

21st CENTURY FRONTIERS

Moving Beyond Prediction to Control
Free Surface, Turbulence, and Magnetohydrodynamics:
Interactions and effects on
flow control and interfacial transport

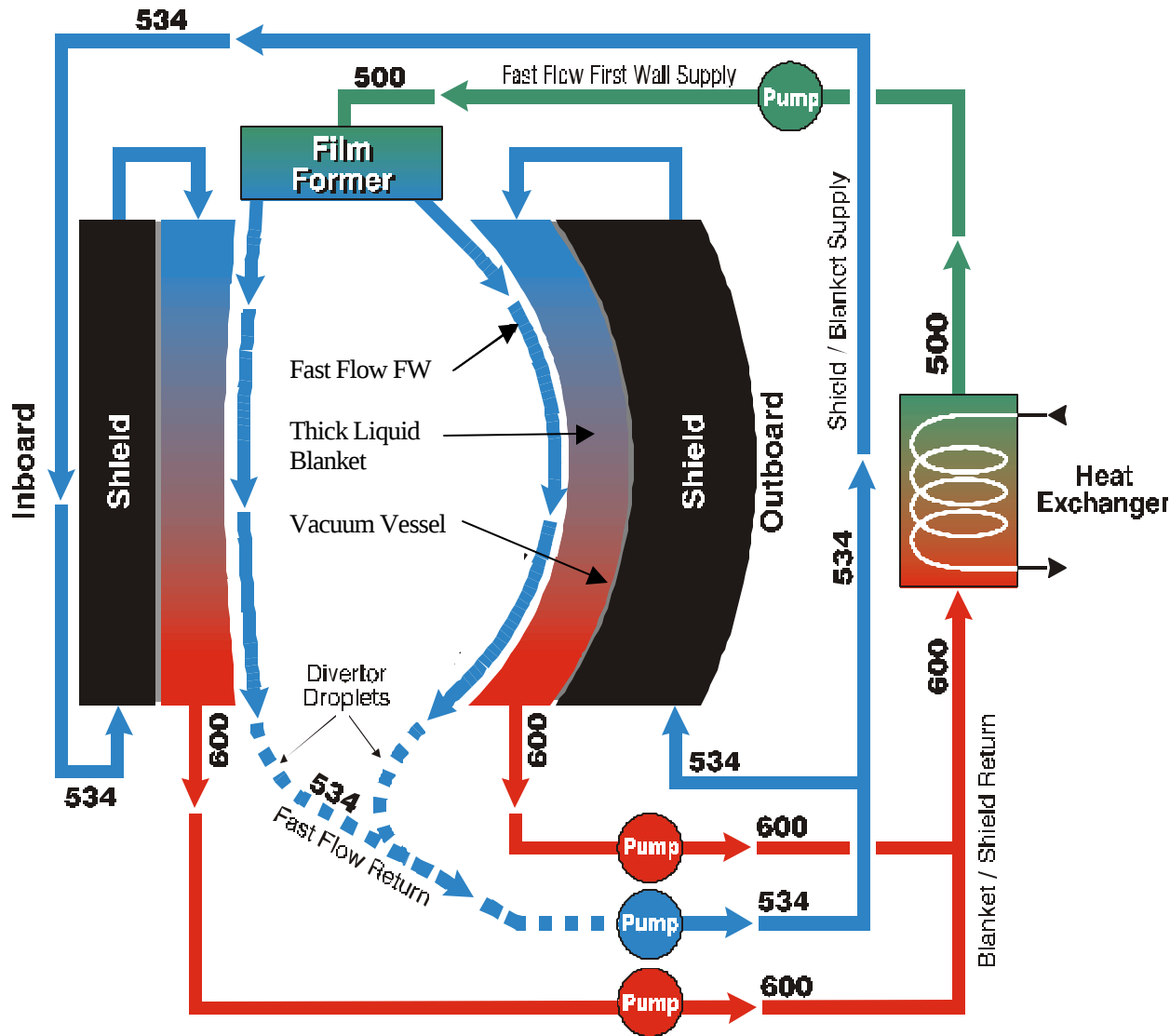
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**First International Symposium on Free Surface Flow and
Interfacial Transport Phenomena**

