RESEARCH ON LIQUID WALLS FOR FUSION SYSTEMS

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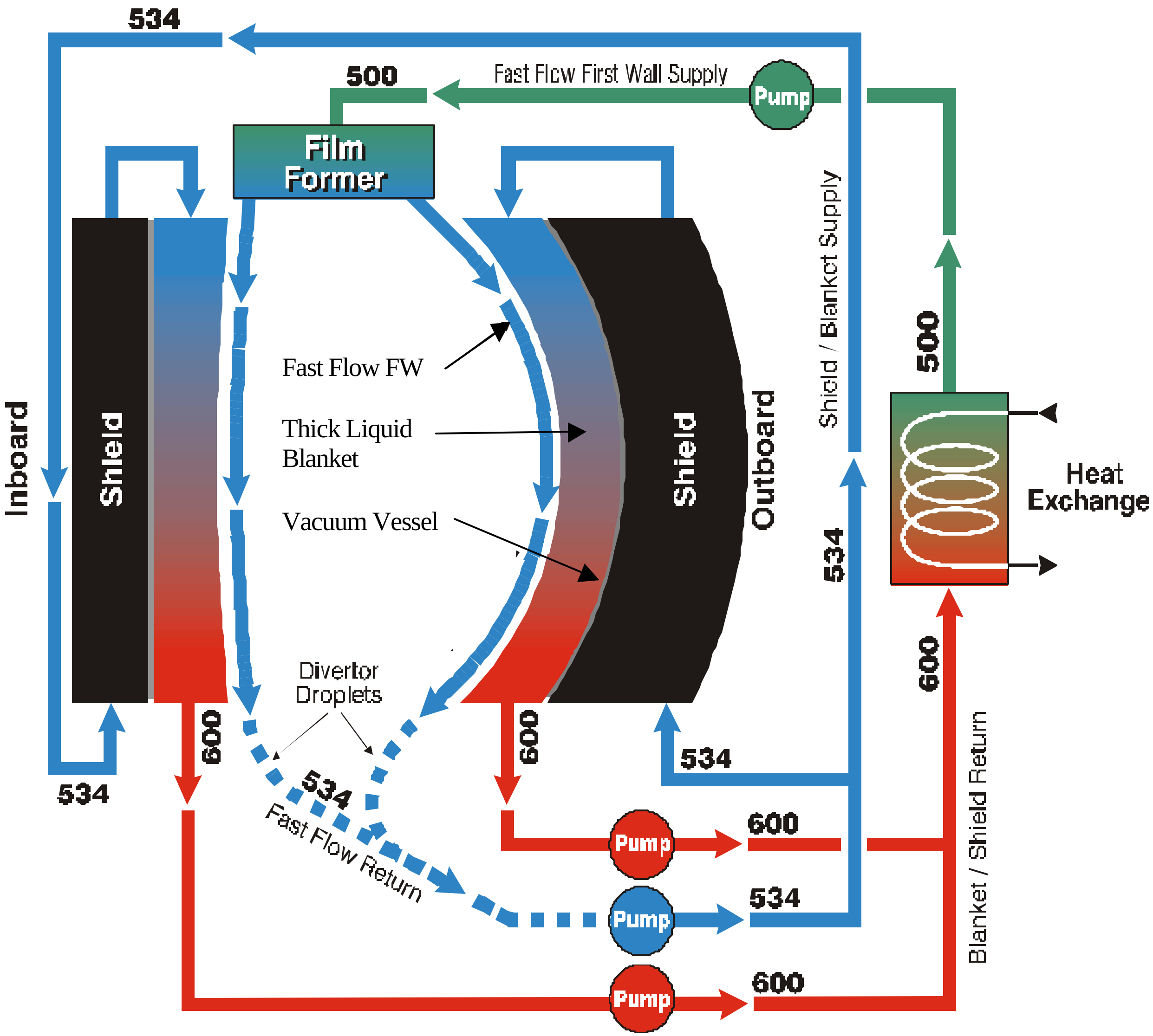
Illustration of Liquid Walls



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

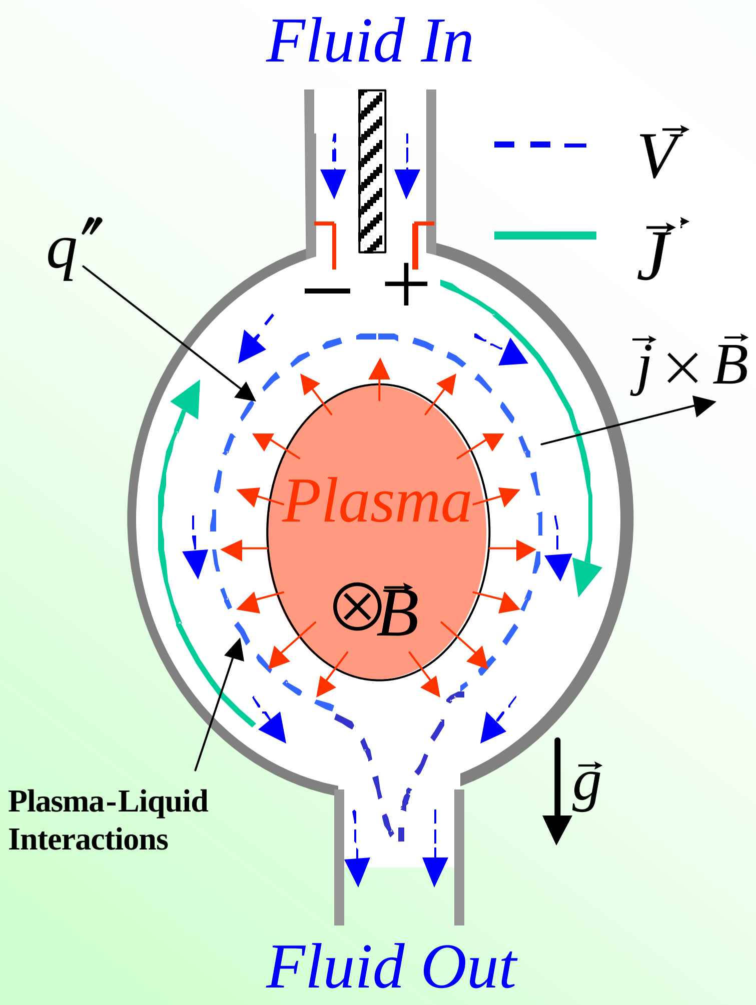
Motivation for Liquid Wall Research

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"**

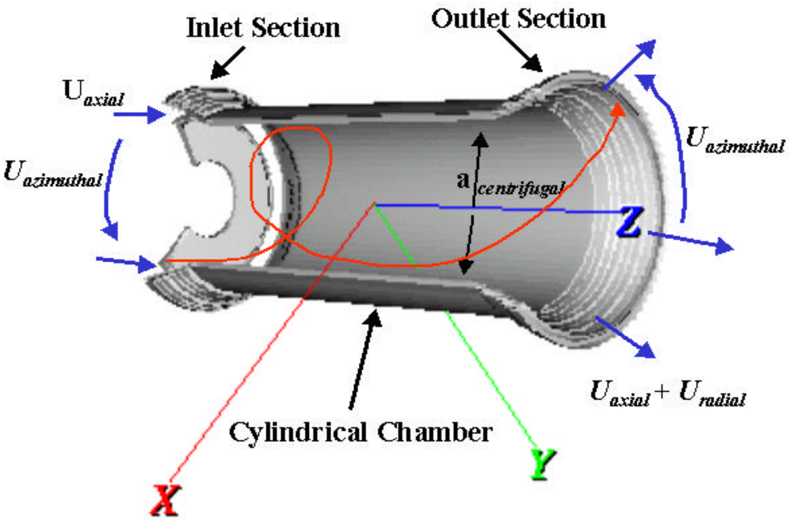
  a) Working fluid: Liquid Metal, low conductivity fluid

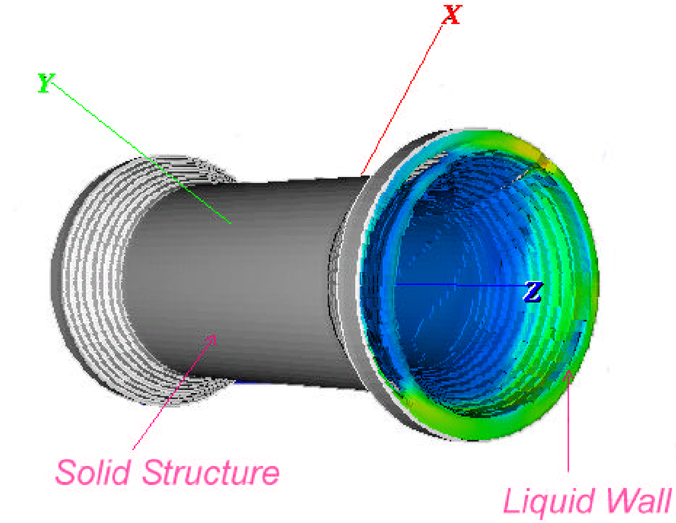
  b) Liquid Thickness
  - thin to remove surface heat flux
  - thick to also attenuate the neutrons

