# Recent Advances in Chamber Science and Technology

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# Recent Advances in Chamber Science & Technology

## Outline

- Highlights of Major World Programs on Chamber/Blanket
- Recent Progress on **Liquid Walls**
    - IFE & MFE
    - Basic Principles
    - Plasma-Liquid Surface Interactions
    - Bulk Plasma-Liquid Interactions
    - Fluid Dynamics and Heat Transfer
        - *Modelling*
        - *Experiments*
        - *Analysis & Design*

# Highlights of Major World Programs on Chamber (Blanket) Technology

- Several overview and detailed papers at this conference
- Here, only a Quick Summary

# Blanket Activities in Europe

- Program emphasis aims for DEMO, w/ test blanket modules (TBM) in ITER
- Emphasis on R&D for two near-term concepts that represent modest extrapolation in technology

| **1 - Water-cooled Pb-17Li** | **2 - He-cooled pebble bed** |
|---|---|
| $P_{nw} = 2.2\ MW/m^2$ | $P_S = 0.4\ MW/m^2$ |

- R&D Focus
  - Characterization of materials
    - Reduced activation Ferritic-Martensitic steel (EUROFER )
    - Breeding materials (Pb-17Li, $Li_4SiO_4$, $Li_2TiO_3$)
    - Beryllium
  - Manufacturing technology (HIP, joining, tritium permeation barrier)

- Other efforts on advanced concepts

A - Intermediate: PbLi with ferritic/martensitic steel
SiC is used only as flow channel inserts

B - Long Term: Other possibilities, e.g. SiC/SiC as structure

# Blanket Activities in Japan

- **Main Concepts**
  - **Solid Breeder Blanket** (Key Organization: JAERI)

    Reference: Water cooled blanket with RAFS

    Advanced: He gas cooling system with SiC/SiC
  - **Liquid Breeder Blanket** (Key Organization: NIFS & Universities)

    Research on several advanced concepts: FLiBe, Li, LiPb with ferritic steel, V, and SiC

- **Key Milestones**
  - Demonstration of electrical power generation and tritium breeding in a DEMO-Relevant Test Blanket Module (TBM) in ITER is one of the most important milestones
  - The first TBMs will be installed in ITER around 2015.
  - In parallel with the TBM activity, material R&D should proceed with existing reactors and a fusion neutron source, such as IFMIF

# Blanket Activities in Japan (cont'd)

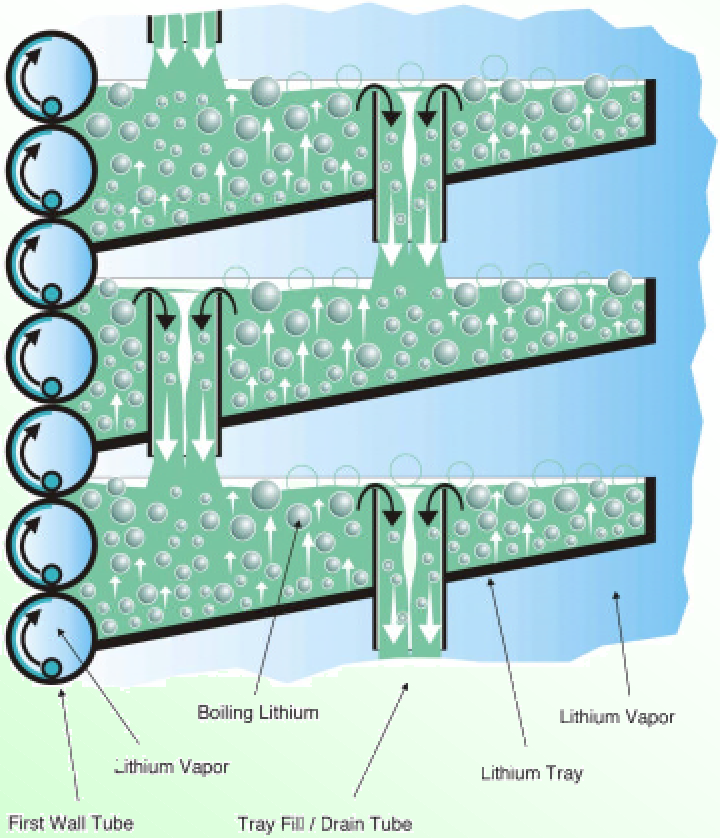
## Key R&D items under investigation

- **Solid Breeder Blanket**
  - Development of base manufacturing technology for TBMs
  - Development of manufacturing technology of breeding material and neutron multiplier, such as $Be_{12}Ti$
  - Irradiation performance of RAFS, and ODS
  - Thermal/mechanical and irradiation performance of pebble beds
  - Supercritical water cooled blanket system for higher thermal efficiency
  - High temperature gas cooled blanket system with SiC/SiC
- **Liquid Breeder Blanket**
  - Development of FLiBe-based blanket with RAFS
  - Research on thermal hydraulics/heat transfer
  - Research on Tritium recovery technology
  - Research on Insulation/Tritium-permeation coating technology
- **JUPITER-II**
  - Collaborative program between Japan (mainly Universities) and USA covers materials, tritium, thermofluids, and pebble bed/SiC thermomechanics

# Chamber Science & Technology in the USA

- Distinct, but collaborative Chamber Programs for IFE & MFE
- Last 3 years: strengthened interactions among Materials, PFC, and Chamber Programs
- The effort on “conventional” blankets is limited to:
  - Thermomechanics of pebble bed beryllium and ceramic breeders (IEA, JUPITER-II)
  - Insulators for liquid metal blankets (part of JUPITER-II)
- The major emphasis in Chamber Science & Technology over the past 3 years has been on Innovative Concepts that:
  1 - In the near-term: enable plasma experiments to more fully achieve their research potential
  2 - In the long-term: substantially improve the attractiveness of Fusion as an Energy Source
- Key research programs initiated: APEX (Chamber) and ALPS (PFC)
- Innovative concepts proposed: 1) Advanced Solid Walls 2) Liquid Walls

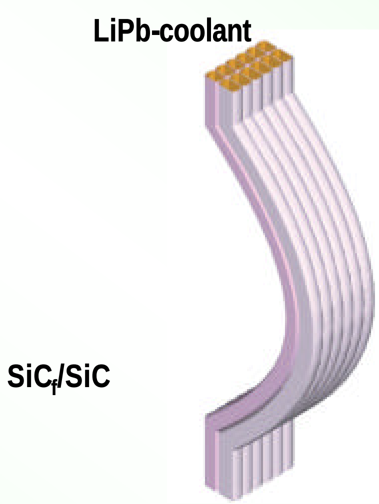
# Innovative Solid Wall Concepts




## EVOLVE (APEX)

- Novel Concept based on use of high temperature refractory alloy (e.g. tungsten) with innovative heat transfer/transport scheme for vaporization of lithium
- Low pressure, low stresses
- Low velocity, MHD insulator not required
- High Power Density / Temperature / Efficiency
- Key Issues Relate to Tungsten

**ARIES-AT FW/Blanket Segment**




- **SiC/SiC-LiPb proposed by ARIES**
  - SiC allows high temperature, but power density may be limited
  - Low activation
  - Key Issues relate to SiC/SiC

# Reflections on Advanced Solid Walls

- Attempts to extend the capabilities and attractiveness of solid walls have required very advanced structural materials
- EVOLVE requires W alloy for high power density, high temperature

  *But the Material Community is not enthusiastic (risky, costly, very long-term)*
- High temperature with LiPb or other coolants/breeders relied on SiC/SiC

  Recent advances in SiC/SiC development are remarkable

  *But some scientists are asking: Is SiC/SiC appropriate for FW?*

  A Viewpoint: SiC cannot address all the issues of the first wall: heat load, pressure boundary, erosion, helium retention issue, etc.

  A Suggestion: Focus on utilizing SiC for suitable applications such as inserts (for insulation), and deeper regions of the blanket.
- Emerging Trend:

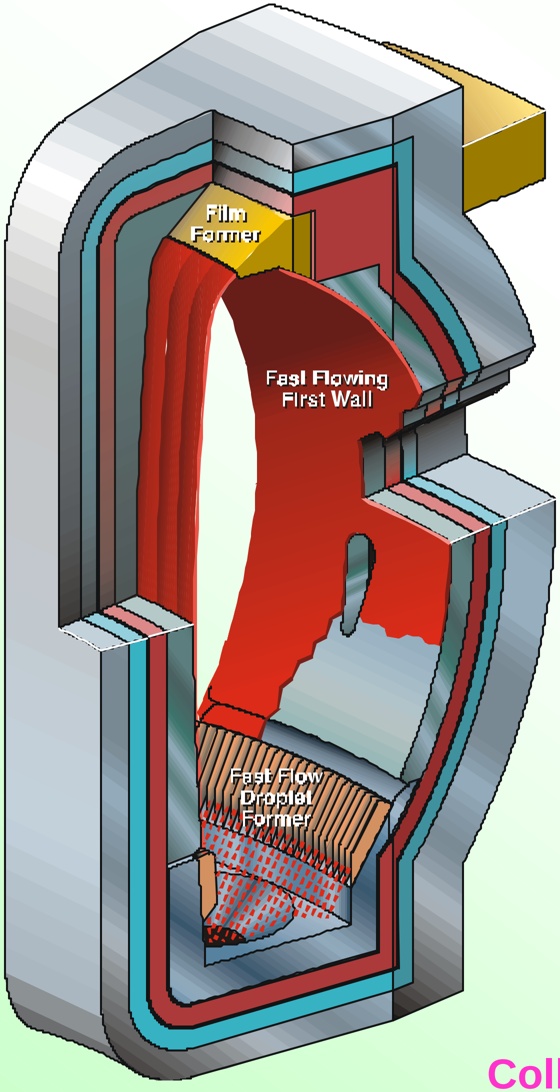
  - Emphasize advanced higher-temperature ferritic steels
  - EU/J/US: ODS
  - US: Nano-Composited Ferritic Steel (max. temp ~ 800 C)

# Recent Progress on

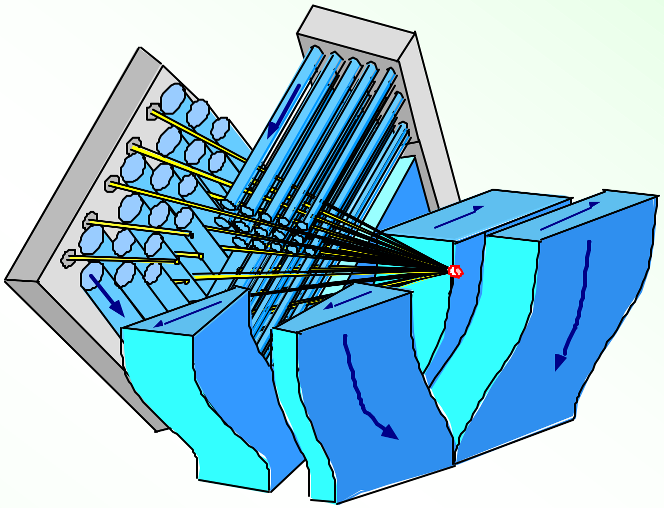
# LIQUID WALLS

**The remainder of this presentation will focus on Liquid Walls**

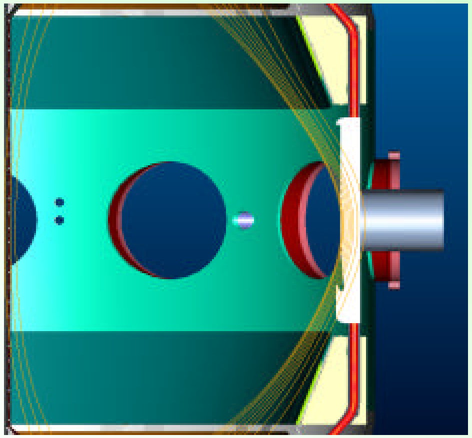
# Liquid Wall Science & Technology are being Advanced in Several MFE & IFE Research Programs