Yugawara, Atami, Japan - May 10-11, 2001

Illustration of Liquid Walls



Thin Liquid Wall

- Thin (1-2 cm) of liquid flowing on the plasma-side of First Wall

Thick Liquid Wall

- Fast moving liquid as first wall
- Slowly moving thick liquid as the blanket

Motivation for Liquid Wall Research

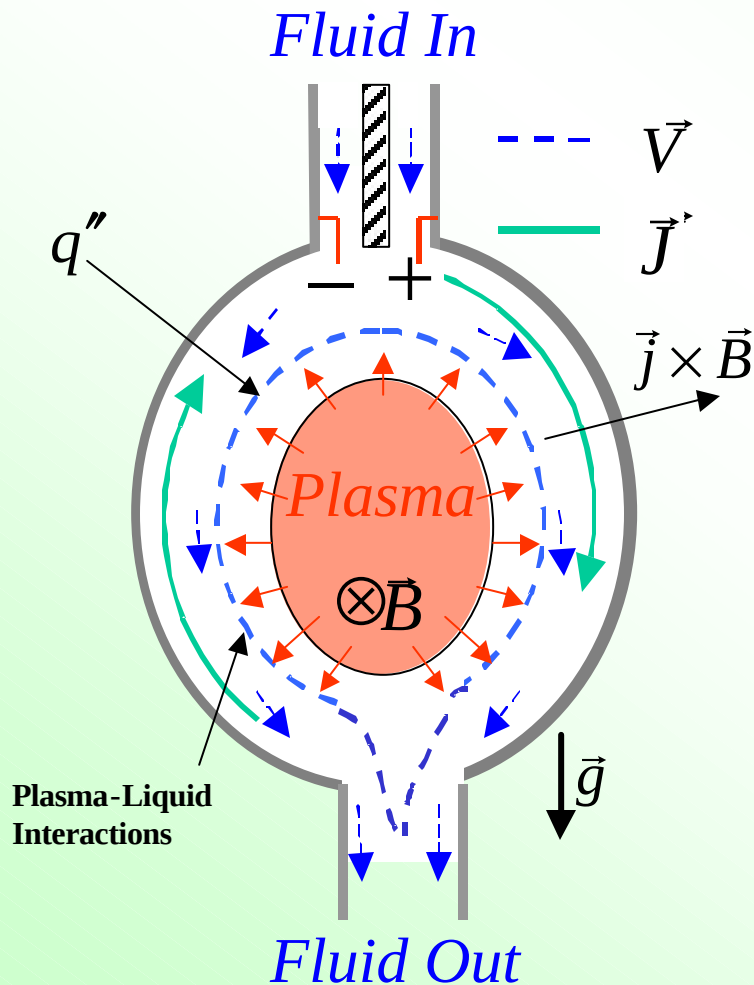


What may be realized if we can develop good liquid walls:

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

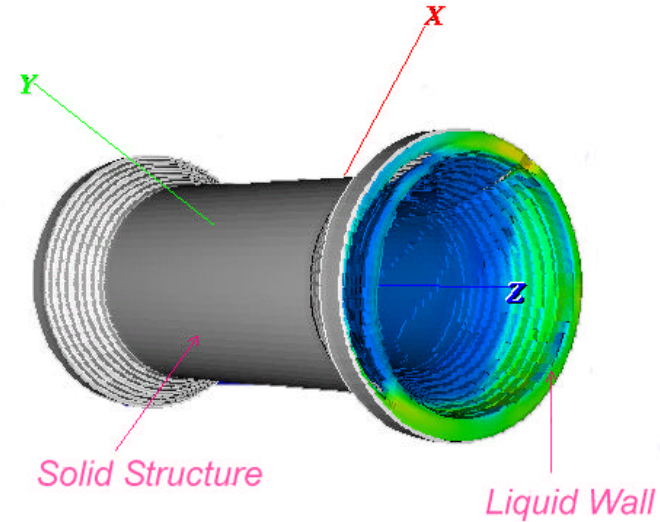
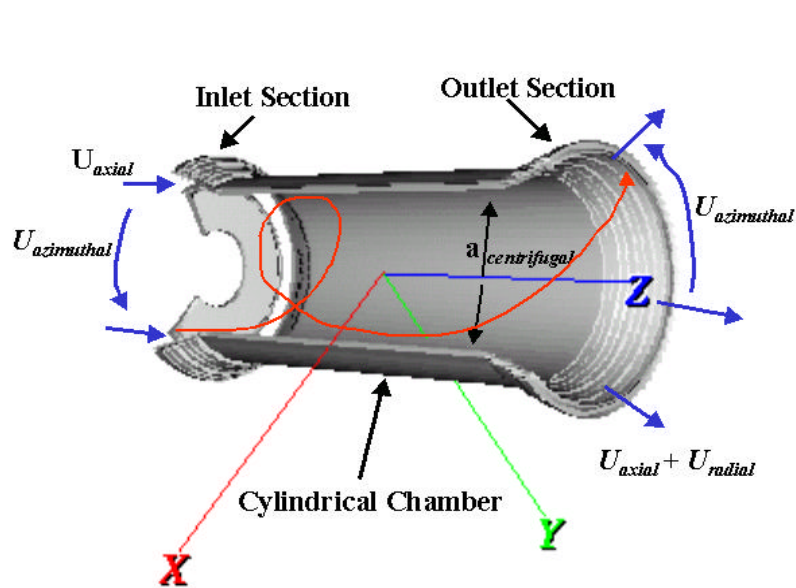
No single LW concept may simultaneously realize all these benefits, but realizing even a subset will be remarkable progress for fusion

