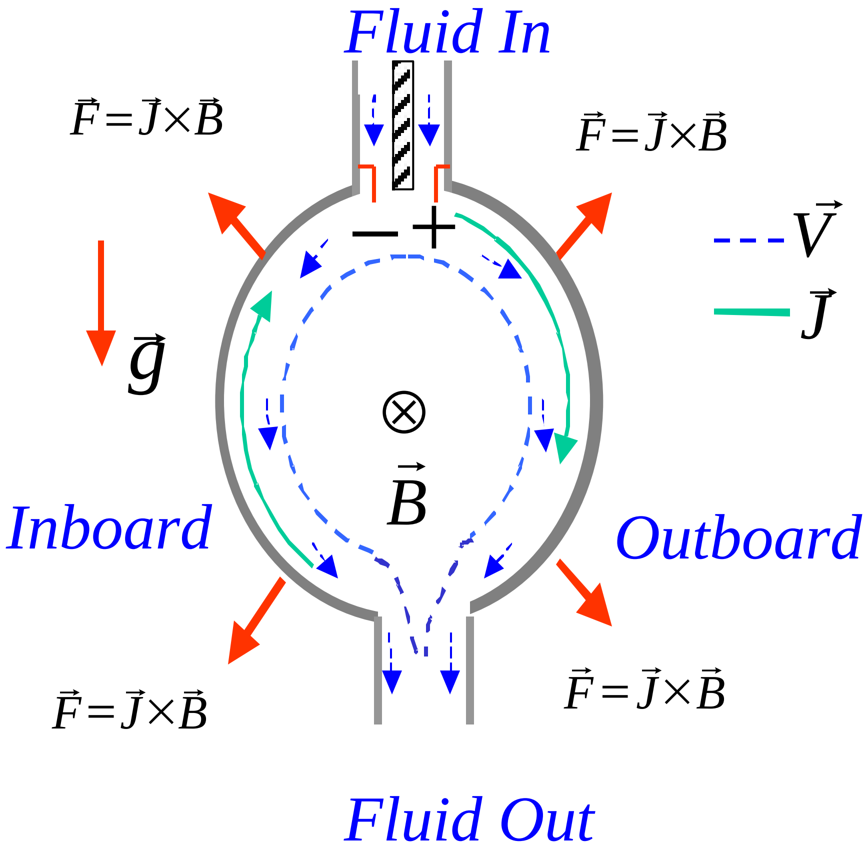
ELECTROMAGNETIC FLOW CONTROL: electric current is applied to provide adhesion of the liquid and its acceleration

Electromagnetically Restrained LM Wall (R.Woolley)

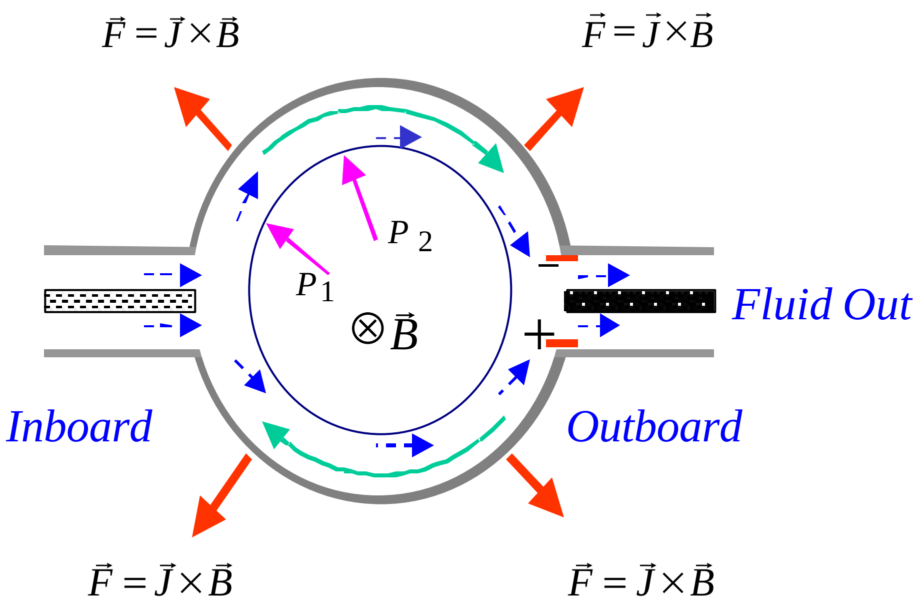
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



