Remarks on Liquid Wall Research

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Note
For recent presentations and papers on liquid wall research by the APEX team see website:
www.fusion.ucla/APEX

Presented to the Academy’s “Fusion Science Assessment Committee”, November 17, 1999, Seattle, WA

Liquid Wall Research Advances the Science and Energy Goals of Fusion in a Perfect Fit

- If we can make liquid walls work:

  They might tremendously enhance the attractiveness of fusion energy

- But to make liquid walls work requires Understanding and Solving a number of Challenging Scientific Issues

  - Research on these scientific issues will push the frontiers of several scientific disciplines such as plasma-liquid interaction, free-surface turbulence, and magnetohydrodynamics

  - Advances are needed in theory, modelling, computer simulation, and experimental techniques

Liquid Wall Research

- Enhances partnership between plasma physicists and engineering scientists
- Enhances synergism between IFE and MFE
- Provides excellent opportunities for strong interactions with scientists in fields outside fusion

The Challenging Scientific Issues of Liquid Walls require the collective ingenuity and creative minds of scientists in several technical disciplines.

Several “Ideas” Have Been Proposed for Liquid Walls

Fluids

1) High-conductivity, low Pr fluids (liquid metals)
2) Low-conductivity, high Pr fluids (e.g. molten salts)

Hydrodynamics “Driving Forces”

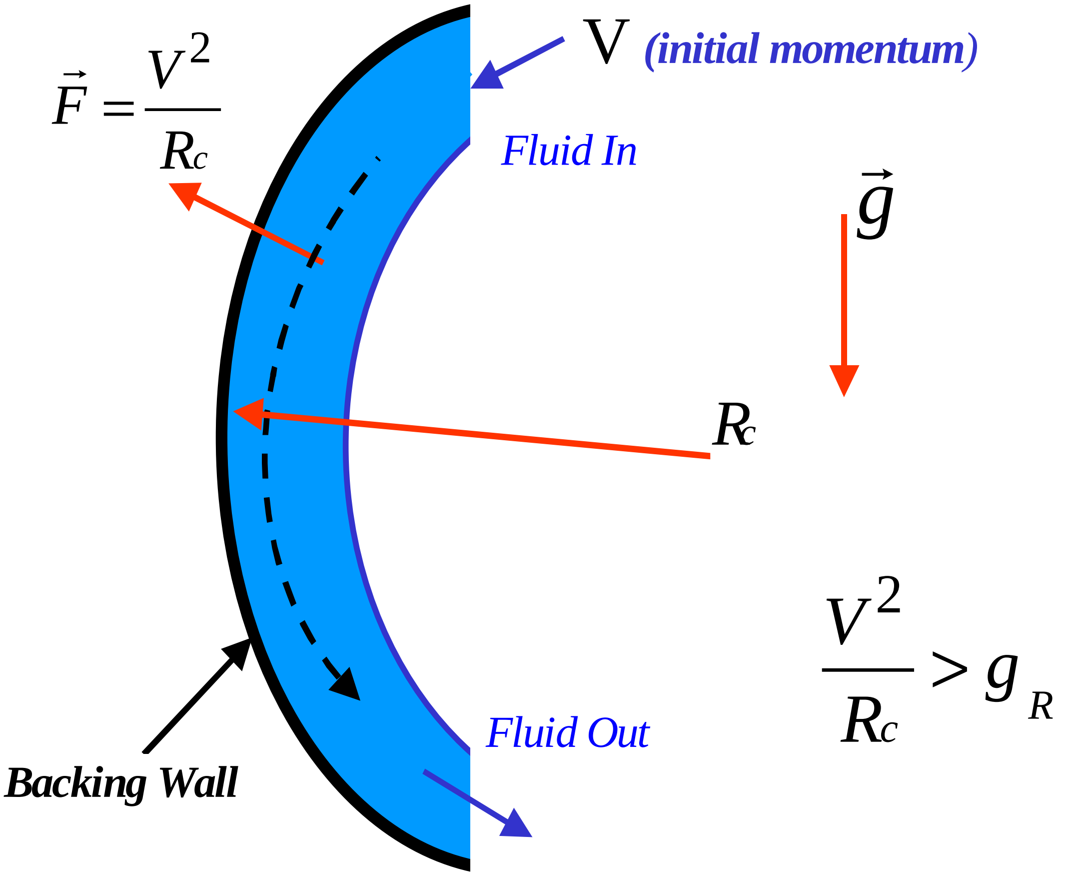
- Gravity-Momentum Drive (GMD)
- GMD with Swirl Flow
- Electromagnetically Restrained
- Magnetic Propulsion

Plasma-Liquid Interface

- Fluids with low vapor pressure at high temperature (e.g. Sn-Li discovered last year)
- Ideas for enhancing turbulence at the free surface
- Ideas for “two-stream flows”
- Etc.

DIFFERENT MECHANISMS FOR ESTABLISHING LIQUID WALLS

- ***Gravity-Momentum Driven (GMD)***



  - *Liquid adherence to back wall by centrifugal force.*
  - *Applicable to liquid metals or molten salts.*

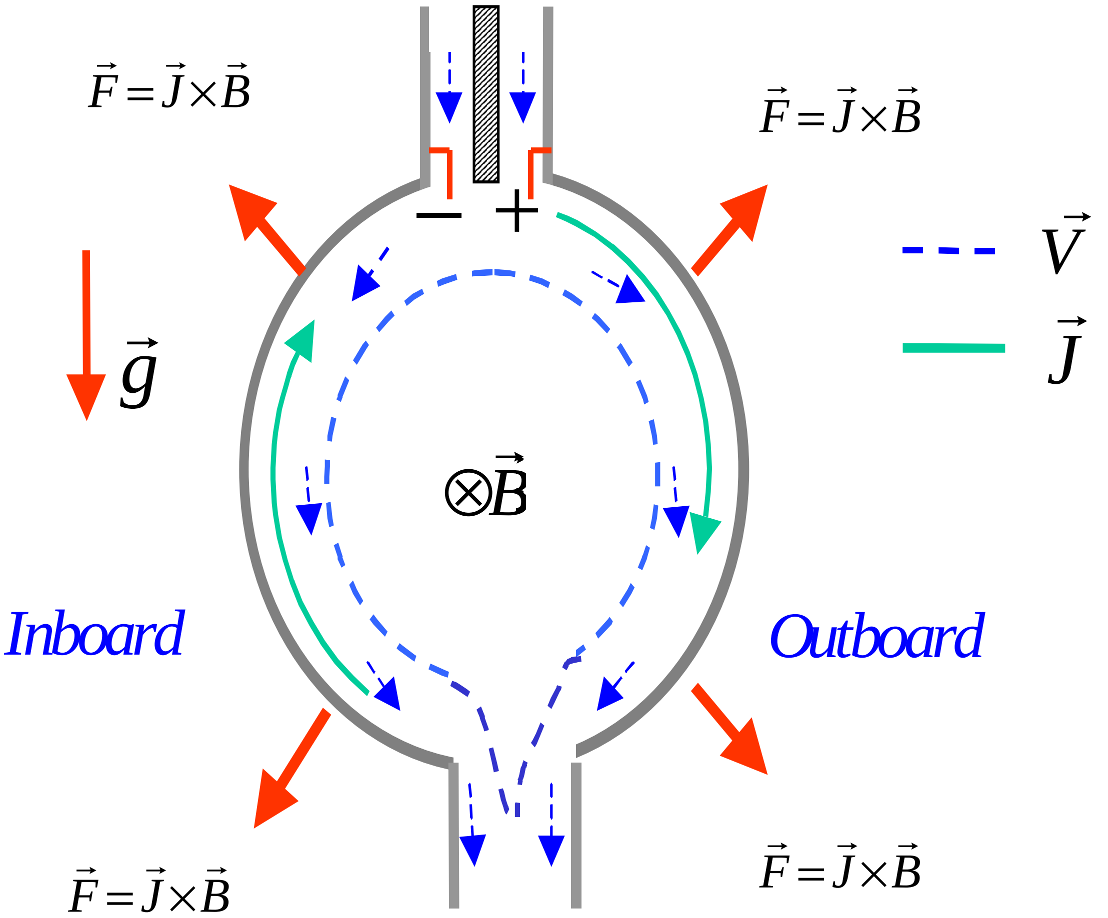
- ***GMD with Swirl Flow***
  - *Add rotation.*

