Brief Remarks on
Status and Progress
Fusion Technology/Chamber Technology

Chamber Technology

All Technical Disciplines Related to Components Surrounding the Plasma:
-First Wall/Divertor/Blanket/Vacuum Vessel/etc.

-Presented at the Fusion Power Associates Annual Meeting, San Diego, July 17, 2000

-Presented by M. Abdou with input from R. Mattas, C. Wong, A. Ying, N. Morley, and S. Smolentsev

The Fusion Technology Community is Working Hard in Partnership with the Physics Community to Make Advances in the Challenging Area of Chamber Technology

New Initiatives (motivated by the US Restructured Program and FESAC Goals)

ALPS: Advanced Limiter-Divertor Concepts

APEX: Advanced Chamber Technology Concepts

Emphasis of the Initiatives

1. Innovation
   - To improve attractiveness and lower the cost and time of R&D
2. Science
   - Understanding and advancing Engineering Sciences prerequisite for innovation
   - Outreach to scientific community outside fusion
3. Partnership
   - Among different areas within technology
   - Between the Physics and Technology Communities

Chamber Technology Research is Exploring Innovative Concepts for

1. Solid Walls

2. Liquid Walls

Goals to Calibrate Progress

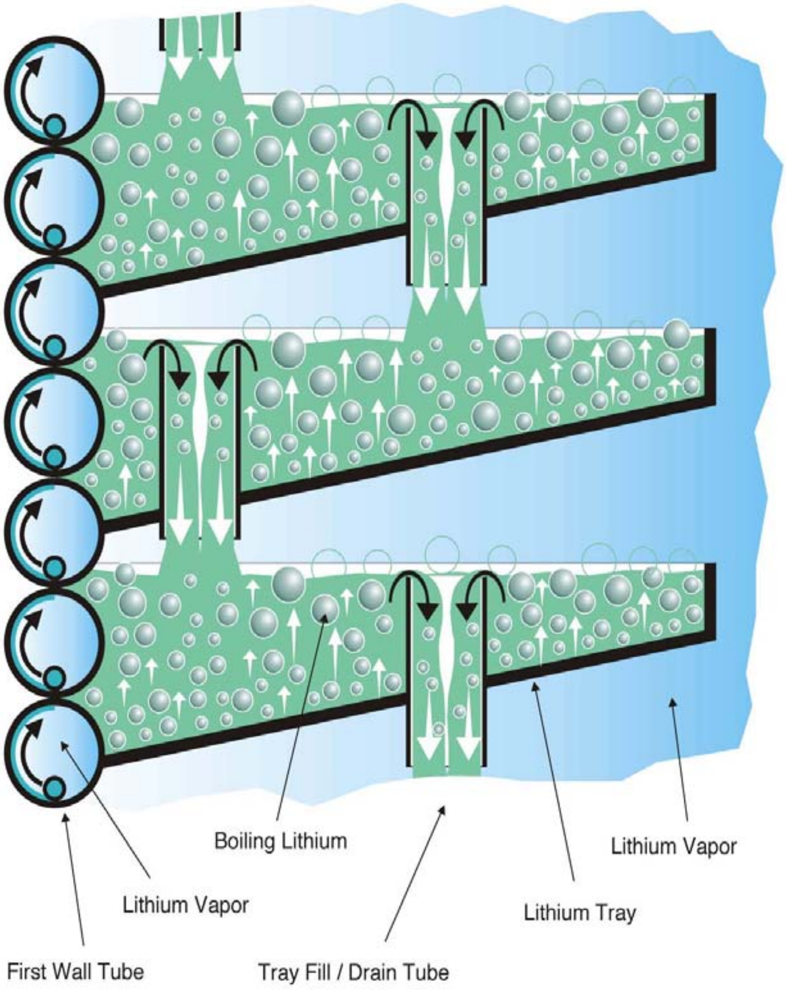
1. High Power Density Capability
2. High Power Conversion Efficiency
3. High Availability
4. Simpler Technological and Material Constraints

EVOLVE: Example of Innovative Solid Wall Concept

Cooling: Vaporization of Lithium at ~1200˚C

Structure: High-Temperature Refractory (W-5Re)

Attractiveness: High Efficiency (58%), low pressure/low stress, low flow rate/no insulators



Key Issues:

1) Tungsten fabrication and radiation effects
2) Modelling of 2-phase flow with MHD
3) Afterheat
4) Failure rate?

