Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device (e.g. NSTX)

Review of Progress

Participants and Contributors

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APEX Task I has been aimed at exploring flowing liquid wall options and, within a 5-year time frame (~2004), operating a flowing liquid wall experiment in an experimental physics device.

The goals of Task I are to help develop and provide liquid wall technology systems that meet experimental physics device (such as NSTX) conditions before installation.

Nov. 7, 2001
Scottsdale, Arizona

FY01 Task Details

I.1 **Characterization of projected plasma operating conditions in NSTX and CMOD (PPPL, SNL)**

I.2 **Design and analysis of flowing liquid wall options (for long pulse operations) in NSTX and other operating plasma devices (UCLA, ORNL, SNL, ANL)**

- **a)** **Conceptual design (ORNL)**
- **b)** **Divertor Integration**
- **c)** **Magneto-Hydrodynamics and Heat Transfer (UCLA, SNL)**
- **d)** **Off-normal events (ANL)**

I.3 **Plasma-Liquid Interactions (LLNL)- Under Task B**

Characterize NSTX edge-plasma with liquid wall to aid design (LLNL)

I.4 **LM-MHD experiments with magnetic field gradients and applied currents (UCLA, PPPL-Woolley)**

I.5 **Identification of key issues and development of a R&D plan for implementing liquid walls in NSTX and other operating plasma devices (SNL,UCLA, PPPL)**

Progress reports have been presented at the NSTX Forum, and at APEX Regular and Electronic Meetings

NSTX Forum: Contributed to various aspects of the analyses that are required to support the ALIST proposal "Liquid Surface Module for Particle Control."

April Meeting

ALIST- Application of Liquid Surfaces in Fusion Devices

Design Analysis and Modeling –

- Effects of surface normal magnetic fields on concepts for fast surface flows of liquid metals
- 3-D MHD simulation
- Modeling of edge plasma instabilities

August Electronic Meeting

Device Characterization- Magnetic fields in fusion (experimental physics) devices

Design Analysis and Modeling - 3D MHD simulation update

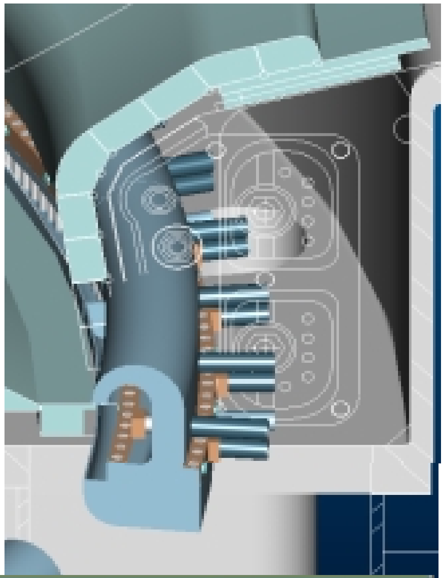
Concept Exploration- Explorative analysis of a self-pumped divertor concept for CMOD

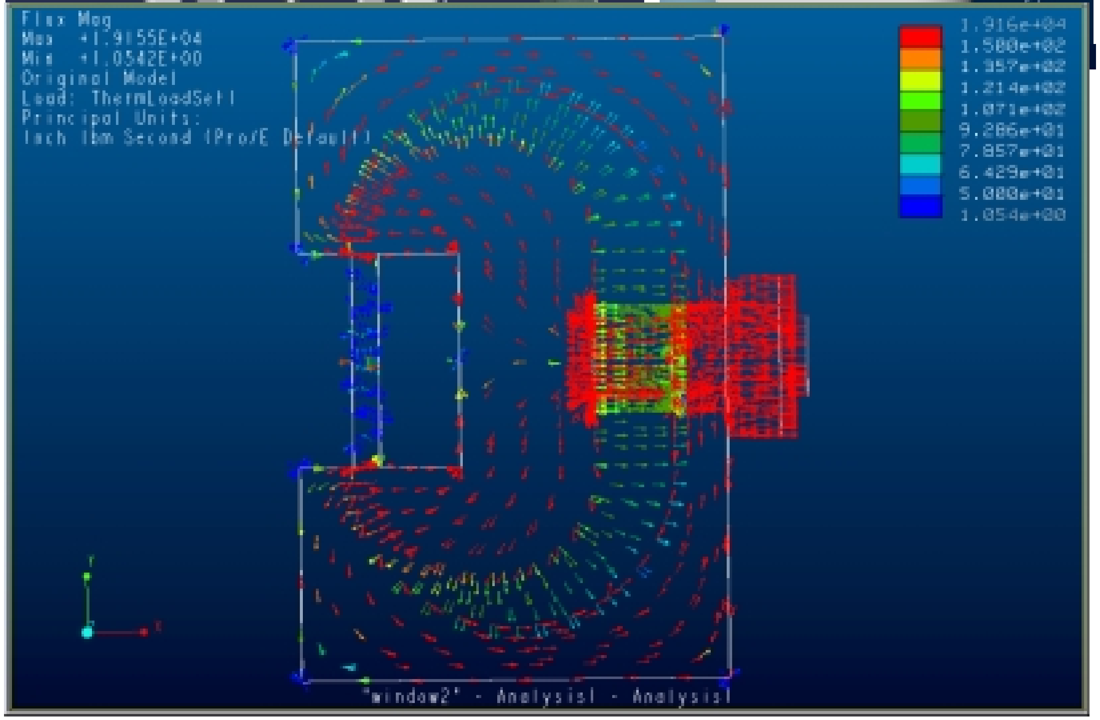
Summary of Disruption Analysis- Hassanein

During plasma disruptions on a liquid lithium surface, the net power flux reaching the surface, where the disruption originally occurred (due to the vapor-cloud shielding effect) is significantly reduced to <10 % of the initial incident power from the scrape-off layer. Mass losses from atomic surface vaporization due to this reduction in radiation power may be tolerated for the expected disruption frequency. However, mass losses due to splashing can be high. Splashing is defined as mass loss in the form of macroscopic particles (MPs), i.e., droplets of liquid metals. The MPs will interact with incoming plasma particles and with the vapor cloud above the surface. Therefore, the dynamic behavior of MPs in the vapor cloud and their influence on the total erosion rate are critically important problems.

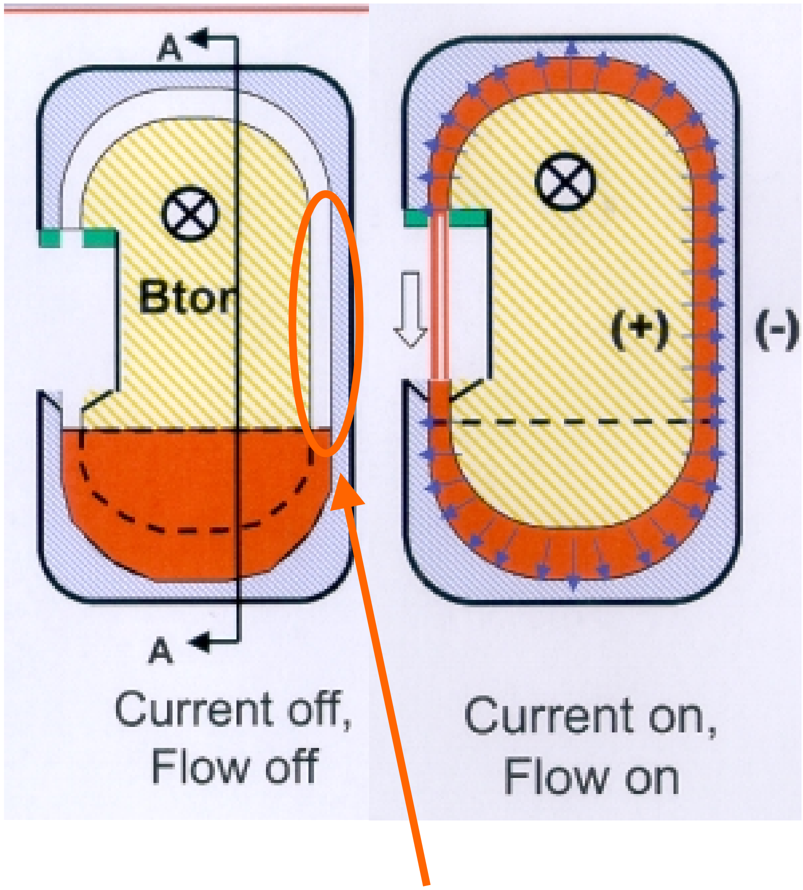
Results of unique models and very detailed self-consistent magneto-hydrodynamic calculations are obtained. The dynamics of both vapor clouds and MP interactions are coupled with incoming plasma ions and electrons from the scrape-off layer during the disruption. Depending on the stability of the initially formed vapor cloud above the disruption area and on the physics of droplet interaction with this layer, the splashed lithium thickness can range from ~ 1 mm thick to ~ 4 cm for a typical disruption energy of 100 MJ/m^2 deposited in a 1 ms duration. Other disruption parameters will have different effects on the response of the liquid metal surface.

