LMX-U studies: model validation and development of the divertorlets concept

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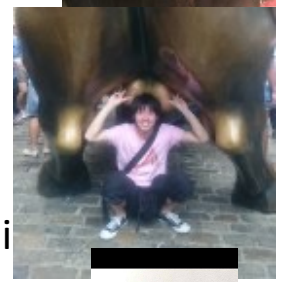
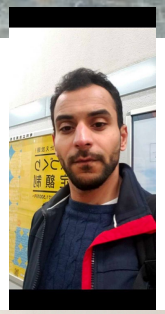
PPPL PRINCETON PLASMA PHYSICS LABORATORY

US-Japan WS, Mar 10, 2022

PPPL – Japan Collaboration on LM





1. Koji Kusumi (Kyoto Univ.): Ran Experiments at LMX-U (Built mini-LMX in Japan)
2. Shoki Nakamura (Kyoto Univ.): Ran Experiment at LMX-U – Adv. Tomoaki Kunugi
3. Jabir Al-Salami (Kyushu Univ.): Simulations with LMX-U data –Adv. Kazuaki Hanada
4. Adam Fisher (Princeton Univ.): Ran Experiments at Oroshhi-2, Japan

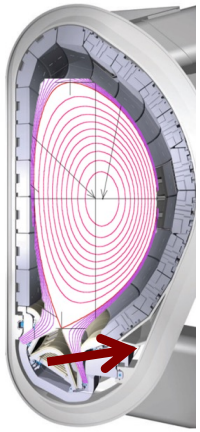
Overview

1. **LM flow in open channel:** **Experiment + Simulations**

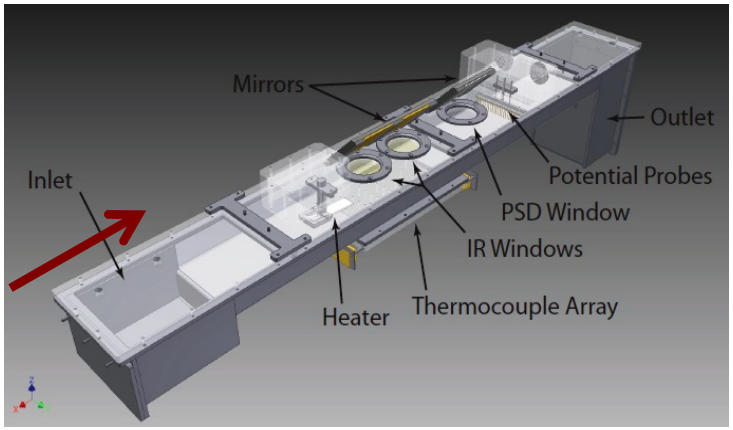
2. **Divertorlets:** **Experiment + Simulations**

3. **Bonus: Cassette configuration**

Flowing Liquid Metal R&D without Plasma



Tokamak



Liquid Metal Experiment (LMX) at PPPL

- LMX operating at PPPL (Kolemen Group)
- **Aim:** Understand LM flow at small scale
- Developing diagnostics and control for LM flow
  - **Surface waves: Measurement and stabilization**
  - **Heat transfer: Enhance mixing using vortex generators**
  - **New Divertor Ideas: jxB forces to control of the LM flow and pumping**

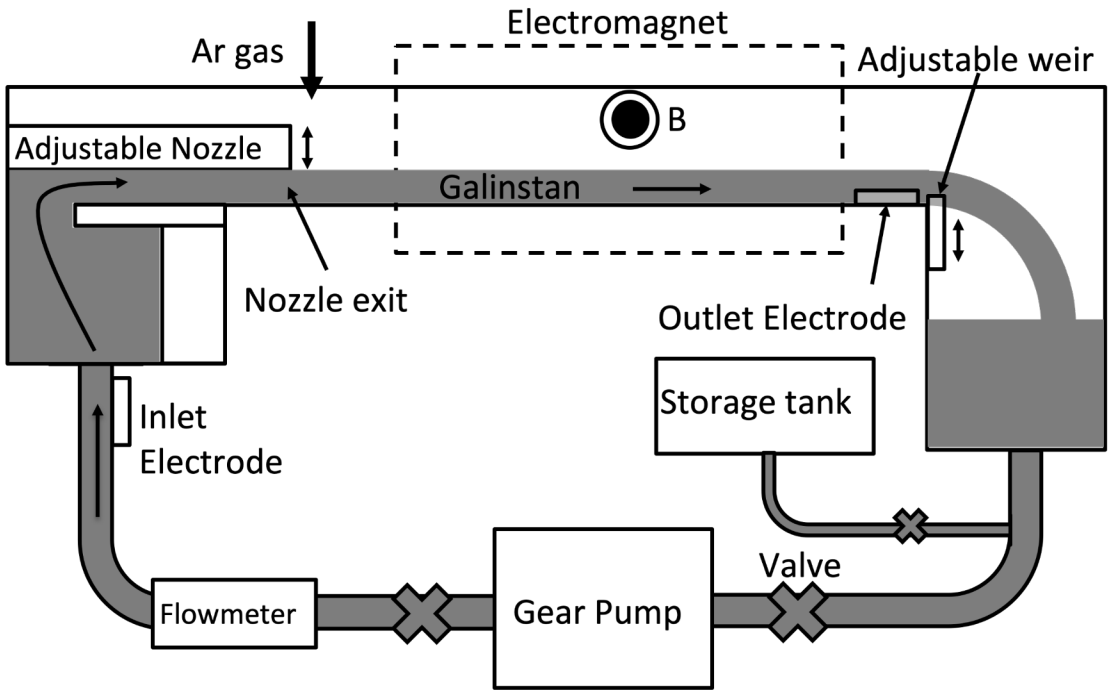
LMX publications by Kolemen group:

1. Kusumi, FEDC 111 1193 (2016)
2. Kusumi, FEDC 72,4, 796 (2017)
3. Kusumi, FEDC 01, 067 (2018)
4. Hvasta, RSI 88 013501 (2017)
5. Hvasta, Nucl. Fusion, (2017)
6. Hvasta, MST (2017)
7. Hvasta, MST (2018)
8. Hvasta. FST (2020)
9. Modestov, Nucl. Fusion, (2017)
10. Fisher, Phys. Fluids (2018)
11. Fisher, NME, 19, 101-106 (2019)
12. Fisher, NME, (2020)
13. Kolemen, NME (2019)
14. Saenz, Nucl. Fusion, Accepted, (2022)

LMX platform

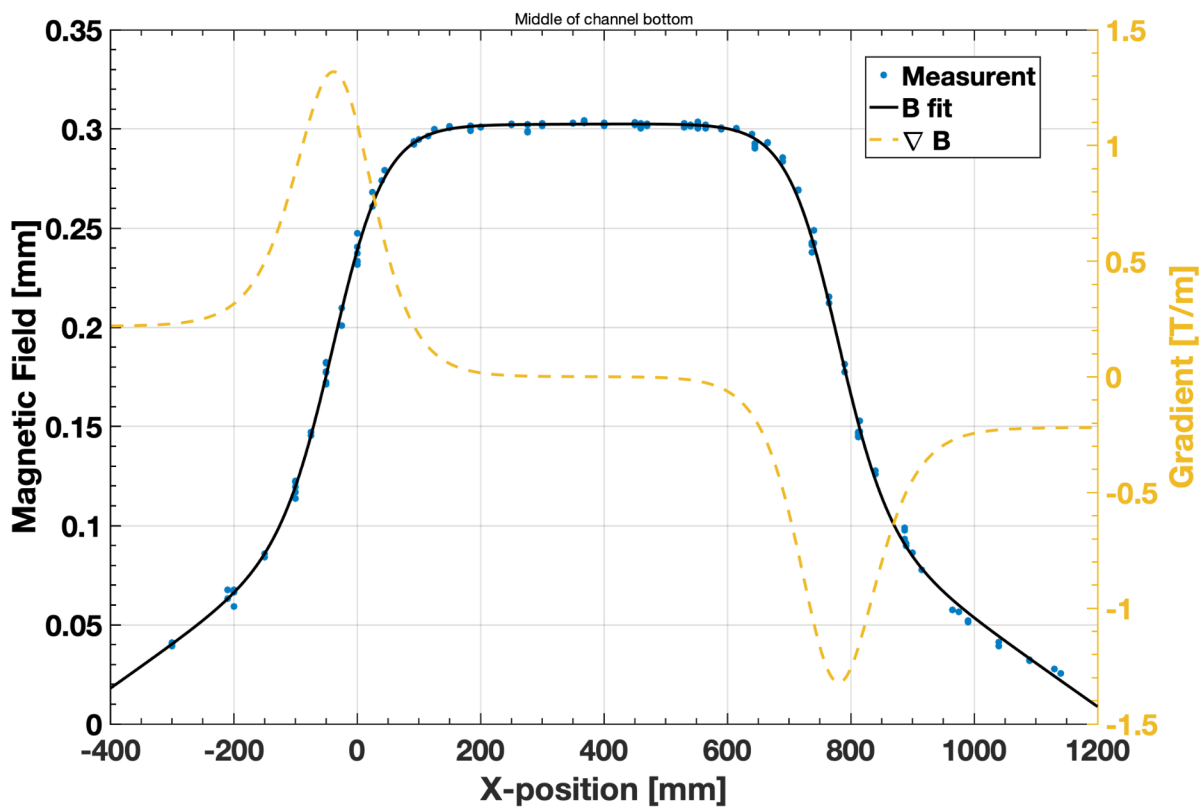
- **Rotary gear pump to circulate Galinstan**
- **B=0-0.33 Tesla**
- **Height-adjustable planar nozzle at inlet allows the inlet flow depth and speed to be changed for a given flow rate**
  - Nozzle height range: 0-20mm
  - No nozzle, LM enters the channel like a fountain
- **Channel liner: acrylic base**
  - Width: 109-acrylic(Cw=0)
- **Inclination angle range: 0-6 deg.**