The Joint Physics-Technology, APEX-ALPS Effort is Making Progress in Exploring Liquid Walls

- **Key Scientific Issues and Current Effort**

1. Effects of LWs on Core Plasma
   - Bulk Plasma-Liquid Interactions Modeling (PPPL, U. Texas)

2. Edge Plasma-liquid Surface Interactions (Largest Effort)
   - Modelling (LLNL, ANL, others)
   - Experiments (CDX-U, DIII-D, PISCES, U. IL)

3. Free Surface Hydrodynamic Control and Heat Transfer (with and without MHD) in Complex Geometries including Penetrations, Inverted Surfaces.
   - Modelling (UCLA, ANL, PPPL, SBIR)
   - Experiments (UCLA, PPPL, ORNL, SNL)

Motivation for Liquid Wall Research

What may be realized if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement
  Enable high β, stable physics regimes if liquid metals are used

- High Power Density Capability

- Increased Potential for Disruption Survivability

- Reduced Volume of Radioactive Waste

- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials more problems tractable

- Potential for Higher Availability
  -Increased lifetime and reduced failure rates
  -Faster maintenance

Flowing LM Walls may Improve Plasma Stability and Confinement

Several possible mechanisms identified at Snowmass…

Presence of conductor close to plasma boundary (Kotschenreuther) - Case considered 4 cm lithium with a SOL 20% of minor radius

- Plasma Elongation $\kappa > 3$ possible – with $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
- Size of plasma devices and power plants can be substantially reduced

High Poloidal Flow Velocity (Kotschenreuther)

- LM transit time < resistive wall time, about ½ s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and E×B shearing rates (transport barriers)

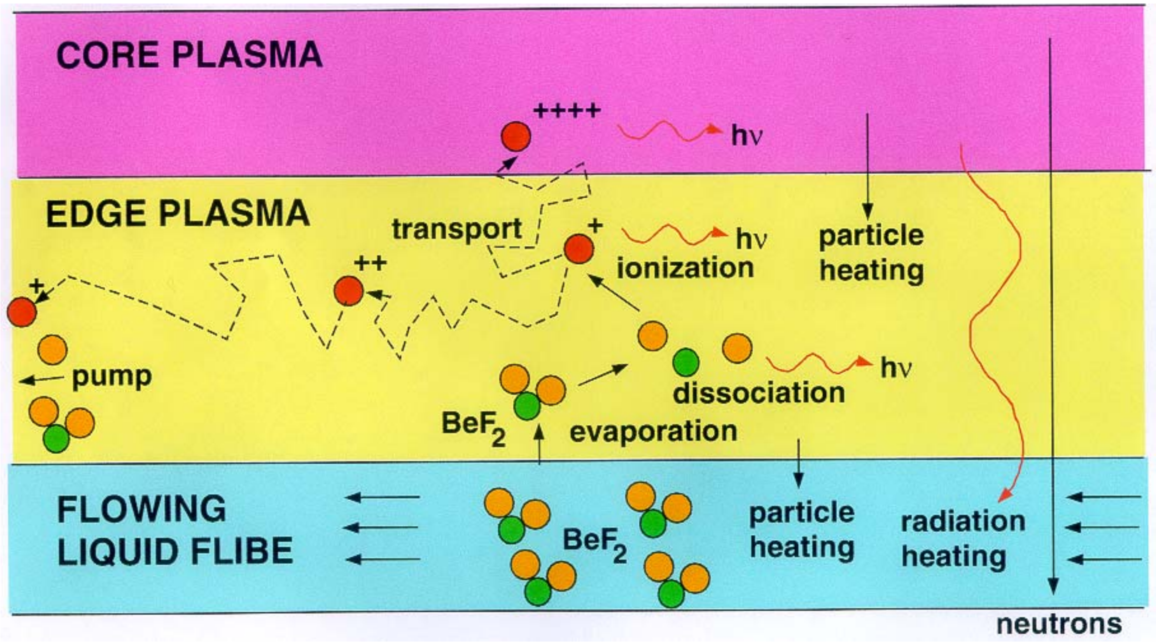
Hydrogen Gettering at Plasma Edge (Zakharov)

