FLIT: Flowing LIquid metal Torus

Egemen Kolemen,

D. Majeski, R. Maingi, M. Hvasta, A. Fisher, A. Brooks, T. Kozub

Assistant Professor
Mechanical & Aerospace Engineering
Jointly appointed with the Andlinger Center for Energy and the Environment
and the Princeton Plasma Physics Laboratory (PPPL)

Presented at the

IAEA Divertor Workshop

Nov, 2017

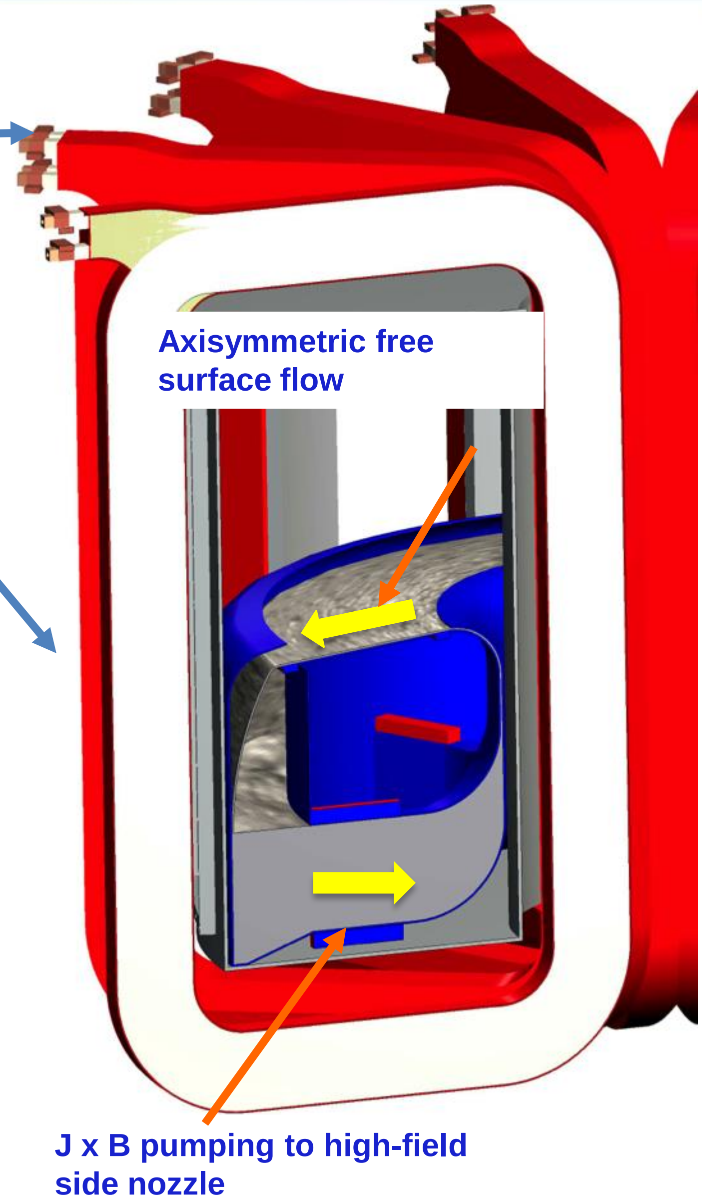
PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

andlinger center for energy + the environment

Introduction to Fast Liquid Metal Divertor

Flowing Liquid Metal Torus (FLIT) aim: understand the physics/engineering of fast flowing liquid metal (LM) systems

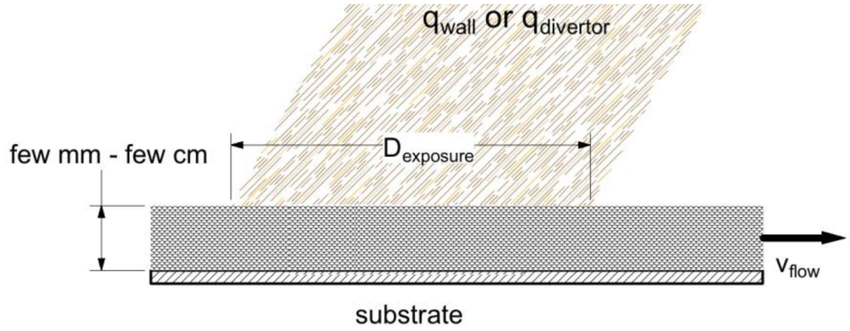


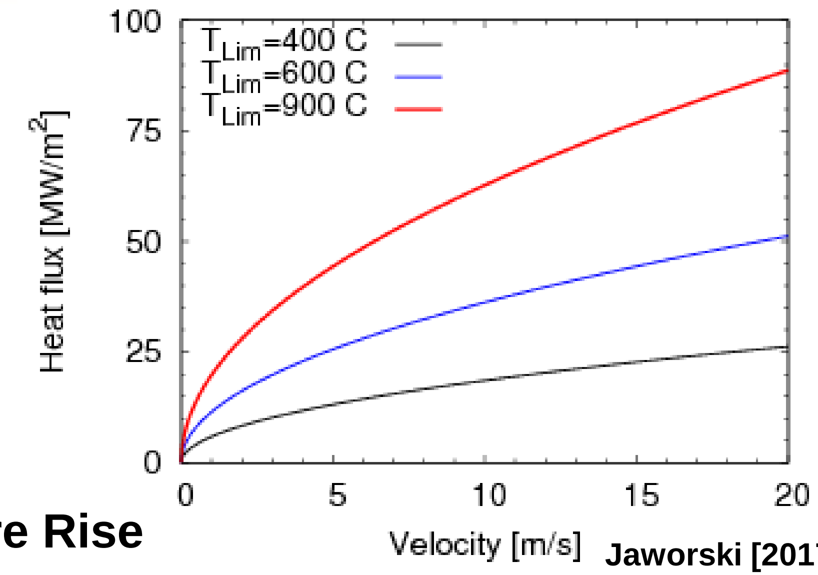
- **Proof of principle R&D at PPPL:**
  - Show the feasibility of fast, controlled flow divertor
  - Develop the engineering for fast flow system (jxB pumps, nozzles – jets/open surface, etc)
  - Optimize liquid metal divertor concept for reactors
  - Use Gallinstan (Ga, In, Sn) to simplify tests
  - *No plasma in these tests*
- **Test axisymmetric liquid metal flows in toroidal fields in realistic B to show feasibility of fast LM divertor concept for NSTX-U at high heat fluxes**

Develop fast flowing liquid metal divertor solutions for reactors should be explored

- **Problem:** It is unclear that a solid divertor solution exists for a long pulse D-T fusion reactor. PFC high heat and neutral flux.
- **Idea**: Develop fast flow liquid li PFCs to handle all the cooling. Solid wall behind only need to handle neutrons. Possibly remove all He (no cryopump). This would complement slow flow Li and Sn R&D.
- **Benefit:** Smaller more economic fusion reactor.
- **Issues to Address:** Previous studies showed flow instabilities: Hydraulic jump, stopping, splashing, magnetic drag etc.
- **Strategy:** Symmetric toroidal flow (avoid Ha layer), Current in LM, jxB Pump, nozzle and surface design for stability.

Heat Removal by Fast Liquid Metal (LM) Flow Divertor
Get Rid of the Divertor Material Issues





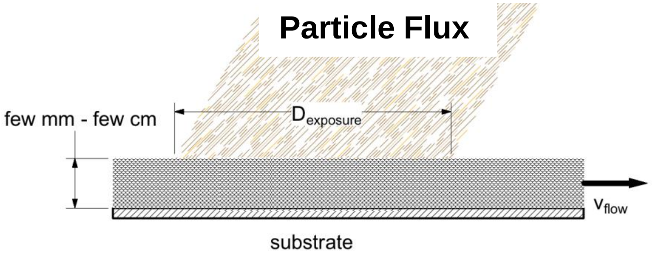
Jaworski [2017]

- **Moving Slab Approximation for Temperature Rise**

$$\Delta T = 2q_{wall}(W/cm^2)\sqrt{\frac{t}{\pi k \rho_m C_p}} = 0.92 q_w \sqrt{D_{exp}/v_{flow}}$$

- **Just flow faster to take more heat!**
- **ΔT Sn > Li (Sn lower speed requirement)**
- **For reactor level loads ~1-20 m/s**
- **The solid substrate behind only need to handle neutrons (no cooling system)**
- **Simplifies the design for compact reactor**
  - **Currently available steel for divetotr, no water pipes, etc.**

Fast LM System Acts as a Particle Pump



KIT completes design of ITER cryo pump

"Helium is a headache for cryo pumps, as it hardly sticks to surfaces even as cold as four or five kelvin. KIT's vacuum experts spent years looking for the most efficient carbon structure to trap helium and finally settled for coconut charcoal from a certain patch of land in Indonesia. Now KIT possesses an entire year's harvest – enough to supply ITER and several future fusion plants."

https://www.euro-fusion.org/newsletter/kit-completes-design-of-iter-cryo-pump/

- **Hydrogen isotope (D/T) particles are likely be trapped in the LM surface (e.g., Li) due to the high chemical solubility of hydrogen**
- ***Reasonable chance* of adequate He self-trapping in flowing lithium as PFC without active pumping at 10-30 m/s**
  Hassanein, JNM 302 (2002) 41 + JNM 307 (2002) 1517–1519,*Free Surface Flowing Liquid-Plasma Interaction Facility GRANT # DE-FG02-01ER86134, (Stubbers and G.H. Miley)*
- ***This might reduce/avoid requirement for additional reactor cryo pumping***

  ➔ Smaller/cheaper reactor

Background to Fast Liquid Metal Divertor

7

TM-3 and FLiLi (EAST) Tokamak Flowing Lithium Experiments (Thin film slow free surface flow)

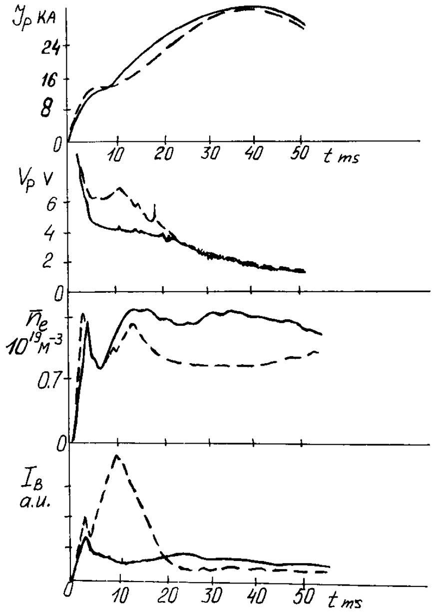
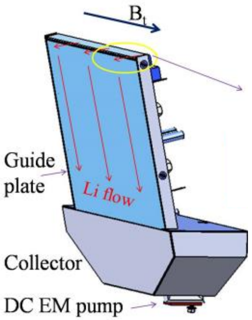
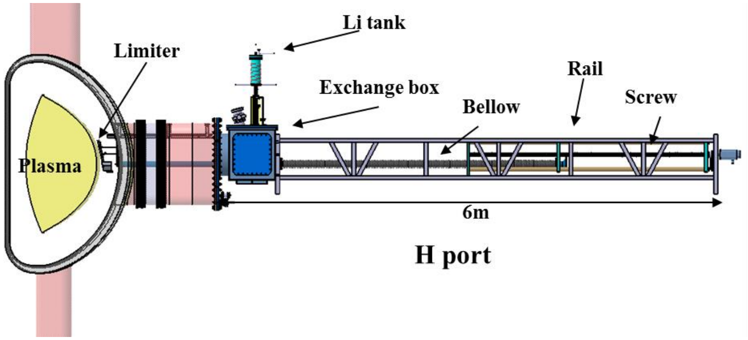


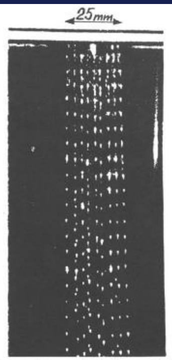
Fig. 8. Experiments on T-3M with jet-drop curtain limiter [14]: $J_p(t)$–discharge current; $V_p(t)$–voltage; $n_c(t)$–plasma density; $I_R(t)$–radiation losses

- TM-3, Russian tokamak, in 80s tested liquid metal sheet
- 10s ms ramp, 1 Tesla B (very fast)
  ➔ MHD drag, flow stopping/ejection
- Not representative of fusion reactor conditions (hours of rampup)➔ *Wrongly cited*
- FLiLi at EAST: shown the engineering concept works for a slow flowing thin film Lithium system with EM pump. Exp. continuing





Fast Jet (Droplet Curtain) Divertor:
ISTOK, FFH-d1 Stellarator Proposal (NIFS, Japan)



. Photograph of a regular jet-drop curtain. Test facility MK [12].

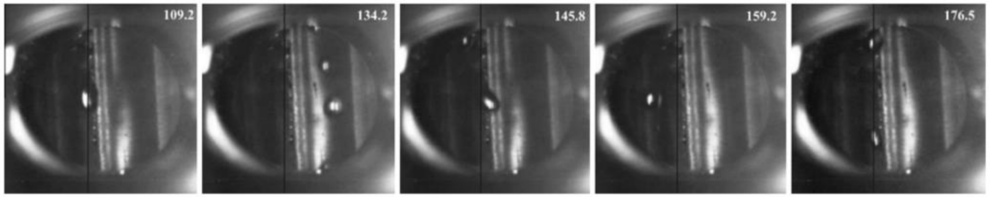


Fig. 2. Frames sequence from a movie showing the dynamic behavior of gallium droplets due to the influence of an ISTTOK discharge.

