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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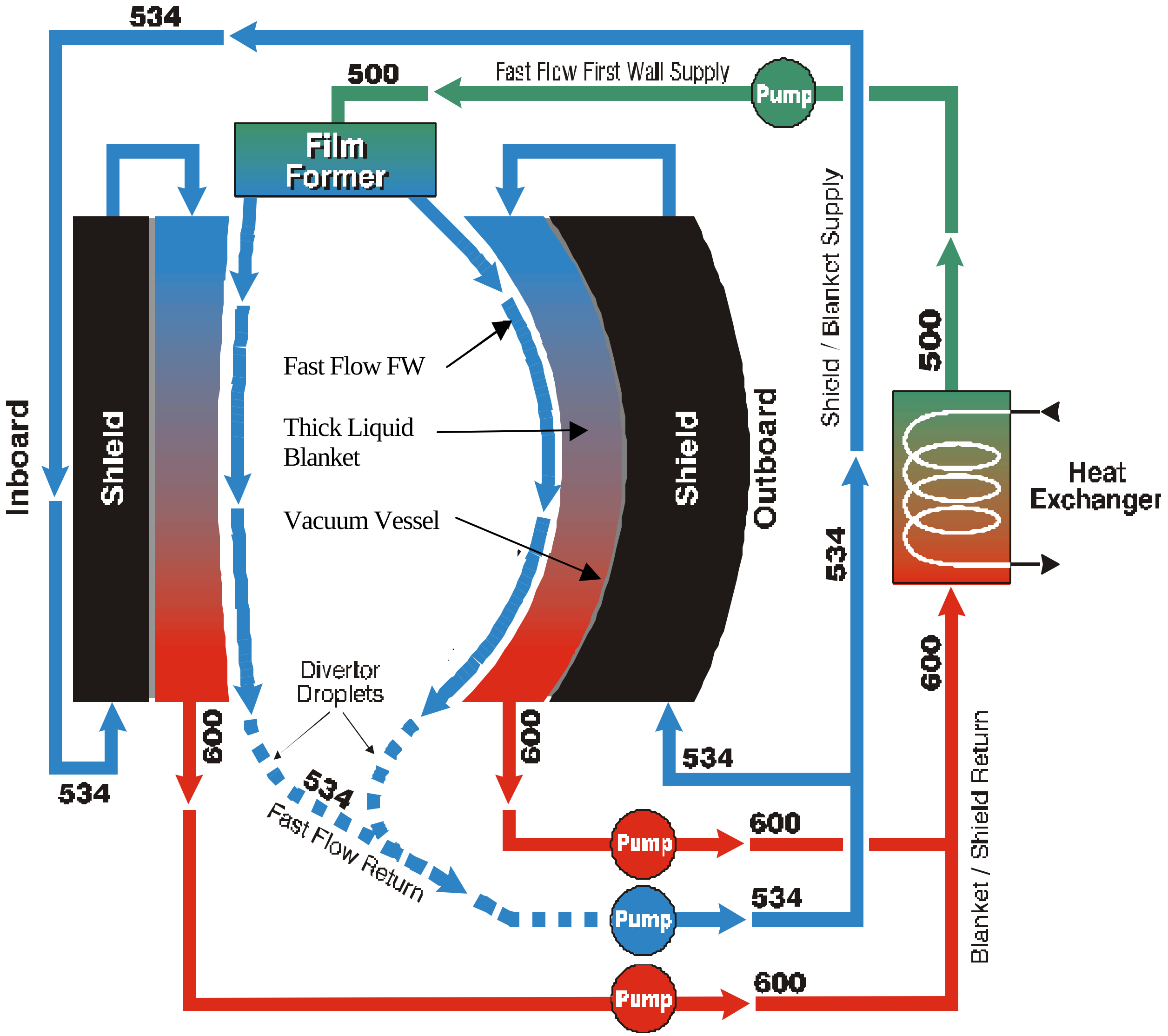
First International Symposium on Free Surface Flow and Interfacial Transport Phenomena

