Recent Progress on M-TOR Liquid Metal Free Surface Flow Experiments and Modeling for ALIST Module B

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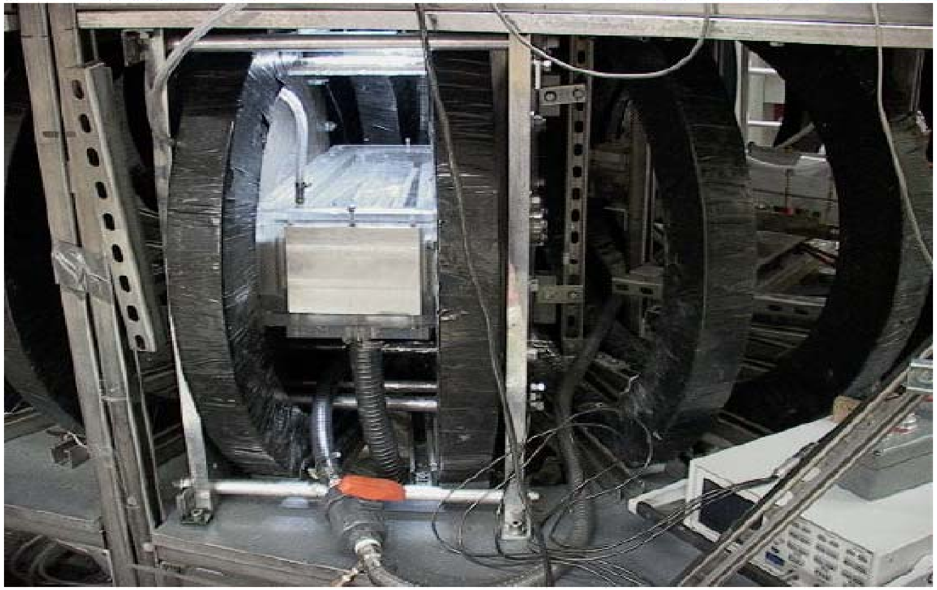
Outline

- **The work on Test Section –I (Summer 2003)**
- **Design of Test Section -2**
- **Modeling of liquid metal free surface flows: HIMAG**

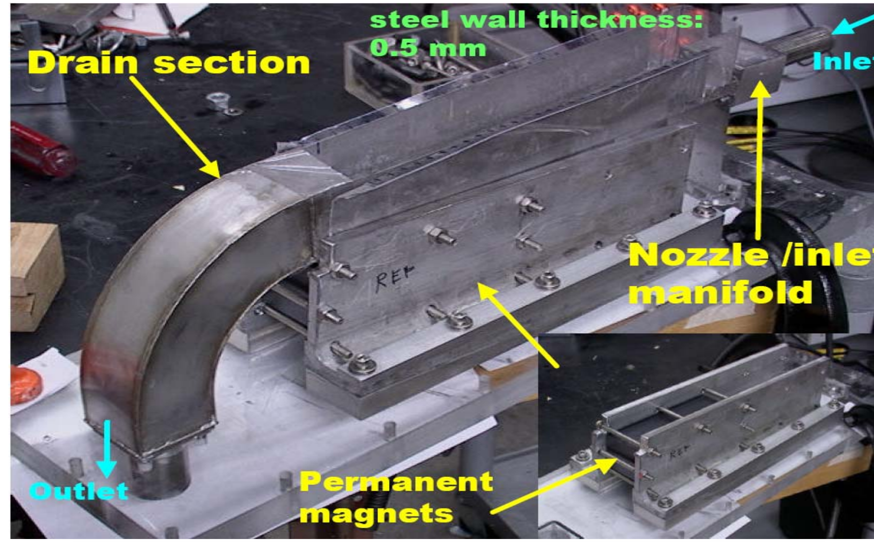
Magnetic Torus (M-TOR)

- 24 Electromagnetic coils arranged in a toroidal configuration
- Major Radius (R) = 0.78m
- Minor Radius (r) = 0.39m
- Maximum current through each coil : 1700A
- Max inboard magnetic field : 0.62 T / 1.2 T
- Max outboard magnetic field : 0.21 T / 0.6 T
- Test section is placed inside a vacuum box (argon atmosphere)
- GaInSn alloy is used (safety issues)
- Liquid flows from inboard to outboard (reverse configuration possible)
- Liquid flow is controlled by an electromagnetic pump
- Test section inclination with the horizontal can be varied (zero for the current experiments)
- A set of induction probes is used to determine the liquid metal film thickness

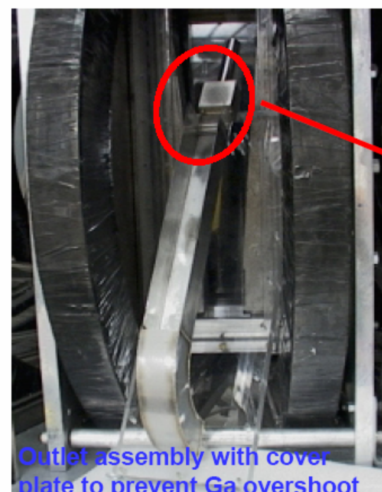


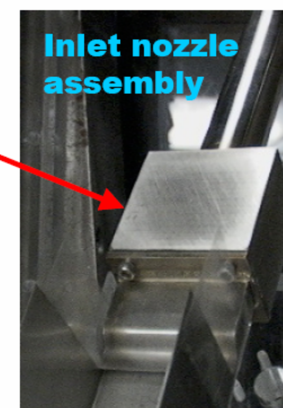
Test Section-I

- Test section-I is a straight channel with thin conducting walls (thin sheet 304 stainless)
- The conductance ratio for the channel is 0.0067 $c = \frac{\sigma_s t}{\sigma_f a}$
- The flow length obtained is 34cm, with a width of 5cm (which is a constant, stream-wise)
- Initial film thickness at the inlet : 2.5mm (produced by a nozzle with an area reduction of 5)
- A pair of permanent magnets is put below the channel bottom wall near the outboard to simulate the surface normal component



Stainless steel walls conducting channel
steel wall thickness: 0.5 mm





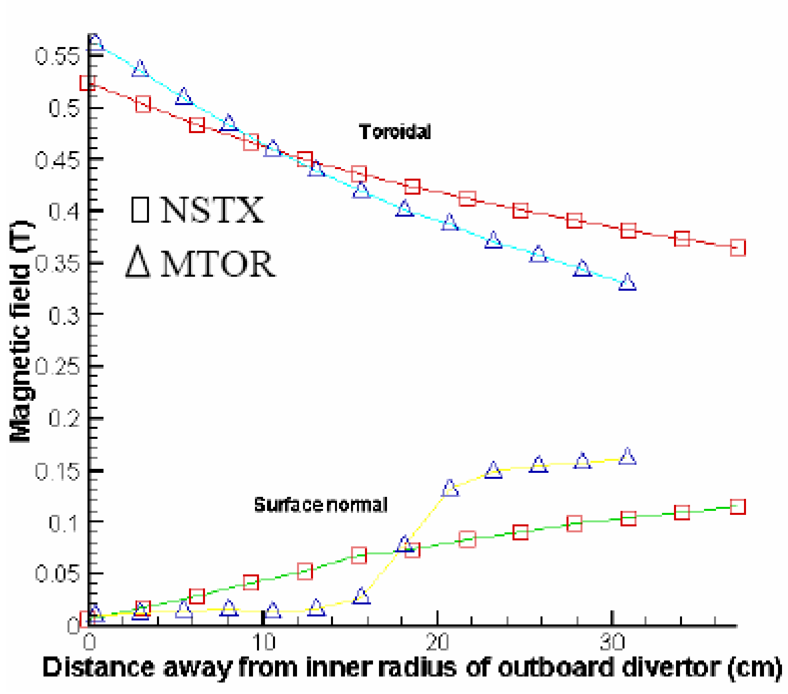
$$c = \frac{\sigma_w t_w}{\sigma_f a} = 1/150$$

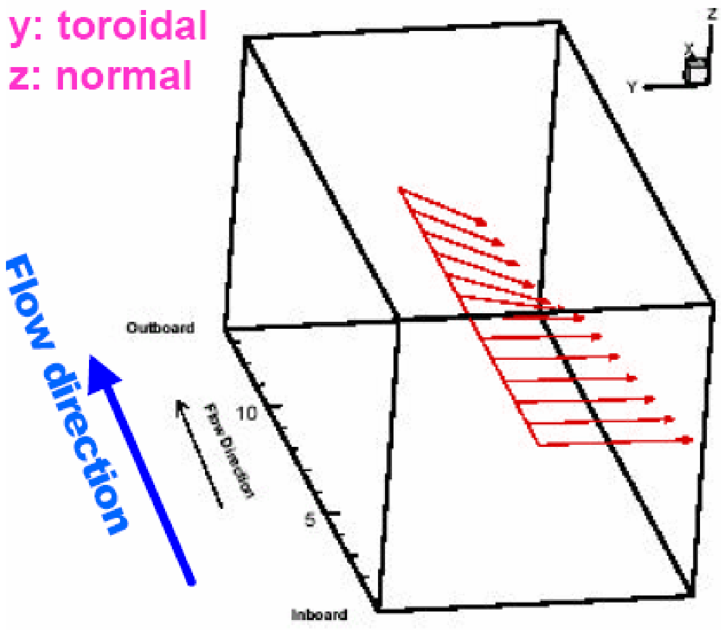
'c' is the conductance ratio; *a* = channel half-width