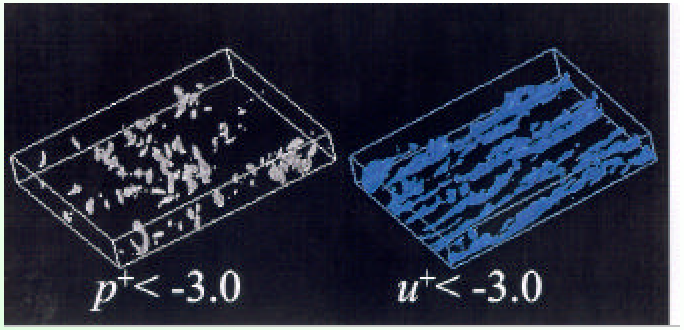

APEX CLiFF



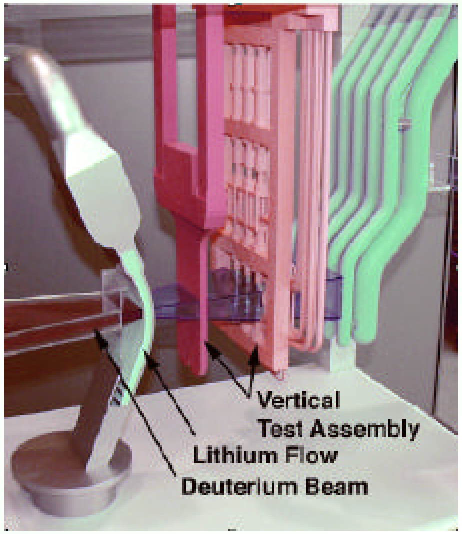
HYLIFE-II



ALPS/APEX NSTX Li module

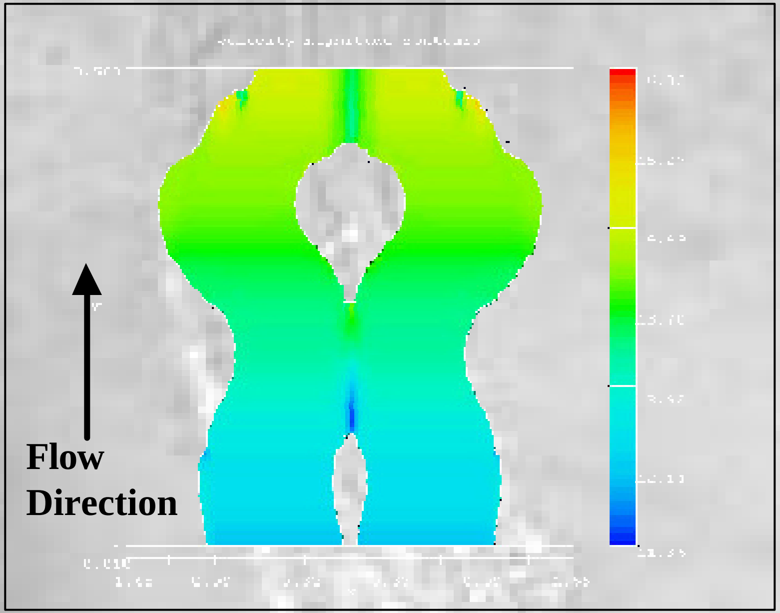



DNS Free Surface Simulation
Collaboration with non-fusion scientists
US-Japan Collaboration

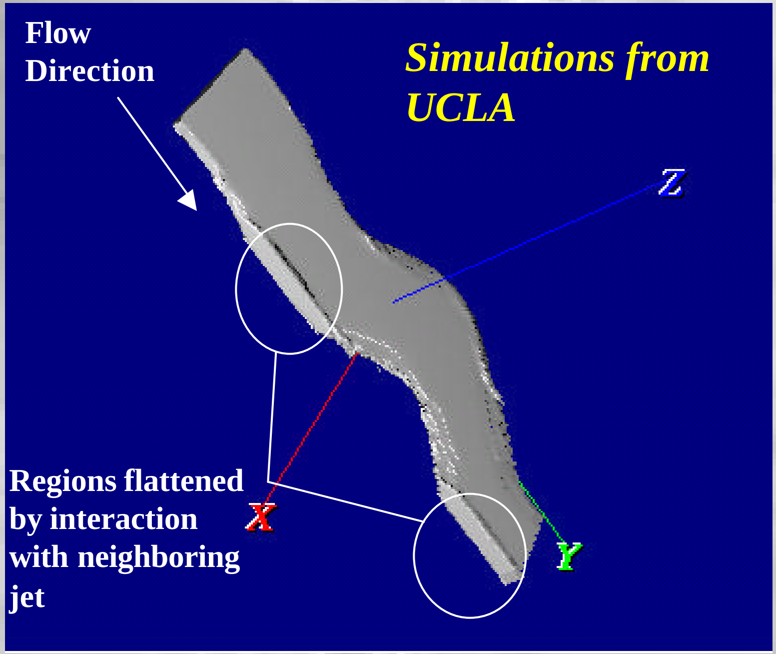



IFMIF

# Oscillating IFE jet experiments and simulations




•Single jet water experiments and numerical simulations demonstrate control of jet trajectory and liquid pocket formation at near prototypic Re




*Experimental Data from UCB*

# Remarkable Progress on Liquid Wall Research in the Past 3 years

- New Design Ideas for Liquid Walls in MFE Have Evolved
  (Elaborate Liquid Wall Designs for IFE have long existed)
- Key Technical Issues Identified & Characterized
- R&D Effort on Top Issues Initiated: Significant Progress
  - Modeling
    - Plasma Physics Edge & Core
    - Fluid Mechanics, MHD, Heat Transfer
  - Experiments
    - Laboratory Experiments on Thermofluids (w/ & w/o MHD)
    - Laboratory Experiments on Sputtering & Particle Trapping, etc.
    - Tokamak Experiments: Liquid Lithium in Actual Plasma Devices

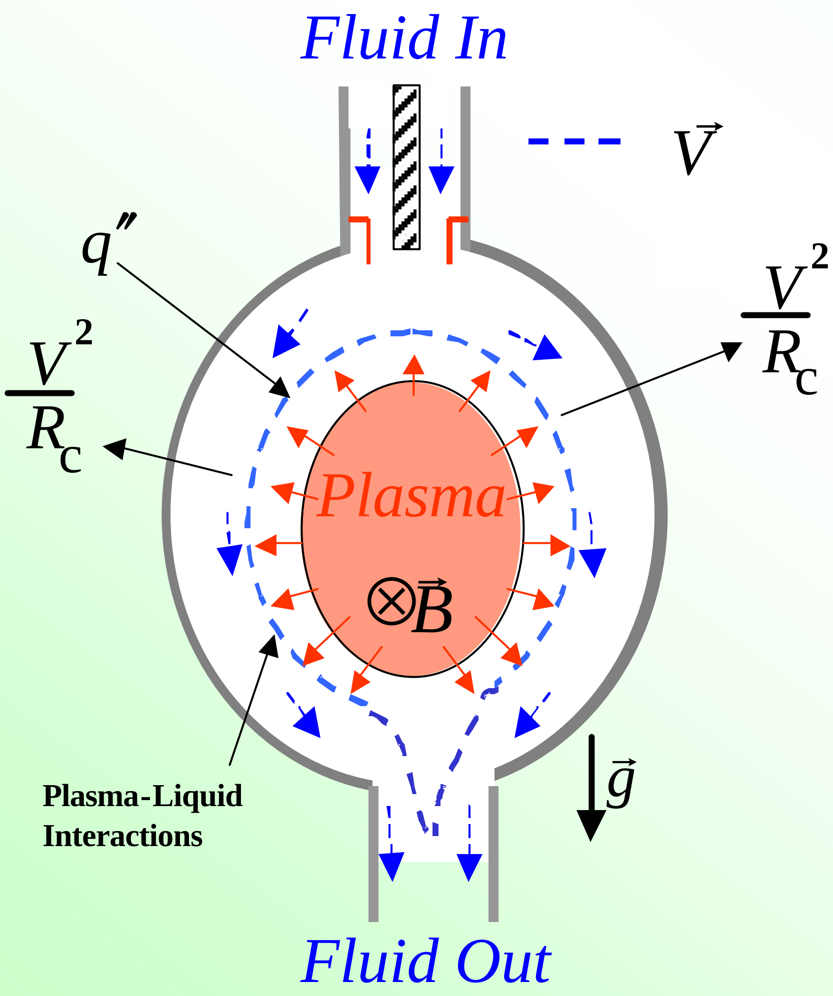
# Potential Benefits if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement
  - Enable high ß, stable physics regimes if liquid metals are used
- High Power Density Capability
  - Eliminate thermal stress and erosion as limiting factors in the first wall and divertor
  - Results in smaller and lower cost components
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
  - Makes difficult structural materials problems more tractable
- Potential for Higher Availability

*No single LW concept may simultaneously realize all these benefits, but realizing even a subset will be remarkable progress for fusion*

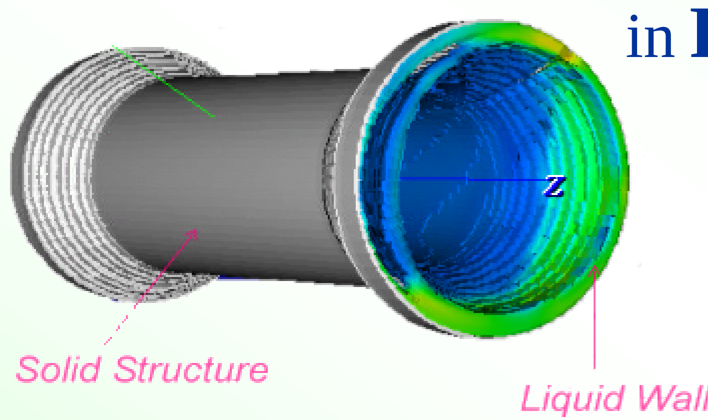
# "Liquid Walls" Have Many Design Options

*1) Type of Flow Control* *2) Working Fluid* *3) Liquid Thickness*




- **Gravity-Momentum Driven (GMD)**
  - Fast liquid adheres to back wall by centrifugal force
  - Applicable to LM's or molten salts
- **GMD with Swirl Flow**
  - Add rotation
  - Good for cylindrical geometry (e.g. FRC or IFE)

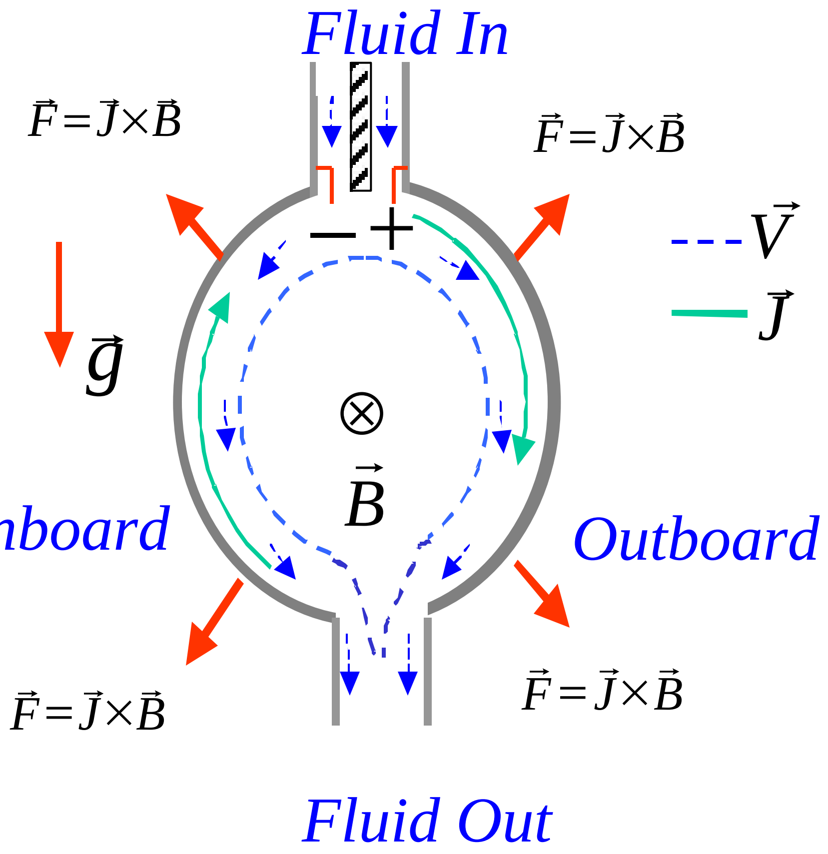
Swirl Flow in **FRC**



# ELECTROMAGNETIC FLOW CONTROL: electric current is applied to provide adhesion of the liquid and its acceleration

*Electromagnetically Restrained LM Wall (R.Woolley)*

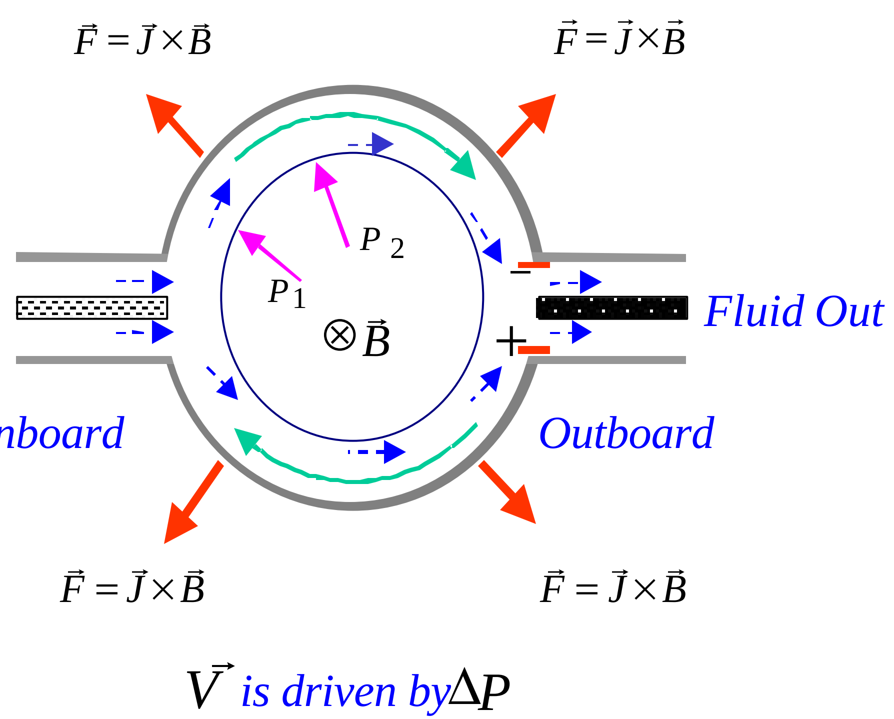
***- Adhesion to the wall by*** $\vec{F} = \vec{J} \times \vec{B}$