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

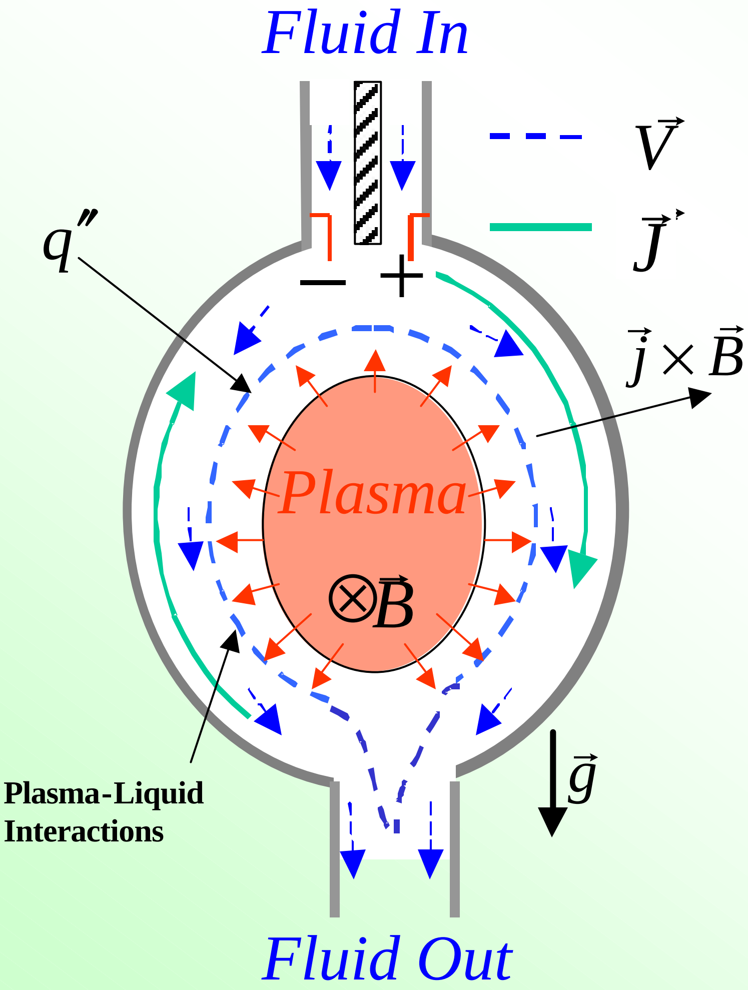
Motivation for Liquid Wall Research

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

- Improvements in Plasma Stability and Confinement
  Enable high ß, 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”**

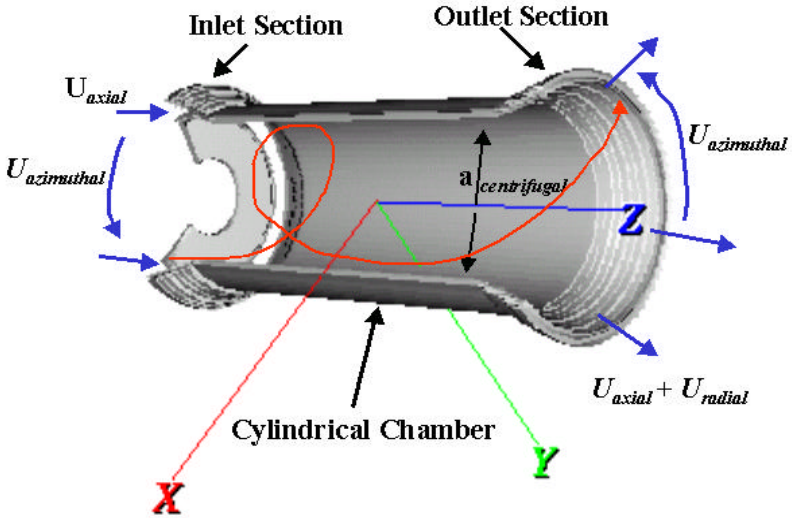
  a) Working fluid: Liquid Metal, low conductivity fluid

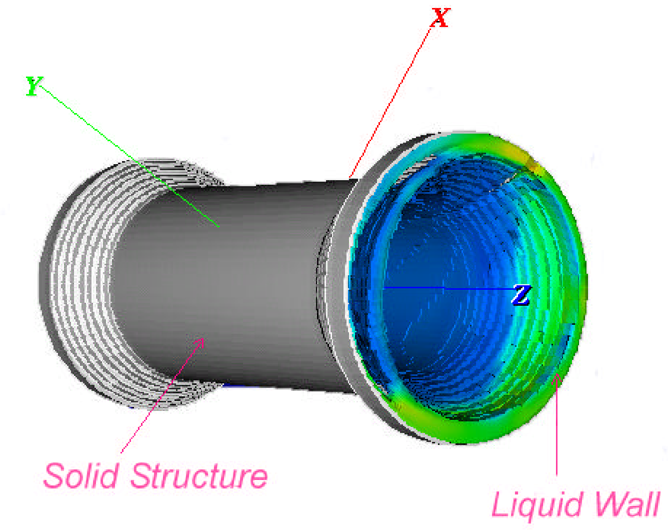
  b) Liquid Thickness
  - thin to remove surface heat flux
  - thick to also attenuate the neutrons