Movable channel



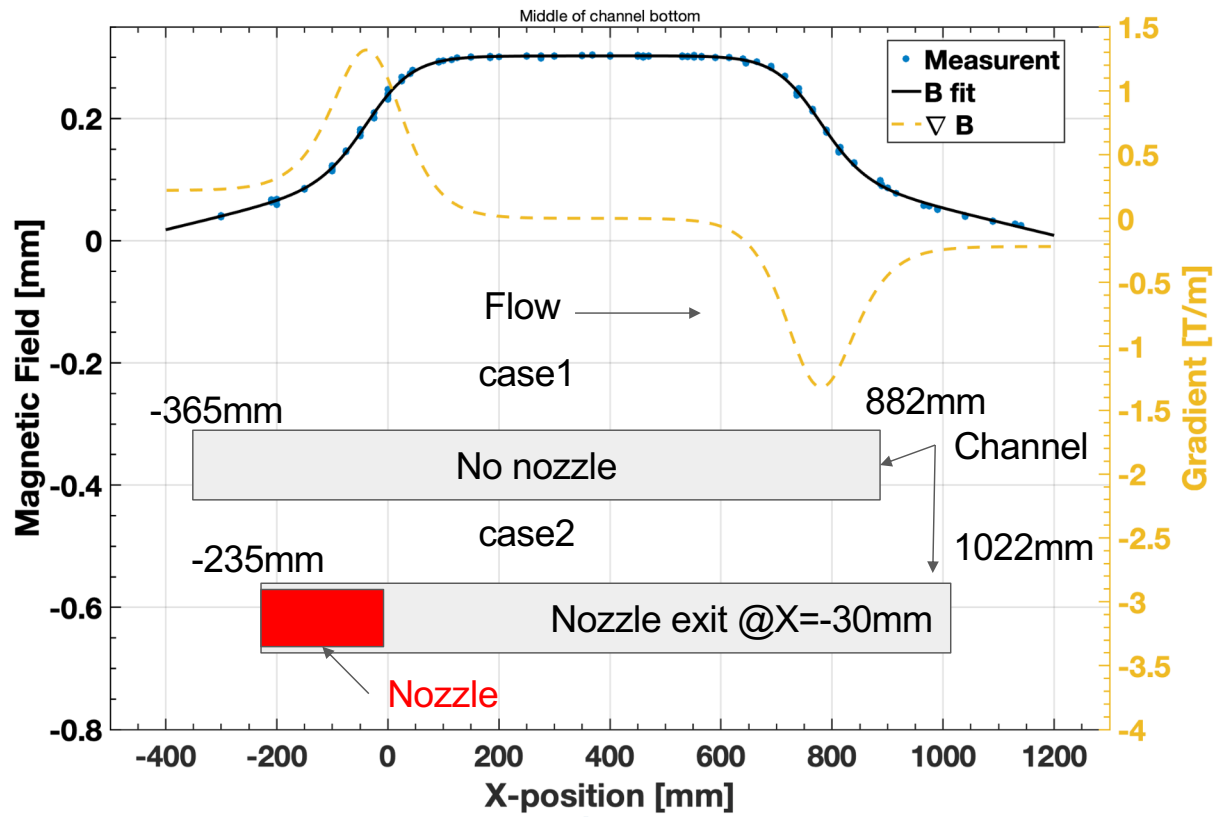
Magnetic field distribution

- Electromagnetic edge:0-740mm
- Uniform region: ~130mm-610mm
- Peak Grad B: X=-40 and X=780mm, ~1.3T/m, NSTX grad Bt ~0.4T/m
- Symmetric



Experiment to study **MHD Drag**

- Case 1: channel covers two Grad_B peaks
- Case 2: move channel close to the uniform region, nozzle applied, one Grad_B peak, less fringe
- Case1: Brass, SS, Cu, and plastic
  - Electric conductivity (10.E6 Siemens/m) Cu= 58.7, Brass=17, SS316=1.32, Galinstan~3.46, Li 10.8
- Case2: Brass and SS liners



MHD effect observed with Brass liners

- Nozzle vertical ~10mm, nozzle exit position x=-30mm, 16.3L/min, B~ 0.3T vs 0

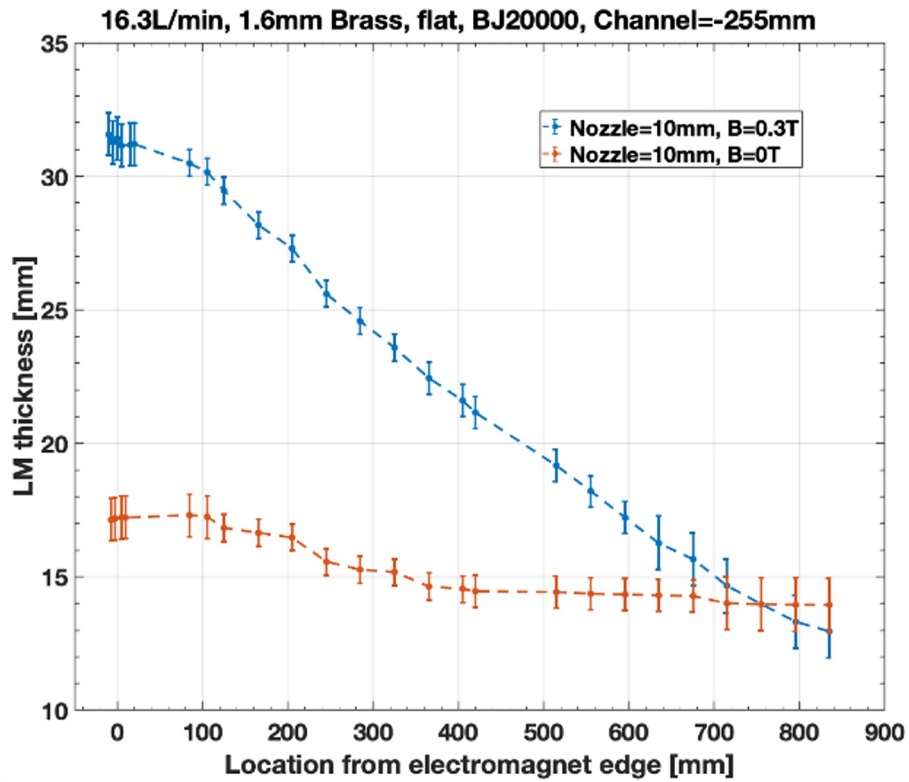
- Hydraulic jump(HJ) near the nozzle exit without magnetic

  Re~5200; Fr=0.82(nozzle), 0.37(X=85mm)