*R. Gomes J. Nucl. Mater. **415** (2011) S 989–92*

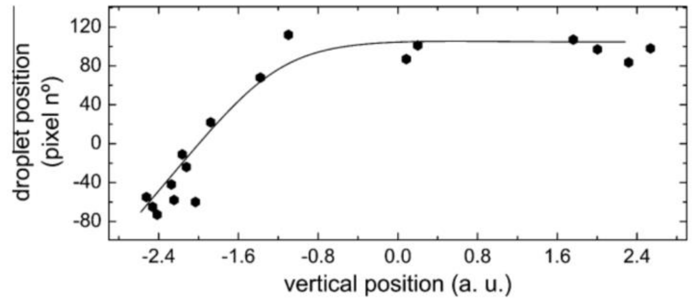
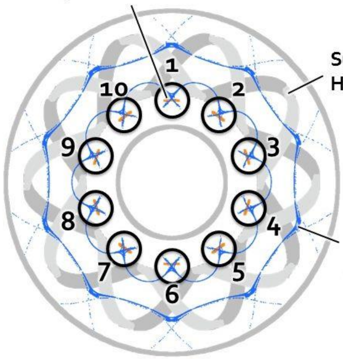
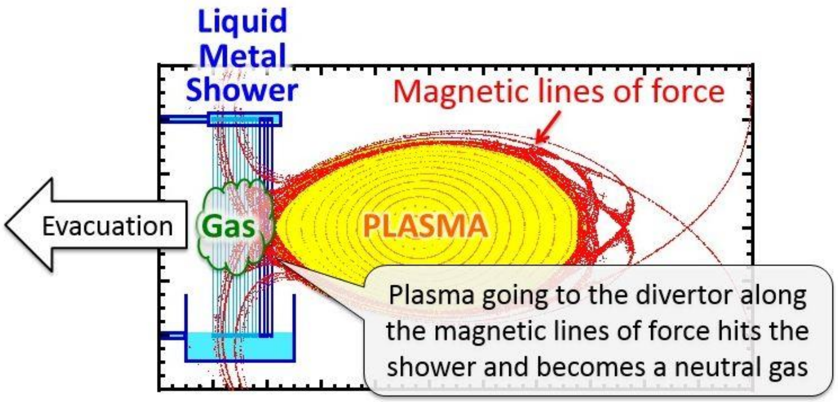


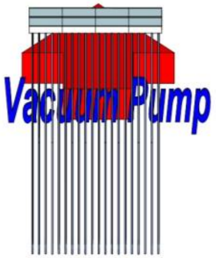
Fig. 4. Droplet positions (from unperturbed trajectory) as a function of the plasma vertical position.

TM-3

ISTTOK LM Curtain: Shown feasibility of heat extraction; droplet motion due to MHD



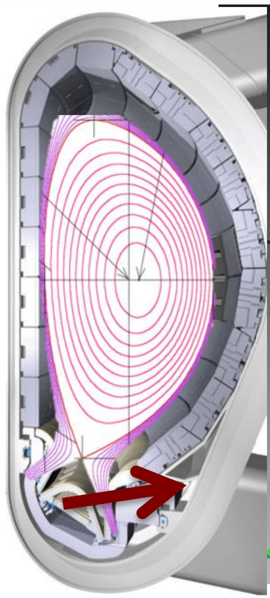




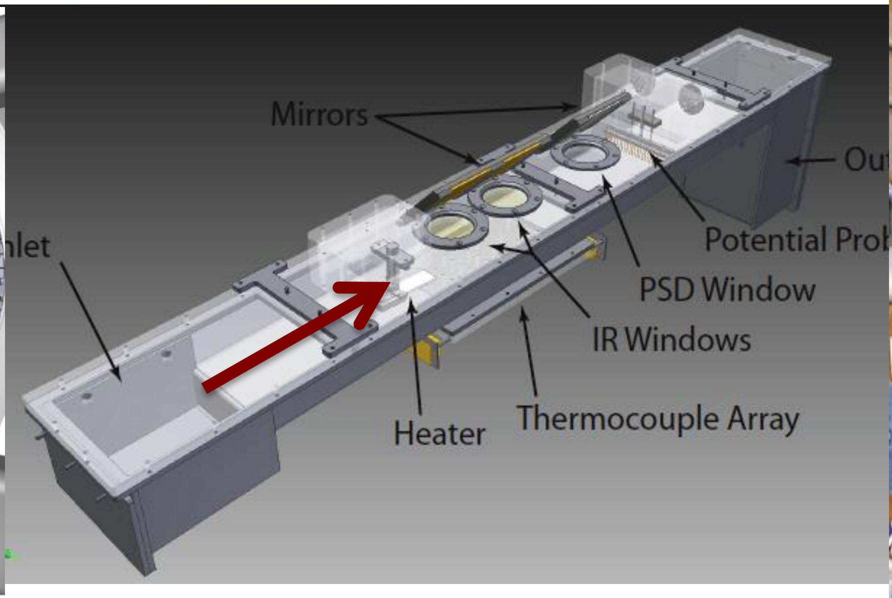
FFHR-d1 LM Curtain (proposed J. Miyazawa, NIFS, ~LHD-U)

Tin LM due to low melting temperature, low vapor pressure

Flowing Liquid Metal R&D without Plasma



Tokamak

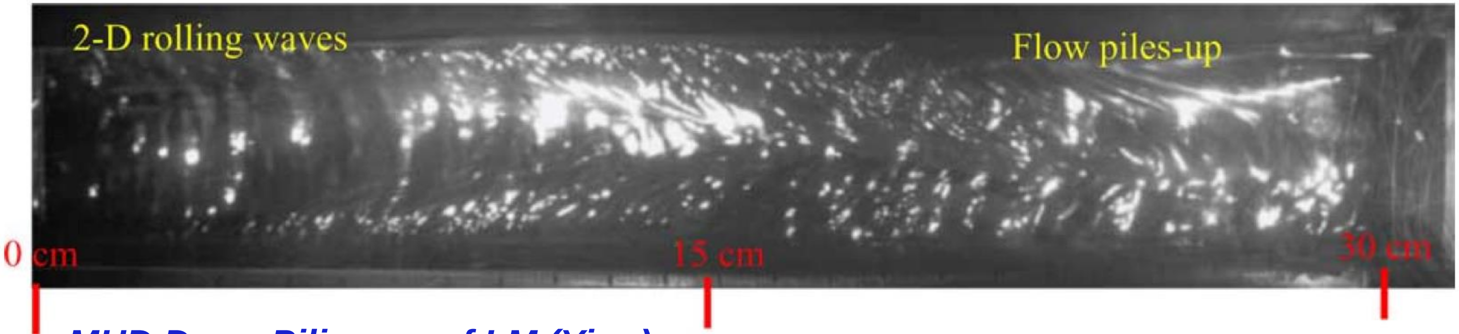


Liquid Metal Experiment (LMX) at PPPL

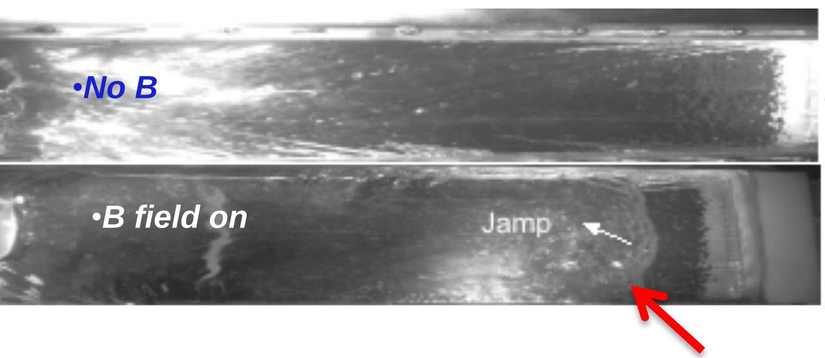
MTOR (UCLA)

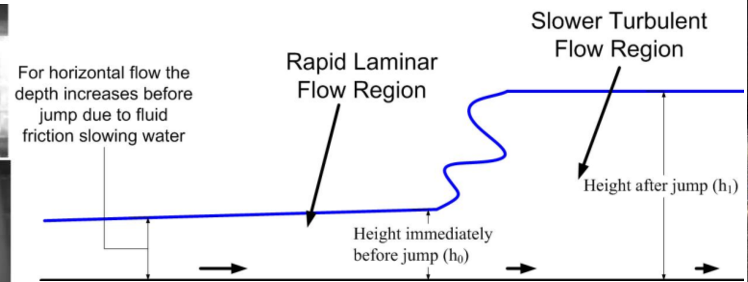
- **Ex: MTOR 0.5 T, 1/R field; LMX 0.3 T**
- **Aim:** Understand liquid metal flow at small scale
- Main issues with MHD flow can be addressed without need for plasma
- Developing diagnostics and control system to analyze LM flow
  - **Surface waves: Measurement and stabilization**
  - **Heat transfer: Enhance mixing using vortex generators**
  - **Holding Study jxB forces control of the LM flow**

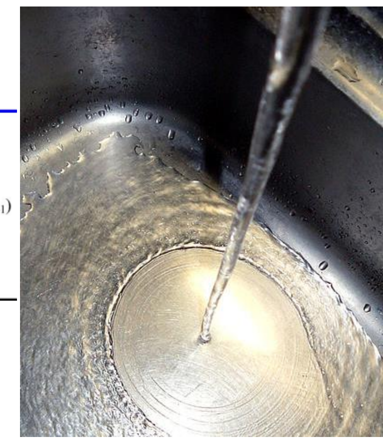
Main Challenge: MHD Flow Instabilities



MHD Drag: Piling up of LM (Ying)





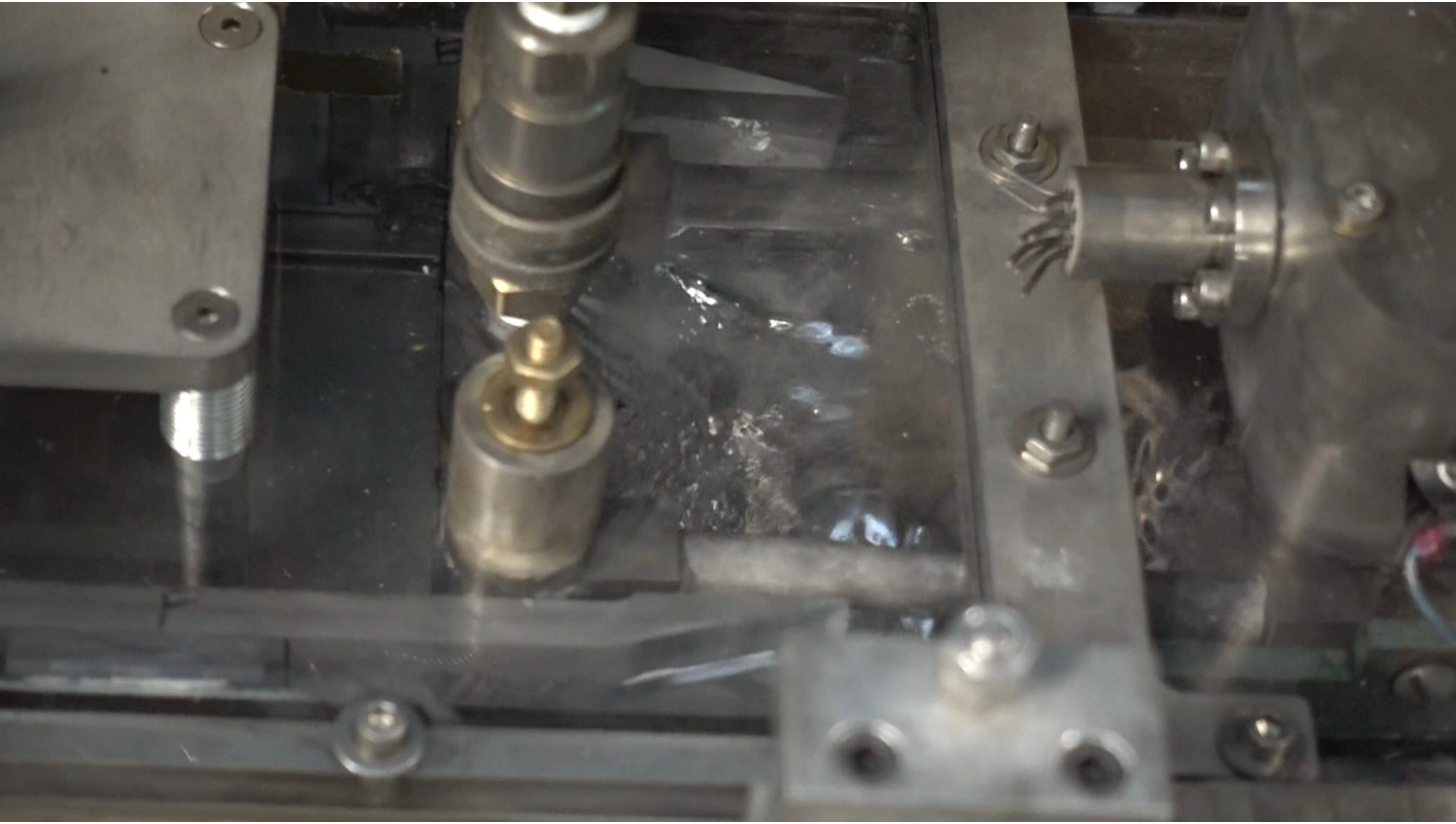


Hydraulic Jump: Transition to slow, high flow (Narula)

Solutions:

- ***jxB force** can be used to reduce these effects (stop hydraulic jump)*
- ***Axisymmetric** annular (as opposed to channel) flow*
  ➔ No Hartman current, MHD drag for flow along flux surface (Morley FED 2002)
- ***Reduce flow speed** requirement by increasing advection*

Introduction/Orientation:
fast free surface LM flow in a channel (LMX)



MHD Stability Analysis: Rayleigh–Taylor

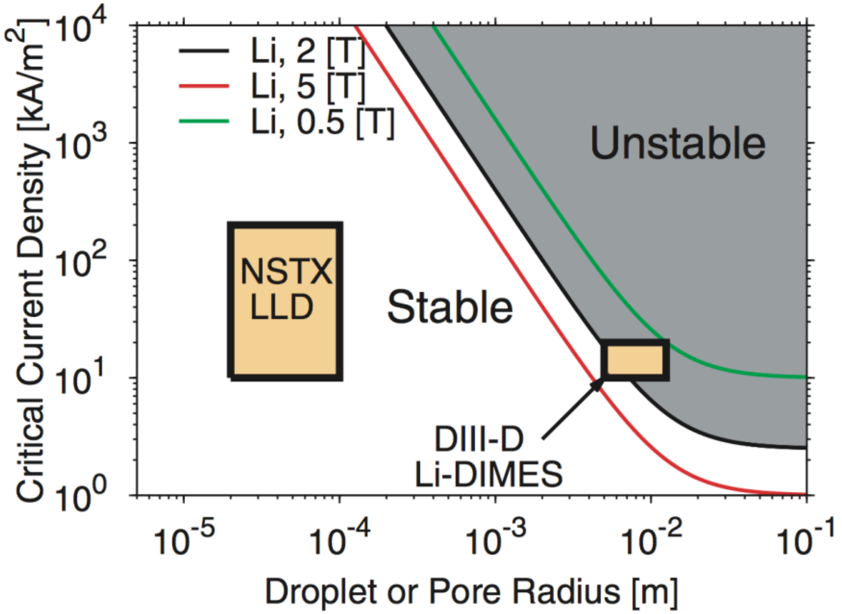
- **Jaworski studied the stability liquid metal in magnetic fields**

$$\nabla \cdot \vec{u} = 0$$

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right) = \rho\vec{X} - \nabla p + \vec{J}\times\vec{B} + \mu_f \nabla^2 \vec{u},$$

