Recent Advances in Chamber Science and Technology

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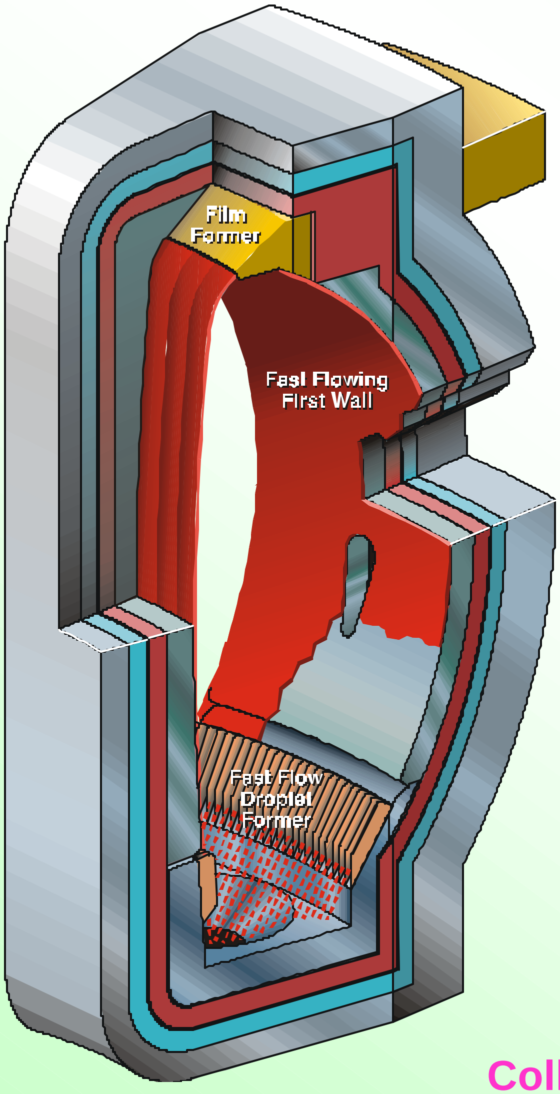
Recent Progress on

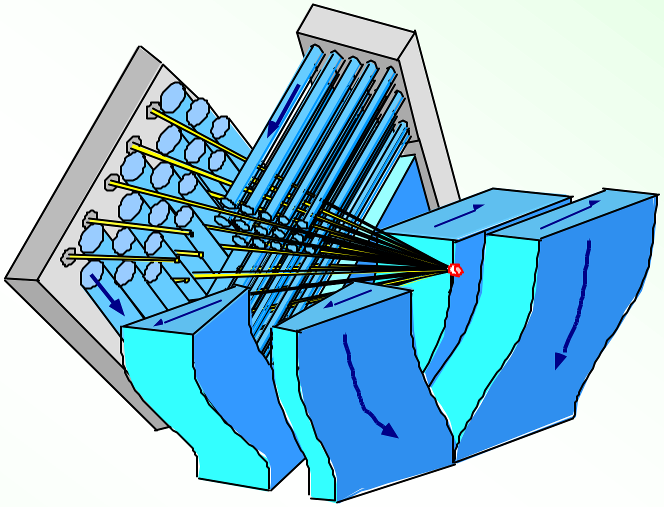
LIQUID WALLS

The remainder of this presentation will focus on Liquid Walls

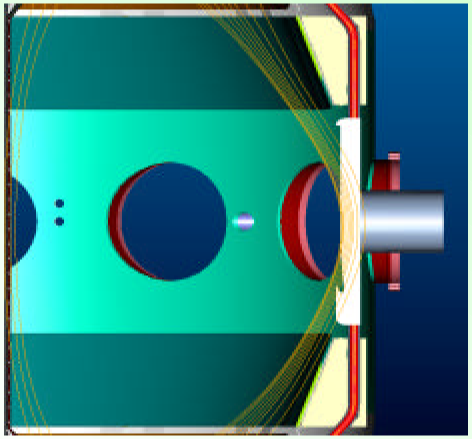
Liquid Wall Science & Technology are being Advanced in Several MFE & IFE Research Programs



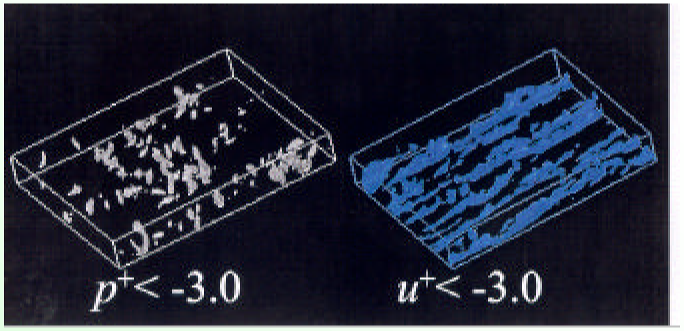
APEX CLiFF



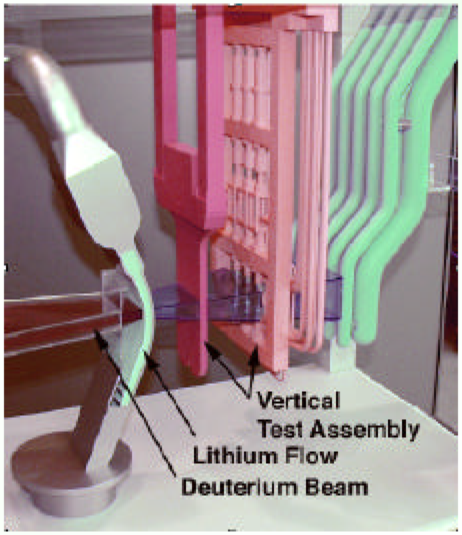
HYLIFE-II



ALPS/APEX NSTX Li module

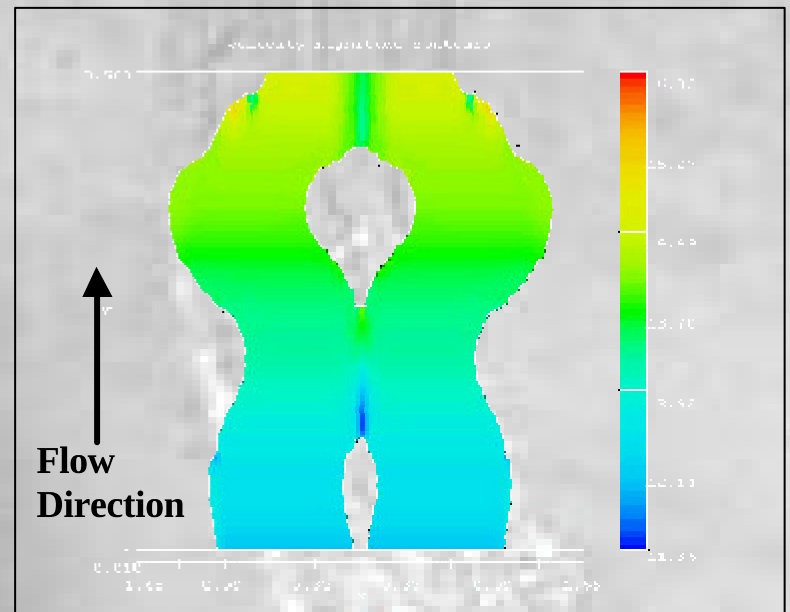


DNS Free Surface Simulation
Collaboration with non-fusion scientists
US-Japan Collaboration

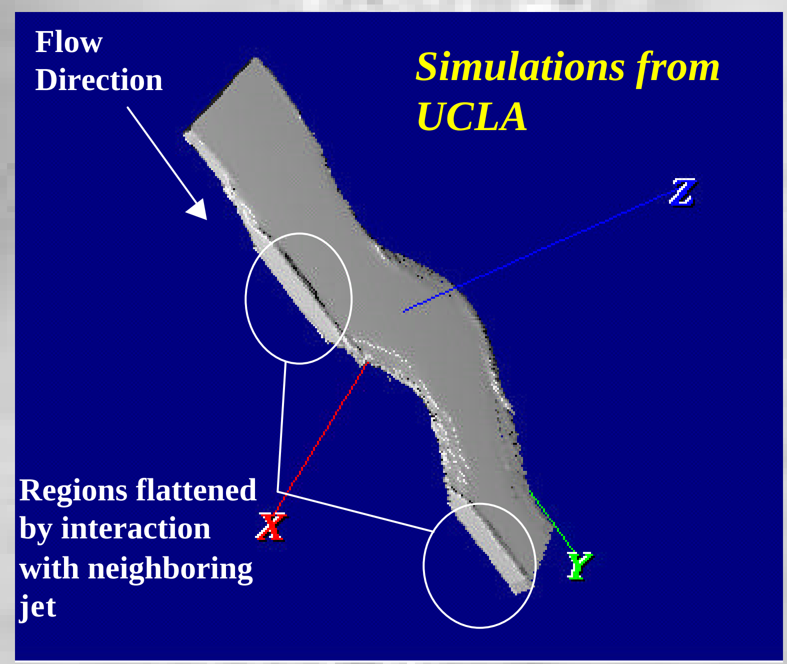


IFMIF

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

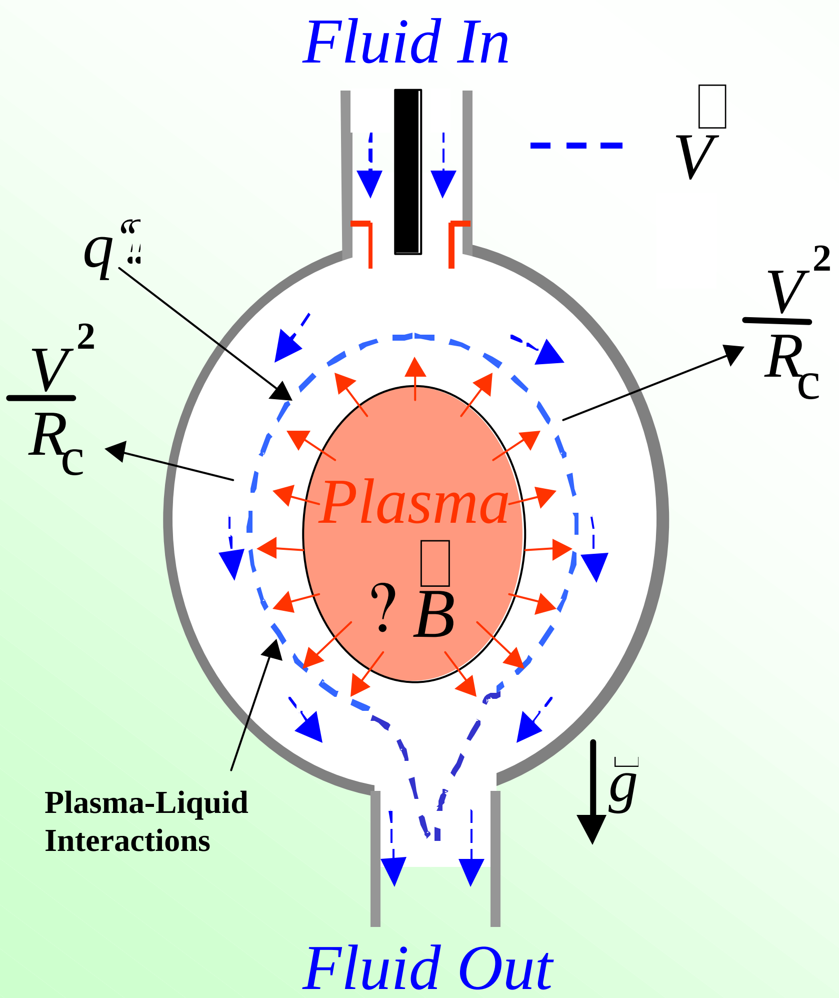
? Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials problems more tractable