  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

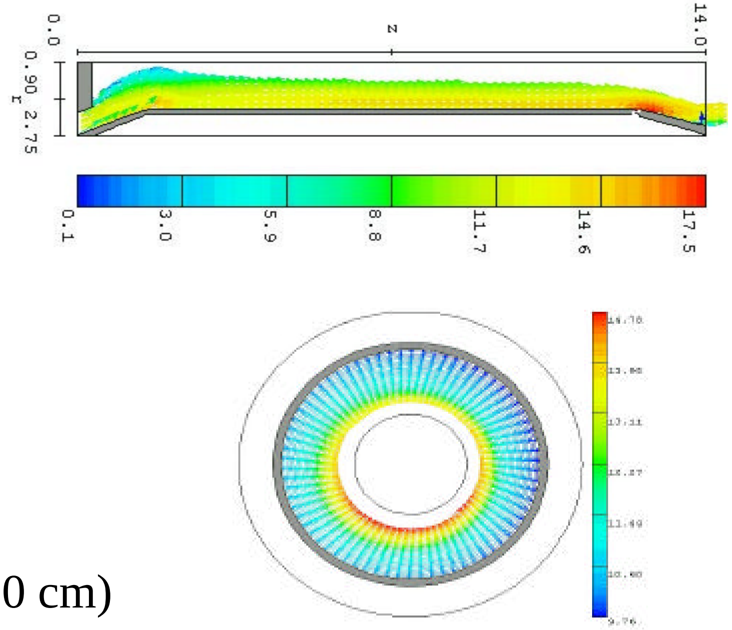




- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

- **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

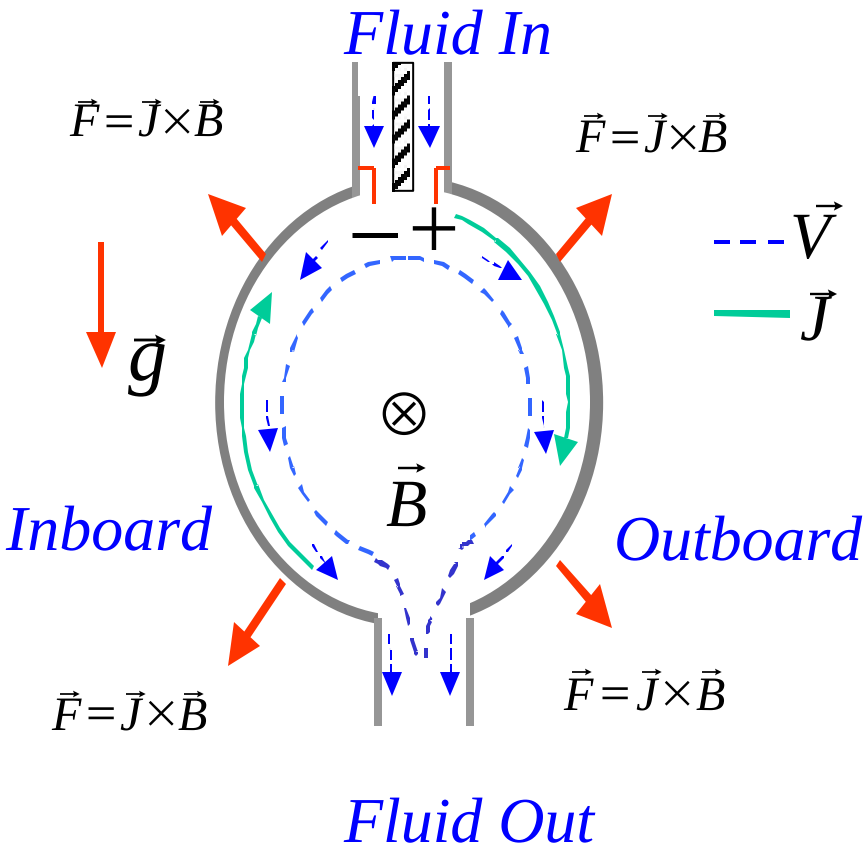


Calculated velocity and surface depth

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

Electromagnetically Restrained LM Wall (R.Woolley)

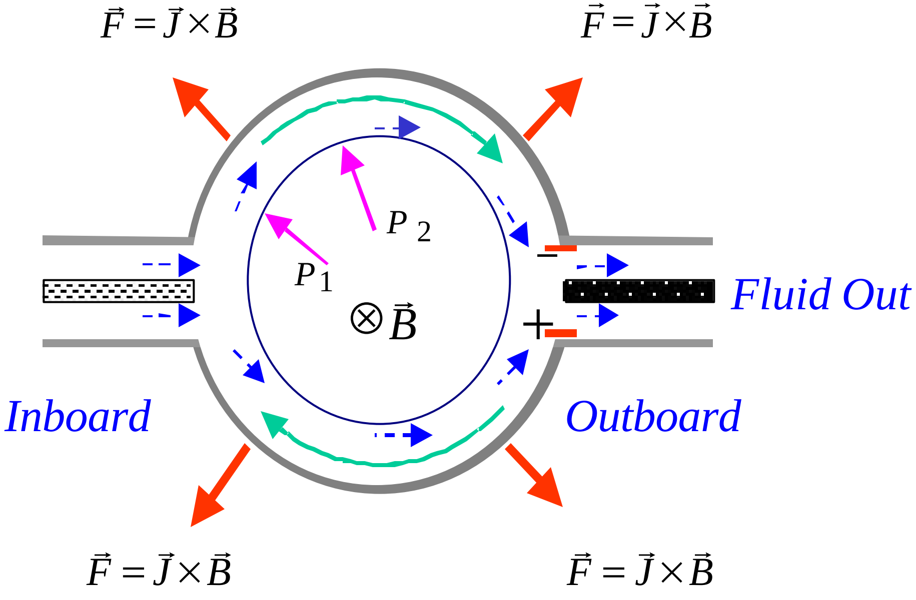
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



Magnetic propulsion scheme (L.Zakharov)

