MTOR Experiments for the Liquid Surface Module

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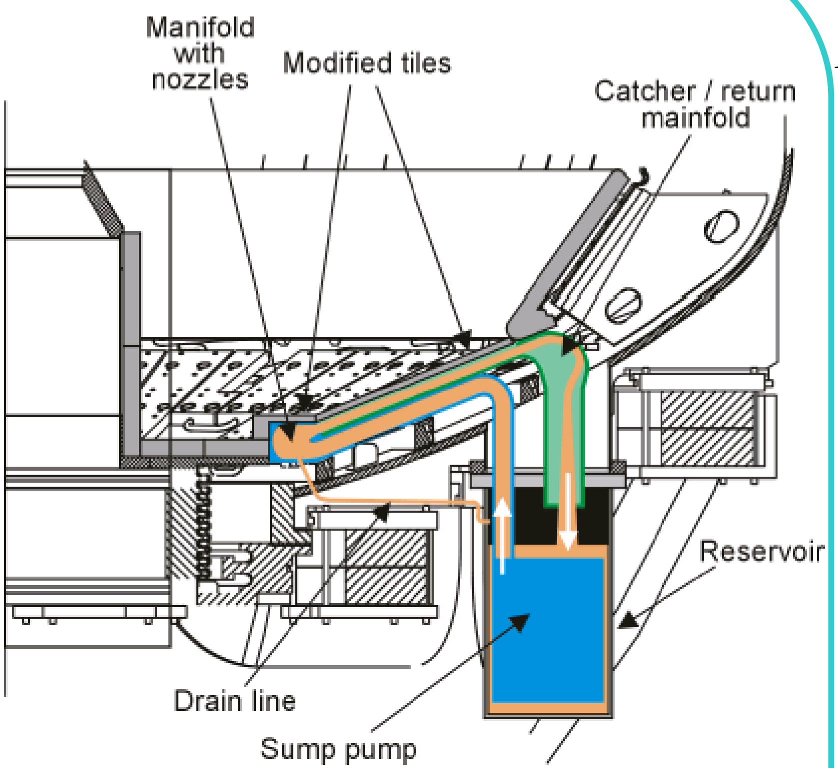
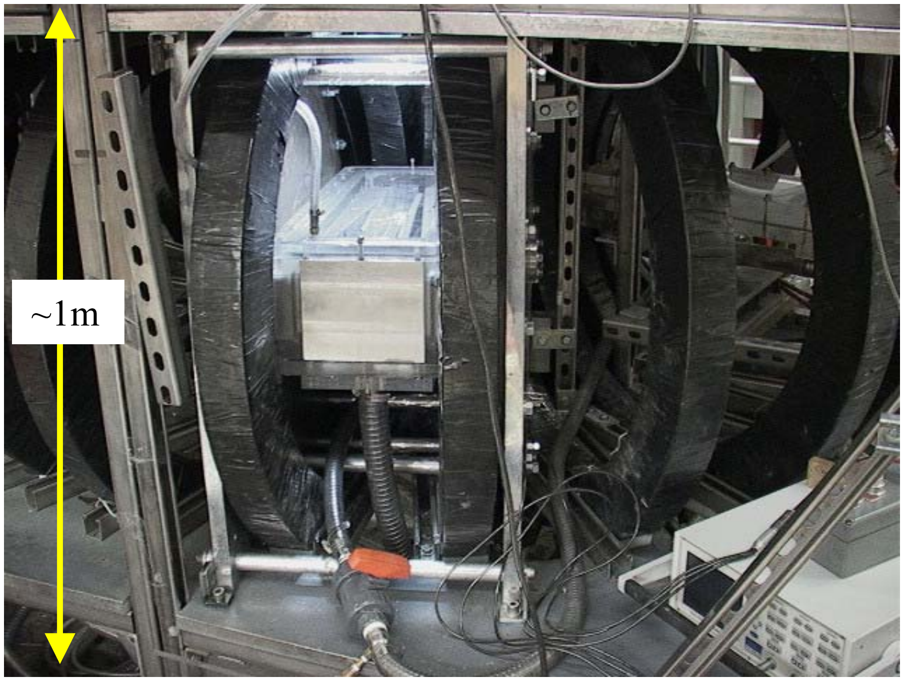
Experimental Investigation Tailored for Flowing Film Concept Evaluation



The concept: **NSTX Lithium Free Surface Module (ORNL)**

$$Fr = \sqrt{\frac{u^2}{g \sin \theta L}}$$

	NSTX	MTOR
Θ	21°	1.85°
u(m/s)	10	3
Fr	7.95	7.95

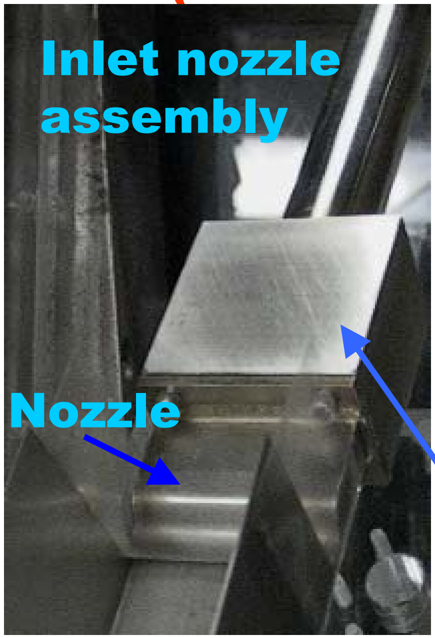


MTOR experimental set-up for NSTX film flow concept evaluation

Electrically Conducting Walls Test Article Fabricated from Stainless Steel

Stainless steel walls conducting channel

(5 cm wide/45 cm long) steel wall thickness: 0.5 mm

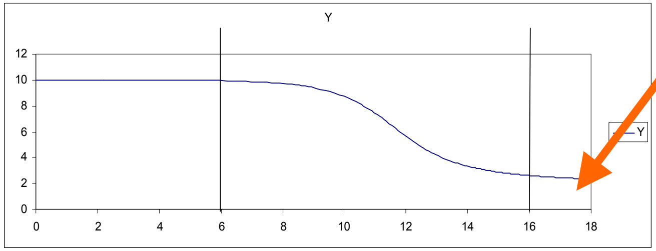


$$c = \frac{\sigma_w t_w}{\sigma_f a} = 0.0067$$

'c' is the conductance ratio;