? 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

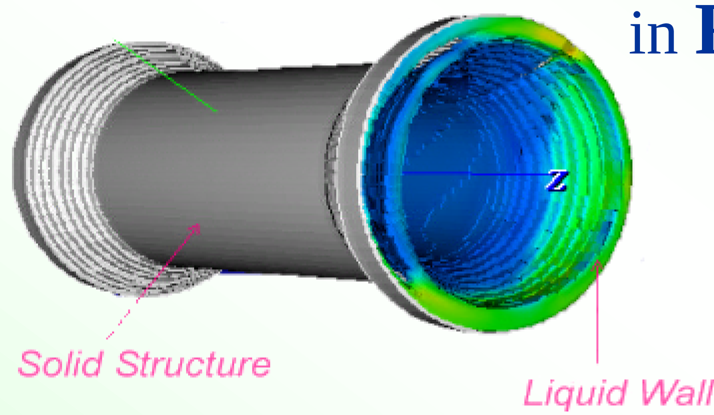
"Liquid Walls" Have Many Design Options

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)

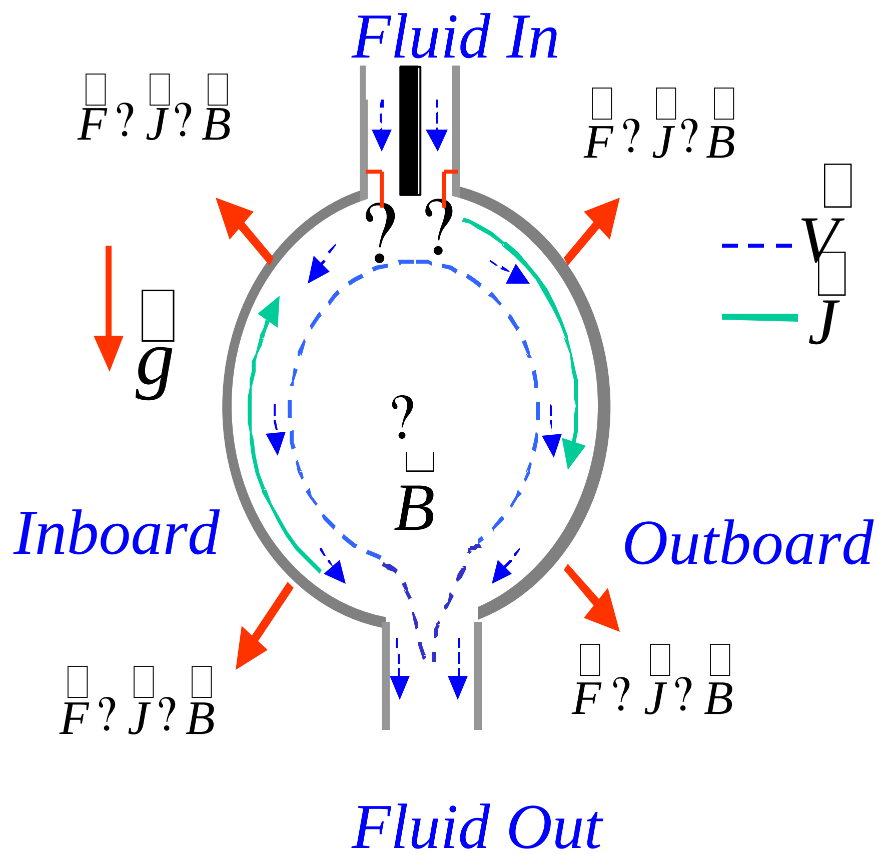
Swirl Flow in **FRC**



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

Electromagnetically Restrained LM Wall (R.Woolley)

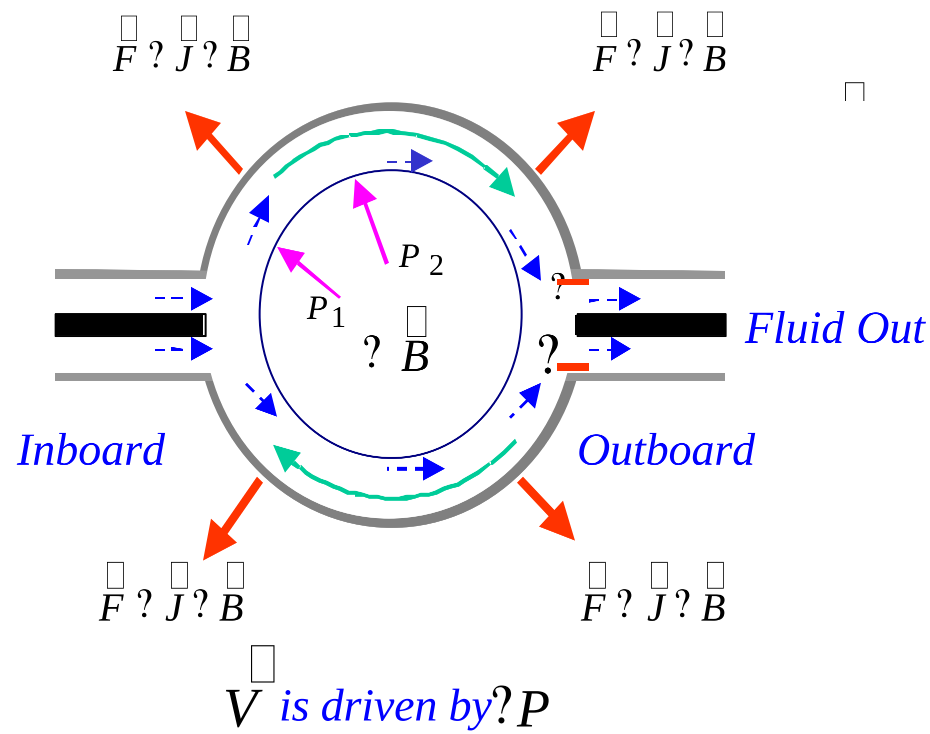
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



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

- **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 > 20MW/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:

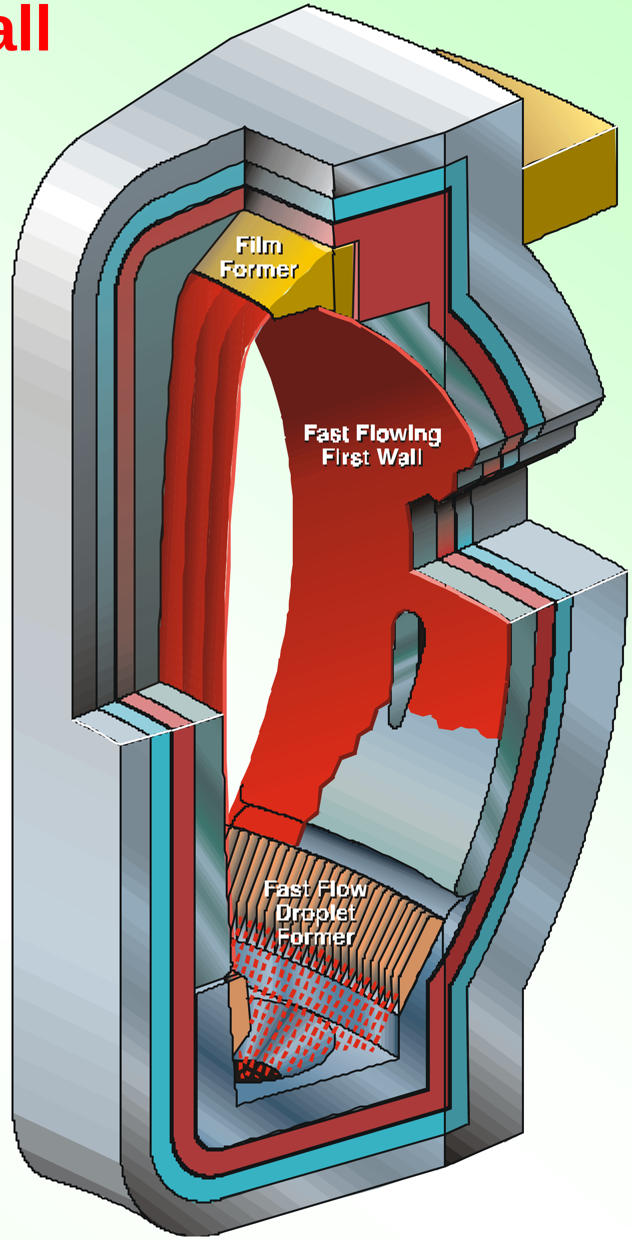
a) Provide High Power Density Capability (surface heat flux, not neutron heating, is what limits power density in fusion)