“Liquid Walls” Emerged in APEX as one of the Two Most Promising Classes of Concepts



- The Liquid Wall idea is **“Concept Rich”**
 - a) Working fluid: Liquid Metal, low conductivity fluid
 - b) Liquid Thickness
 - thin to remove surface heat flux
 - thick to also attenuate the neutrons
 - c) Type of restraining force/flow control
 - passive flow control (centrifugal force)
 - active flow control (applied current)
- We identified many common and many widely different merits and issues for these concepts

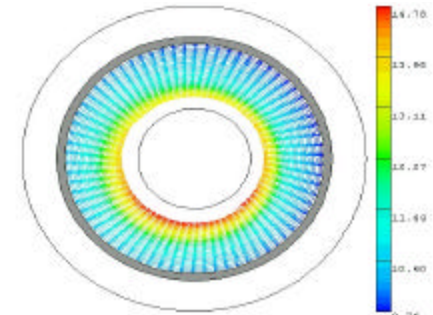
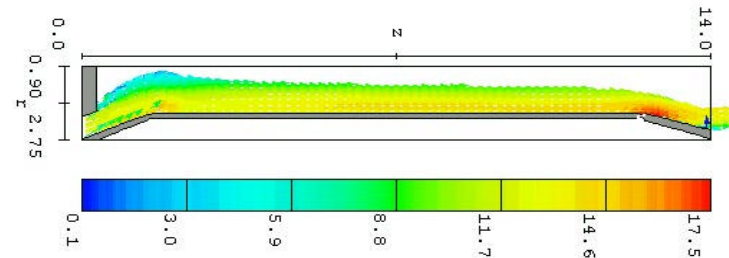
Swirling Thick Liquid Walls for High Power Density FRC



• **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

• **Computer Simulation:** 3-D time-dependent Navier-Stokes Equations solved with RNG turbulence model and Volume of Fluid algorithm for free surface tracking

• **Results:** Adhesion and liquid thickness uniformity (> 50 cm) met with a flow of $V_{axial} = 10$ m/s, $V_{q,ave} = 11$ m/s



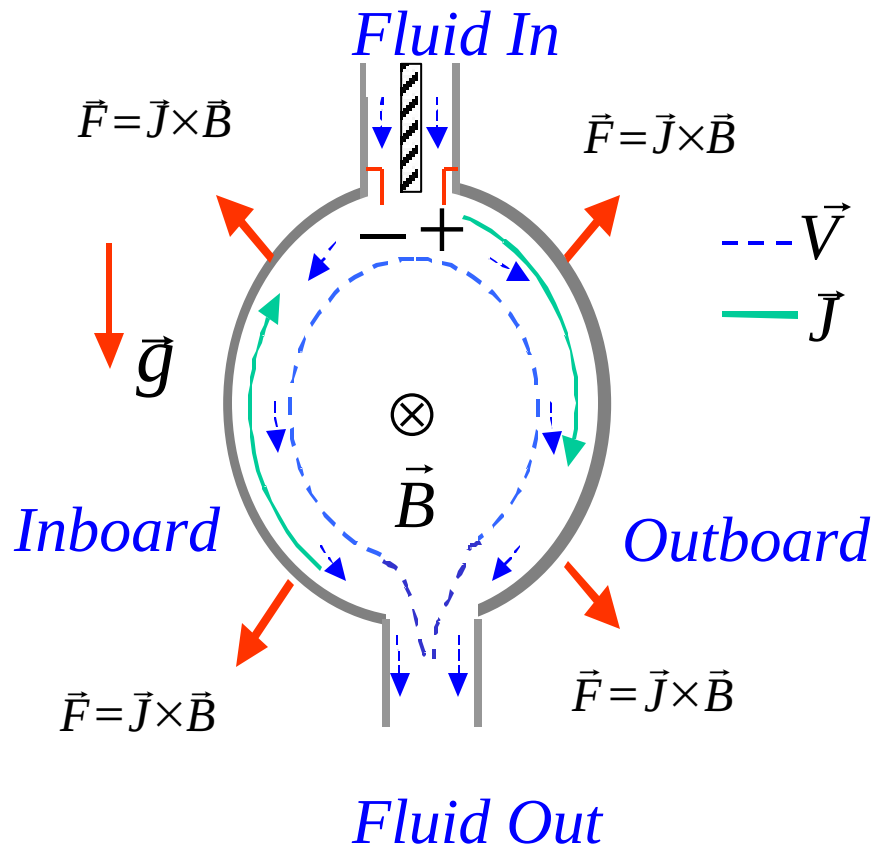
Calculated velocity and surface depth

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



Electromagnetically Restrained LM Wall (R. Woolley)