- **Linear modes grow as**

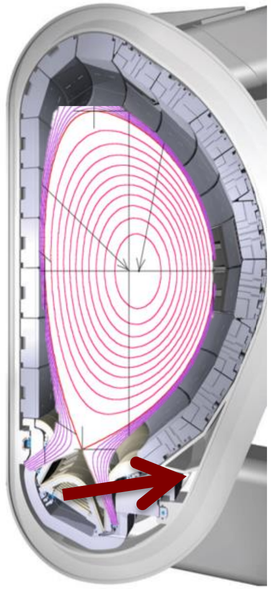
$$\exp(\mathrm{i}k_x x + \mathrm{i}k_y y + nt) \quad k_{\mathrm{cr}} = \sqrt{\frac{jB - \rho g}{\Sigma}}$$



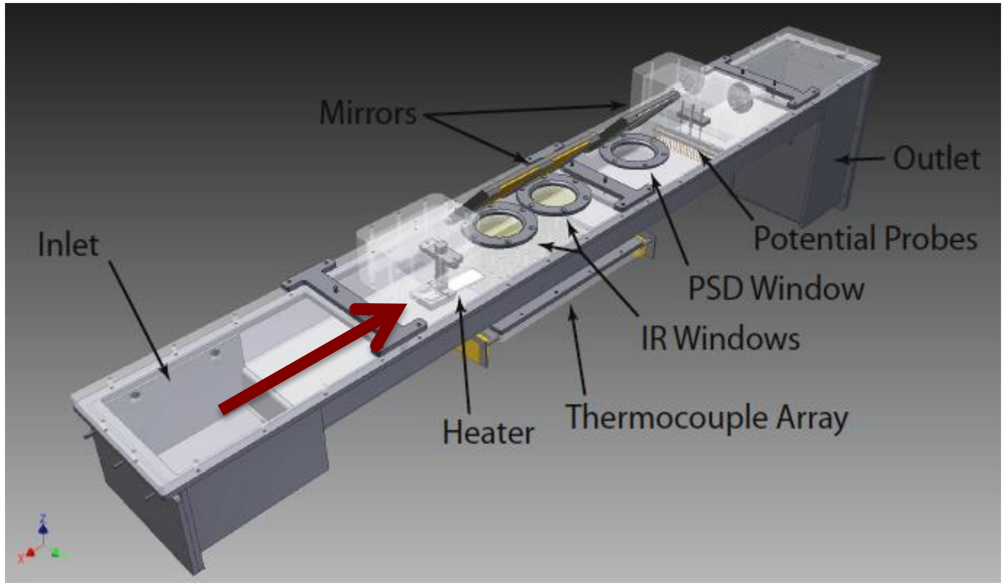
- **Stable if total jxB > surface tension**
- **J, the total current including, self induced + ELMs + Applied**
- **If $J_{applied} > J_{ELM}$ + … we get stable flow**
- ***➔ With applied J_{pol} theoretically LM should be stable***

Current Fast Liquid Metal Divertor Experiments at PPPL

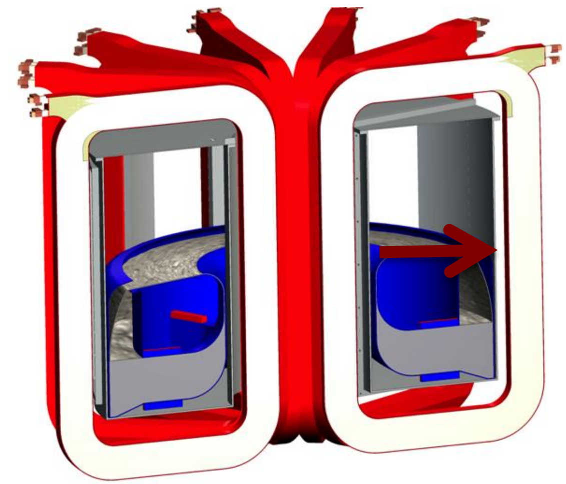
Flowing liquid metal R&D presently being done in linear geometry on Liquid Metal eXperiment (LMX)



Tokamak



Liquid Metal Experiment (LMX)



FLIT

- Liquid Metal Experiment (LMX) operating at PPPL (Kolemen Group)
- **Aim:** Understand liquid metal flow at small scale
- Developing diagnostics and control system to analyze LM flow
  - **Surface waves: Measurement and stabilization**
  - **Heat transfer: Enhance mixing using vortex generators**
  - **Holding Study jxB forces control of the LM flow**
- Diagnostics and studies move to FLIT

LMX publications by Kolemen group:
Kosumi, FEDC 111 (2016) 1193
Hvasta, RSI 88 (2017) 013501
Hvasta, Nucl. Fusion, (2017)
Hvasta, MST, (2017)

Reduce Speed Requirements by Better Mixing: Heat transfer and flow under JxB force

Lorentz force: $\frac{\partial \mathbf{u}}{\partial t} \propto [\mathbf{J} \times \mathbf{B}]$

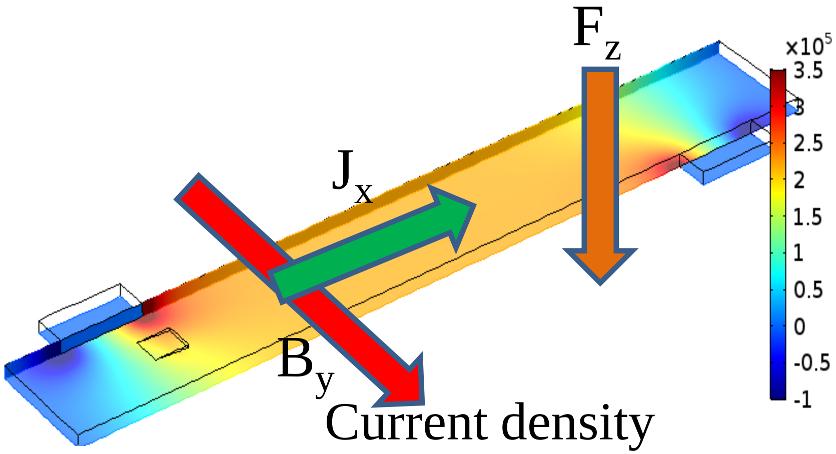
Heat transfer: $\frac{\partial T}{\partial t} \propto \mathbf{u} \cdot \nabla T$

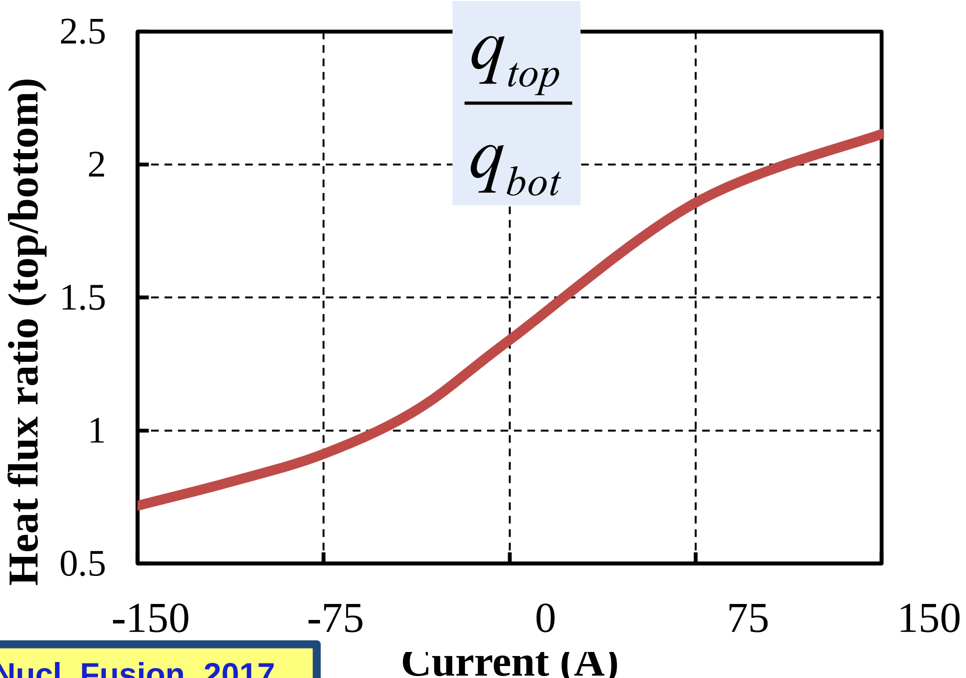
Experimental setup: $J_x \cdot B_y \to F_z$

$F_z < 0$

Enhance heat transfer
+ Push LM to the wall

Use electric current and magnetic field to control LM *flow* and *heat flux*





Modestov, Nucl. Fusion, 2017

Simulations: Heat transfer and flow under JxB force (M. Modestov)

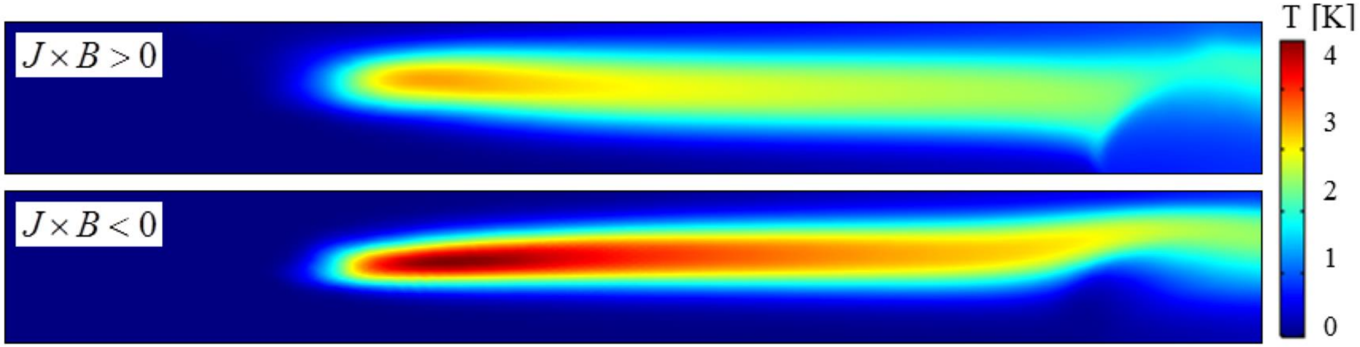
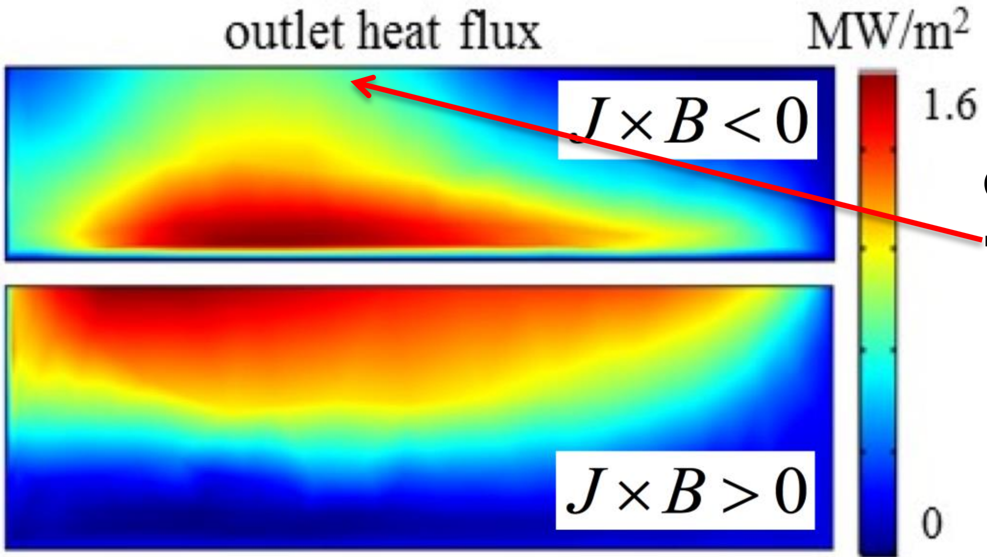


FIG. 6: Temperature field at the bottom for two directions of the $\mathbf{J} \times \mathbf{B}$ force.