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

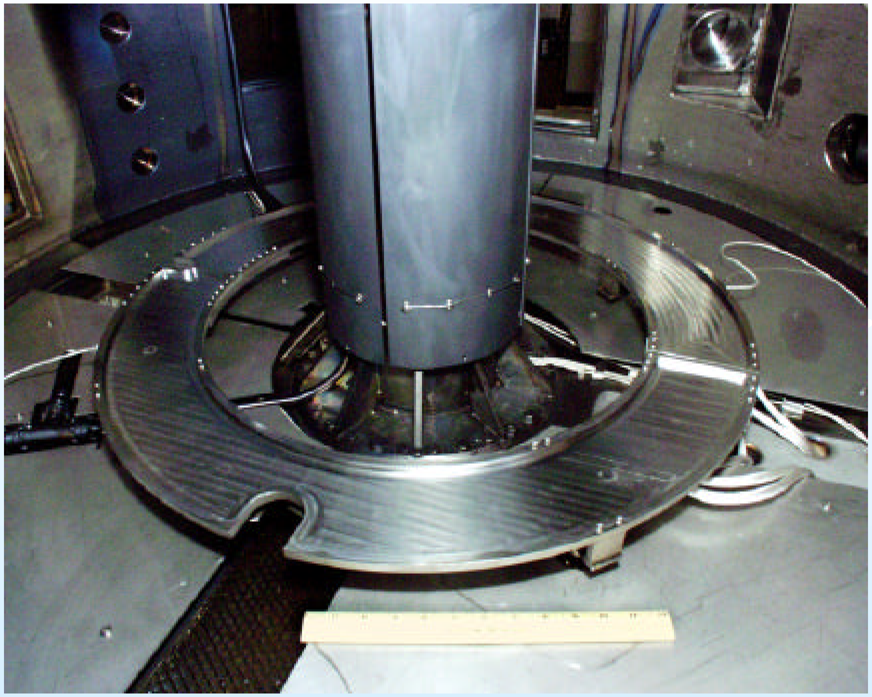
Progress on R&D for Plasma-Liquid Surface Interactions

- **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



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

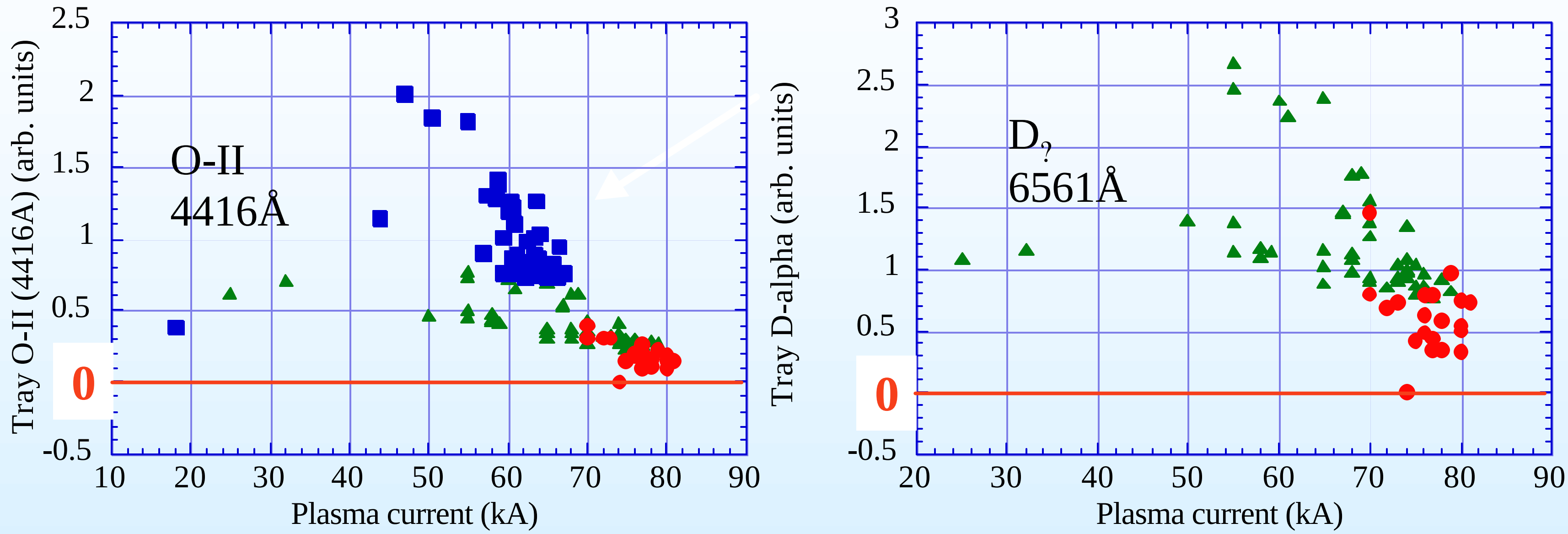
CDX-U Parameters:

R_0	34 cm
a	22 cm
$A=R_0/a$	?1.5
?	?1.6
$B_T(0)$	2.2 kG
I_P	? 80 kA
P_{rf}	<200 kW
$?_{disch}$	<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

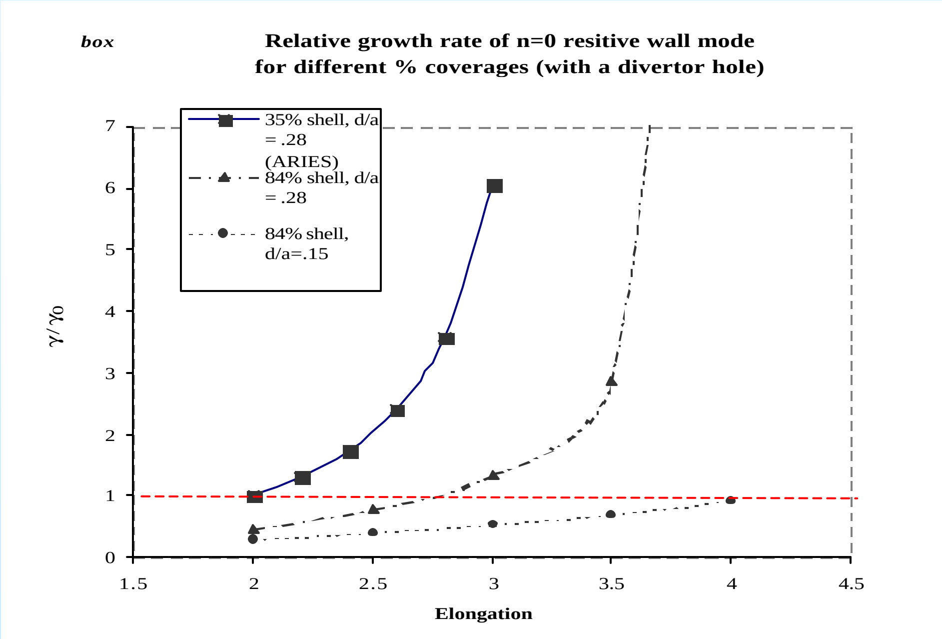


† Bare SS tray limiter † Cold lithium limiter † Liquid lithium limiter (250° C)

- 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 <u>shaped conducting shell</u>**
- **Liquid metals may be used for the <u>conducting shell</u>**
- **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)

?	?*
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

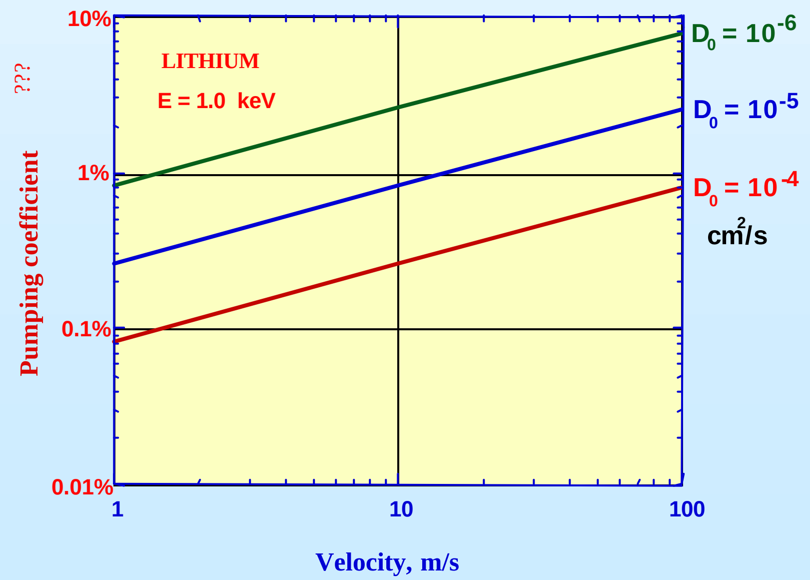
How to Pump Helium Particles with Liquid Walls?

- 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

Passive & Active Scalar Transport

$$?C_p[\frac{?T}{?t} ? (V ??)T] ? k?T$$

$$\frac{?C}{?t} ? (V ??)C ? D?C$$

Free Surface Phenomena

$$\frac{??}{?t} ? (V ??)? ? 0$$

Electromagnetism

$$\frac{?B}{?t} ? \frac{1}{s\mu_0} ?B ? ? ?(V ? B);$$

$$j ? \frac{1}{\mu_0} ? ? B \quad ? ?B ? 0$$

Hydrodynamics

$$\frac{?V}{?t} ? (V ??)V ? -\frac{1}{?} ? p$$

$$? ? ?\mathbf{t} ? g ? \frac{1}{?} j ? B$$

$$? ?V ? 0$$

- 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

MHD

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

Low-conductivity fluids
(Flibe, Flinabe)
? =10² 1/Ohm-m
k=1 W/m-K

CLiFF
U=10 m/s L=8 m
h=2 cm R=4 m
q=1.4 MW/m²
B? =0.1 T Bt=10 T

High-conductivity fluids
(Li, Sn, Sn-Li, etc.)
? =10⁶ 1/Ohm-m
k=50 W/m-K (Li)

Effect of a magnetic field on the fluid flow characteristics

$?U^2/R ? 5?10^4 \quad ?g ? 2?10^4$

$j ? B ? (?UB_?)B_? \quad ? 10^1$

$?U^2/R ? 1.25?10^4 \quad ?g ? 0.5?10^4$

$j ? B ? (?UB_?)B_? \quad ? 10^5$

Effect of magnetic field on turbulence suppression and heat transfer

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

Laminarization:
$Ha/\mathrm{Re} ? (Ha/\mathrm{Re})_{cr} \; ? \; 0.005$

$Ha/\mathrm{Re} ? 0.07$
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?