- ***Electromagnetically Restrained LM Wall***

- *Externally driven current* ($\vec{J}$) *through the liquid stream.*

- *Liquid adheres to the wall by EM force* $\vec{F}=\vec{J}\times\vec{B}$

Fluid In

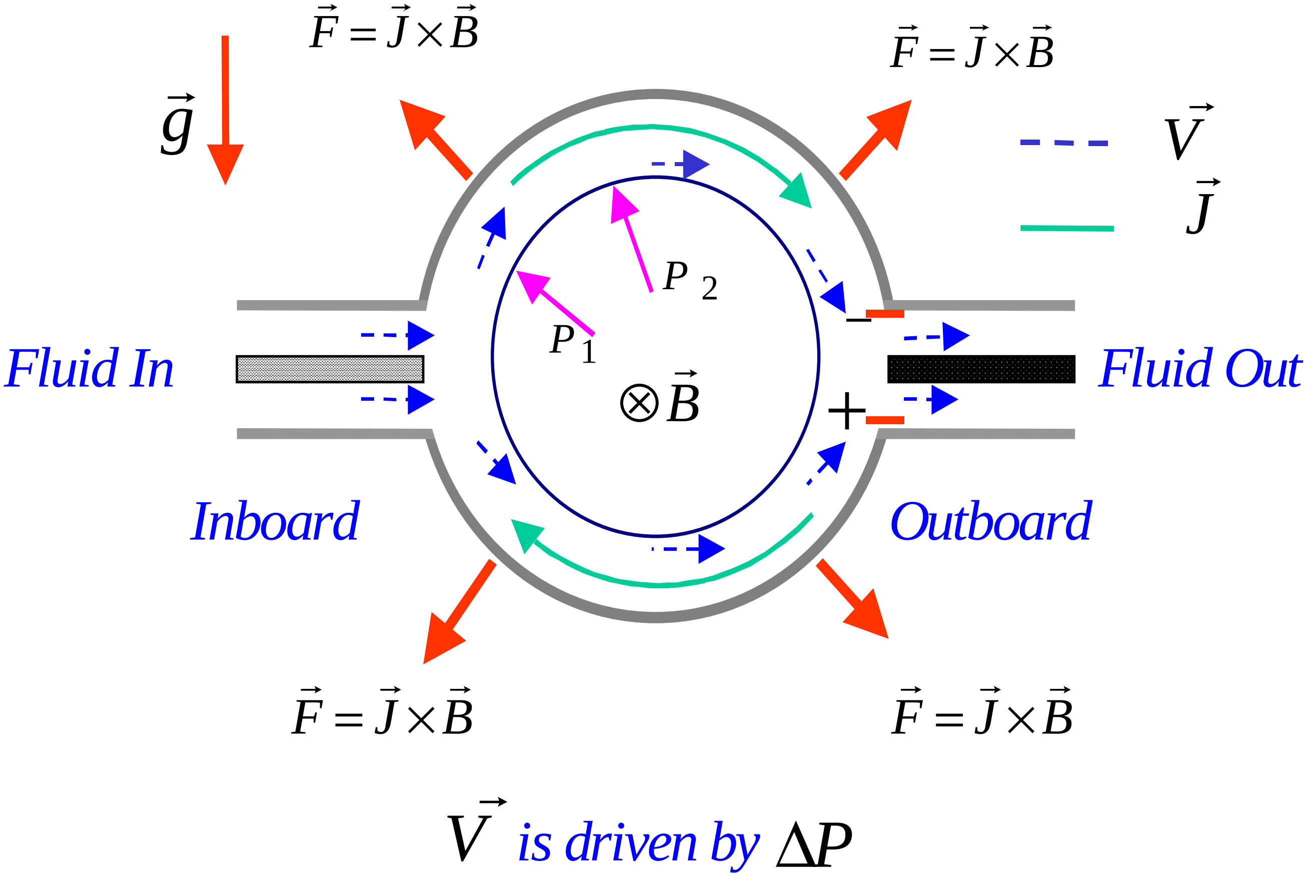


Fluid Out

- **Magnetic Propulsion Liquid Metal Wall (L. Zakharov)**

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

- Utilizes 1/R variation in $\vec{F} = \vec{J} \times \vec{B}$ to drive the liquid metal from inboard to the outboard.