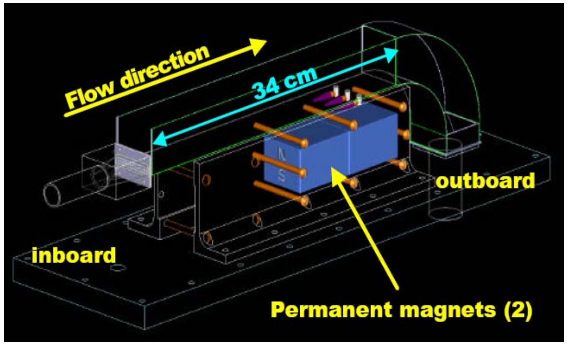
A word on M-TOR scaling…

$$\frac{B_{M-TOR}}{B_{NSTX}} = 1.9, \frac{U\delta_{Li}}{U\delta_{Ga}} = 3.41$$

- GaInSn flow in M-TOR is used to simulate Li flows under the NSTX outboard divertor conditions
- Matching of Hartmann Number, Reynolds Number and Froude Number







M-TOR Magnetic Fields

Distance away from nozzle inlet (cm)	B_x (axial), Tesla	B_y (toroidal), Tesla	B_z (surface normal), Tesla	$\lvert\vec{B}\rvert$, Tesla
0.4	0.023	-1.121	-0.019	1.121
2.94	-0.003	-1.068	-0.021	1.068
5.48	-0.009	-1.015	-0.026	1.015
8.02	-0.012	-0.964	-0.029	0.9645
10.56	-0.01	-0.918	-0.024	0.918
13.1	-0.034	-0.876	-0.03	0.877
15.64	-0.068	-0.837	-0.052	0.841
18.17	-0.135	-0.799	-0.152	0.824
20.72	-0.101	-0.771	-0.262	0.820
23.26	-0.074	-0.738	-0.297	0.799
25.8	-0.038	-0.712	-0.306	0.776
28.34	-0.019	-0.685	-0.314	0.754
30.87	0.047	-0.656	-0.32	0.731

Test Section- I

- Understand the effect of the different magnetic field components and the field gradients on the liquid metal film flow on conducting substrates. Understanding individual effects…!!!
- To help provide insights into the design of Test Section-II (better simulate the NSTX Li flow environment)

Experiment Details (Test Section-I)

- All experiments were performed at zero inclination to the horizontal (NSTX ~ 21.5^0, M-TOR ~ 1.85^0)

- Liquid flow from inboard towards outboard

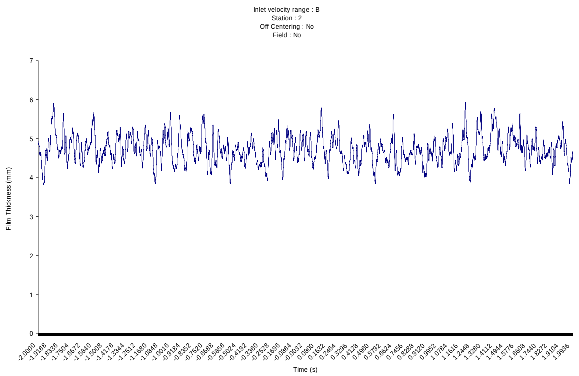
- Three different inlet velocity ranges were tested
  - Range A (1.2 – 1.3 m/s @ 2.5mm) corresponding to an NSTX Li flow (5.3 m/s @ 2mm)
  - Range B (1.7 – 1.8 m/s @ 2.5mm) corresponding to an NSTX Li flow (7.0 m/s @ 2mm)
  - Range C (2.2 – 2.3 m/s @ 2.5mm) corresponding to an NSTX Li flow (9.6 m/s @ 2mm)

- Four magnetic field scenarios
  - No magnetic field
  - Toroidal magnetic field only (electromagnetic coils, no permanent magnets)
  - Surface normal field only (permanent magnets, no field from coils)
  - Combined surface normal and toroidal fields

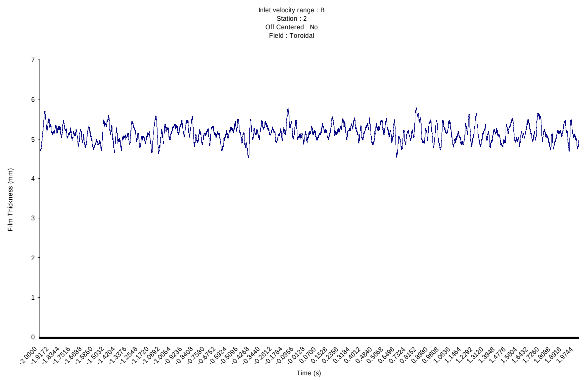
Experiment Details (continued)

- Three stream-wise measurement stations (Inductive Probes)
  - Station 1 : 2 cm from inlet nozzle (strong toroidal component)
  - Station 2 : 14 cm from inlet nozzle (gradient location)
  - Station 3 : 26 cm from inlet nozzle (strong surface normal component)
- Span-wise off-centering (Three configurations)
  - Configuration A : All center
  - Configuration B : Off center Right (wrt flow direction)
  - Configuration C : Off center Left (wrt flow direction)
- A 4 s voltage signal from the inductive probes was sampled using a digital oscilloscope. This technique also captures the fluctuations in the flow, the standard deviation of the 10,000 digitized voltage points can give an idea of the free surface fluctuations

Inductive probe traces at a particular location for the four different magnetic field scenarios