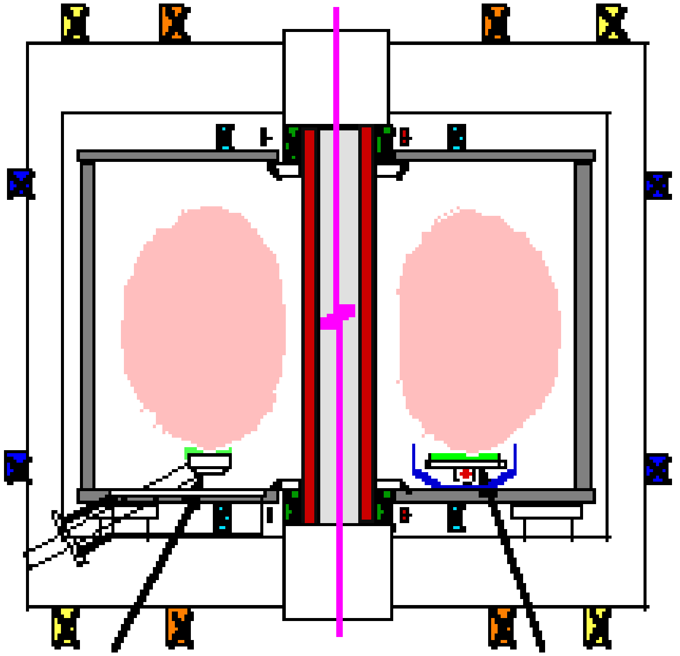
- Low edge density gives flatter temperature profiles, reduces anomalous energy transport
- Flattened or hollow current density reduces ballooning modes and allowing high β

Plasma-Liquid Surface Interactions Affect both the Core Plasma and the Liquid Walls

- **Multi-faceted plasma-edge modelling is in progress**
- **Experiments have started (in PISCES, DIII-D and CDX-U)**

Processes modeled for impurity shielding of core




UCSD liquid lithium probe-mounted limiter

Toroidal liquid lithium limiter target

Liquid lithium limiter in CDX-U

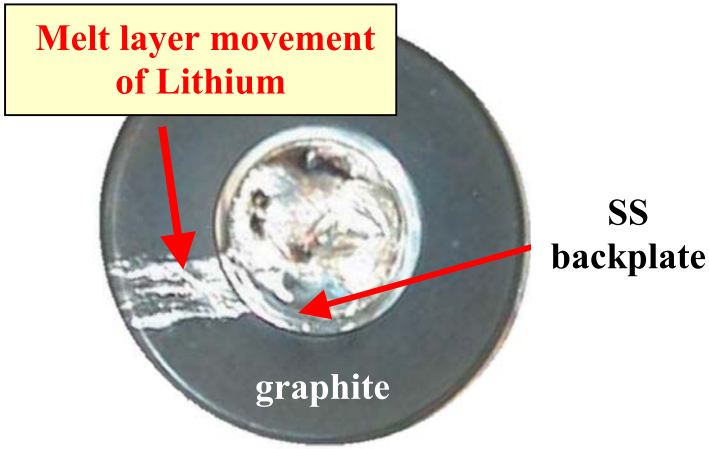
Testing of Liquids in Tokamaks

- DIII-D: a DIMES probe with solid Li was exposed during several shots
    - Analysis of results is underway
    - Further tests are planned with increased heat flux

- CDX-U: tokamak at PPPL will test liquid Li limiters
    - Installation and testing of the rail limiter is scheduled for August
    - A liquid Li toroidal belt limiter is planned as the next step in testing