$\vec{V}$ is driven by ΔP

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

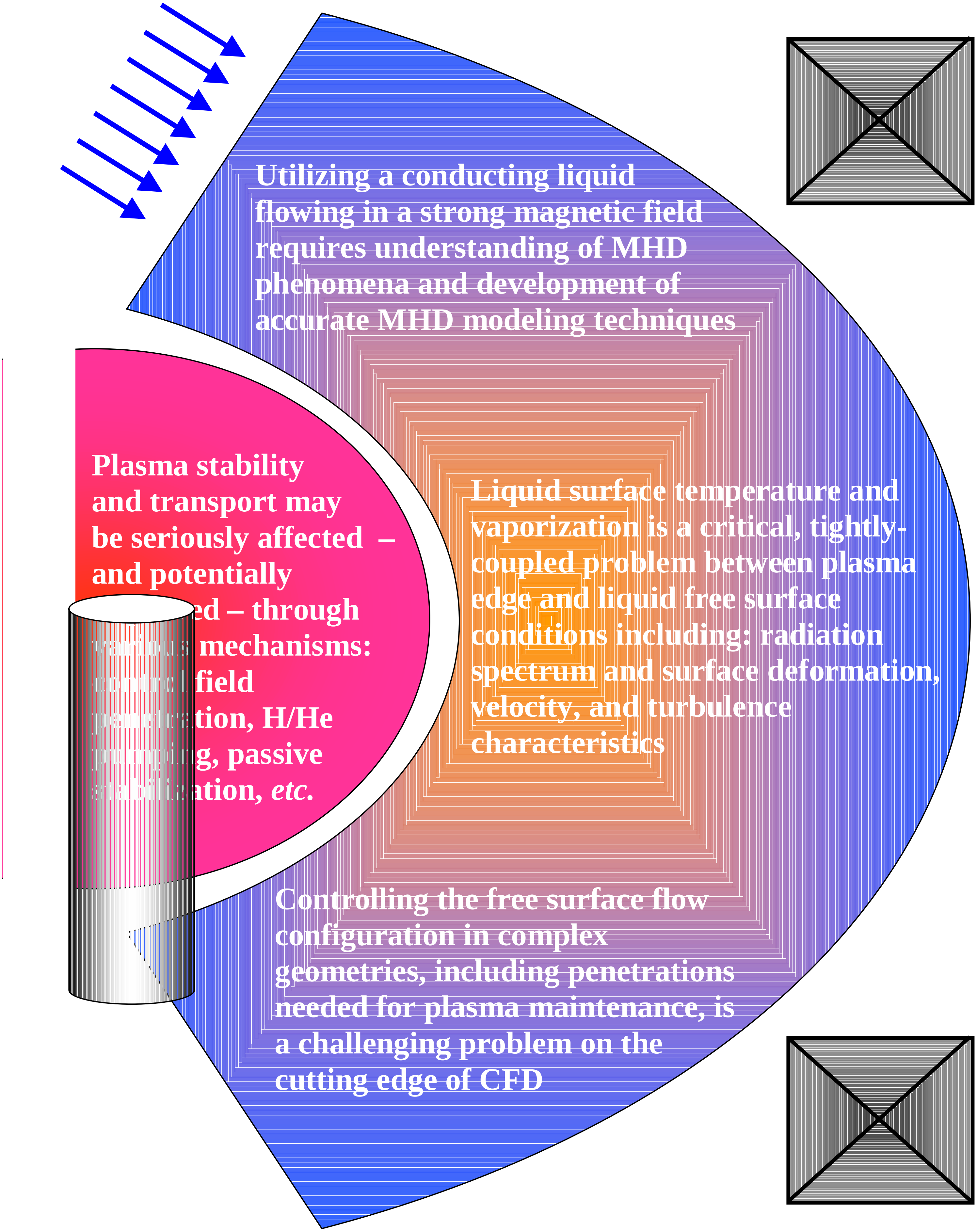
- Reduced Volume of Radioactive Waste

- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials more problems tractable

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

Scientific Issues for Liquid Walls

- Effects of Liquid Walls on Core Plasma including:
  - Discharge evolution (startup, fueling, transport, beneficial effects of low recycling)
  - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma-Liquid Surface Interactions
- Turbulence Modifications At and Near Free-Surfaces
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc.



Utilizing a conducting liquid flowing in a strong magnetic field requires understanding of MHD phenomena and development of accurate MHD modeling techniques

Plasma stability and transport may be seriously affected – and potentially [illegible]ed – through various mechanisms: control field penetration, H/He pumping, passive stabilization, *etc.*

Liquid surface temperature and vaporization is a critical, tightly-coupled problem between plasma edge and liquid free surface conditions including: radiation spectrum and surface deformation, velocity, and turbulence characteristics

Controlling the free surface flow configuration in complex geometries, including penetrations needed for plasma maintenance, is a challenging problem on the cutting edge of CFD

Flowing LM Walls may
Improve Plasma Stability and Confinement

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 κ > 3 possible – with β > 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)

Hydroden 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

Plasma-Liquid Surface Interaction and Temperature Control (Conflicting Requirements on Temperature and Velocity)

1. Plasma-Wall Interaction

$T_s^{max} < T_s^{p}$ (Plasma allowable) T_s^{p} Uncertain

2. High Thermal Efficiency

$T_b^{out} > T_b^{e}$ (for efficiency)