No Field

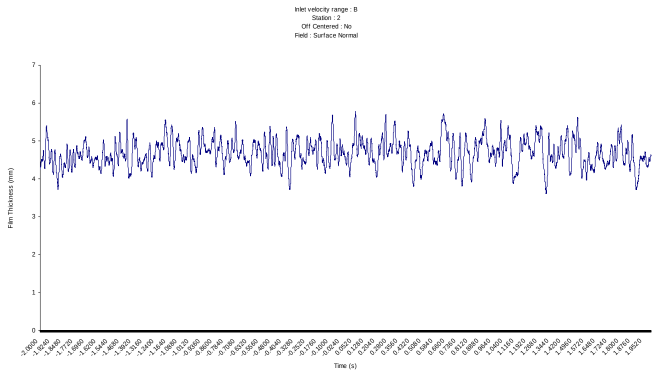


Toroidal Only

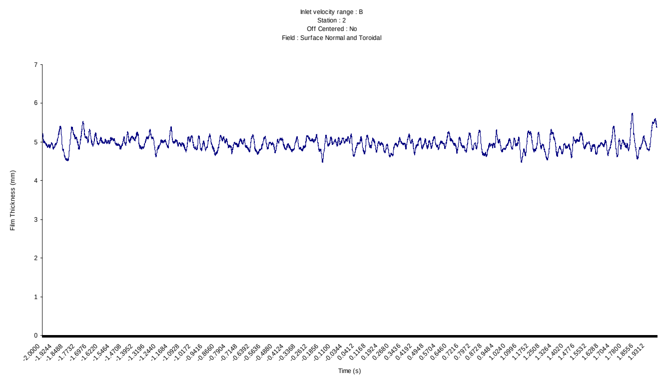
Station 2

Centered

Velocity range B



SN Only

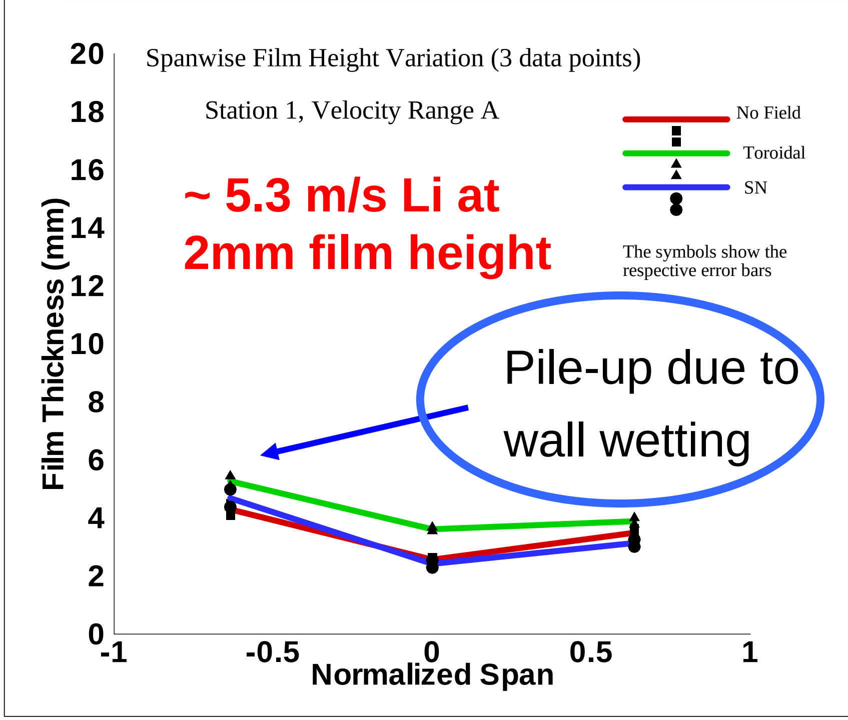


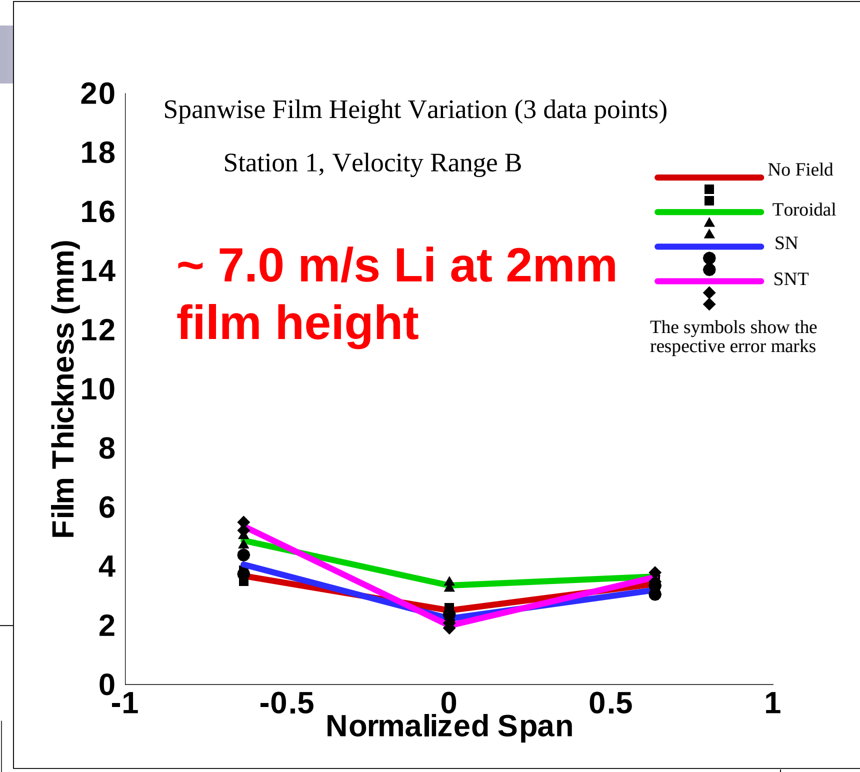
Combined SNT

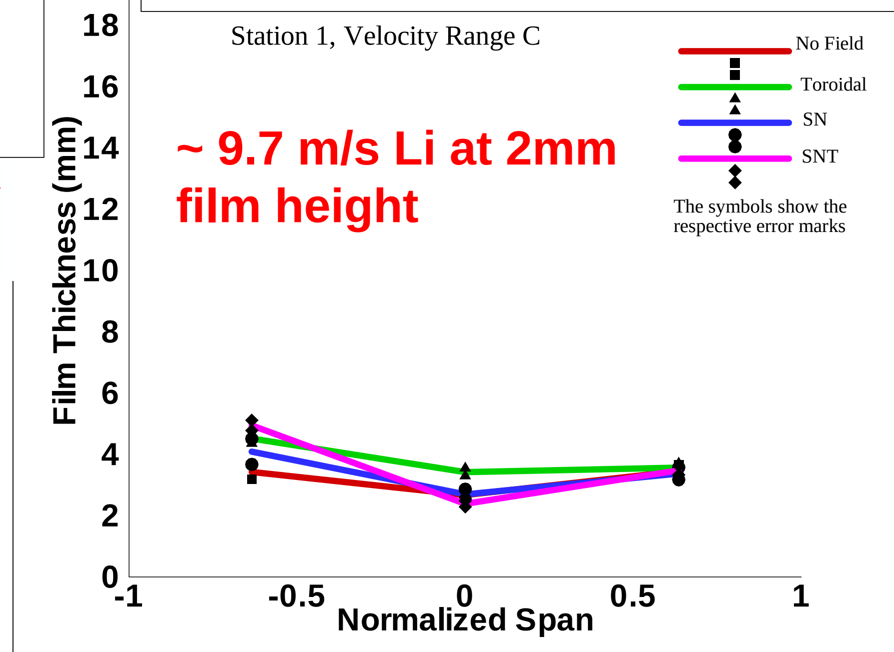
Experimental Findings (Important Effects)

- MHD pressure drop (MHD braking), typical drop in the average inlet fluid velocity on turning on the magnetic field is between 20-30%
- MHD braking gives rise to a critical velocity below which the liquid metal flow becomes stagnant in the channel and fills it up, this was estimated to be around 5-6 m/s for Li flow under NSTX outboard divertor conditions
- There is a significant thickening of the liquid film as the flow progresses downstream, typical increase in the film thickness over the entire length of the channel ranges from **x**3 – **x**6 (velocity dependent)
- The flow thickening is non uniform in the span-wise direction (No toroidal uniformity)
- Significant wall effect is observed
- The free surface structure is significantly modified by the toroidal magnetic field, while the surface normal field alone doesn't have much effect