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***



$\vec{V}$ *is driven by* ΔP

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:

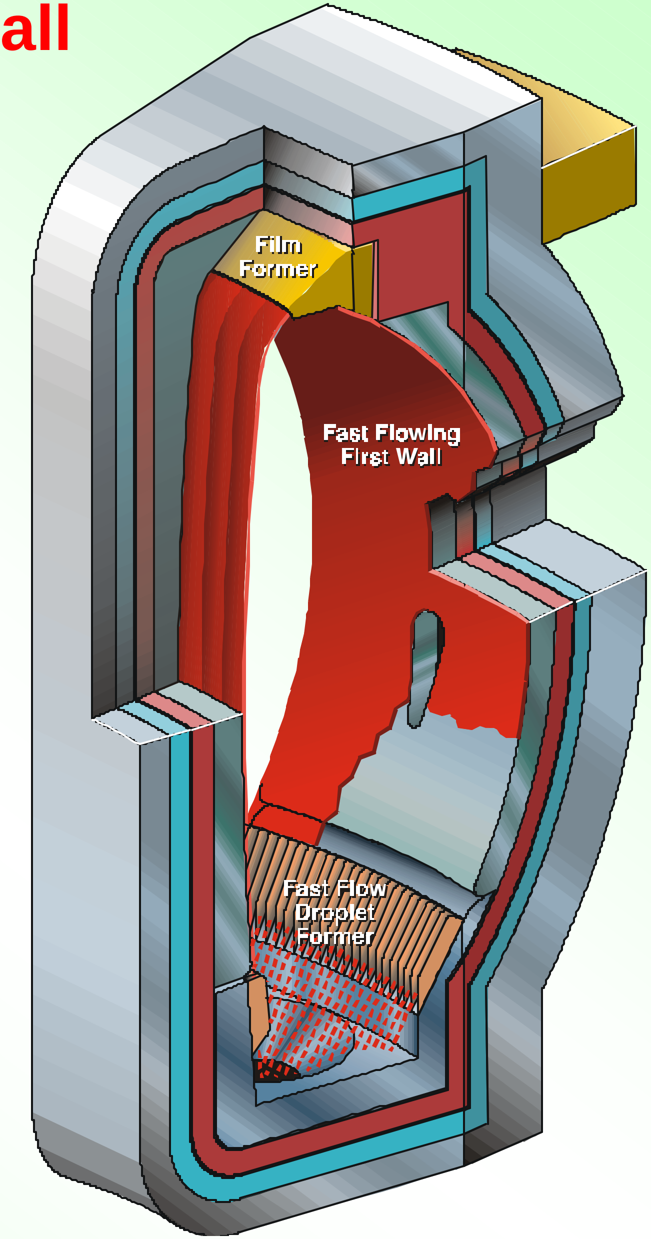
  a) Provide High Power Density Capability (surface heat flux, not neutron heating, is what limits power density in fusion)