***a* = channel half-width**

Inlet manifold with perforated plate for uniform flow distribution



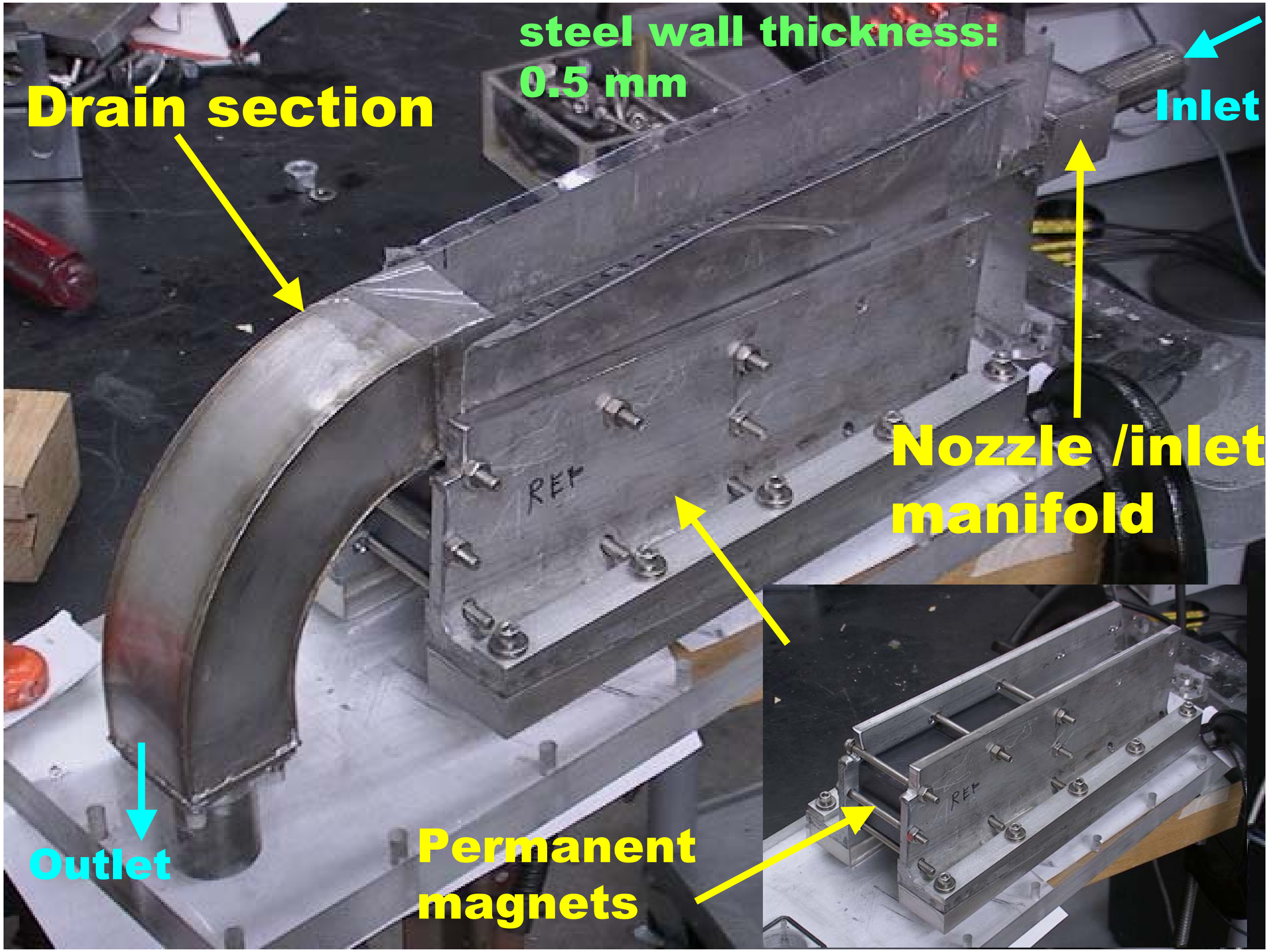
The entry nozzle profile

Exit = 2 mm

Contraction ratio: 5

Outlet assembly with cover plate to prevent Ga overshoot

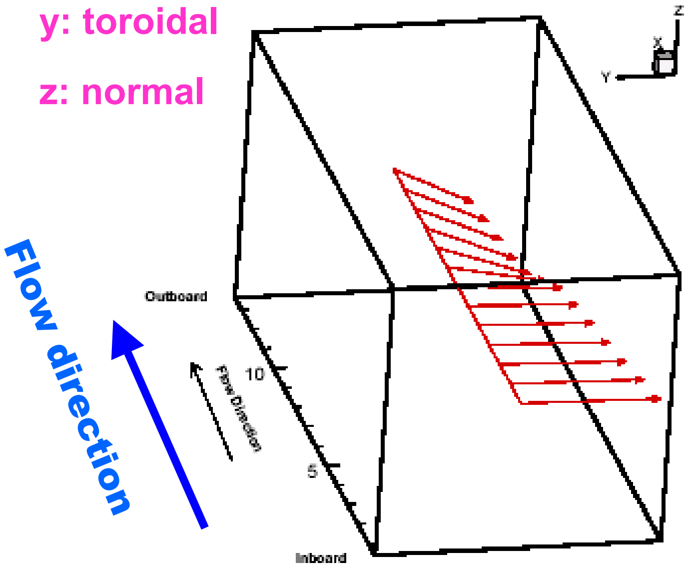
Stainless Steel Conducting-Walls Test Article with Permanent Magnets