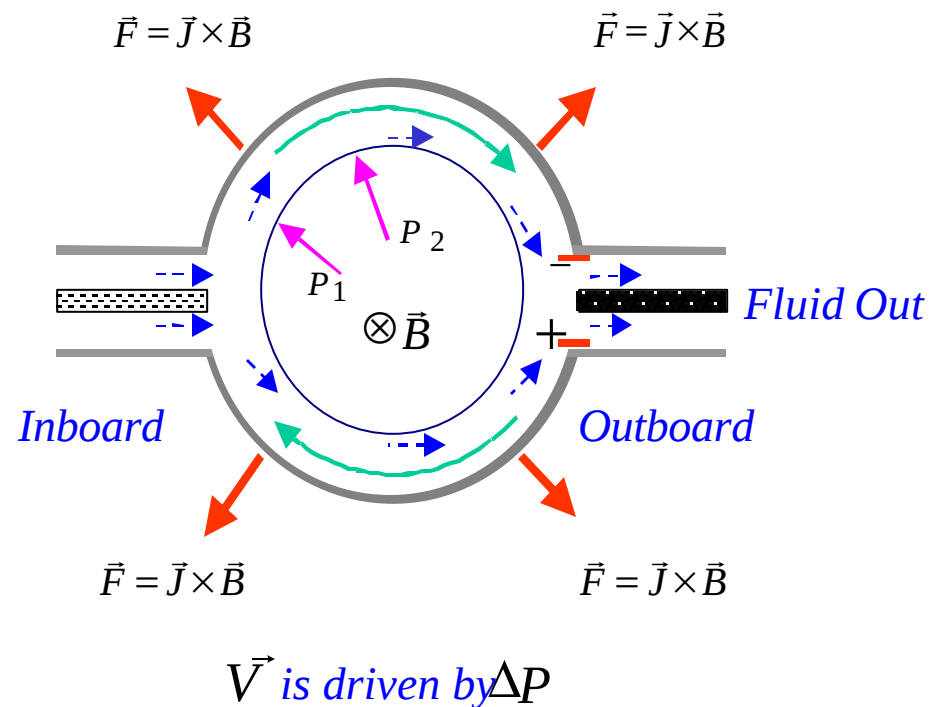
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



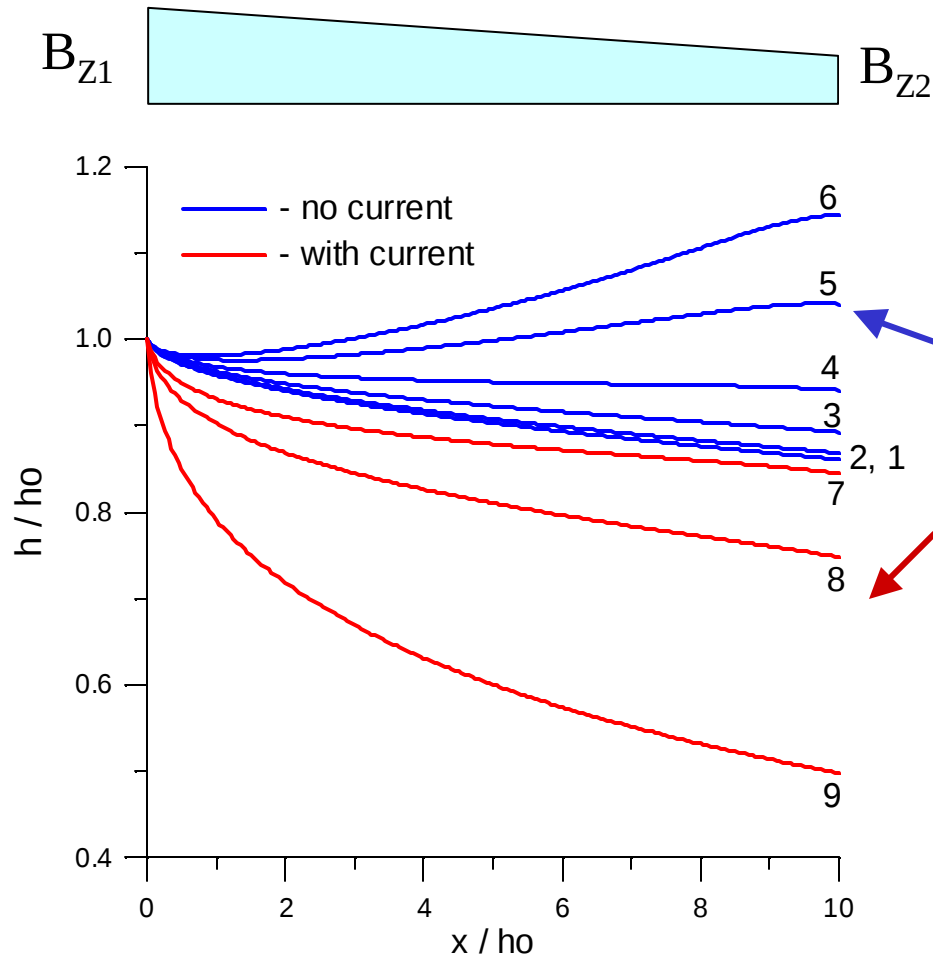
Magnetic propulsion scheme (L. Zakharov)

