Moving Beyond Prediction to Control

Free Surface, Turbulence, and Magnetohydrodynamics: Interactions and effects on flow control and interfacial transport

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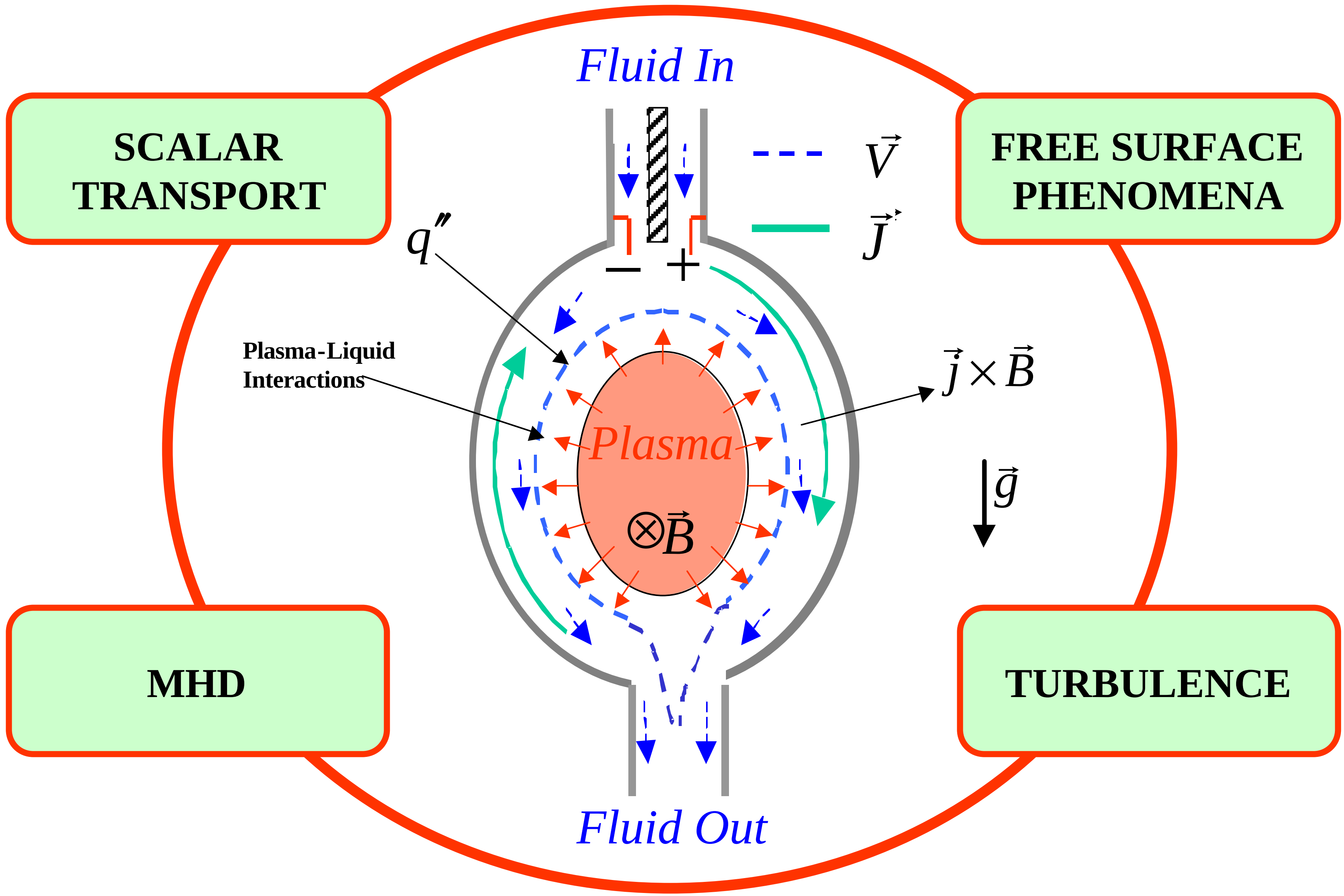
Liquid Wall Researchers are Advancing the Understanding of Interacting Multi-Scale Phenomena at the Frontiers of Fluid Dynamics