*Magnetic propulsion scheme (L.Zakharov)*

***Adhesion to the wall by*** $\vec{F} = \vec{J} \times \vec{B}$

***Utilization of 1/R variation of*** $\vec{B}$ ***to drive the liquid from the inboard to outboard***



# Liquid Wall Options Explored

- **Working Fluid:**
  - Liquid Metals: Li, Sn-Li, Sn
    Sn is considered because of low vapor pressure at elevated temperatures
  - Molten Salts: Flibe, Flinabe
    Flinabe is an attractive alternative to flibe because it has low melting point (240-310 C)
- **Flow Control:** - Gravity-Momentum - Electromagnetic
- **Thickness:**
  - Thin (1-2 cm) to remove surface heat flux, tolerate disruptions
  - Thick (40-50 cm) to also attenuate neutrons

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- **Reference Loading Parameters**
  - Average/Peak neutron wall load 7/10 $MW/m^2$
  - Average/Peak heat flux 1.4 / 2 $MW/m^2$
    (80% of the Alpha Power radiated to first wall divertor loading)
  - Peak heat flux on divertor > 20$MW/m^2$
- **Representative reactor configurations**
  - Tokamaks: ARIES-RS
  - Alternative confinement systems: FRC, RFP, Spheromak

- Present Focus is on a **THIN Liquid Wall** because it is sufficient to:

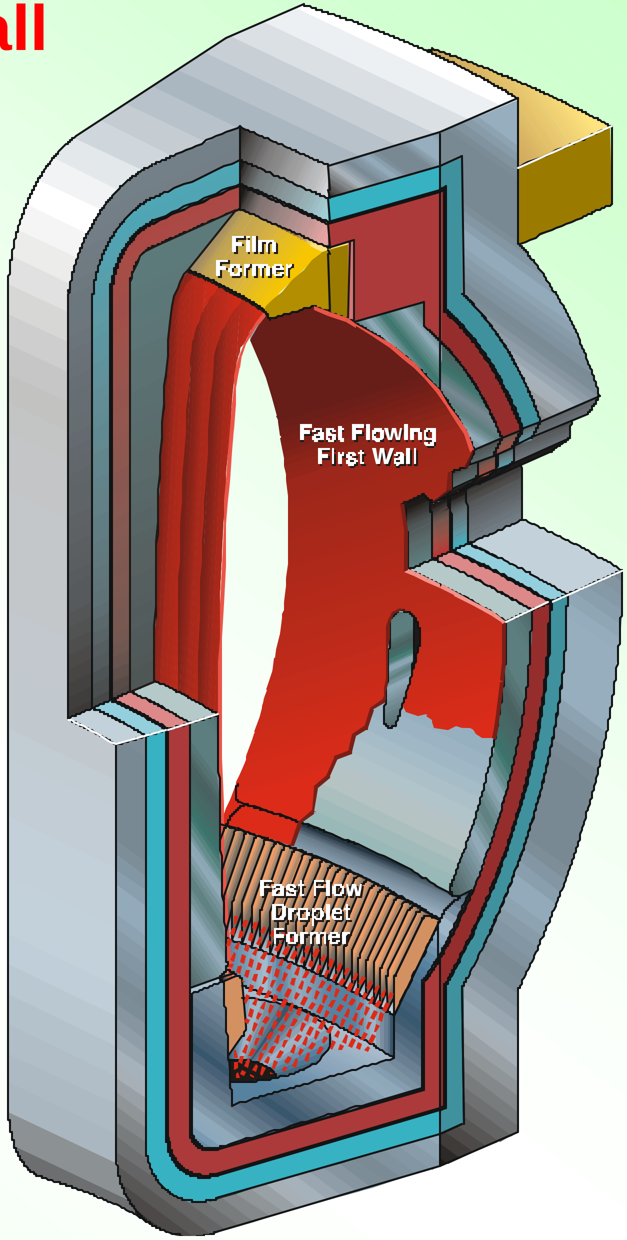
a) Provide High Power Density Capability (surface heat flux, not neutron heating, is what limits power density in fusion)

b) Make the structural wall thermomechanics & other material issues more tractable

c) Tolerate Disruptions

d) Realize almost all the potential benefits of LM's in improving plasma performance

- The more ambitious thick Liquid Wall idea, proposed to greatly reduce/eliminate structural material radioactive waste and radiation damage, can be addressed later if we succeed with thin LW's




**CLiFF - Convective Liquid Flow Firstwall**

# Scientific Issues for Liquid Walls

## 1. Plasma-Liquid Surface Interactions

- Vaporization, sputtering, impurity transport
- Limits on operating temperature for liquid surface

## 2. Bulk Plasma-Liquid Interactions

**Effects of Liquid Wall on Core Plasma including:**

- Discharge Evolution (startup, fueling, transport, beneficial effects of low recycling)
- Plasma stability including beneficial effects of conducting shell and flow

## 3. Thermofluid Issues

- Interfacial Transport and Turbulence Modifications at Free-Surface
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids

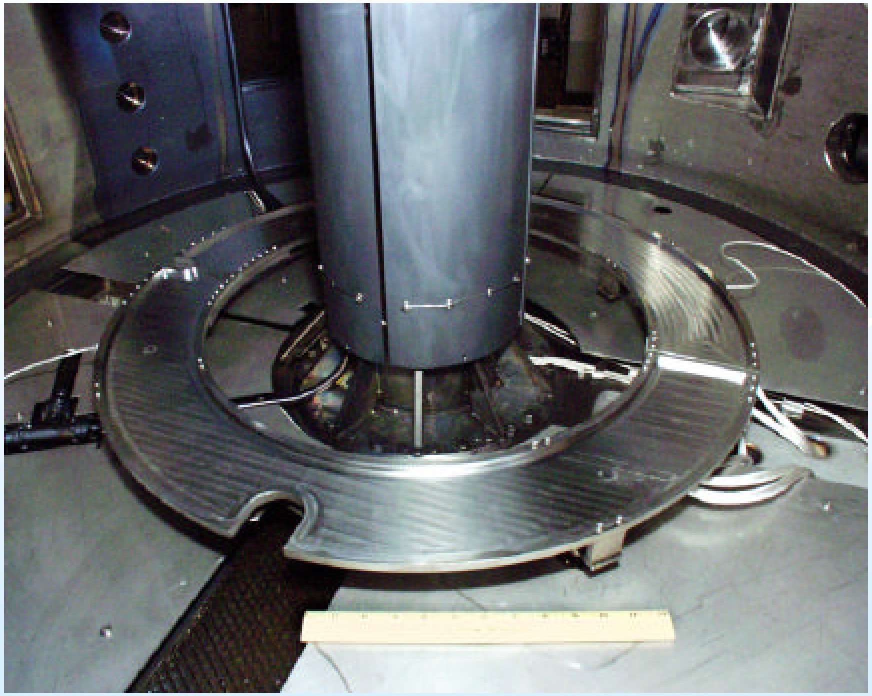
# Progress on R&D for Plasma-Liquid Surface Interactions

- **Plasma Edge and PMI Modeling**
  (ANL, GA, LLNL, PPPL, SNL, UCSD, UIUC, ORNL)
  - Erosion / Redeposition
  - Hydrogen and Helium Pumping
  - Impurity Vapor Intrusion to Core Plasma
  - Determine Allowable Temperature of Liquid Surfaces on PFCS and First Wall

- **PMI Laboratory Experiments**
  (SNL, UCSD, UIUC, INEEL)
  - Provide Key Data on sputtering yields, reflection coefficients, evaporation rates, H & He retention/release properties, etc.

- **Tokamak Experiments**
  - Study interaction of candidate liquids with tokamak plasmas
    * CDX-U at PPPL dedicated to Plasma-Liquid Interactions
    * DIMES Li Probe Experiments on DIII-D at GA

# CDX-U, ST Tokamak at PPPL, is Now Dedicated to Exploring Plasma-Liquid Interaction Issues



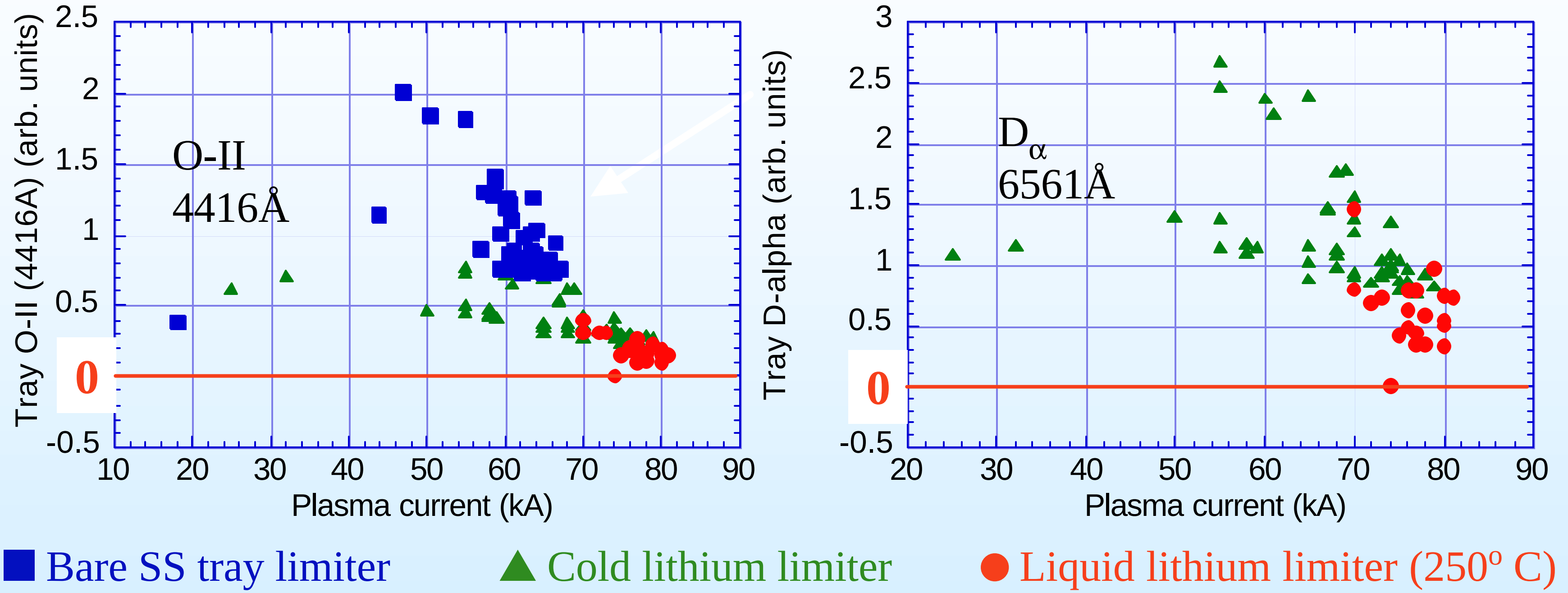
CDX-U Parameters:

- Stainless steel tray for fully toroidal lithium limiter
- 34 cm major radius, 10 cm wide, 0.64 cm deep

| | |
|---|---|
| $R_0$ | 34 cm |
| a | 22 cm |
| $A=R_0/a$ | ≥1.5 |
| κ | ≤1.6 |
| $B_T(0)$ | 2.2 kG |
| $I_P$ | ≤ 80 kA |
| $P_{rf}$ | <200 kW |
| $\tau_{disch}$ | <25 msec |
| $T_e(0)$ | 100 eV |
| $n_e(0)$ | $6x10^{19}$ $m^{-3}$ |

- CDX-U research program utilizes static and flowing lithium limiter and divertor targets to investigate:
  - > Plasma performance improvement with reduced recycling
  - > Effects of high localized heat loads on lithium targets
  - > Lithium motion due to J x B forces during plasma operations

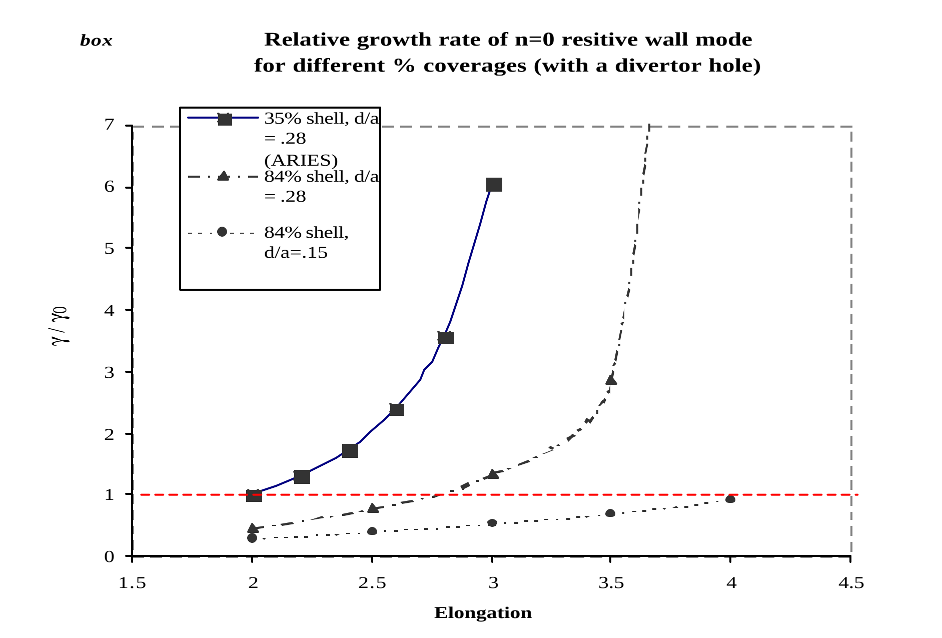
# Best CDX-U Plasmas Achieved with Liquid Lithium Limiter