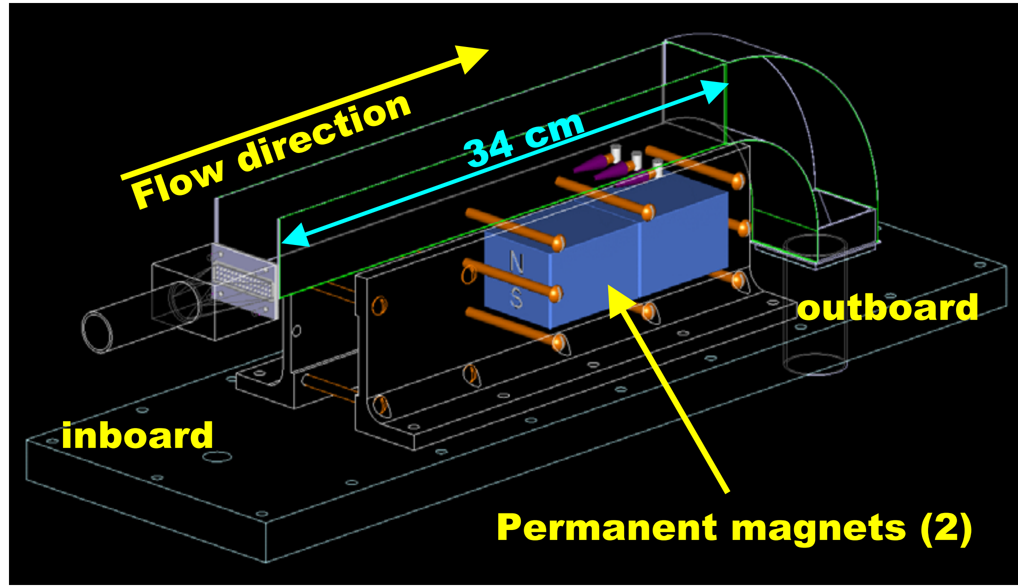


Conducting-Walls Film Flow Test Article (schematic) and MTOR Magnetic Fields

x: axial (flow direction)
y: toroidal

z: normal





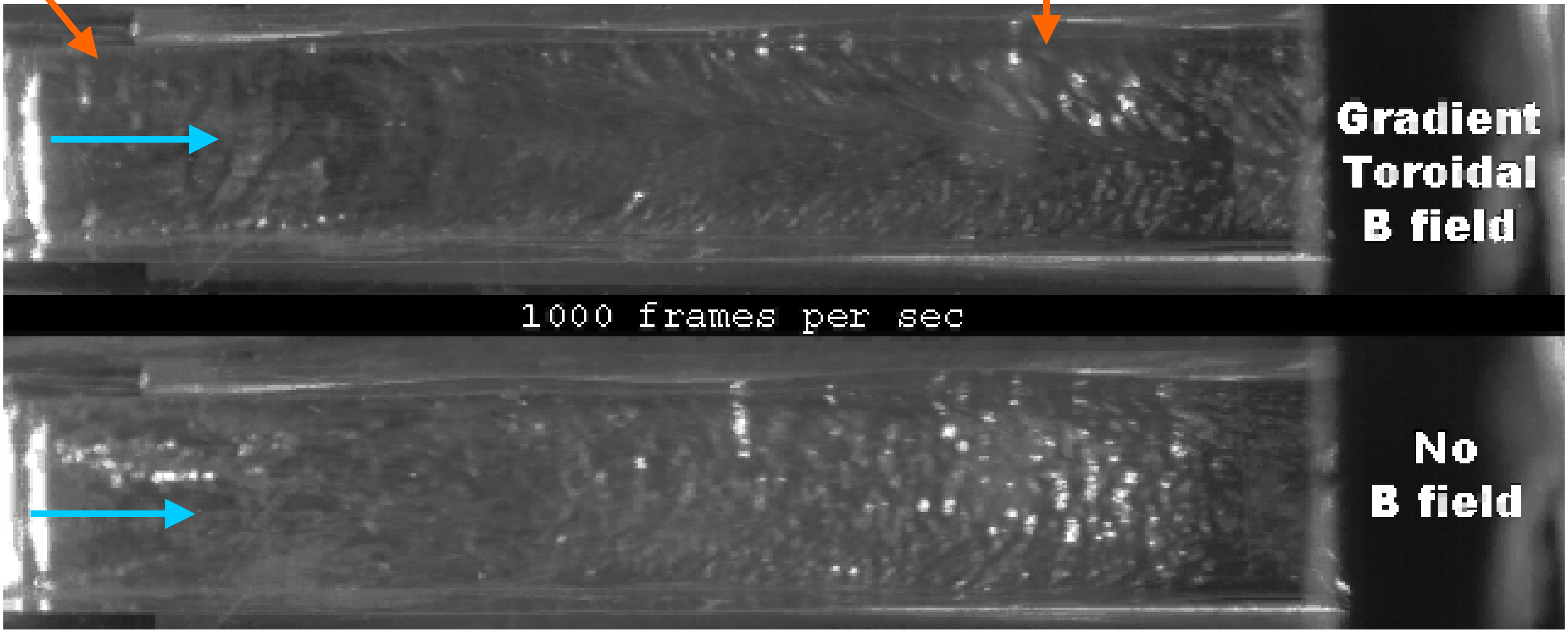
MTOR field vector plot to illustrate field direction and relative strength