Side view

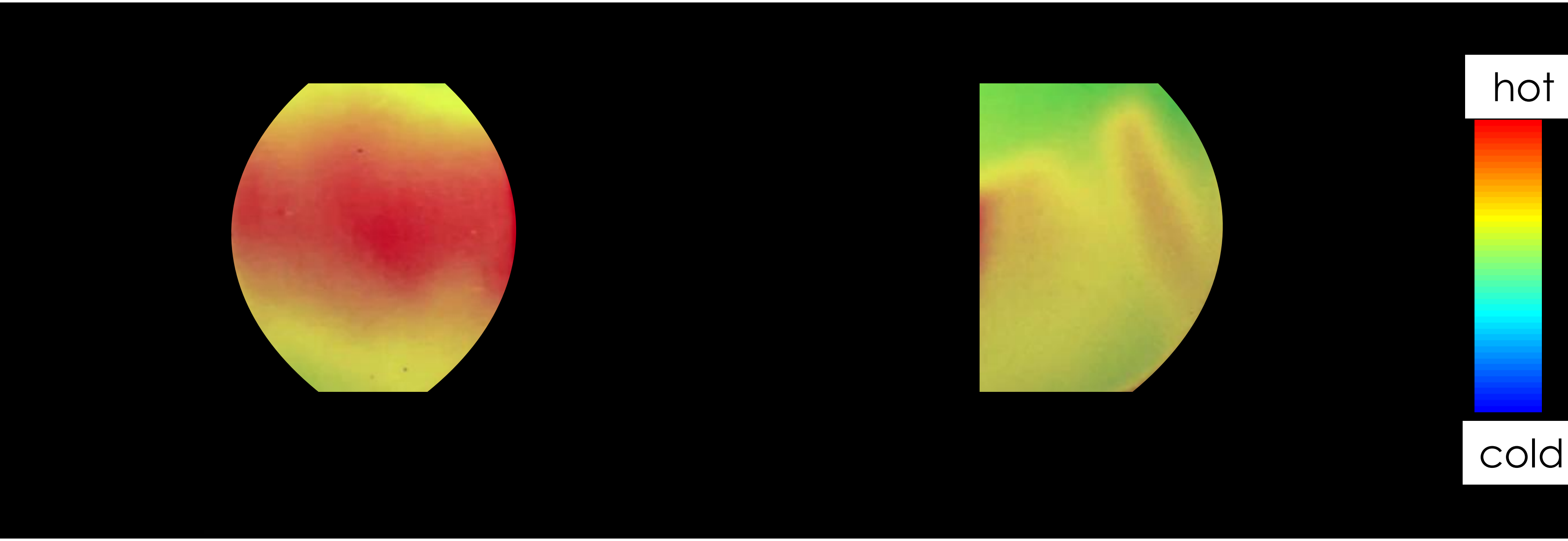


Colder Top
➔ Less Evaporation

Modestov, Nucl. Fusion, 2017

Current in LM can enhance the heat transport

- **jxB causes mixing in flow, improving heat flux to the bottom and sides of the channel. (A. Fisher and J Hinojosa). Thus, reducing the LM speed requirement for reactor.**



Thermal Camera on top of the flow

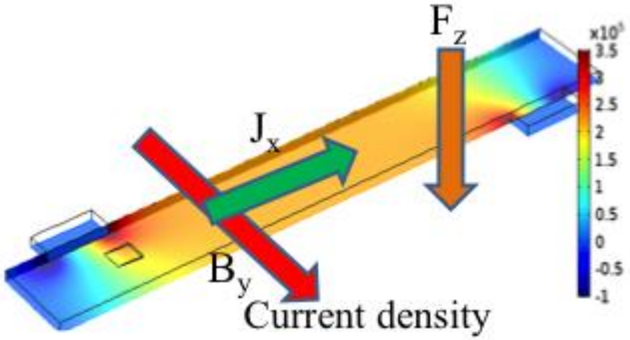
jxB Control: Liquid metal velocity and height (M. Hvasta and A. Fisher)

- **jxB affect model for bulk flow:**
  - Mass conservation

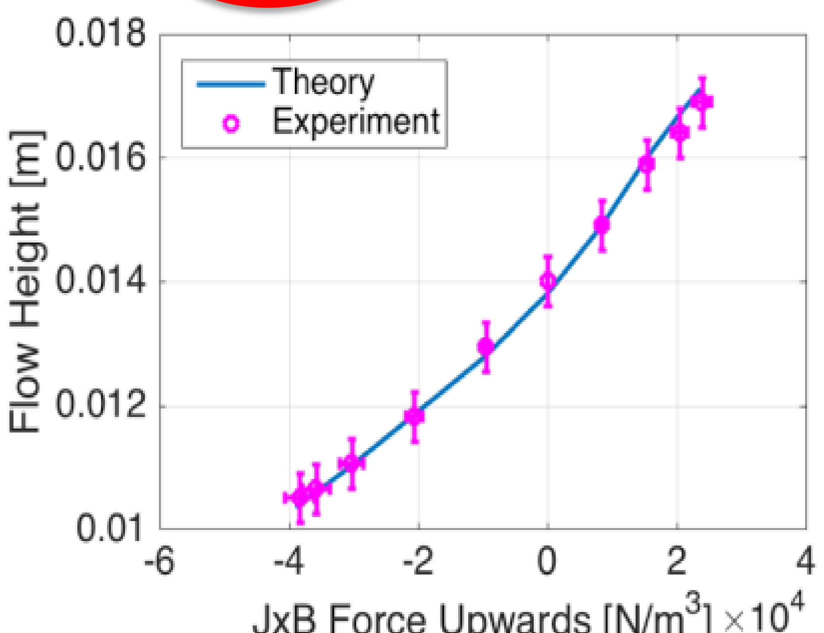
$$v_0 h_0 = v_1 h_1 = q$$

  - Momentum conservation

$$\rho v_0^2 h_0 + \frac{\rho g h_0^2}{2} = \rho v_1^2 h_1 + \frac{\rho g h_1^2}{2} + \frac{\boldsymbol{jBh_1^2}}{\boldsymbol{2}}$$



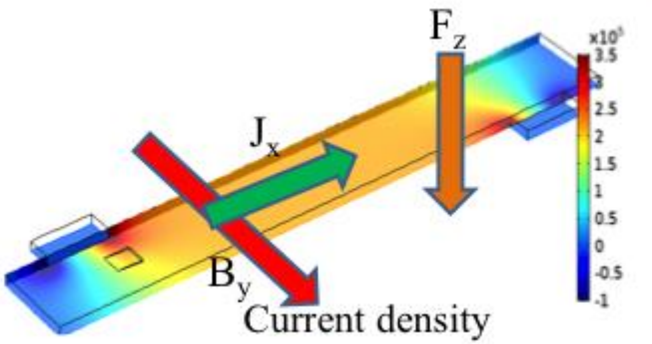
- **Proof of principle:**
  We can get >>g in a reactor
- ***Increase velocity*, reduce height**

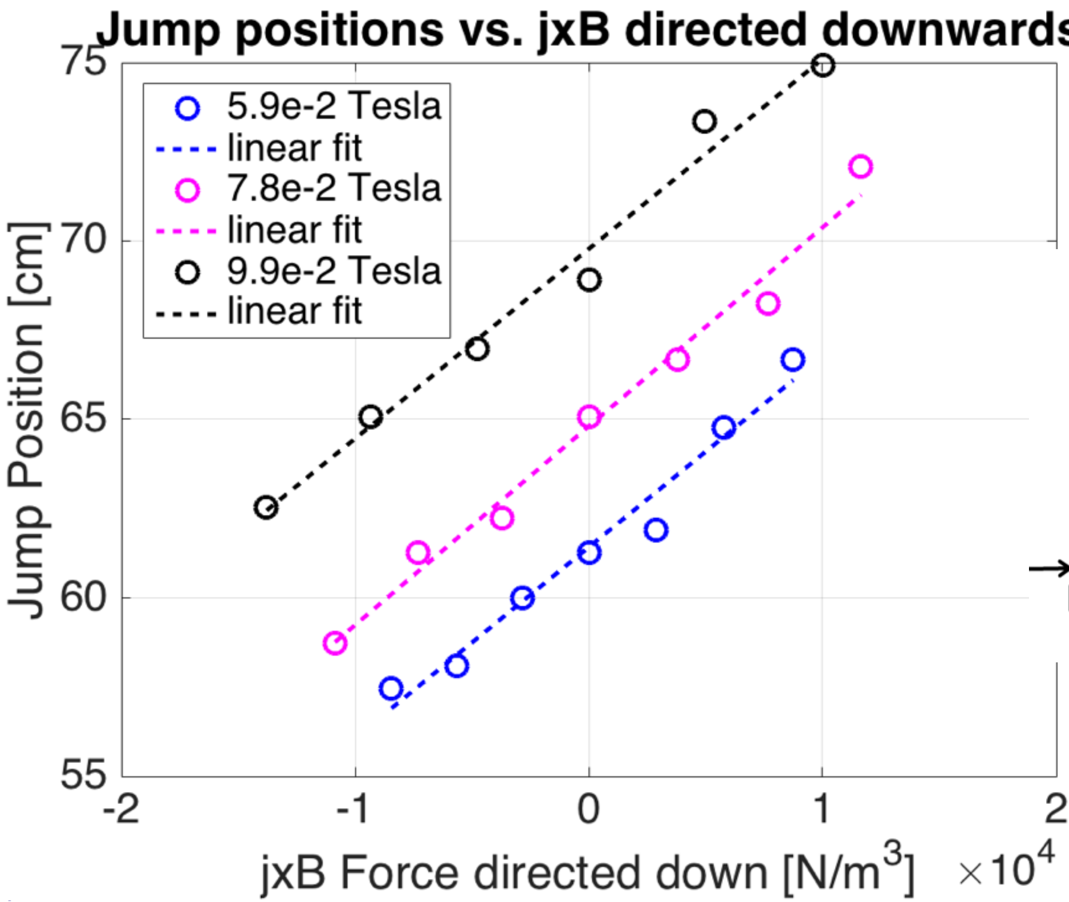


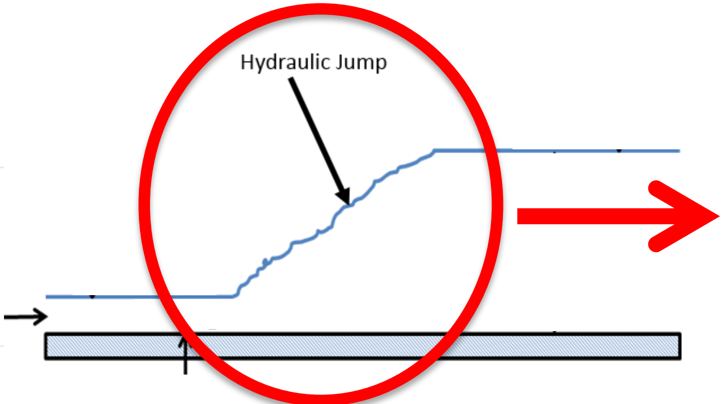
Hvasta, Nucl. Fusion, 2017

jxB Control: Move the hydraulic jump (A. Fisher and M. Hvasta)

- **Increase the downward jxB to move the hydraulic jump downstream (max 100 amps)**







Move the jump downstream and out of the divertor area

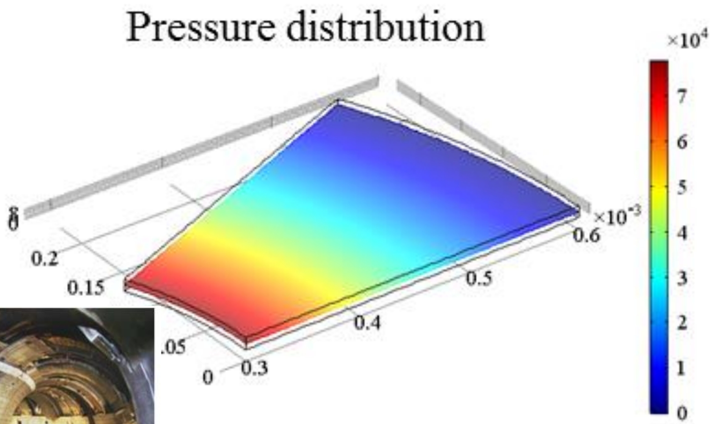
FLIT: Flowing Liquid Torus

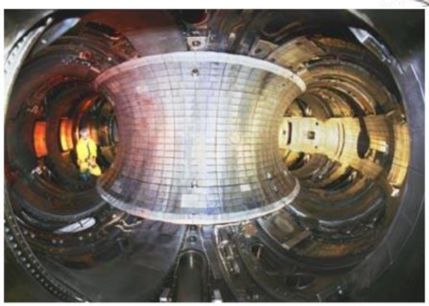
21

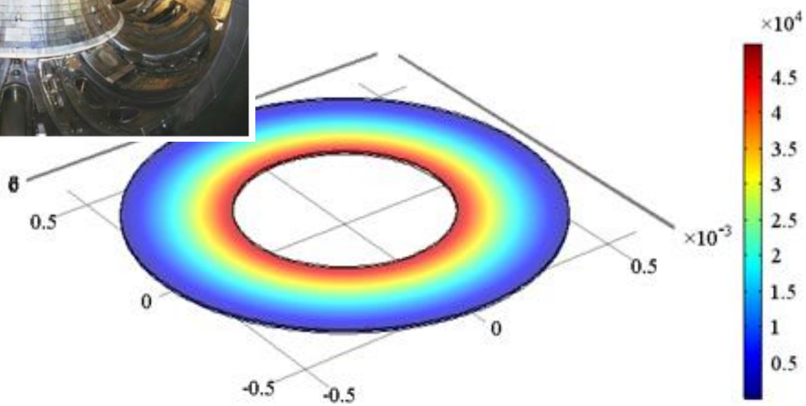
Purpose of FLIT: Develop Fast Flow Liquid Metal Divertor for Fusion

- ***Study the fast flow LM divertor - No Plasma (Galinstan):***
  - ***Prove the jxB pump for LM pumping in a tokamak***
  - ***Prove annular flow under high B***
  - ***Control of flow sticking to the wall (probably using J current)***
  - ***Avoid MHD and fluid related flow issues***
  - ***Enhance heat flux via advection***
  - ***Study the heat flux carrying capability (using e-beam or non-plasma source)***
  - ***Study the B perturbations (poloidal, copper plasma etc…)***
  - ***Compare different nozzles open surface vs jets/sprays***

FLIT Aims to Study Annular Flow: More Realistic and Favorable







3D MHD numerical calculations
M. Modestov (Princeton Univ.).