- Highest plasma currents and lowest impurity emission ever obtained in CDX-U were achieved with liquid lithium in the tray limiter
- Plasma recycling is very low on liquid lithium
  - Possible that the recycling coefficient is *zero*

# Utilization of Liquid Metals for a Conducting Shell May Allow Higher Power Density Tokamak Plasma

- **Initial results from new WALLCODE resistive MHD code: Stable highly elongated plasmas possible with appropriately shaped conducting shell**
- **Liquid metals may be used for the conducting shell**
- **Implications for fusion:**
  - High power density plasma (plus power extraction capability)
  - Overcome physics-engineering conflicting requirements that reactor designers have struggled with for decades




Beta Limits for high elongation
(example of initial results)

| k | b* |
|---|---|
| **2** | 7.6 % |
| **3** | 15.8 % |
| **4** | 21.8 % |

# What is the Allowable Liquid Surface Temperature?

- Comprehensive Plasma-Edge Modeling shows that the liquid surface temperature is limited by:
  - First Wall Region: Impurity Vapor Intrusion to Core Plasma
  - Divertor Region: Sheath super-heat runaway due to surface thermal emission

| | *Temperature Limits for High-Recycling Tokamaks* | | | |
|---|---|---|---|---|
| | Lithium | Sn-Li | Sn | Flibe/ Flinabe |
| *First Wall Surface Temperature, C* | 420 | 630 | 840 | 480 |
| *Divertor Surface Temp, C* | 475 | 700 | 1600 | 700 |

- Other Key Conclusions
  - Temperature Limits are higher for low-recycling devices
  - Temperature Limits appear to be higher for compact high power density devices (e.g. Spheromak, FRC) because of better shielding of impurity intrusion

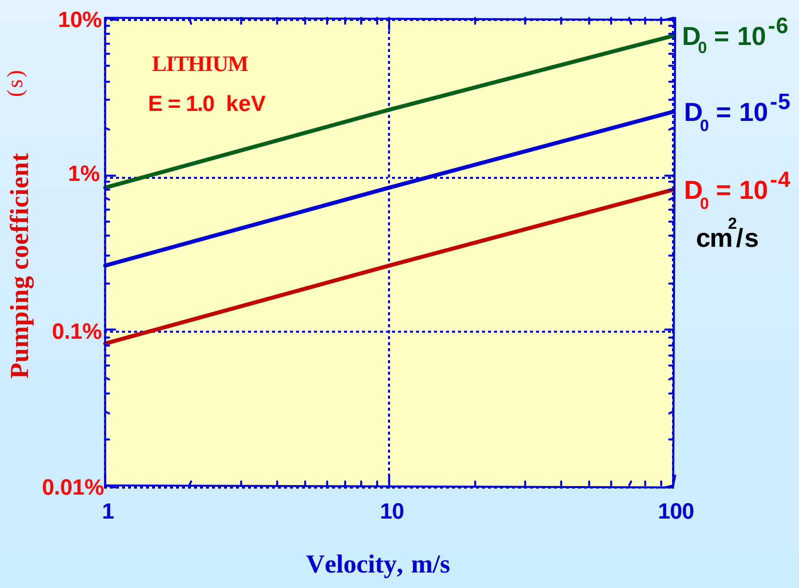
# How to Pump Helium Particles with Liquid Walls?

- With Vacuum Ducts (same scheme as with Solid Walls)
- Vacuum Ducts may be smaller with LW's
  - If helium trapping by liquid surfaces is significant

## *Liquid Lithium a Unique Case?*

- D-T particles are completely pumped by flowing lithium
  - Improved plasma performance
  - Helium pumping?
- HEIGHTS calculations show that flowing lithium at 10-20 m/s can pump He at the required rate (~5%) if the He Diffusion Coefficient is < $10^{-4}$ $cm^2/s$ (i.e.He self pumping with Li, no ducts needed)
- These diffusion values may be feasible: need measurements

**HEIGHTS Calculations of He Pumping Coefficient as a Function of Lithium Velocity**



# FLUID DYNAMICS & HEAT TRANSFER

- Modeling
- Experiments
- Analysis & Design

# Need for Predicting LW behavior has motivated Modeling and Experiments at the forefront of Fluid Dynamics Physics and Ultra High-Speed Computer Simulation

Interfacial Transport

## Many interacting phenomena

- Interfacial Transport and Turbulence Modifications at Free-Surface
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc.
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids

### Passive & Active Scalar Transport

$$?C_p[\frac{\partial T}{\partial t} + (\vec{V}\cdot\nabla)T] = k\Delta T$$

$$\frac{\partial C}{\partial t} + (\vec{V}\cdot\nabla)C = D\Delta C$$

### Free Surface Phenomena

$$\frac{\partial j}{\partial t} + (\vec{V}\cdot\nabla)j = 0$$

### Electromagnetism

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{s\,\mu_0} ?\vec{B} + \nabla\times(\vec{V}\times\vec{B});$$

$$\vec{j} = \frac{1}{\mu_0}\nabla\times\vec{B} \qquad \nabla\cdot\vec{B} = 0$$

### Hydrodynamics

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}\cdot\nabla)\vec{V} = -\frac{1}{?}\nabla p$$

$$+ \nabla\cdot\mathbf{t} + \vec{g} + \frac{1}{?}\vec{j}\times\vec{B}$$

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

MHD

# ISSUES OF FLUID FLOW & HEAT TRANSFER ARE SUBSTANTIALLY DIFFERENT FOR LM AND MOLTEN SALTS

**Low-conductivity fluids**
**(Flibe, Flinabe)**
**s =$10^2$ 1/Ohm-m**
**k=1 W/m-K**

**<u>CLiFF</u>**
**U=10 m/s L=8 m**
**h=2 cm R=4 m**
**q=1.4 MW/$m^2$**
**$B_{\wedge}$=0.1 T $B_t$=10 T**

**High-conductivity fluids**
**(Li, Sn, Sn-Li, etc.)**
**s =$10^6$ 1/Ohm-m**
**k=50 W/m-K (Li)**

## Effect of a magnetic field on the fluid flow characteristics

Low-conductivity fluids:

$$rU^2/R = 5\times10^4 \quad rg = 2\times10^4$$

$$j\times B = (sUB_{\perp})B_{\perp} = 10^1$$

High-conductivity fluids:

$$rU^2/R = 1.25\times10^4 \quad rg = 0.5\times10^4$$

$$j\times B = (sUB_{\perp})B_{\perp} = 10^5$$

## Effect of magnetic field on turbulence suppression and heat transfer

$Ha/\mathrm{Re} = 0.0007$
Reduced turbulence but k is low

Laminarization:
$Ha/\mathrm{Re} > (Ha/\mathrm{Re})_{cr} \approx 0.005$

$Ha/\mathrm{Re} = 0.07$
Laminarized (but k high)

## Dominant issues are different

Free Surface Heat Transfer
- Surface Waviness & Suppression by MHD
- Surface Renewal

MHD Effects on Fluid Dynamics

# Models for Fluid Dynamics and Heat Transfer for LW's

- Several models/codes developed/adapted to serve the immediate need of LW Design Exploration
  - Several 2-D, 2.5-D free-surface codes with and without MHD were developed at UCLA and used successfully for design exploration and analysis, and understanding/identifying key LW thermofluid issues
  - FLOW 3-D: Commercial code; has free surface but no MHD
    - adapted/utilized for analysis of complex 3-D geometry non-MHD restraining forces, flow around penetrations, surface stabilities, etc.
    - UCLA added MHD: very useful (but limited)
- Started ambitious development of a new 3-D free surface MHD code with complex geometry (because none exists)

***Why need 3-D MHD?***

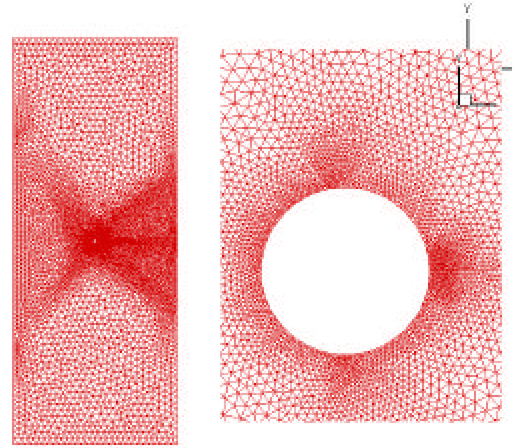
1 – Departure from axisymmetry

2 – Gradients in the 3-component magnetic field ( $B_{\perp}$ and $B_{T}$)

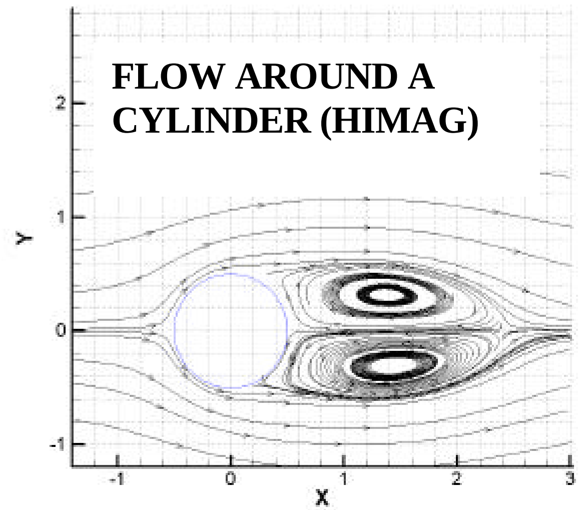
3 – Obstacles (penetrations), nozzles, etc.

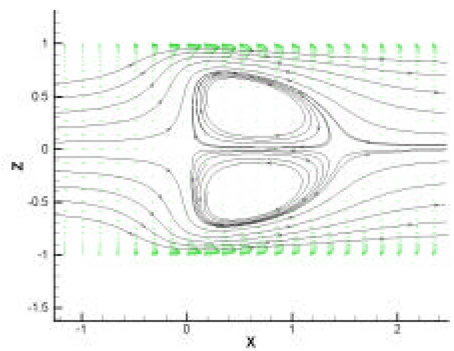
# A Computer Code is being developed by HyPerComp and UCLA for 3-D Free Surface, MHD flow with Complex Geometry

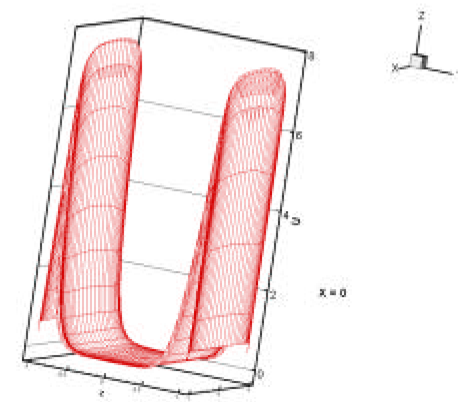
- Very challenging, but much needed development, because none exists
- Parallel iterative solver, based on latest in CFD and CEM
- Unstructured mesh
- Free surface tracking techniques of VOF and Level Set Methods
- Implicit methods to ease stiffness and time step constraints
- Different 3-D MHD formulations (? , B, and J) are being tested
- Extensive benchmarking part of code development
- Initial results encouraging but much development remains



UNSTRUCTURED GRID



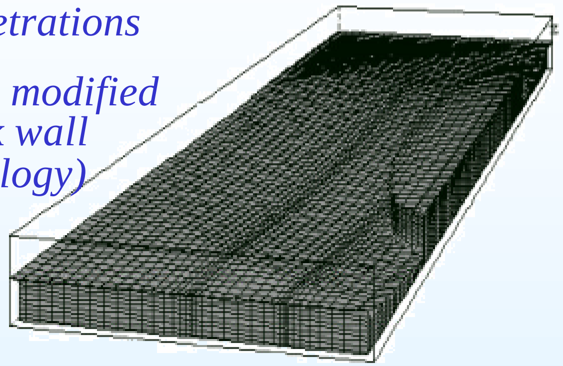
<u>Flow in a square duct</u>
Magnetic field is ramped up from 0 to 1 at Ha = 1000, N = 1000