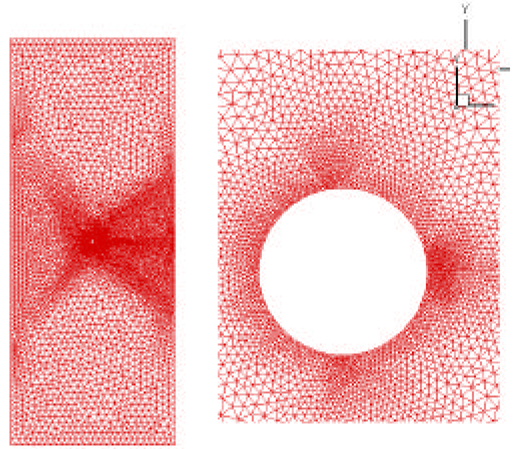
1 – Departure from axisymmetry

2 – Gradients in the 3-component magnetic field ($B_?$ and B_T)

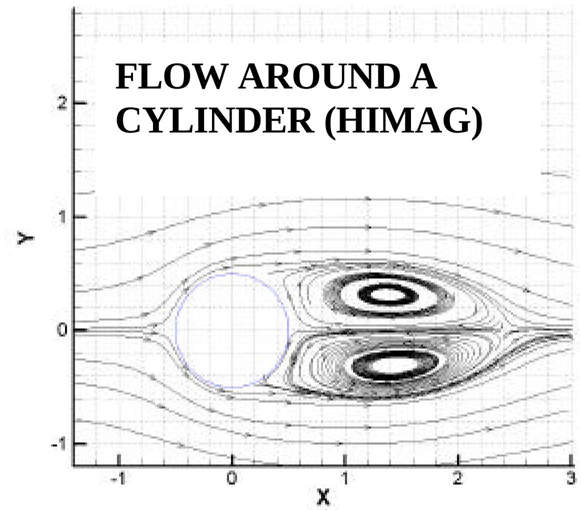
3 – Obstacles (penetrations), nozzles, etc.

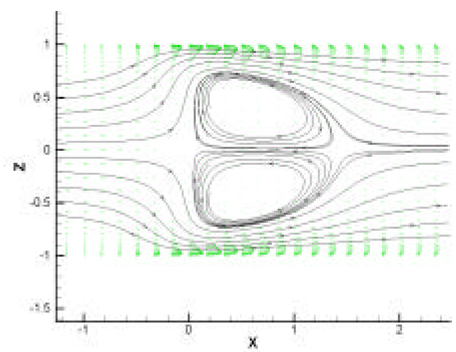
A Computer Code is being developed by HyPerComp and UCLA for 3-D Free Surface, MHD flow with Complex Geometry

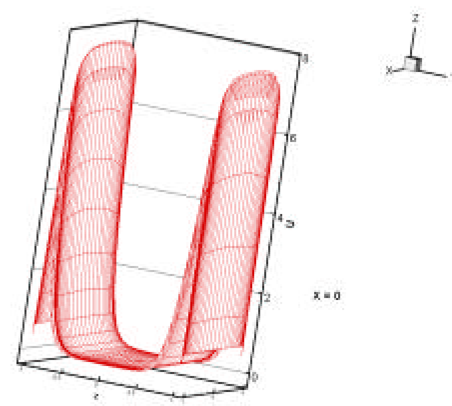
- Very challenging, but much needed development, because none exists
- Parallel iterative solver, based on latest in CFD and CEM
- Unstructured mesh
- Free surface tracking techniques of VOF and Level Set Methods
- Implicit methods to ease stiffness and time step constraints
- Different 3-D MHD formulations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



UNSTRUCTURED GRID







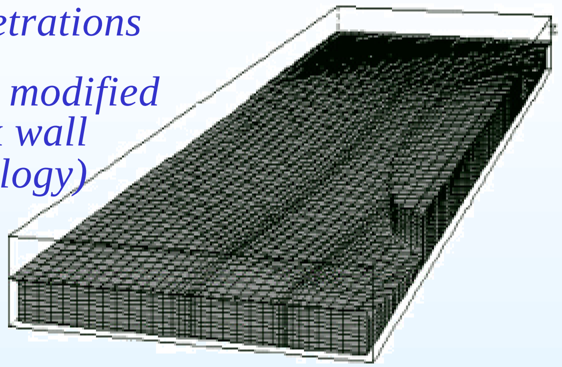
Flow in a square duct
Magnetic field is ramped up from 0 to 1 at Ha = 1000, N = 1000

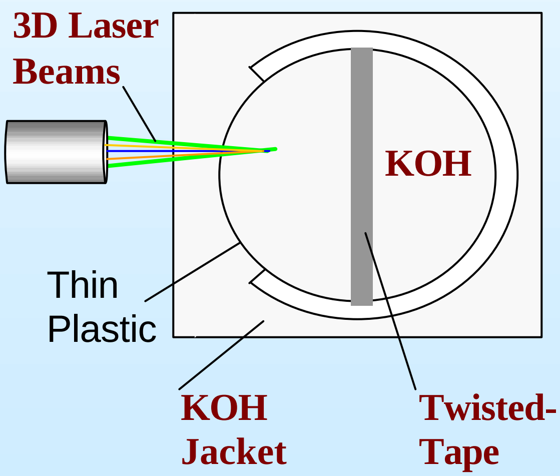
FLIHY constructed as a flexible facility that serves many needs for Free-Surface Flows in low-k, high Pr fluids

Flow Control

Penetrations

(e.g. modified back wall topology)