3. Newton's Law of Cooling

$T_s - T_b = q/h$ Free Surface h Uncertain

4. Adheres to Wall

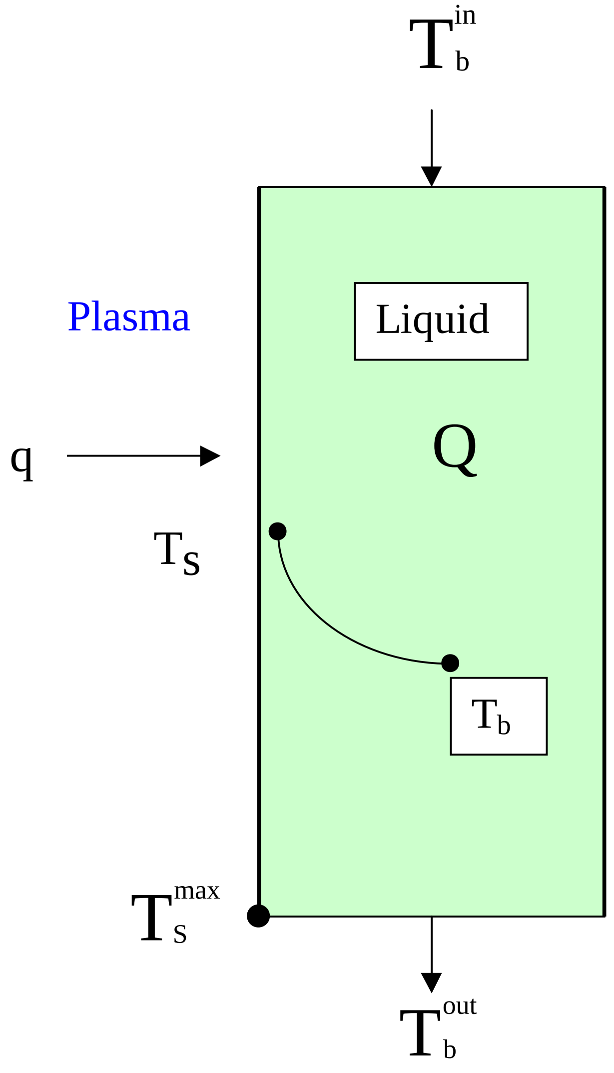
$V^2/R > g$

5. Overcome Thinning

$\dot{m} = \rho V A$ $V(t) = V_o + V_g(t)$ $V_o >> V_g(t)$

6. Higher V increases pumping power, reduces temp. rise

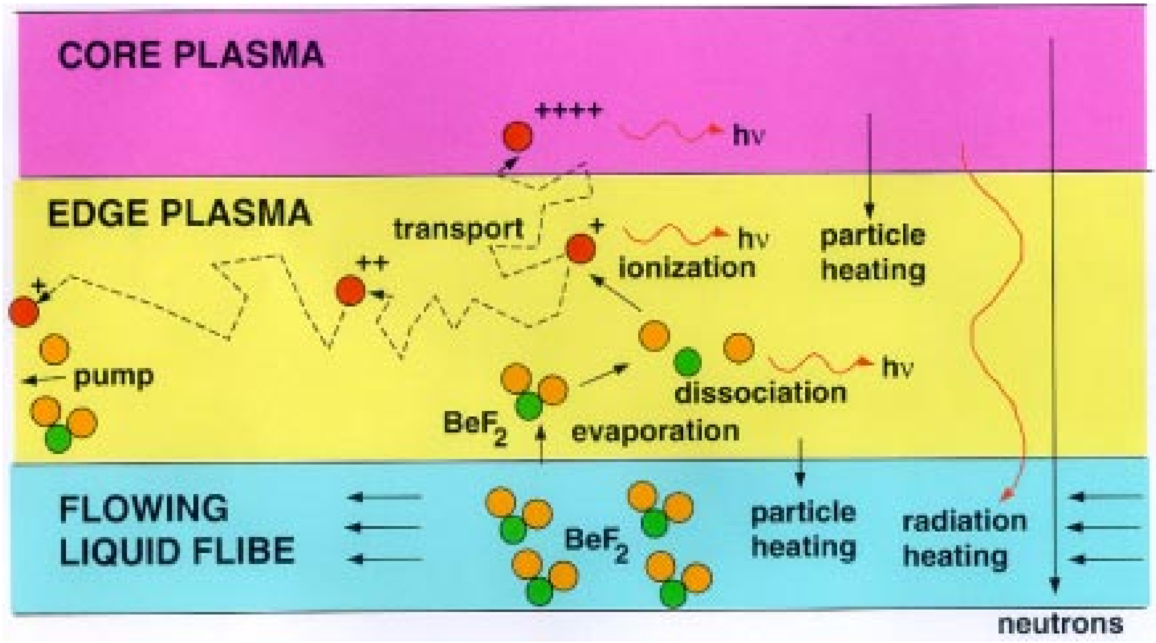
$\Delta P \sim \rho V^2$ $T_b^{out} - T_b^{in} = (Q + q) / \dot{m} C_p$

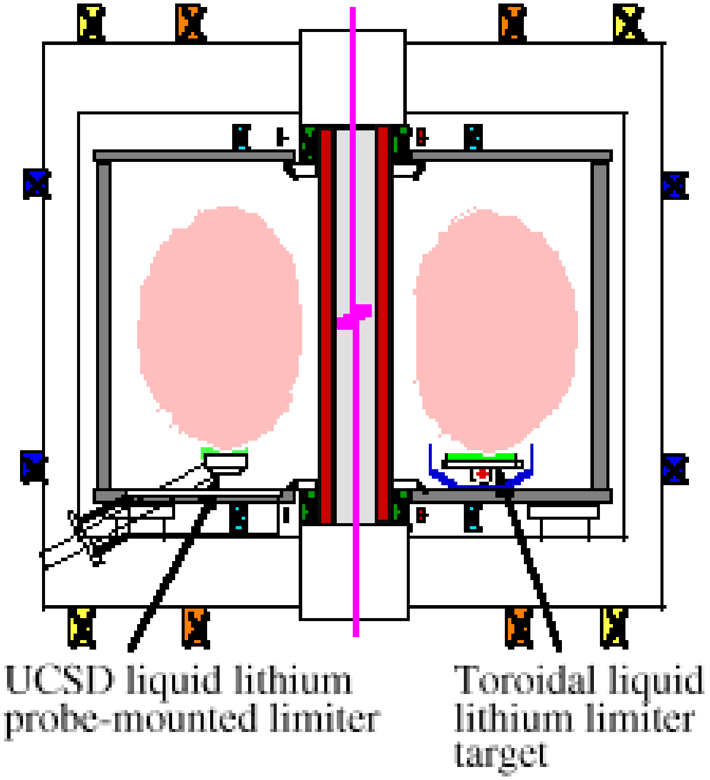


Plasma-Liquid Surface Interactions Affect both the Core Plasma and the Liquid Walls

- Multi-faceted plasma-edge modelling has started (Ronglien et al.)
- Experiments have started (in PISCES, DIII-D and CDX-U)