  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

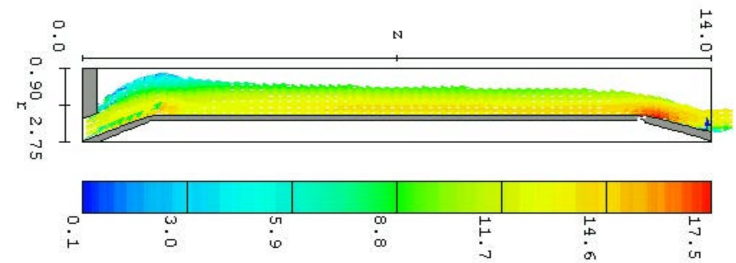


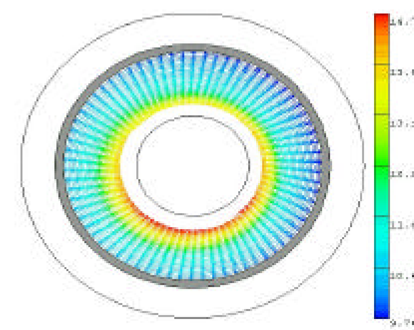


•Design: Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

•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



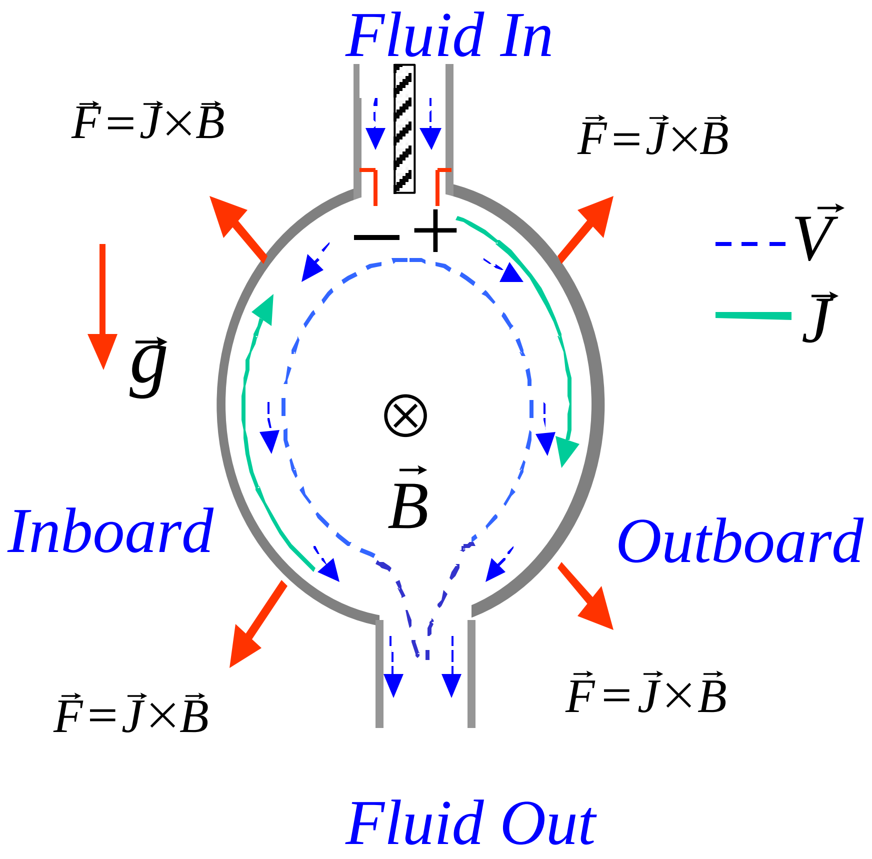


Calculated velocity and surface depth

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

Electromagnetically Restrained LM Wall (R.Woolley)

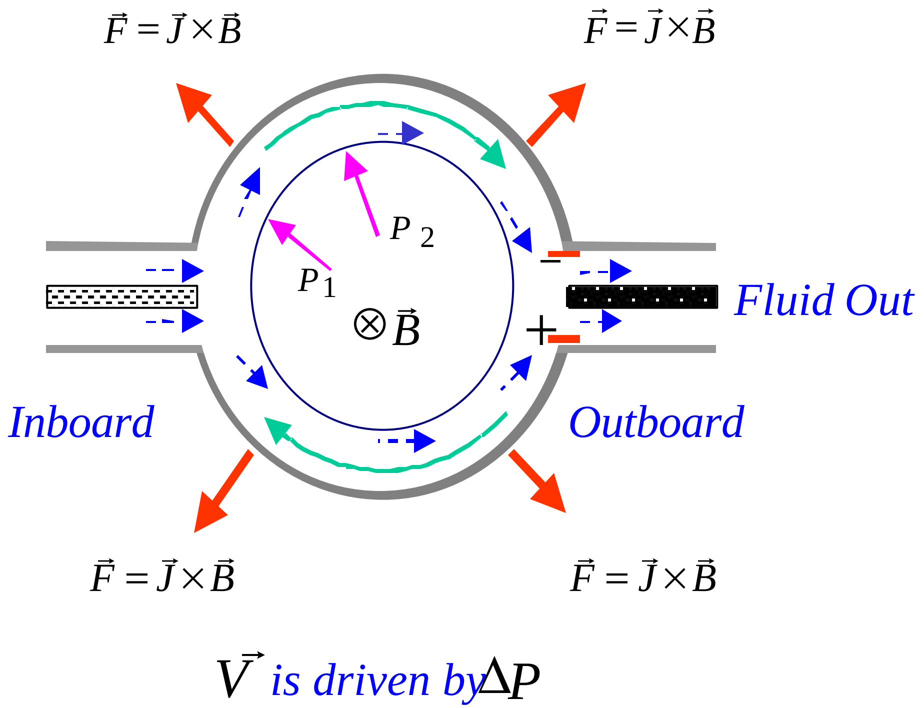
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



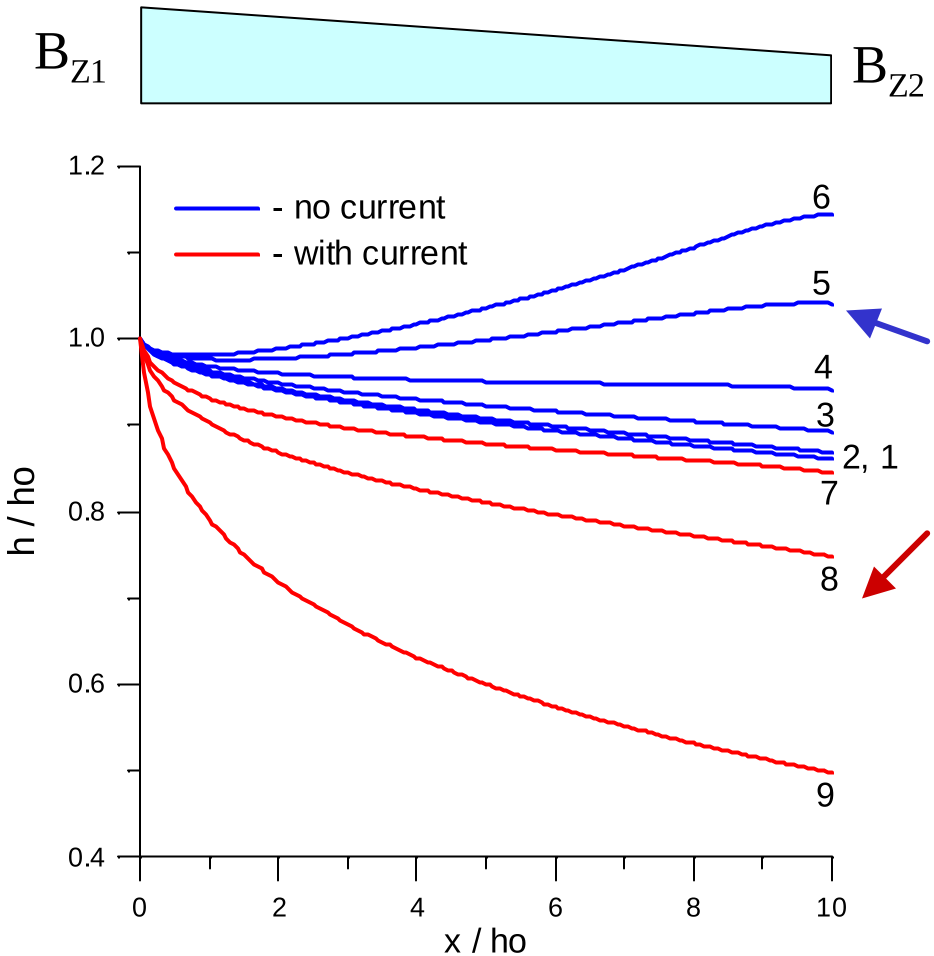
Magnetic propulsion scheme (L.Zakharov)

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***



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

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

Interfacial Transport

SCALAR TRANSPORT

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

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

ELECTRO-MAGNETISM

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

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

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

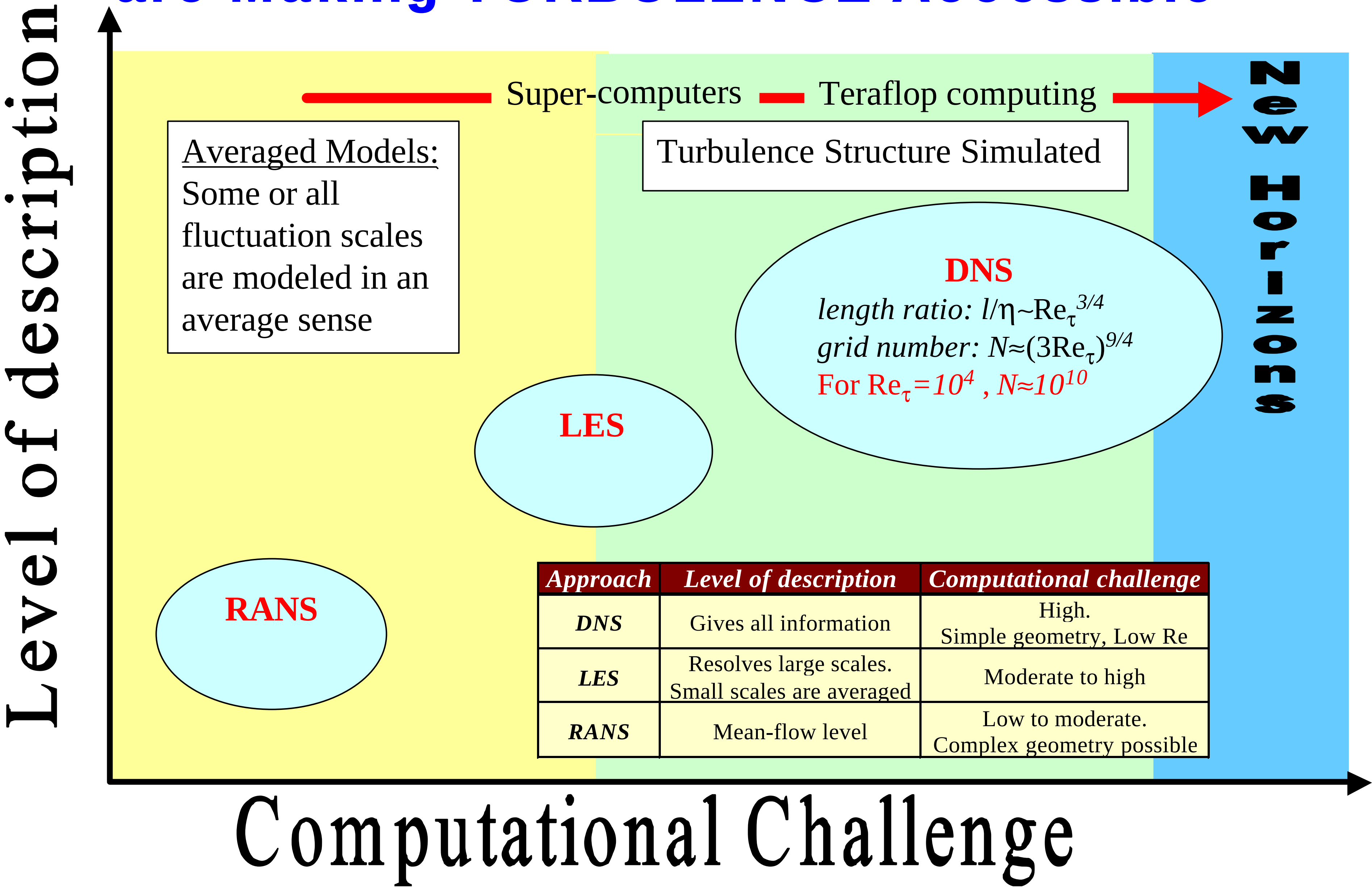
$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}\cdot\nabla)\vec{V} = -\frac{1}{?}\nabla p$$