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

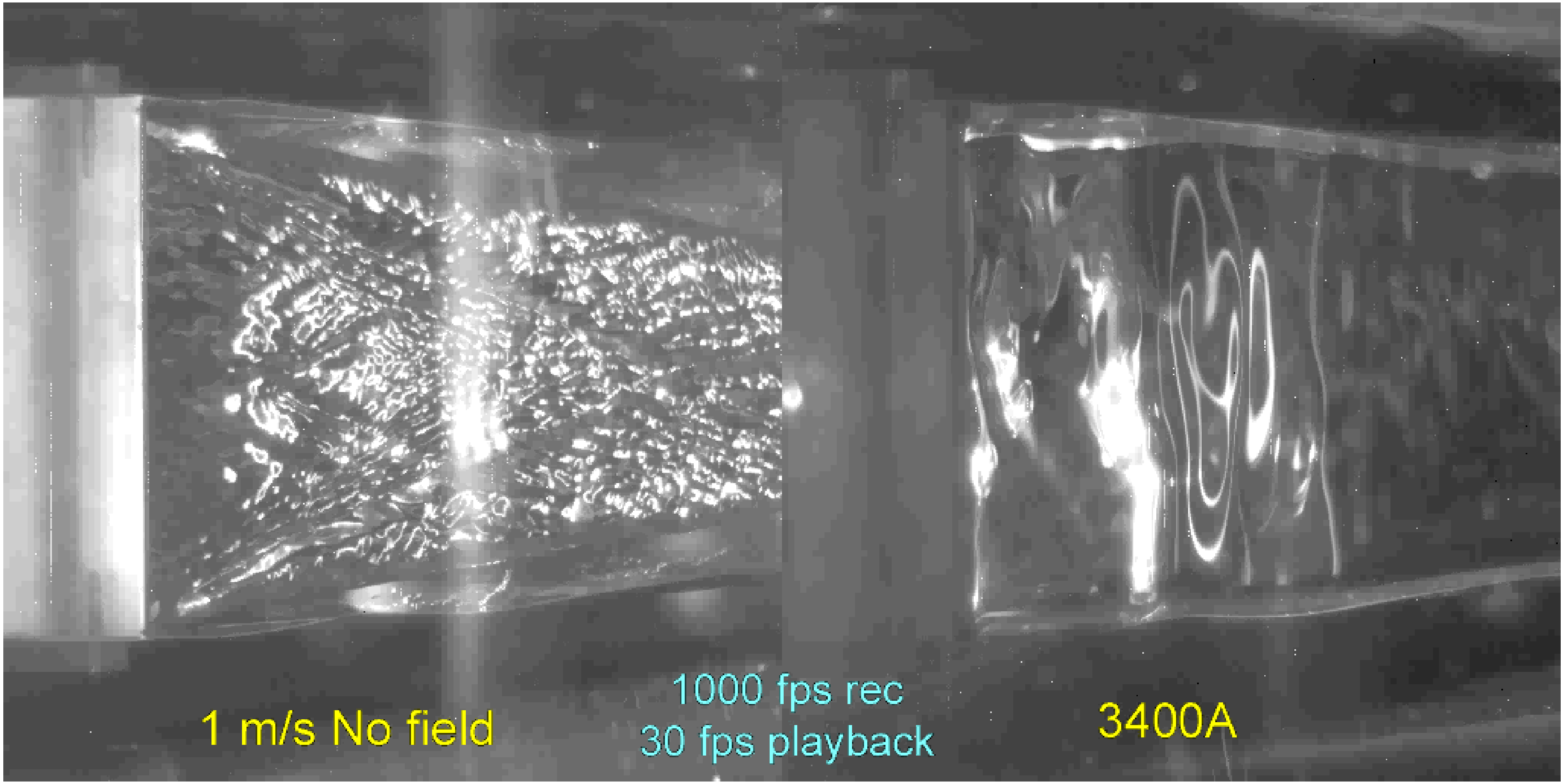
MHD LM (GaInSn) Film Flow Characteristics

(Gradient Toroidal Fields)

- Near the inlet, the MHD effect is the strongest, while the turbulence (normal to field) is quickly damped and the turbulent structures are markedly elongated in the magnetic field direction.
- The stretched 2-D turbulent structures begin to break down as Ga proceeds to the lower field regions (outboard).



Near nozzle closeup view showing different wave structure without and with toroidal field

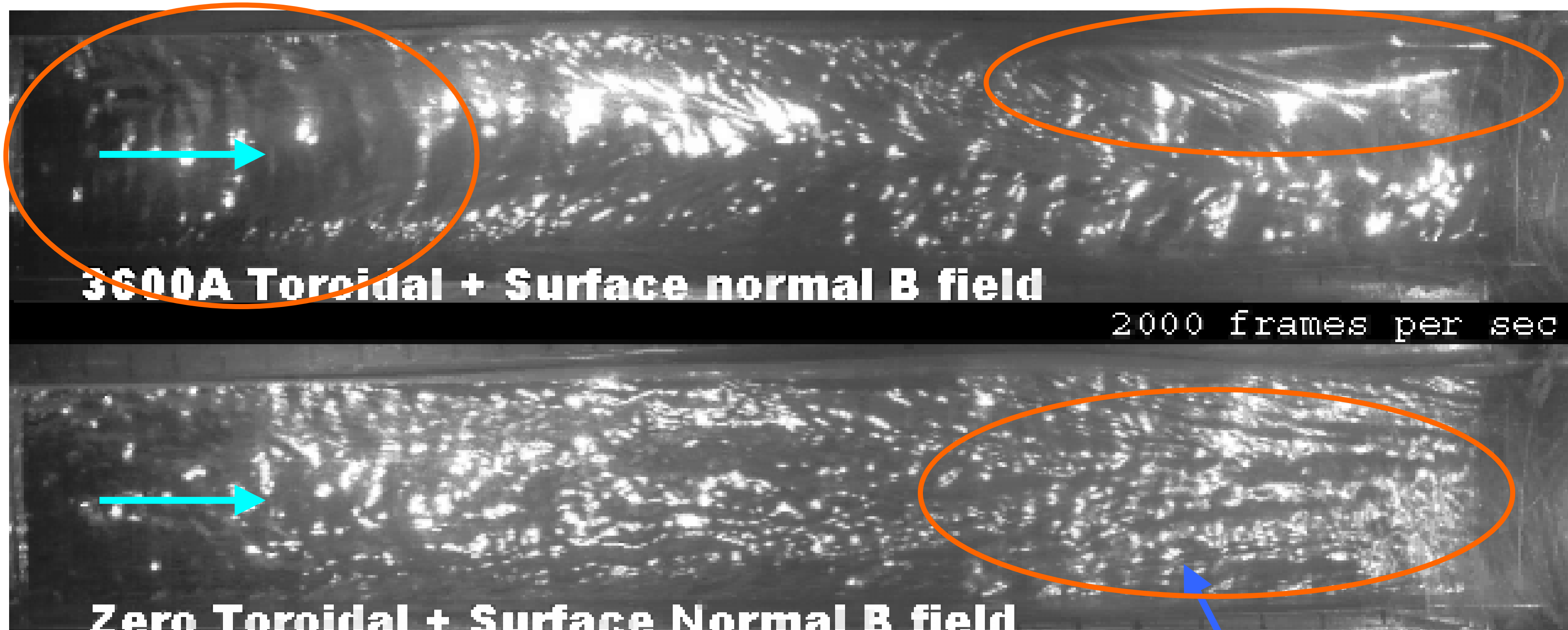


MHD LM (GaInSn) Film Flow Characteristics
(Surface Normal with/without Gradient Toroidal Fields)