- **Advantage over channel flow**

1. No side wall, no Ha layer

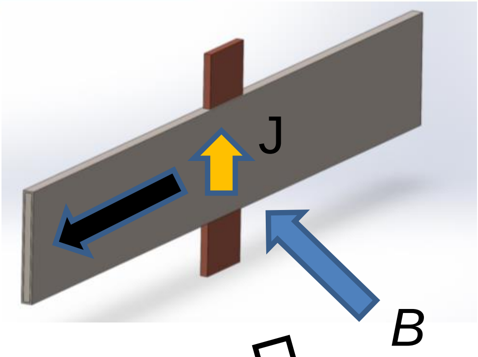
- **As long as flow along field lines [Morley FED 2002], can be used for stellarator**

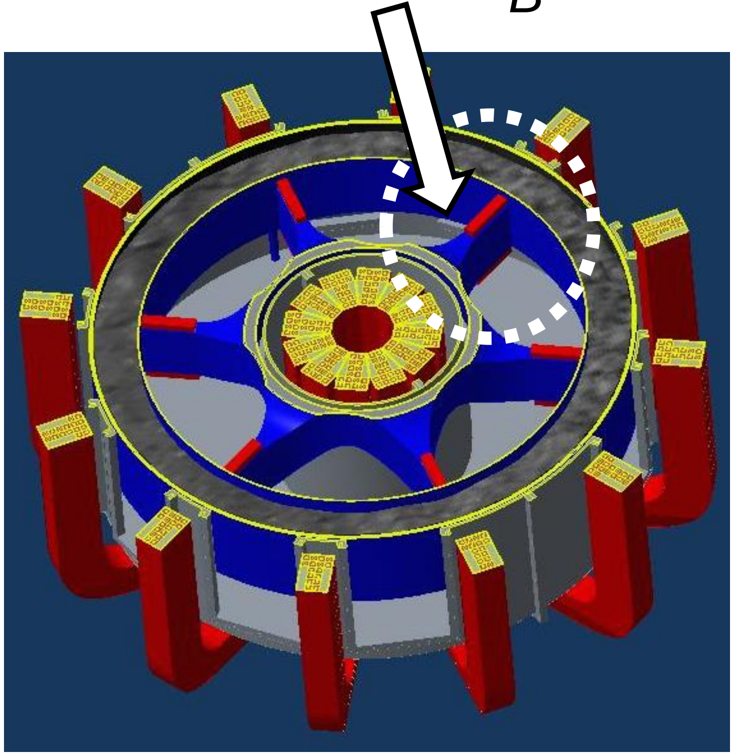
2. Magnetic Propulsion

- **B_t ~ 1/R in tokamak**
- **Pressure due to variation in jxB can propel the liquid metal**
- **Higher pressure on the high field side, lower on the low field side**
- **Annular poloidal flow can be propelled [Zakharov PRL 2003]**

- **Need to test this realistic and more favorable configuration**

FLIT: Flowing Liquid Torus, Engineering/Physics Development on a Torus LM System

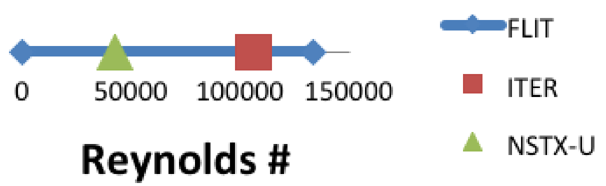


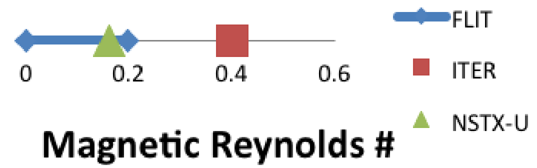


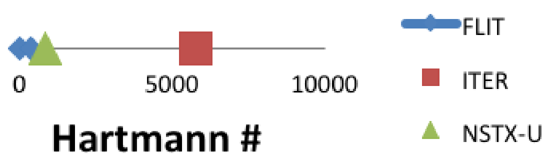
Horizontal cut showing JxB pumping system

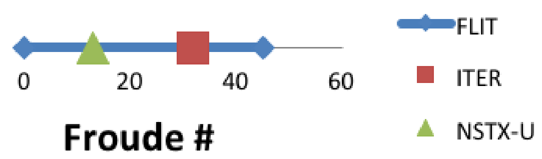
- **Heat Flux Handling Capacity:** 10-20 MW/m^2
  - Flow rate 1-10 m/s and LM height of ~1-20 mm (100 Liters/s capacity) capable of convecting high q
  - *Limited test heat input planned*
- **Magnetic Field:** 1 Tesla
  - To study and prove the concept for a possible upgrade to NSTX-U with a liquid metal divertor
- **Operation Duration:** >10 seconds at full field
  - Stabilization of the flow for physics studies
- **Coil Design:** 12 Rectangular coils (detachable)
  - Set by the machine size, ease of access, specs of the available power supplies, and I^2t heating limits
- **Magnet size:** 75 cm radial x 105 cm vertical
  - Space for flow path, diagnostics, jxB pumps
- **Liquid Metal:** ~30 gallons Galinstan (Ga-In-Sn)
  - Safety; Lithium building needed for Li operation
- **Pumps:** 6 jxB pumps (26 kA @ 4.38 Vdc, 1 T)
  - Based on drag calcs and available power supplies

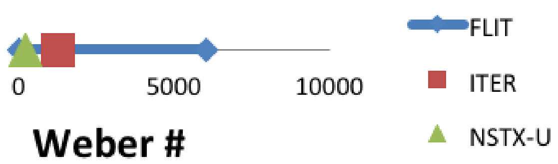
Need Flexibility to Project Fast LM Flow to Reactor: Comparison of FLIT with ITER and NSTX-U

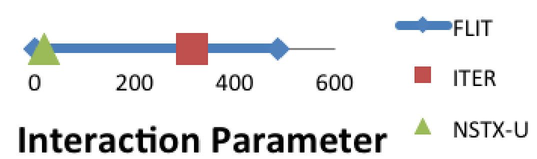












- ***FLIT will allow achieve the important non-dimensional parameters***
- ***Compare simulations to experiments at relevant parameters***
- ***Note: Can achieve larger range with more galinstan (e.g. Ha)***
- ***Next test the system on a tokamak/stellarator (such as NSTX-U)***

FLIT timeline: Full FLIT Design and Simulations Have Been Completed

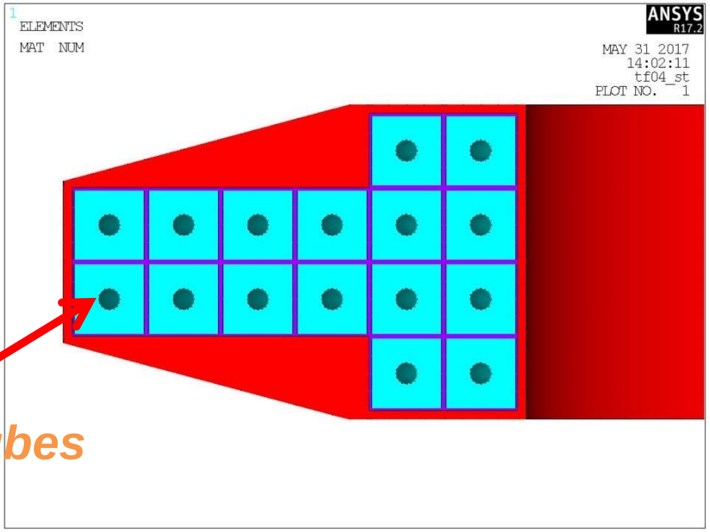
- ***Coil Final Design Review (FDR) Approved***
- ***Full System FDR in two weeks (PDR Approved)***
- ***Procurement delayed***

	2017		2018		2019		
Coils	Design TF Coils	Procure TF Coils		Install Coils on Stand			**System Startup**
Coil Stand	Design Coil Stand		Fab. Stand				
Vessel			Design Vessel	Fab./Procure Vessel	Install Vessel		
Test Article				Design Test Article	Fab./Procure Test Article	Install Test Article	
Pump	Design jxB Pump				Procure Power Supplies	Install jxB Pumps	
LMX	Diagnostic Development					Install Diagnostics	
Galinstan	Procure Galinstan						

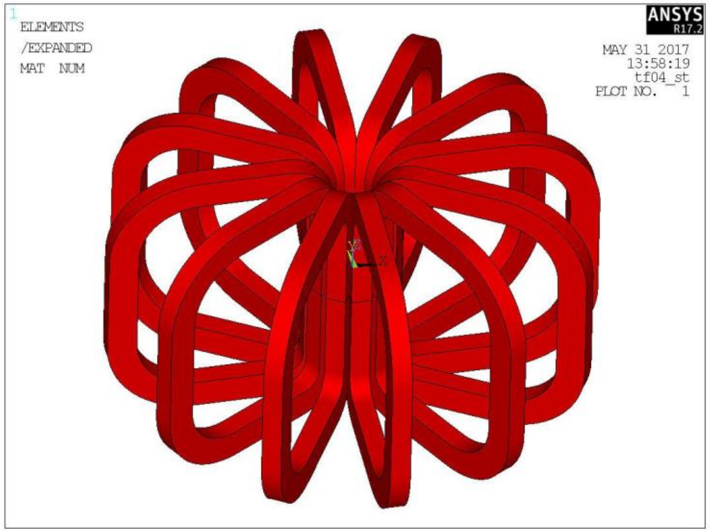
Engineering Details of FLIT

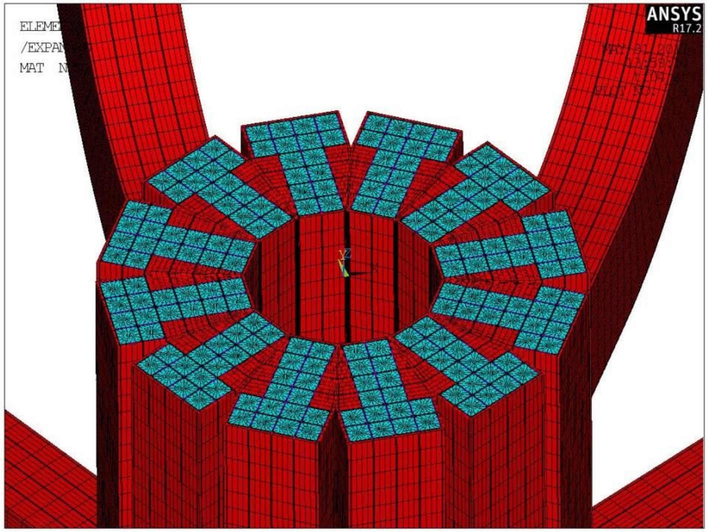
Full Copper FLIT Optimized for Maximum Space, Cooling and Simple Operations

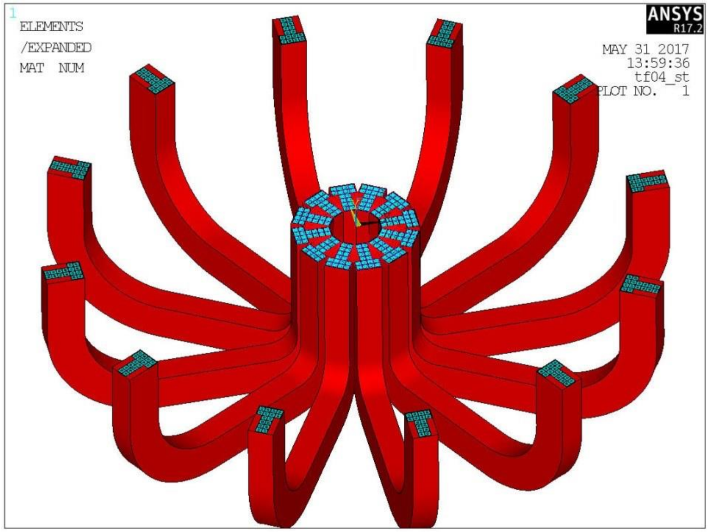
ANSYS Model – 12 Fold Cyclic Symmetry



Cooling Tubes

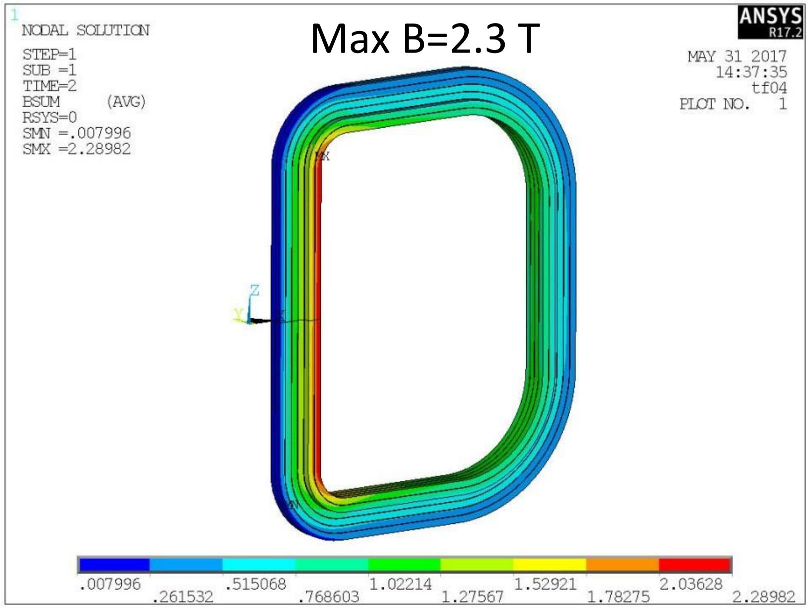




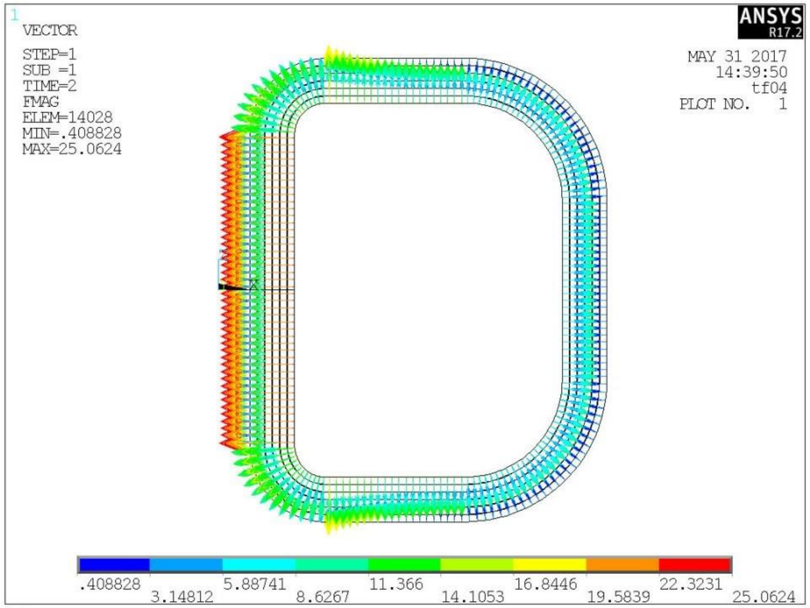


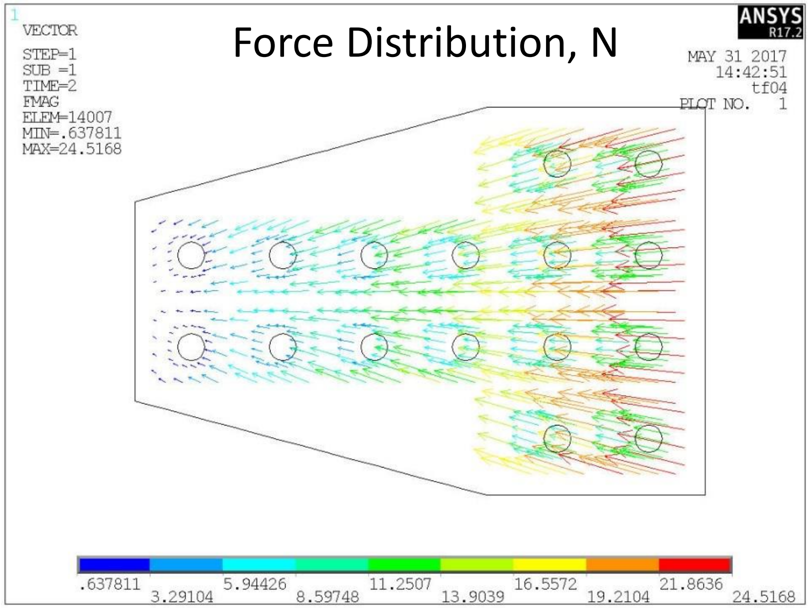
FLIT Coil Optimized for Magnetic Forces and Inner Space