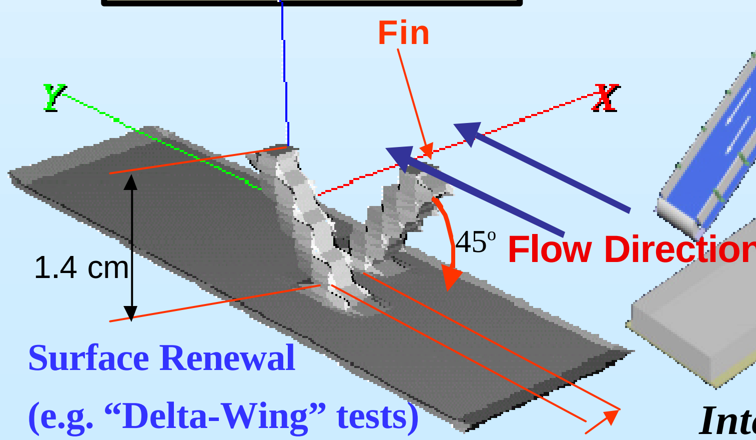




JUPITER-II

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**



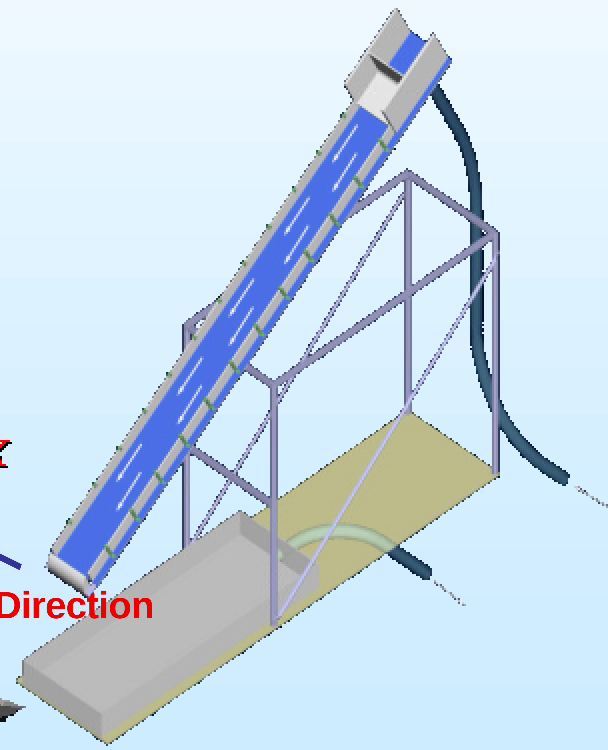
Surface Renewal

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

Free Surface Interfacial Transport

- Turbulence at Free Surface

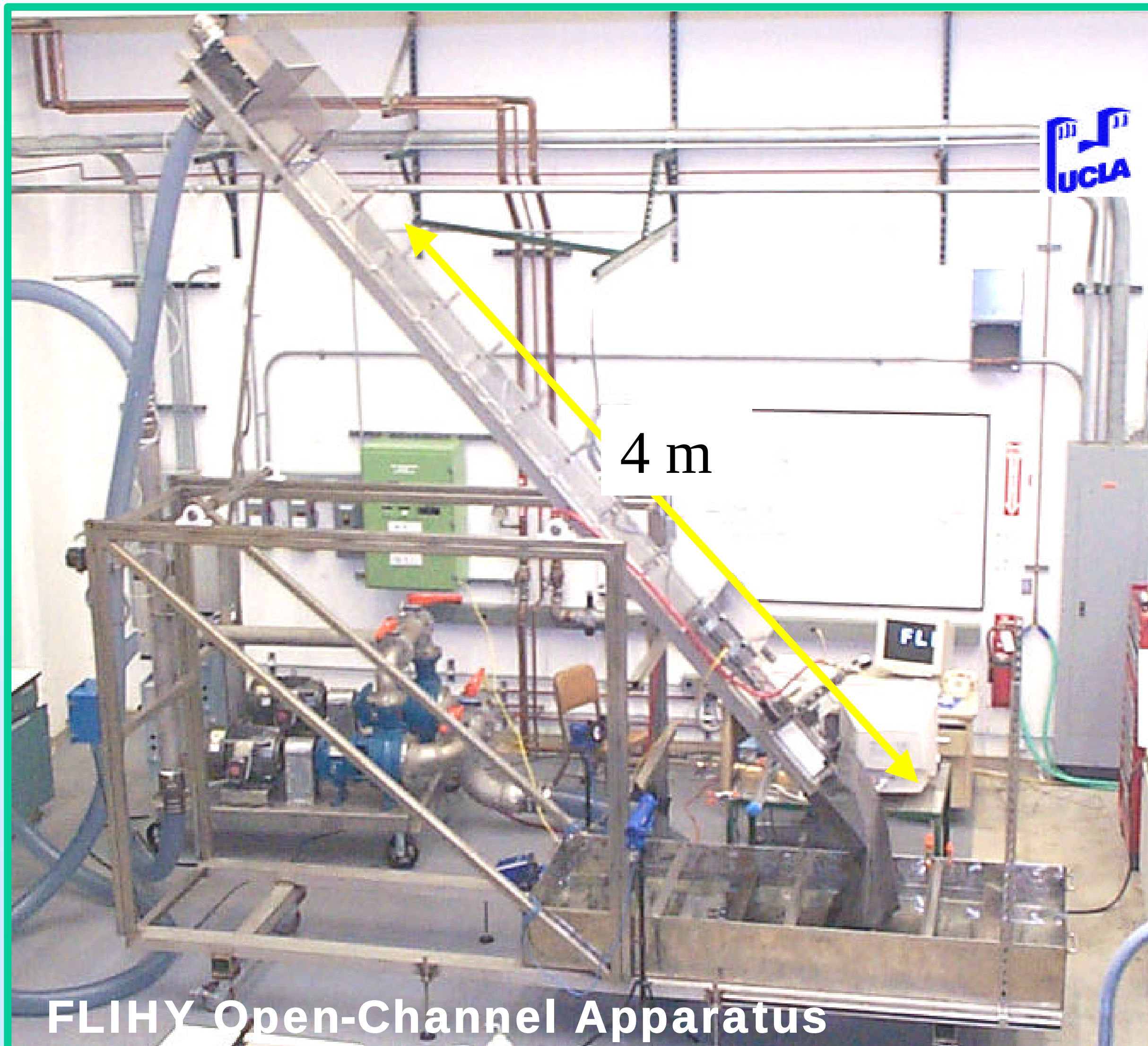
- Novel Surface Renewal Schemes



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

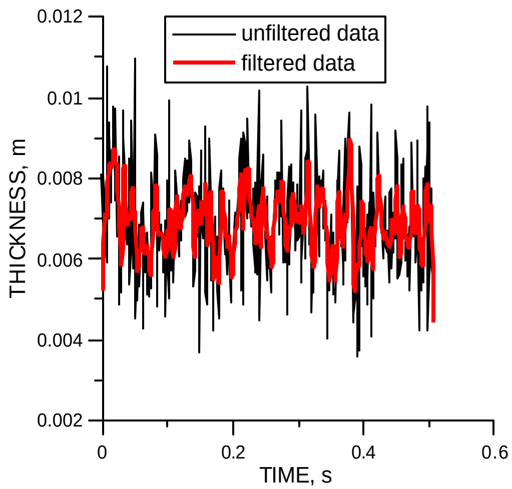


FLIHY Open-Channel Apparatus

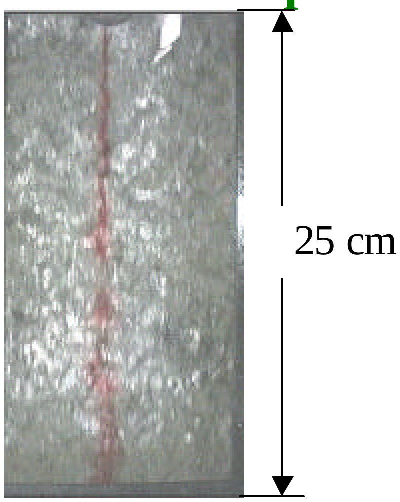
Example of FLIHY EXPERIMENTAL RESULTS: SURFACE WAVINESS is the KEY FACTOR for HEAT TRANSFER in Free-Surface Turbulent Flows

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

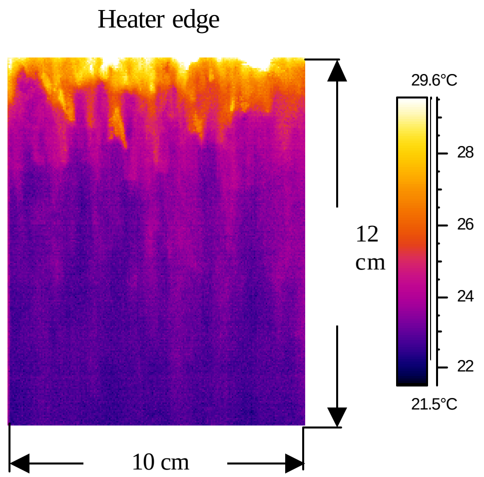
Surface waviness enhances heat transfer through the surface renewal mechanism but leads to pronounced temperature non-uniformity



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



Dye experiment evidences the surface renewal mechanism



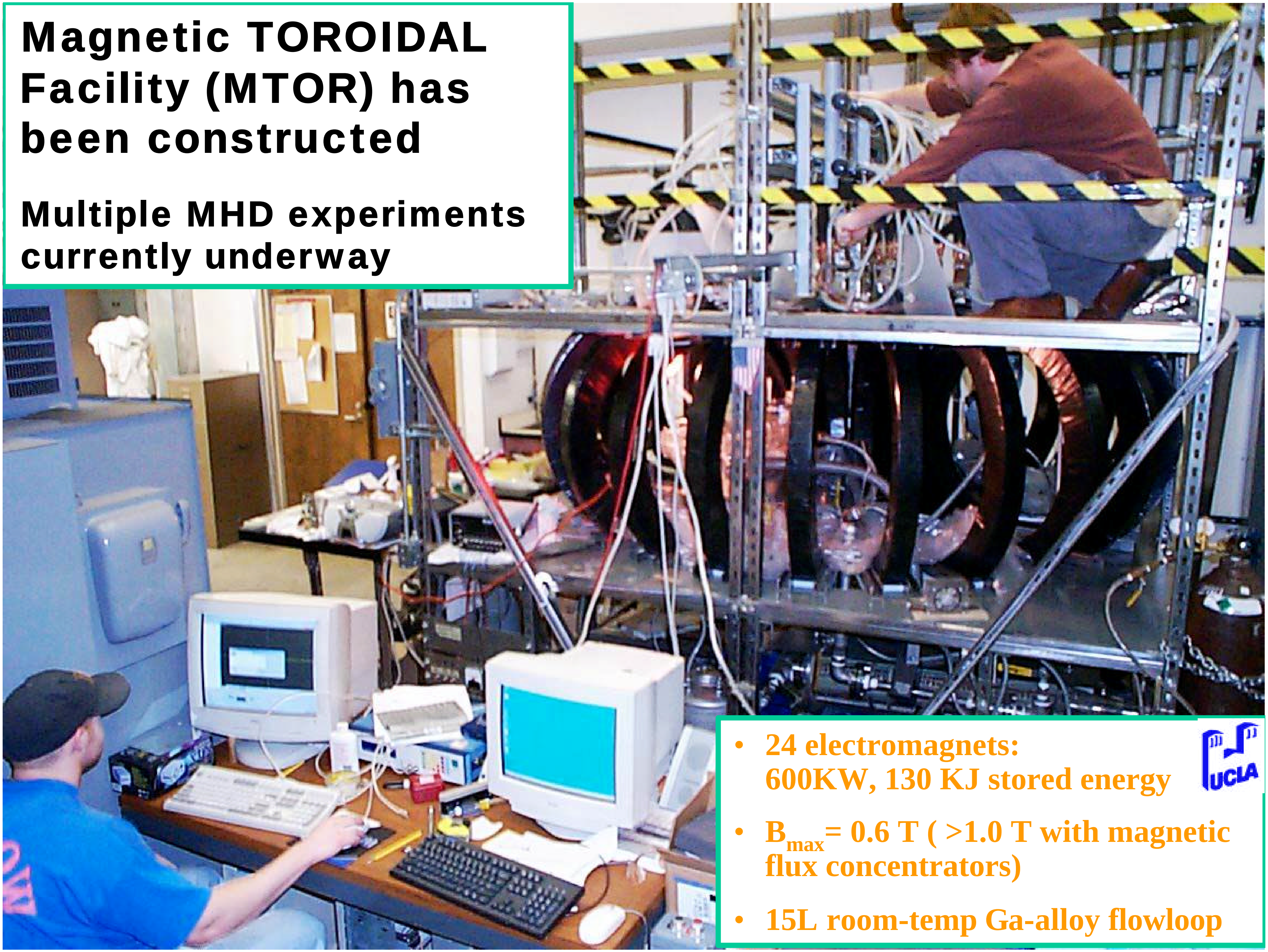
IR images of the surface show "cold" and "hot" strikes $20 kW/m^2$, 30?, 10 L/s flow

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

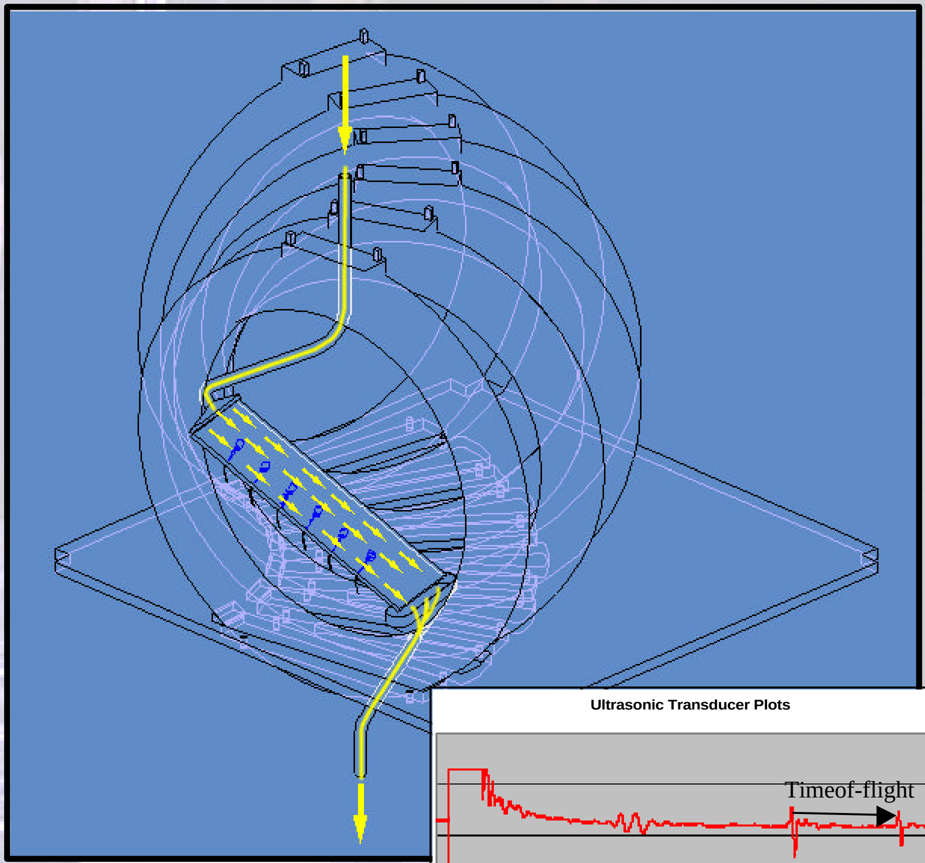
•**Study toroidal field and gradient effects:** Free surface flows are very sensitive to drag from toroidal field 1/R gradient, and surface-normal fields