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

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

MHD

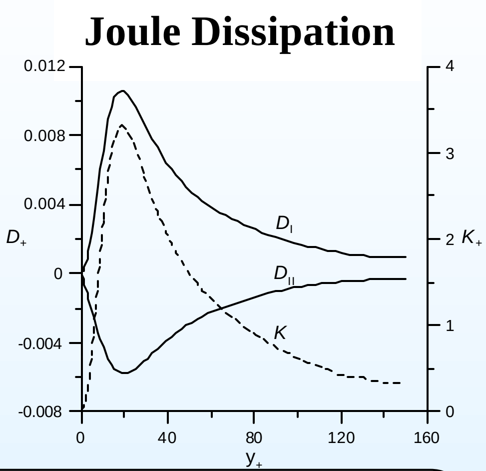
Teraflop Computers
are Making TURBULENCE Accessible



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

Our Science-based CFD Modeling and Experiments are Utilized to Develop Engineering Tools for LW Applications

D N S
for free surface MHD flows developed as a part of collab-oration between UCLA and Japanese Profs Kunugi and Satake

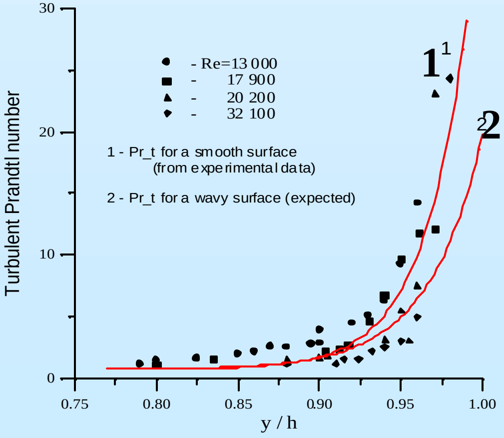


DNS and Experimental data are used at UCLA for characterizing free surface MHD turbulence phenomena and developing closures in RANS models

Extend RANS Turbulence Models for MHD, Free Surface Flows

- **K-epsilon**
- **RST model**

EXPERIMENTS
underway at UCLA for near surface turbulence and interfacial transport measurements

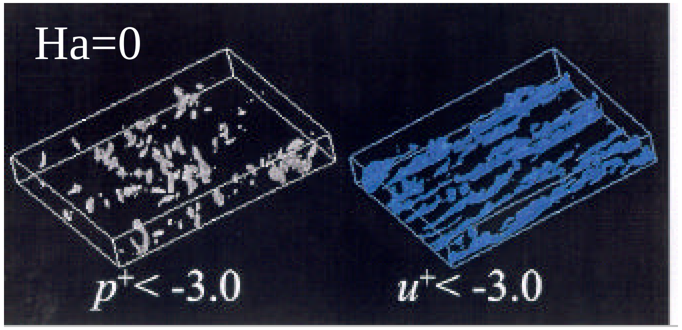


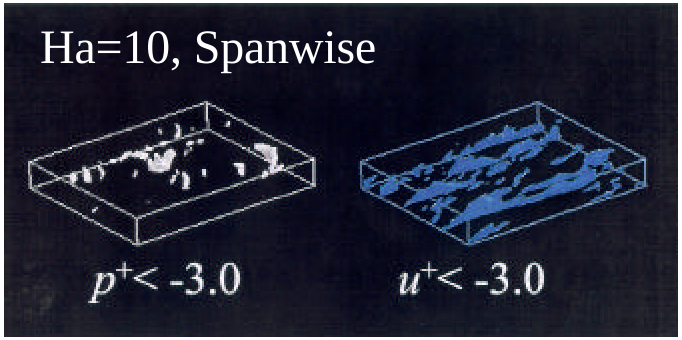
Turbulent Prandtl Number

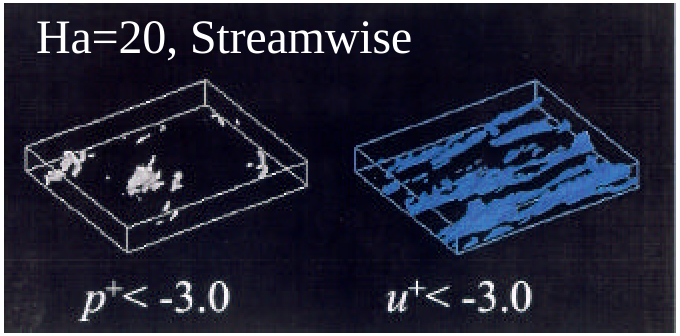
Curve1: Available Experimental Data
- Missing 0.95-1 and restricted to smooth surface, non-MHD flows

Curve2: “Expected” for wavy surface

A BIG STEP FORWARD -
(1st FREE SURFACE, MHD TURBULENT DNS)







- Strong redistribution of turbulence by a magnetic field is seen.
- Frequency of vortex structures decreases, but vortex size increases.
- Stronger suppresion effect occurs in a spanwise magnetic field
- Free surface approximated as a free slip boundary. Work proceeding on a *deformable* free surface solution.

"DNS of turbulent free surface flow with MHD at Ret = 150" - *Satake, Kunugi, and Smolentsev, Computational Fluid Dynamics Conf., Tokyo, 2000*

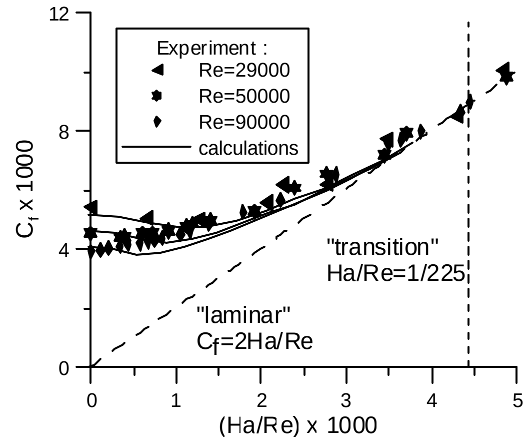
Extending the state-of-the-art in RANS with MHD and free surface effects

MHD K- ε TURBULENCE MODEL

$$\frac{\partial K}{\partial t} + \left\langle v_j \right\rangle \frac{\partial K}{\partial x_j} = \underbrace{\nu_t \left(\frac{\partial v_i}{\partial x_j} \right)^2}_{Production} + \underbrace{\frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_K} \right) \frac{\partial K}{\partial x_j} \right]}_{Diffusion} - \underbrace{\varepsilon - \varepsilon_{em}^K}_{Dissipation} ;$$

$$\frac{\partial \varepsilon}{\partial t} + \left\langle v_j \right\rangle \frac{\partial \varepsilon}{\partial x_j} = C_1 \frac{\varepsilon}{K} \nu_t \left(\frac{\partial v_i}{\partial x_j} \right)^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_2 \frac{\varepsilon}{K} \varepsilon - \varepsilon_{em}^{\varepsilon} .$$

$$q_t = -\rho C_p < t' v_n' > = -\rho C_p \frac{\nu_t}{\mathrm{Pr}_t} \frac{\partial T}{\partial n}; \quad \mathrm{Pr}_t = \nu_t / \alpha_t$$



Comparison of UCLA model to experimental data

MHD DEPENDENT TURBULENCE CLOSURES

Magnetic field direction	ε_{em}^K	$\varepsilon_{em}^{\varepsilon}$	C_3	C_4
Streamwise	$C_3 \frac{\sigma}{\rho} B_0^2 K$	$C_4 \frac{\sigma}{\rho} B_0^2 \varepsilon$	0.02	0.015
Wall-normal	$C_3 \frac{\sigma}{\rho} B_0^2 K$	$C_4 \frac{\sigma}{\rho} B_0^2 \varepsilon$	$1.9\exp\{-1.0N\}$	$1.9\exp\{-2.0N\}$
Spanwise	$C_3 \frac{\sigma}{\rho} B_0^2 K$	$C_4 \frac{\sigma}{\rho} B_0^2 \varepsilon$	$1.9\exp\{-1.0N\}$	$1.9\exp\{-2.0N\}$

1.5-D MHD K-ε Flow Model

- unsteady flow
- height function surface tracking
- turbulence reduction near surface is treated by specialized BCs
- effect of near-surface turbulence on heat transfer modeled by variation of the turbulent Prandtl number

Remarkable Progress on Small-Scale Experiments with Science, Education, and Engineering Mission

Two flexible free surface flow test stands were planned, designed, and constructed at UCLA with modest resources in less than a year

Purpose:

Investigation of critical issues for liquid wall flow control and heat transfer

M-TOR Facility

For LM-MHD flows in complex geometry and multi-component magnetic field

FLIHY Facility

For low-conductivity fluids (e.g. molten salt) flow simulation (including penetrations) and surface heat and mass transfer measurement

Our Experimental Approach

1. Cost Effective

- M-TOR built with recycled components, mostly by students
- FLIHY dual use with JUPITER-II funds from Japan

2. Science-Based Education Mission

- Several MS and Ph.D student theses
- Scientists from outside institutions

3. Collaboration among institutions

- UCLA, PPPL, ORNL, SNL

4. International Collaboration

- JUPITER-II (Tohoku Univ., Kyoto Univ., Osaka Univ., etc.)
- Several Japanese Professors/Universities participate
- IFMIF liquid target