- HJ disappears with B~0.3T

  Ha~590, Re~4270

- Deformed surface, similar as the non-nozzle experiment



Magnetic strength affects the LM pile up

Brass wall

Measurement location: X~85mm

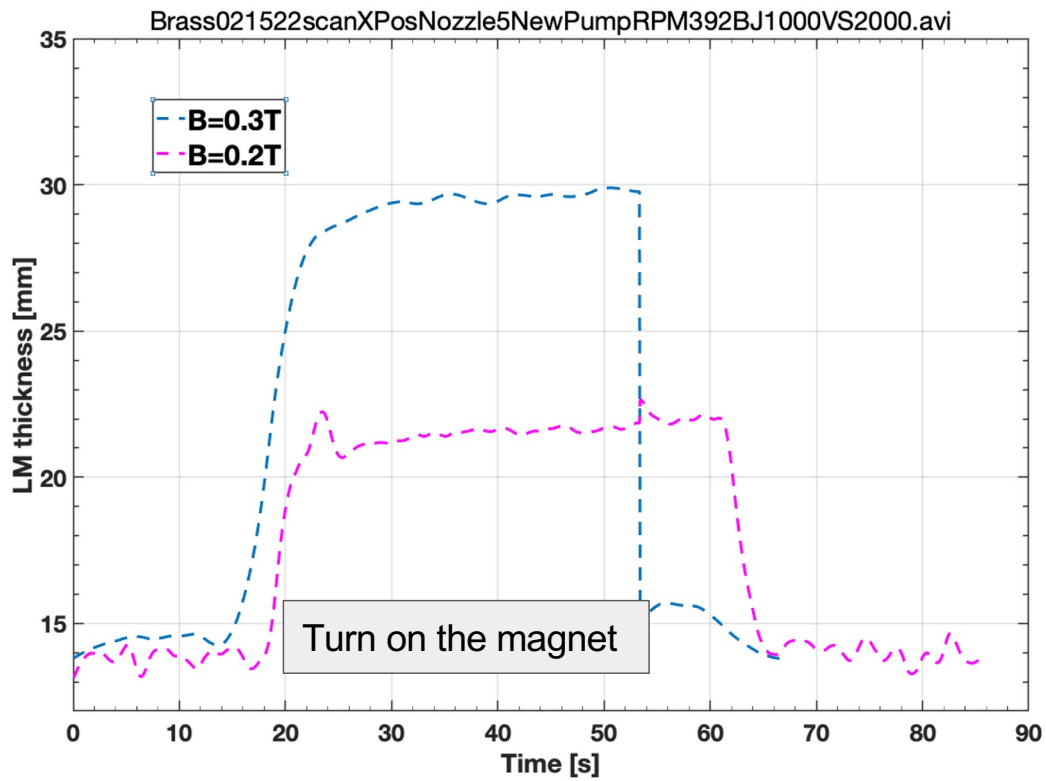
Same flow rate

Nozzle vertical gap~5mm

0.3T(Ha~594) Δh ~16mm

0.2T(Ha~376) Δh ~7.5mm

B^2~2.23X, Δh ~2.1X



Higher flow rate→ larger liquid height change

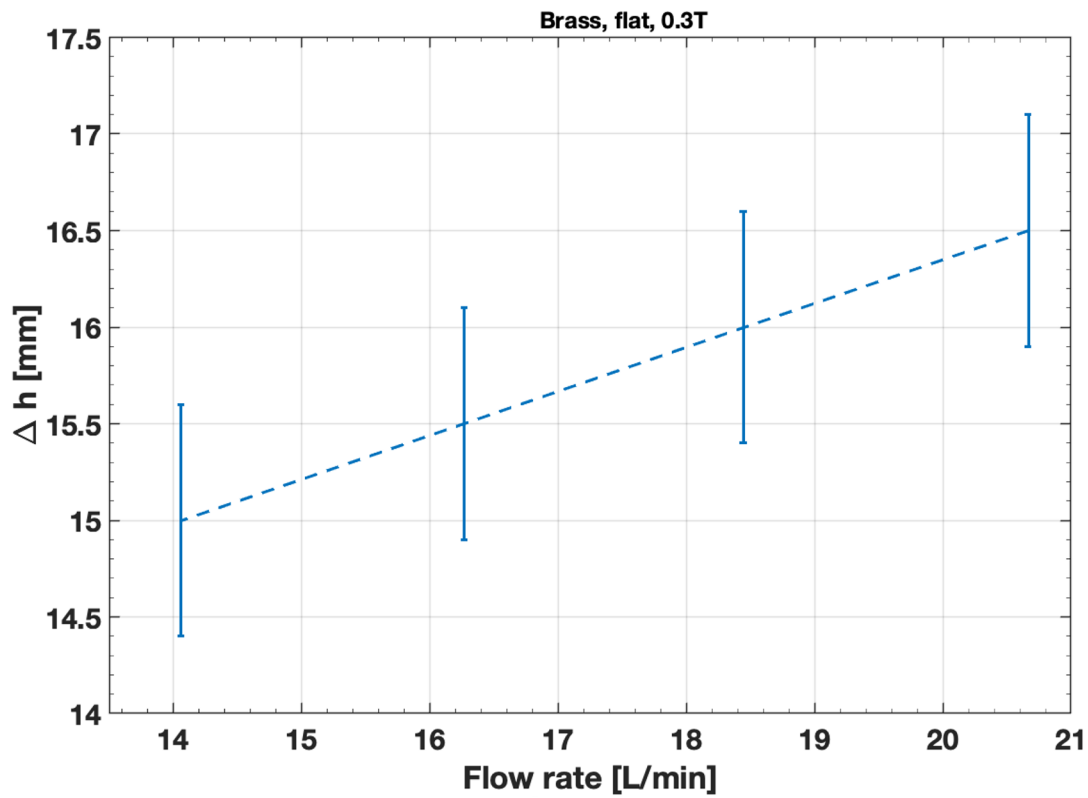
Height measurement location X~5mm

Brass wall

B~0.3T

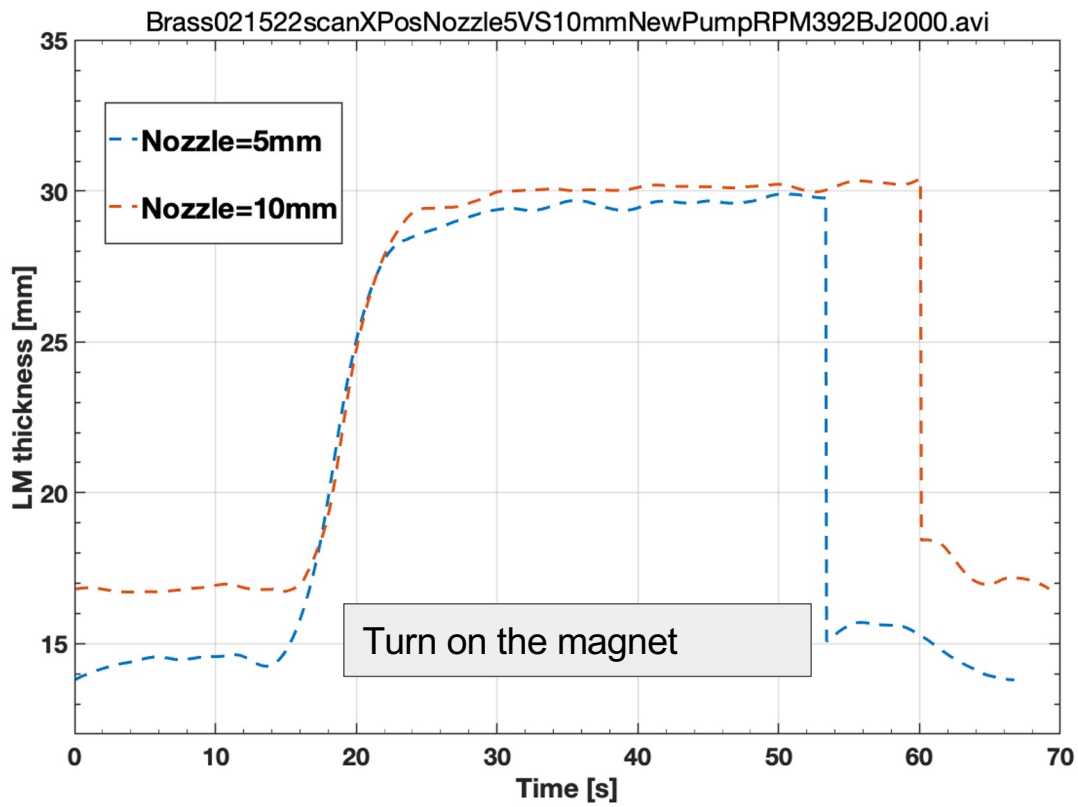
Flow rate~14.1: △h =15mm

Flow rate~20.7: △h =16.5mm



Nozzle gap has minor effect on the LM height

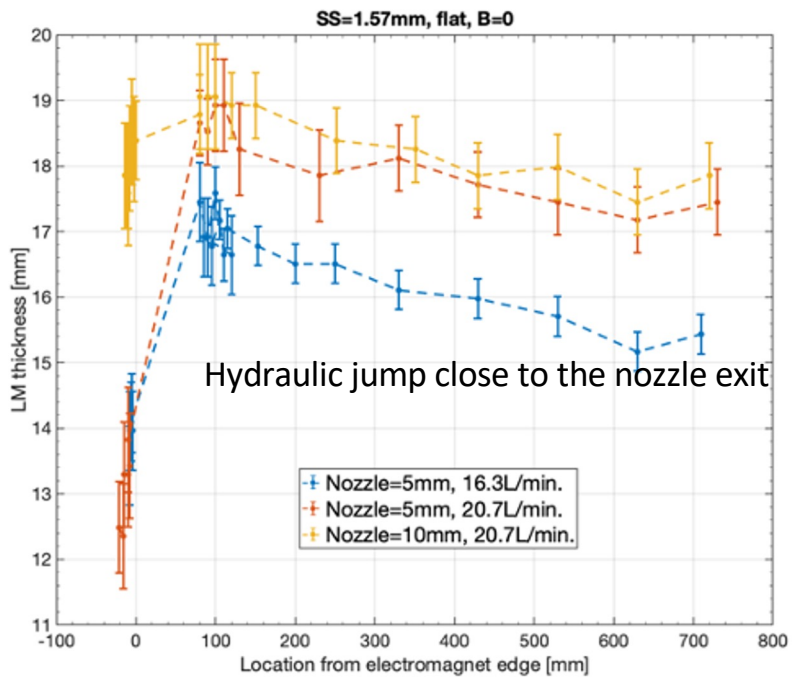
- Nozzle gap=5 and 10mm
- Height measurement location X~85mm
- Brass wall
- B~0.3T
- Flow rate~ 16.3L/min