- **Distinct wavy flow pattern appeared/observed as magnet field configuration becomes complicated** (inlet velocity 3 m/s)

2-D stretched-rolling waves

Ga flow appears thickened/frozen



0 4 8 12 16 20 24 28 32(cm)

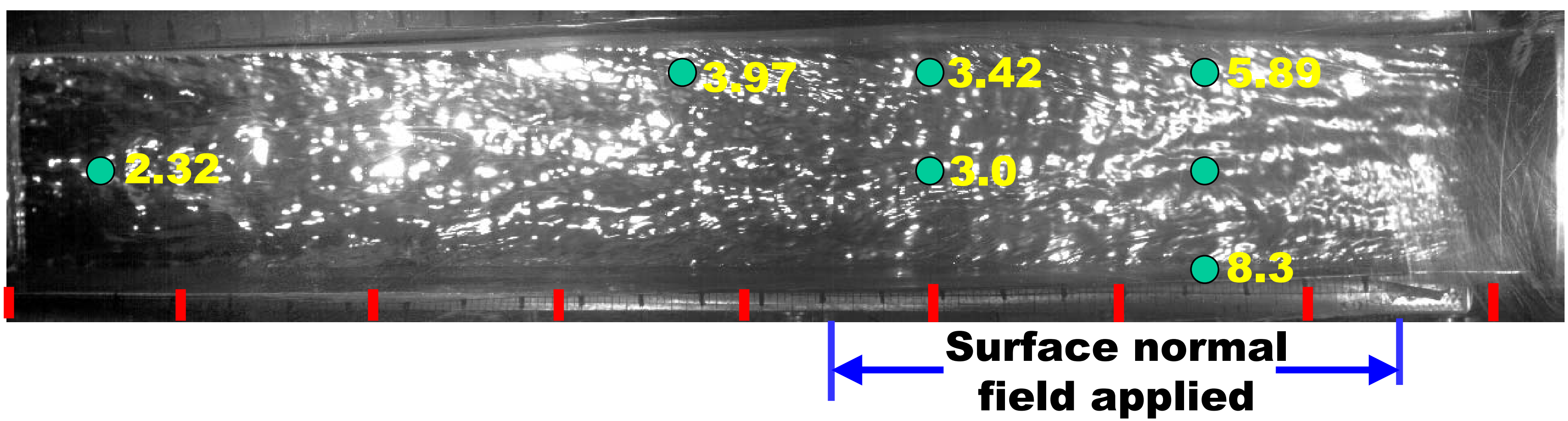
Surface normal field applied at ~18 cm downstream and increases from 0.15 T to 0.32 T (at 30.87 cm downstream) and 0T thereafter (see slide #3 for field values)

Significant damping force from surface normal field $\sigma V B_{\perp}^{2}$

Ultrasonic Film Height Transducers

- 7 ultrasonic film height transducers used
- Speed of sound for Ga alloy measured 2740 m/s
- Speed of sound for stainless steel measured 5400 m/s (a thicker and larger plate needed to differentiate time-of-flight)
- Ultrasonic transducers mounted directly touching Ga alloy
- Ga alloy oxidation results in no signal (cleaned Ga alloy)
- Turbulent fluctuation of liquid surface causes energy to be lost before the wave reflects back to sensor (loss of signal)
- Shown difficulties to use for high velocities such as 3 m/s

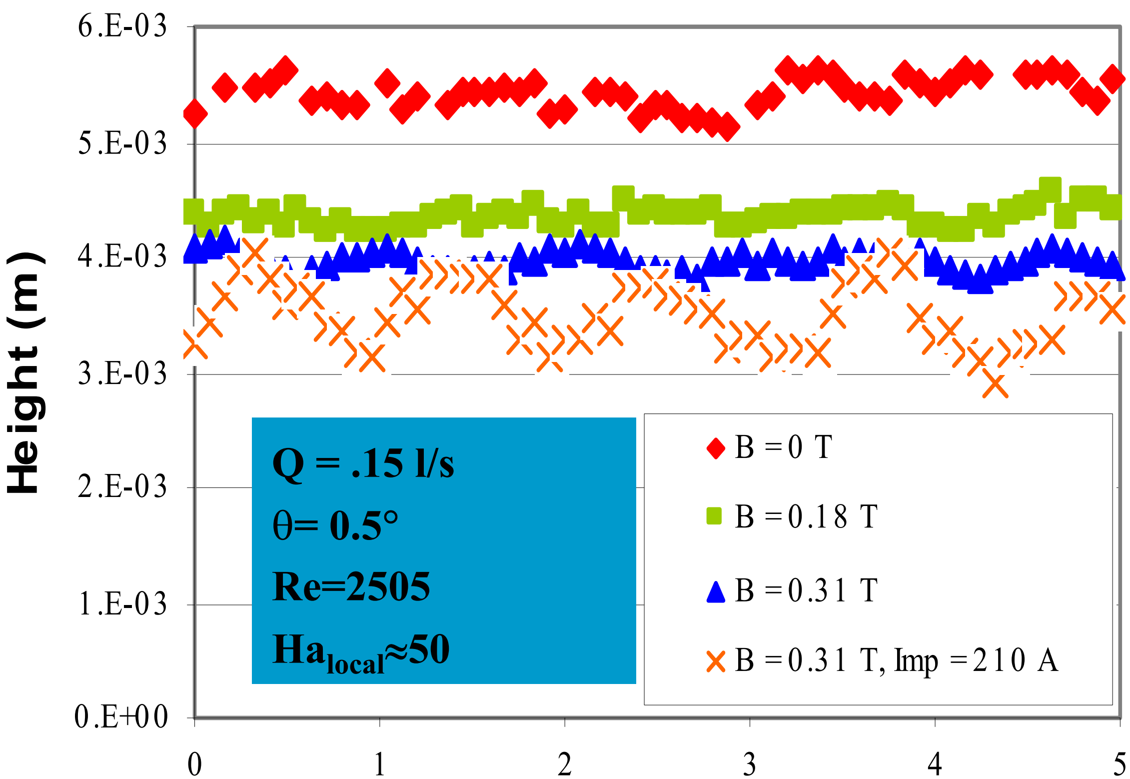
Unit: mm; inlet ga alloy velocity = 2.0 m/s