Span-wise Film Height Characteristics for Different Operating Conditions







30% reduction in velocity when toroidal field on

Station 1

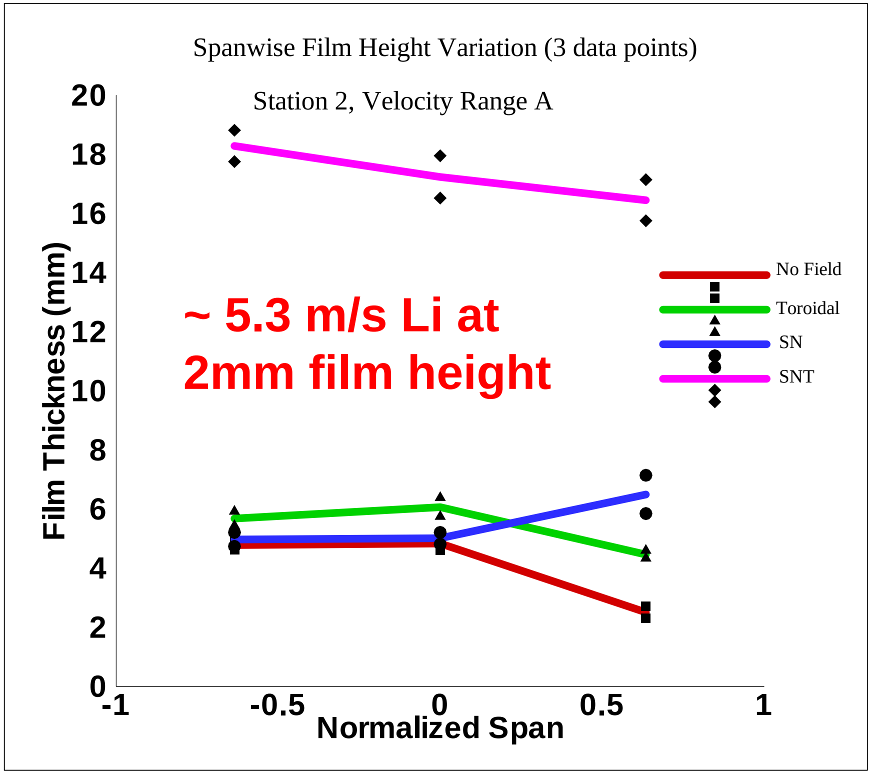
All Velocity Ranges

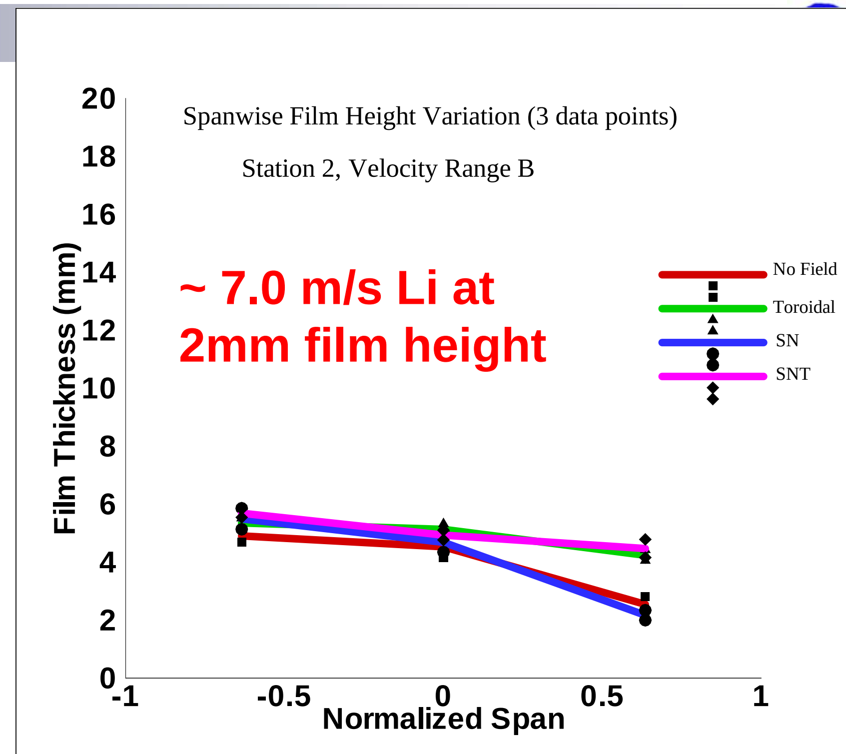
All Scenarios

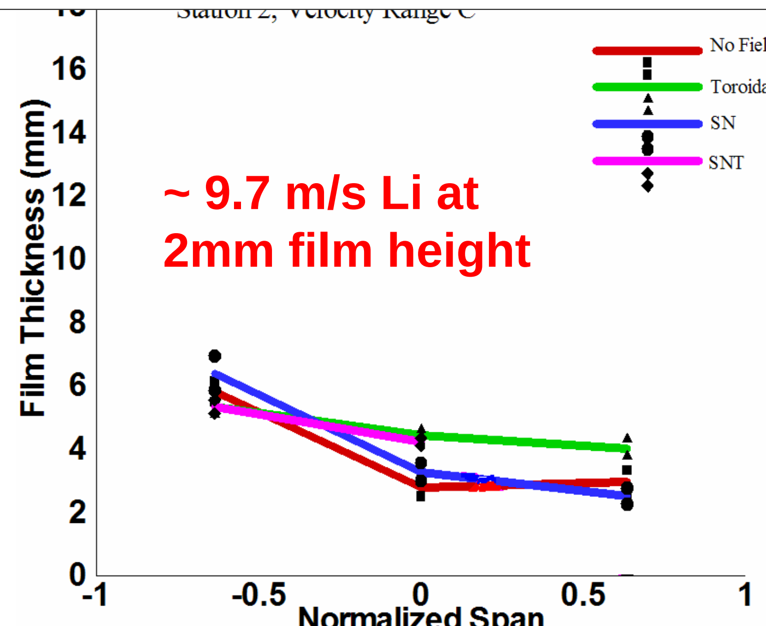
Toroidal Field : 1.08 T

Surface Normal Field : 0.01 T

Span-wise Film Height Characteristics for Different Operating Conditions

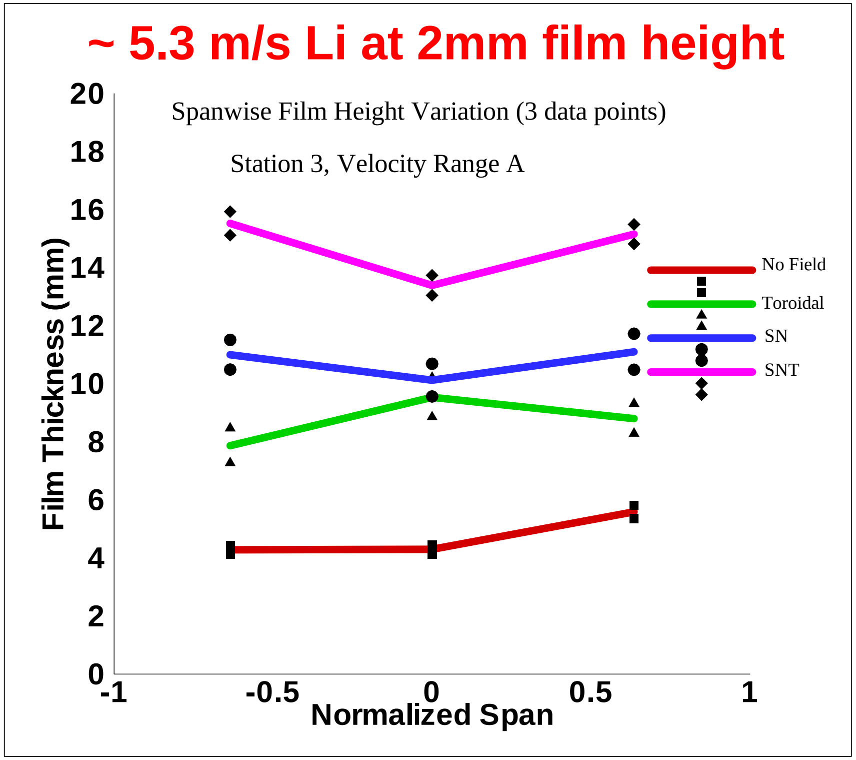


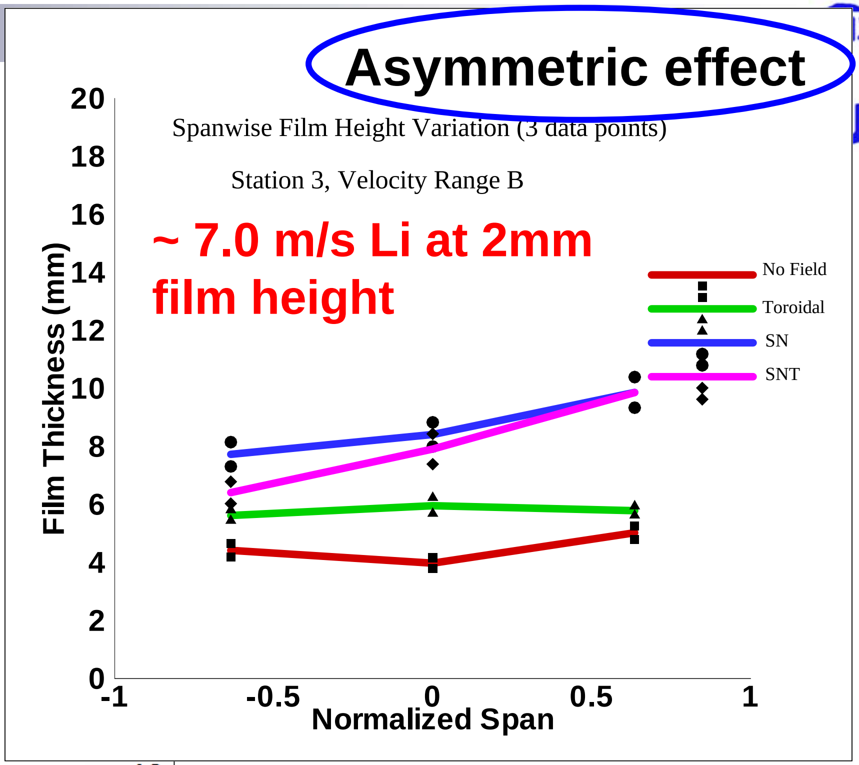


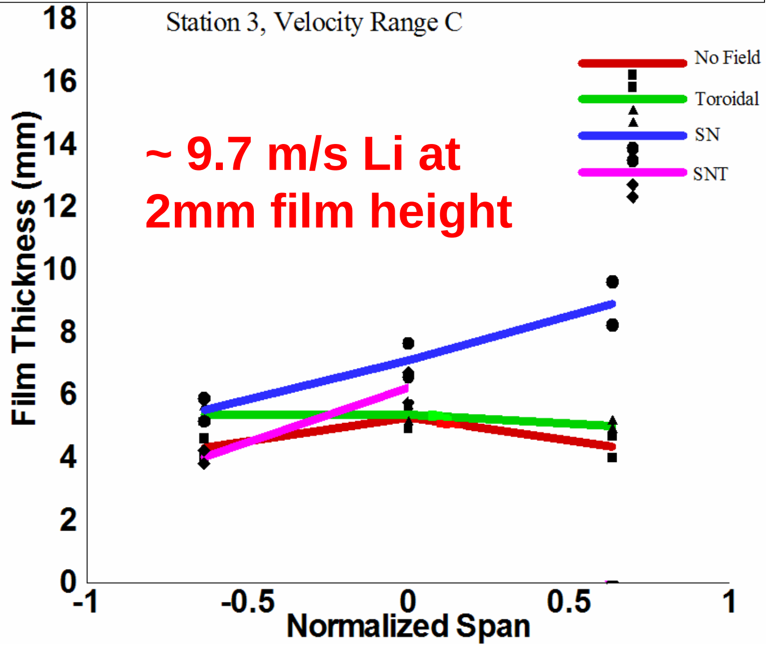


Station 2
All Velocity Ranges
All Scenarios
Toroidal Field : 0.86 T
Surface Normal Field : 0.04 T
SN gradient : 0.025 T/cm