  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

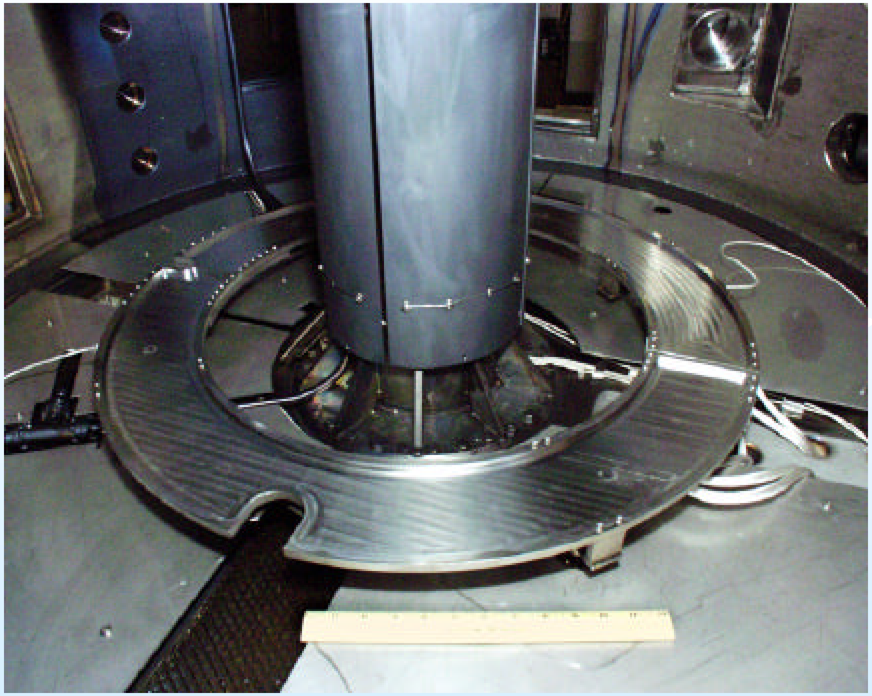
Progress on R&D for Plasma-Liquid Surface Interactions

- **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



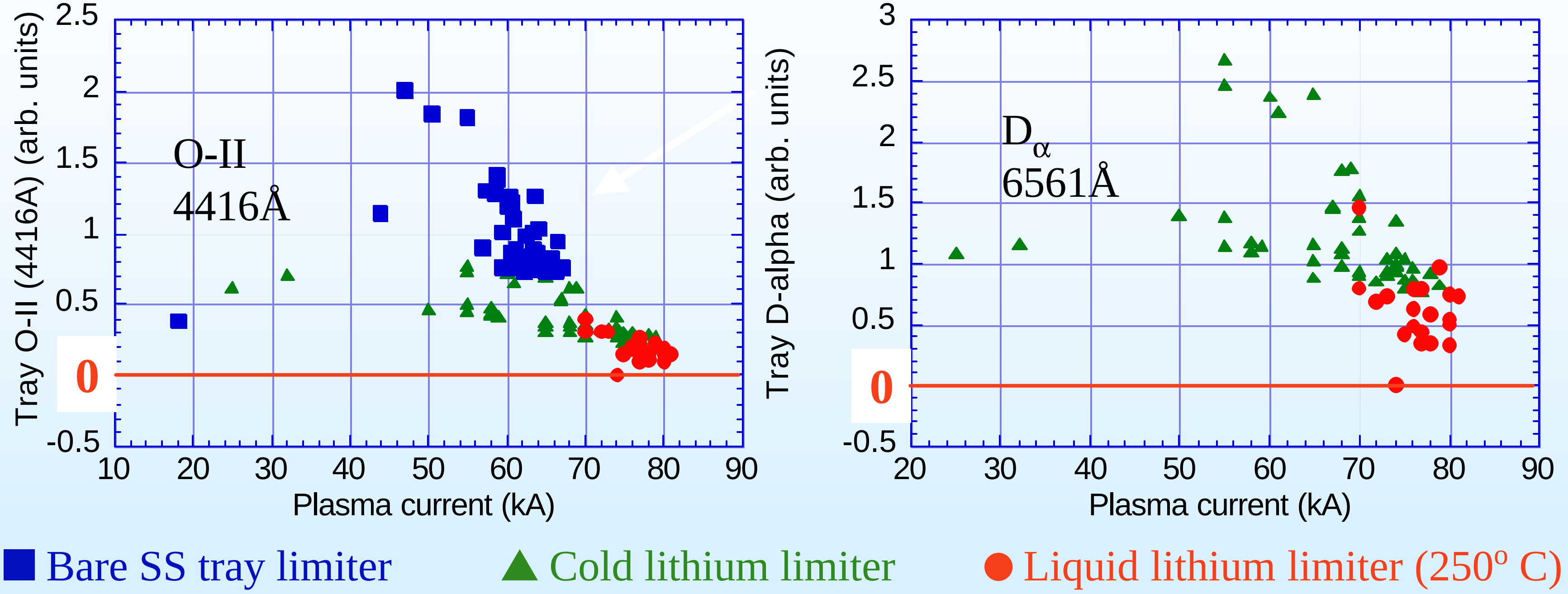
- Stainless steel tray for fully toroidal lithium limiter
- 34 cm major radius, 10 cm wide, 0.64 cm deep