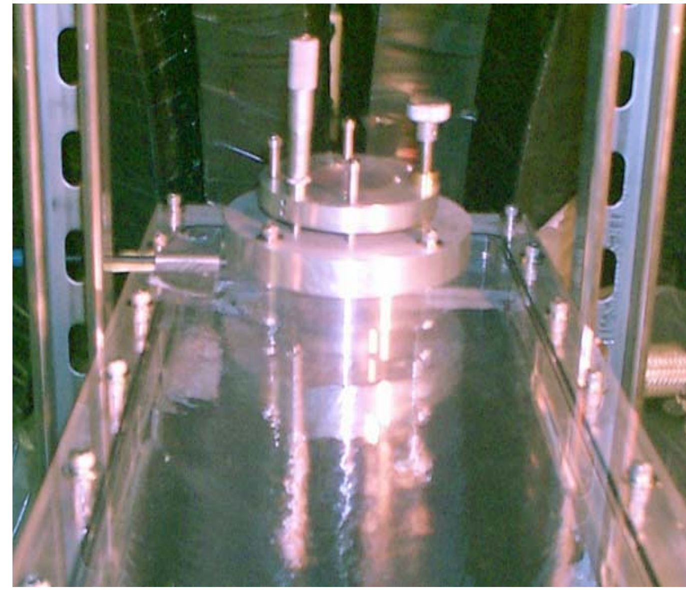
Magnetic propulsion effective, but data also shows some instability

APEX

2mm nozzle followed by hydraulic jump, Subcritical Flow



data from probe 4, 22 cm downstream from nozzle



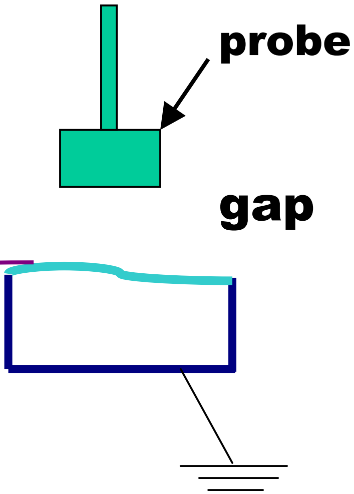
- B-field acts to laminarize flow – **Reducing flow resistance & surface waves**
- **Presence of magnetic propulsion current triggers surface wave with ~1 s period**

UCLA

Capacitance Probe Film Height Measurements

- **As a mean to measure film height at higher velocities(> 2.5 m/s)**

Principles of Operation



- The capacitive reactance is proportional to the spacing of a parallel-plate capacitor, which is made up of the probe and an electrically conductive measuring surface (Ga surface)
- As the distance varies due to the change of the film height, the capacitive reactance varies accordingly

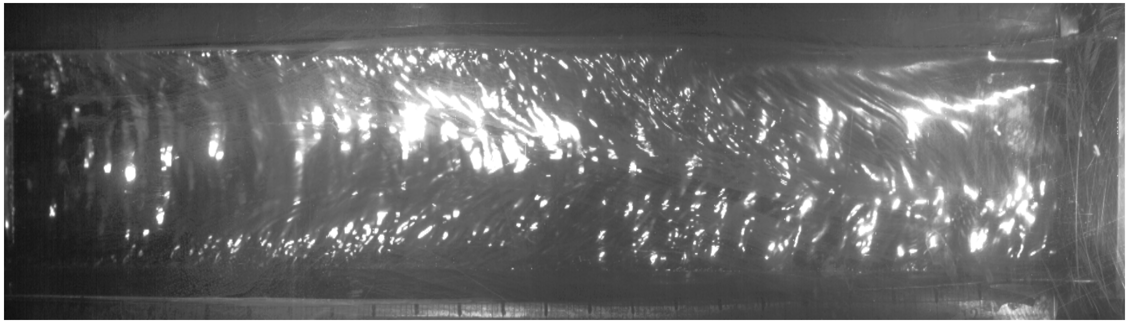
Results using in-house capacitive probe have obtained for static films

- However, those in house probes are meant to measure sub-millimeter gaps encountered in thermomechanics experiments. A different type, with a larger gap capability, will be needed for MTOR experiments.
- Inductive probes are also a possibility also

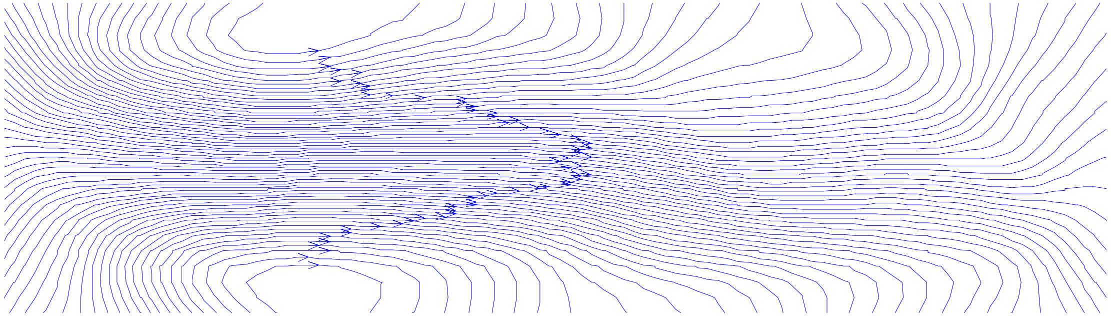
PIV and UVP free surface pattern tracking

Concept:

- Method for identifying liquid metal free surface flow patterns using Particle Image Velocimetery
- Light scattering associated with local free surface slopes can be cross-correlated to identify and track pattern at the surface
- Application of Ultrasonic Velocity Profiling for free surface elevation and tracking.
- Combination of PIV and UVP to map free surface status in time and space.