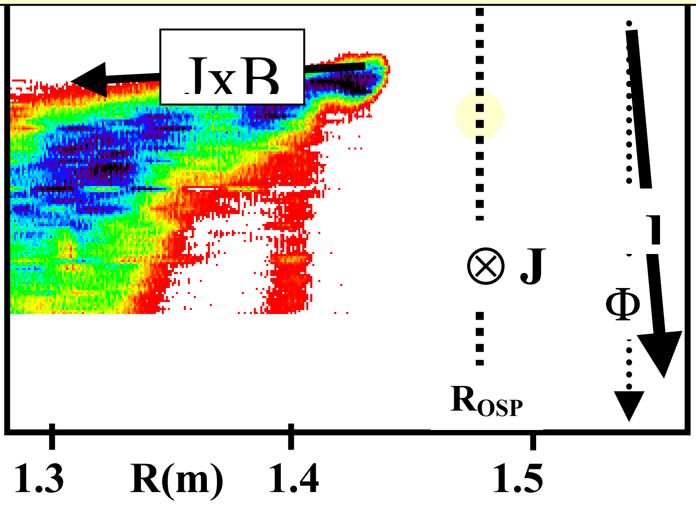
- NSTX: Options, benefits, and issues of implementing liquid walls in selected regions of NSTX are being explored
    - Excellent collaboration among NSTX, APEX, and ALPS teams
    - Time frame for implementation is ~ 5 years from now

DiMES has exposed three lithium samples at the DIII-D lower divertor to locked mode and type-I ELMs events



Melt layer movement of Lithium

Li I light from DiMES during locked mode (Δt ~ 16 ms)