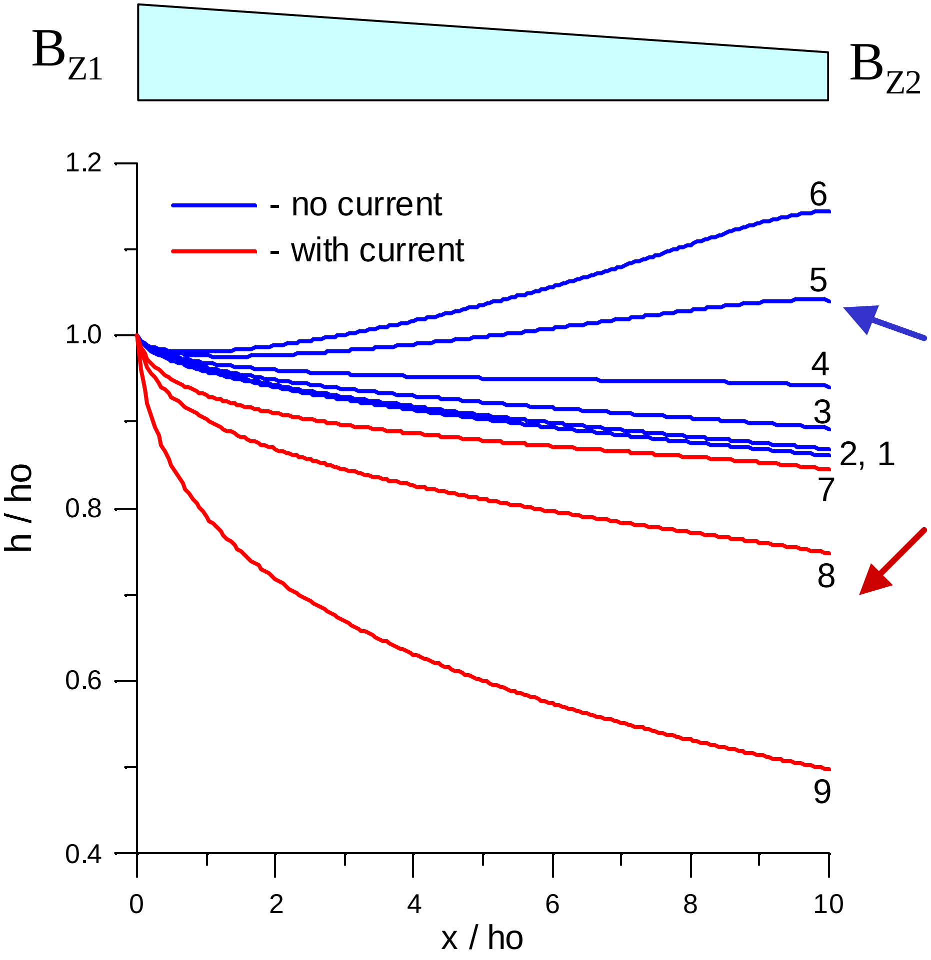
Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$

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



$\vec{V}$ is driven by ΔP

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



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

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)

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

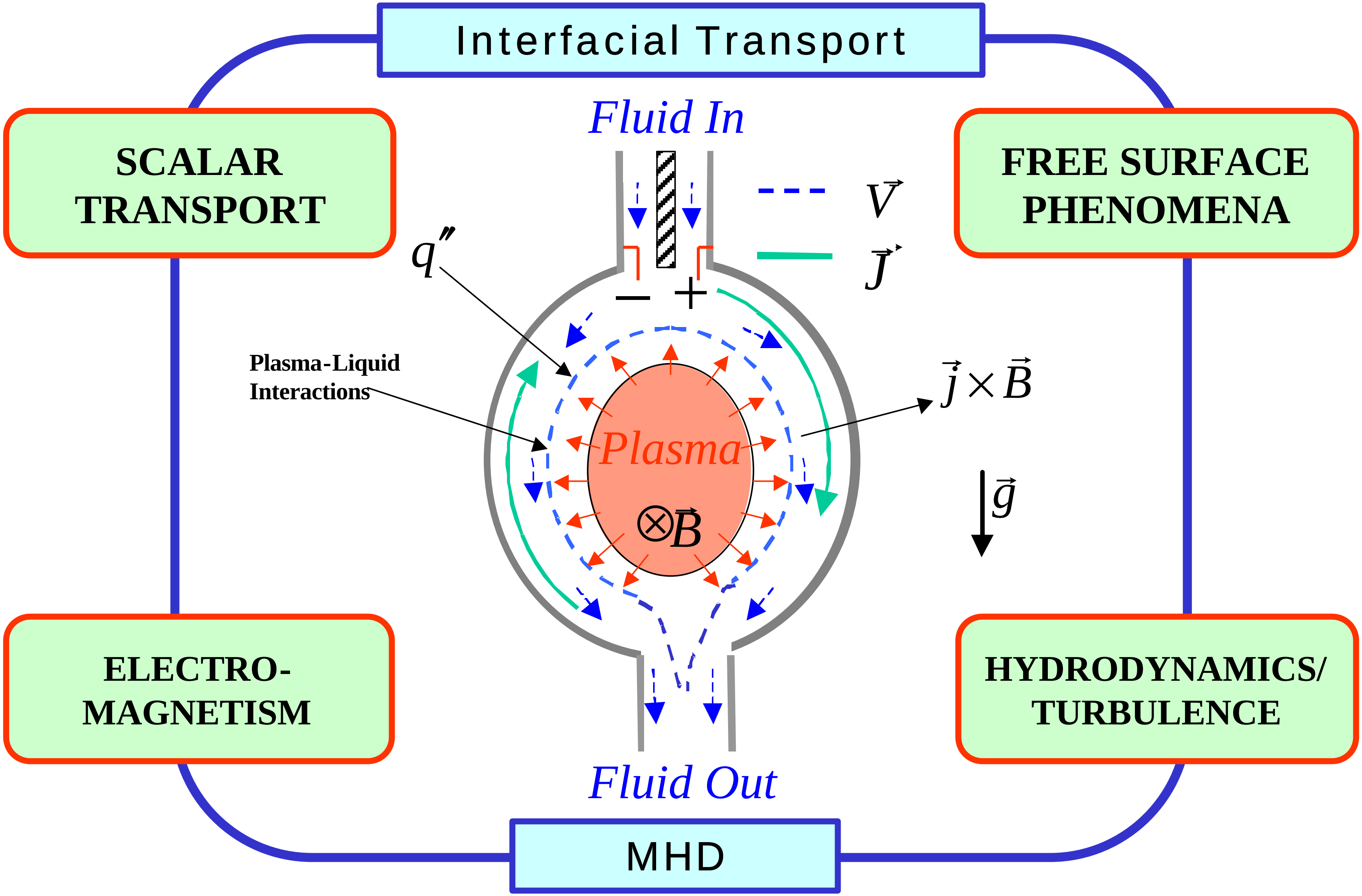
2. Effects of Liquid Wall on Core Plasma