Processes modeled for impurity shielding of core



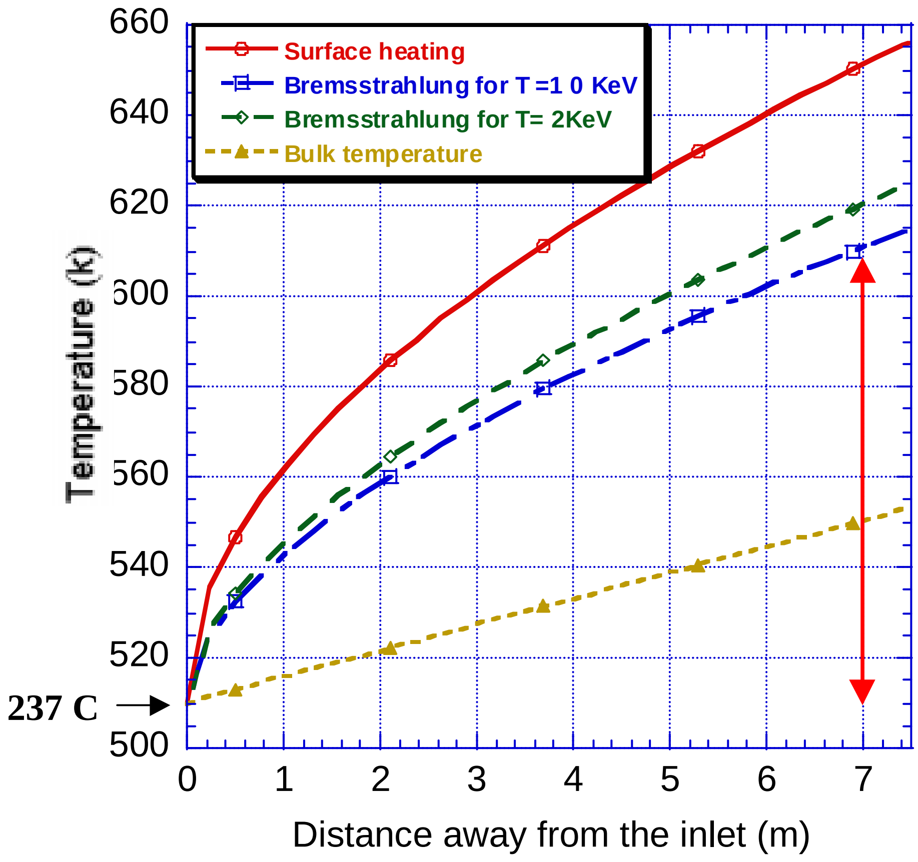


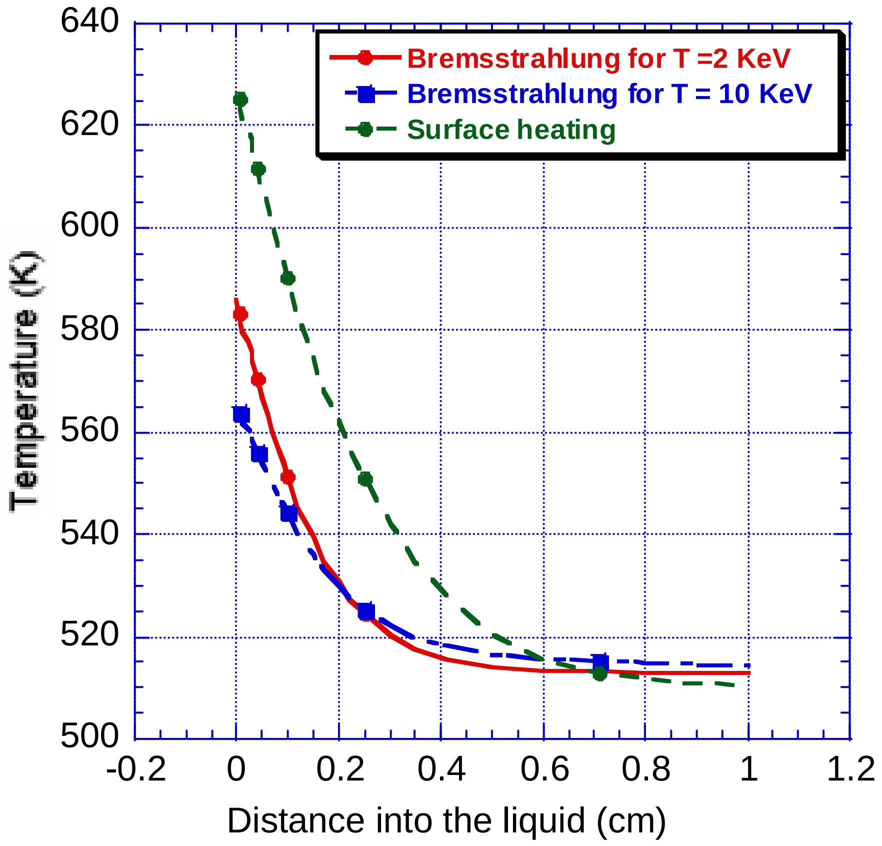
Liquid lithium limiter in CDX-U

Lithium Free Surface Temperature

- Predictable heat transfer (MHD-Laminarized Flow), but 2-D Turbulence may exist
- Laminarization reduces heat transfer
- But Lithium free surface appears to have reasonable surface temperatures due to its high thermal conductivity and long x-ray mean free path

Li velocity = 20 m/s
Surface heat load = 2 MW/m^2

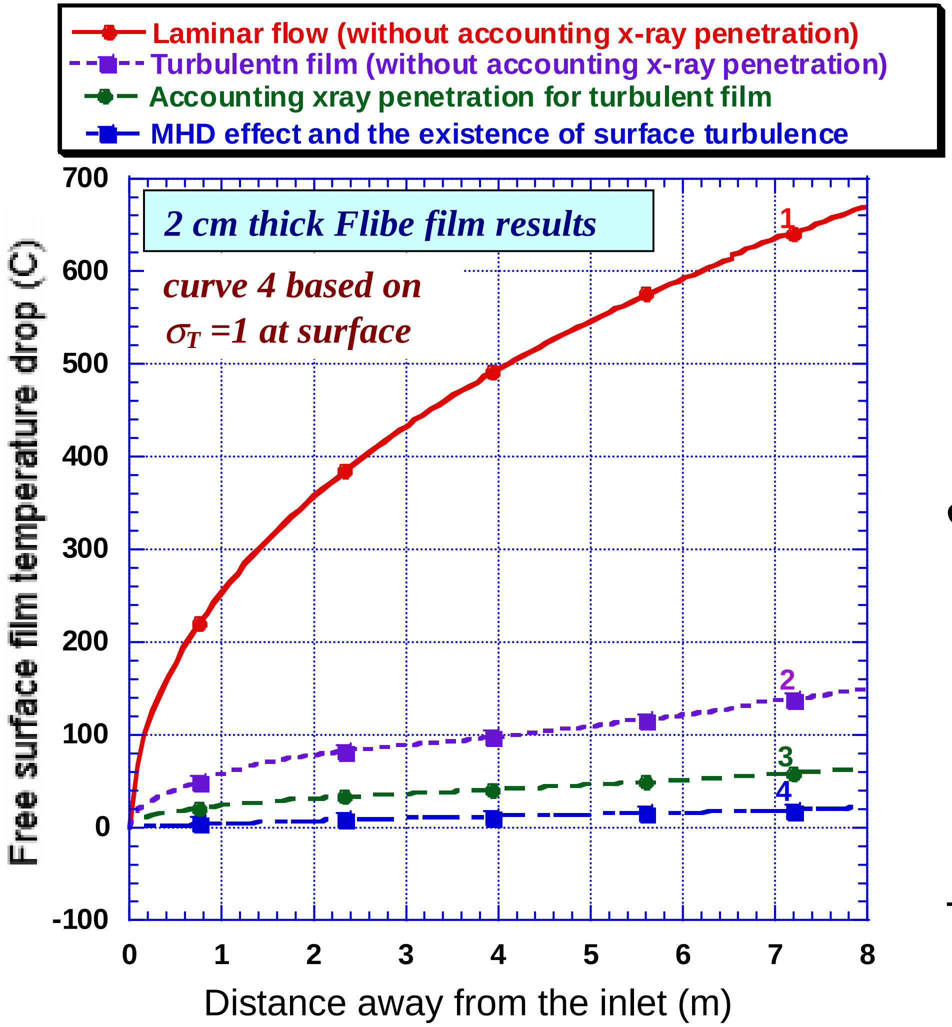




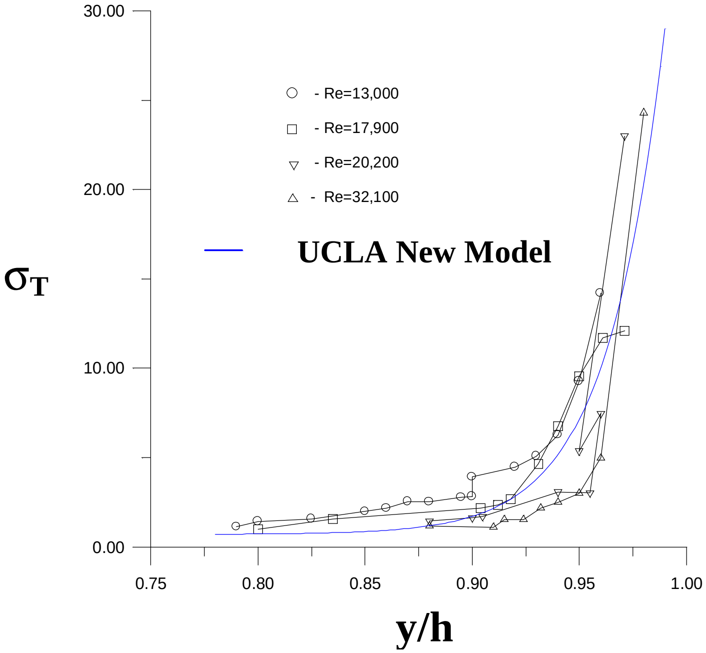
Flibe Free Surface Temperature Magnitude Highly Depends on the Turbulent Activities near the Surface

Heat transfer degradation at Flibe free surface results from both the damping of the normal velocity component at the free surface and suppression of turbulence by the field.