A Self-Pumped Divertor Concept was Proposed for CMOD



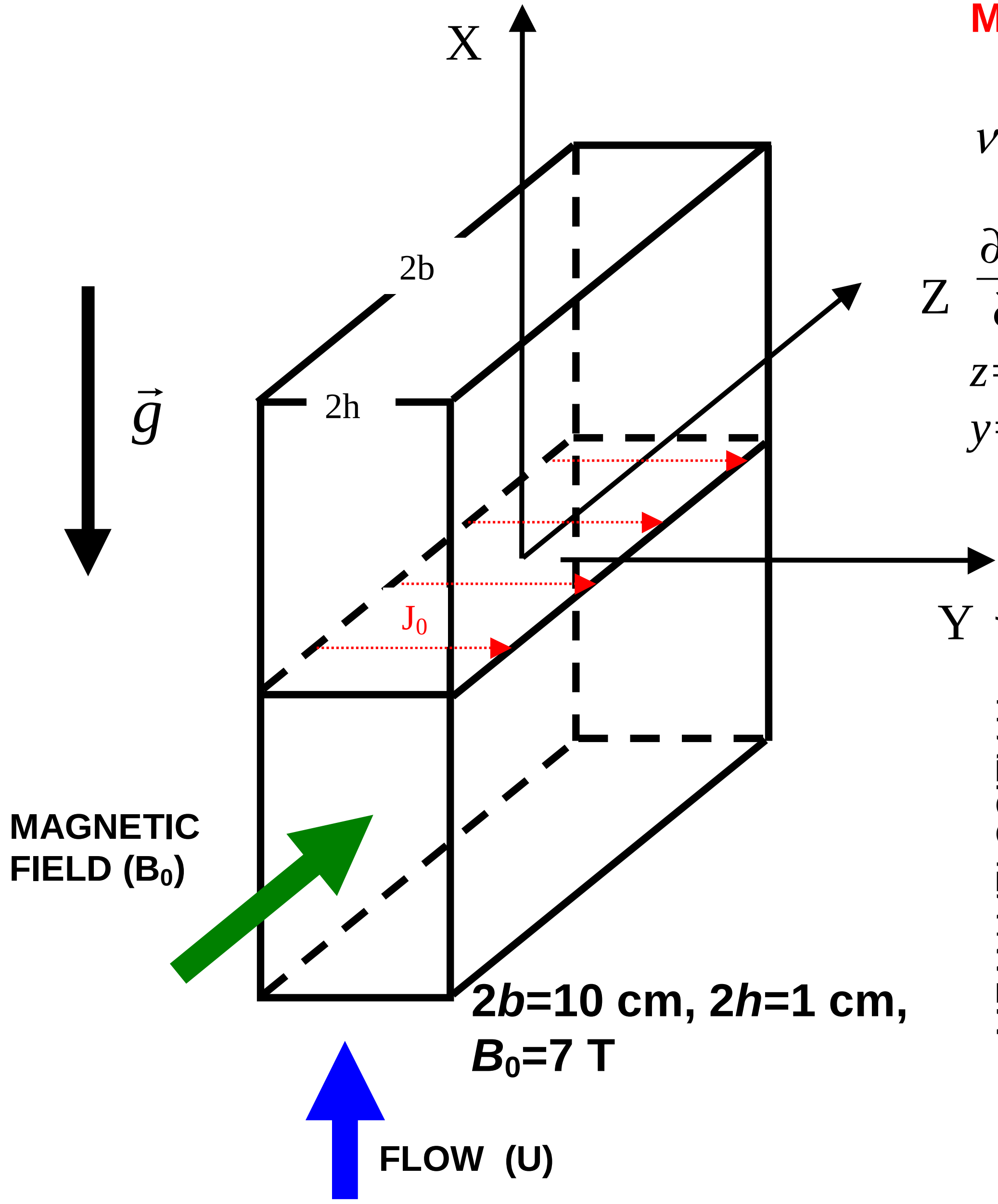


Flux Mag
Max +1.9155E+04
Min +1.0542E+00
Original Model
Load: ThermLoadSet1
Principal Units:
Inch lbm Second (Pro/E Default)



MHD analysis was performed to define the current density requirements

Initial MHD calculations indicate a small current (~ 100 A/module) can produce > 10 m/s velocity in free jets



2*b*=10 cm, 2*h*=1 cm, *B*$_0$=7 T

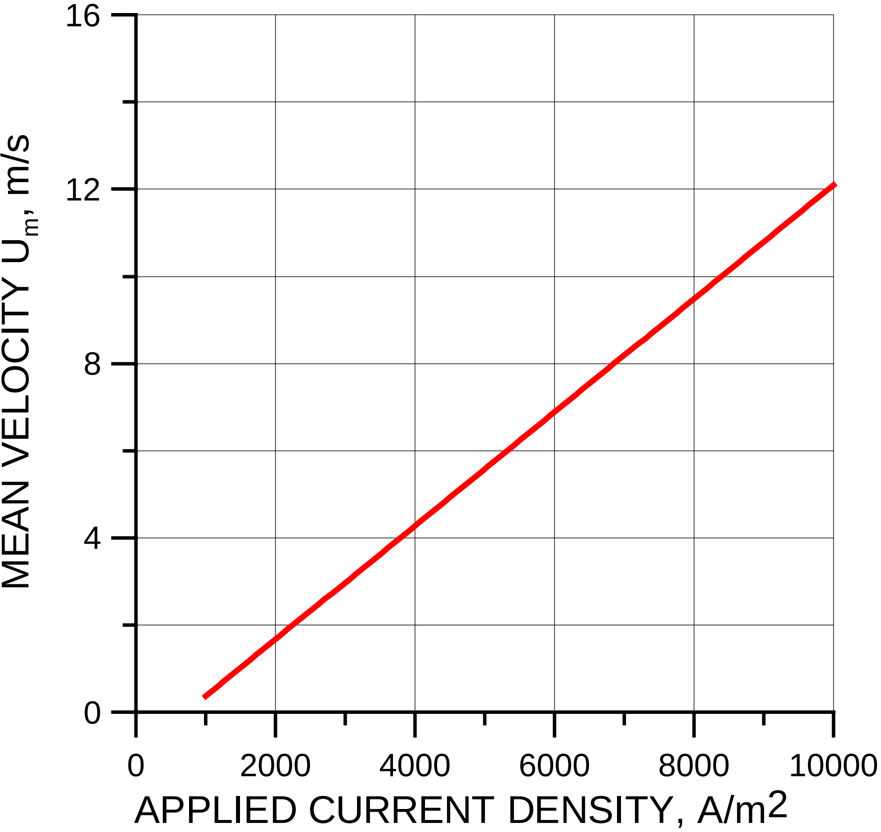
MATHEMATICAL MODEL (fully developed flow):

$$\nu\left(\frac{\partial^2 U}{\partial z^2}+\frac{\partial^2 U}{\partial y^2}\right)+\frac{B_0}{\rho\mu_0}\frac{\partial B_x^{/}}{\partial z}-g+\frac{1}{\rho}j_0 B_0=0$$

$$\frac{\partial^2 B_x^{'}}{\partial z^2}+\frac{\partial^2 B_x^{'}}{\partial y^2}+\sigma\mu_0 B_0\frac{\partial U}{\partial z}=0$$

$z=\pm b$: $U=0$, $B_x'=0$ (isolated walls)

$y=\pm h$: $U=0$, $B_x'=0$



Progress on ALIST Liquid Metal Module MHD Characterizations

Prior to March 2001- Several MHD approximations were used to obtain preliminary data for the designs of LM modules (since no 3D tool for MHD calculations was available).