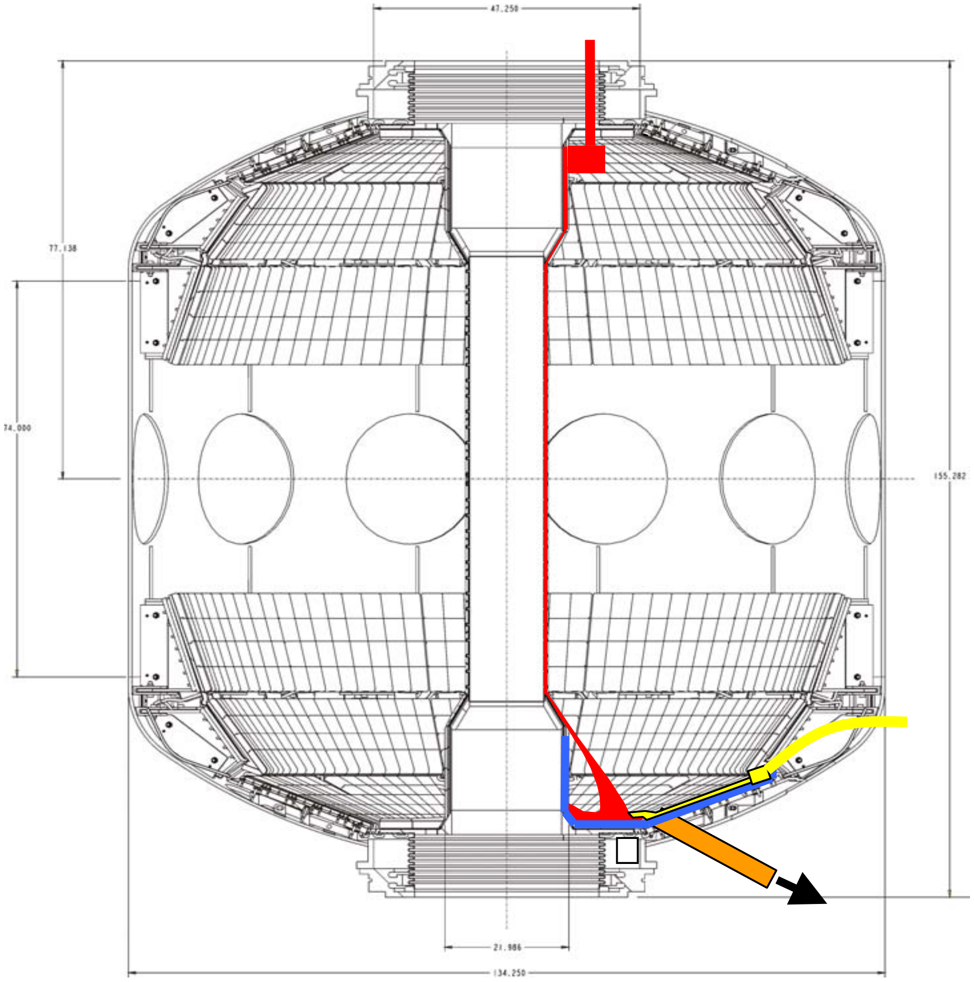


- At 1 MW/m2 heat flux, lithium is melted (~200 C) in seconds.
- Once melted, JxB forces during locked mode and type-I ELMs displaced lithium, ~1 mm of Li was removed.
- Lithium was measured in the core during displacement despite of the Li surface is ~10e-4 area fraction of the DIII-D divertor.
- Contaminated lithium with Li_2O did not melt and was not displaced.
- Significant neutral lithium was measured from charge exchange neutrals when the sample was in the private region.
- Further details will be obtained from continuing data analysis, the 4th dedicated experiment and detailed modeling.

NSTX Provides an Excellent Opportunity for Testing the Physics and Technology Benefits and Issues of Liquid Walls

Example of one of the options being explored:

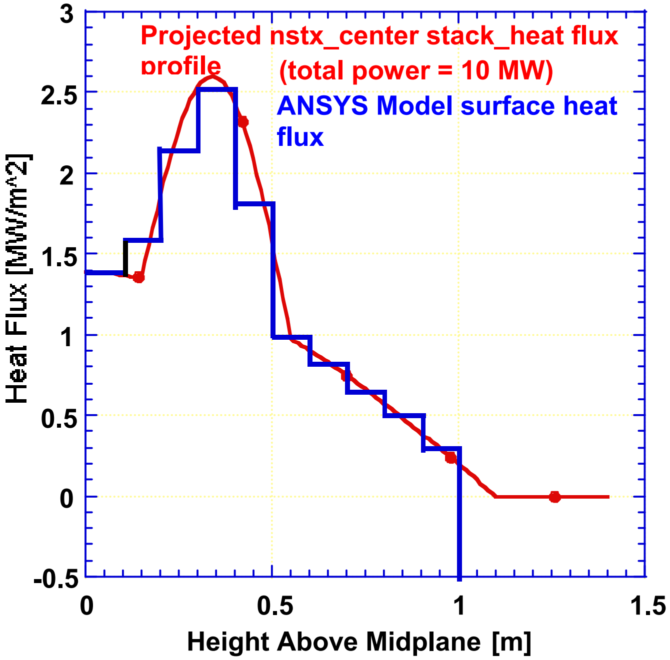
- Flowing Liquid Walls on Center Stack and OB Divertor



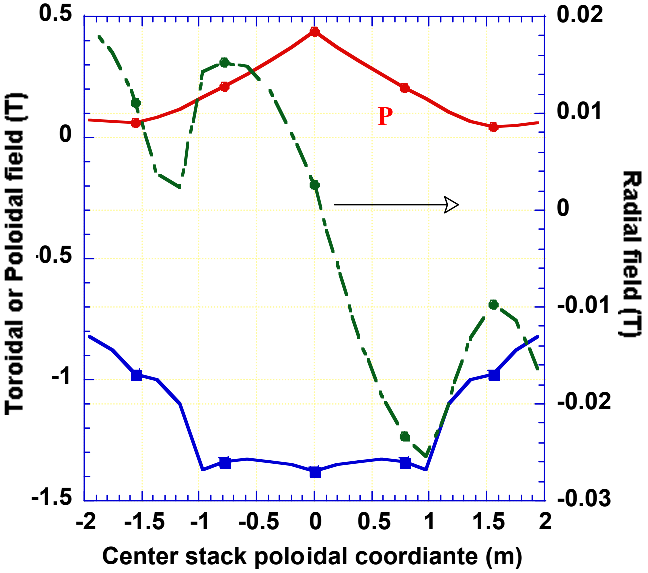
Flowing Lithium Surface Temperature Appears Acceptable along the NSTX Center Stack Even with an Inlet Velocity of 2 m/s