- *FLIT will have max 2.3 T (1 T in the center)*
- *Rounded edges (2nd design) optimized for magnetic forces*

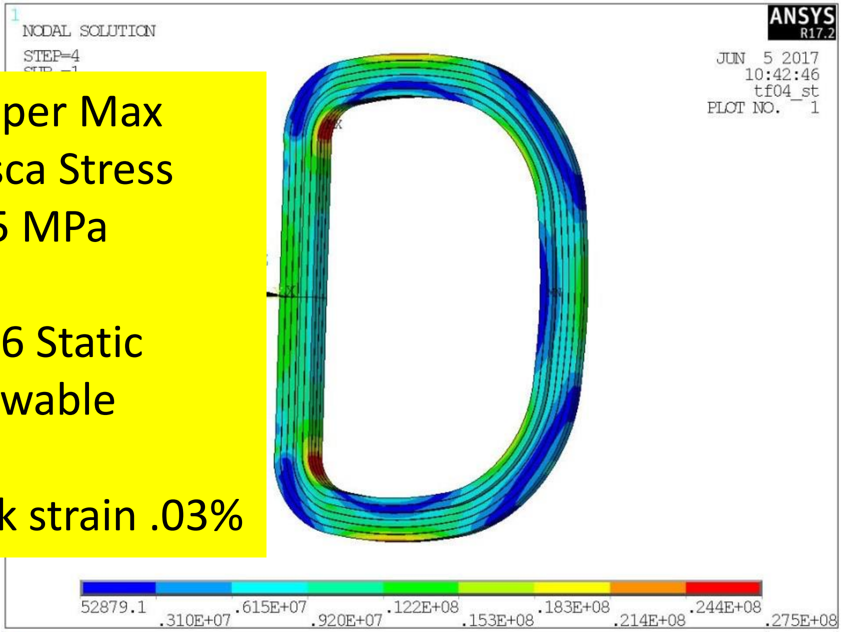


Total Field, T





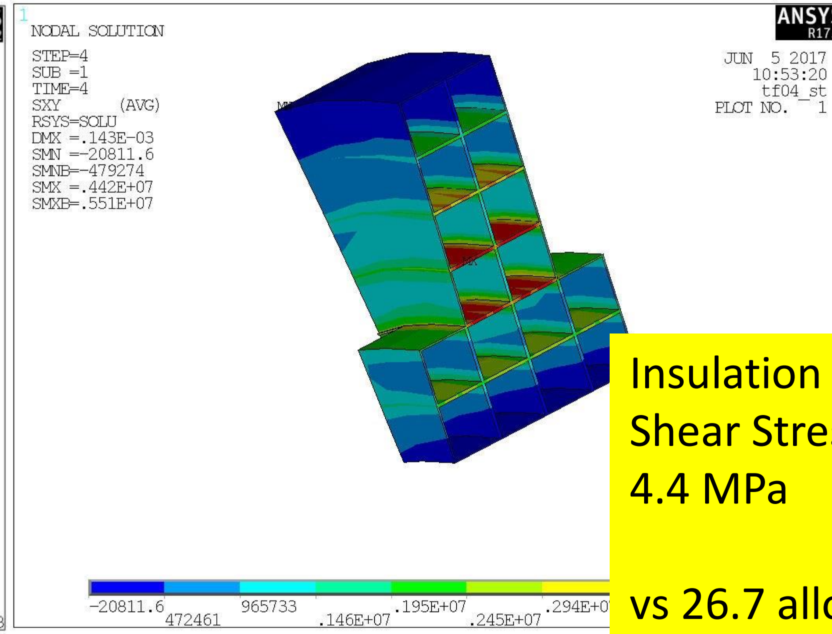
Stresses (TF Inner Legs Bucked): EM + Thermal