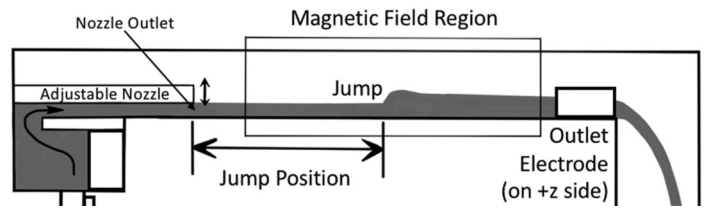


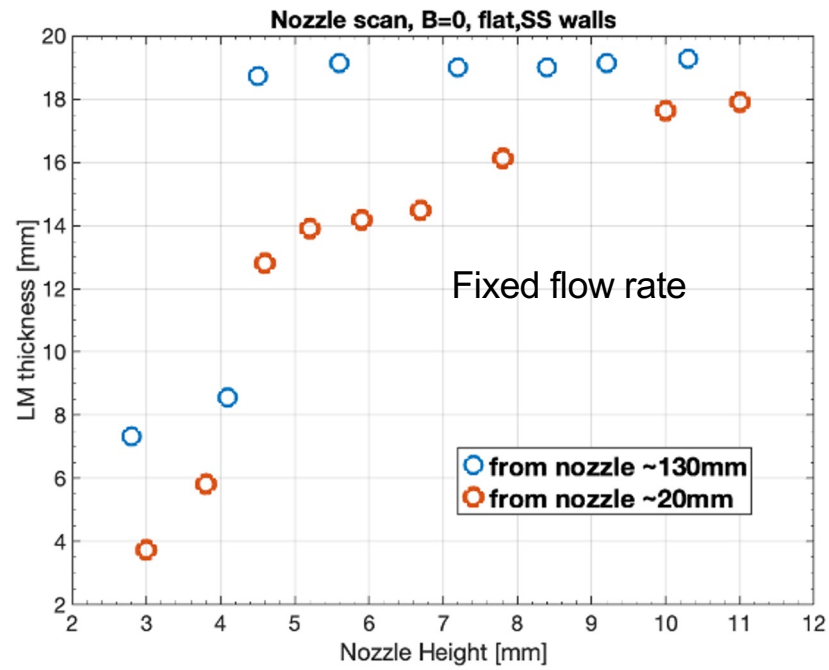
Occurrence of hydraulic jumps makes it difficult for the nozzle gap to control flow velocity

B=0: Nozzle gap>~4.5mm, Jump position~130mm

No HJ with magnetic field

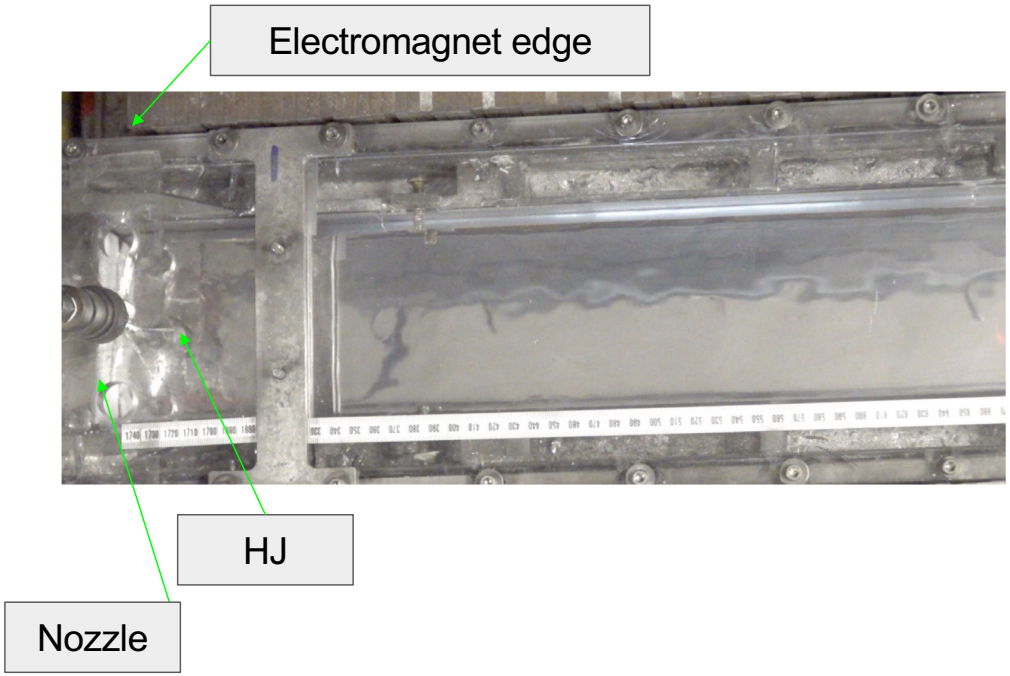


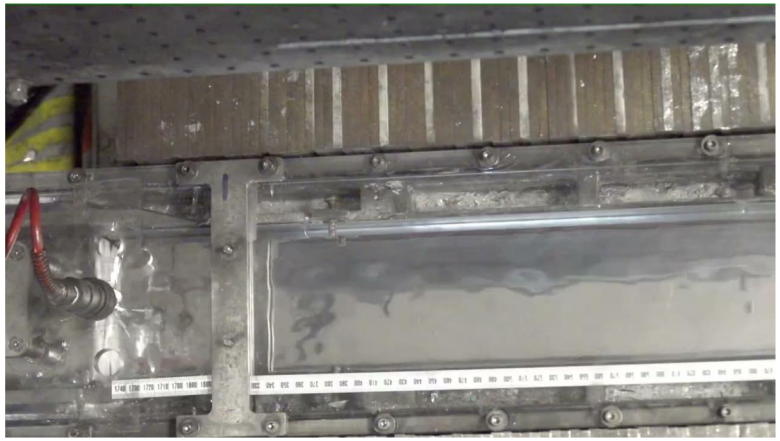




LM flow after the HJ looks smooth

No magnetic; 16.3L/min; nozzle=10mm, full width flow; uniform height along width





Material conductivity is a key factor for LM thickness

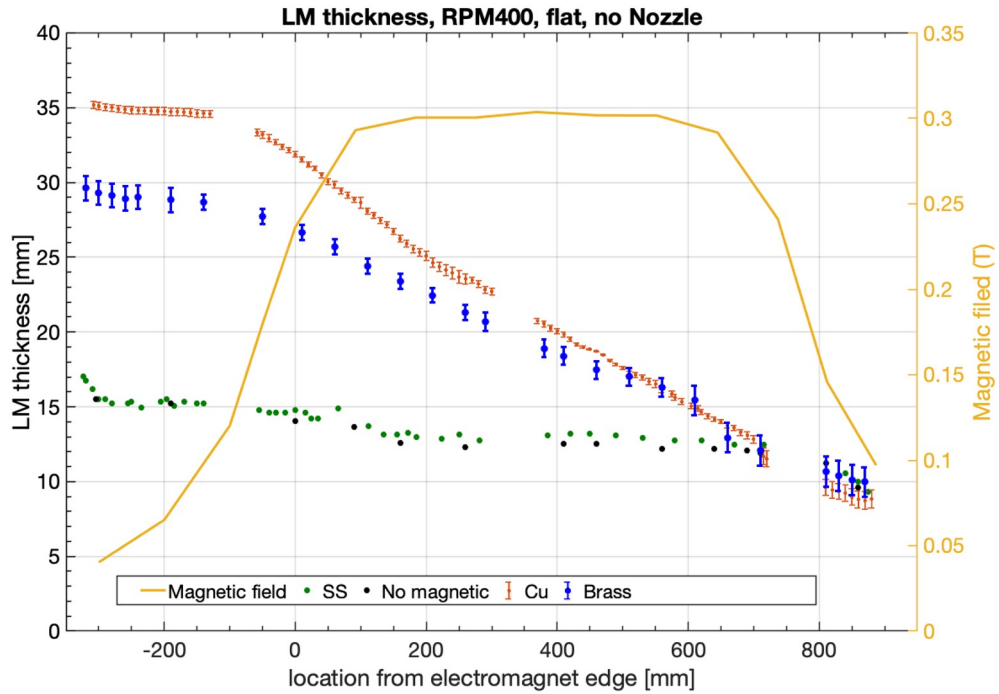
Case 1, B=0.3T, 16.3L/min, no nozzle

Electric conductivity (10.E6 Siemens/m) Cu= 58.7, Brass=17, SS316=1.32, Galinstan~3.46, Li 10.8

Closed flow:

$$c_w = \frac{t_w \sigma_w}{b\sigma}$$

$$\Delta p = \lambda \frac{l}{2b} \frac{\rho U_m^2}{2} \quad \frac{\lambda}{\lambda_0} = \frac{1}{3} \frac{c_w}{c_w + 1} Ha^2$$