Exploring Free Surface LM-MHD in MTOR Experiment

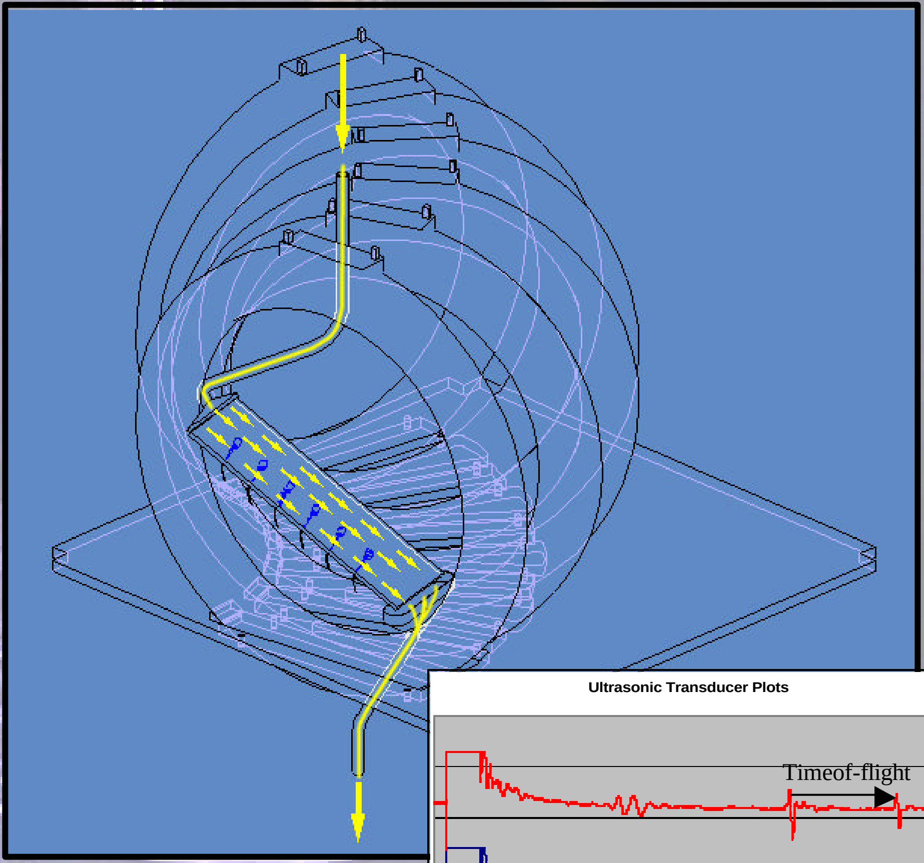
•Study toroidal field and gradient effects: Free surface flows are very sensitive to drag from toroidal field 1/R gradient, and surface-normal fields

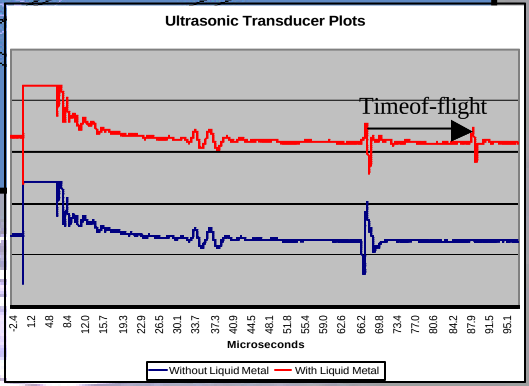
•3-component field effects on drag and stability: Complex stability issues arise with field gradients, 3-component magnetic fields, and applied electric currents

•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: module testing and design





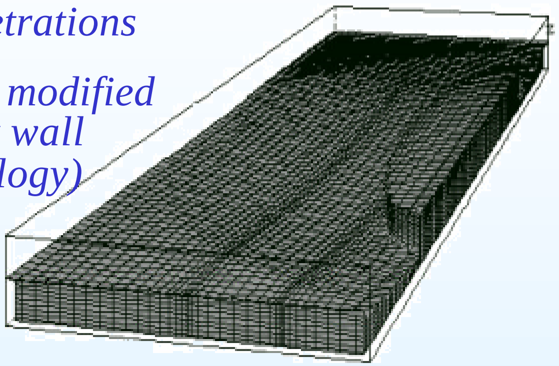
MTOR Magnetic Torus and LM Flowloop: Designed in collaboration between UCLA, PPPL and ORNL

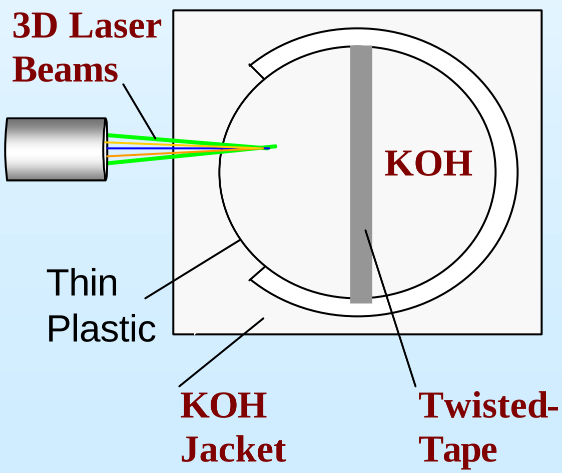
FLIHY is a flexible facility that serves many needs for Free-Surface Flows

Flow Control

Penetrations

(e.g. modified back wall topology)

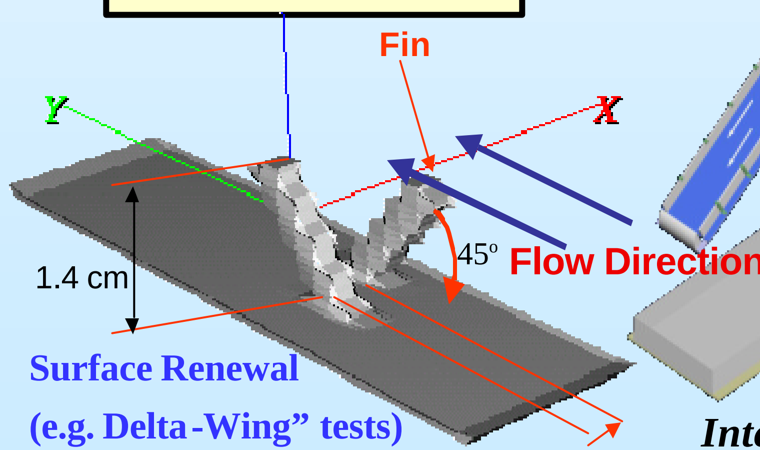




JUPITER-II

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**



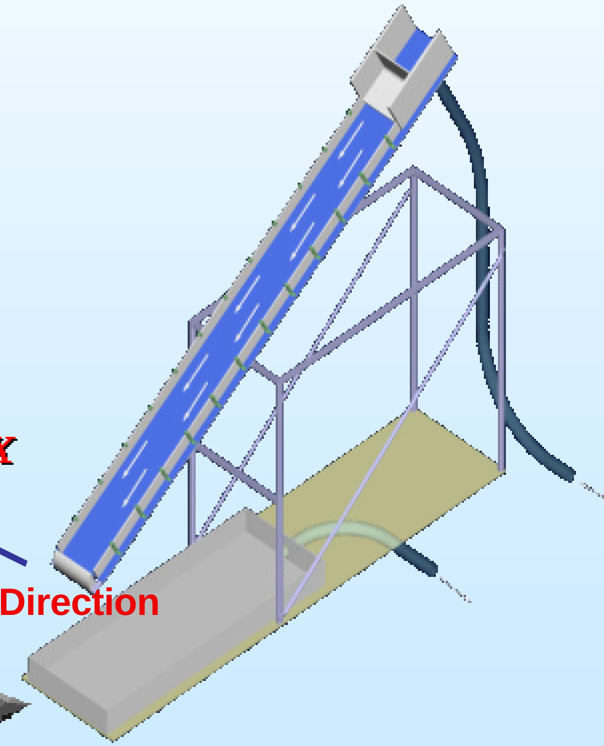
Surface Renewal

(e.g. Delta-Wing" tests)