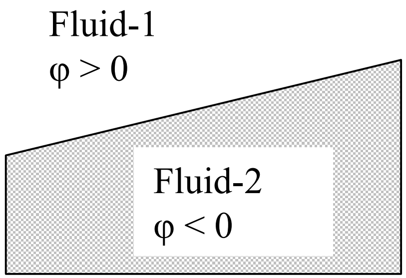


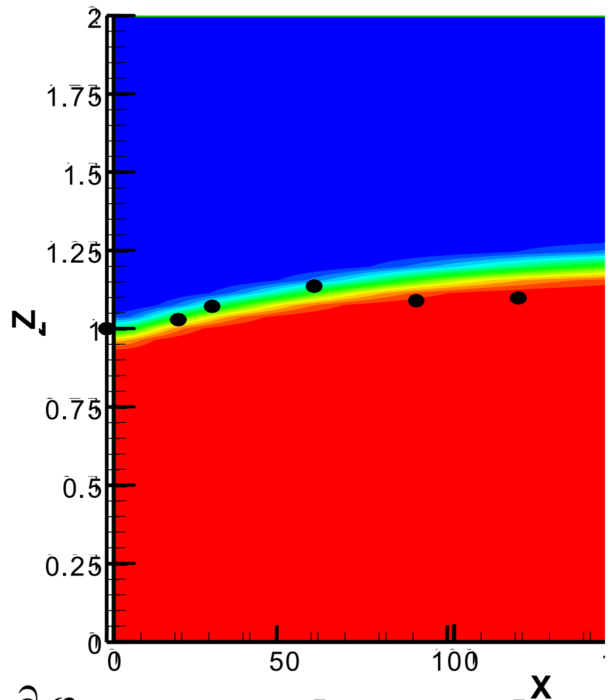
A 30 cm by 5 cm channel flow of liquid Gallium free surface obtained by high speed digital camera. Light scattering from the surface



Streamlines at the free surface calculated via PIV using reflected light at the surface for cross-correlation.

3D free surface MHD modeling effort





Contour for interface shape data from HIMAG with experimental data from MTOR

(each data point represents average of 64 height measurements over 5 s period)

Governing equations

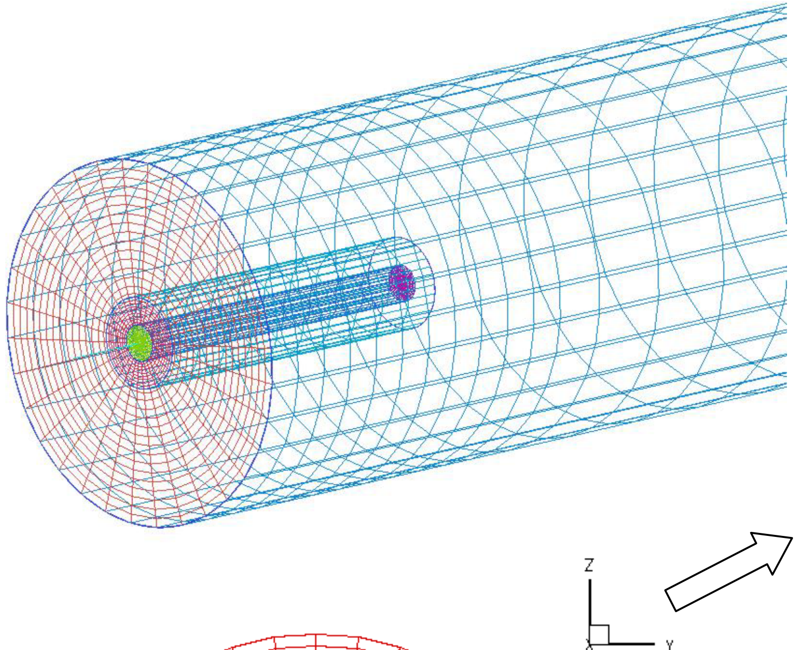
Continuity
$$\frac{\partial u_i}{\partial x_i} = 0,$$

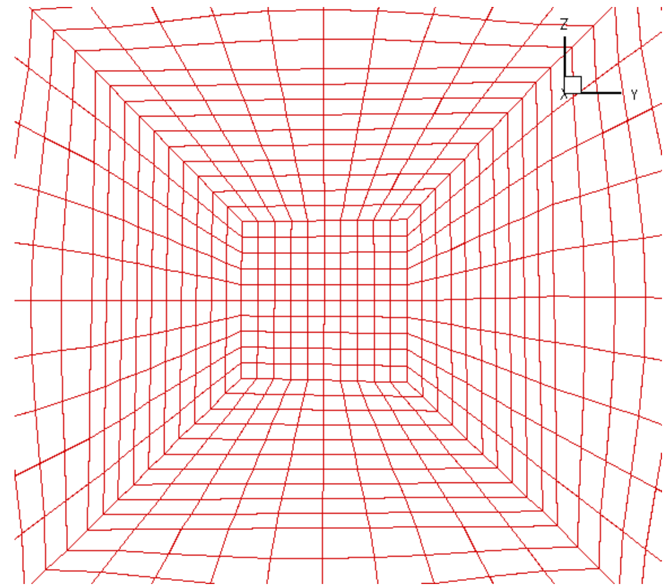
Levelset
$$\frac{\partial \varphi}{\partial t} + u_i \frac{\partial(\varphi)}{\partial x_i} = 0, \rightarrow \frac{\partial \varphi}{\partial \tau} = sign(\varphi_0)\left[1 - \left|\nabla(\varphi)\right|\right]$$

$$\rho = \rho_1 + (\rho_2 - \rho_1)H(\varphi) \quad , \quad \mu = \mu_1 + (\mu_2 - \mu_1)H(\varphi)$$