OpenFoam simulations in reasonable agreement with experimental results

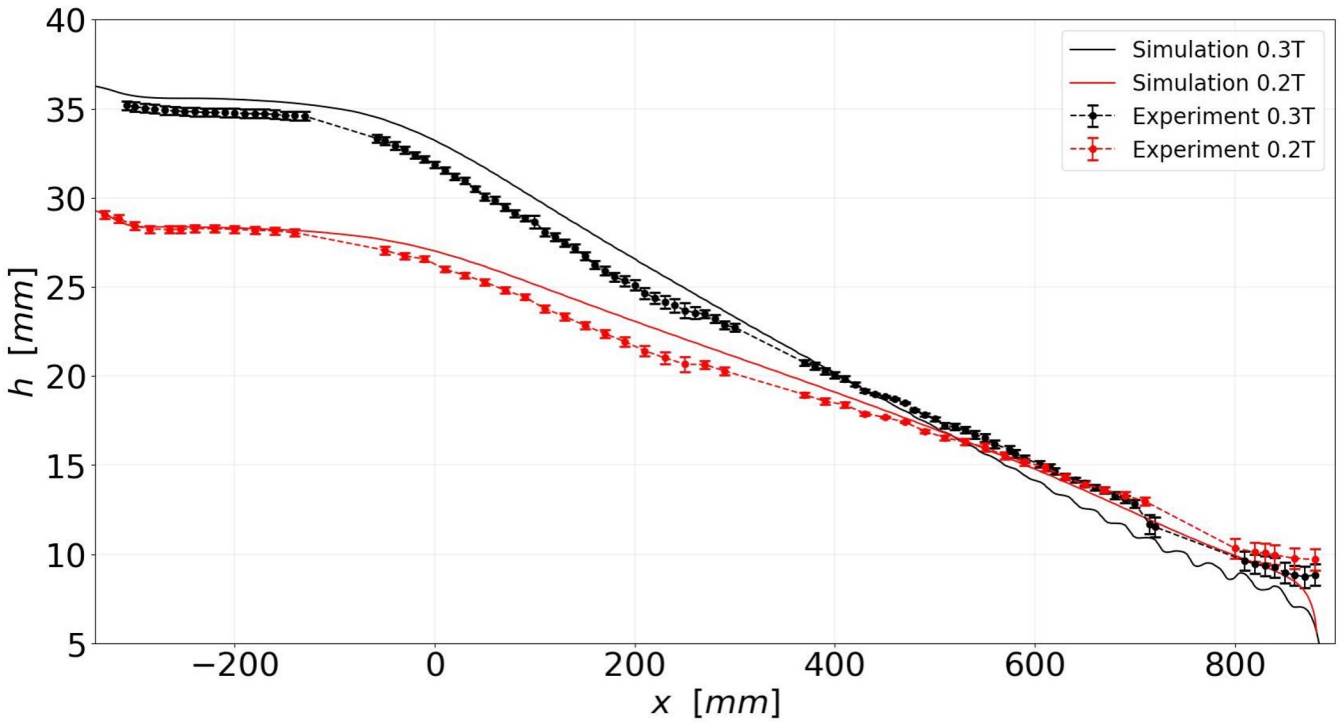
2.36mm Cu

No nozzle

Channel -365mm

Flow rate ~16.3L/min

Full 3D MHD



By J. Al-Salami

Some Thoughts

- ***MHD drag leads to liquid to pile up at the nozzle for open channel flow with walls***

  1. ***Nozzle height does not seem to effect this much***
  2. ***Nozzle distance to the magnetic field does not seem to effect this much***
  3. ***Bernoulli type of equation can explain this behavior***
  4. ***Simulations with no hand tuned knobs can reproduce this result***

- ***Next, I will present two ideas to overcome this issue:***
  - ***Divertorlets***
  - **Running currents between walls/cassette**

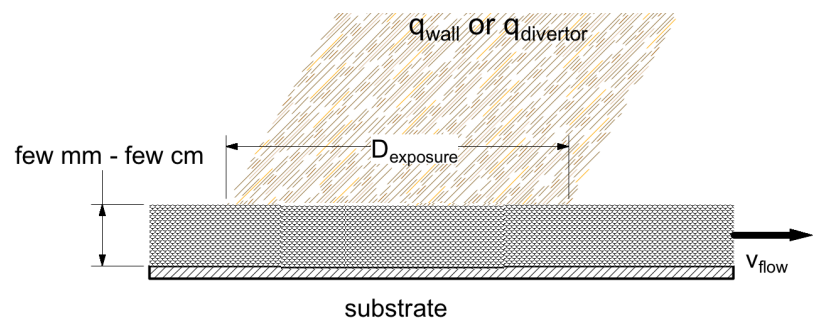
LMX as testbed for novel Divertor Design for Low-Recycling Regime Tokamak

- ***Non-evaporative*** **LM divertor is needed for low-recycling regime tokamak**

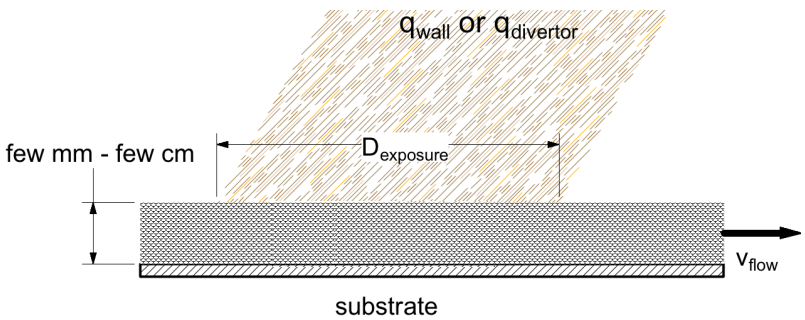
- **Issues:**
- **1) Safety issues related to a high lithium inventory;**
- **2) The power requirement for pumping of the lithium against MHD drag;**
- **3) The stability of open channel LM flow in high speeds under MHD forces; and**
- **4) Separation of tritium from LM.**

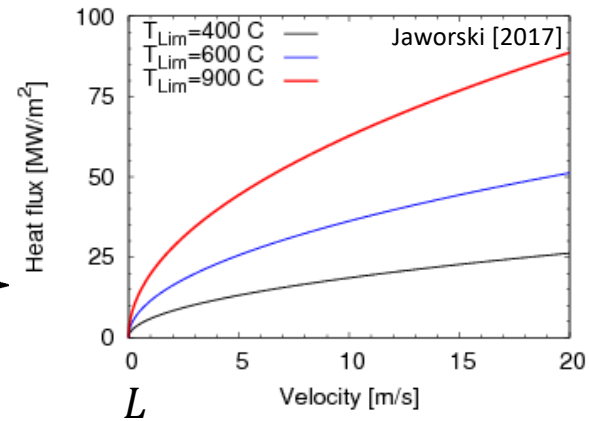
- **We need**
  - **Less power requirement**
  - **Less Li inventory**

- **Solution:**
  - **Alternative designs**



Can we reduce velocity requirements?

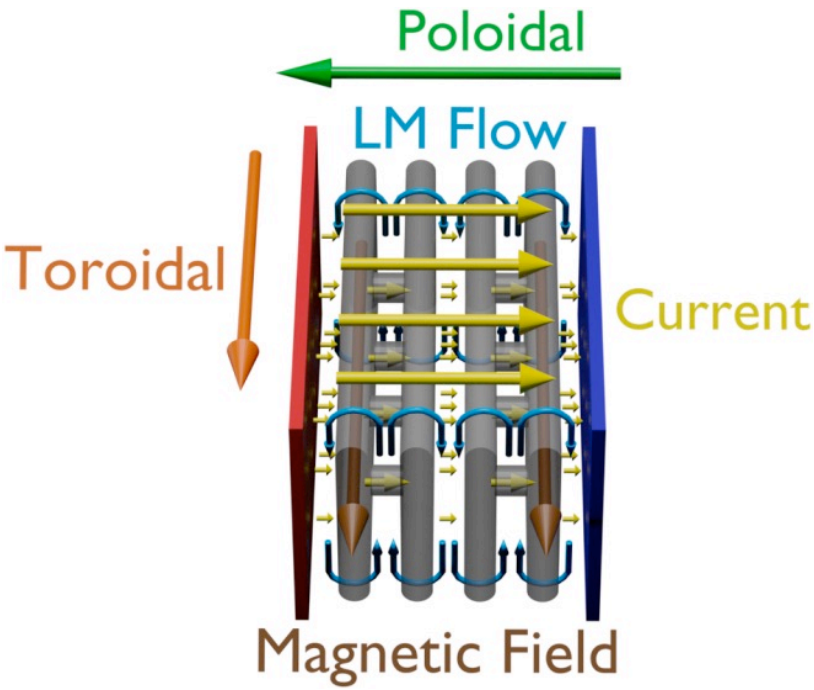




$$t_{cr} = (\Delta T/2q)^2 \pi k \rho c_p \ , \qquad v = \frac{L}{t_{rc}}$$

- ***Non-evaporative*** **LM divertor requires fast flow ~1-20 m/s**
- **This is for a flow across standard length divertor (10s cm)**
- **Can we reduce the speed?**
  - **Less power need**
  - **Less Lithium in the reactor**

Divertorlets (Fisher, Saenz, Sun)