Free Surface Interfacial Transport

- Turbulence at free surface

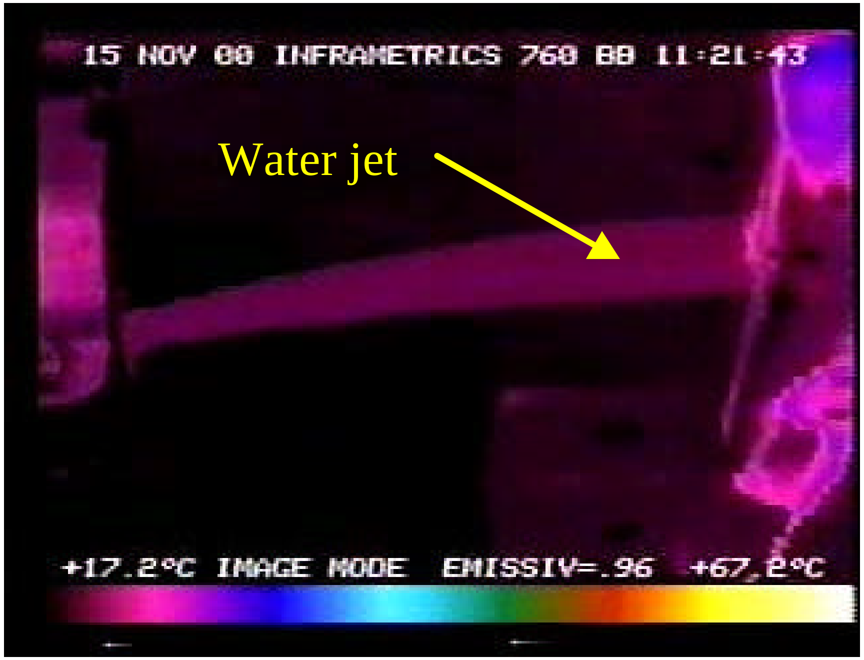
- Novel Surface Renewal Schemes

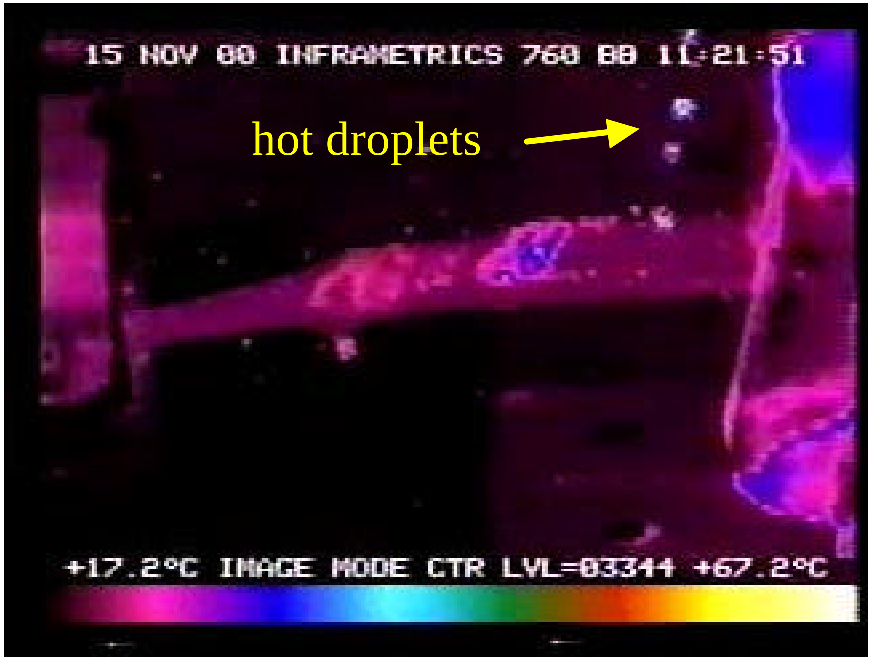


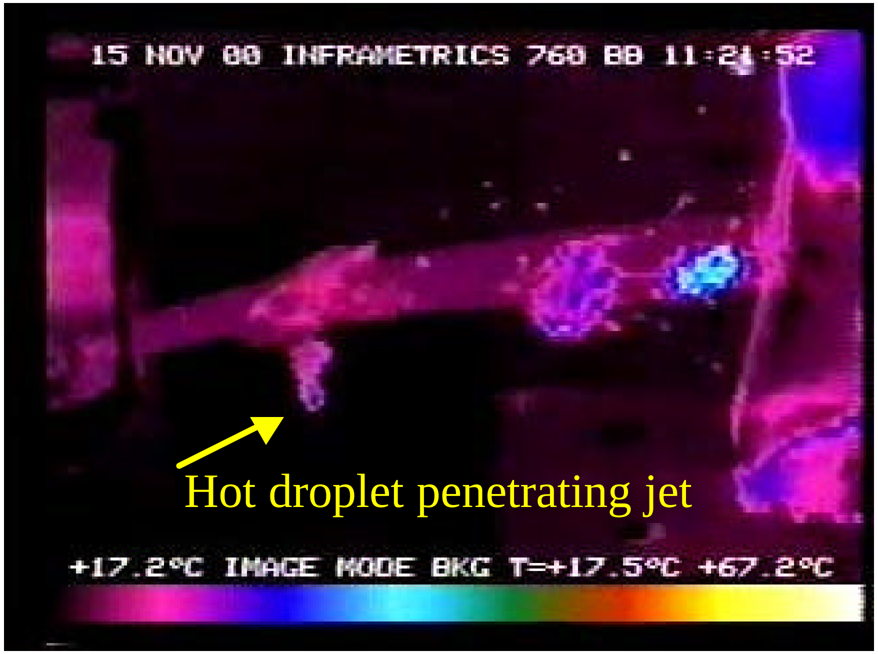
Interfacial Transport Test section length = 4 m

Dynamic Infrared measurements of jet surface temperature

Impact of hot droplets on cold water jet (~8 m/s) thermally imaged in SNL/UCLA test





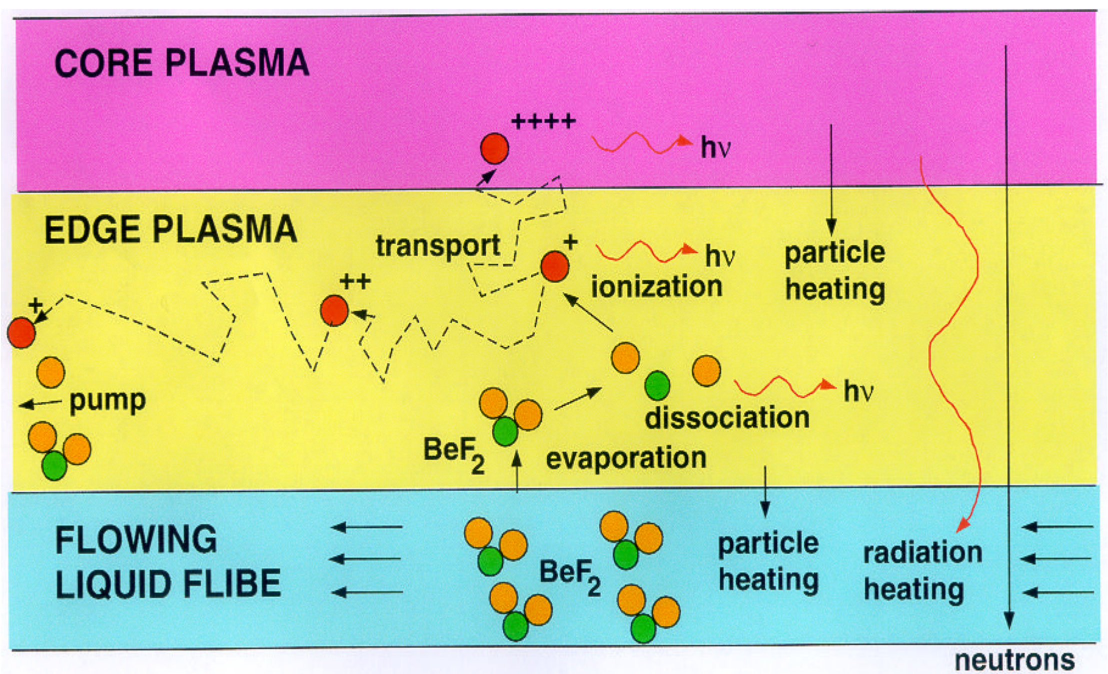


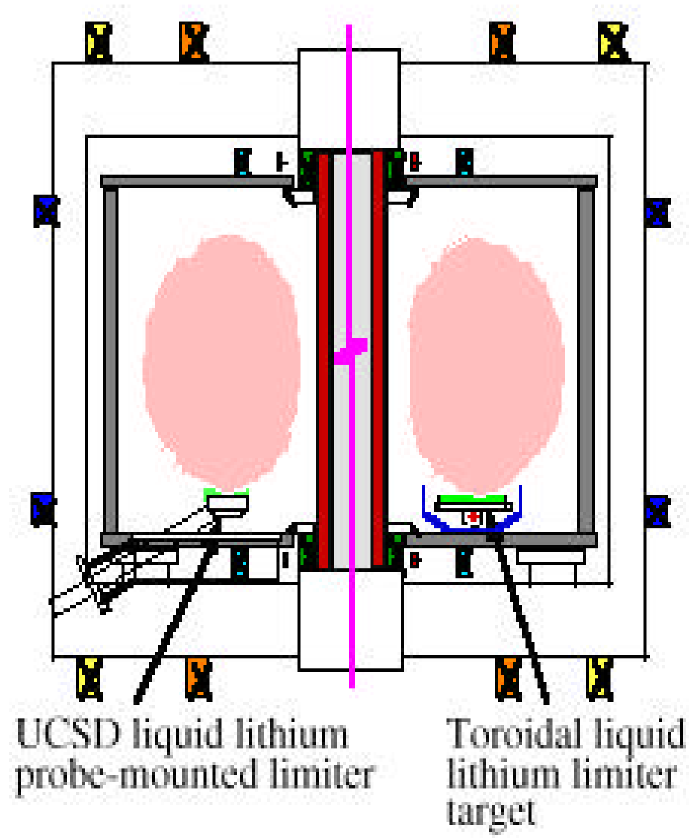
Plasma-Liquid Surface Interactions

- Multi-faceted plasma-edge modeling validation with data from experiments

- Experiments in plasma devices (CDX-U, DIII-D and PISCES)

Processes modeled for impurity shielding of core





Liquid lithium limiter in CDX-U

Flowing LM Walls may Improve Plasma Stability and Confinement

SNOWMASS

Several possible mechanisms identified at Snowmass…

Presence of conductor close to plasma boundary (Kotschenreuther) - Case considered 4 cm lithium with a SOL 20% of minor radius

- Plasma Elongation $\kappa > 3$ possible – with $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
- Size of plasma devices and power plants can be substantially reduced

High Poloidal Flow Velocity (Kotschenreuther)
- LM transit time < resistive wall time, about ½ s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and E×B shearing rates (transport barriers)

Hydrogen Gettering at Plasma Edge (Zakharov)
- Low edge density gives flatter temperature profiles, reduces anomalous energy transport
- Flattened or hollow current density reduces ballooning modes and allowing high β

APEX Plasma-Liquid Interaction Tasks are Utilizing and Extending State-Of-The-Art Codes with Comparisons to the Latest Data, and Exploring Exciting Possibilities Identified in Snowmass

- **Dynamic modeling of plasma equilibria uses the Tokamak Simulation Code (TSC), a PPPL code validated with NSTX data. For example, TSC simulations of NSTX equilibria were used to estimate the magnitude of forces due to eddy currents on the liquid surface test module for NSTX**

- **Physicists are contributing exciting ideas for liquid walls**
  - Electromagnetically Restrained Blanket (Woolley)
  - Soaker Hose (Kotschenreuther)
  - Magnetic Propulsion (Zakharov)

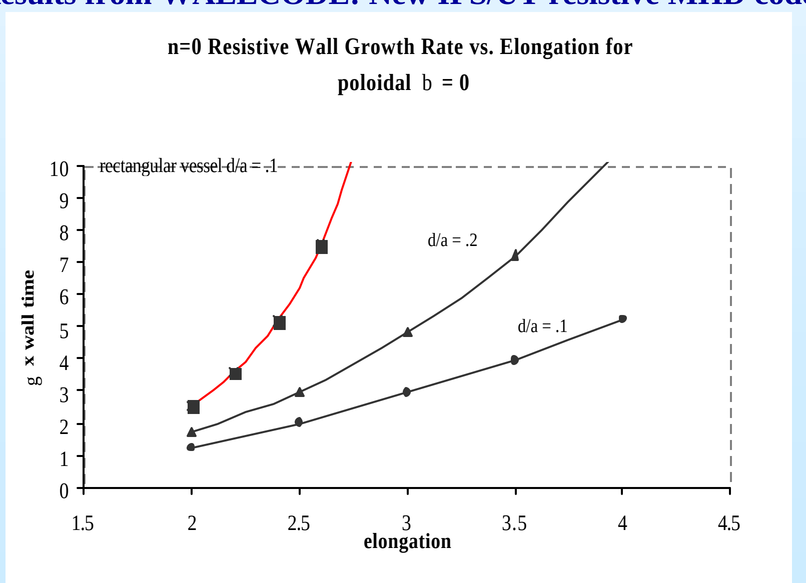
- **Studies of Innovative Wall Concepts are providing insight into nature and control of plasma instabilities**
  - Stabilization schemes for resistive wall modes and neoclassical tearing modes are of broad interest to the fusion community
  - A new resistive MHD Code (WALLCODE) has been developed by IFS/UT to explore the stabilizing properties of various conducting wall geometries

- **Initial Results: Liquid metals can be used as conducting walls that offer a means for stabilizing plasma MHD modes**