Results of MHD and Heat Transfer Calculations for NSTX Center Stack Lithium Film *(The effect of the poloidal field on the flow characteristics has not yet been taken into account)*

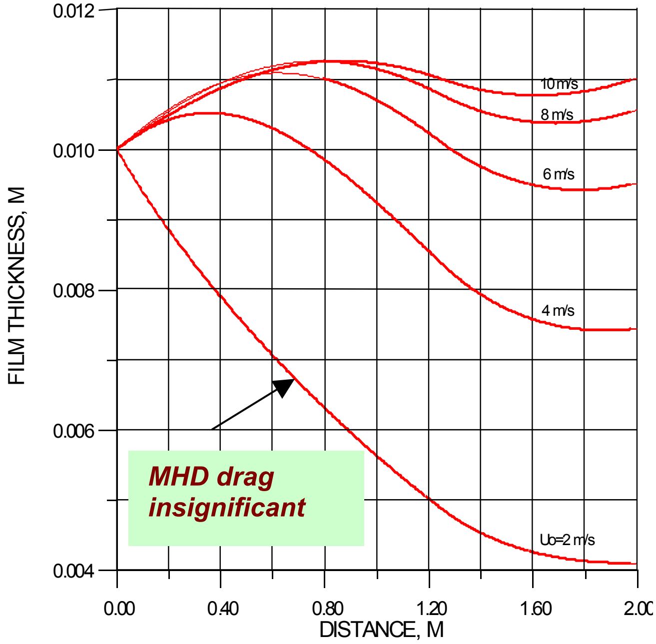
- **Flow damping occurs as a result of the MHD drag from the radial field.**
- **However, during normal operation, lithium appears to have reasonable surface temperatures along the NSTX center stack.**



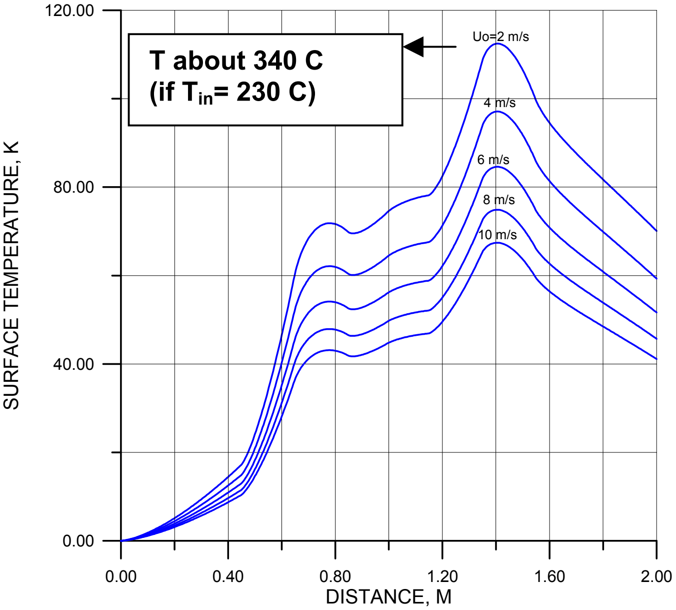
NSTX Center Stack Magnetic Field Characteristics



Film thickness varies as flowing lithium proceeds center stack downstream as a function of velocity