- 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



Interfacial Transport

SCALAR TRANSPORT

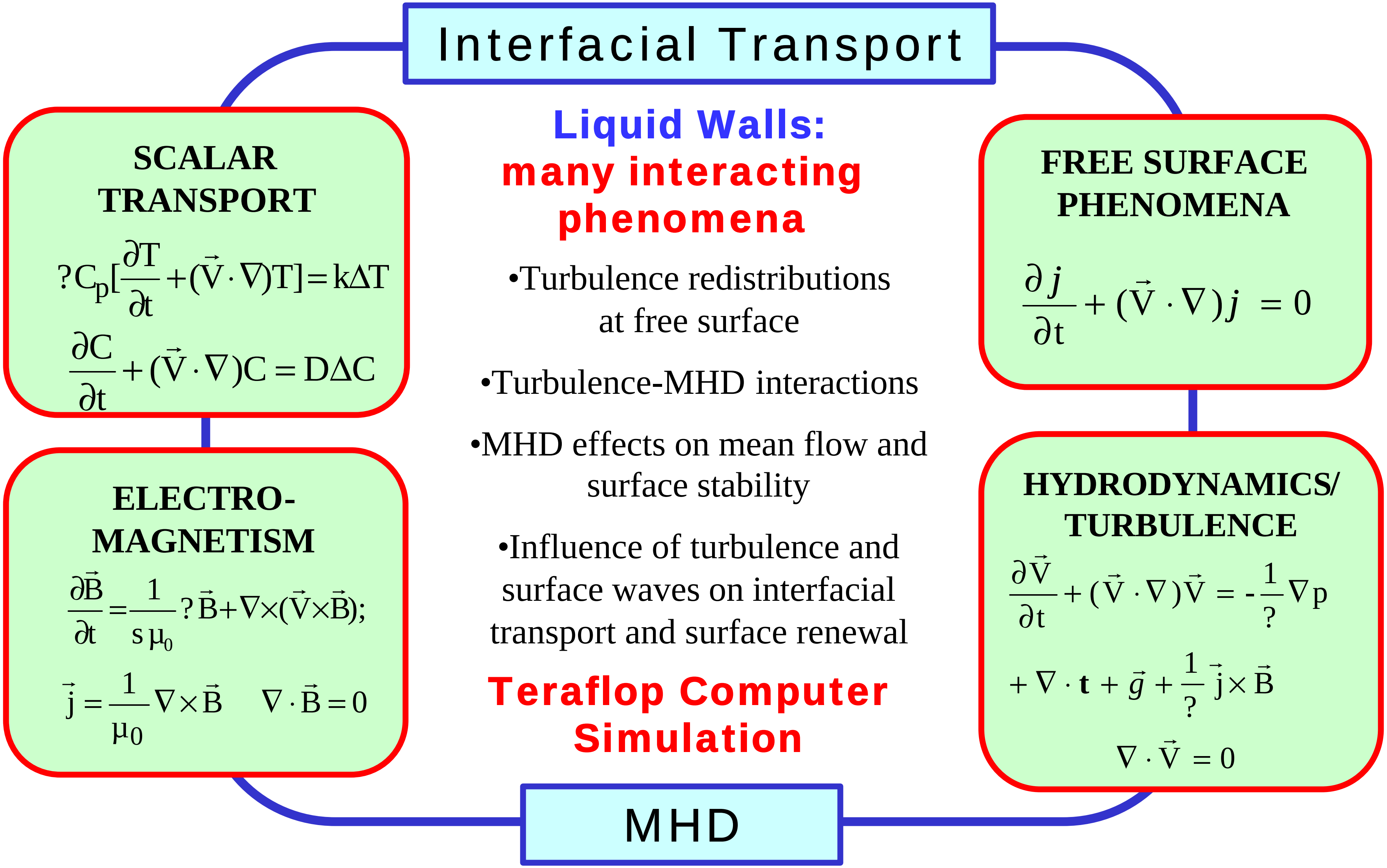
FREE SURFACE PHENOMENA

ELECTRO-MAGNETISM

HYDRODYNAMICS/ TURBULENCE

MHD

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



Interfacial Transport

SCALAR TRANSPORT

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

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

ELECTRO-MAGNETISM

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

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

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