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

Results from WALLCODE: New IFS/UT resistive MHD code



* Instability growth rate depends on conformity of wall to plasma

Beta Limits for high elongation
(example of initial results)

k	d	D	b*
2	.7	0	4.3%
3	.78	0	11.5%
4	.9	.1	14%
5	1.28	.5	22%

D º **indentation/minor radius**

Progress toward Practical and Attractive Liquid Walls: Many Creative Innovations

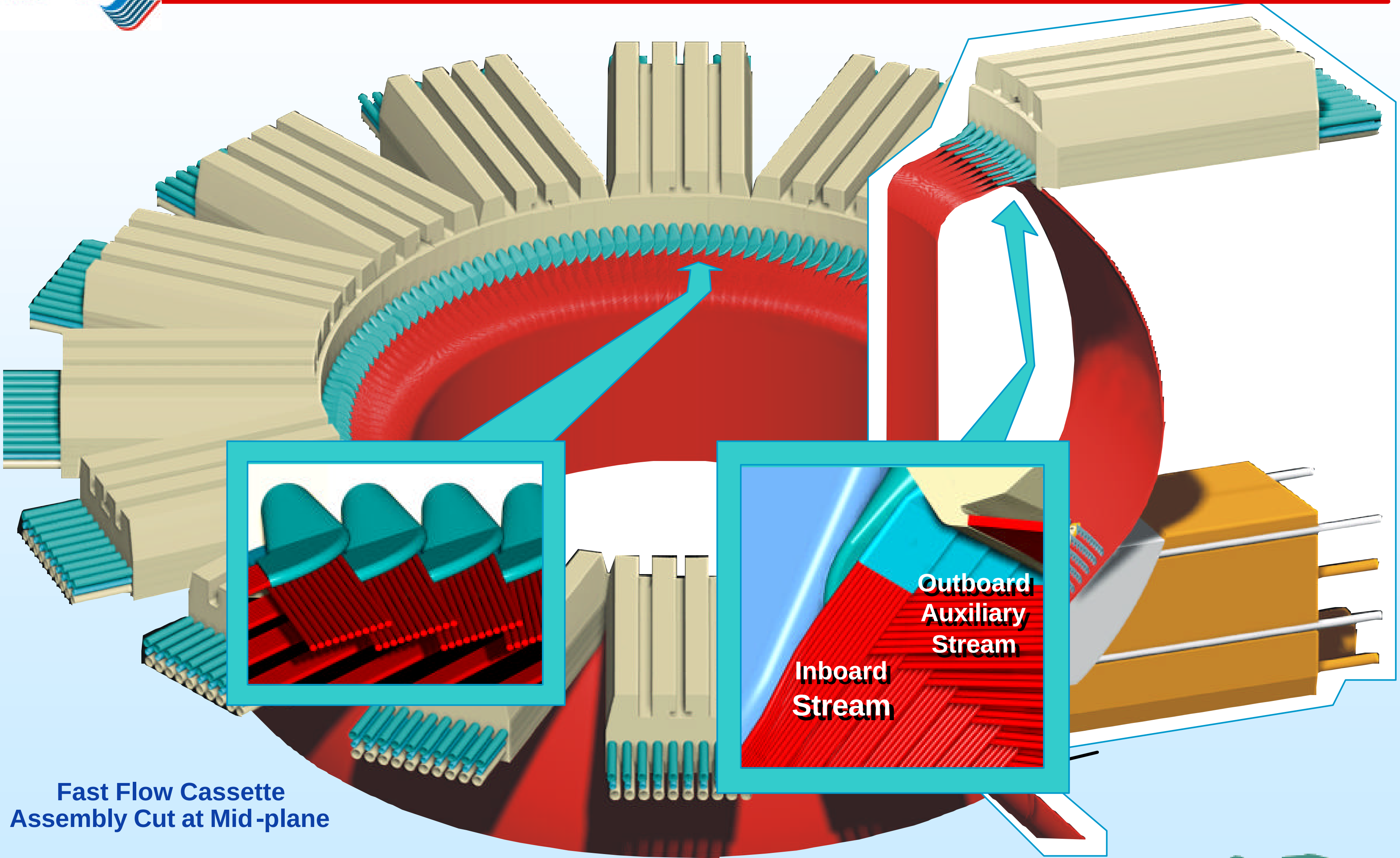
The APEX Approach to Problems

- Understand problems and underlying phenomena and science
- Search for Innovative Solutions: Our job is “to make things work”
- Modeling, analysis, and experiments to test and improve solutions

Examples of Creative Innovations

- New fluid candidates with low-vapor pressure at high temperatures (SnLi, Sn)
- “Surface Renewal”: New schemes to promote controlled surface mixing and wave formation to reduce surface thermal boundary layer resistance
- Flow tailoring schemes to “control” flow around “penetrations”
- Two-stream flows to resolve conflicting requirements of “low surface temperature” and “high exit bulk temperature”
- Toroidal Flow (“Soaker Hose”) concept to reduce MHD effects
- Novel schemes for electromagnetic flow control
- Creative design with over laid inlet streams to shield nozzles from line-of-sight
- Innovative design of “bag concept” with “flexible” SiC fabric structure

Clever creative design with overlaid streams shields nozzles from line-of-sight to plasma



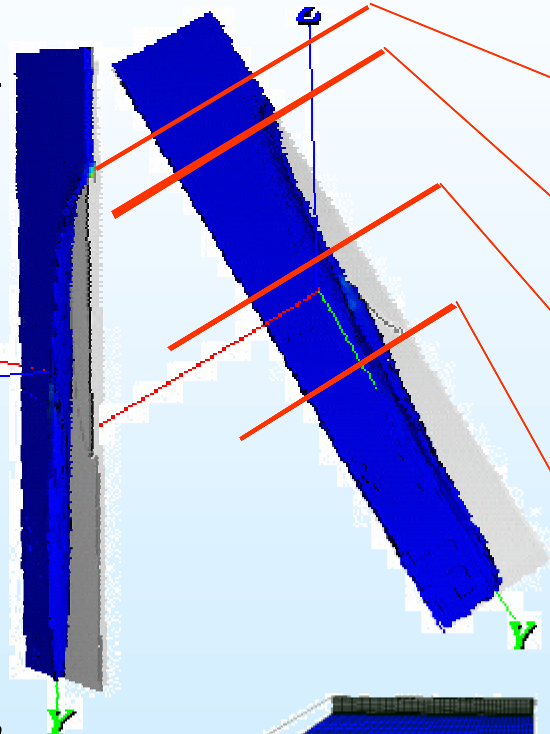
Fast Flow Cassette
Assembly Cut at Mid-plane

STATE-OF-THE-ART 3-D TIME DEPENDENT FLOW 3-D CALCULATIONS WAS KEY TO UNDERSTANDING PENETRATION PROBLEMS

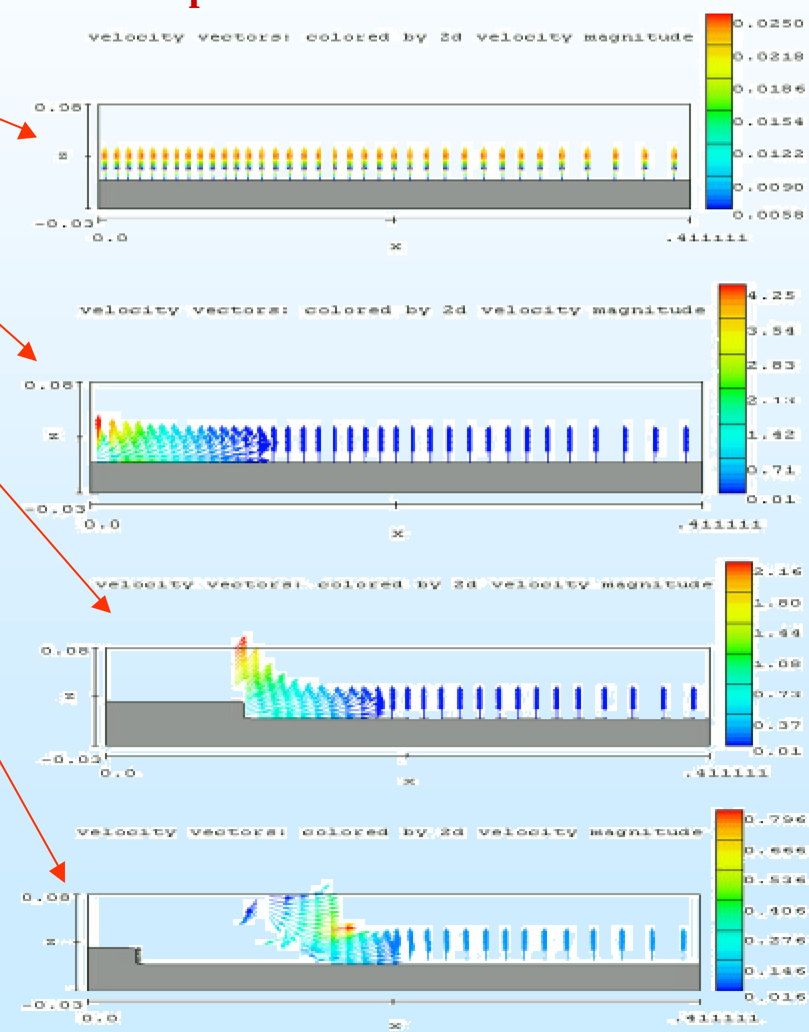
3-D CFD Simulation Results

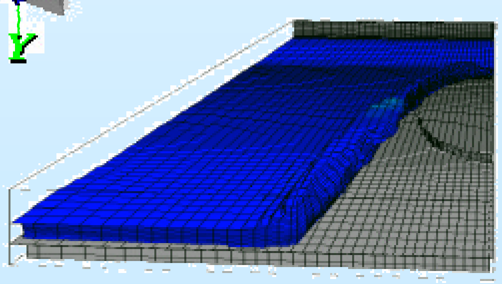
Potential Problems

- *Fluid splash*
- *Fluid level rise*
- *Wake formation*



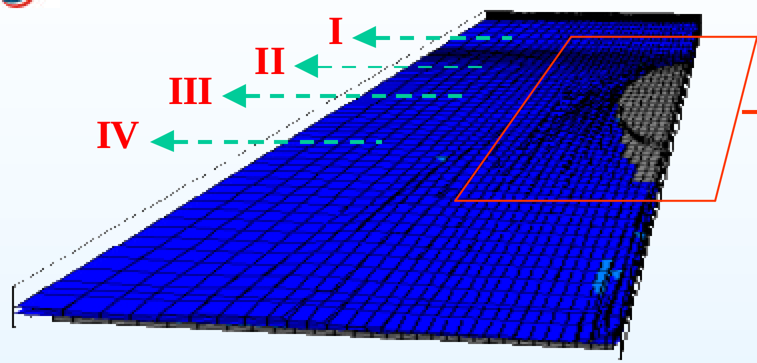
2-D Velocity Magnitude in Planes Perpendicular to the Flow Direction



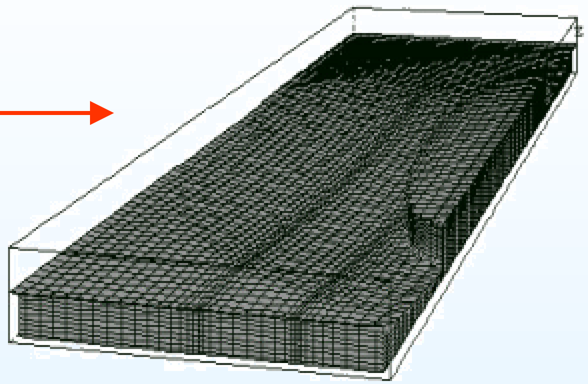


3-D View of the Wake Following the Penetration.