Energy Eq. $$\rho C_p U \frac{\partial T}{\partial x} = \frac{\partial}{\partial y}[\lambda(1+\varepsilon_t \frac{\mathrm{Pr}}{\sigma_T})\frac{\partial T}{\partial y}]$$

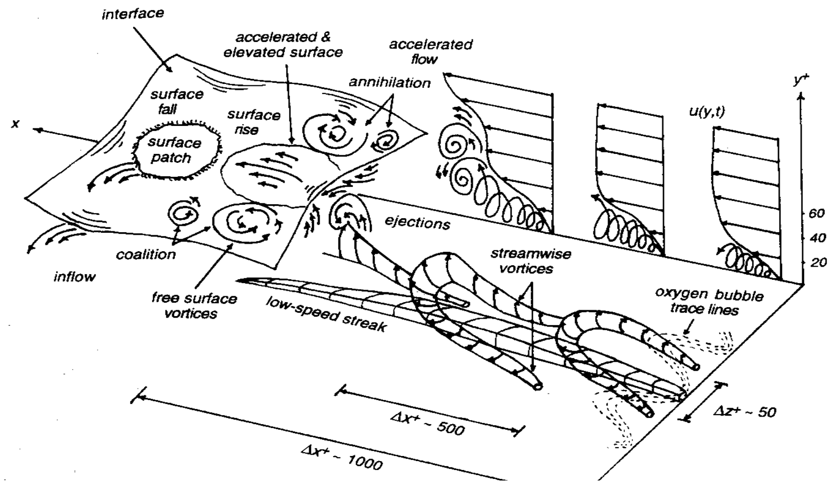


K–ε model update:
In the improved model, the empirical data obtained by Ueda et al. for the eddy diffusivity for heat was considered, which results in an increase in the turbulent Prandtl number near the free surface.

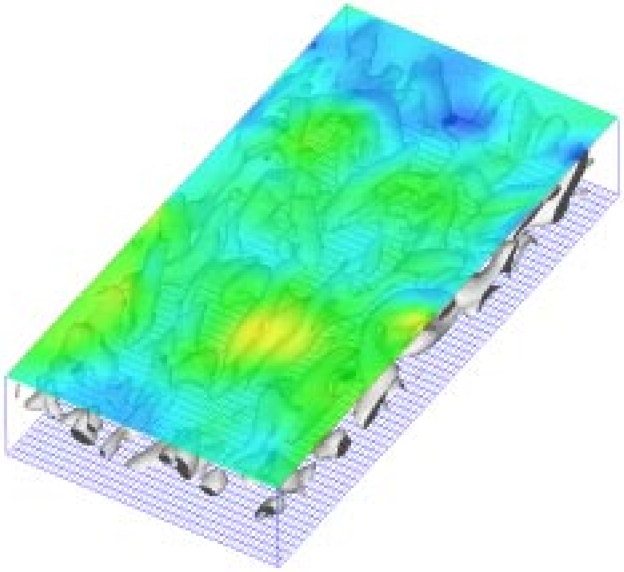


Turbulent Prandtl number growth near the free surface

TURBULENT FREE SURFACE FLOWS ARE COMPLEX



Conceptual illustration of experimental observation of burst-interface interactions



Vortex structure and free surface deformation (DNS calculation)

The flow is dominated by the generation of wall ejections, formation of spanwise "upsurging vortices", and interaction of such structures with the free surface. The spanwise "upsurging vortices" are seen to evolve near the wall, reach the free surface, form surface patches, roll back in form of spanwise "downswinging vortices", and mix into the bulk flow. There is evidence of "horseshoe" and "hockeystick" type vortices in relation to the bursting events. The ejection-inflow events are associated with the deformation of the free surface and a redistribution of near surface vorticity and velocity fields.

From Mehdi Rashidi, *"Burst-interface interactions in free surface turbulent flows"*, Phys.Fluids 9 (11), November 1997

SIMULATION of TURBULENT FREE SURFACE FLOWS REQUIRES SEVERAL LEVELS of MODELING

- Direct Numerical Simulation (DNS) can model small sections of free surfaces and provide insight into the nature of turbulent flow phenomena

- Reynolds-Averaged models (*e.g.* k-ε models) can calculate flow and turbulence statistics at high Re and Ha numbers, if fundamental phenomena are accurately modeled in turbulence-closure equations

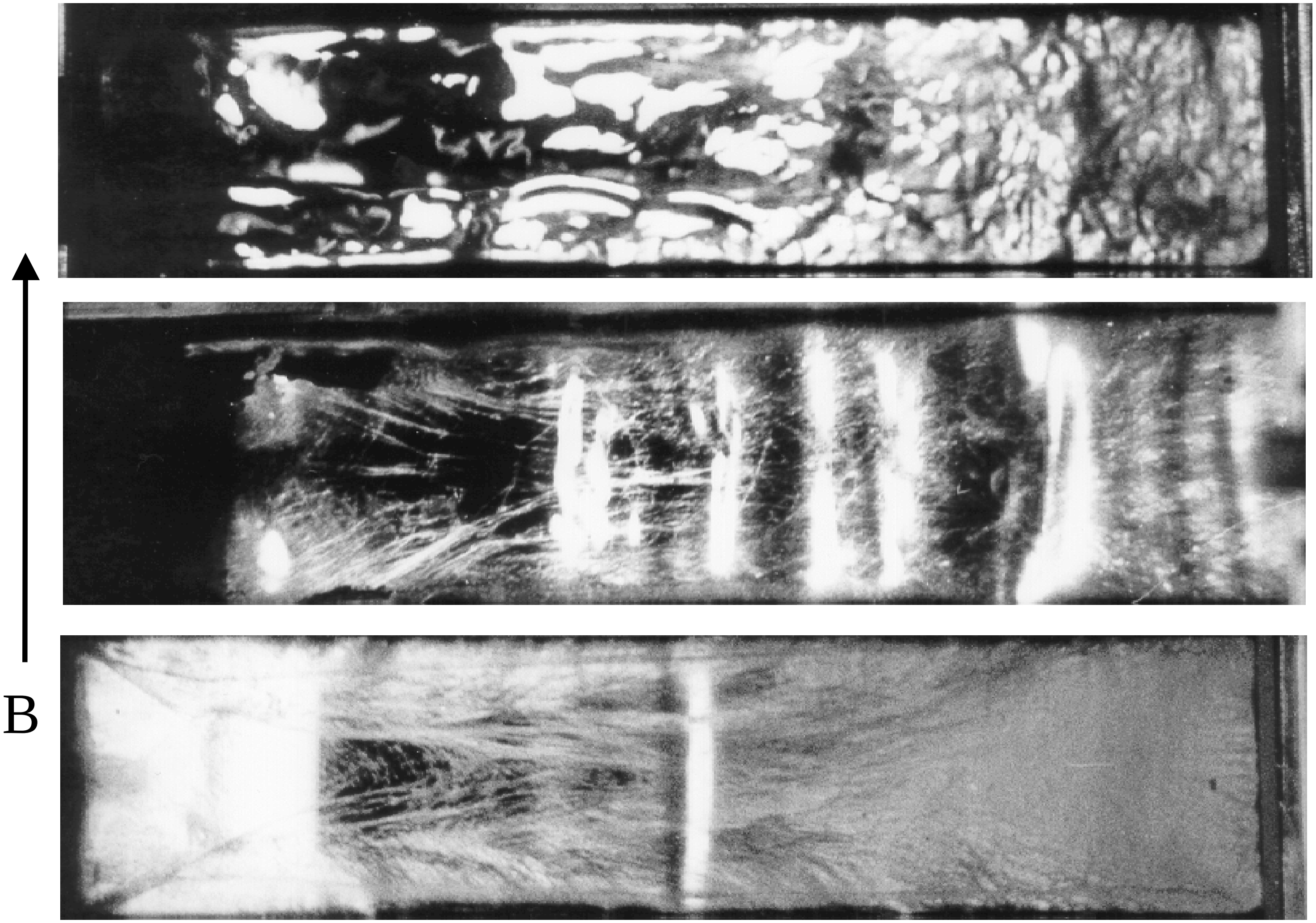
General Form of MHD k-ε equations developed at UCLA