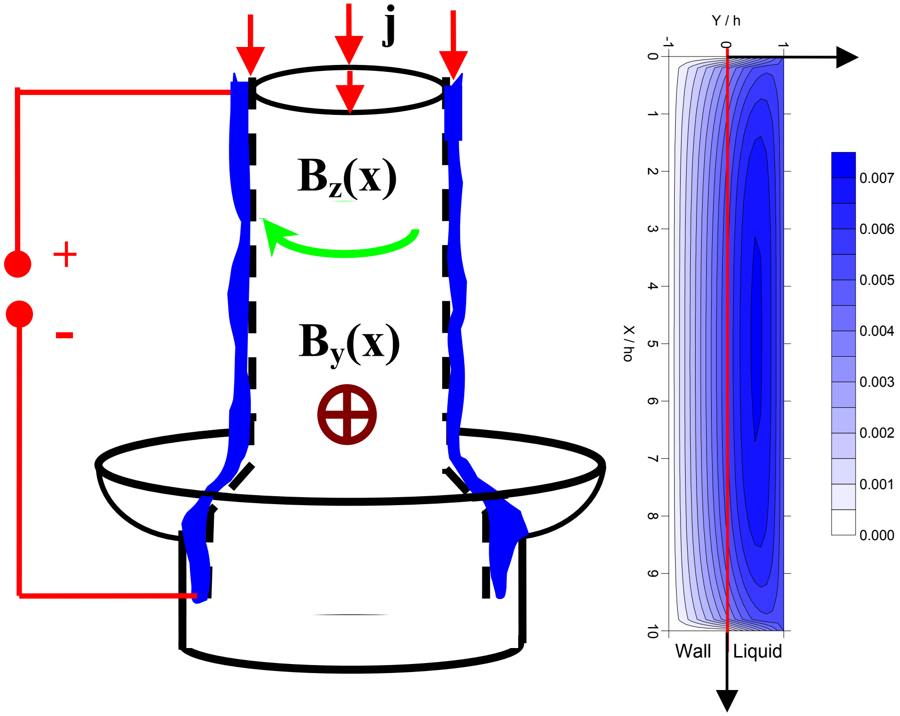

MHD drag insignificant

Lithium surface temperature increases as flow proceeds downstream as a function of lithium inlet velocity

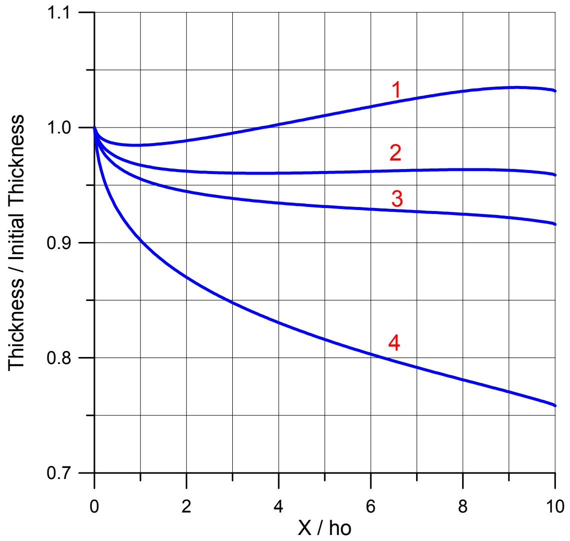

T about 340 C (if T_{in}= 230 C)

Modeling of Free-Surface MHD Fluid Flow

- A powerful code is under development at UCLA (in collaboration with Japanese fluid flow professors) to predict free-surface fluid flow behaviour with MHD effects
- The code has been applied to flowing liquids in NSTX
- Key Results: Applied currents in LMs are very useful in:
  1. restraining LM against back wall to: a) overcome centripital instabilities, and b) avoid liquid-wall separation;
  2. accelerating fluid in divertor region to allow higher heat removal capability with less LM inventory



Flow sketch (left) and the contour lines of the induced magnetic field in the wall+liquid region (right)



Flow development in the gradient toroidal magnetic field with and without applied currents.

B_r=0.02 T. B_z=1.0-0.3×X/L, T.