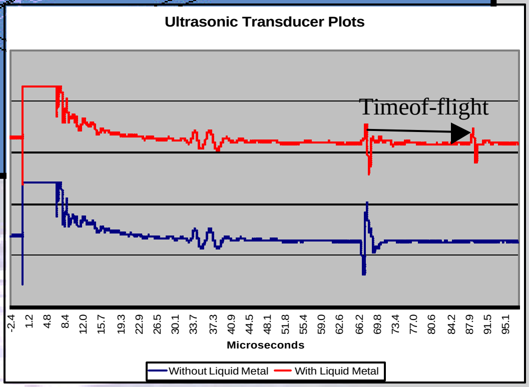
•**3-component field effects on drag and stability**: Complex stability issues arise with field gradients, 3-component magnetic fields, and applied electric currents

•**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

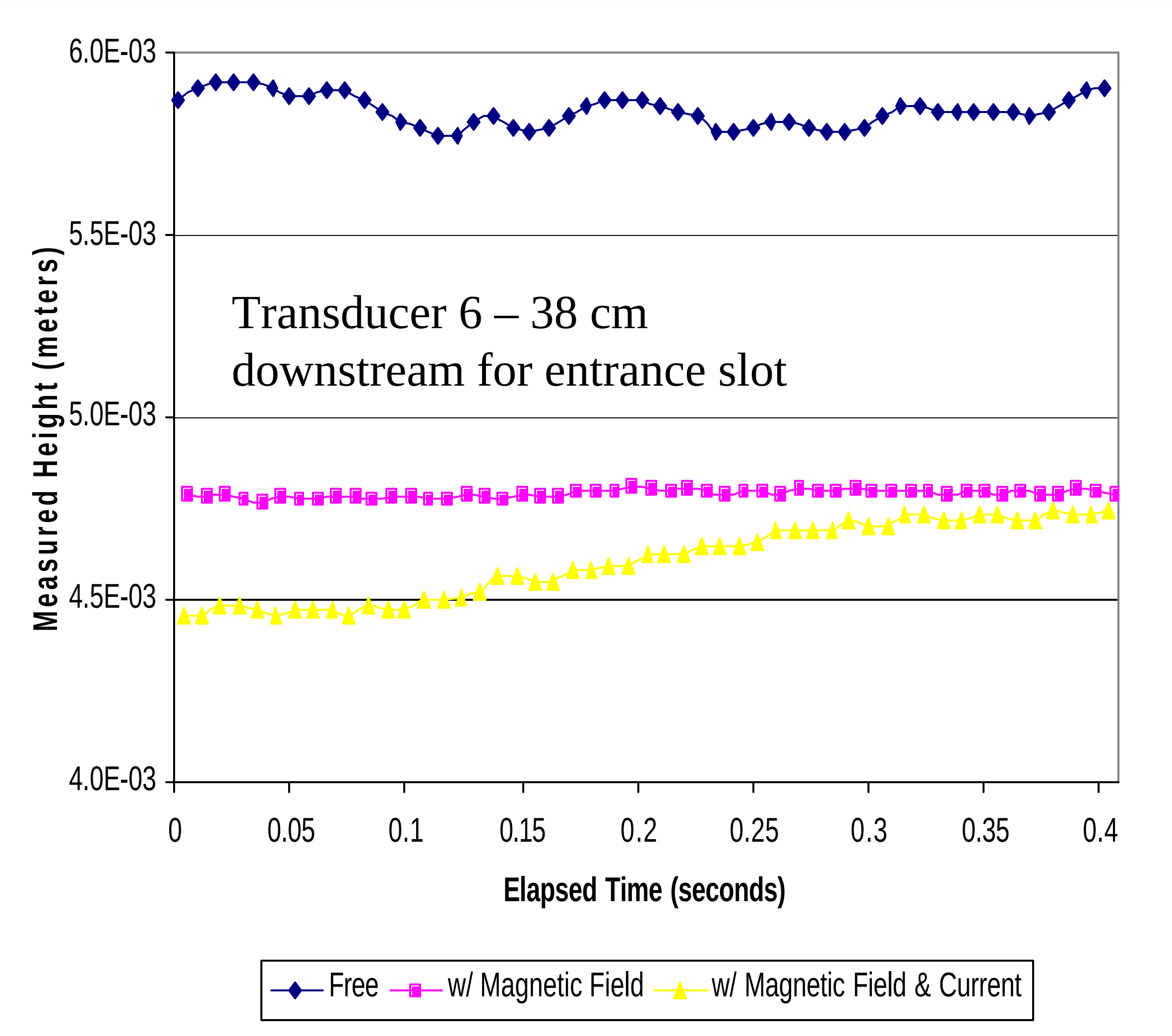
•**NSTX environment simulation**





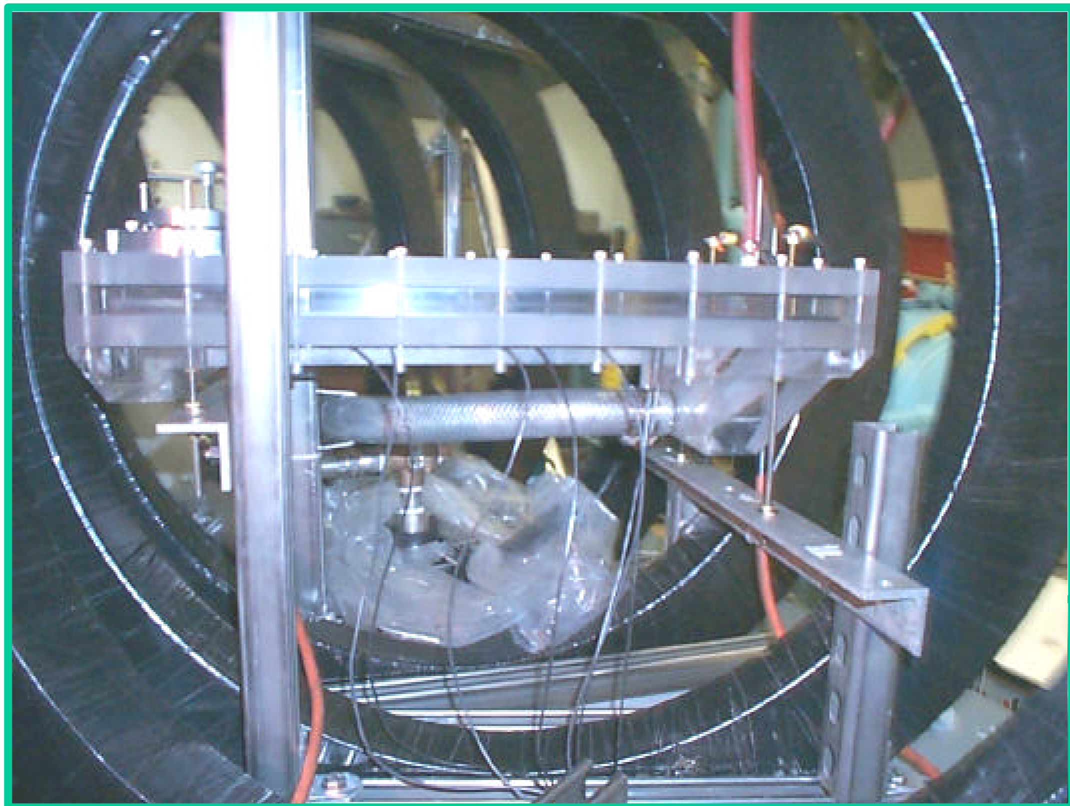
MTOR designed and constructed in collaboration between UCLA, PPPL and ORNL

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



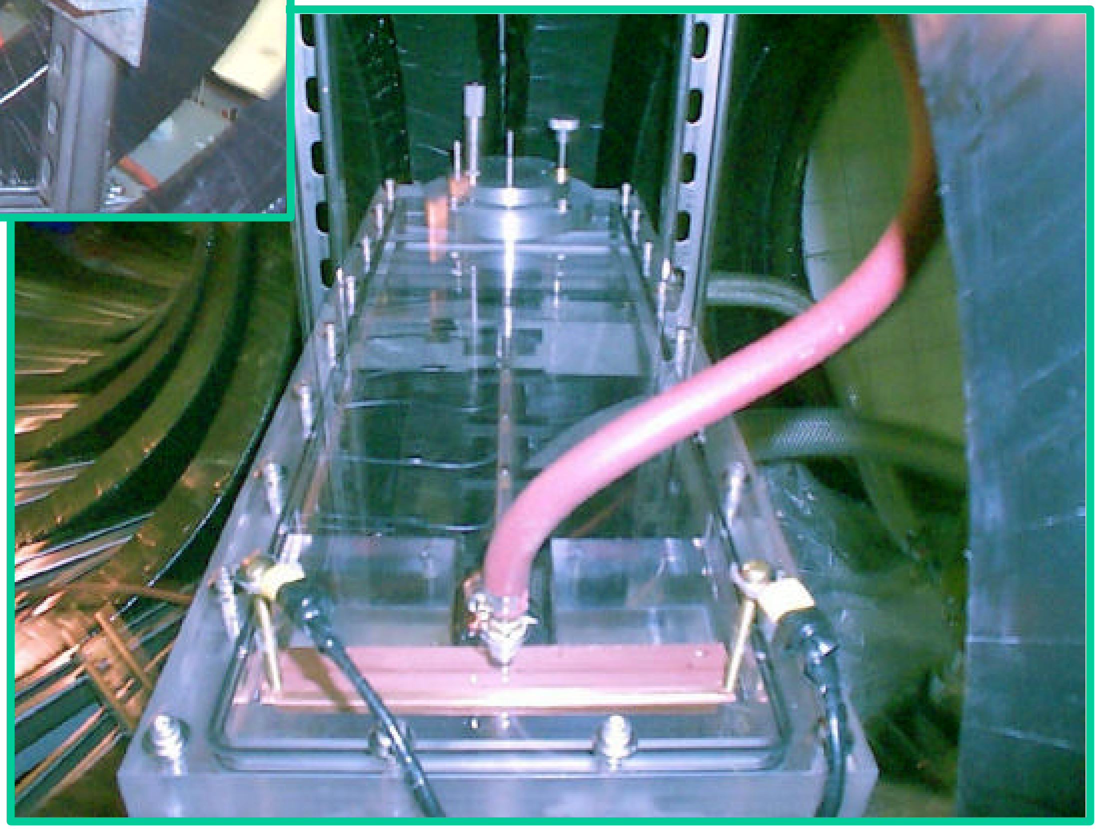
B field acts to laminarize flow – **Reducing flow resistance and eliminating surface waves**