Span-wise Film Height Characteristics for Different Operating Conditions





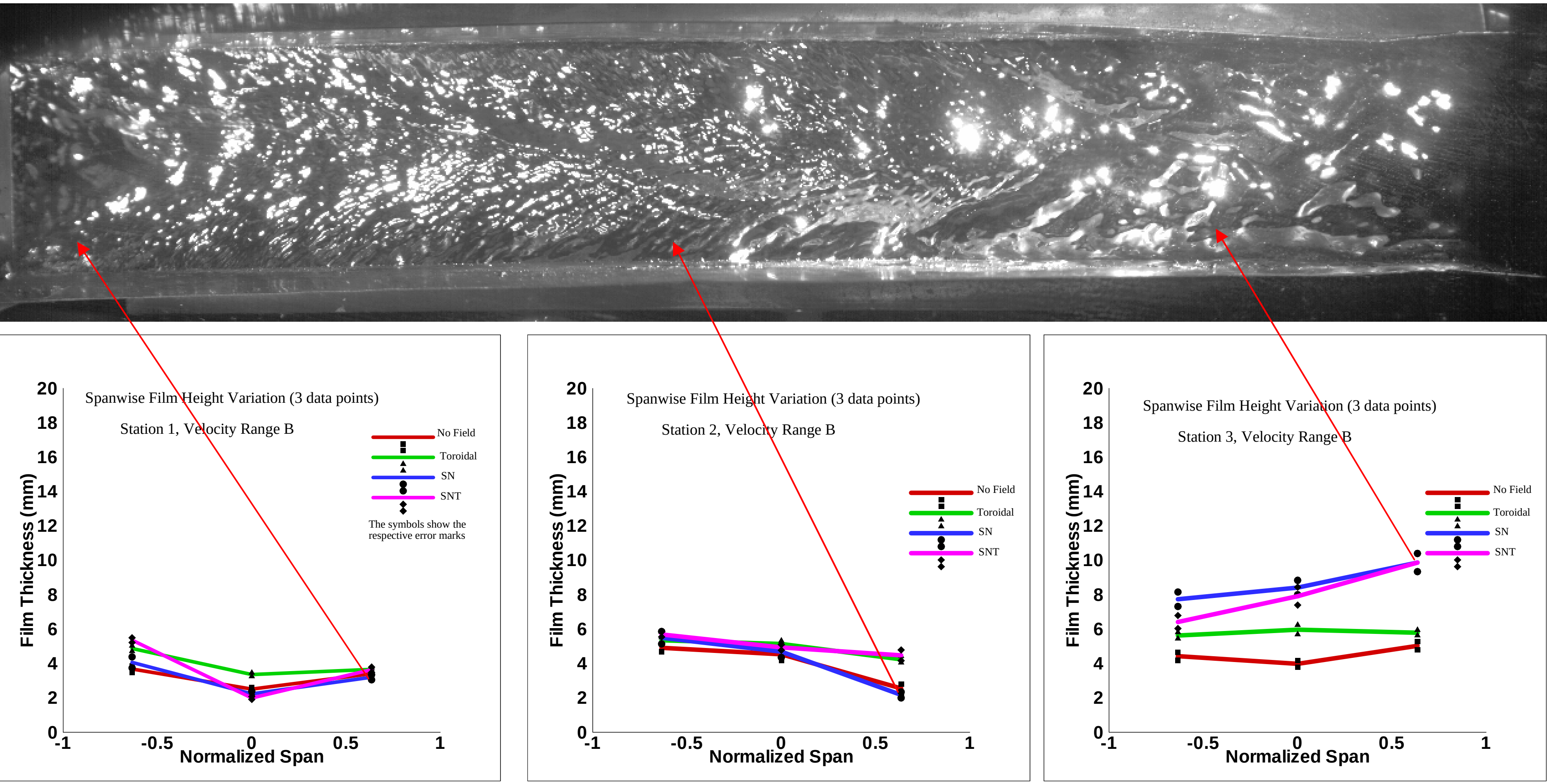


Station 3
All Velocity Ranges
All Scenarios
Toroidal Field : 0.7 T
Surface Normal Field : 0.3 T

Stream-wise and Span-wise film thickness variation

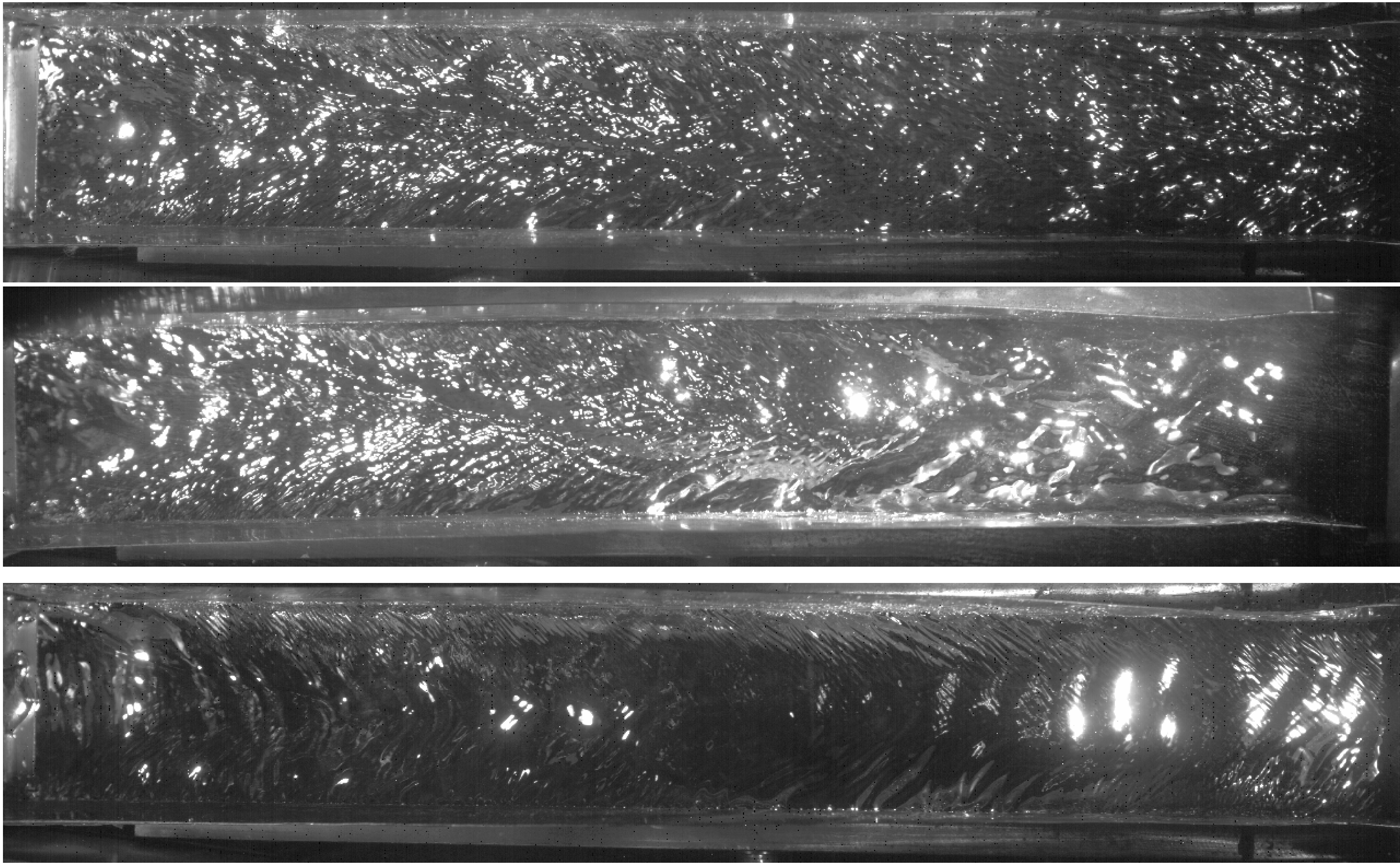
Only Blue !!