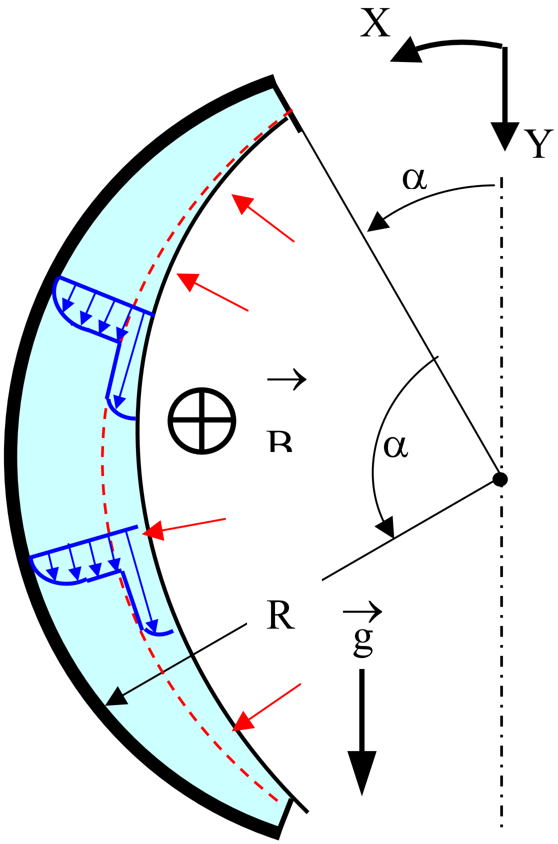
1 - j=0; 2 - j=4 kA/m^2;

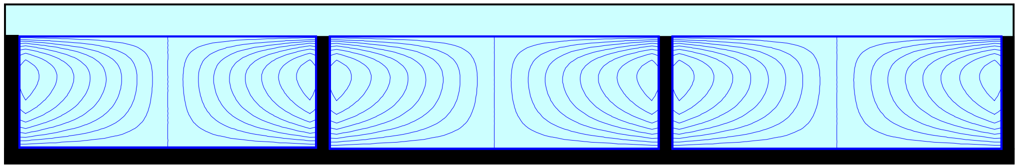
3 - j=8 kA/m^2; 4 - j=40 kA/m^2.

Novel Concept to Achieve Two-Stream Liquid Wall

- Fast moving layer facing the plasma with low-temperature (to reduce vaporization).

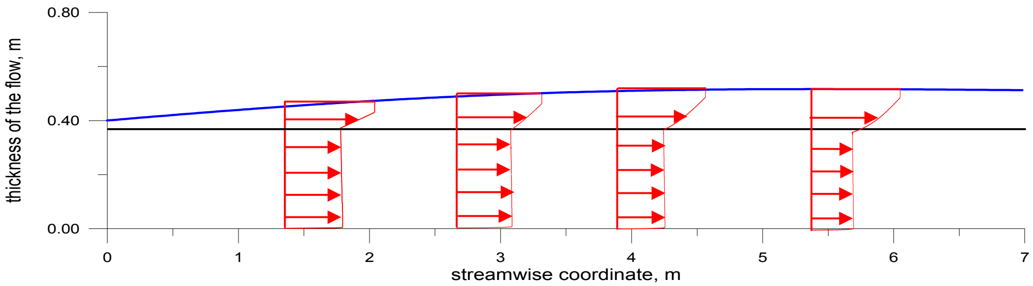
- Slowly moving layer behind it at high temperature (for higher efficiency).





- MHD drag slows down liquid between submerged walls

- Free surface layer can accelerate to high velocity



UCLA Data

Chamber Technology

5 – Year Goals

Liquid Walls (LW's)

1. Develop a more fundamental understanding of free surface fluid flow and plasma-liquid interactions
2. Operate flowing LW's in an experimental physics device (e.g. NSTX)
3. Initiate construction of an Integrated Thermofluid Research Facility for MFE/IFE
4. Understand advantages & implications of LW's in fusion systems.

Solid Walls

5. Advance novel concepts that can extend the capabilities and attractiveness of solid walls
6. Contribute to international effort on key feasibility issues where US has unique expertise