Approximations:

- ☐ **The model assumes a Hartmann type velocity profile in the toroidal field direction.**
- ☐ **The influence of B_{rad} has been taken into account through an additional term on RHS of the momentum equation standing for the Hartmann effect at the backplate.**

Results:

- ☐ **The MHD drag caused by the surface normal field has been significantly reduced because the segment walls have cut down the toroidal electric current.**
- ☐ **Additional MHD drag due to the Hartmann effect at the walls perpendicular to the toroidal field appears not significant for a flow module with electrically isolated walls.**

However, the ALIST liquid metal module is intrinsically 3D, whereas calculations based on approximations give poor information.

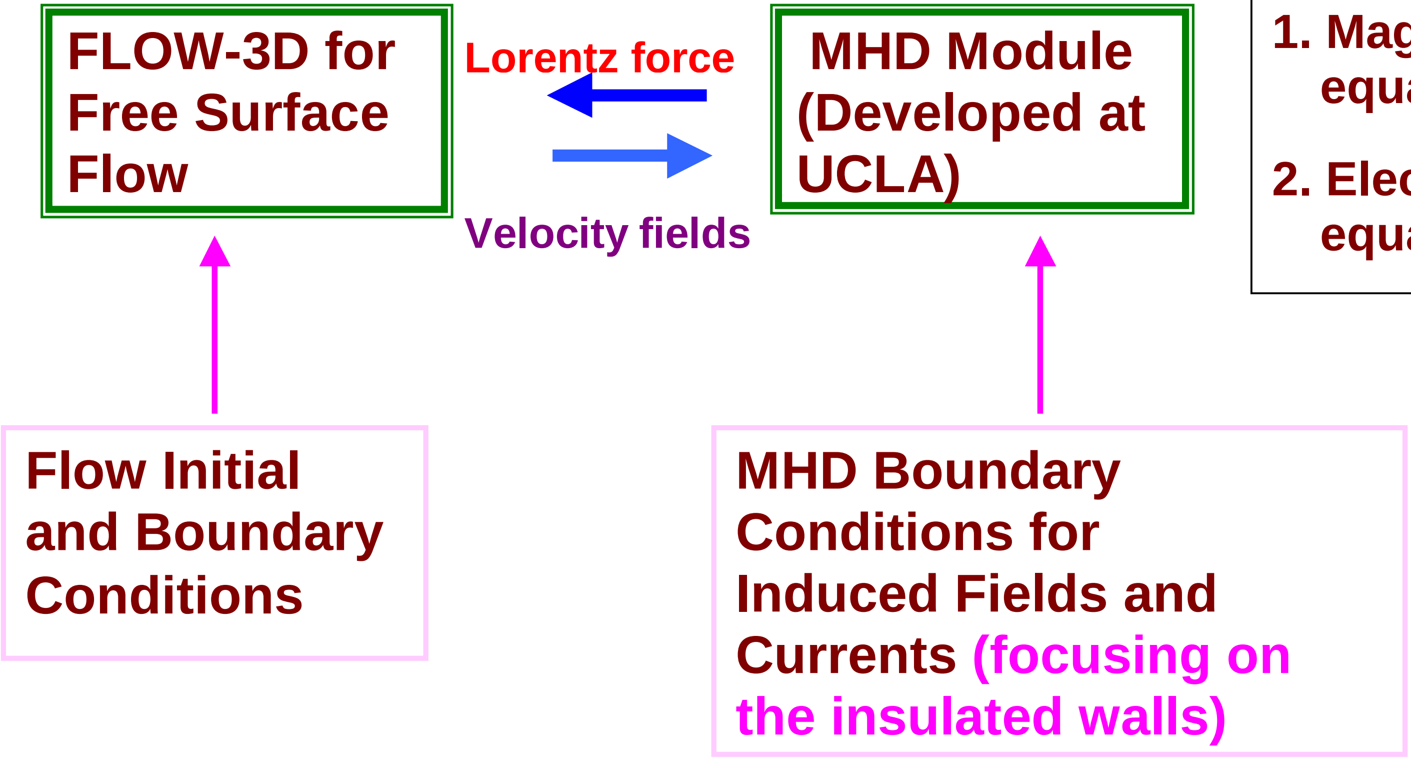
Task I Aimed at Extending FLOW-3D for MHD Flow Calculations

(3D in nature, post graphics capability, verified Navier-stoke's solver for free surface flow)

MHD modules were added to the FLOW-3D computational code

MHD models are based on:

1. **Magnetic induction equation**
2. **Electric potential equation**



FLOW-3D for Free Surface Flow

Lorentz force

Velocity fields

MHD Module (Developed at UCLA)

Flow Initial and Boundary Conditions

MHD Boundary Conditions for Induced Fields and Currents (focusing on the insulated walls)

A much longer CPU time is needed to obtain convergent solutions that incorporate MHD effects. It can easily take more than 10 hours of CPU time for the fluid to proceed 1 cm in a 1/5th scaled film flow module.

Mathematical Formulations for 3D MHD Simulation

Magnetic Induction Equation

$$\frac{\partial B}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 B + \nabla \times (\vec{V} \times \vec{B})$$

with $\nabla \cdot \vec{B} = 0$

$$\vec{J} = \frac{1}{\mu} \nabla X \vec{B}$$

Electric Potential Formulation

$$\nabla^2 \varphi = \nabla \cdot [U \times B]$$

$$\vec{j} = \sigma[-\nabla \varphi + U \times B]$$

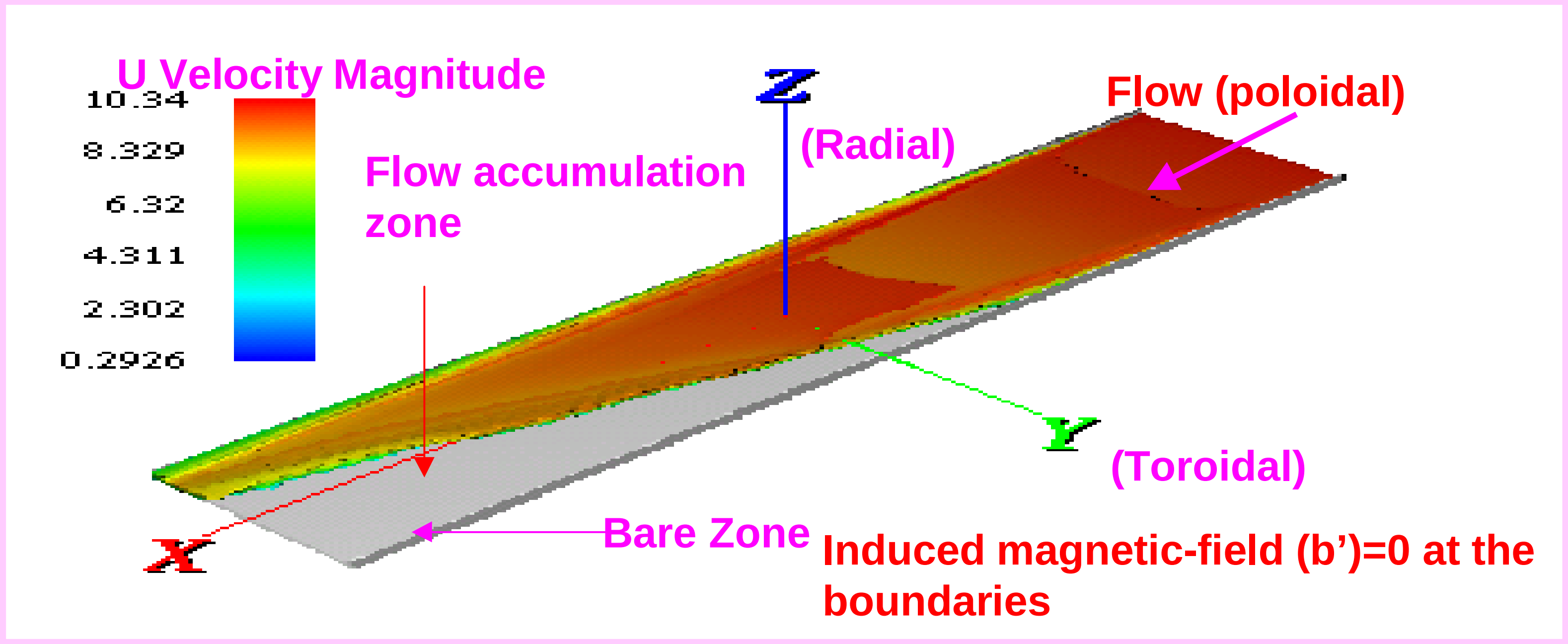
Comments on electric potential formulation (Smolentsev)

- ➢ Restricted to stationary applied fields
- ➢ Restricted to small magnetic Re number
- ➢ In 3-D, restricted to Ha number of about 400-700

Advantage:

Electric potential can be calculated within a finite domain using the well-known “thin conducting wall” boundary conditions at the interface.