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

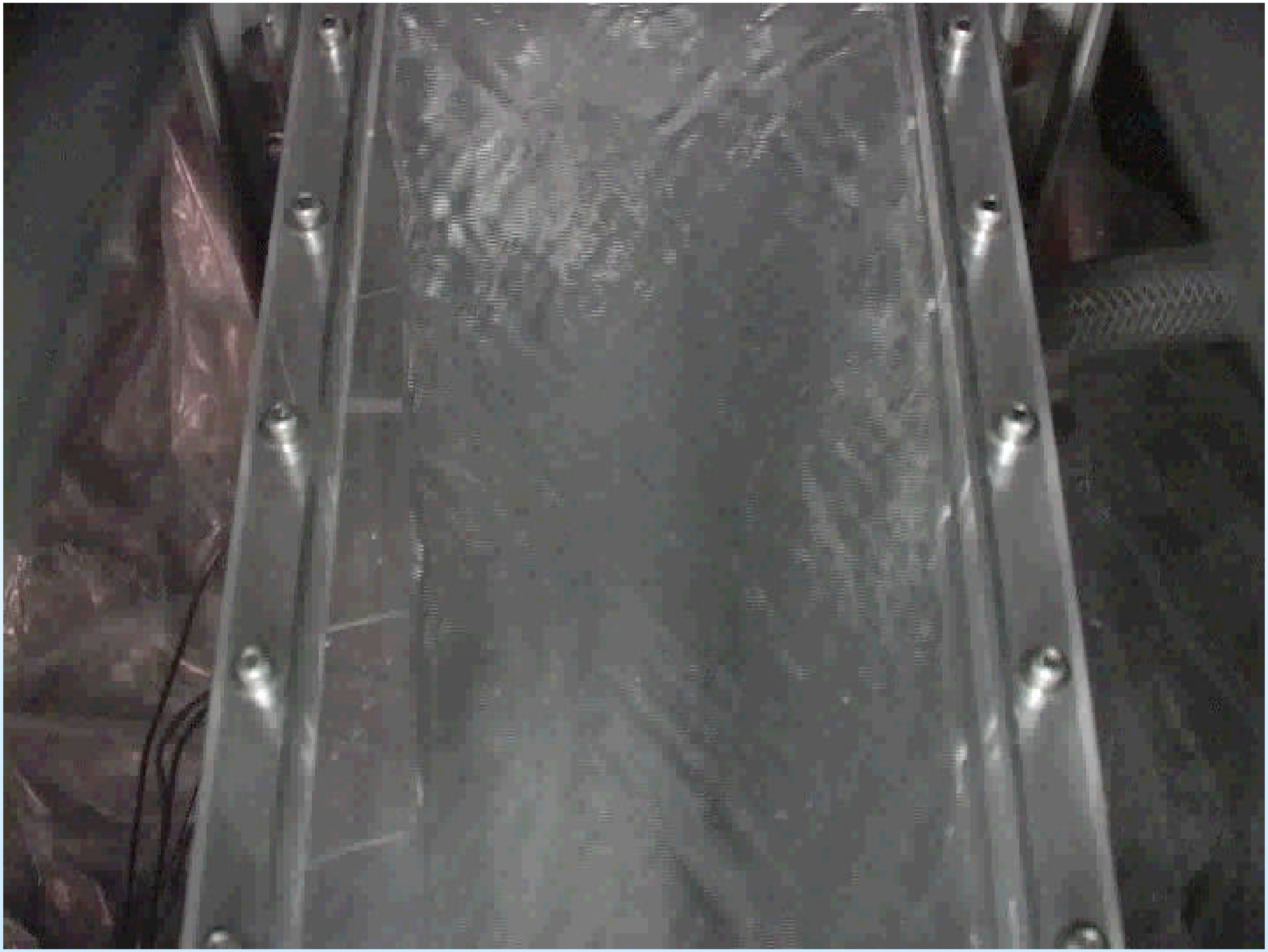


Inclined-Plane Test Section

- 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



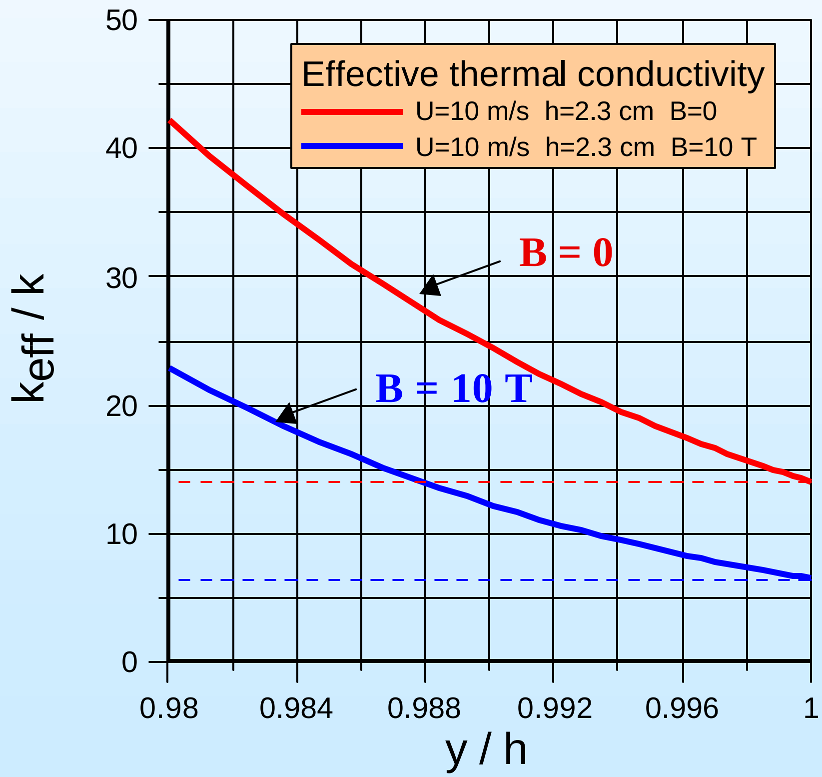
Liquid Metal Integrated Test System

- 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

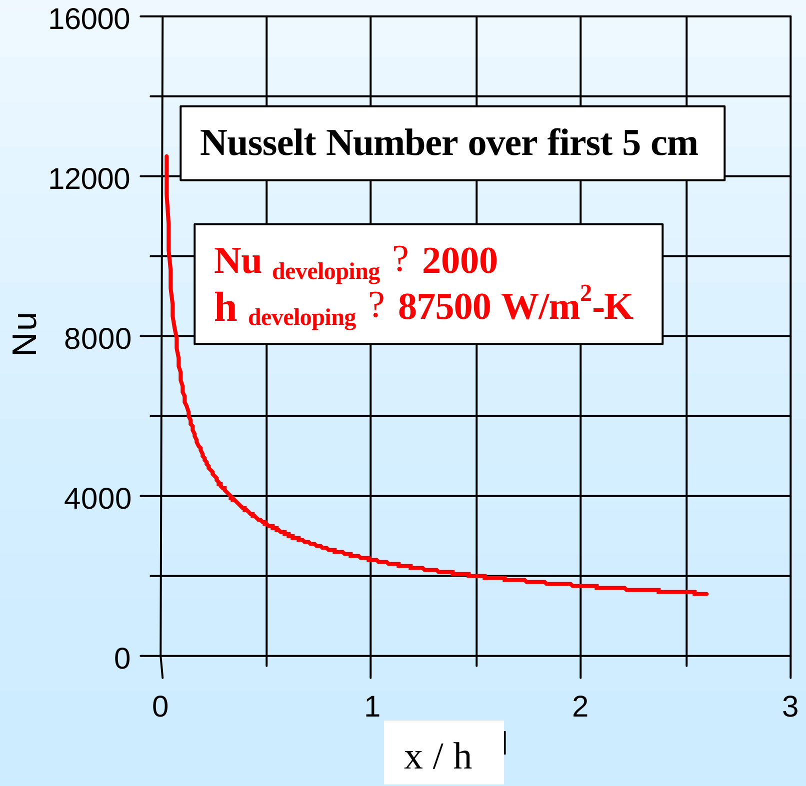
Results of Modeling Heat Transfer in Flinabe