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



Magnetic Propulsion is one way to use MHD forces to overcome drag



Innovative idea from L. Zakharov (PPPL) where applied current is used to induce pressure gradient that propels flow!

- Increase of the field gradient, $(B_{Z1} - B_{Z2})/L$, results in the higher MHD drag (blue curves 1-6)
- Applying an electric current leads to the magnetic propulsion effect and the flow thickness decrease (red curves 7-9)

In calculations: $L=20$ cm; $h_0=2$ cm; $U_0=5$ m/s



Scientific Issues for Liquid Walls

1. 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

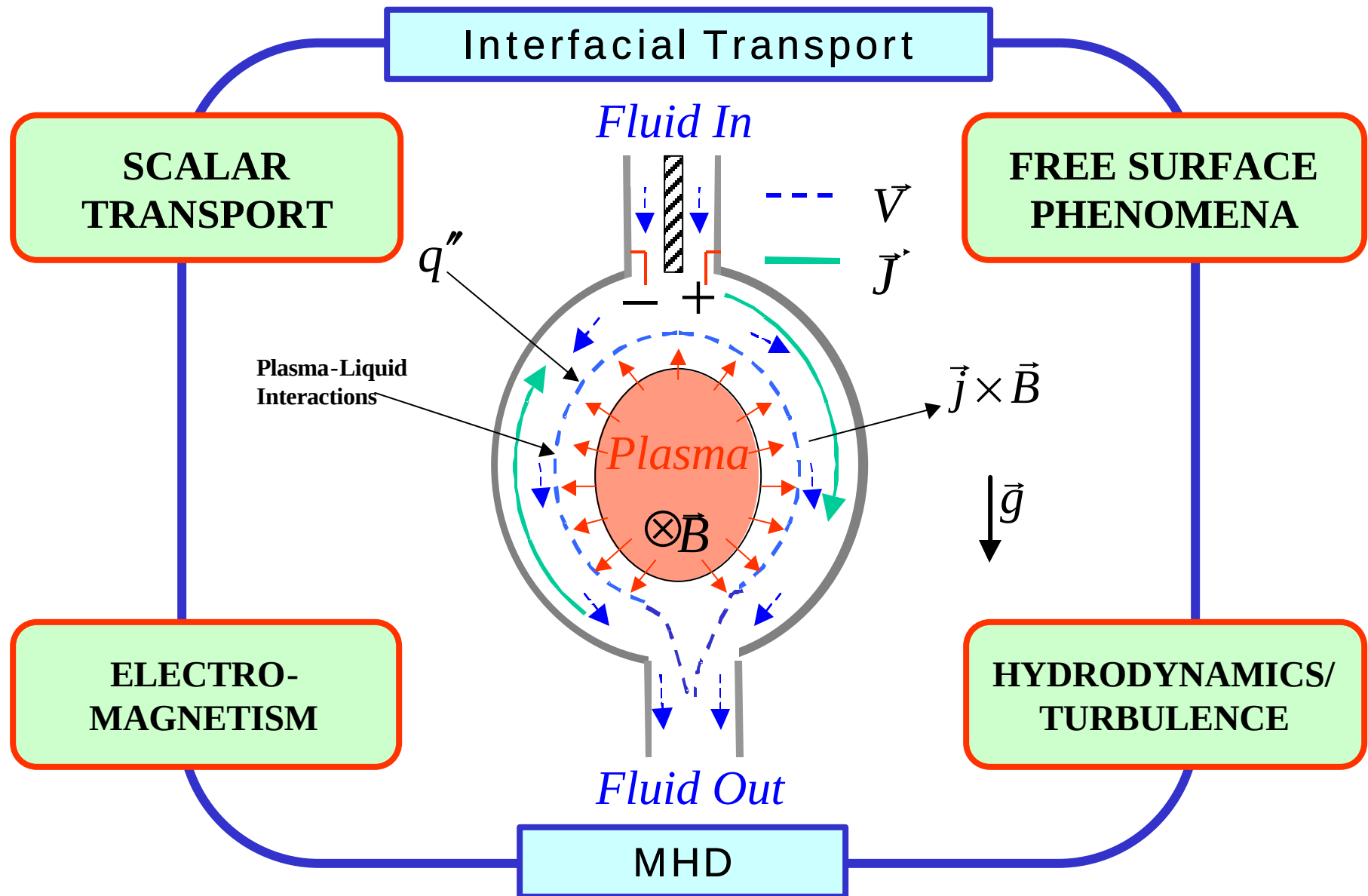
2. Effects of Liquid Wall on Core Plasma