MHD module based on magnetic-field induction equation was first developed to obtain 3D MHD results, which were presented at the previous APEX meeting (April 01)



Comment associated with this calculation (in which an induced field boundary condition for the 2-D problem is assumed):

The induced field can permeate and can be zero only at some distance away. Not clear how this assumption affects the flow.

- **Accordingly, a case was run for the condition where the induced field decays to zero at some distance (distance was determined by Laplacian equation).**

The difficulty with magnetic induction equations is in deriving a correct mathematical description for boundary conditions

Previous simulations obtained were based on the simplified 2D induced field condition ($\vec{B}'$ =0).

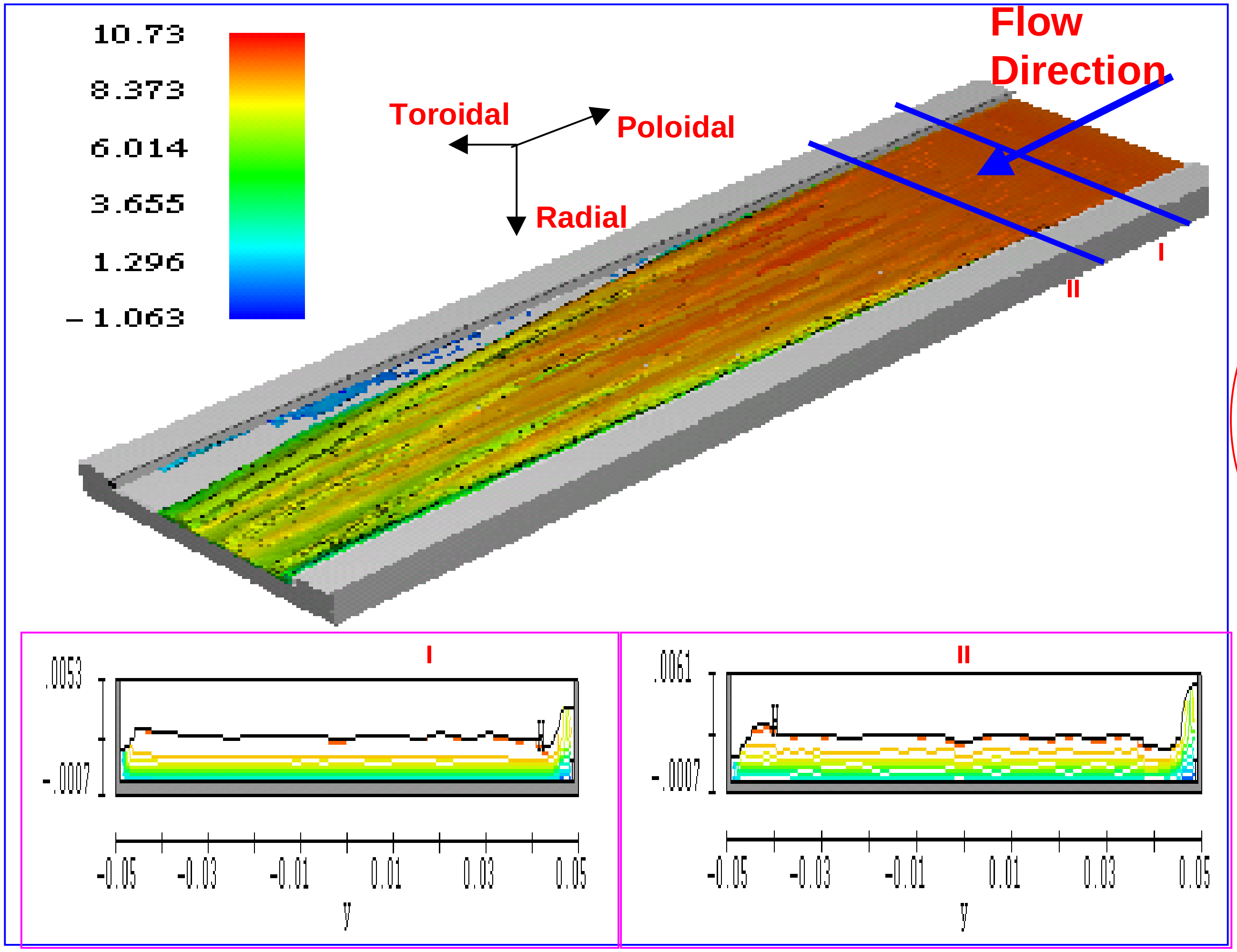
This is valid for some 2-D or axis-symmetrical problems, because there is only one component of the induced magnetic field. In such cases, the problem is completely closed because the additional boundary conditions on $\vec{B}'$ are not needed. It is not clear for 3D problems. Further understanding is required to model 3D boundary conditions at the interface and solid wall.

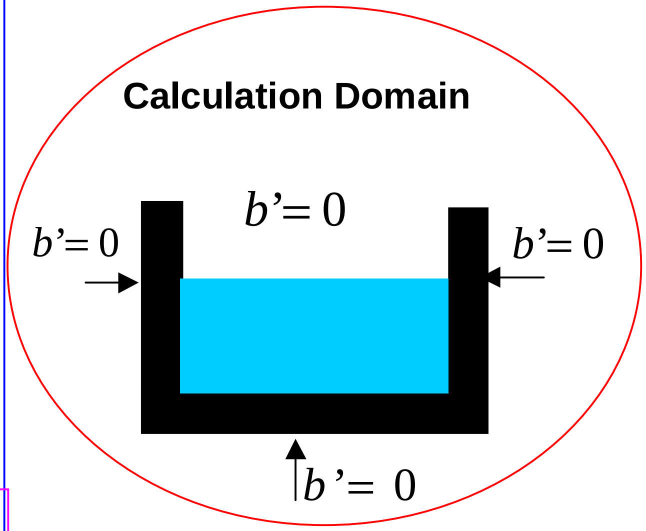
Advantages:

- **High possibility of obtaining a convergent solution for High Hartmann Number and Non-uniform Magnetic Fields.**
- **Can be applied to a larger magnetic field Reynolds number (Re_m>1)**

A Benign MHD Flow is Obtained by Assuming b’ =0 at the Extended Wall Boundaries

- fluid separation starts further downstream
- the pushing force is weaker, leading to a small bare region.