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

Liquid Walls: many interacting phenomena

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

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

MHD

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

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

TURBULENCE

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

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

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

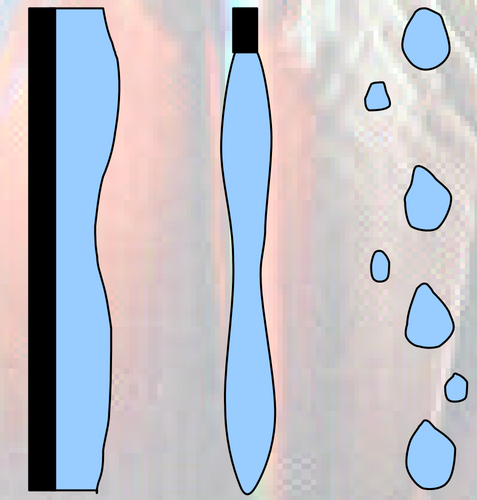
- Turbulence redistributions at free surface
- Turbulence-MHD interactions
- MHD effects on mean flow and surface stability
- Influence of turbulence and surface waves on interfacial transport and surface renewal

Teraflop Computer Simulation

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]

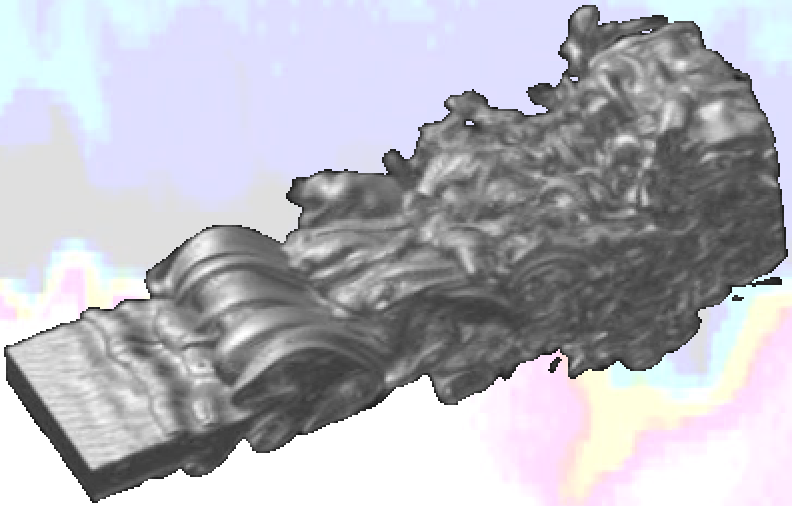
Level-Set Method: **The method involves advecting a continuous scalar variable. An interface can thus be represented by a level set of the scalar variable. This is a different approach from VOF where the discontinuity represents the interface.**

OTHERS:

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

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

CHALLENGE: TURBULENCE



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

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

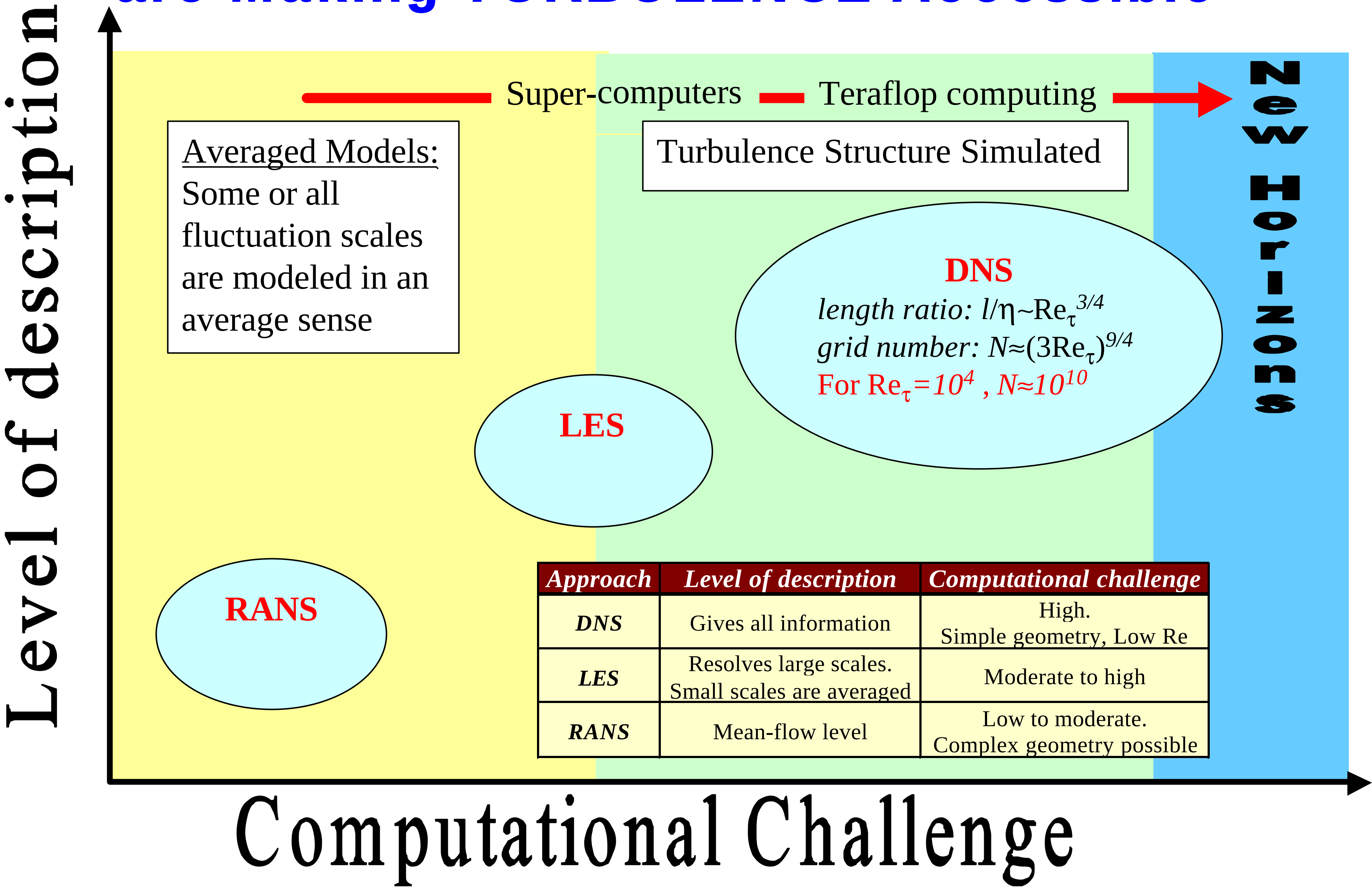
•**Turbulence is the rule, not the exception, in most practical flows. Turbulence is not an unfortunate phenomena. Enhancing turbulence is often the goal.**

•**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.**

Horace Lamb, British physicist:

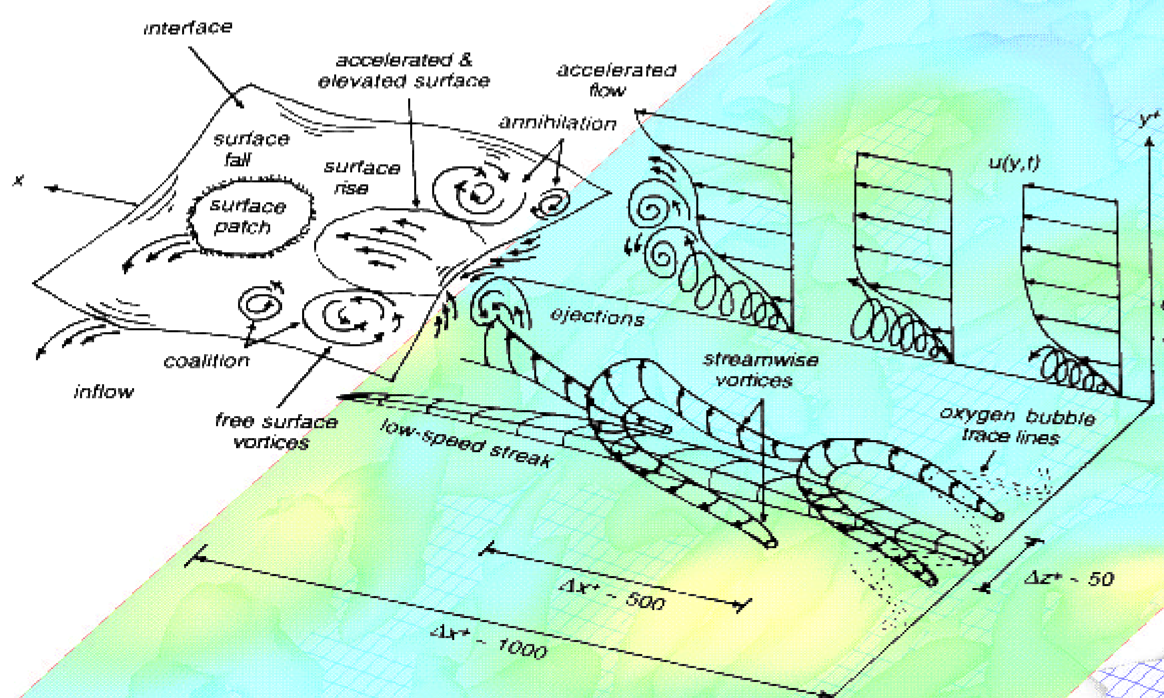
"I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."

Teraflop Computers are Making TURBULENCE Accessible



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

Turbulence / free surface interaction produces new phenomena - anisotropic near-surface turbulence