Toroidal Divertorlets V2 design

$$t_{cr} = (\Delta T/2q)^2 \pi k \rho c_p$$

$$v = \frac{L}{t_{rc}}$$

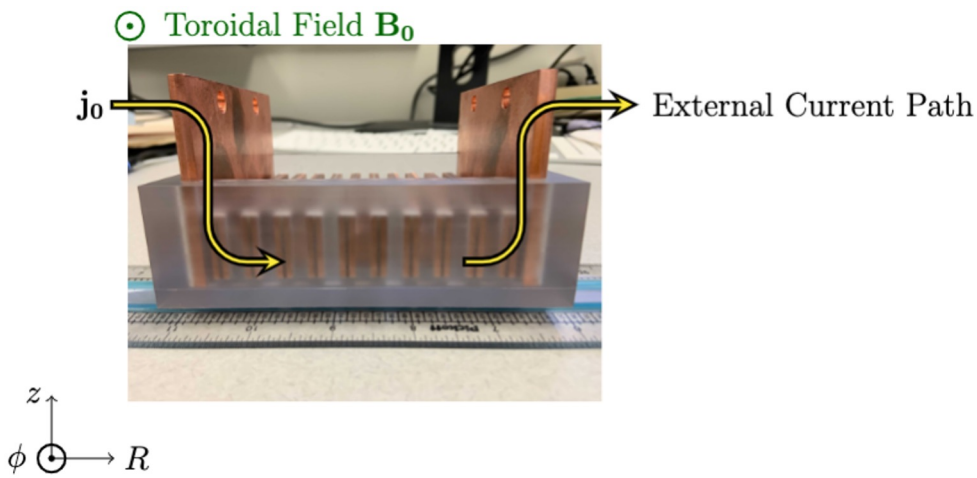
- **↓ L➔ ↓ v (m/s ➔ cm/s)**
- **Reduce drag, reduce splashing**
- **Possible to use simpler flowing setups**

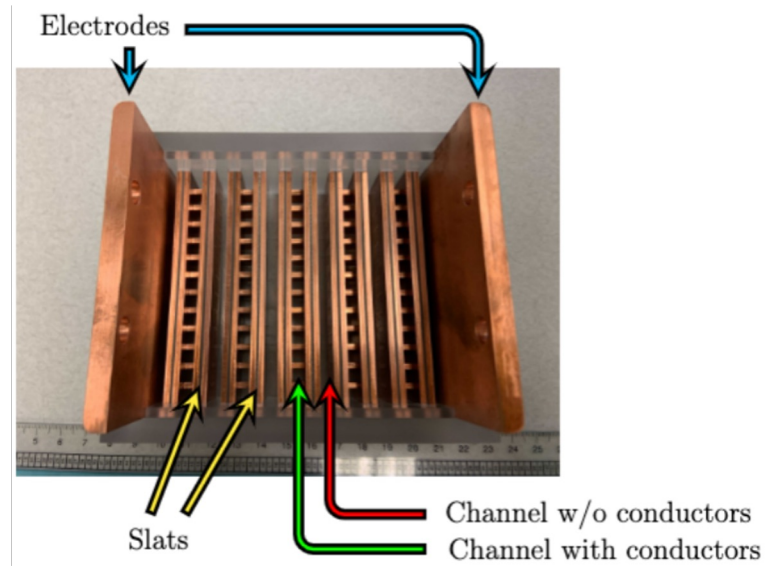
- **Looking at many options**
- **Mainly use of jxB**

- **Divertorlet: J_{pol} that runs through LM and metal ➔ Induces GradP between channels**

1) Fisher et al. NME 2020, 2) Saenz et al., Experimental validation of the toroidal divertorlets concept NF 2022

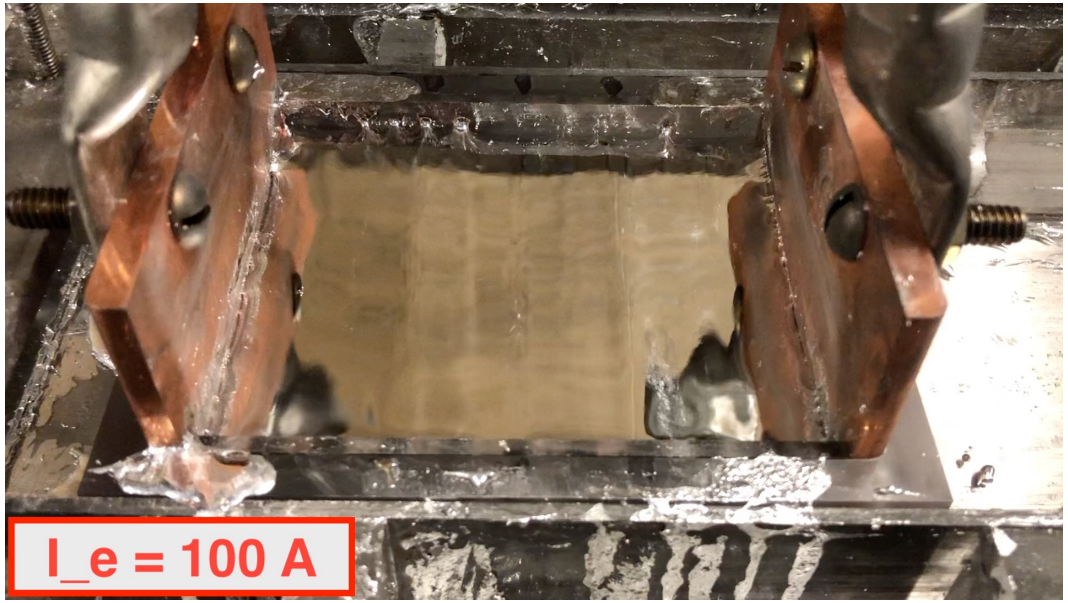
Divertorlets prototype for experiments





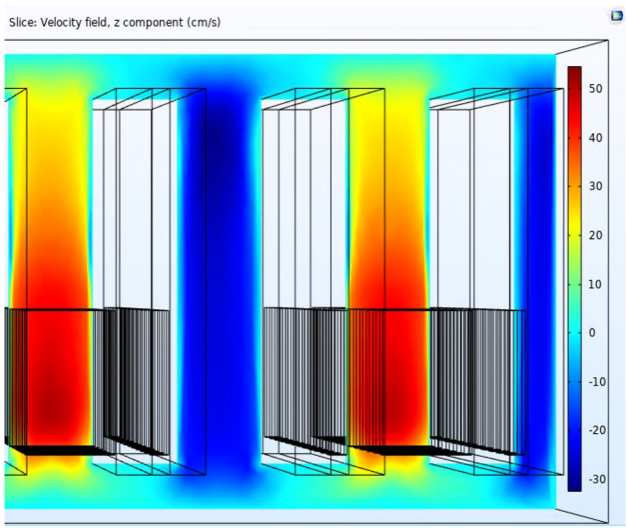
Experimental tests of divertorlets in LMX

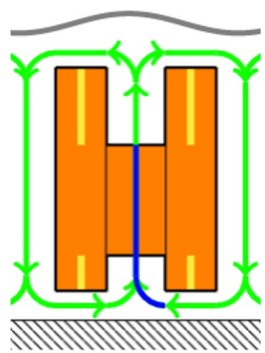
- Peak-valley deformation on the surface
- For smaller channel size, surface tension should get rid of deformations



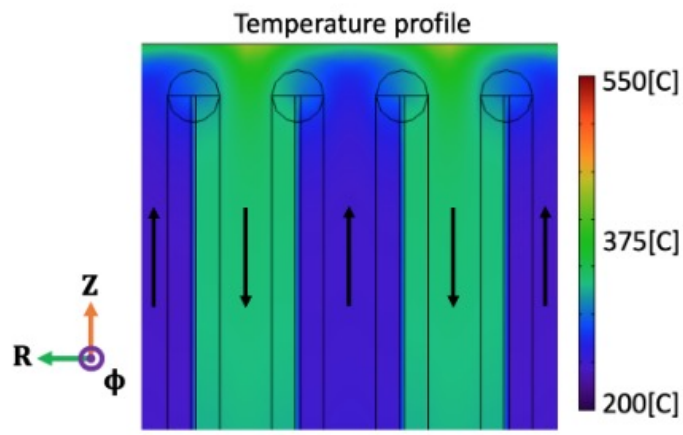
Simulation Results

- COMSOL simulations confirmed the desired flow loop around slats.
- Average upward velocities were compared to experimental results.
- Simulations with heat flux at free surface show stable operation.