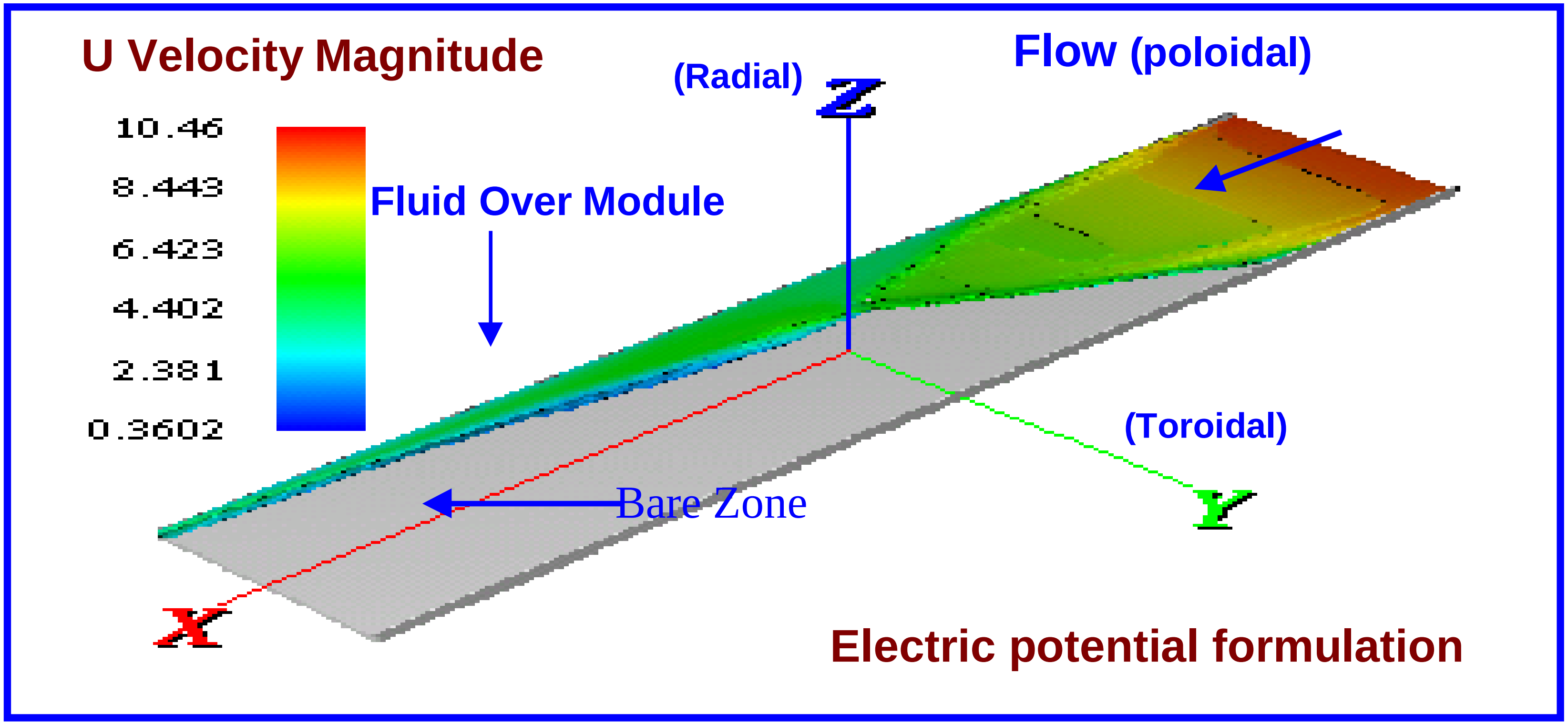



Calculation Domain

Preliminary Results based on the Electric Potential Formulation Show a Stronger 3D MHD Effect

(Initial calculations were performed for NSTX outboard Mid-plane film flow using the electric potential formulations based on a Self-Correcting Procedure numerical technique)

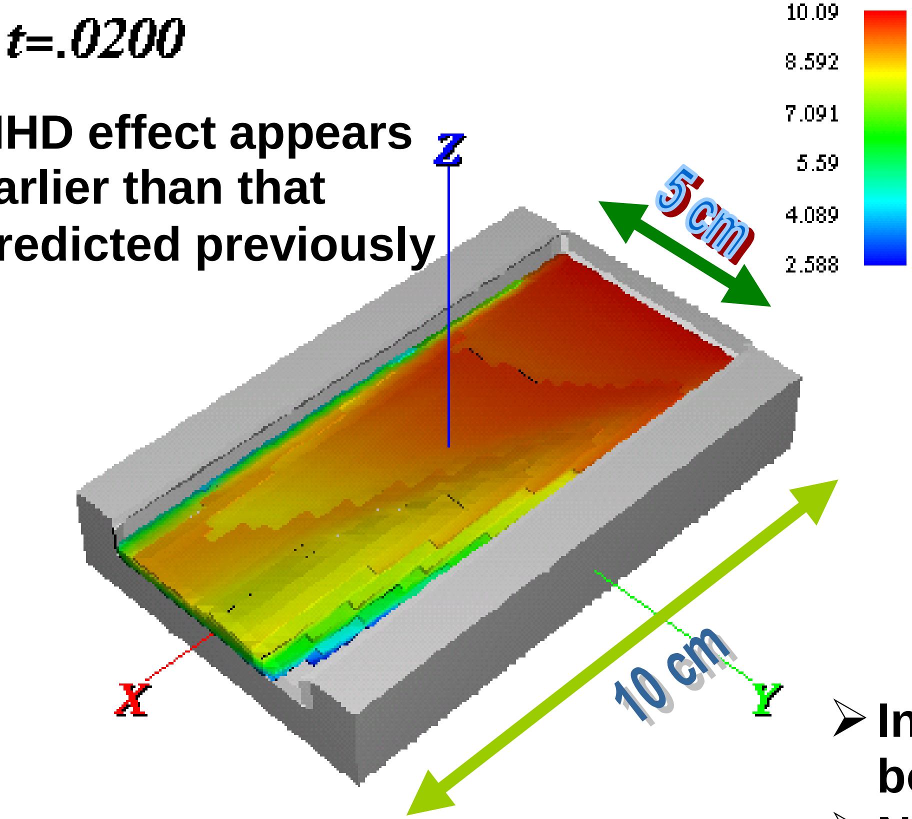
The Lorentz force (J×B) is much stronger and thus causes a larger bare spot and a stronger velocity reduction than the results based on the magnetic induction formulation.

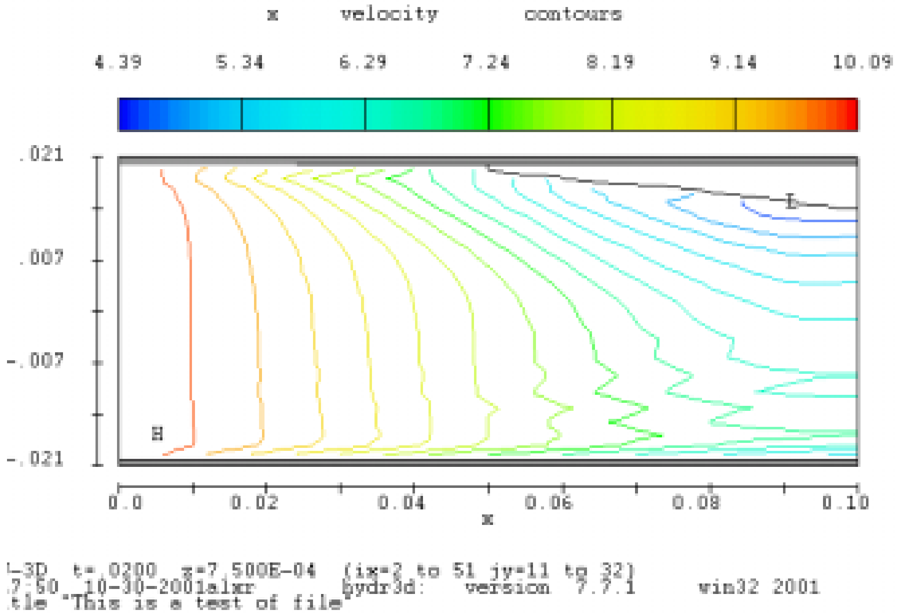


A numerical scheme that consistently solves the magnetic induction formulation is obtained

This was to solve the problem of $\nabla \cdot \vec{B} \neq 0$, which was found in our previous results