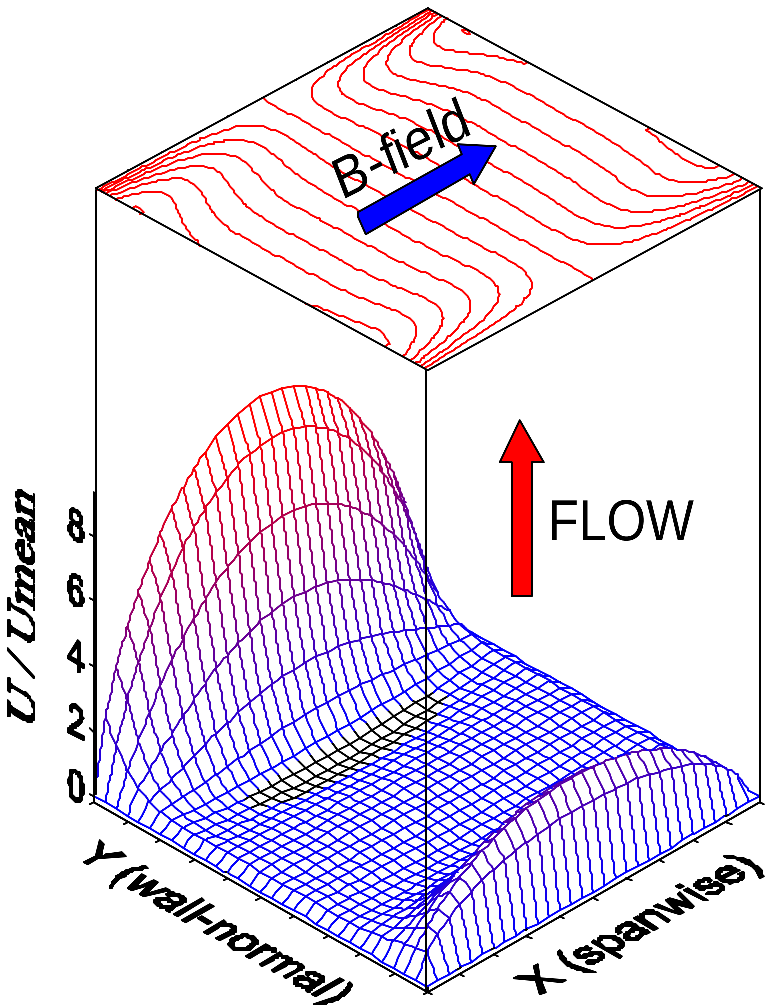


Conceptual illustration of experimental observation of burst-interface interactions - From Rashidi, Physics of Fluids, No.9, November 1997.

Watermark - Vortex structure and free surface deformation (DNS calculation)

- **Turbulent production dominated by the generation of wall ejections, formation of spanwise "upsurging vortices"**
- **Upsurging vortices reach free surface, form surface deformation patches, roll back in form of spanwise "downswinging vortices", with inflow into the bulk.**
- **The ejection - inflow events are associated with the deformation of the free surface and a redistribution of near surface vorticity and velocity fields.**

CHALLENGE: MAGNETOHYDRODYNAMICS



Free surface flow velocity jets produced from MHD interaction - UCLA calculation

- **Complex non-linear interactions between fluid dynamics and electrodynamics**
- **Powerful mechanism to "influence" fluids**
- **Strong drag effects, thin active boundary layers, large (possibly reversed) velocity jets are characteristic MHD phenomena**
- **Large currents with joule dissipation and even self-sustaining dynamo effects add to computational complexity**

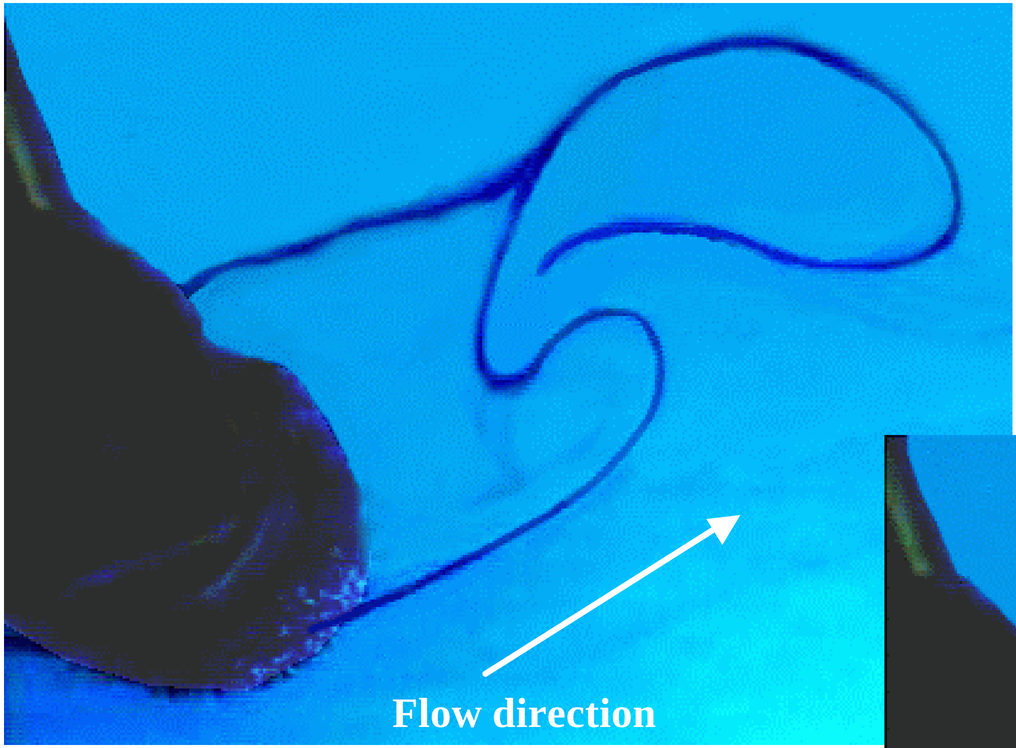
Computational Challenge Li flow in a chute in a transverse field with: b=0.1 m (half-width); B_0=12 T (field)