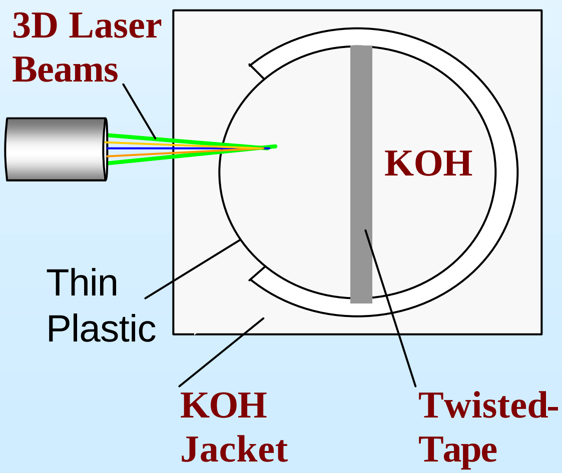
# FLIHY constructed as a flexible facility that serves many needs for Free-Surface Flows in low-k, high Pr fluids

## Flow Control

*Penetrations*

*(e.g. modified back wall topology)*

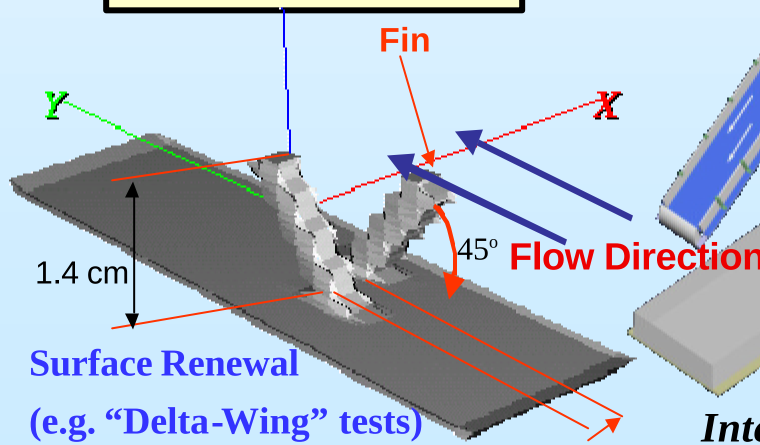





**JUPITER-II**

US-Japan Collaboration on Enhancing Heat Transfer

- **Large scale test sections with water/KOH working liquid**
- **Tracer dye and IR camera techniques**
- **PIV and LDA systems for quantitative turbulence measurements**



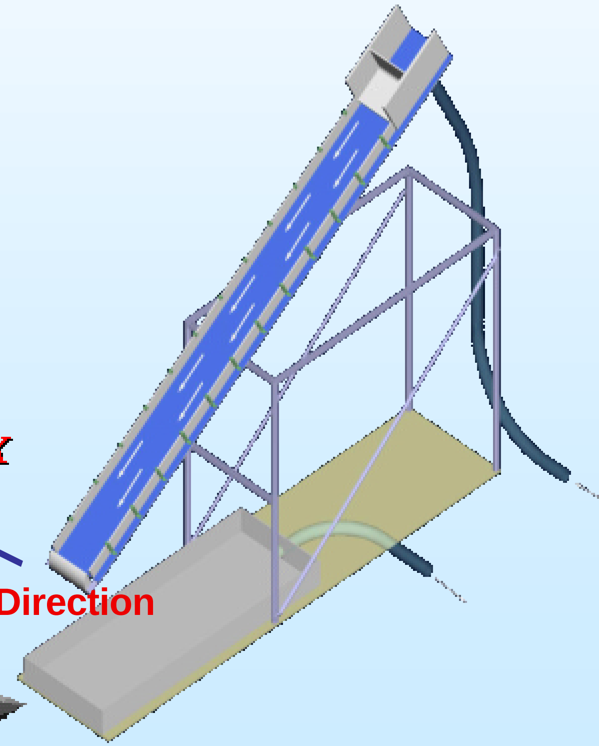

**Surface Renewal**

**(e.g. "Delta-Wing" tests)**

## Free Surface Interfacial Transport

- Turbulence at Free Surface

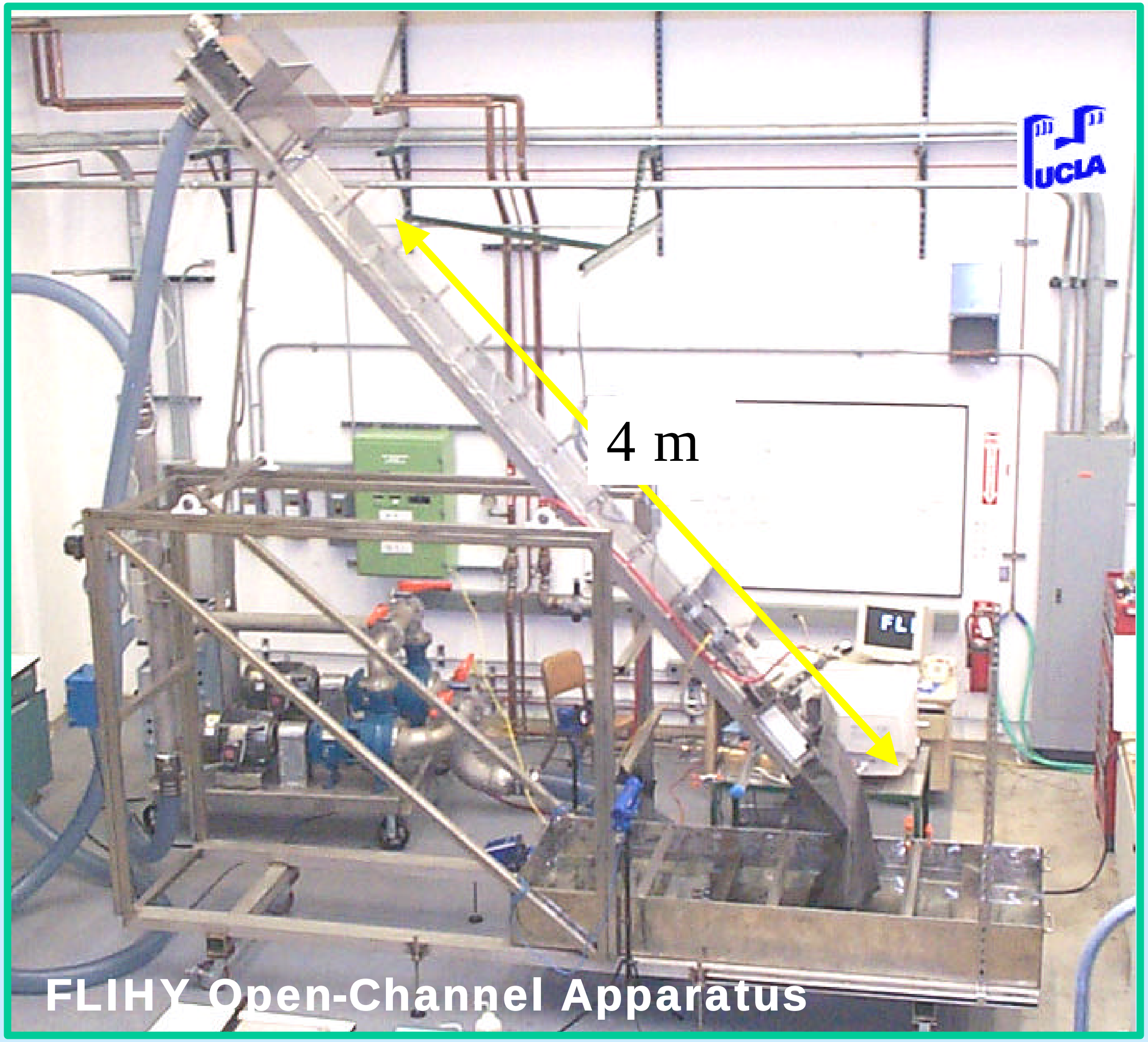
- Novel Surface Renewal Schemes



***Interfacial Transport Test section length = 4 m***

# A Series of Experiments for Free Surface Heat Transfer are under way in FLIHY

- Modular flow systems to accommodate large test article sizes up to 4 m in length
- Large flowrate capability up to 80 liters/sec
- Ultrasonic depth measurement system for free surface wave characterization
- IR surface heating and thermometry systems for surface heat transfer measurements

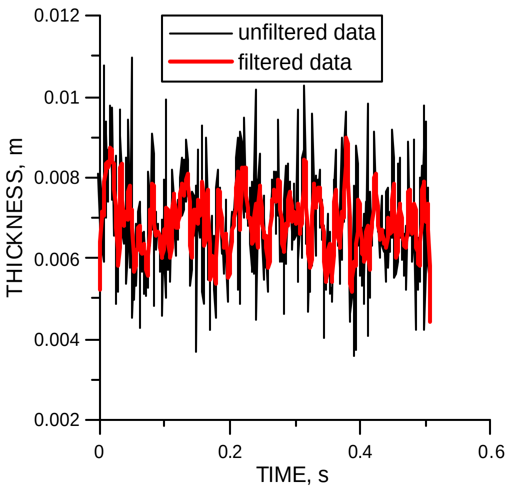



FLIHY Open-Channel Apparatus

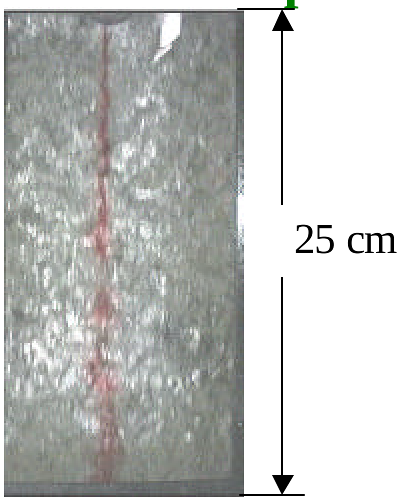
# Example of FLIHY EXPERIMENTAL RESULTS: SURFACE WAVINESS is the KEY FACTOR for HEAT TRANSFER in Free-Surface Turbulent Flows

**Statistical analysis based on the ultrasound measurements of the flow thickness demonstrates complicated wavy phenomena at the surface**

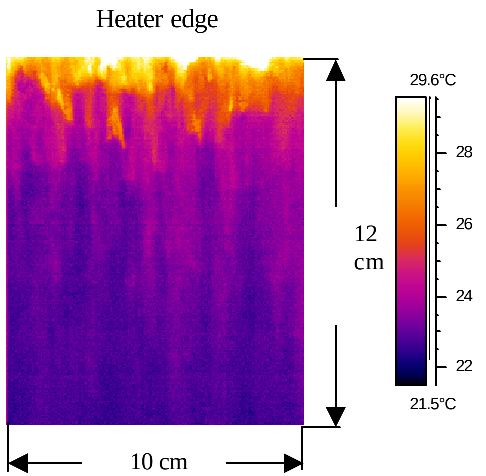
**Surface waviness enhances heat transfer through the surface renewal mechanism but leads to pronounced temperature non-uniformity**




**Finite-amplitude surface waves of 10-250 Hz propagate downstream**




**Dye experiment evidences the surface renewal mechanism**



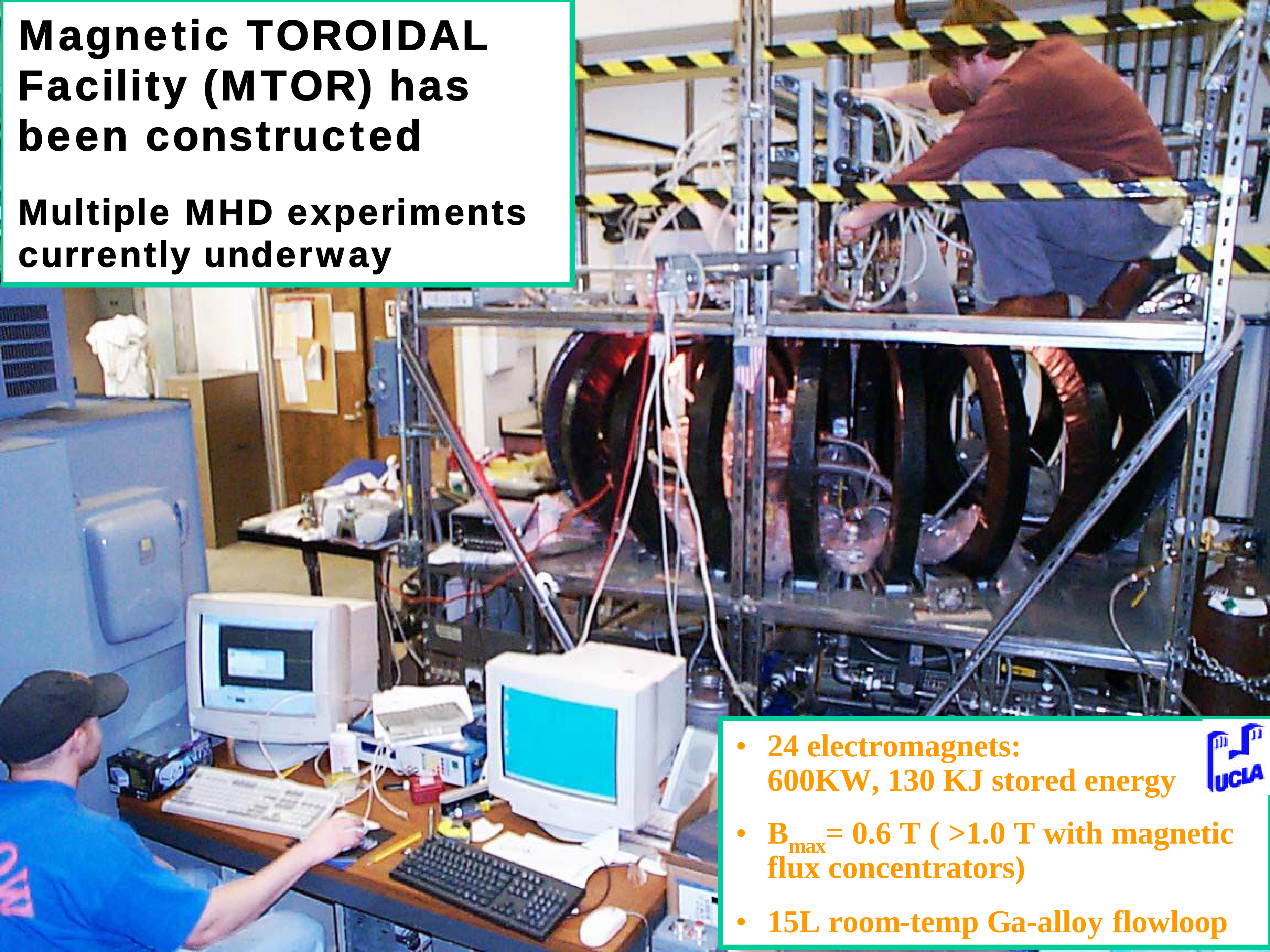

**IR images of the surface show "cold" and "hot" strikes $20 kW/m^2$, 30°, 10 L/s flow**

## Current data analysis and experiments are used for :

- **Correlation between hydrodynamic and heat transfer parameters**
- **Evaluation of $Pr_t$ to be used in "K-epsilon" model**