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

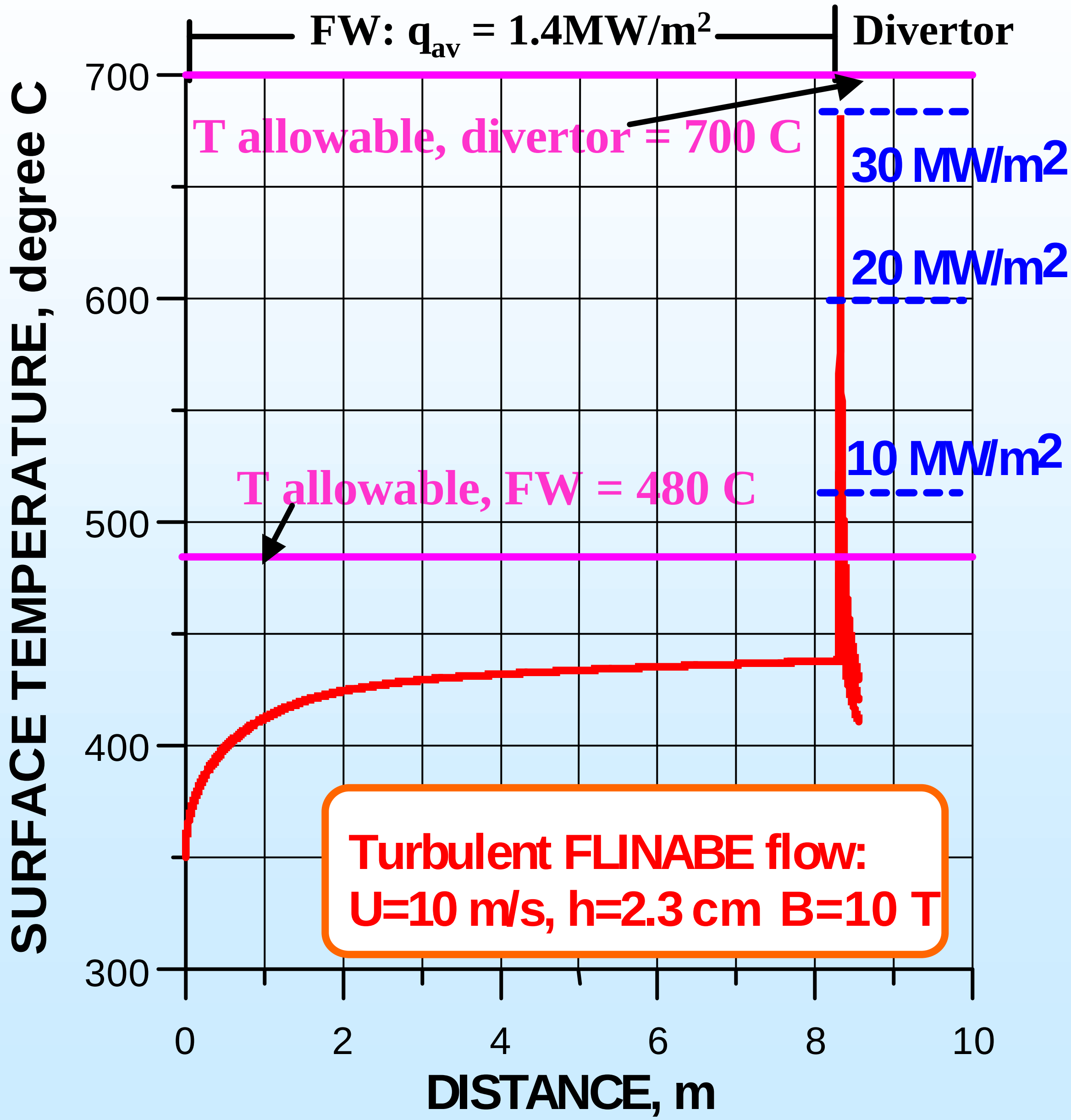
Flinabe

? 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

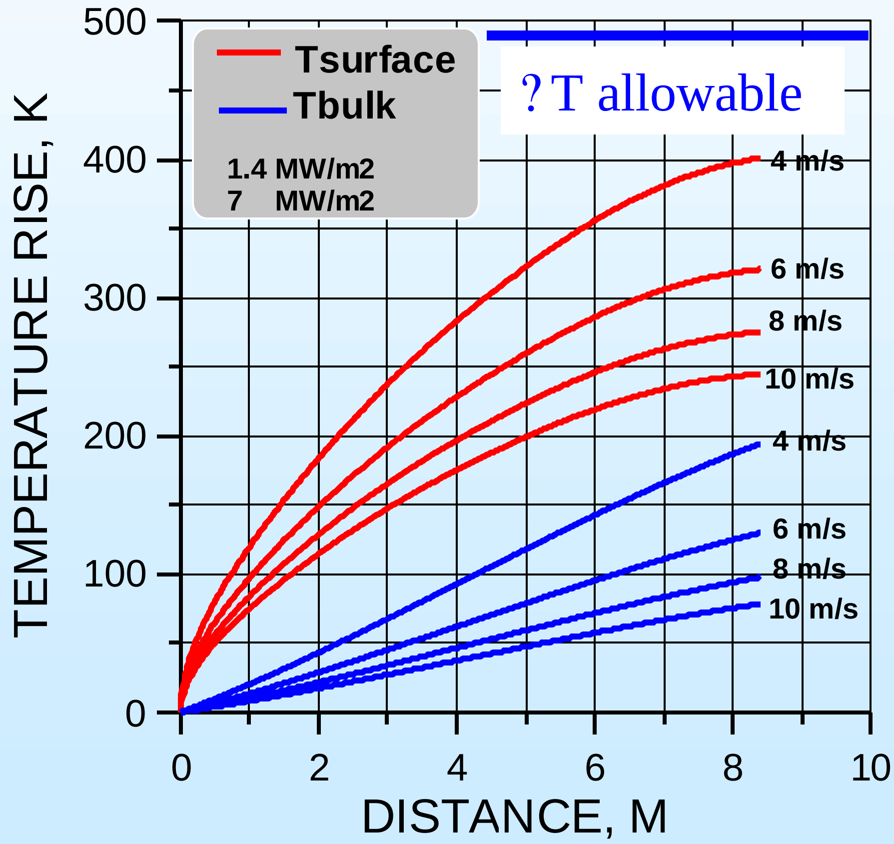
Melting T=**232**?

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



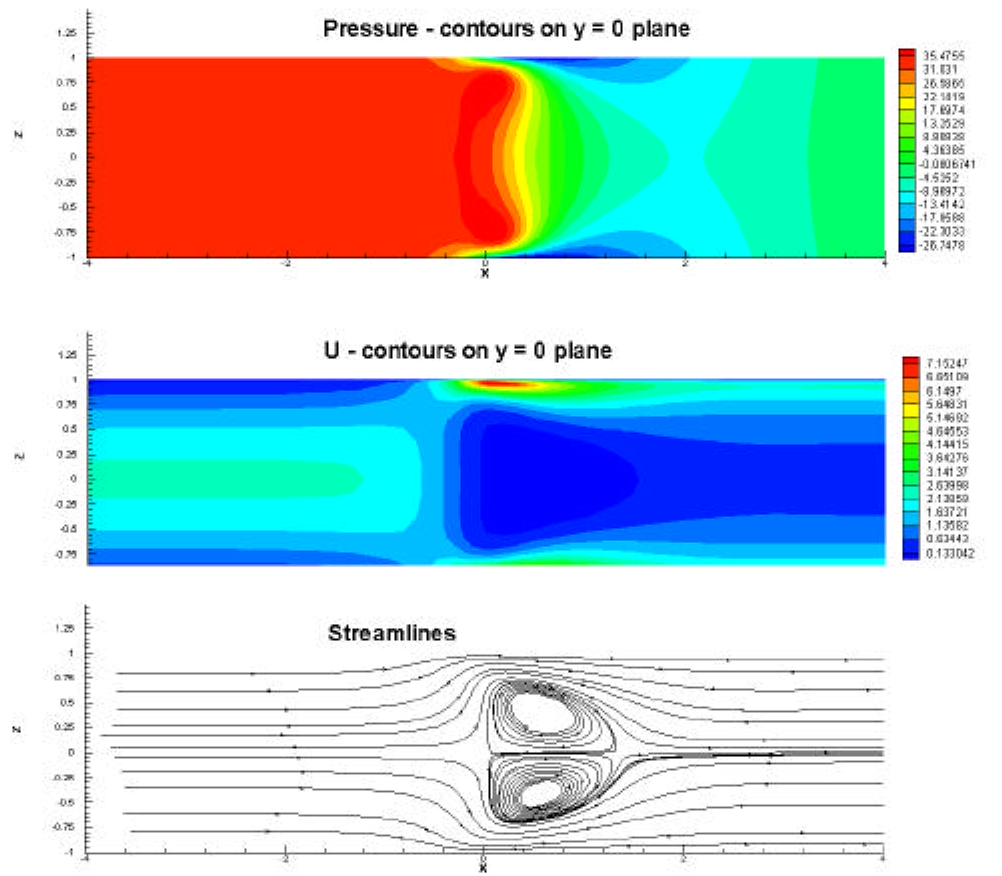
EFFECT OF MAGNETIC FIELD GRADIENTS ON LM FLOW IS VERY IMPORTANT

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

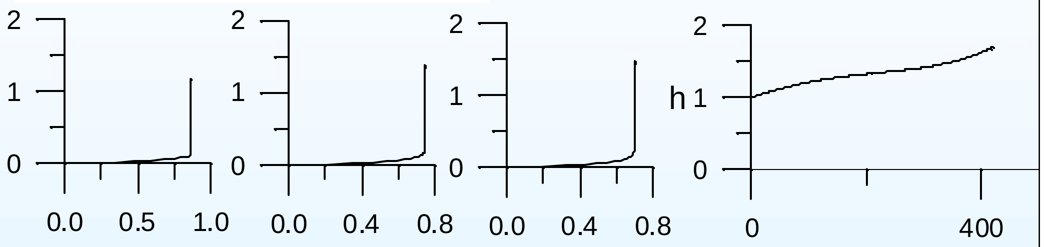
INITIAL CONCLUSIONS

(ACCOUNTING FOR BOTH TOROIDAL AND NORMAL FIELDS)

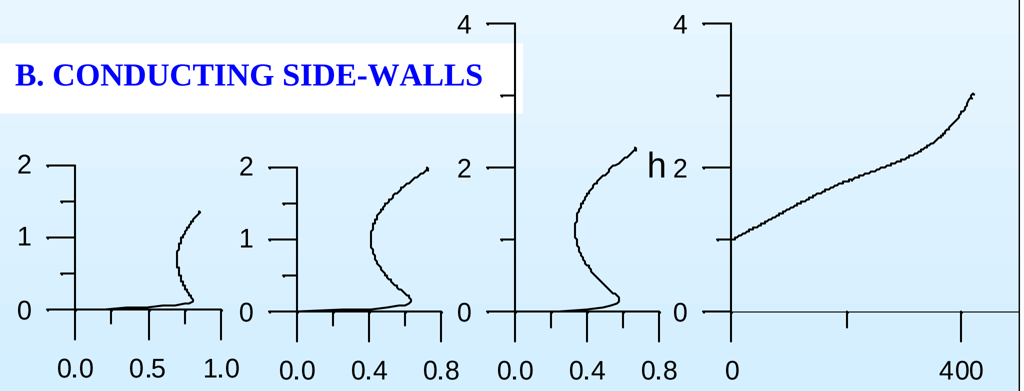
- **METALLIC SIDE-WALLS ARE UNACCEPTABLE**
- **SIC SIDE-WALLS ARE ACCEPTABLE PROVIDED THEY ARE FAR APART (2B > 8 M) INSULATORS ALLOW SMALLER SPACING**
- **IN AN AXI- SYMMETRIC FLOW (no side-walls), THE MAXIMUM ALLOWBALE WALL-NORMAL FIELD IS (Bn)max=0.015 T**
- **IN A SECTIONED FLOW WITH ISOLATED SIDE-WALLS,**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

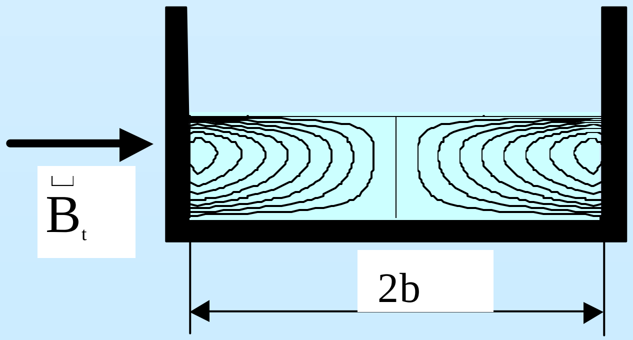
VELOCITY PROFILES AND DOWNSTREAM FLOW THICKNESS VARIATION IN Li CLiFF.

A. ISOLATED SIDE-WALLS



B. CONDUCTING SIDE-WALLS





I am Done !