through the applied wall normal magnetic field. The liquid metal film thickens as it flows downstream and tends to pinch in away from the walls.

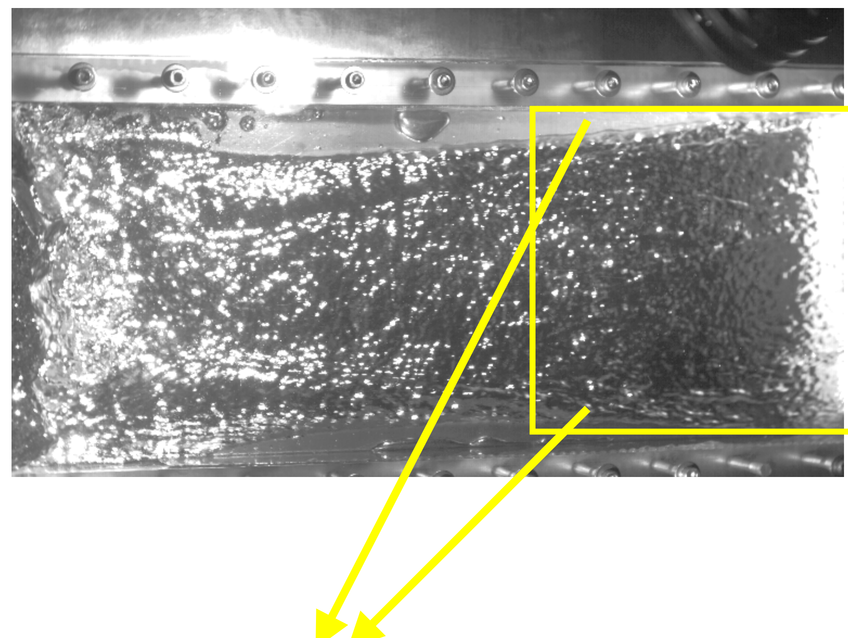
The animation shows 10 frames covering one flow through time, for good convergence further simulation is needed.

The computational domain was distributed over eight processors with 110000 computational cells each, a total of 880000 cells were used.

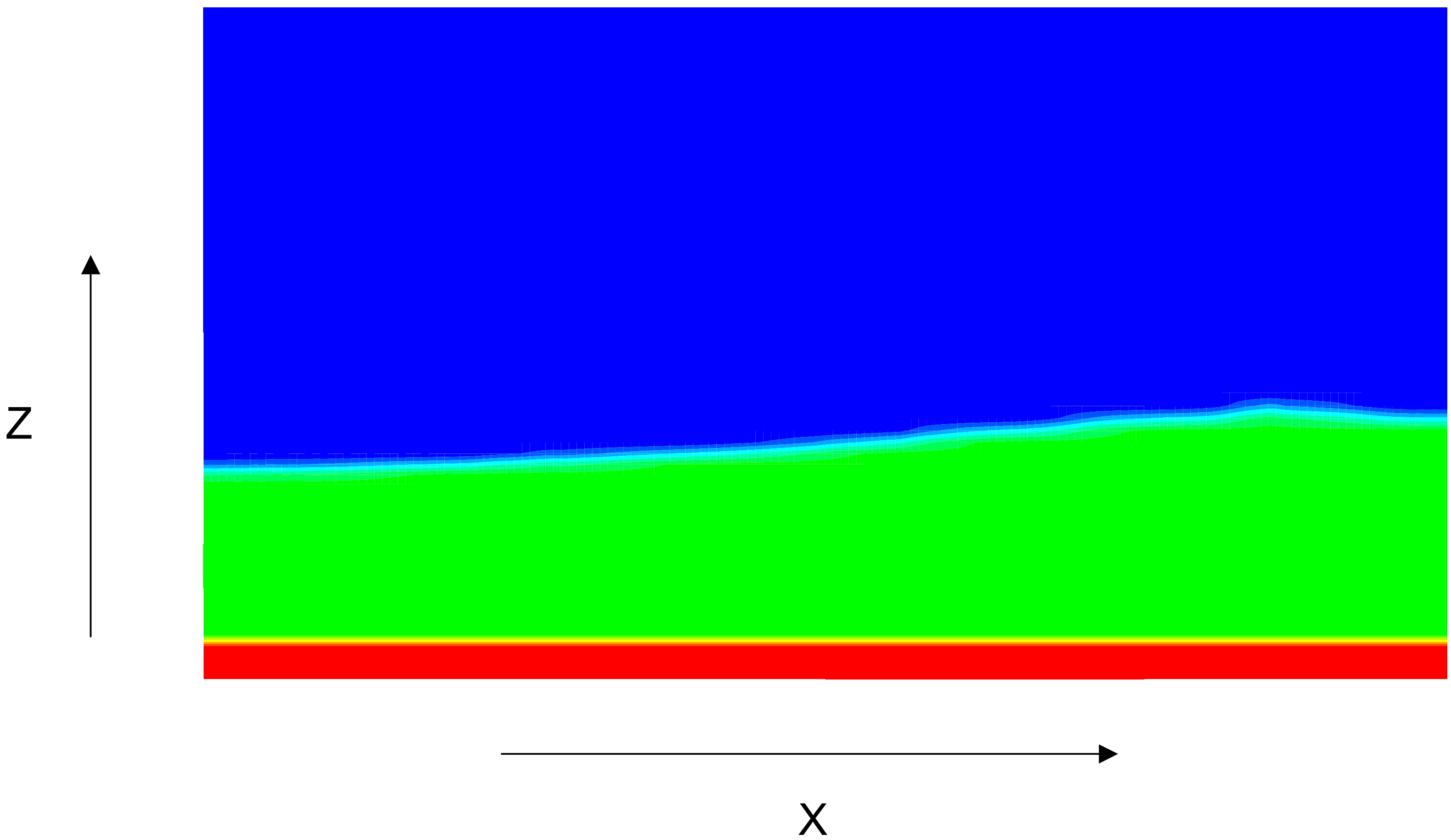
HIMAG SIMULATION, comparison with experiment

- **The increase in film thickness by 1mm at 18cm downstream for an inlet velocity of 3m/s, predicted by HIMAG compares well with that observed experimentally. (Experimental value shows an increase of 1.5mm at 16cm downstream for an inlet velocity of 2.5m/s)**
- Experiments show the liquid being pushed away from the walls at inlet velocities (2.5-3m/s), the same tendency is observed in the numerical simulation.





Film depth increase with downstream distance



Gallium film thickness increases along the stream wise direction from 2mm at inlet to around 3mm at 18cm downstream.

Summary of MTOR film flow experiments and simulation

- Experimental simulation
  - Better surface normal magnetic field
  - Addition of toroidal field ~ 1T
  - More quantitative data on surface height and velocity
- HIMAG simulations
  - Longer time and geometry simulations
  - Including toroidal field

Future work on free surface MHD modeling and experiments for ALPS

- Fast Flowing System
  - Continued experiments on wide film flows in MTOR
  - Continued simulations of experiments with HIMAG
  - NSTX flowing module design (choice of films or jets)
- Quasi-Stagnant System
  - Characterization of plasma current driven motion of very-thin Li films using HIMAG
  - Initial experiments of thin film LM surface control with porous substrates
- Continued HIMAG development with Hypercomp