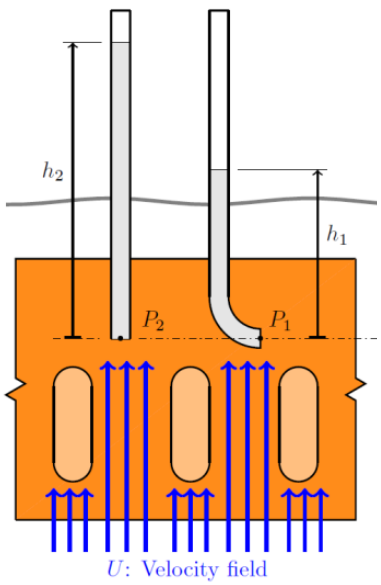


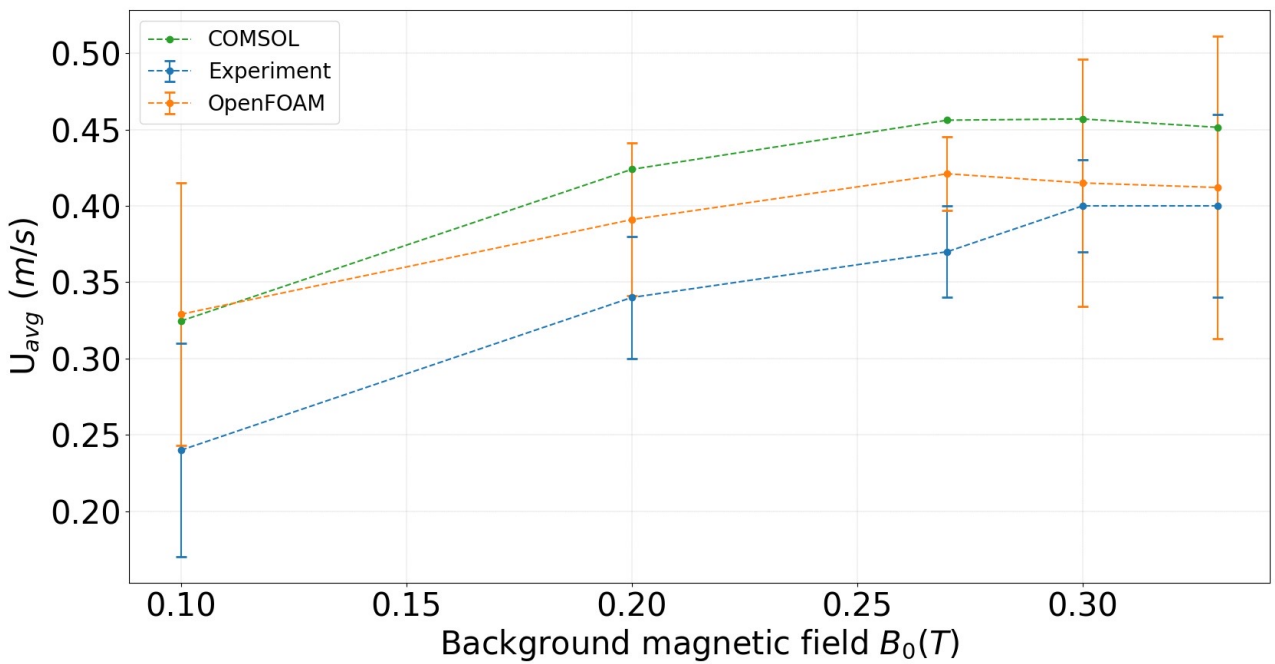
Contour used for average velocity



Simulation vs. Experiments

$$\|\mathbf{U}\| \approx \sqrt{2g\Delta h}$$





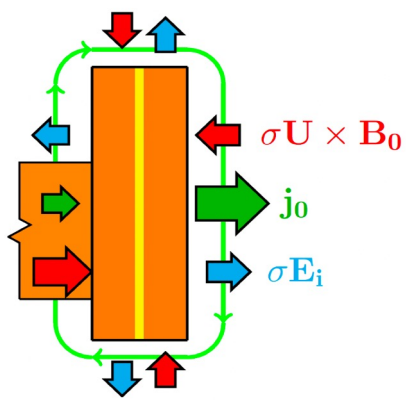
COMSOL: F. Saenz; OpenFOAM: J. Al-Salami

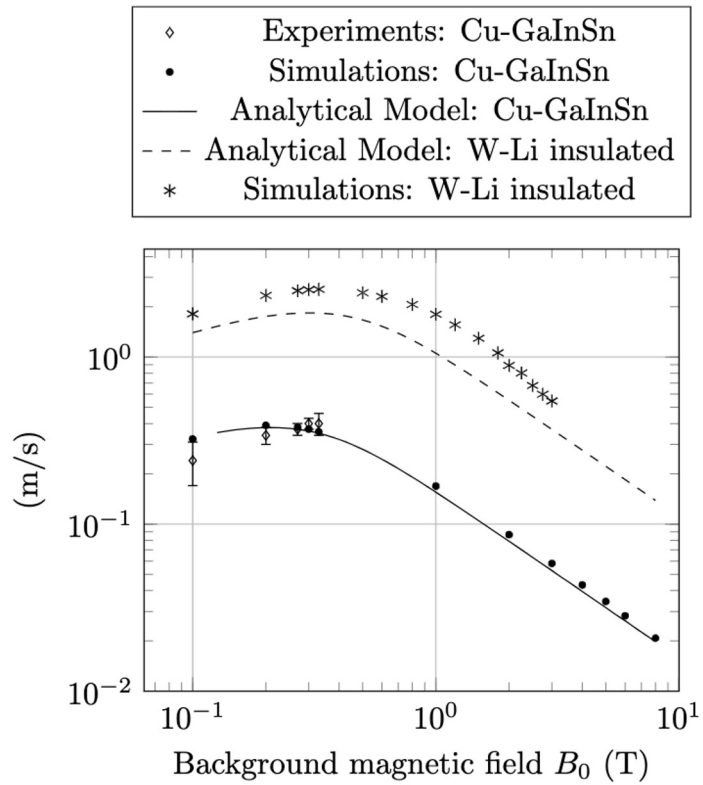
Analytical model

$$\Delta P_{j\times B} - \Delta P_{\text{visc}} \approx 0$$

$$\Delta P_{j\times B} \approx (\Delta j_0)_{\text{avg}} B \cdot h_s + \sigma \oint_C (\mathbf{E_i} + \mathbf{U} \times \mathbf{B}) \times \mathbf{B} \cdot dl$$

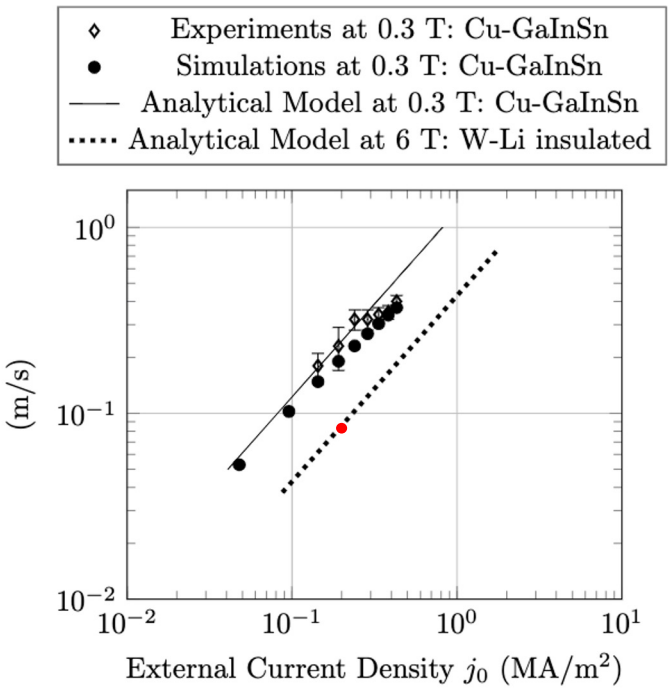
$$\Delta P_{\text{visc}} \approx \frac{1}{2}\rho U^2 \left[\left(\frac{A_0}{A_c} \right)^2 (C_D)_{\text{conds}} + 2(C_D)_{\text{branch}} \right]$$

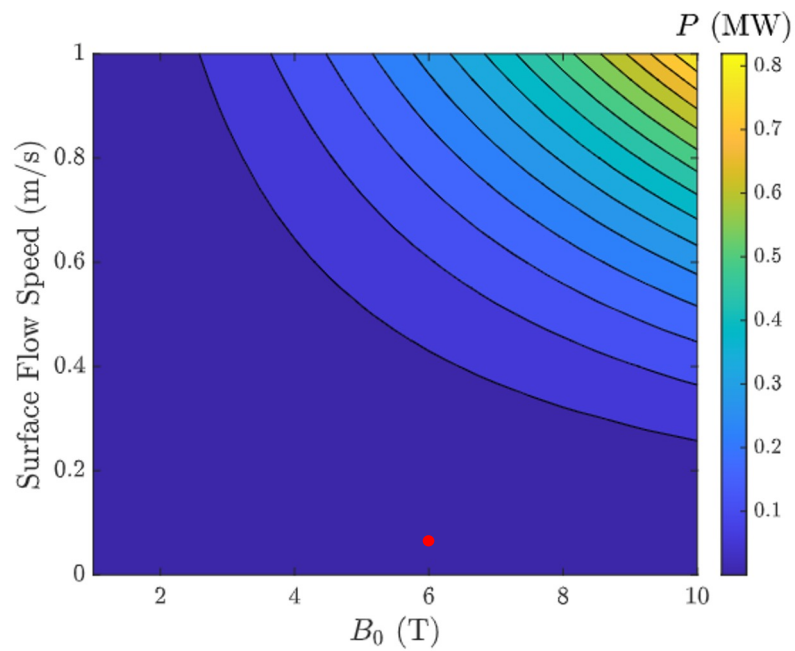




Projections of divertorlets to ITER

- 100 micron tungsten 3D printing capability available (Dunlee).
- Operation with channel gap of 1 mm for ITER





Separation LiD/LiT before leaving the vessel (Patent disclosure Kolemen & Majeski)