$$\mathrm{Ha} = \mathrm{B_0 b}\sqrt{\frac{s}{nr}} \approx 100{,}000 \qquad d_{Ha} = \frac{b}{Ha} = 10^{-6}\,m$$

Each cross-section requires MANY uniform grids, or special non-uniform meshes.

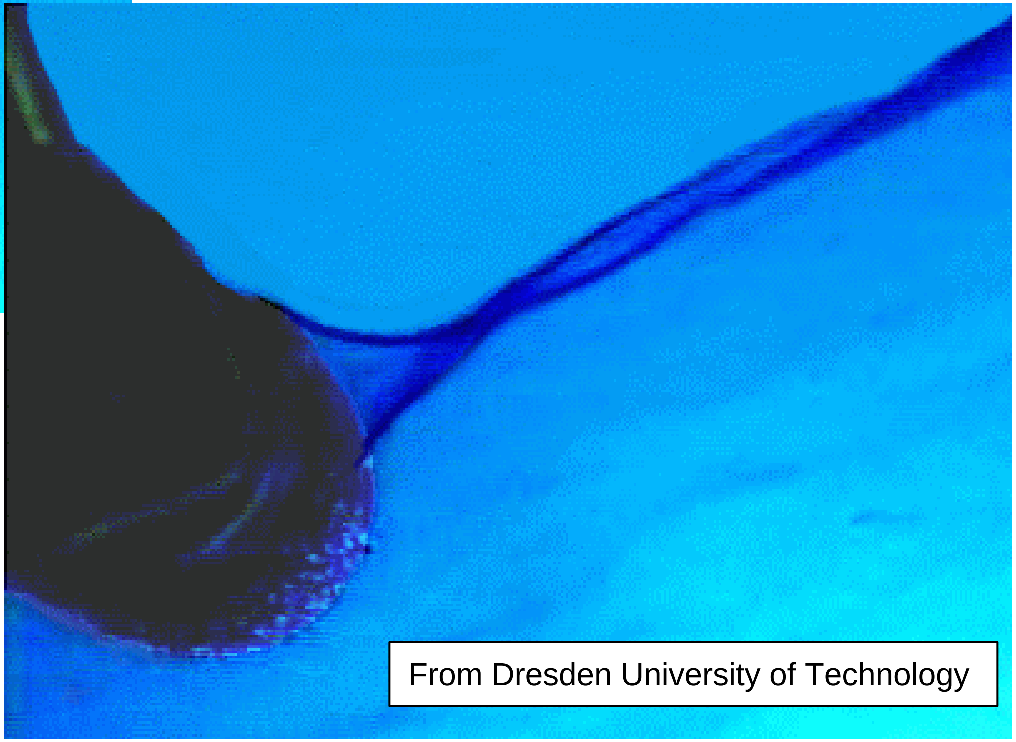
$$(b / d_{Ha})^2 = 10^{10}$$

MHD interactions can change the nature of turbulence - providing a lever of CONTROL



•Applied Lorentz forces act mainly in the fluid regions near the walls where they can prevent flow separation or reduce friction drag by changing the flow structure.

•Because heat and mass transfer rely strongly on the flow structure, they can in turn be controlled in such fashion.



Experimental control of flow separation by a magnetic field:

fully developed von Kármán vortex street without a magnetic field (upper)

with a magnetic field (right)