Surface Normal field alone, Inlet velocity : 1.8m/s



Free Surface Structure

No Field, SN alone, T alone Inlet velocity : 1.8 m/s



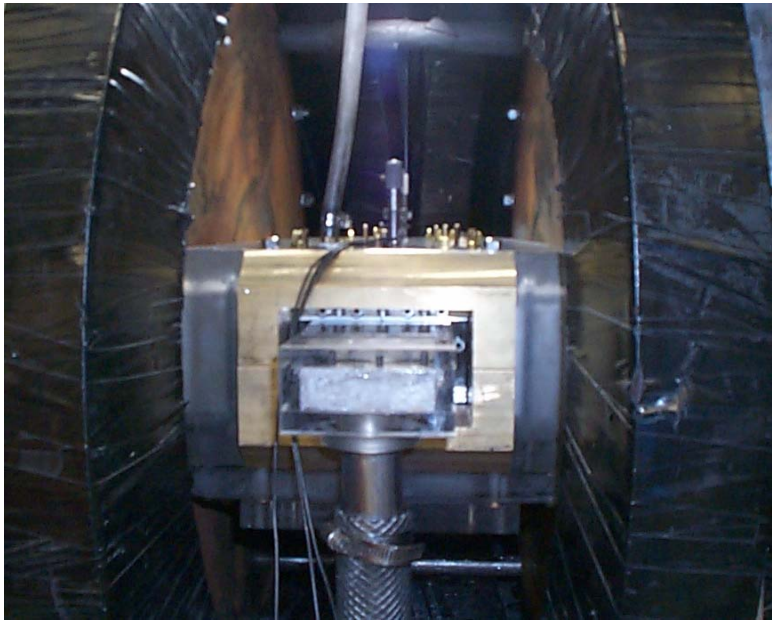
Test Section-II

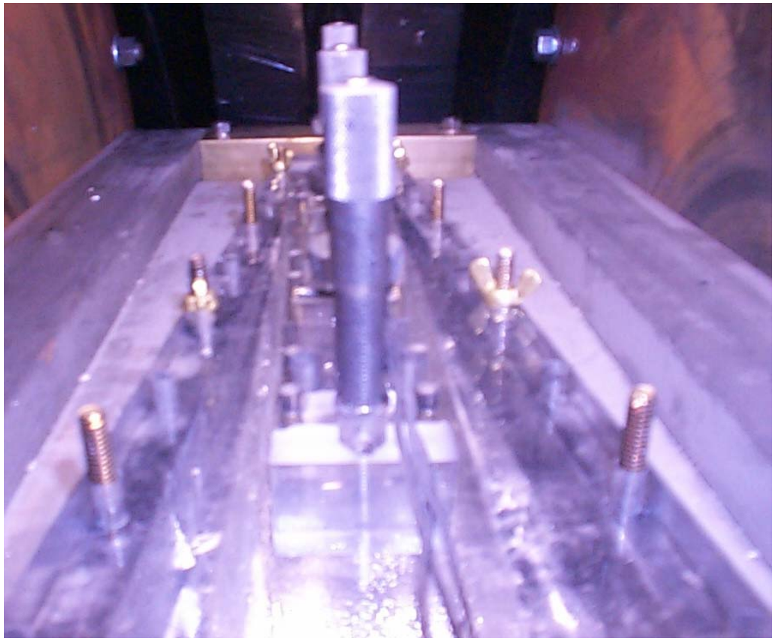
- To get as close to the NSTX outboard divertor lithium flow conditions as possible
- We are good with the flow length, the magnetic field condition. We still have the width problem
- The experiments will be performed at an inclination of 1.85^0 (corresponding to 21.5^0 for Li flow)
- Emphasis will be given to the study of the effect of transient magnetic field conditions coming from the pulsed operation of the machine (M-TOR current ramp up time is of the order of 1 sec)

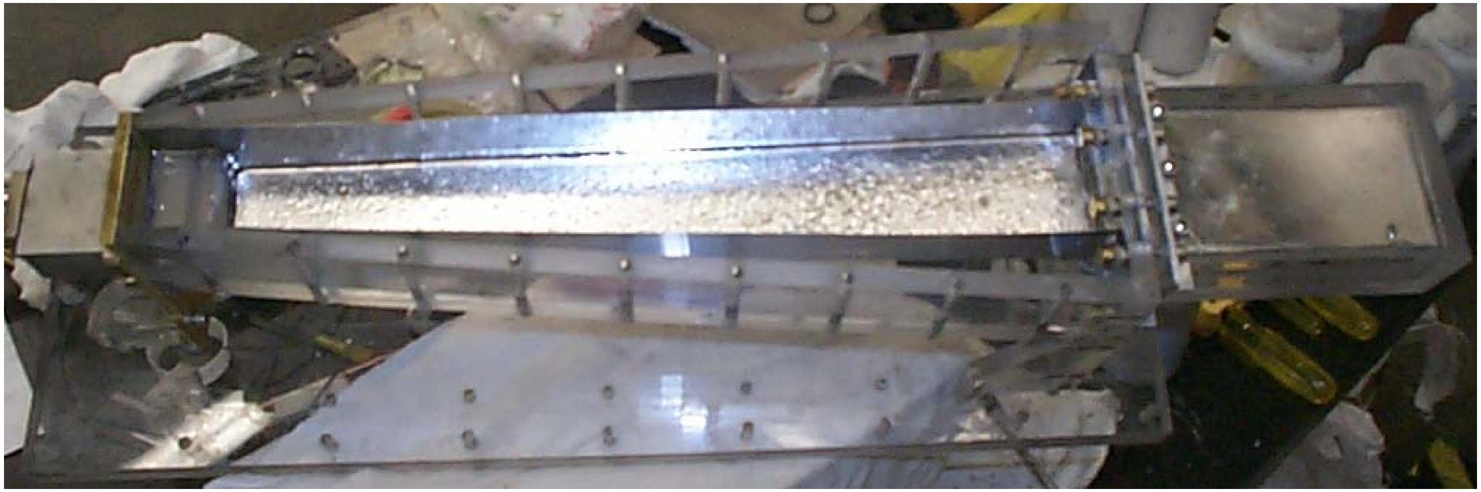
Test Section-II (Features)

- Its longer (45 cm flow path compared to 34 cm at present)
- Downstream area expansion (5 cm inboard to ~8 cm at outboard)
- A new surface normal field set up with 8 permanent magnets over the entire length of the channel (No spurious gradients)
- Smoother flow
- Still looking for a better diagnostic