# Magnetic TOROIDAL Facility (MTOR) has been constructed

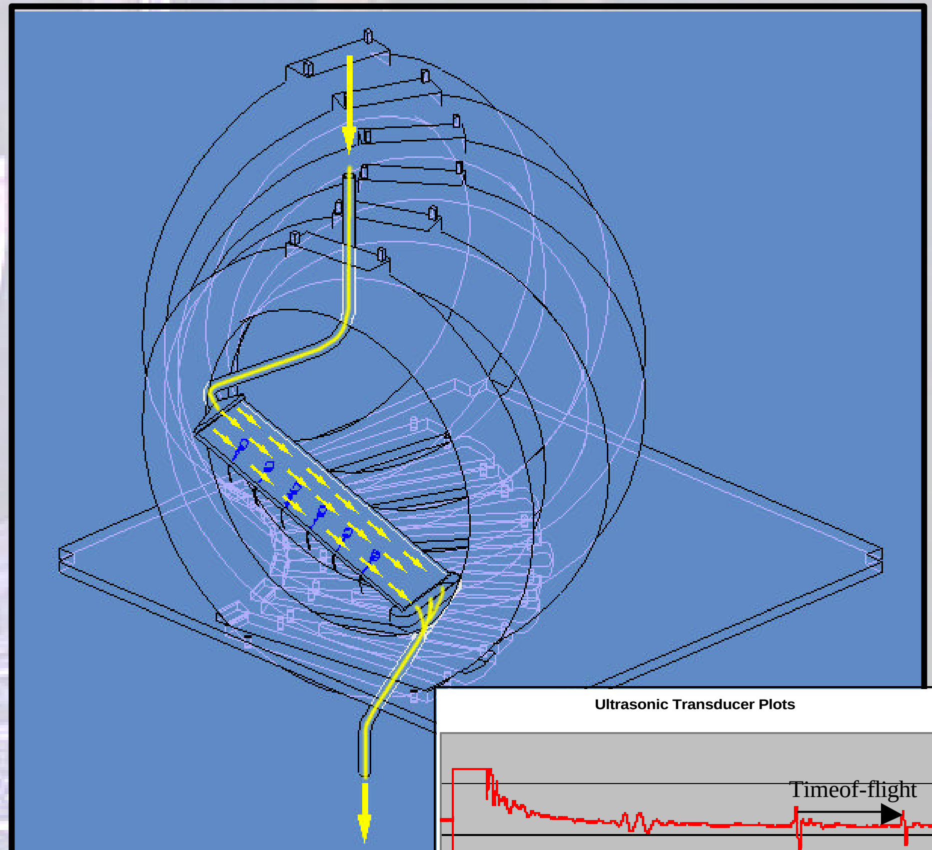
**Multiple MHD experiments currently underway**

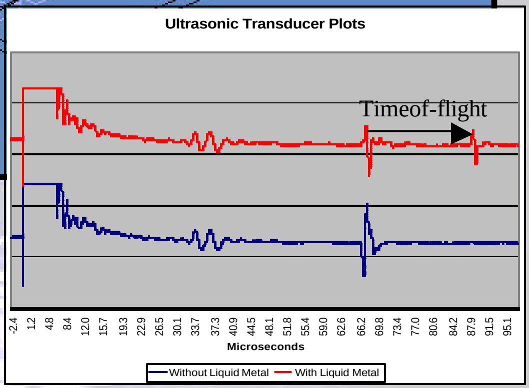


- 24 electromagnets: 600KW, 130 KJ stored energy
- $B_{max}$ = 0.6 T ( >1.0 T with magnetic flux concentrators)
- 15L room-temp Ga-alloy flowloop

# Exploring Free Surface LM-MHD in MTOR Experiment

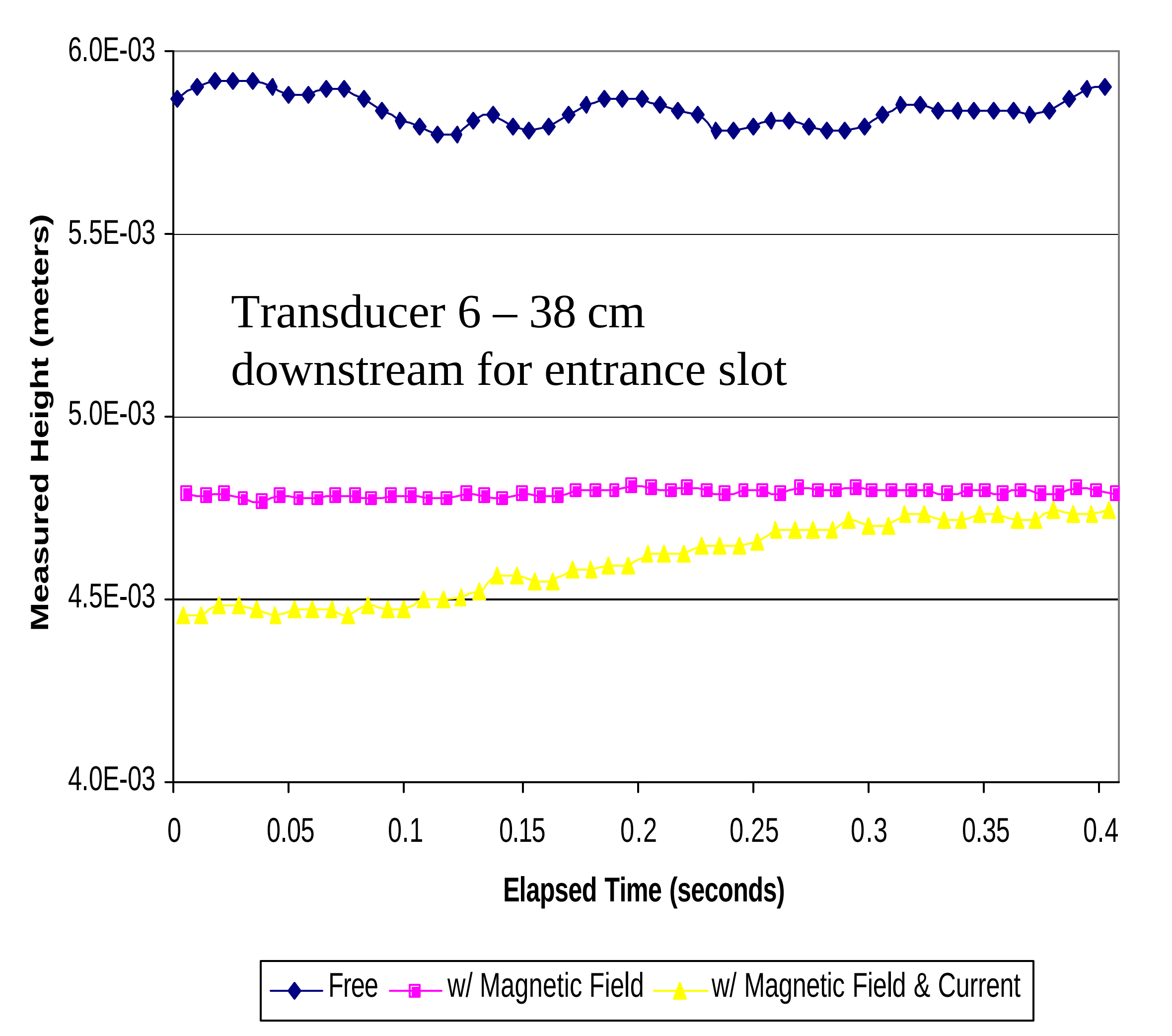
- **Study toroidal field and gradient effects:** Free surface flows are very sensitive to drag from toroidal field 1/R gradient, and surface-normal fields
- **3-component field effects on drag and stability**: Complex stability issues arise with field gradients, 3-component magnetic fields, and applied electric currents
- **Effect of applied electric currents**: Magnetic Propulsion and other active electromagnetic restraint and pumping ideas
- **Geometric Effects**: axisymmetry, expanding / contacting flow areas, inverted flows, penetrations
- **NSTX environment simulation**






***MTOR designed and constructed in collaboration between UCLA, PPPL and ORNL***

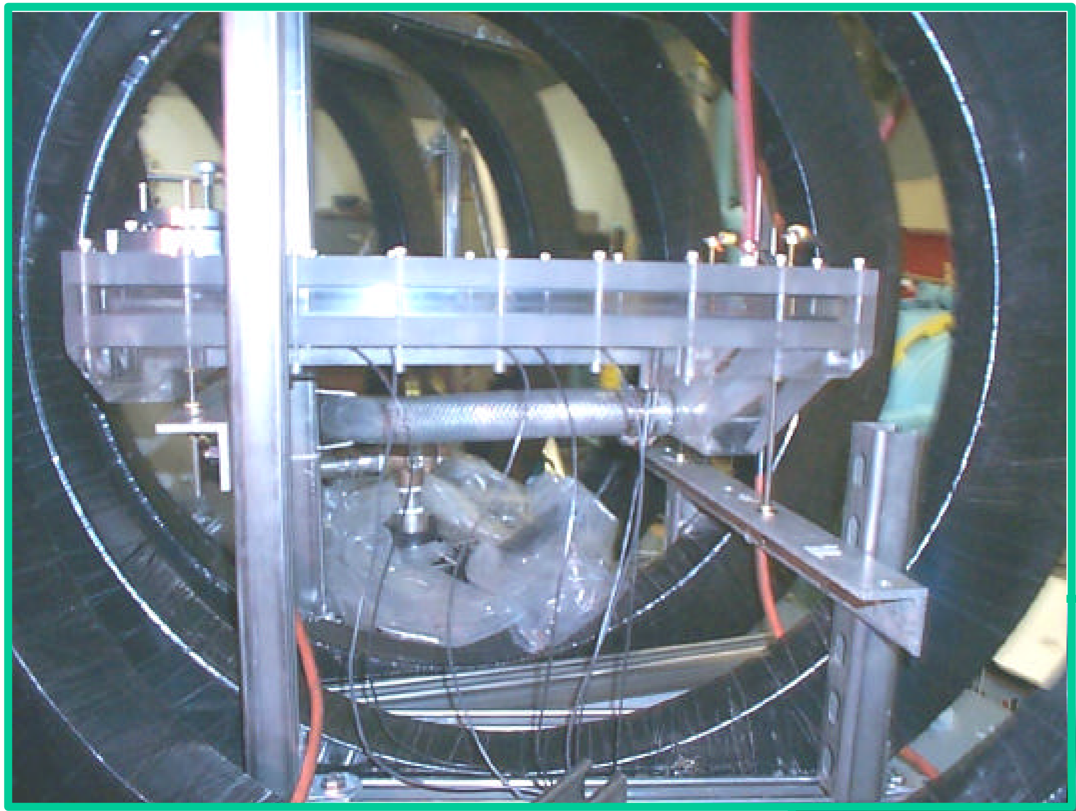
# Example results from MTOR Experiments: Film flow height response to toroidal field and magnetic propulsion current