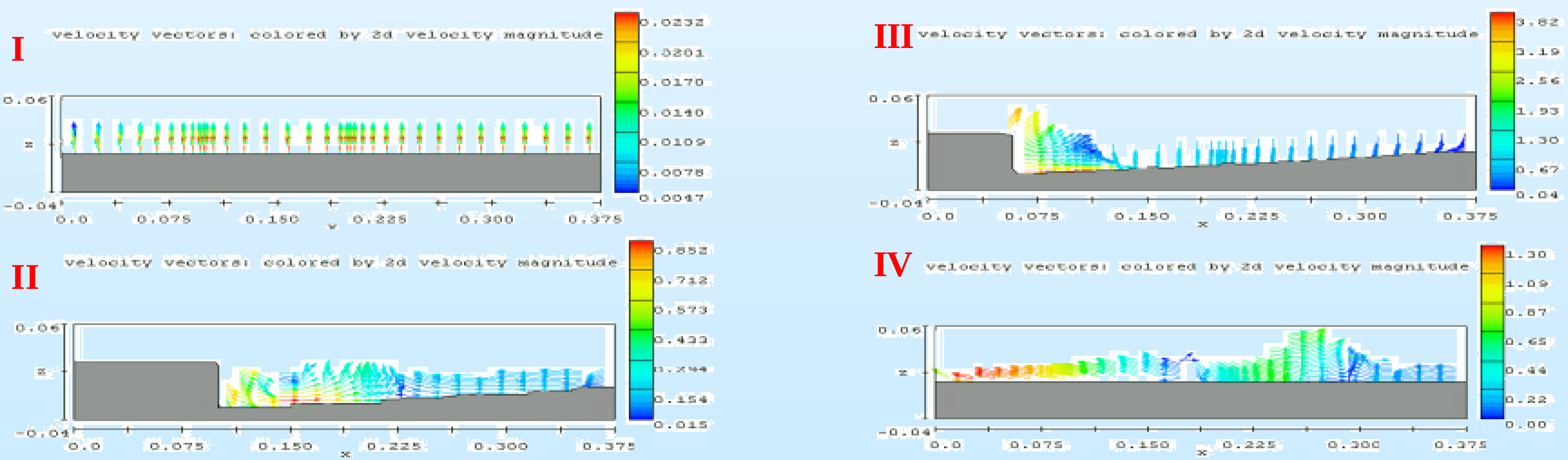
Innovative Solutions Found and Confirmed by FLOW-3D Calculations (experiments also planned)



3-D Hydrodynamic simulation of penetration accommodation when the back wall topology surrounding the penetration is modified.

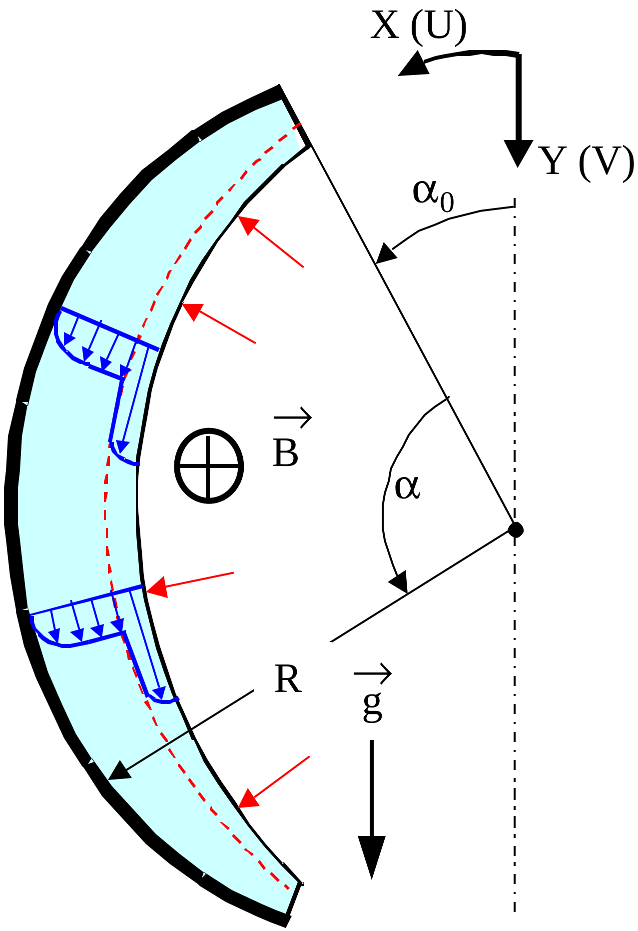


Modified back wall topology surrounding the penetration.



2-D Velocity magnitude in planes perpendicular to the flow direction

TWO-STREAM FLOW HAS THE POTENTIAL TO ACHIEVE BOTH PLASMA COMPATIBILITY AND HIGH THERMAL EFFICIENCY



The fast external stream removes the surface heat flux, while the slow internal stream serves as a blanket:

- **Plasma-facing liquid surface at low temperature (to reduce vaporization; plasma compatibility) while the thick liquid exits at high bulk temperature for high efficiency**
- **Good heat transfer capabilities due to the high velocity near-surface jet and Kelvin-Helmholtz instability between the two streams**
- **Reduced volumetric flow rate**
- **Lower erosion due to slower velocity in the internal stream**

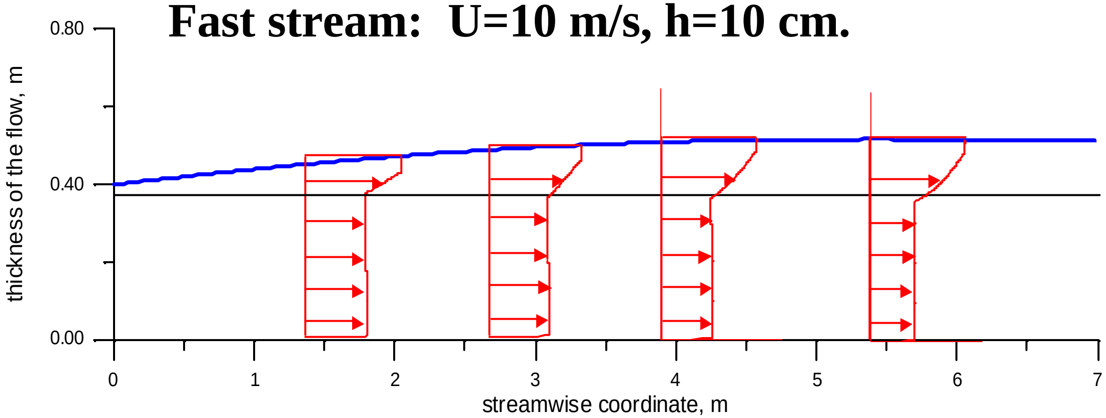
CFD-MHD Calculations Show the Potential for Practical Realization of the TWO-STREAM Idea

Low Conductivity Fluids: with a step-type initial velocity profile.

Liquid Metal: using "submerged walls". Non-conducting or slightly conducting walls submerged into the flowing liquid produce MHD drag forming a "slow stream", while liquid in the near-surface area is accelerated due to the mass conservation.

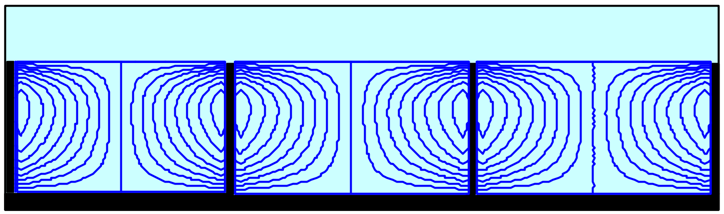
Downstream development of the two-stream flow produced with the submerged walls.

Slow stream: U=7 m/s, h=40 cm.
Fast stream: U=10 m/s, h=10 cm.



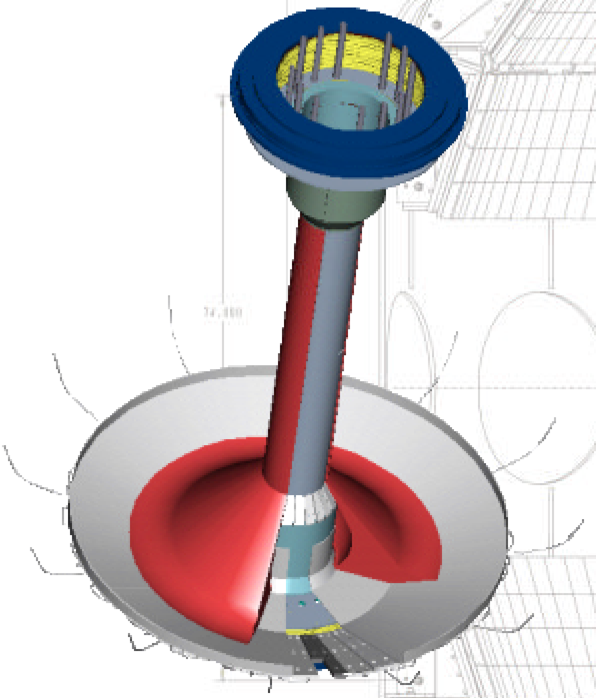
Sketch of the induced current in the cross-sectional area.

The submerged walls are slightly conducting: $c_w=2\times10^{-6}$.