(ε$_{em}$ is a new term responsible for MHD effects)

$$\frac{\partial k}{\partial t} + \overline{V}_1 \frac{\partial k}{\partial x_1} + \overline{V}_2 \frac{\partial k}{\partial x_2} + \overline{V}_3 \frac{\partial k}{\partial x_3} = \Pi + D - \varepsilon - \varepsilon_{em}$$

$$\varepsilon_{em} = \frac{\sigma}{\rho}(1-\gamma)\{2B_0^2 k - B_{01}^2 \overline{V_1'^2} - B_{02}^2 \overline{V_2'^2} - B_{03}^2 \overline{V_3'^2} - 2B_{01}B_{03}\overline{V_1' V_3'} - 2B_{01}B_{02}\overline{V_1' V_2'} - 2B_{02}B_{03}\overline{V_2' V_3'}\}$$

MHD FORCES in CONDUCTING FLUID FLOWS MODIFY and SUPPRESS TURBULENCE



3D fluctuations on free surface

N = 0

Surface fluctuations become 2D along field induction

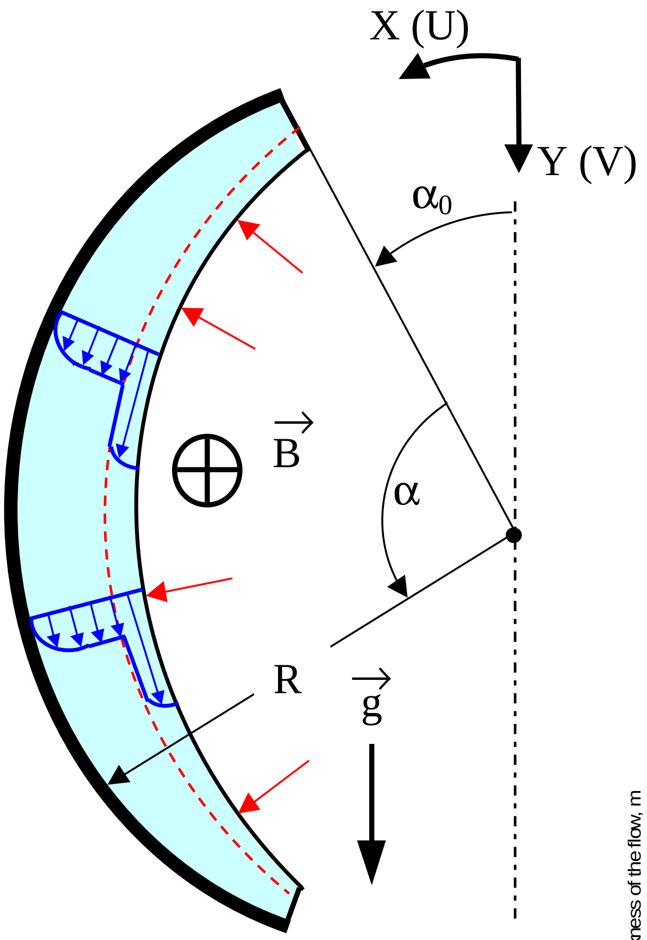
N = 6

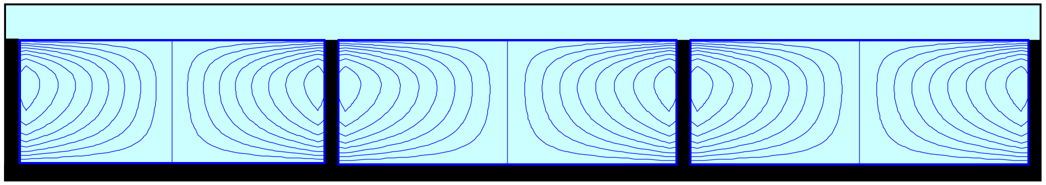
Surface fluctuations are nearly suppressed

N = 10

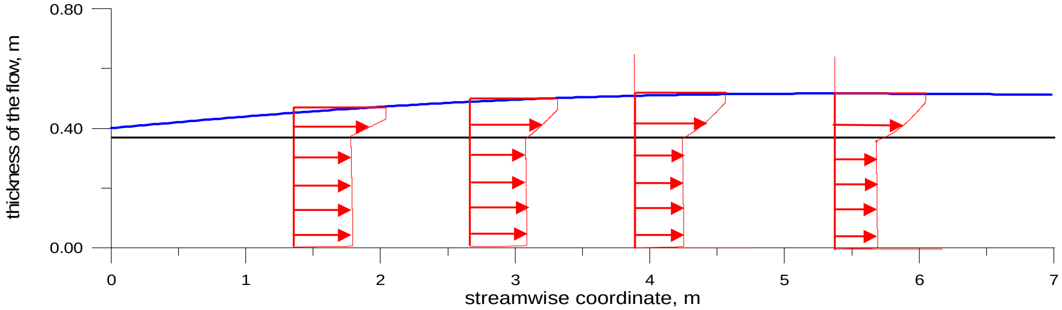
Data from FZK experiment carried out in Riga