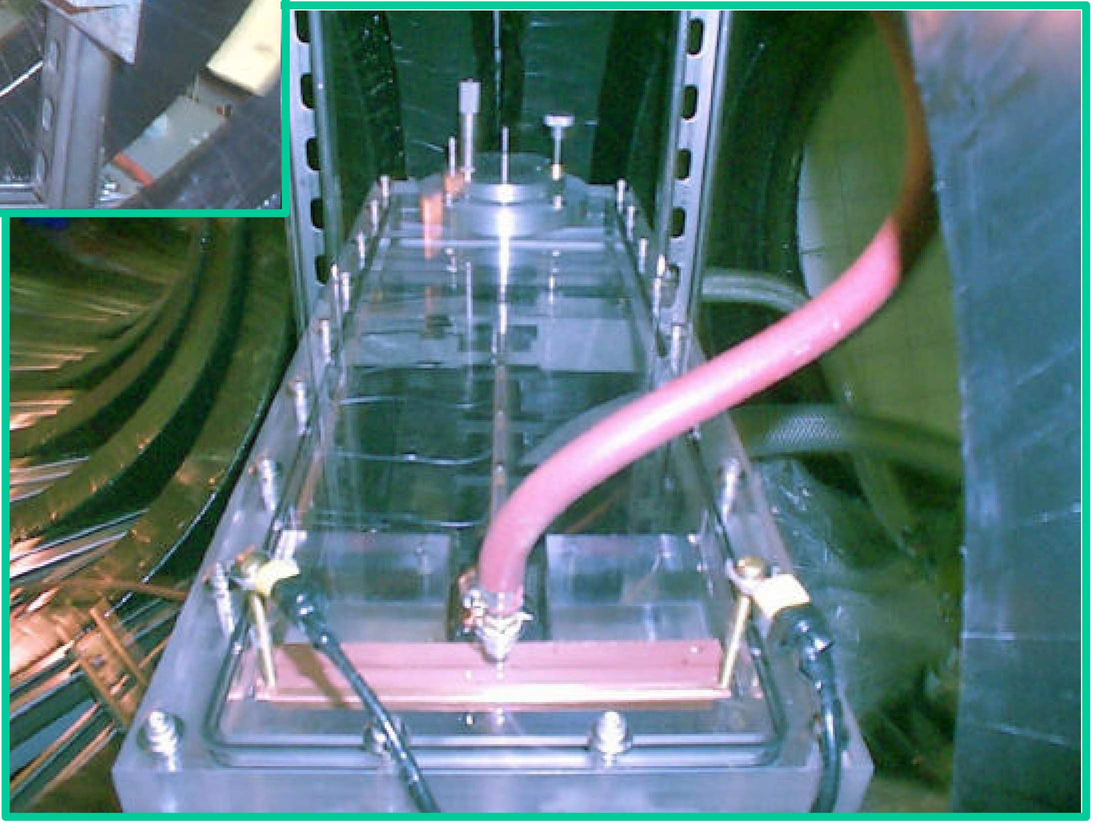

B field acts to laminarize flow – **Reducing flow resistance and eliminating surface waves**

Magnetic propulsion current acts to accelerate flow, but low frequency instabilities observed

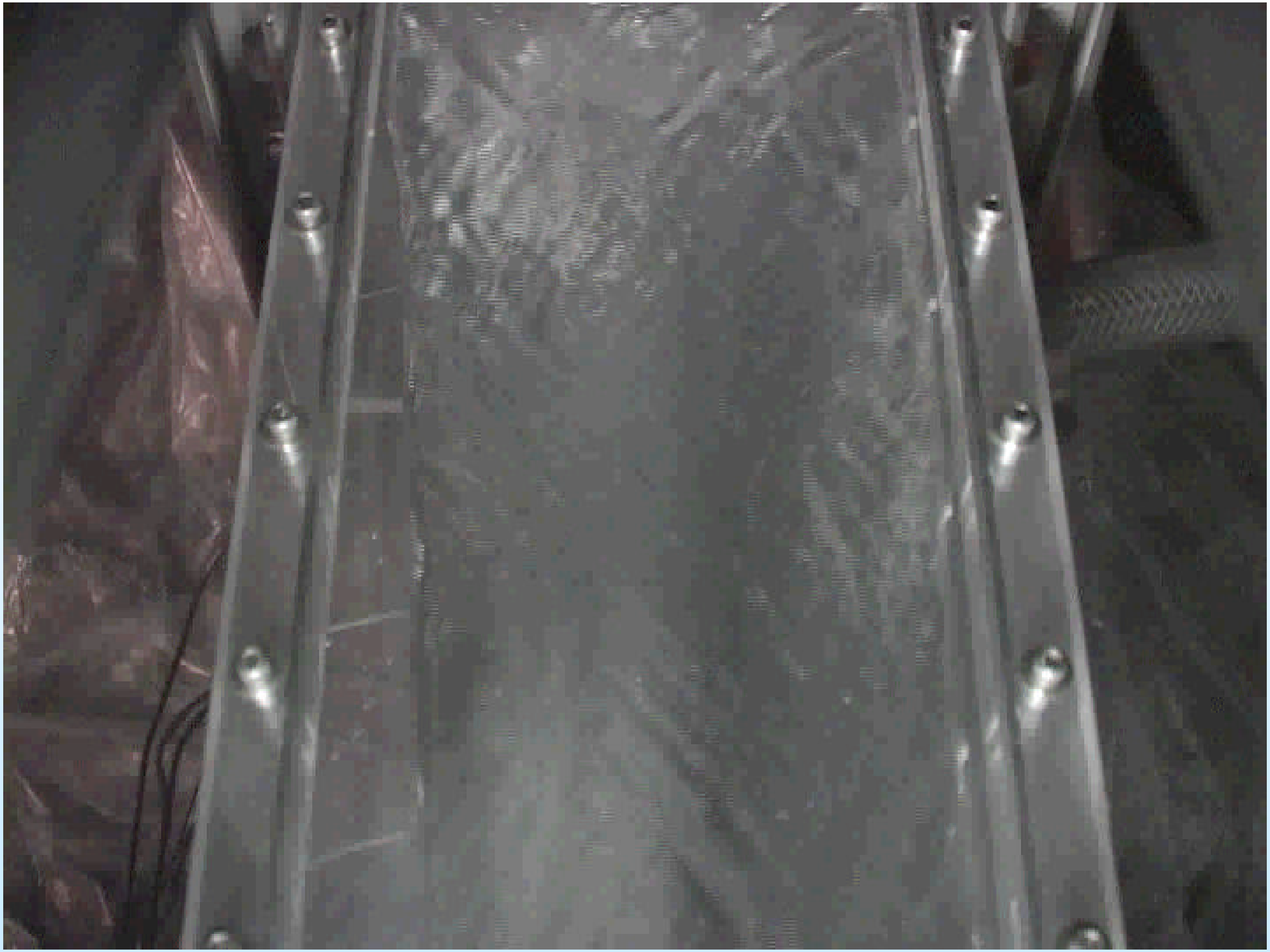
# Inclined-Plane Test Section



- Flow area: 20 cm x 60 cm
- Walls are insulated and do not wet Ga alloy



- 300 A available for magnetic propulsion tests
- 7 Ultrasonic Flow Height Transducers
- Variable inclination +5 to –15 deg



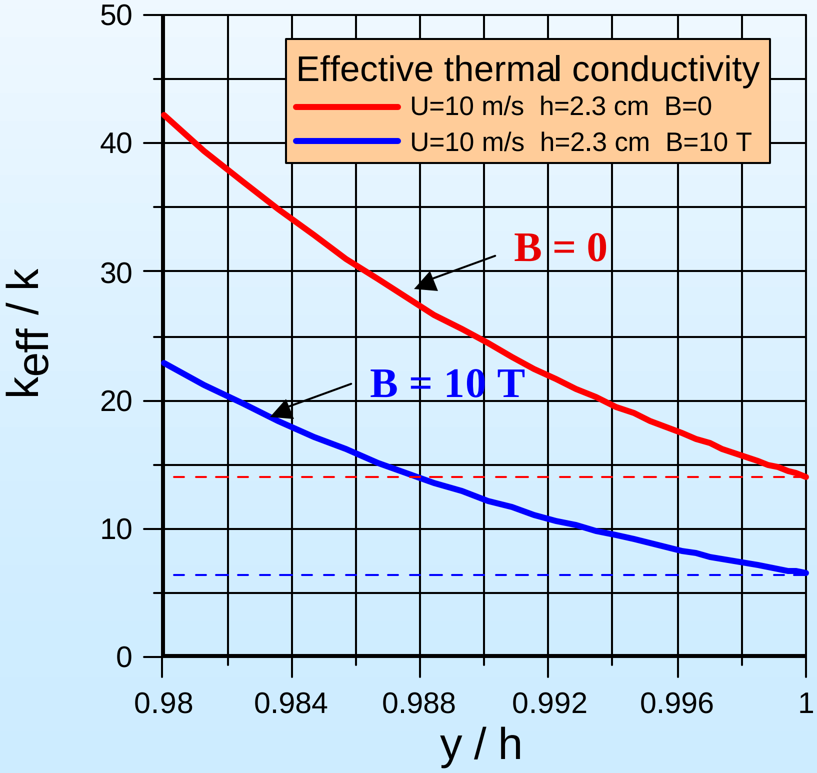
# Liquid Metal Integrated Test System

- LIMITS can operate up to 450C and at 150 psi.
- 15 gpm liquid metal flow loop
- Test chamber with either magnet system for MHD testing or electron beam for HHF testing.
- All hardware completed and final commissioning in progress.
- Full diagnostics set: flow, delta P, delta T, surface T, etc.