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

3. Plasma-Liquid Surface Interactions

- Limits on operating temperature for liquid surface

Liquid Wall Researchers are Advancing the Understanding of Interacting Multi-Scale Phenomena at the Frontiers of Fluid Dynamics



Fusion LW Researchers are Contributing to the Resolution of **GRAND CHALLENGES** in Fluid Dynamics

Interfacial Transport

SCALAR TRANSPORT

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

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

ELECTRO-MAGNETISM

$$\frac{\partial \vec{B}}{\partial t} = -\frac{1}{\sigma \mu_0} \nabla \times (\vec{V} \times \vec{B});$$

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

Liquid Walls: **many interacting phenomena**

- Turbulence redistributions at free surface
- Turbulence-MHD interactions
- MHD effects on mean flow and surface stability
- Influence of turbulence and surface waves on interfacial transport and surface renewal

Teraflop Computer Simulation

MHD

FREE SURFACE PHENOMENA

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

HYDRODYNAMICS/ TURBULENCE

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

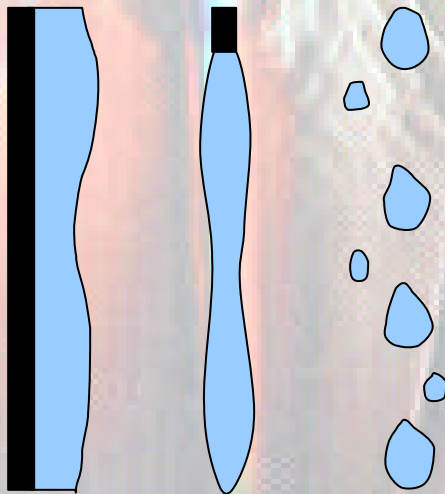
$$+ \nabla \cdot \mathbf{t} + \vec{g} + \frac{1}{\rho} \vec{j} \times \vec{B}$$

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

CHALLENGE: FREE SURFACE FLOW

“Open Channel Flows are essential to the world as we know it” - Munson, Young, Okiishi (from their Textbook)

Free surface flow forms: films, droplets, jets, bubbles, etc. Fluid regions can coalesce, break up, and exhibit non-linear behavior



- The term *free surface* is often used for any gas/void to liquid interface, but denotes an interface between a liquid and a second medium that is unable to support an applied pressure gradient or shear stress.
- Formation of surface waves, a distinguishing feature (for $LW - Fr > 1$, supercritical flow)
- Interfacial flows are difficult to model - computational domain changes in time making application of BCs difficult
- Interfacial tension effects make equations “stiff”- differing time scales for surface wave celerity compared to liquid velocity

*Watermark - Shear layer instability
at water surface - CalTech Data*

Numerically tracking moving interfaces is an ongoing challenge in CFD -

Still NO IDEAL Interface Tracking Method

Volume-of-Fluid (VOF): The method is based on the concept of advection of a fluid volume fraction, j . It is then possible to locate surfaces, as well as determine surface slopes and surface curvatures from the VOF data.



Level-Set Method: The method involves advecting a continuous scalar variable. An interface can thus be represented by a level set of the scalar variable. This is a different approach from VOF where the discontinuity represents the interface.