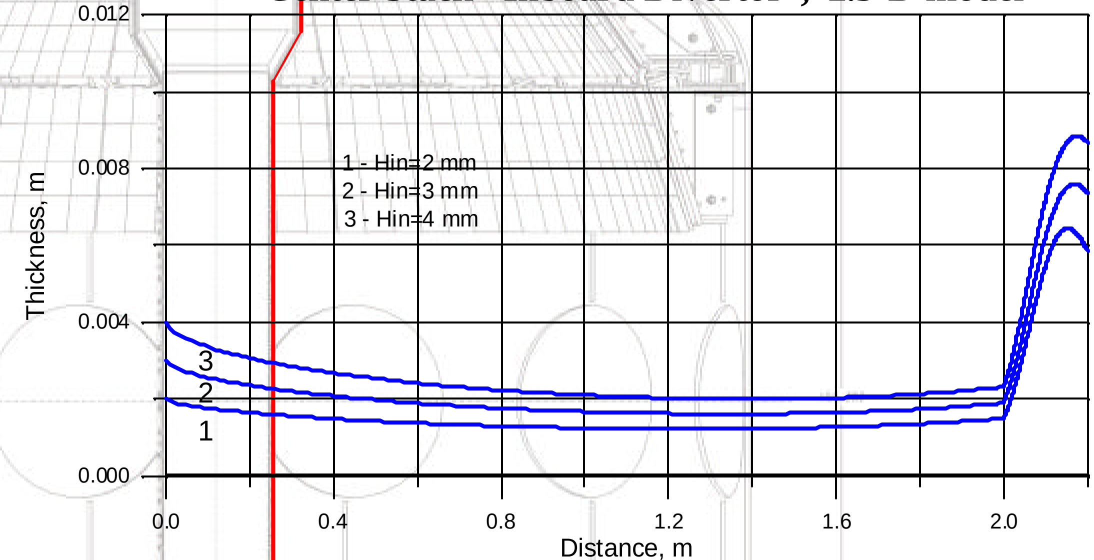


Simulations of Flowing Lithium in NSTX using Newly Developed MHD Free Surface Tools

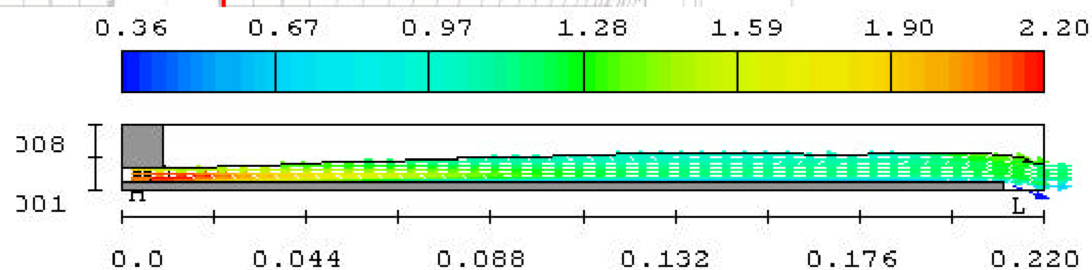
APEX



“Center Stack +Inboard Divertor”, 2.5-D model



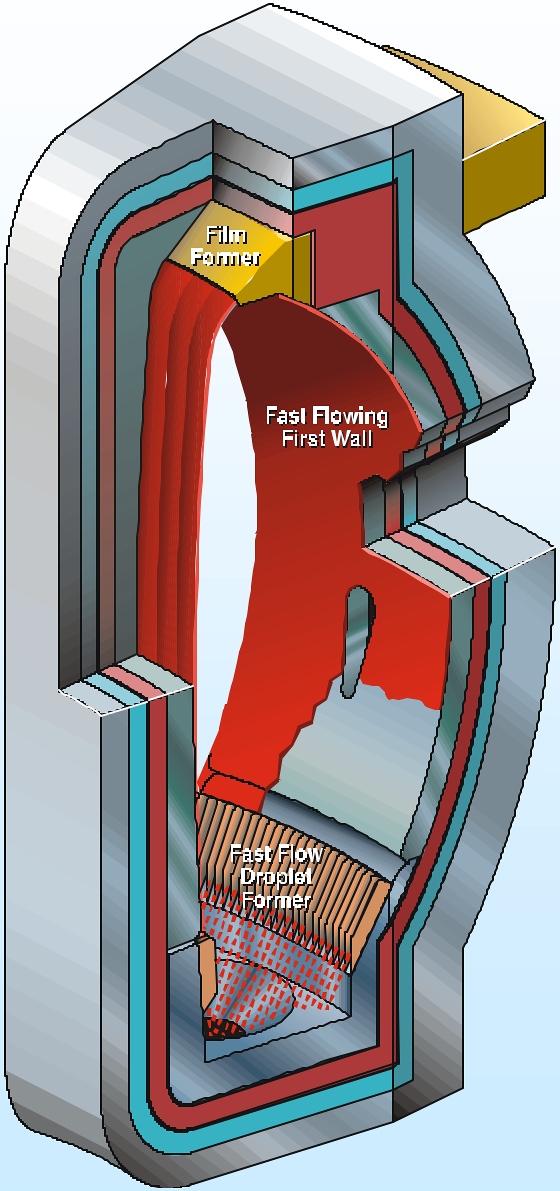
“Inboard Divertor”, Flow3D-M



- **Flow3D code was extended to include MHD effects (Flow3D-M)**
- **New 2.5-D model and computer code were developed to calculate MHD free surface flows in a multi-component magnetic field**

Stable Li film flow can be established over the center stack

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



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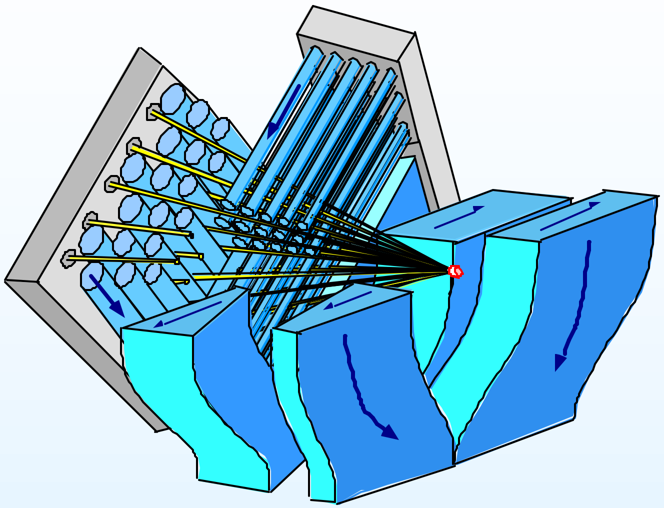
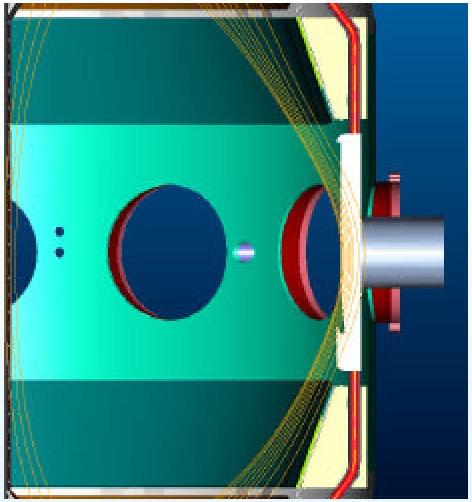
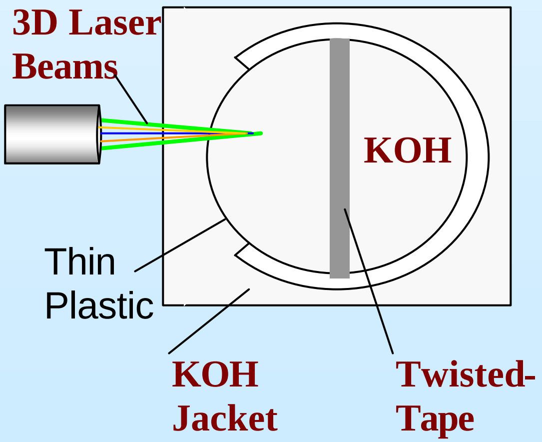


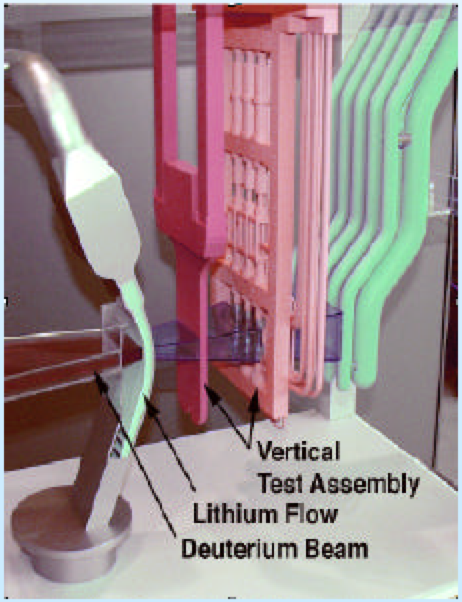
HYLIFE-II



NSTX Li module



JUPITER-II



IFMIF

Reflections on 19th & 20th Centuries

1850: Navier-Stokes Equation

1873: Maxwell's Equations

1895: Reynolds Averaging

1900-1960's:

-Averaging techniques, Semi-empirical approach. Heavy reliance on Prototype Testing (e.g. wind tunnels for aerodynamics).

1960's - 1970's:

-Supercomputers allow direct solution of N-S for simple problems. Advances in Computational Fluid Dynamics (CFD), e.g. utilization of LES technique.

1980's - 1990's:

-Rapid advances to Teraflop Computers

-Rapid advances in CFD and in experimental techniques

-Turbulence structure "simulated" and "observed" for key problems

-Better understanding of fluid physics and advanced "Prediction" tools

-Paradigm Shift:

- **From** "mostly experimental for empirical global parameters" **to** "larger share for CFD: simulation first followed by smaller number of carefully planned experiments aimed at understanding specific physics issues and verifying simulation."

21st Century Frontiers

Moving Beyond "Prediction" of Fluid Physics To "Control" of Fluid Dynamics

• With the rapid advances in teraflop computers, fluid dynamicists are increasingly able to move beyond predicting the effects of fluid behavior to actually controlling them; **with enormous benefits to mankind!**

Examples

• **Reduction in the Drag of Aircraft**

The surface of a wing would be moved slightly in response to fluctuations in the turbulence of the fluid flowing over it. The wings surface would have millions of embedded sensors and actuators that respond to fluctuations in the fluids, P, V as to control eddies and turbulence drag. DNS shows scientific feasibility and MEMS can fabricate integrated circuits with the necessary microsensors, control logic and actuators

• **Fusion Liquid Walls**

Control of "free surface-turbulence-MHD" interactions to achieve fast interfacial transport and "guided motion" in complex geometries ("smart-liquids")

• **Nano Fluidics: Pathway to Bio-Technologies**

Appropriately controlled fluid molecules moving through nano/micro passages can efficiently manipulate the evolution of the embedded macro DNA molecules or affect the physiology of cells through gene expression.