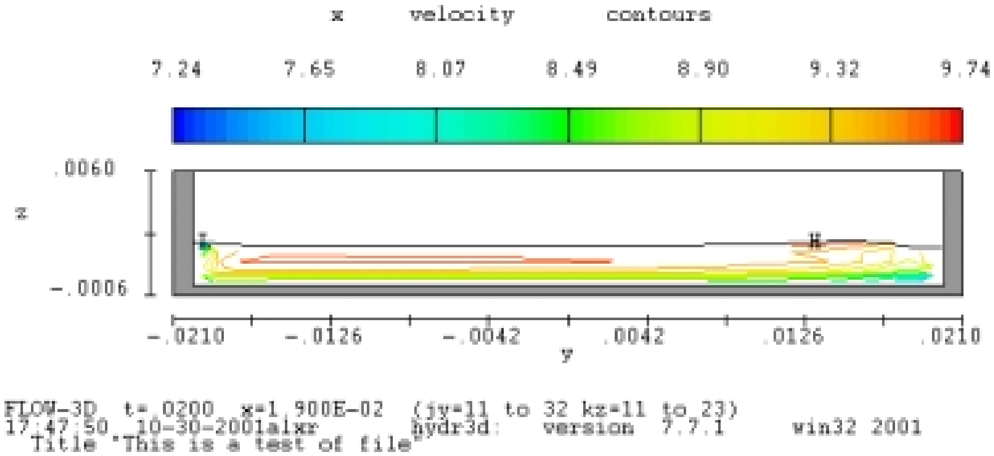
MHD effect appears earlier than that predicted previously





- **Induced fields = 0 at the solid wall boundary**
- **No treatment of the boundary conditions at the solid/liquid interfaces**