OTHERS:

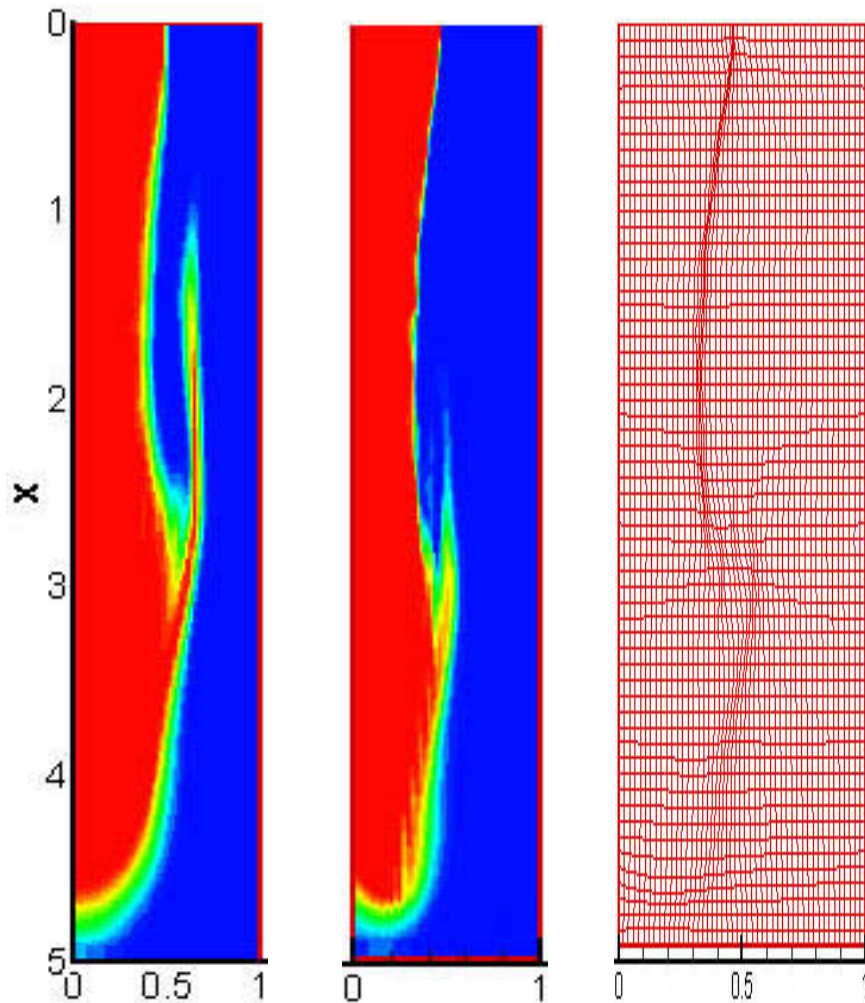
Lagrangian Grid Methods

Surface Height Method

Marker-and-Cell (MAC) Method

*Watermark - milk drop splash simulation
using VOF- Kunugi, Kyoto Univ.*

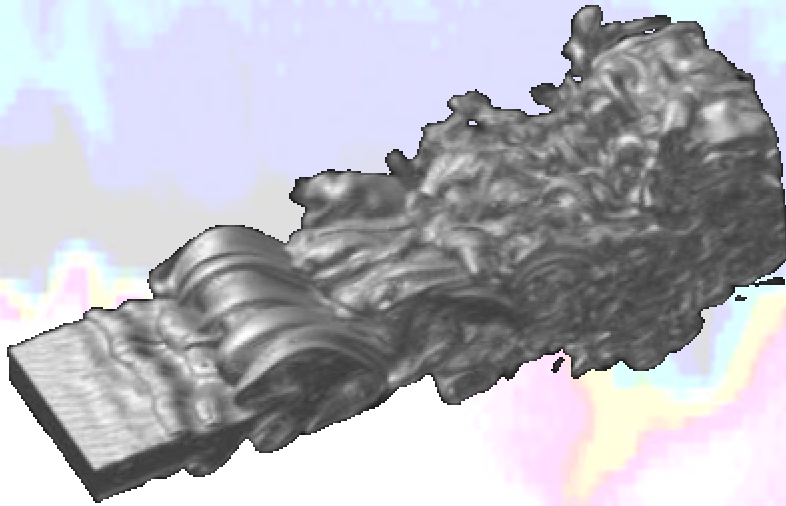
State-of-the-Art Computational Techniques are Required for Intensive LW Simulation



- Grid adaption or multi-resolution
- Parallel Algorithm Implementation
- Unstructured Meshes
- High-order advection and free surface tracking algorithms

*Lithium Jet start-up without and with grid adaption -
HyperComp Simulation*

CHALLENGE: TURBULENCE



Center for Computations Science and Engineering (LBNL). LES simulation of instability in a submerged plane jet.