CDX-U Parameters:

R_0	34 cm
a	22 cm
$A=R_0/a$	≥ 1.5
κ	≤ 1.6
$B_T(0)$	2.2 kG
I_P	$\leq$ 80 kA
P_{rf}	<200 kW
τ_{disch}	<25 msec
$T_e(0)$	100 eV
$n_e(0)$	$6\text{x}10^{19}$ 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

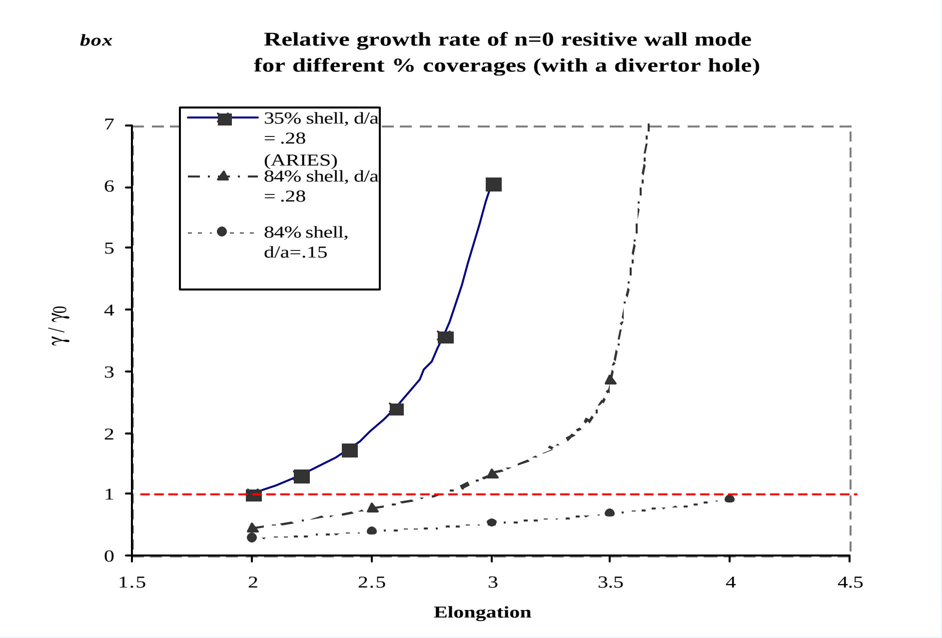
Best CDX-U Plasmas Achieved with Liquid Lithium Limiter



- 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 <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)

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

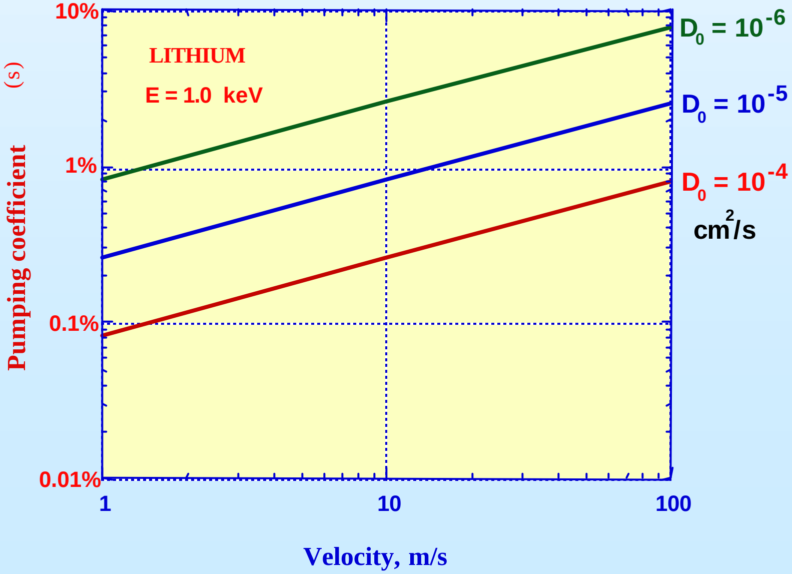
How to Pump Helium Particles with Liquid Walls?