U Velocity Characteristics as Lithium Proceeds NSTX Mid-Plane Downstream



```
FLOW-3D  t=.0200  x=1.900E-02  (jy=11 to 32 kz=11 to 23)
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```
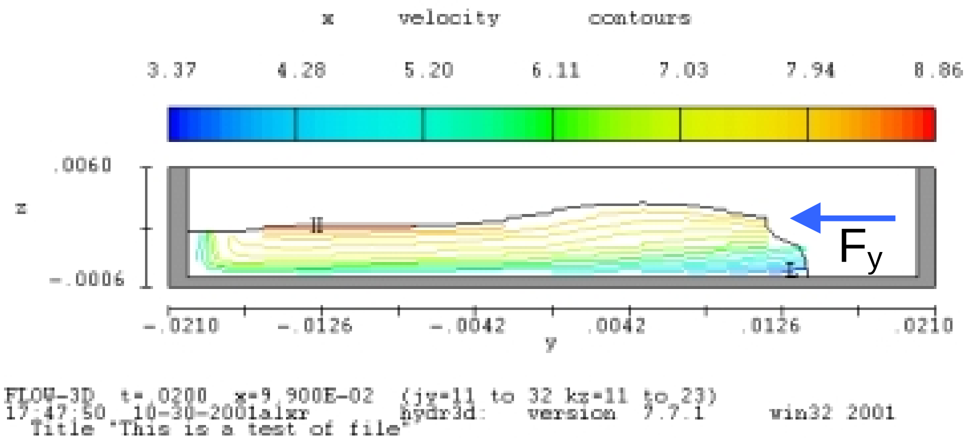

X= 0.019 m



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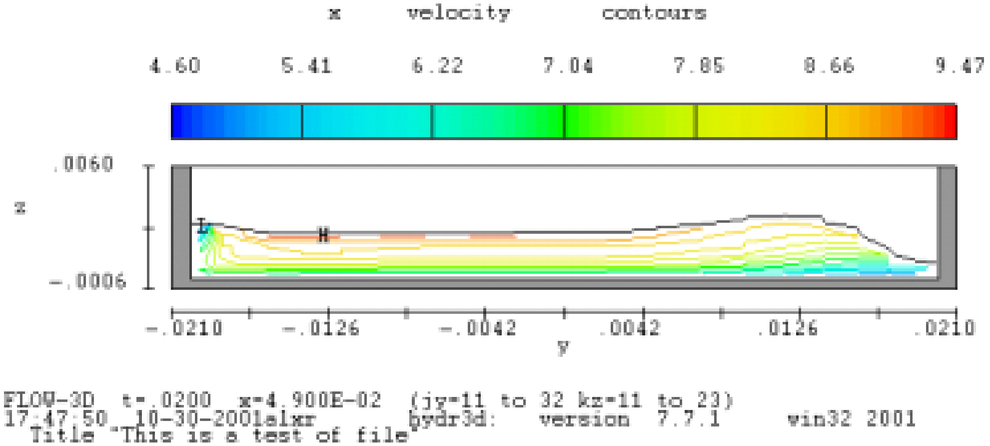
X= 0.099 m



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X = 0.049 m

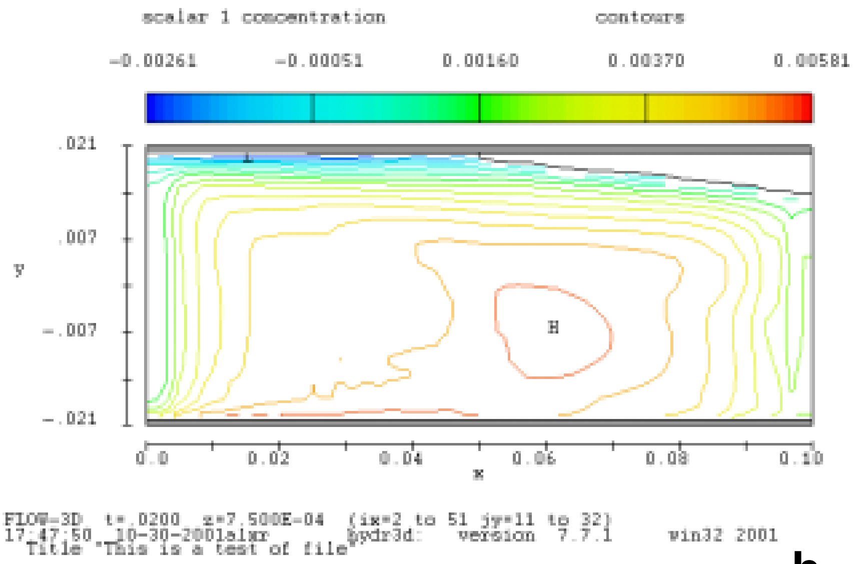
Similar to the previous results, MHD effects result in a preferential flow direction and a bare region.

$$F_y = J_z B_x - J_x B_z$$

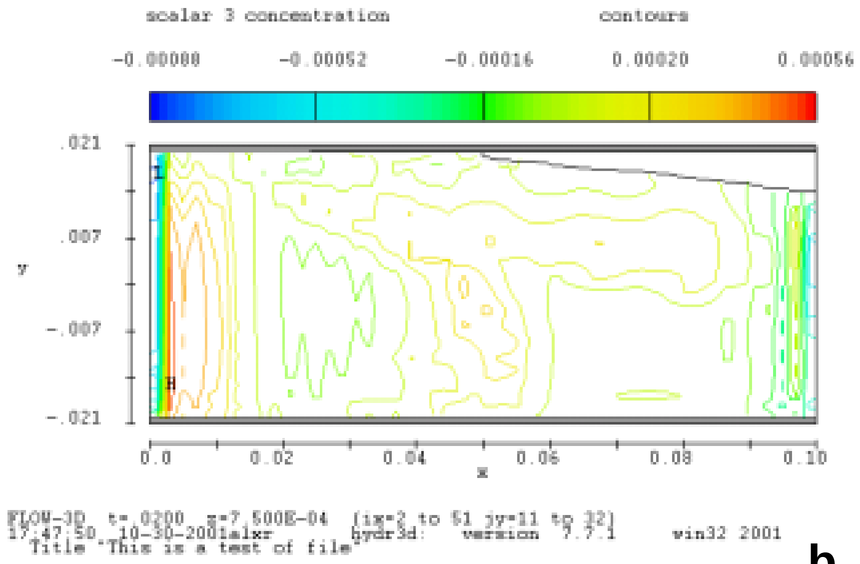
(1/μ is missing from J)

$$J_x = \frac{\partial}{\partial y} b_z - \frac{\partial}{\partial z} b_y \qquad J_z = \frac{\partial}{\partial x} b_y - \frac{\partial}{\partial y} b_x$$

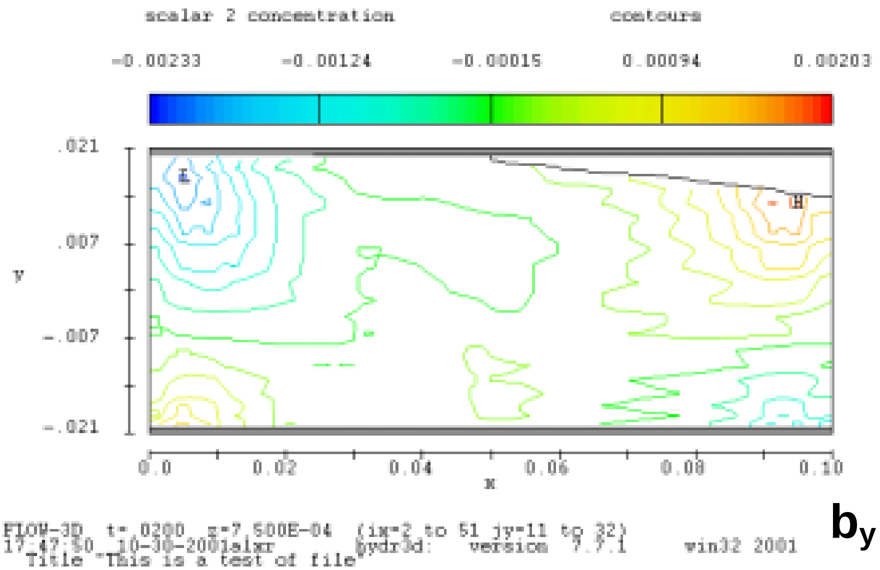
Induced Magnetic Field Characteristics (at 0.75 mm above the solid substrate)



b



b_z



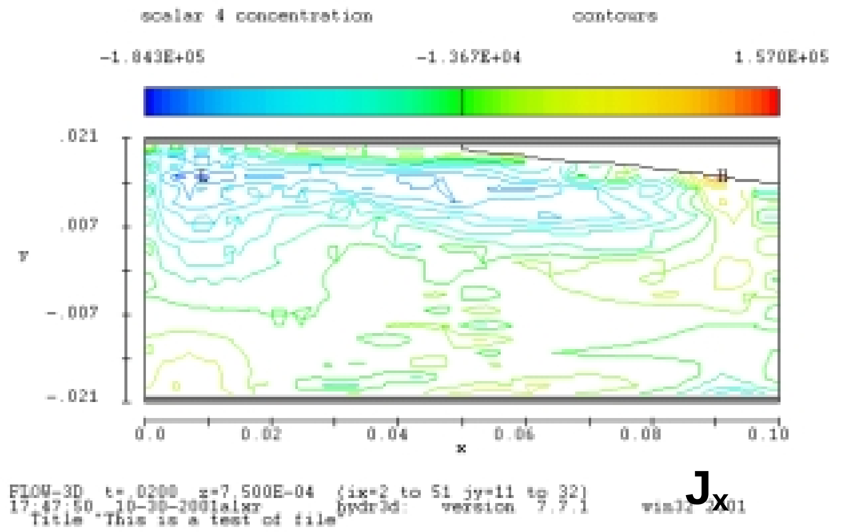
b_y

Note: Film height varies at different downstream locations

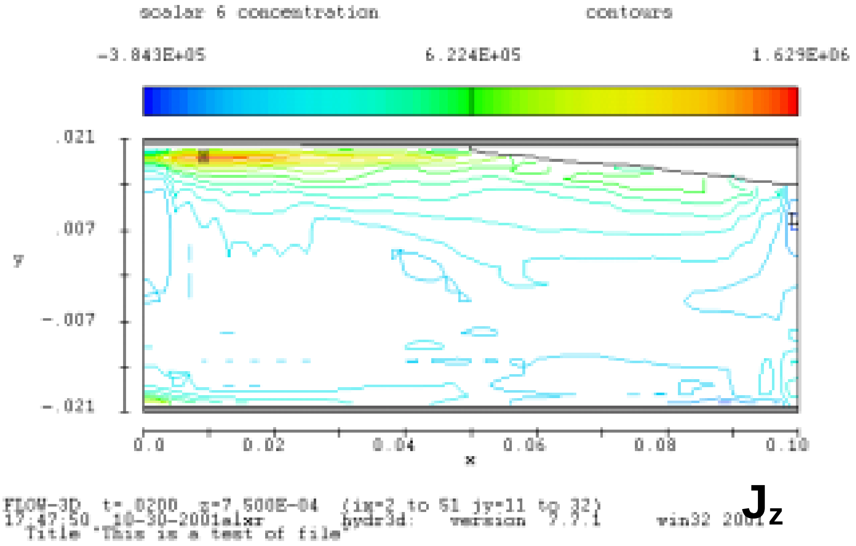
- $\vec{b} \prec\prec \vec{B}$ **($\vec{b}$ diffuses to zero inside the solid wall)**
- $F_x = J_y B_z - J_z B_y$ **, which causes lithium to slow down*** **(1/μ is missing from J)**

$$J_y = \frac{\partial}{\partial z} b_x - \frac{\partial}{\partial x} b_z \qquad J_z = \frac{\partial}{\partial x} b_y - \frac{\partial}{\partial y} b_x$$

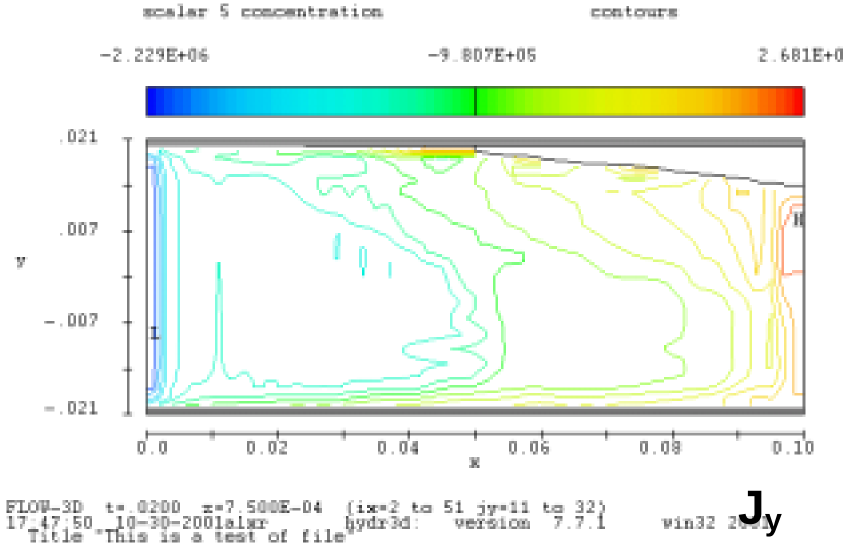
Induced Current Characteristics (at 0.75 mm above the solid substrate)



J_x



J_z



J_y

- **Do the calculated induced current profiles make sense? Is its appearance against any physics laws?**
- **What information available to tell whether the calculations are correct or not?**
- **On-going efforts are to apply “boundary conditions” at the interfaces (e.g. J_{normal} = 0 at the fluid/wall and void Interfaces)**

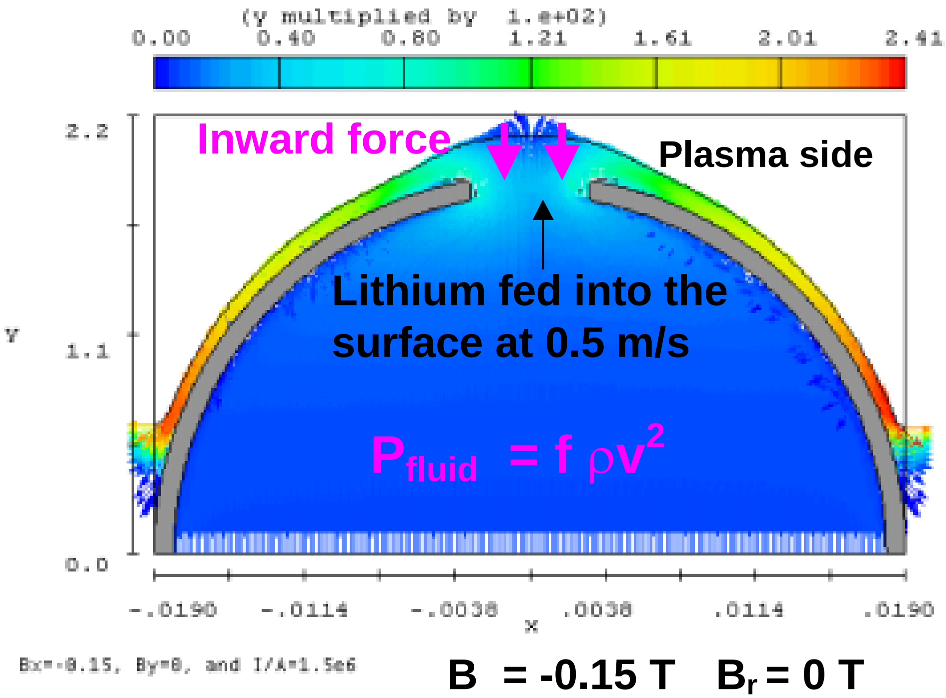
Experimental Studies for Soaker Hose and Free Stream Concepts

A. Soaker Hose Ideas

Requirements

- **A fluid supply mechanism (e.g. differential pressure and flow resistance) that gives an adequate feed to the plasma side**
  (P, f, V)
- **An externally fed current that provides an inward radial force to push fluid back toward the solid surface**