Horace Lamb, British physicist:

“I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.”

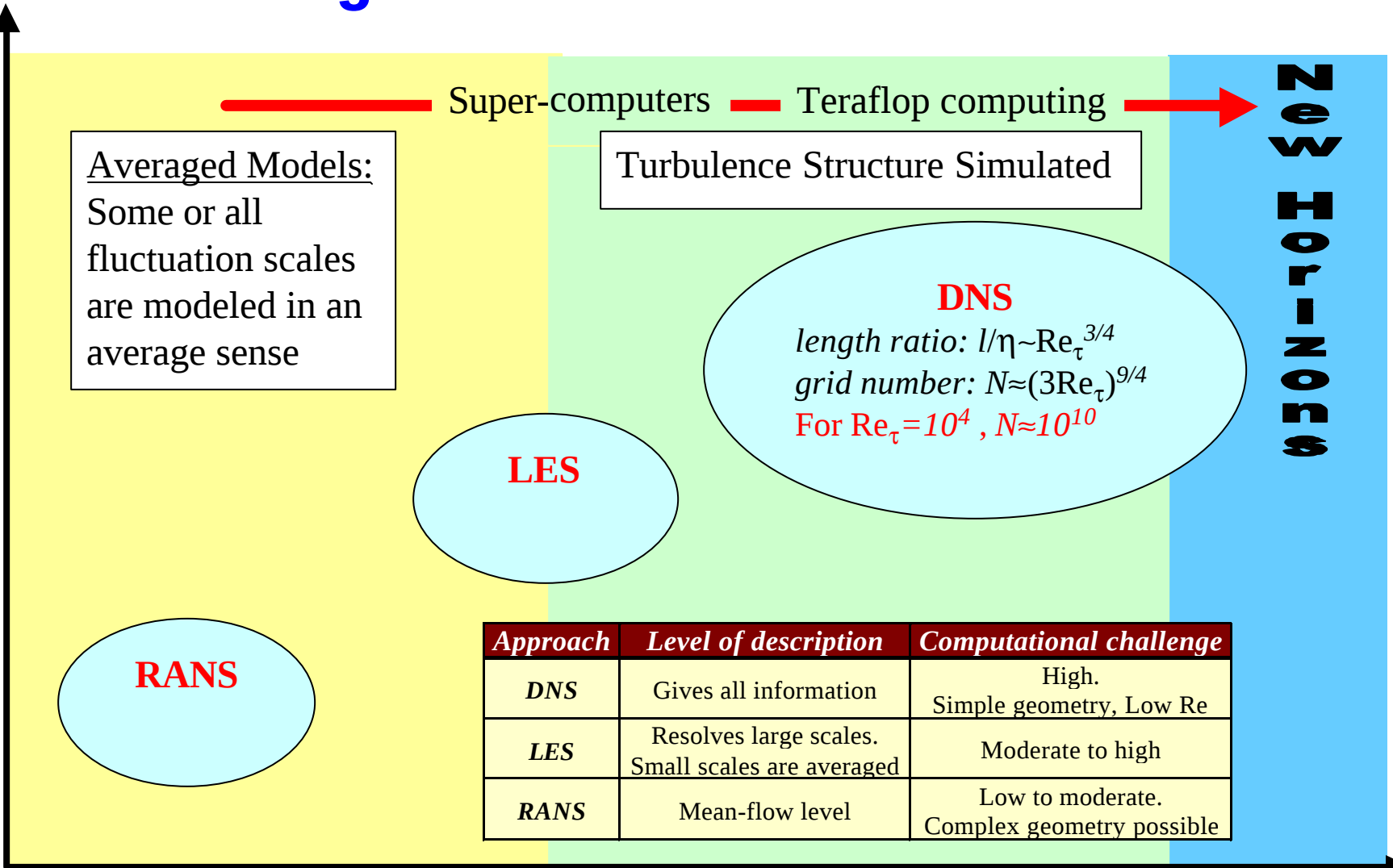
- In Turbulent Motion the “various flow quantities exhibit random spatial and temporal variations” where “statistically distinct average values can be discerned.”
- Hinze

- Turbulence is the rule, not the exception, in most practical flows. Turbulence is not an unfortunate phenomena. Enhancing turbulence is often the goal.

- Vastly different length and time scales make equations stiff - requiring large number of computational cycles. High resolution required to capture all length scales and geometrical complexities.

Teraflop Computers are Making TURBULENCE Accessible

Level of description



Computational Challenge