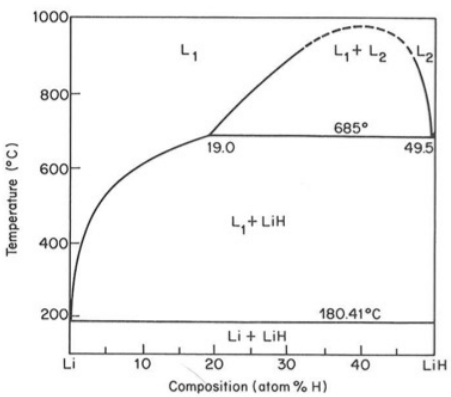
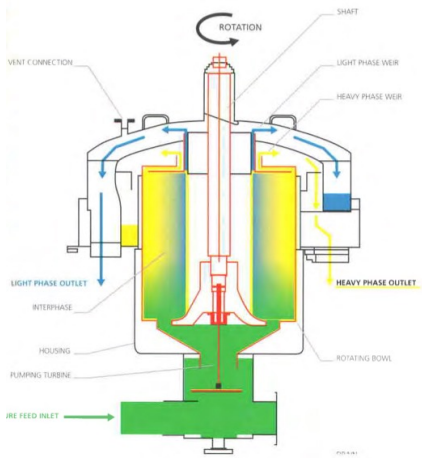
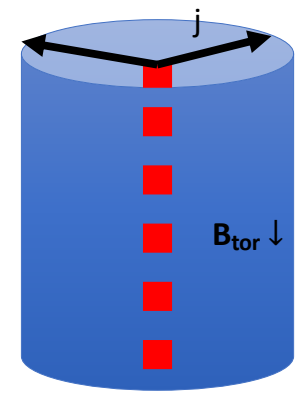
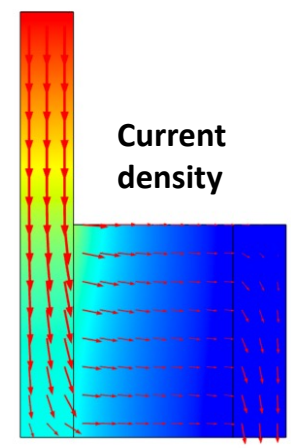


Figure 5.3 Lithium–lithium hydride phase diagram





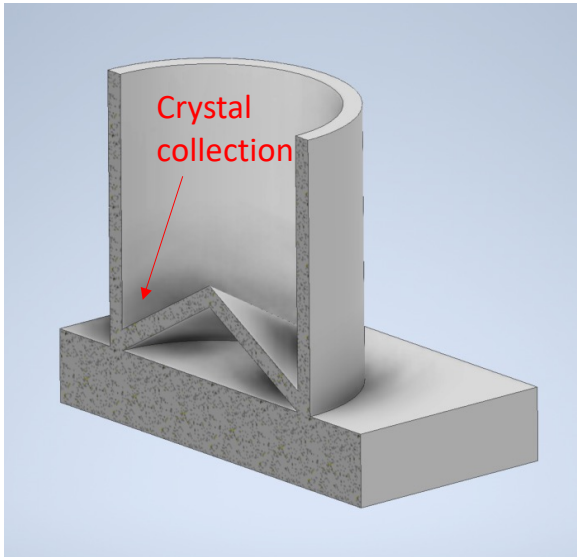
Magnetic centrifuge

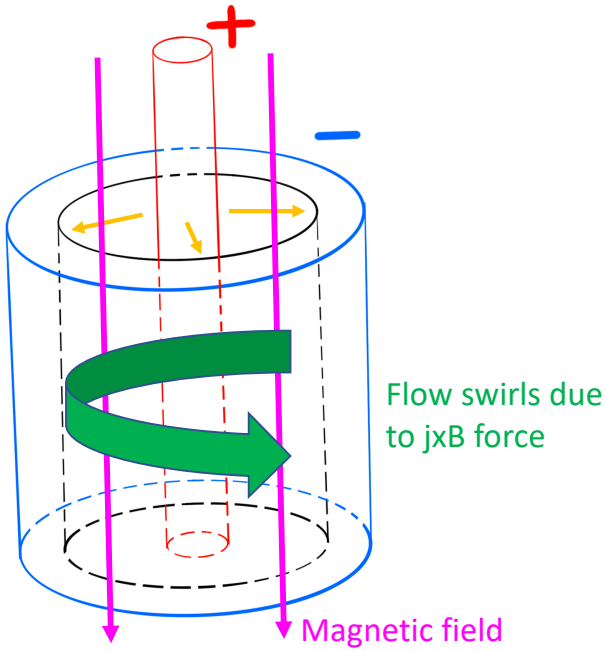


- Solubility of hydrogen in lithium falls rapidly with temperature
  - 0.3 At. % at 300 ˚C ⇨ 0.044% at 200 ˚C.
- LiD, LiT will be formed
- Density of LiT (1.0 g/cm^3), LiD (0.9 g/cm^3) *twice* liquid lithium (0.5 g/cm^3)
- Separation via magnetic centrifuge (We have B in tokamak, need to run j in a cylinder)
  - Centrifuges would operate at ~190˚C
  - Enriched slurry of LiD, LiT removed continuously at periphery
- **Flow to tritium separation unit (miniscule) ↓ ➔ MHD drag ↓ ➔ Power ↓**

Li/LiH separation

- Hope to test with Dan Andruczyk and David Ruzic in Illinois
- Agreed on bringing our setup to Illinois to test Lithium separation

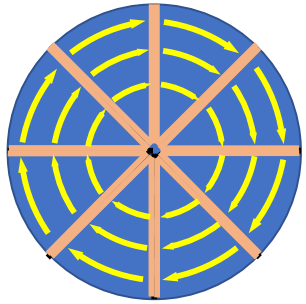


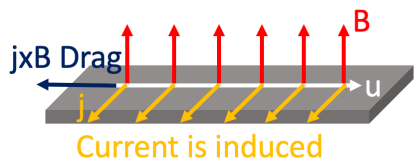


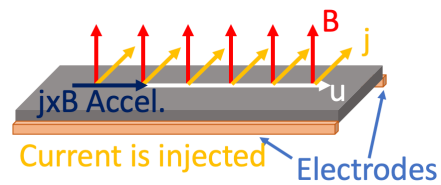
Conclusion and Future Perspective

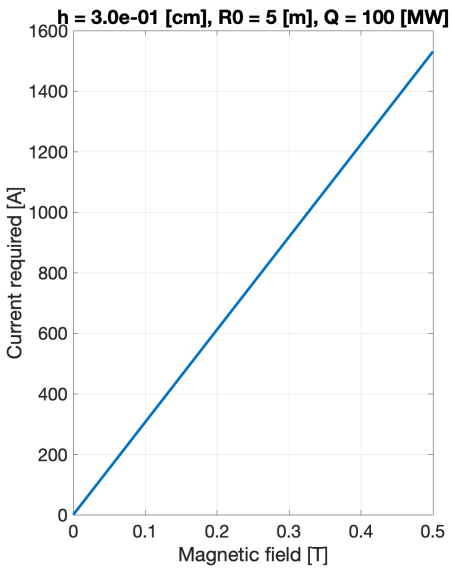
- **LMX-U is studying the LM flow in an open channel flow**
- **We can reproduce open channel flow under various MHD drag conditions with simulations**
- ***Divertorlets* concept is built and tested in LMX**
- **Experiments are reproduced with analytic models and simulations**
- **Divertorlet is projected to fusion reactor looks reasonable**

Overcoming MHD Drag with J_{tor} (A. Fisher)







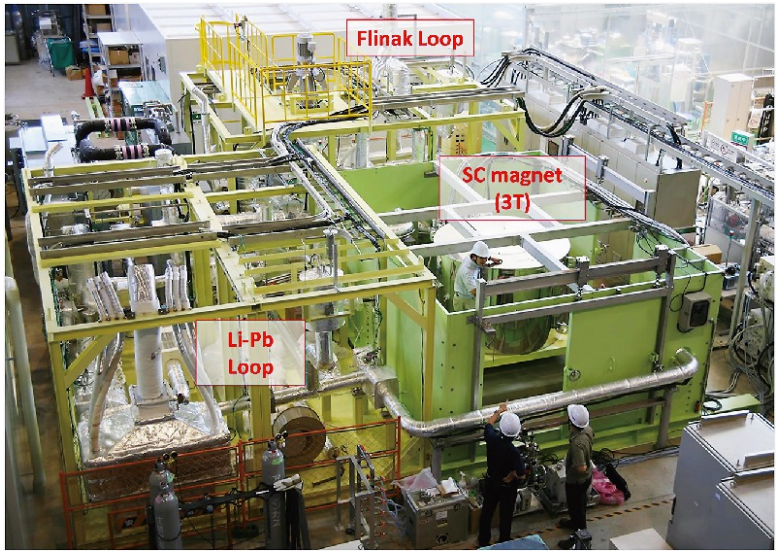


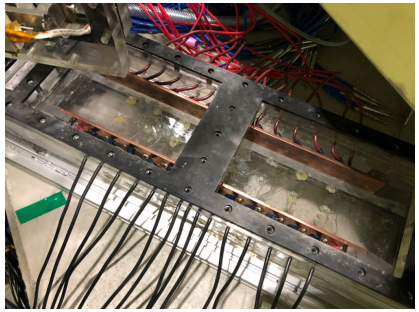
- MHD drag due to vertical B is an issue, but how bad is it?
- Chuck Kessel asked to look at cassette configurations. If we can have toroidal separation, we can run $\mathbf{J_{tor}}$
- Setting drag=forcing, and require velocity from heat flux

  ➔ $j \propto B_{ver} Q^2$ (not dependent on divertor length)
- **Required total current is very low**

Fast LM Experiments at

Oroshhi-2, Japan





Arrangement of mirrors for measurements

- Measurements with laser sheet, at two different positions between electrodes.