$F_r = J_p * B_t$



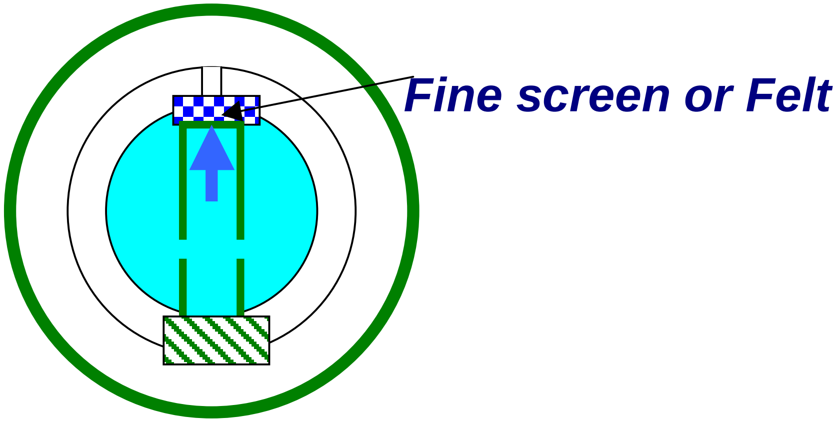
Inward force

Plasma side

Lithium fed into the surface at 0.5 m/s

$P_{fluid} = f \rho v^2$

$B = -0.15$ T $B_r = 0$ T



Fine screen or Felt

Progress - Experimental Study of Soaker Hose Ideas

Several acrylic test articles were constructed and tested for the soaker hose concept to evaluate supply requirements (inlet velocity, pressure, and flow resistance relationship)

It is easy to machine, but difficult to provide a good mechanism for sealing

Different flow resistance techniques based on single and multi-layer fine screens and felt materials have been studied.

Unfortunately, all failed, due to either too much or zero resistance

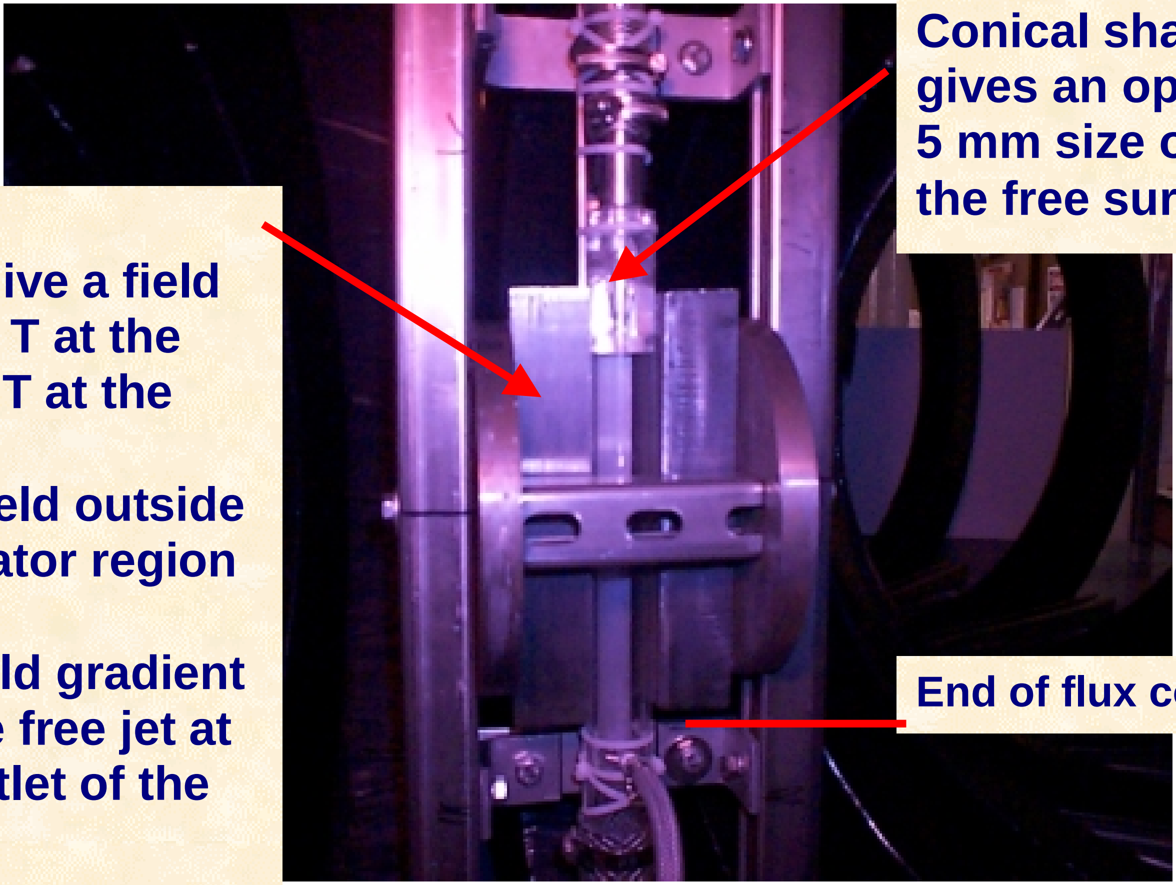
Also, it appears that once screens are wetted they offer zero resistance to the fluid.

Need to rethink robust “passive” schemes to deliver the fluid to the plasma side to ensure a “controlled yet uniform” flow

Experimental Study of Free Stream Concepts

Two test articles with a nozzle opening of 5 mm were fabricated:

- **One fits into a gap of about 1.5 inches with a magnetic field strength of 0.68 T (performed)**
- **The other fits into a gap of about 5/8 inches subjected to a magnetic field strength of 0.9 T**



Conical shape nozzle gives an opening of a 5 mm size of stream at the free surface inlet

- **Magnetic flux concentrators give a field strength of 0.68 T at the mid-plane (0.63 T at the top)**
- **The magnetic field outside of the concentrator region is about 0.36 T**
- **A transverse field gradient is applied to the free jet at the Inlet and outlet of the concentrators**

End of flux concentrator

Experimental Results- Free stream under a transverse field and an abrupt field gradient (0.63 T to 0.36 T)

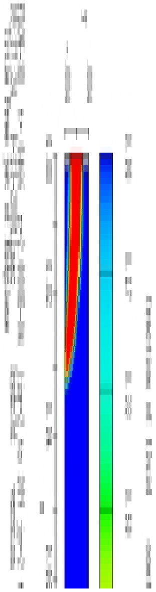
Stream Characteristics

With magnetic field off: **(no effort was put into modifying flow conditions, e.g. no honeycomb, no flow straightener)**

- **behaves like a typical turbulent jet, with a rough surface and an ill-defined boundary**

With magnetic field on:

- **the jet becomes smooth and emulates like a solid rod**



However,

- **the jet deflects back and forth at the exit of the concentrator (where a field gradient exists)**