Copper Max Tresca Stress 27.5 MPa

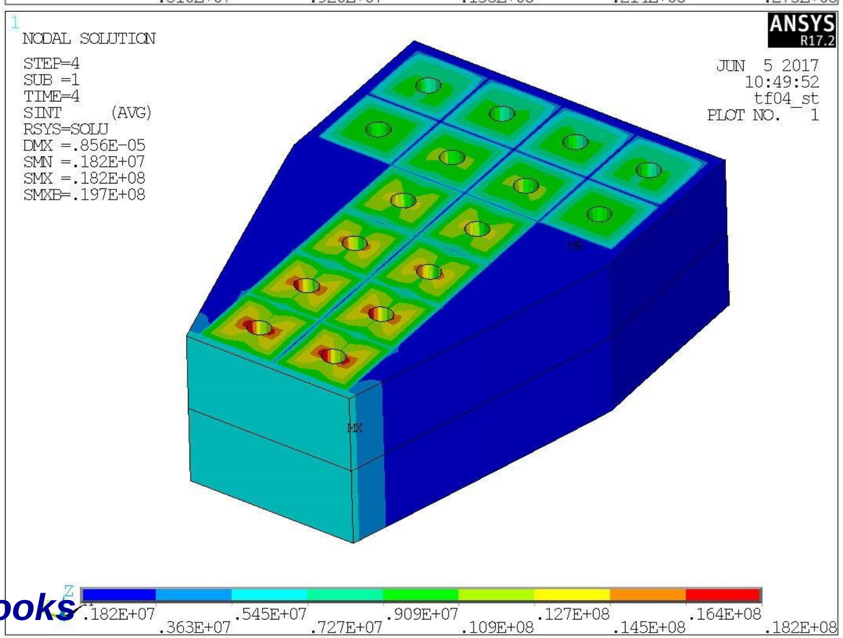
vs 56 Static Allowable

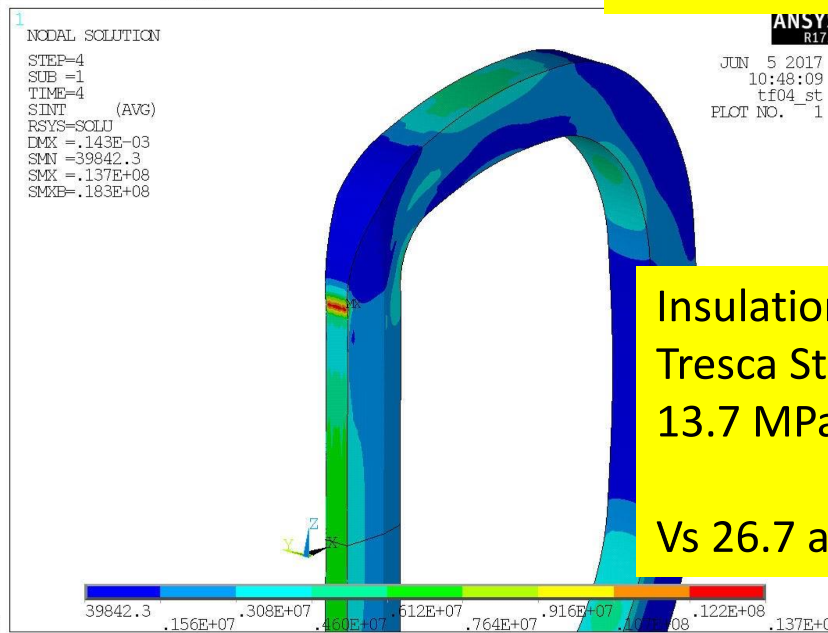
Peak strain .03%



Insulation Max Shear Stress 4.4 MPa

vs 26.7 allow



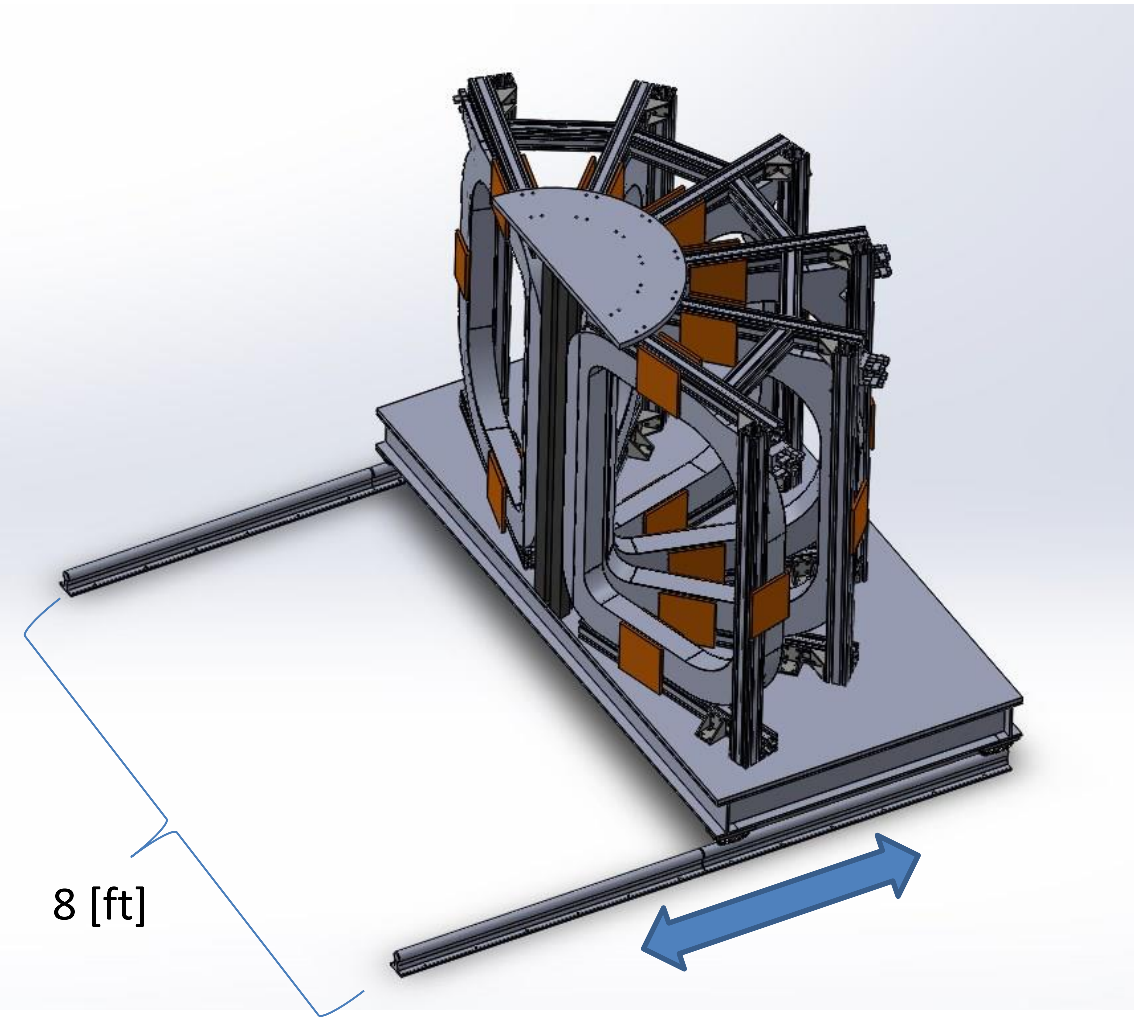


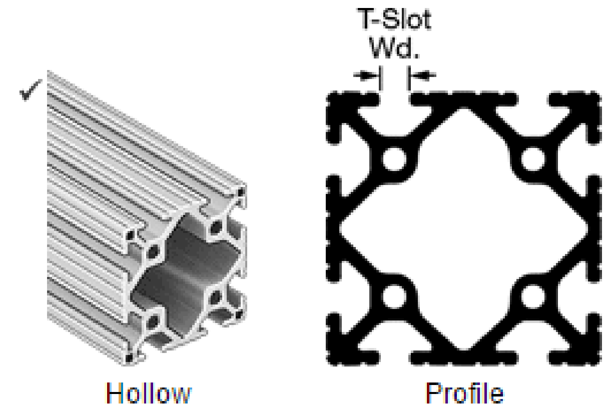
Insulation Max Tresca Stress 13.7 MPa

Vs 26.7 allow

A. Brooks

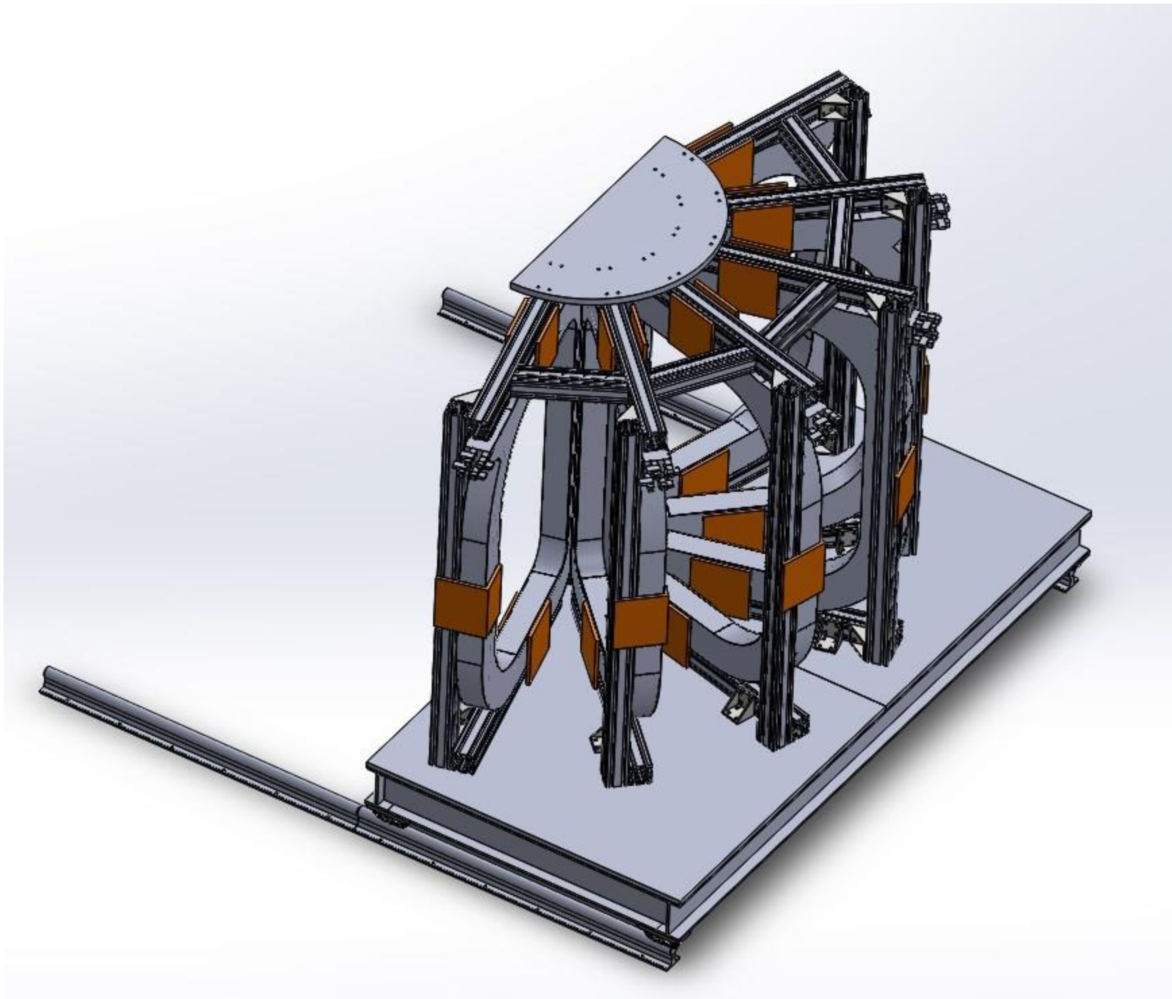
Coil Supports & Stand (1/3)





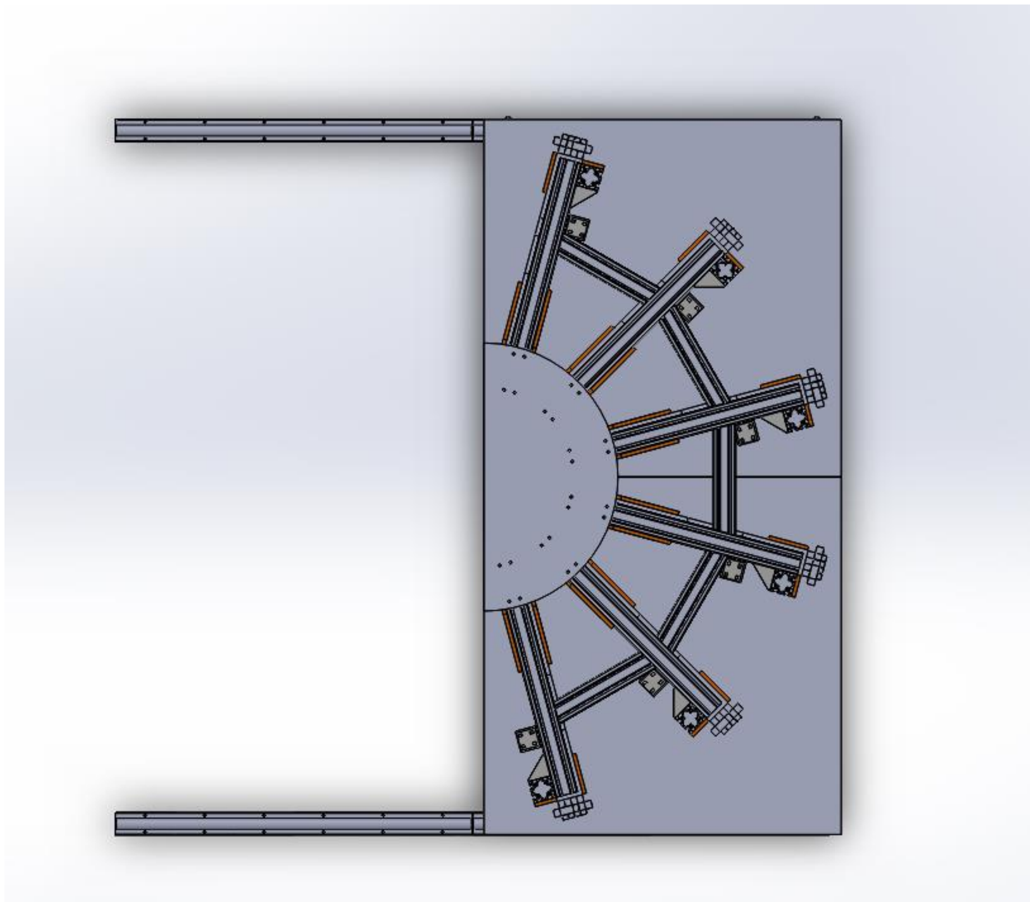
80/20 Quad-Strut
(T-slotted Al Framing & Fittings)

Coil Supports & Stand (2/3)



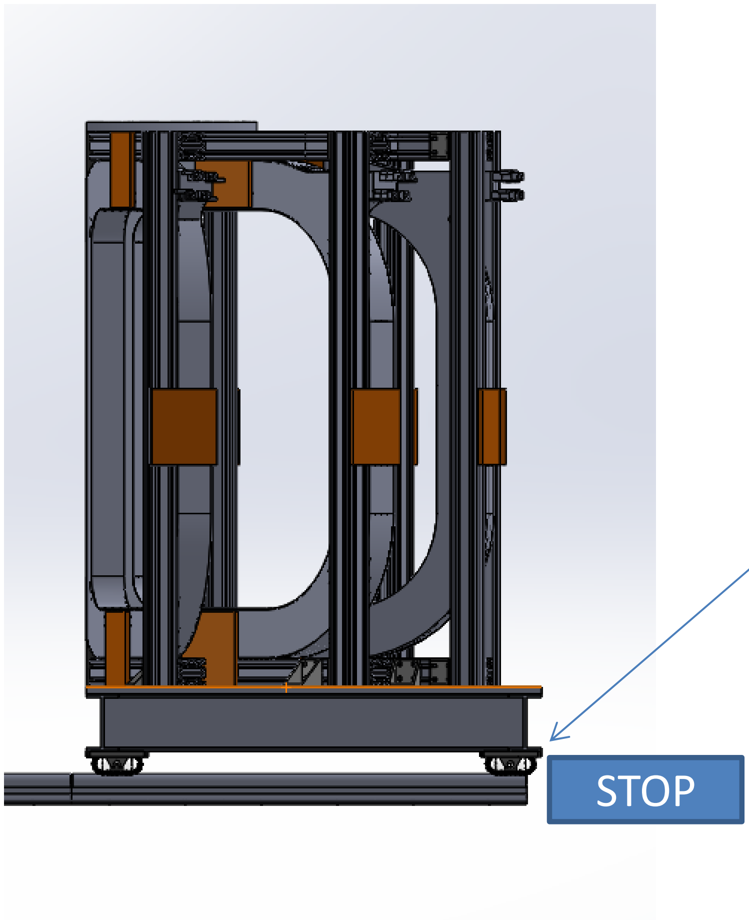
(Outside View)

Coil Supports & Stand (3/3)



(Top View)

Roller Bearings

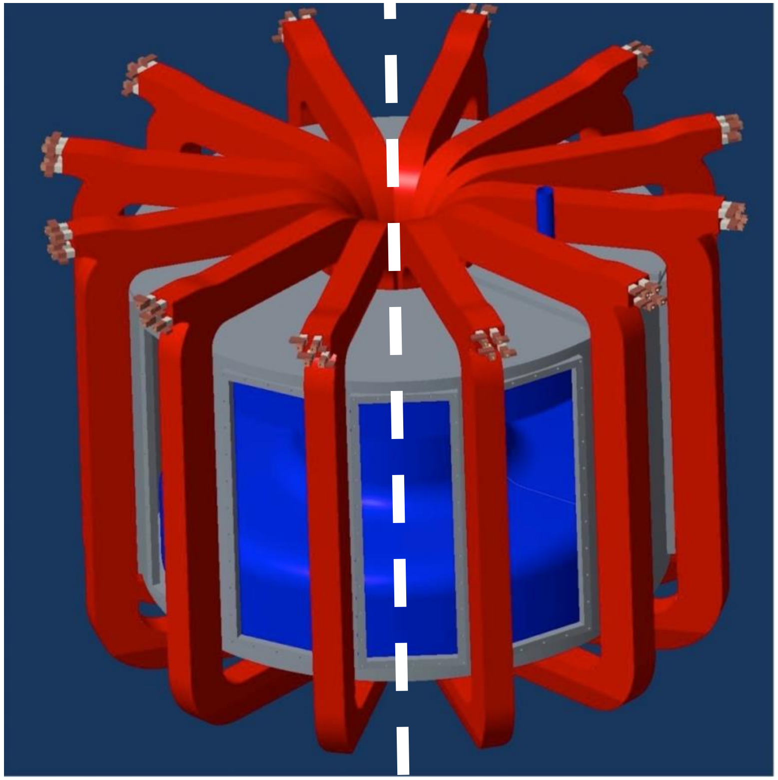


RoundWay® Roller Bearings (RW 24 S)
Dynamic Load Capacity = 6020 [lbf]

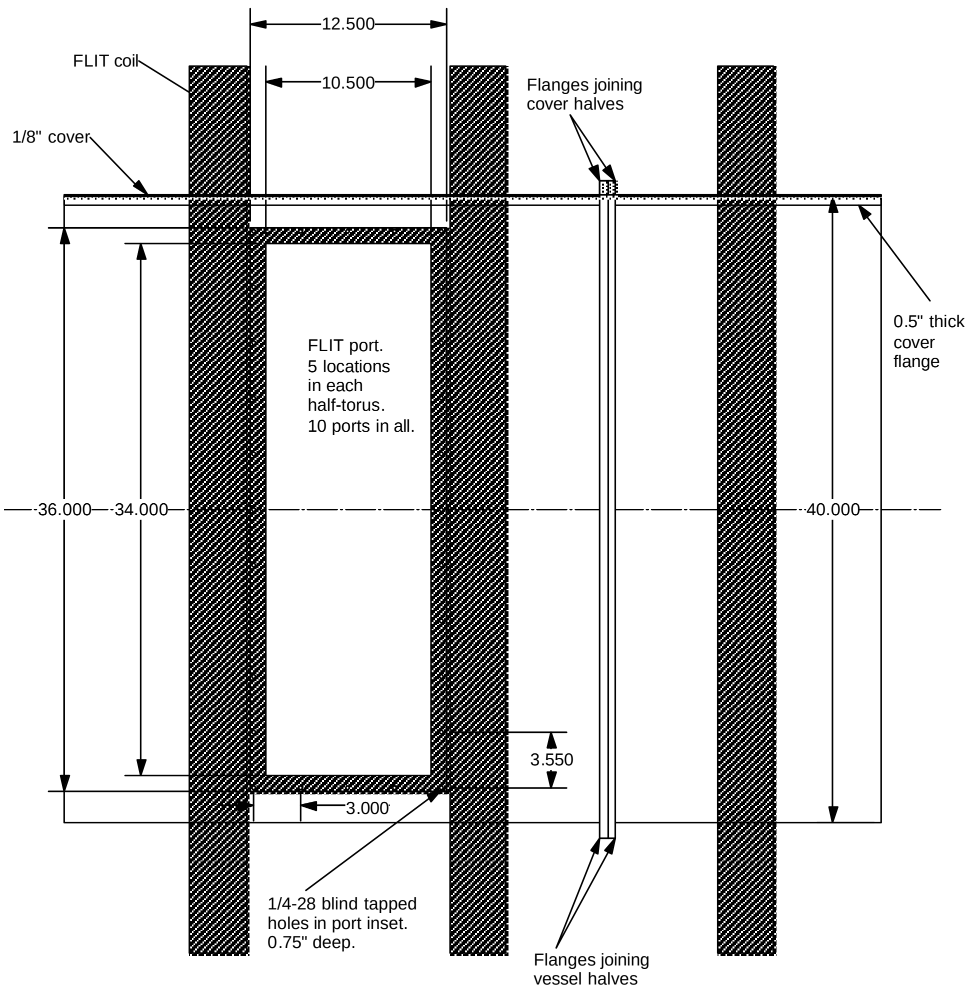
Total Experimental ~ 12,000 [lbf]