FREE SURFACE PHENOMENA

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

HYDRODYNAMICS/ TURBULENCE

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

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

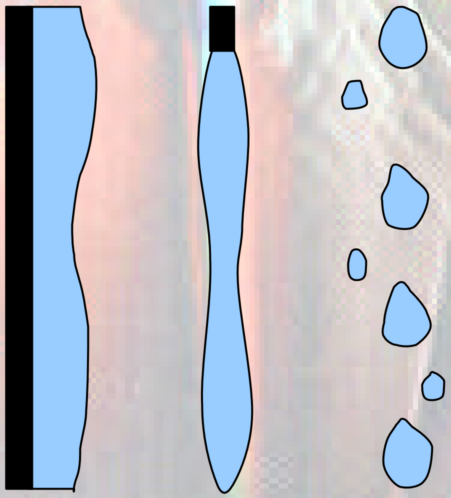
$$\nabla\cdot\vec{V}=0$$

MHD

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

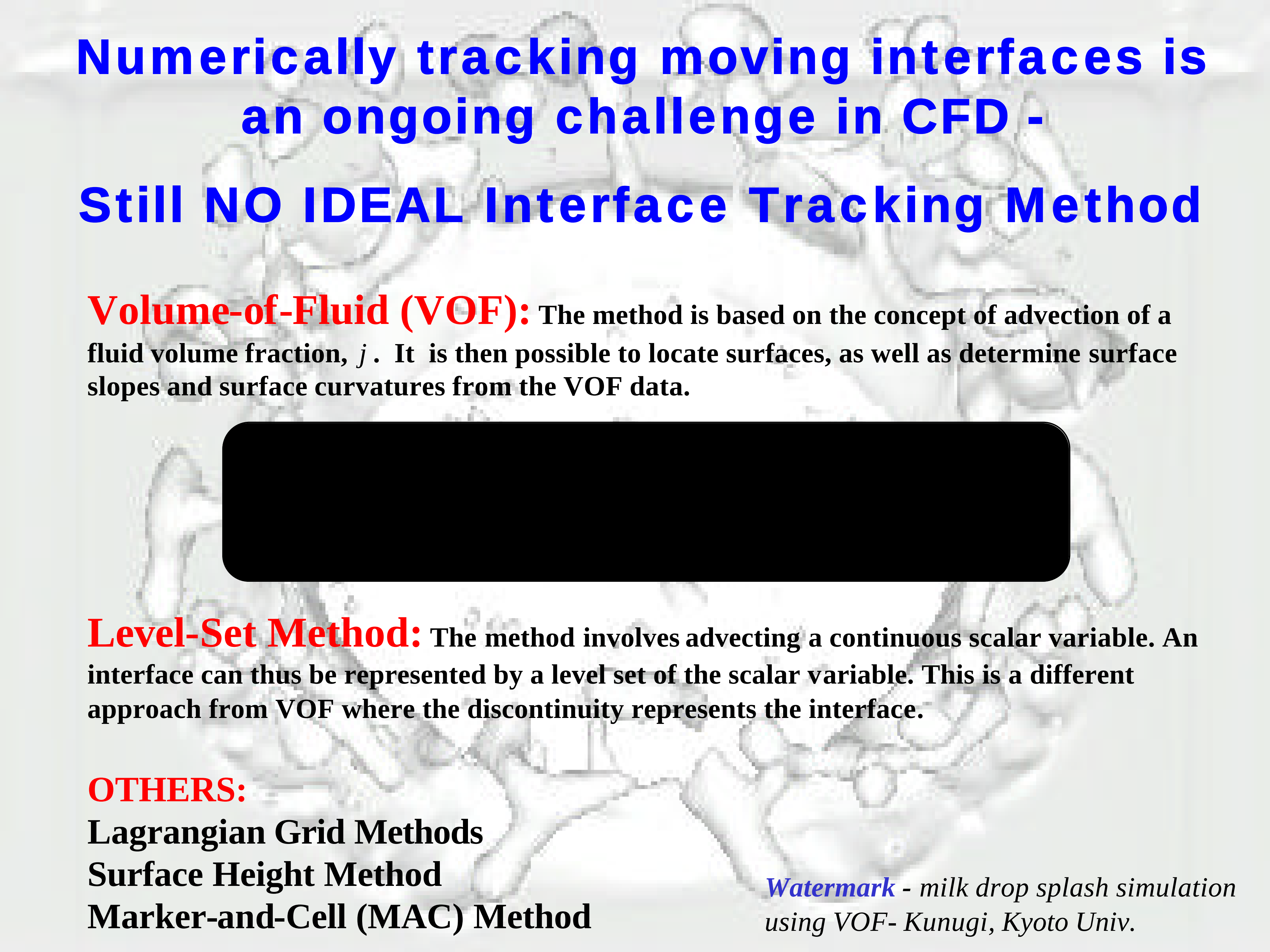
Volume-of-Fluid (VOF): **The method is based on the concept of advection of a fluid volume fraction, j. It is then possible to locate surfaces, as well as determine surface slopes and surface curvatures from the VOF data.**