ESTABLISHING A TWO-STREAM FLOW USING SUBMERGED WALLS to IMPROVE HEAT TRANSFER



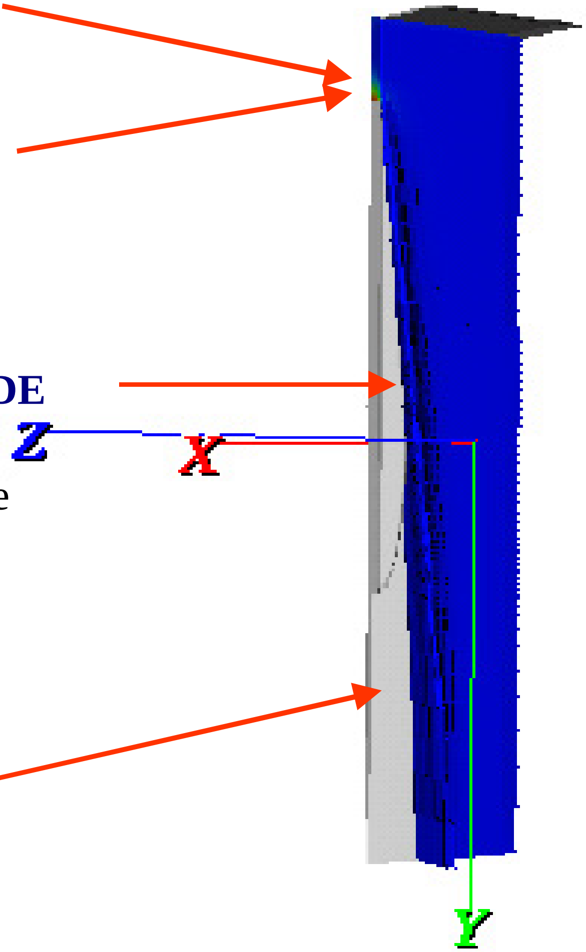


- MHD drag slows down liquid between submerged walls
- Free surface layer can accelerate to high velocity



UCLA Data

POTENTIAL CHALLENGES IN LIQUID WALL BEHAVIOR AROUND PENETRATIONS



STAGNATION

- Minimizes the cooling of the front section of the penetration.
- Discharges fluid towards the plasma.

SPLASH OF THE FLUID AND DROPLET EJECTIONS

- Droplets may be generated and ejected into the plasma as the high velocity liquid layer hits the front section of the penetration.

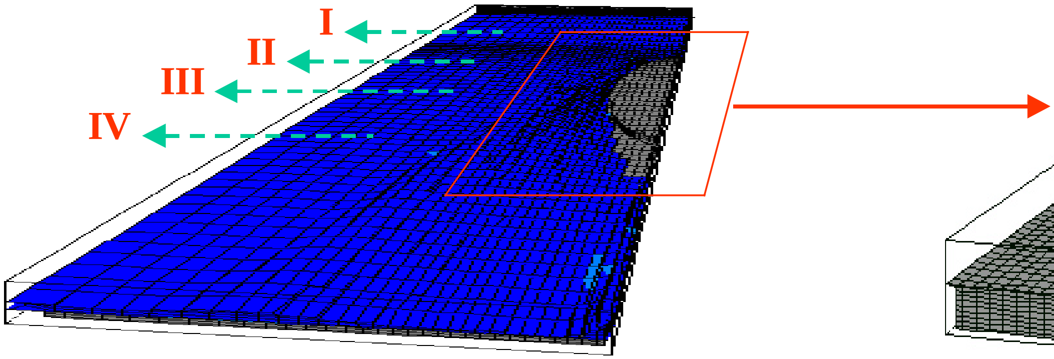
FLUID LEVEL RISE SURROUNDINDG THE FRONT SIDE OF THE PORT

- A stream of rising fluid is diverted to the sides surrounding the penetration due to the obstruction of flow path. (144 m^3 of fluid per hour is displaced for a 20 cm wide (in the flow direction) penetration for the CLIFF concept with a base velocity of 10 m/s.)

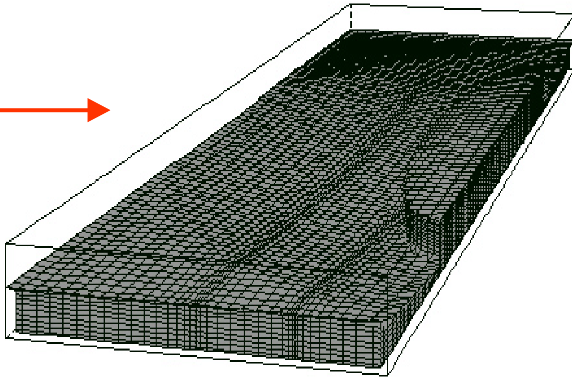
WAKE FORMATION

- The wake formation at the end section of the penetration, as a result of deflection of streamlines by the penetration structure.

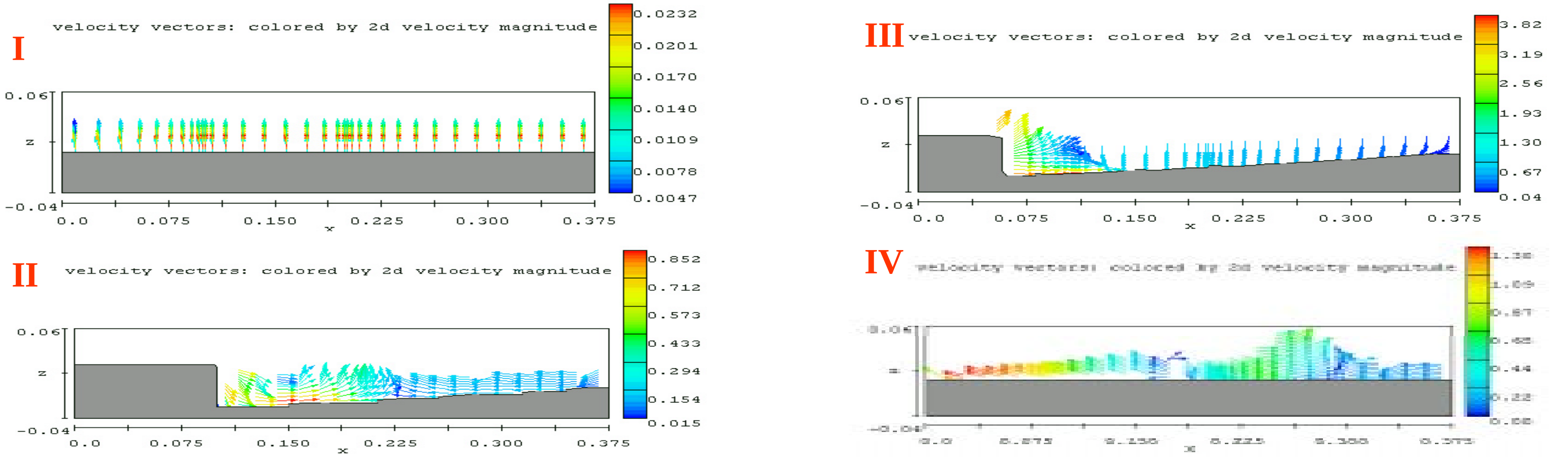
DESIGN SOLUTIONS, SUCH AS MODIFICATIONS TO BACK WALL TOPOLOGY RESULT IN MORE ATTRACTIVE FLUID FLOW CHARACTERISTICS AROUND PENETRATIONS



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

RELATED APPLICATIONS of NEAR SURFACE TURBULENCE MODIFICATION and MHD EFFECTS

- Melt and solid mircrostructure control in metallic casting and crystal growth
- Turbulent drag reduction and MHD ship propulsion
- Oceanography and atmospheric processes
- Droplet formation and fuel mixing for internal combustion and jet engines

5-Year Goals
For Liquid Wall Research

1. Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments.

2. Operate flowing liquid walls in a major experimental physics device (e.g. NSTX, C-MOD, DIII-D, and/or others).

3. Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.

4. Understand and document advantages and implications of using liquid walls in fusion energy systems.