Vessel Design

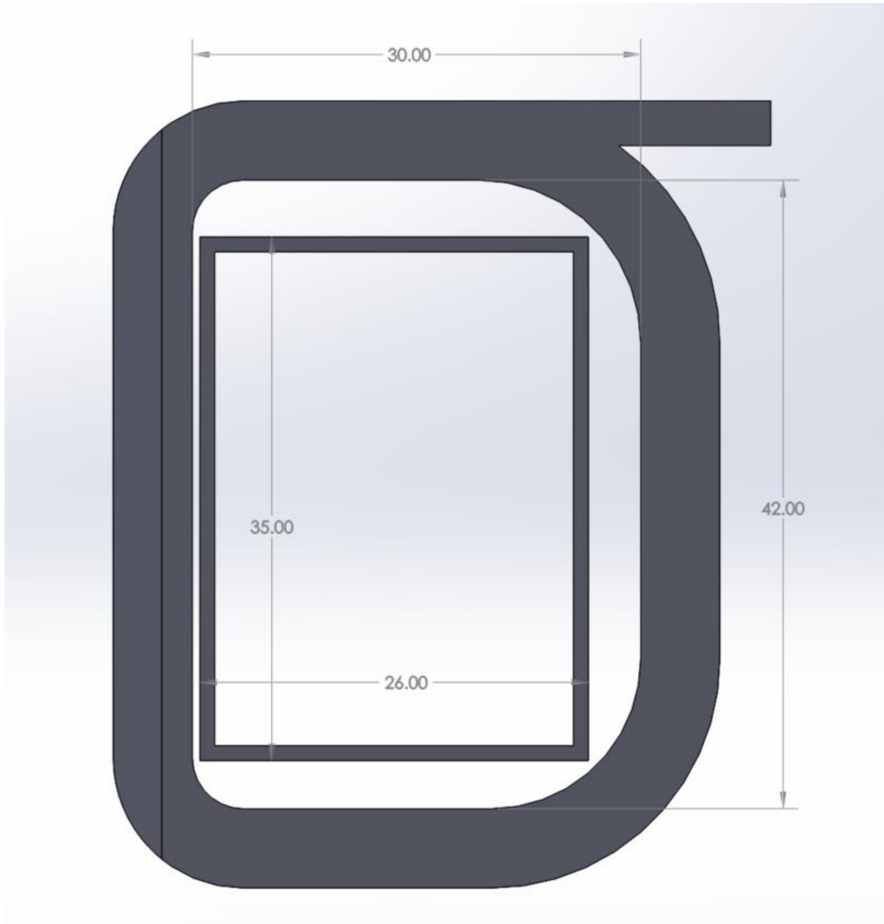
- **Vessel does not necessarily need to hold vacuum or contain high pressure**
  - Hold argon pressure
  - Minimal argon purge
- **2-Part Construction**
  - "C"-shaped to fit within 180°   coil
- **Removable vessel**
- **Large ports for height & flow diagnostics**



Vessel Design



10 Full-Access Ports

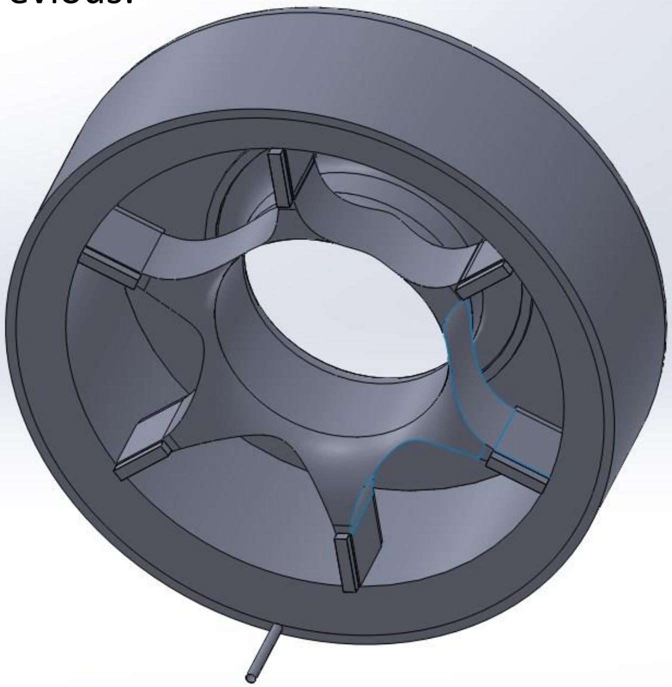


Cross-Section of Vessel in Coil

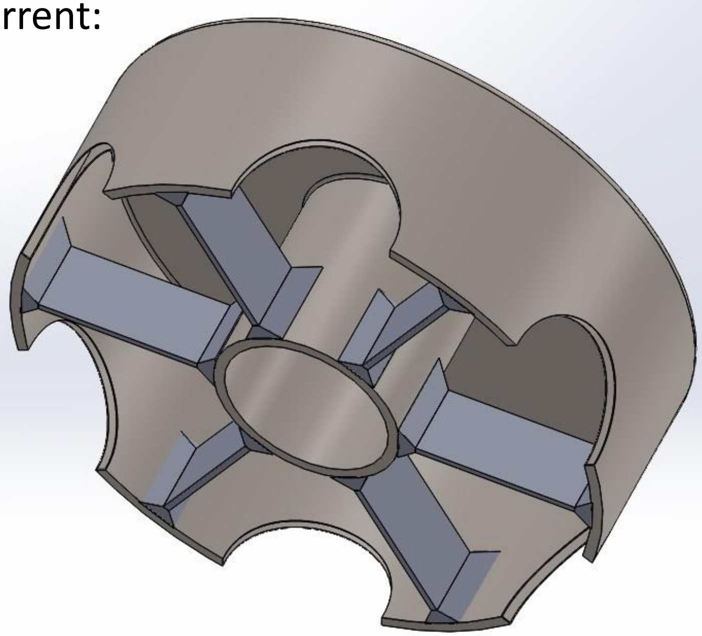
Test Article Optimized

- **Been through various designs**
- **Updated to simple low-cost article**
- **Portions of outer annuls removed to limit galinstan inventory**

Previous:



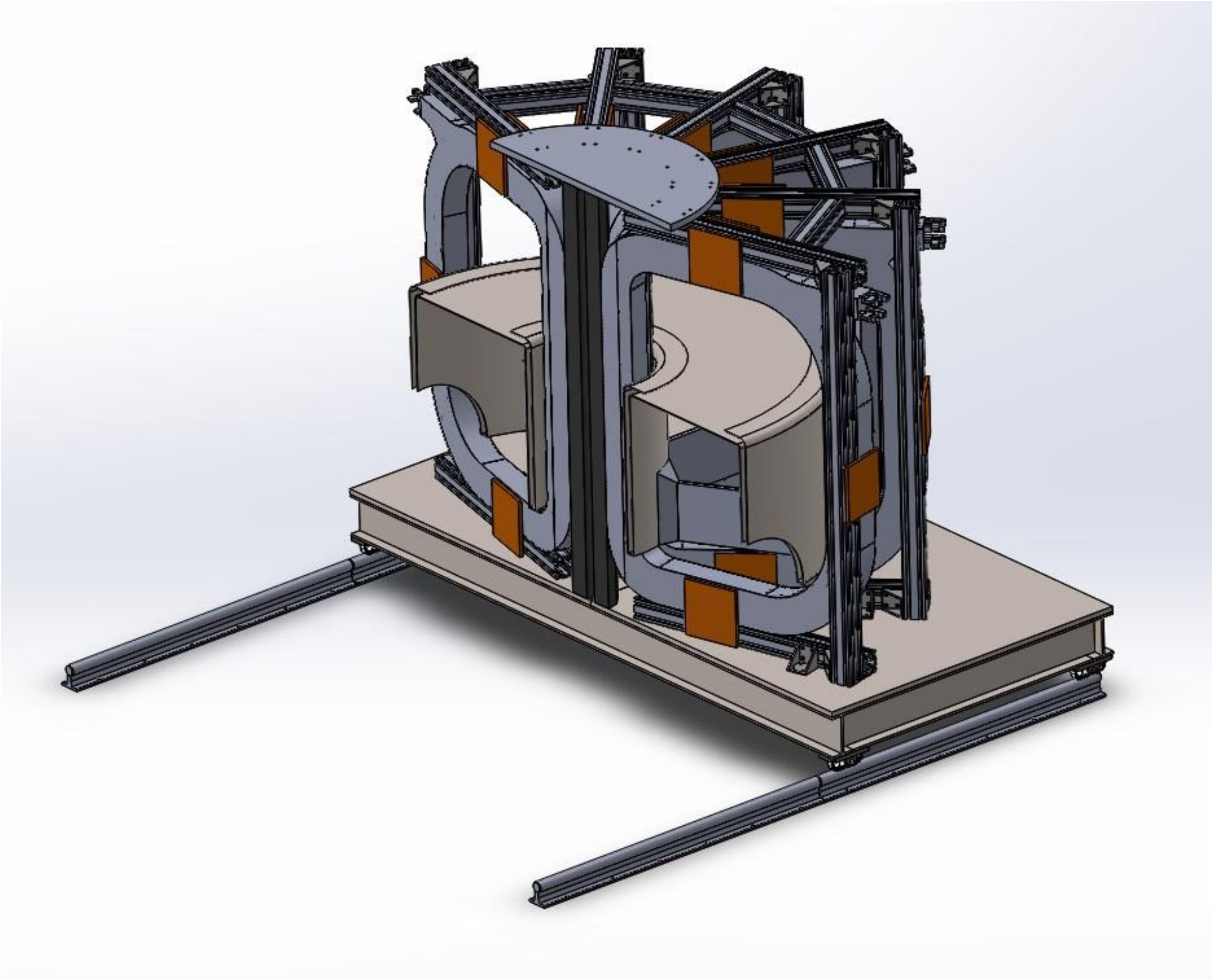
Current:

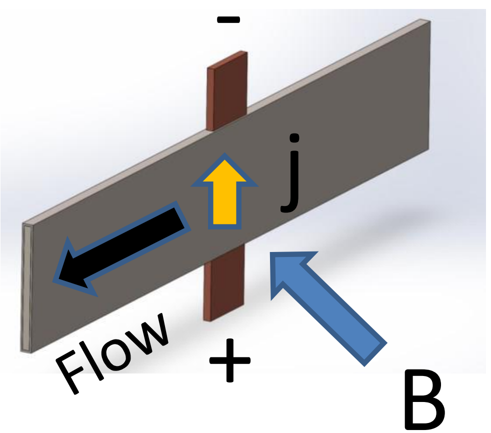


<u>Lead Time:</u>
3-weeks for drawings
12-weeks for fabrication

<u>Cost:</u>
Vendors provided similar pricing
Estimates were within anticipated range

Test Article Modifications Allow for Radial jxB Electrodes

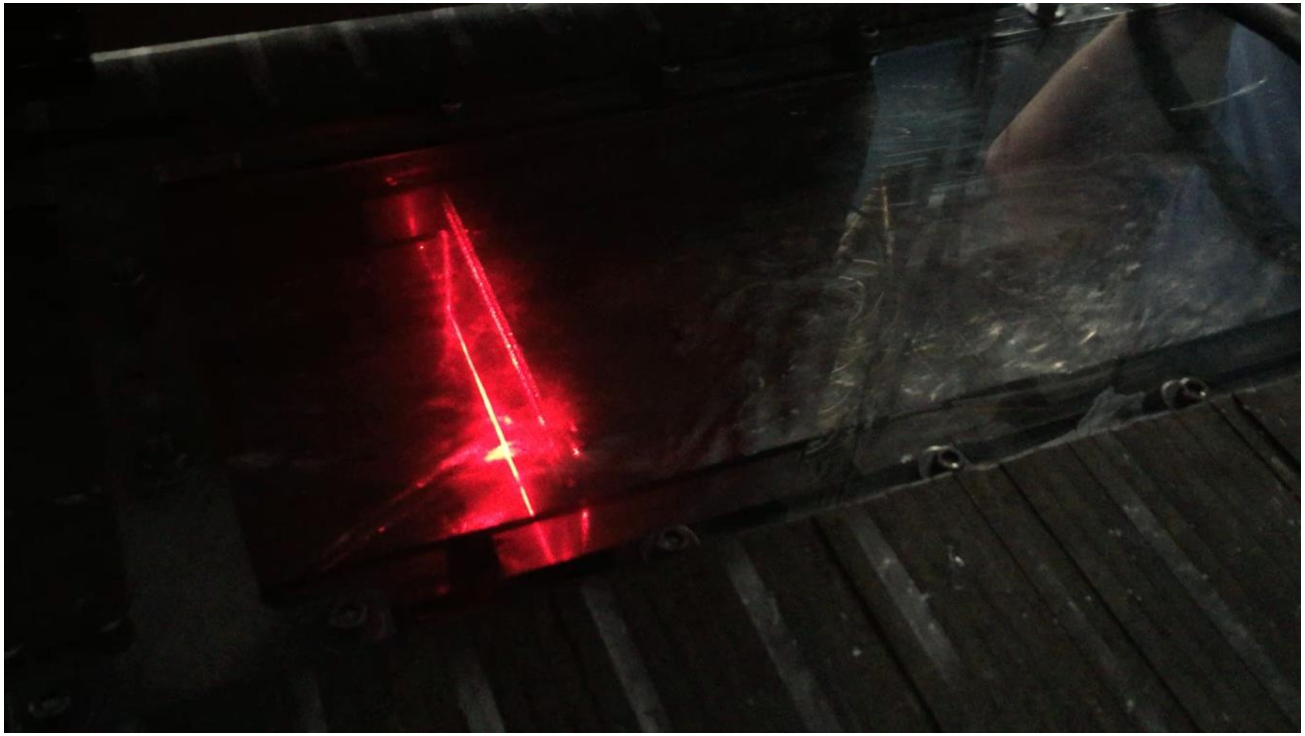


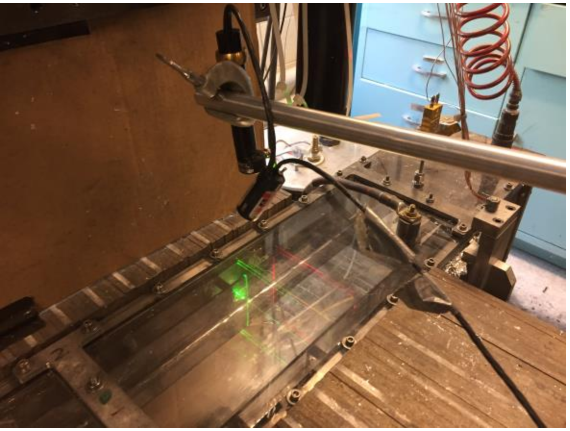


- ***Cross-section showing 6 axisymmetric pumps.***
- ***JxB pumps have no moving parts/seals***
- ***Each pump requires ~ 20 [kA] @ 4 [VDC] for 1500 [gpm]***
- ***Utilizes toroidal field (B ~ 1 [T])***
- ***Compact design reduces cost***

Conclusion and Future Perspective

- FLIT designed and reviewed at PPPL
- LMX is studying the LM flow in a channel flow
- FLIT, initially test open surface flow at up to 10 m/s
- Then, we will compare different nozzles: Jet-Droplet forming nozzles may have advantage
- Later phase to add heat and plasma source (e.g. plasma gun)
- Upgrade for Lithium operation in considered





- Hydraulic Jump instability can be avoided with jxB
- Experimental setup shown