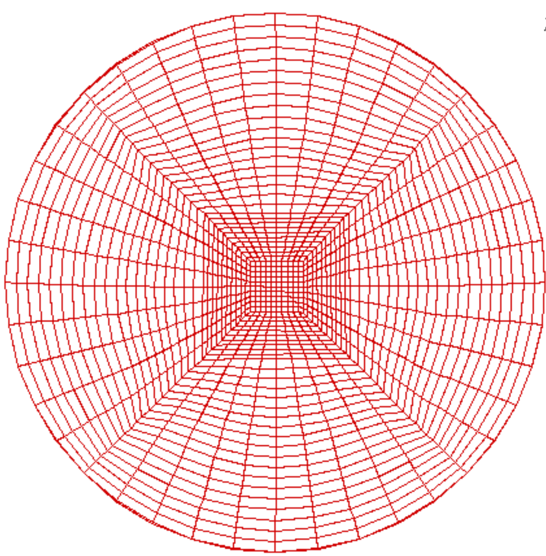
Momentum
$$\frac{\partial(u_i)}{\partial t} + \frac{\partial(u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \underbrace{\frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right)}_{\text{viscous}} + \underbrace{\frac{\vec{J} \times \vec{B}}{\rho}}_{\text{Lorentz}} + \underbrace{\vec{g}}_{\text{gravity}} + \underbrace{\frac{\sigma\kappa(\vec{x})\vec{\nabla}\varphi}{\rho}}_{\text{Surface tension}}$$

NSTX: A cross section of the mesh used
(Total number of cells used = 118440)

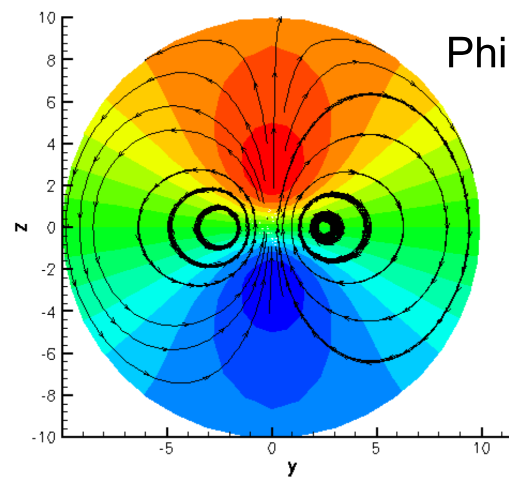


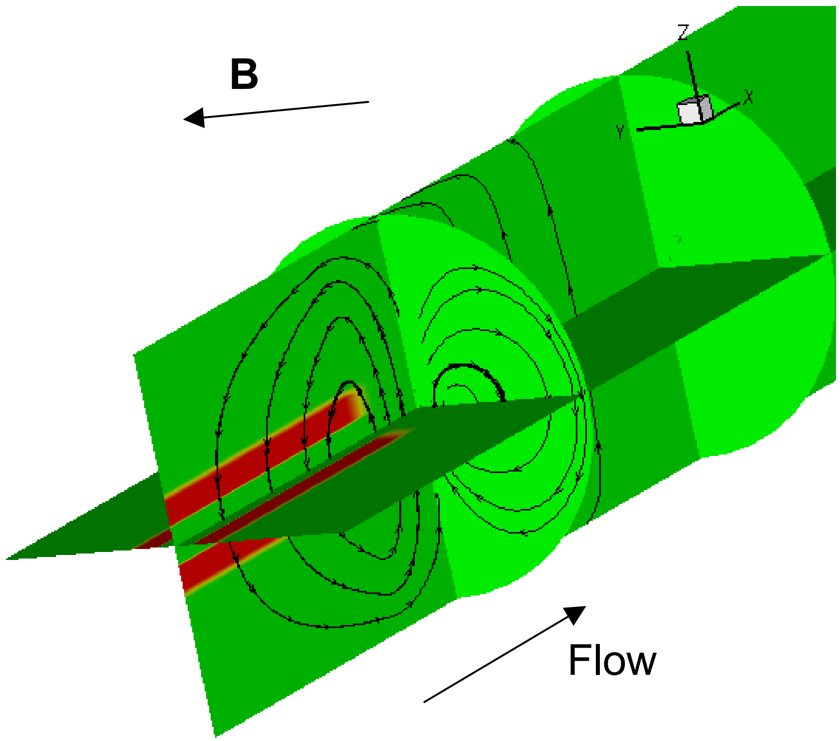


Zoom

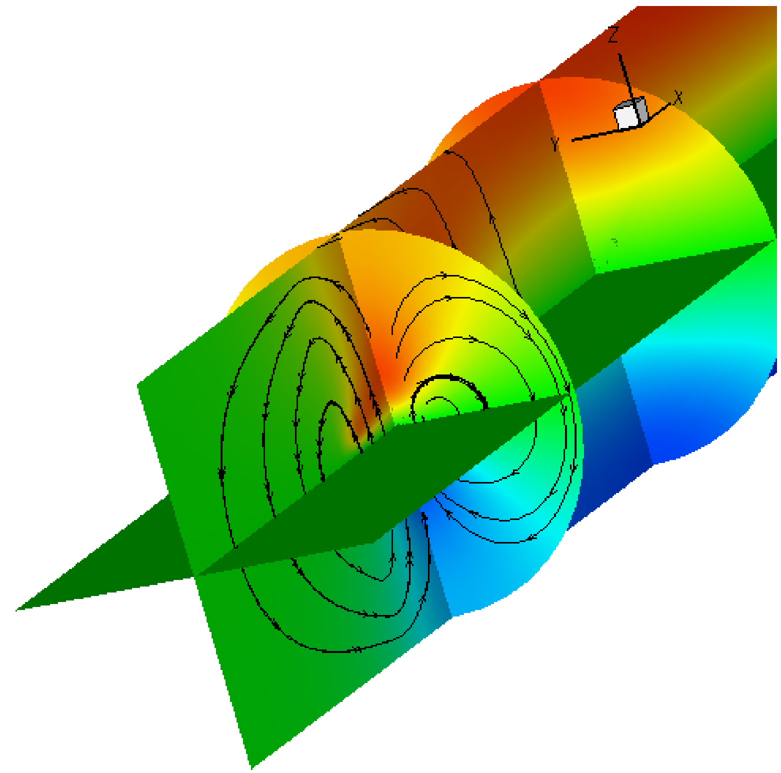


Phi contours





Nozzle location and current lines



Electric potential and current lines