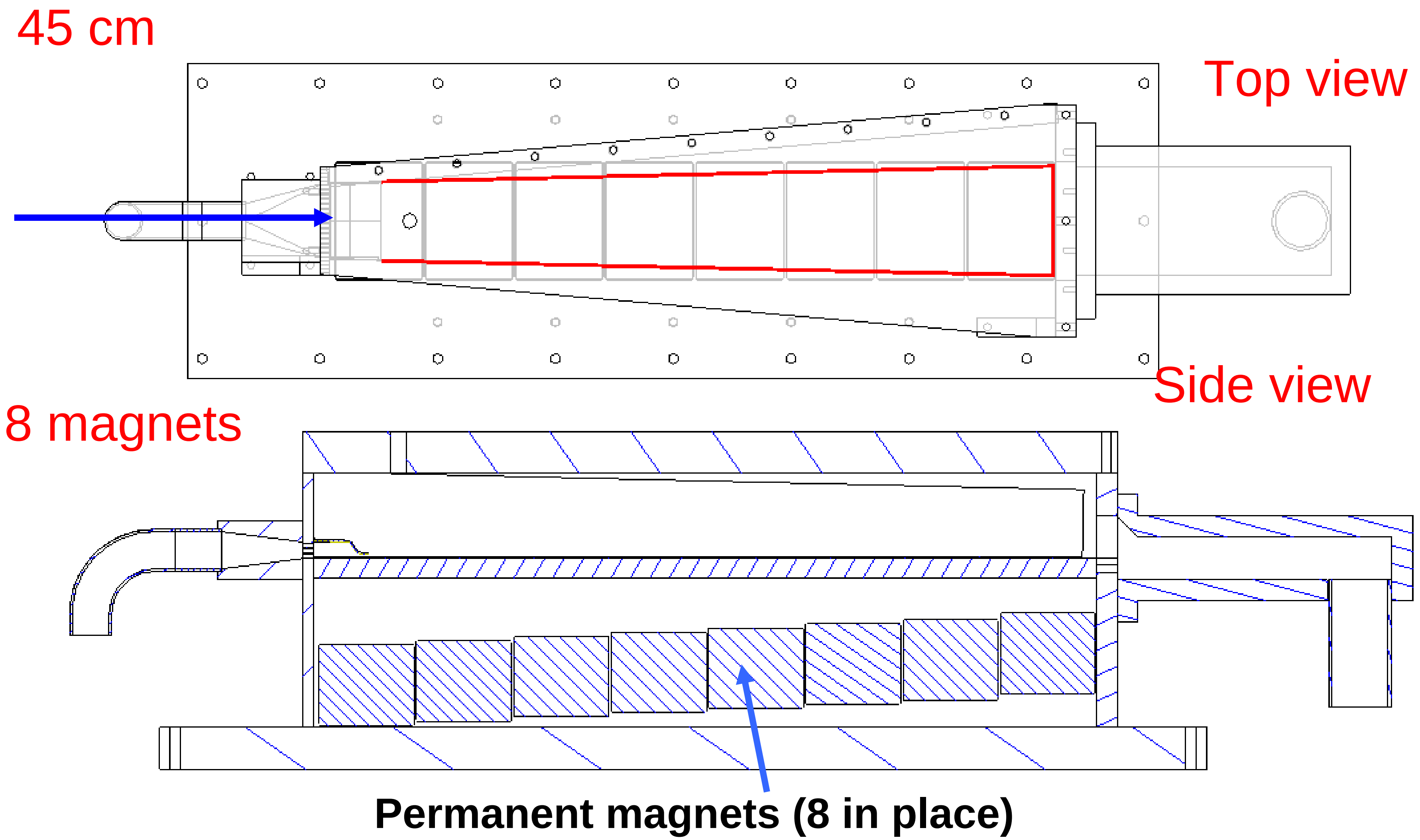
Test Section -II





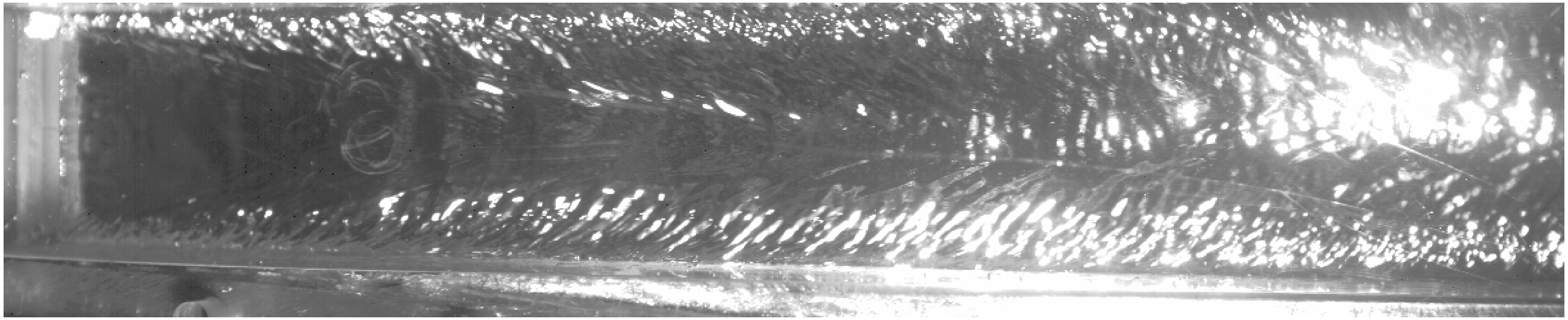


Test Section –II (Magnetic Field System)

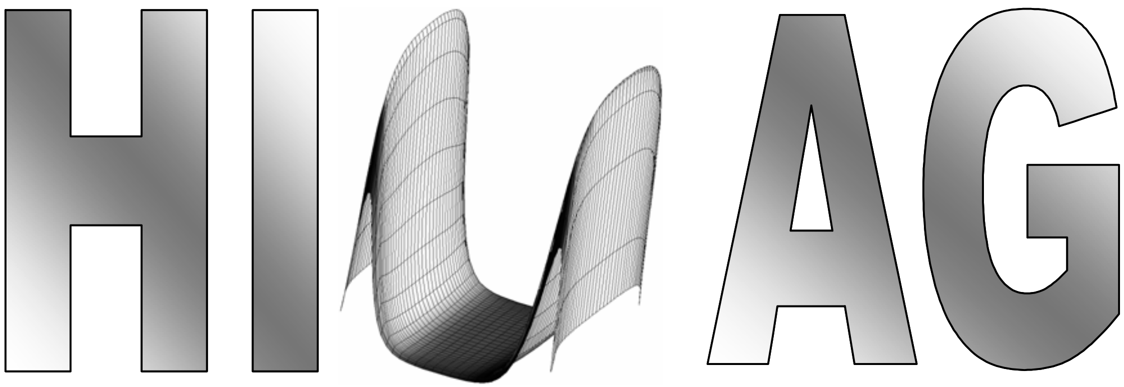


Test Section –II (First Run)

- We’ve just had one run last week without the permanent magnet set up (both with and without the toroidal field)
- No field run (channel is much more well behaved)
- Toroidal only run (no appreciable flow thickening in the stream wise direction)
- Span-wise variation of film thickness still present (not quantified yet)
- We do see significant wall effect



Numerical Modeling

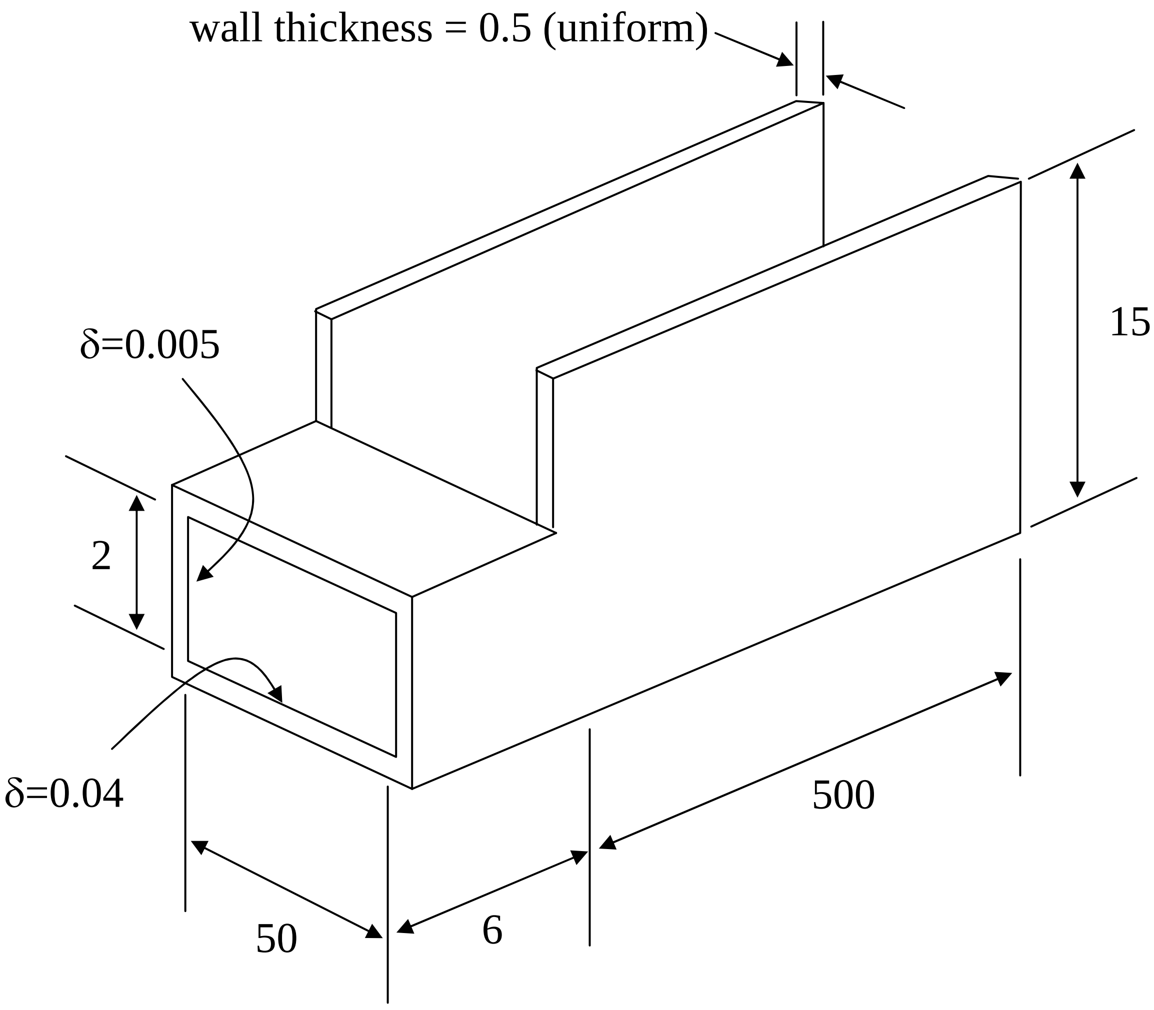


HIMAG is being used to model the M-TOR free surface film flow experiments

Numerical Modelling

- Over the summers, i did a couple of closed channel runs at different Hartmann numbers (Sterl Problem) with insulated channel walls
- Conducting wall capability has been perfected by HyPerComp off lately, Free surface tracking using the level set method has been perfected as well using a mass conserving constraint during re-initialization
- We ‘r GO for M-TOR liquid metal free surface simulations with conducting walls…