[redacted]

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.**

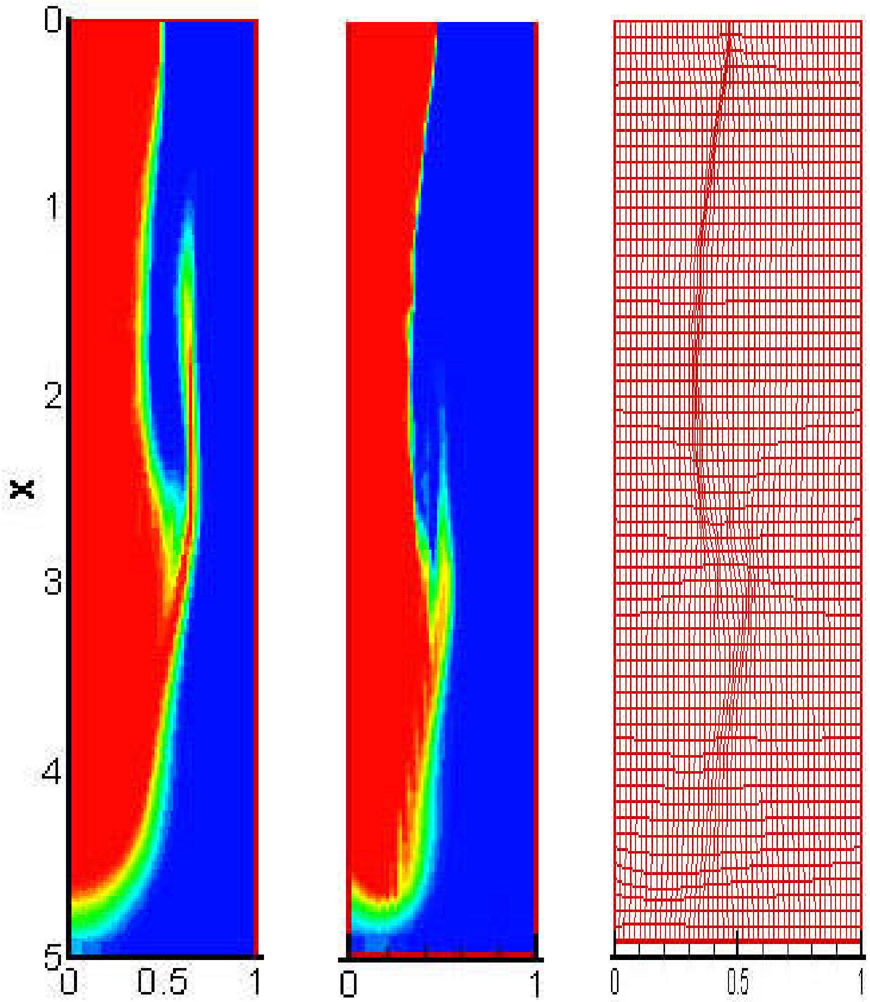
OTHERS:

Lagrangian Grid Methods
Surface Height Method
Marker-and-Cell (MAC) Method



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

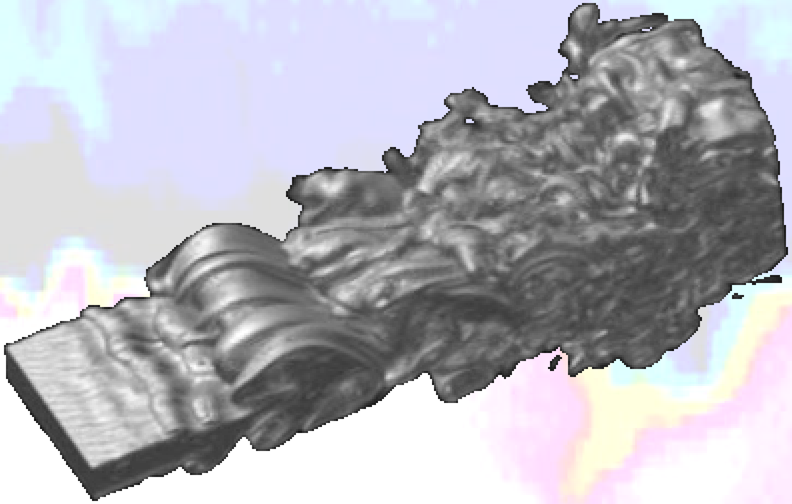
State-of-the-Art Computational Techniques are Required for Intensive LW Simulation