- 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

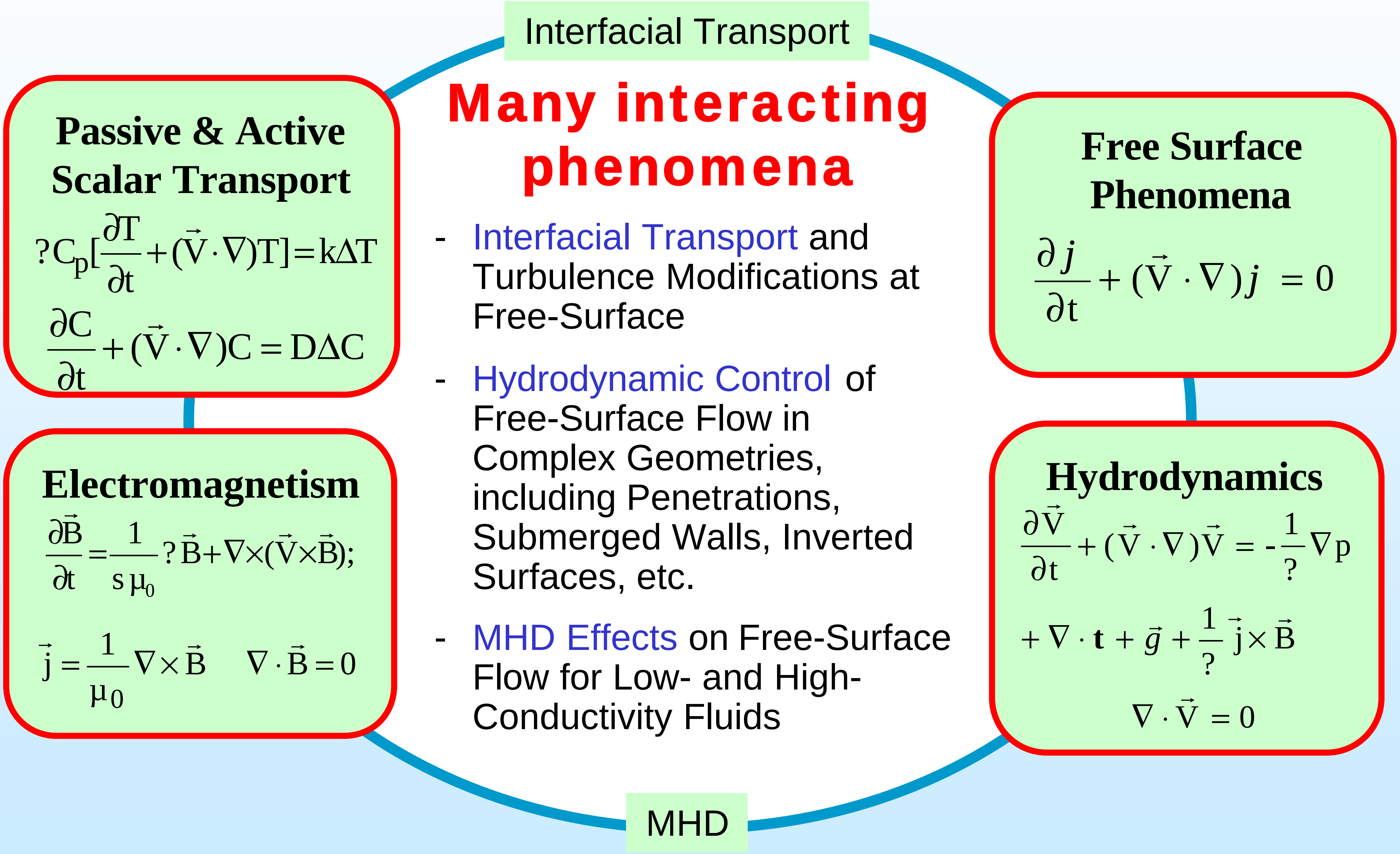
HEIGHTS Calculations of He Pumping Coefficient as a Function of Lithium Velocity



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

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

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

Electromagnetism

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

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

Free Surface Phenomena

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

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

CLiFF
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

$$rU^2/R = 5\times10^4 \quad rg = 2\times10^4$$
$$j\times B = (sUB_\perp)B_\perp = 10^1$$

$$rU^2/R = 1.25\times10^4 \quad rg = 0.5\times10^4$$
$$j\times B = (sUB_\perp)B_\perp = 10^5$$

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?