M-TOR free surface case (conducting and insulating walls)

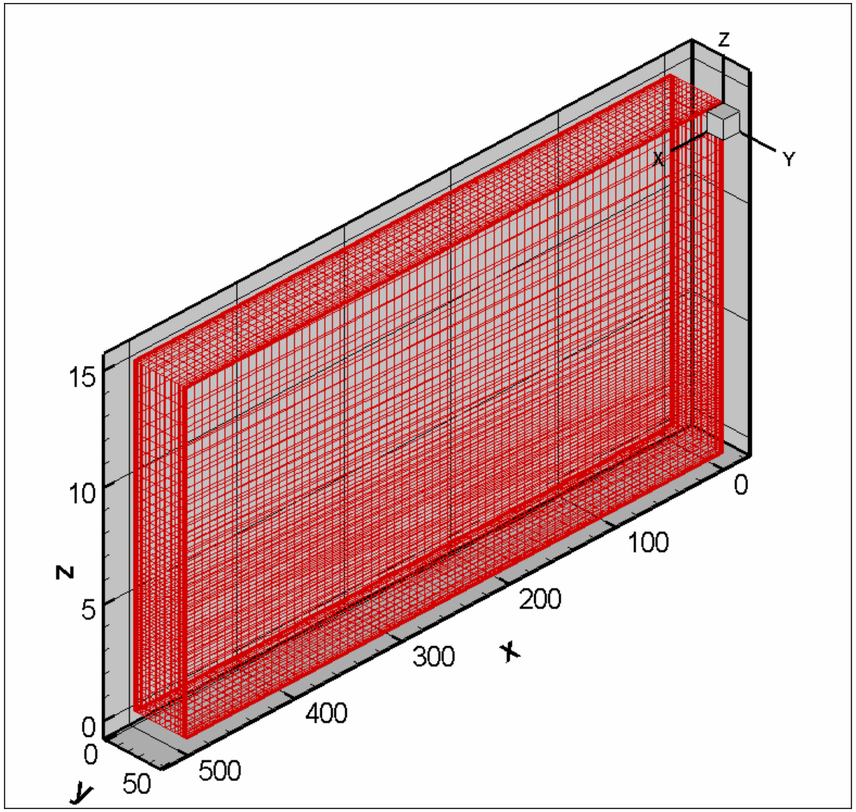


Computational mesh uses 550,000 cells and 566,000 nodes

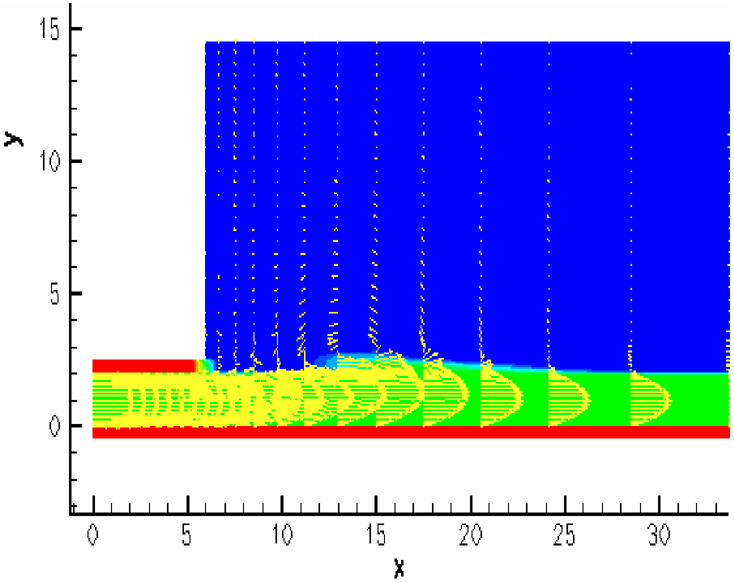
Mean flow velocity = 2.25 m/s
bi-parabolic profile assumed

Ga-In-Sn fluid, steel wall
3-D magnetic field applied as per measured B distribution

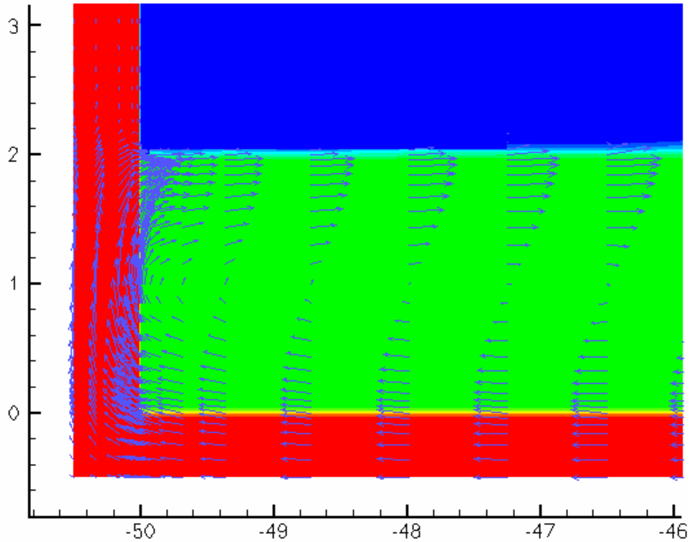
Some Details



Mesh for the Insulated walls case



Velocity Vectors



Current Vectors at a section
x = 15mm

Current Status

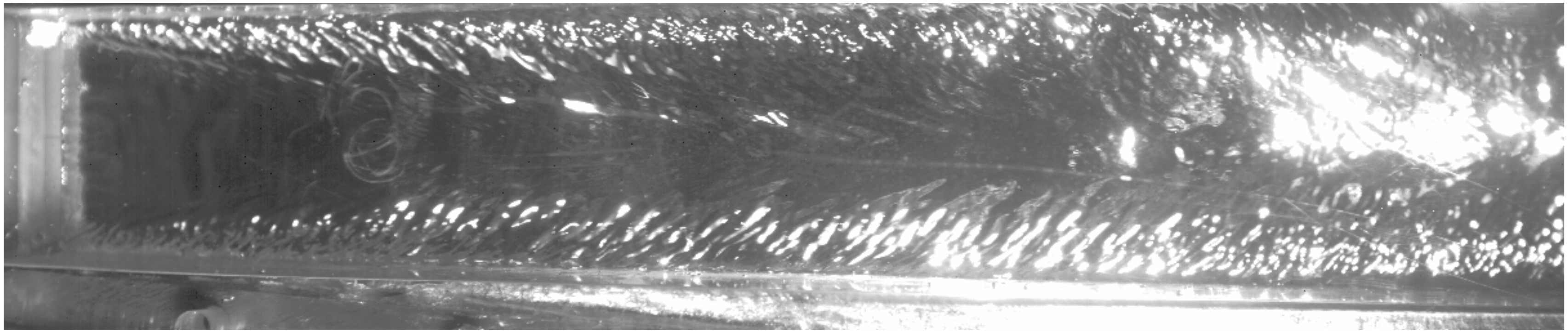
- The conducting wall free surface case is being run at HyPerComp by Dr. Munipalli on 16 processors (We don't have the latest results yet)
- I am running the insulated wall free surface case at UCLA (single processor, 'coz all our nodes are being used for the DiMES run) It should be spewing results soon
- I am also working on implementing a thin conducting wall formulation in HIMAG with the help of Dr. Munipalli and Dr. Ni

What's the current word on Module B

- It appears, its possible to establish liquid metal film flow on a conducting substrate under NSTX outboard divertor magnetic field conditions (if the inlet velocity is above some critical value)
- The current experiments show a significant pile up of the liquid towards the outboard (attributed mainly to the strong surface normal field present)
- The maximum increase in the film thickness for the three velocity ranges at the outboard is as follows
  - **Range A : X 6.2 (corresponding to 5.3 m/s of lithium flow at 2 mm initial film height)**
  - **Range B : X 4 (~7.0 m/s of lithium flow)**
  - **Range C : X 3.5 (~9.7 m/s of lithium flow)**
- Under the simulated conditions, the film thickness is quite uneven with significant stream-wise and span-wise variation

The effect of channel width

- Current test article is much narrow compared to NSTX LSM size of ~40 cm wide (if it would be a module)
- Its difficult to make predictions on the MHD effects in wider channels because our current results are “contaminated” by the strong wall effect
- We need to go for wider sections for a full understanding of the phenomenon. We’ll be helped by HIMAG modeling in this endeavor



Thank you…

Questions for me / Dr. Morley