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

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

CHALLENGE: TURBULENCE



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

Horace Lamb, British physicist:

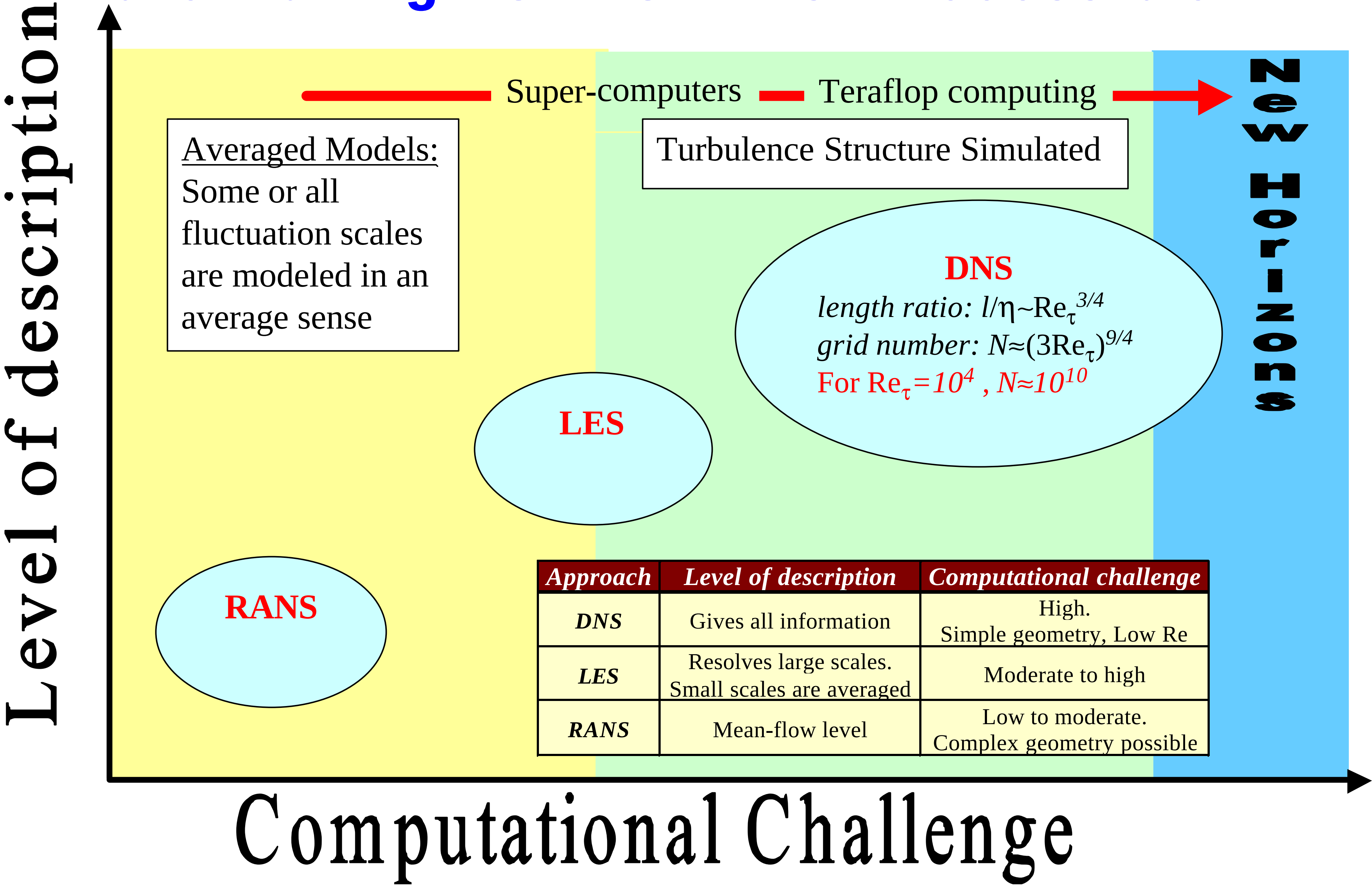
"I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."

- **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



Super-computers — Teraflop computing → New Horizons

Averaged Models: Some or all fluctuation scales are modeled in an average sense

Turbulence Structure Simulated

DNS

length ratio: $l/\eta \sim Re_\tau^{3/4}$

grid number: $N \approx (3Re_\tau)^{9/4}$

For $Re_\tau = 10^4$, $N \approx 10^{10}$

LES

RANS

Approach	*Level of description*	*Computational challenge*
DNS	Gives all information	High. Simple geometry, Low Re
LES	Resolves large scales. Small scales are averaged	Moderate to high
RANS	Mean-flow level	Low to moderate. Complex geometry possible