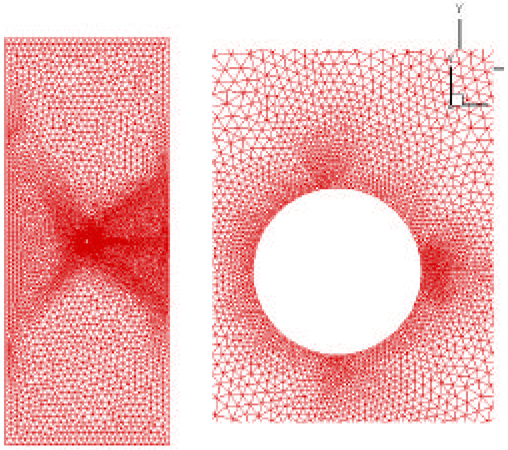
1 – Departure from axisymmetry

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

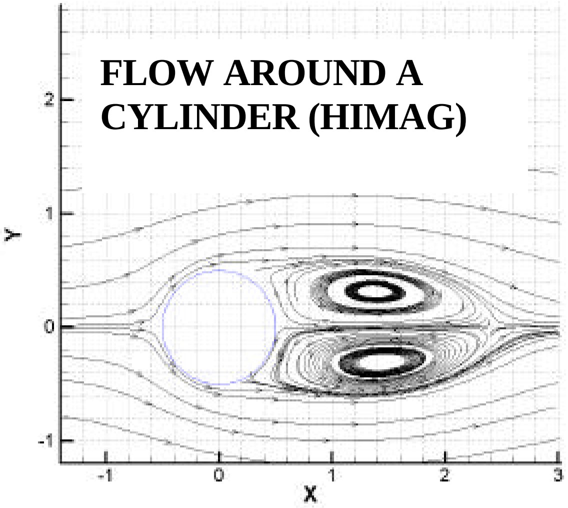
3 – Obstacles (penetrations), nozzles, etc.

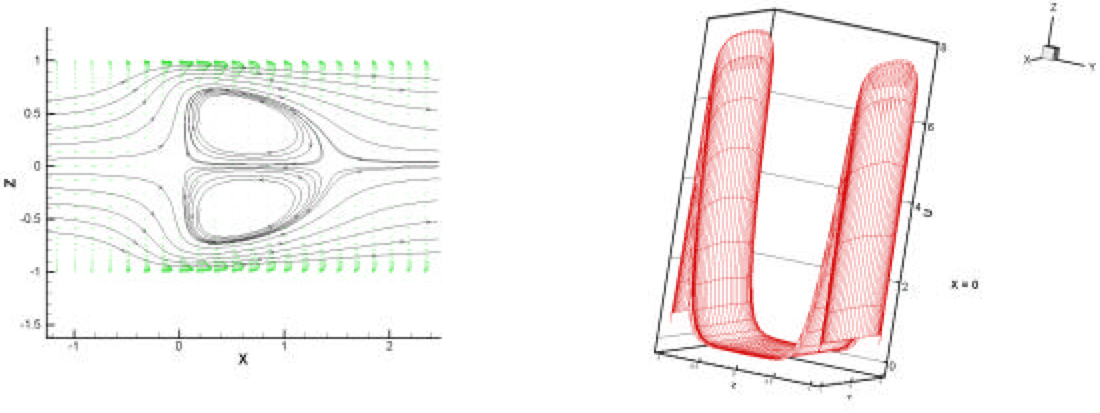
A Computer Code is being developed by HyPerComp and UCLA for 3-D Free Surface, MHD flow with Complex Geometry

- 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


FLOW AROUND A CYLINDER (HIMAG)



Flow in a square duct

Magnetic field is ramped up from 0 to 1 at Ha = 1000, N = 1000