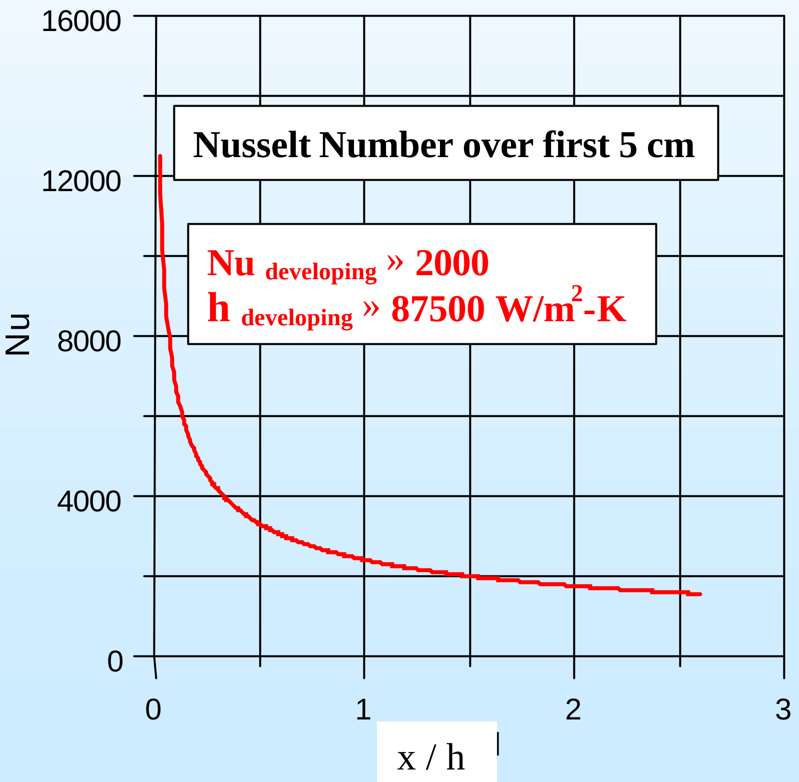
Sandia National Laboratories

# Results of Modeling Heat Transfer in Flinabe

## Magnetic Field Reduces Turbulence



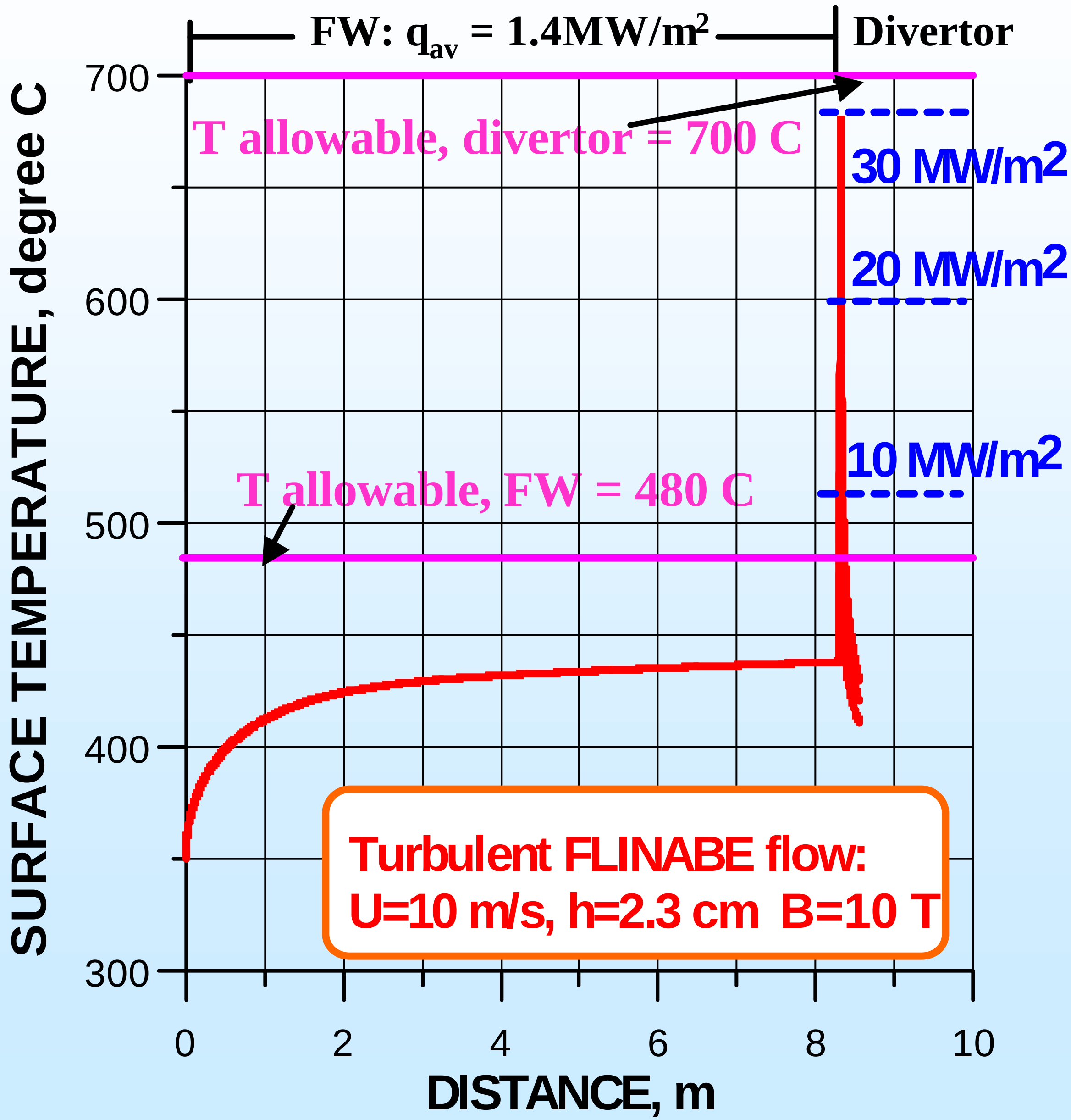

## Heat Transfer is higher in the developing region (can help in divertor region)



# HEAT TRANSFER - EDGE PLASMA MODELING FOR FLINABE FW SHOWS HIGH HEAT LOAD CAPABILITIES

## Flinabe

- **Melting Point = 240 - 310 C**
  **Inlet T ~ 350 C**
- **From Plasma-edge modeling**
  **T (allowable) = 480 C - FW**
  **= 700 C - Divertor**
- **Turbulent FLINABE layer can tolerate high heat fluxes:**
  **FW: *1.4 MW/m² (averaged)***
  **Divertor: *30 MW/m² (peak)***
  ***(accounting for B effect with no flow mixing)***
- **Further improvements are possible through, for example, mixing the liquid right before the divertor inlet**



# Heat Transfer Calculations for Sn Cliff Demonstrate a Wide Design Window

Temperature Limits

| | Li | Sn-Li | Sn | Flinabe |
|---|---|---|---|---|
| **FW** | **420** | **630** | **840** | **480** |
| **Div.** | **475** | **700** | **1600** | **700** |

**TIN**

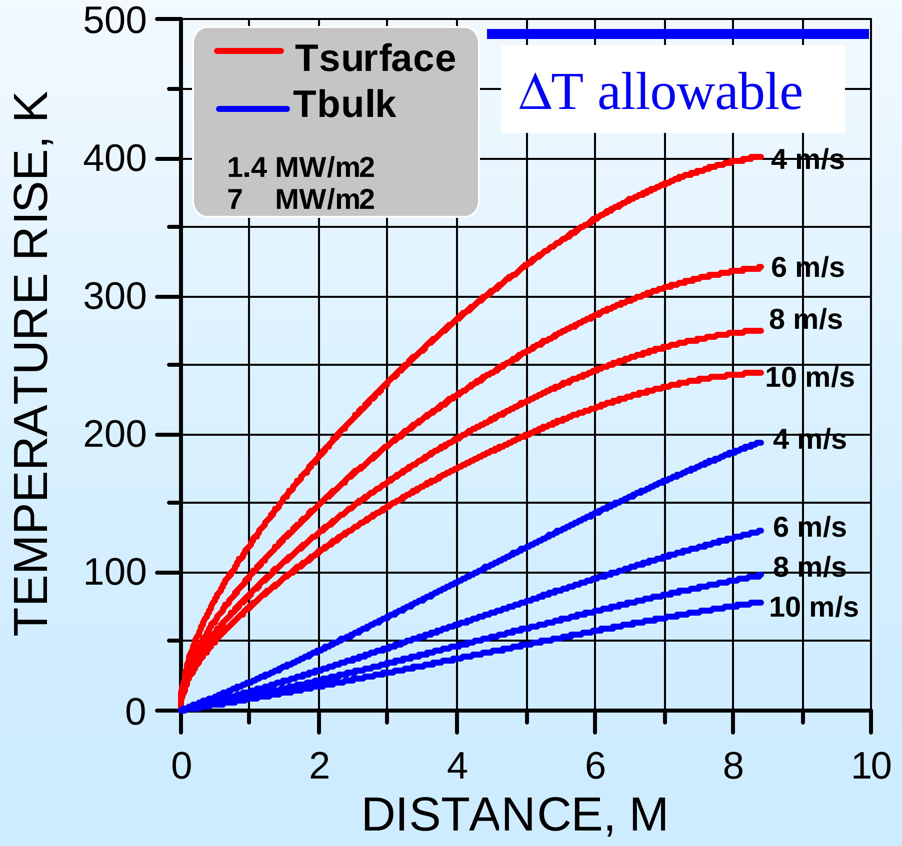
Melting T=**232°**

Inlet T=**300-350°**

$T_{allowable}$=**840°** (FW)

$T_{allowable}$=**1600°** (Divertor)

**Average neutron wall loading = 7 MW/m$^2$**
**Average surface heat flux = 1.4 MW/m$^2$**



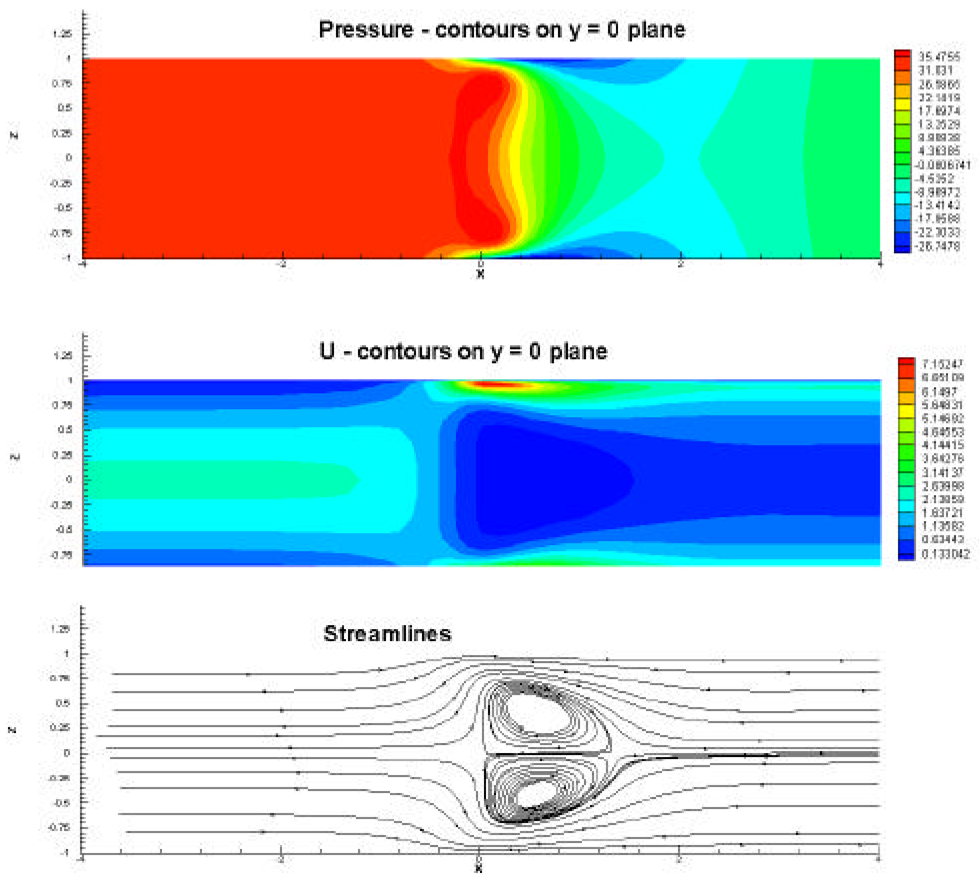
# EFFECT OF MAGNETIC FIELD GRADIENTS ON LM FLOW IS VERY IMPORTANT

**LIQUID WALL WITH AXIAL SYMMETRY:**

- Is affected through spatial variations of the toroidal field
- MHD drag can be reduced by applying a current (magnetic propulsion)

**LIQUID WALL WITH NO AXIAL SYMMETRY (sectioned):**

- Is affected through spatial variations of the wall normal field
- Still needs more quantification




Channel flow in a fringing magnetic field: Ha=1000.
3-D calculations by HIMAG code.
Two trapped vortices can be seen.

# WALL ELECTRICAL CONDUCTIVITY HAS A STRONG IMPACT ON LIQUID WALL DESIGN

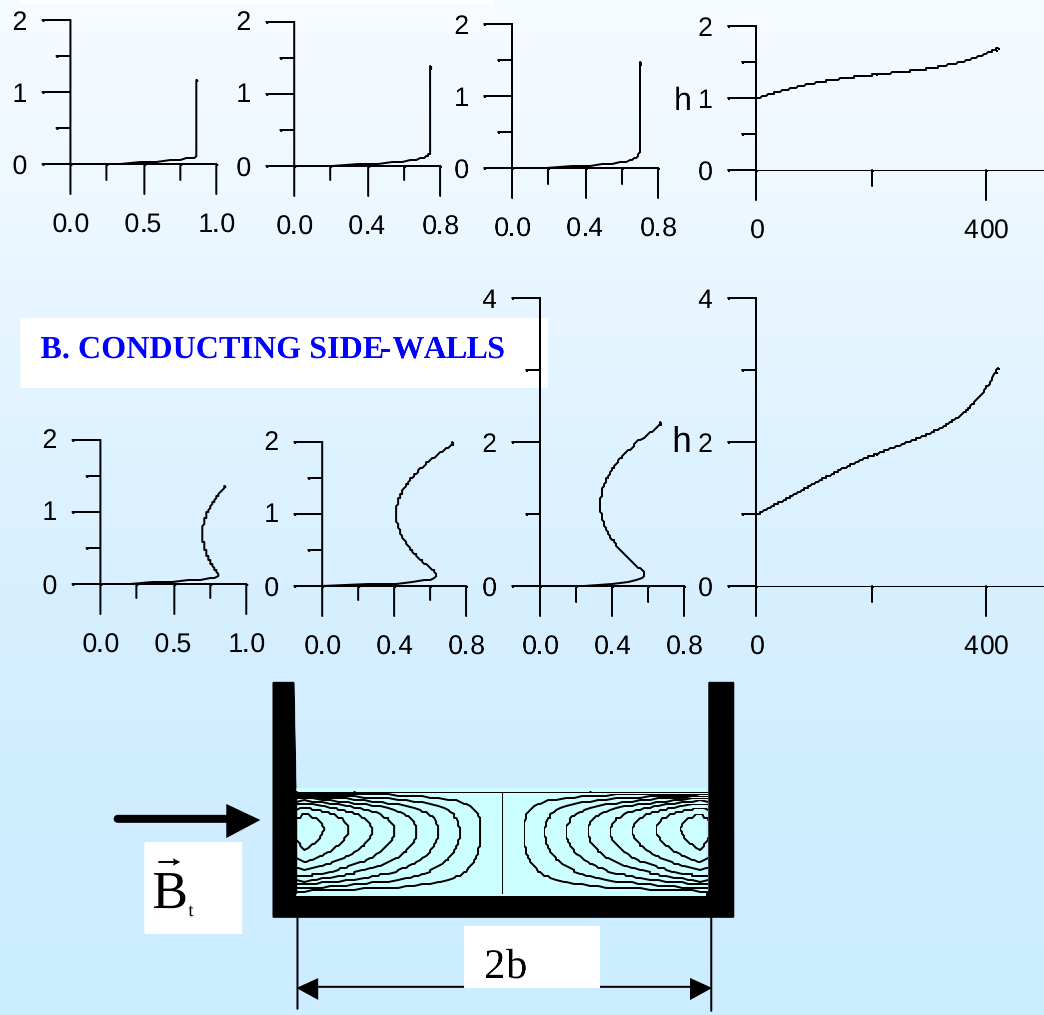
## INITIAL CONCLUSIONS

**(ACCOUNTING FOR BOTH TOROIDAL AND NORMAL FIELDS)**

- **METALLIC SIDE-WALLS ARE UNACCEPTABLE**
- **SIC SIDE-WALLS ARE ACCEPTABLE PROVIDED THEY ARE FAR APART (2B > 8 M) INSULATORS ALLOW SMALLER SPACING**
- **IN AN AXI- SYMMETRIC FLOW (no side-walls), THE MAXIMUM ALLOWBALE WALL-NORMAL FIELD IS (Bn)max=0.015 T**
- **IN A SECTIONED FLOW WITH ISOLATED SIDE-WALLS,**
  - **(Bn)max=0.1 T (metallic back-wall)**
  - **(Bn)max=0.2 T (SiC back-wall)**
  - **(Bn)max=0.5 T (isolated back-wall)**

**VELOCITY PROFILES AND DOWNSTREAM FLOW THICKNESS VARIATION IN LiCLiFF.**

**A. ISOLATED SIDE-WALLS**



# I am Done !