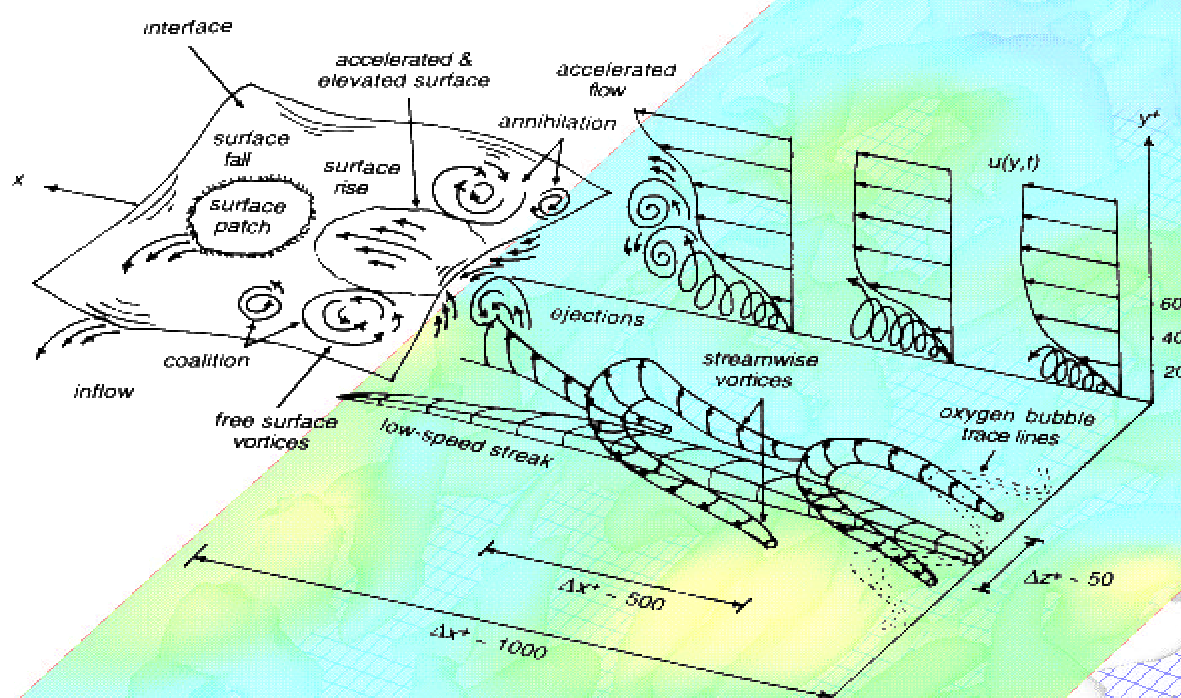
Turbulence / free surface interaction produces key phenomena - anisotropic near-surface turbulence

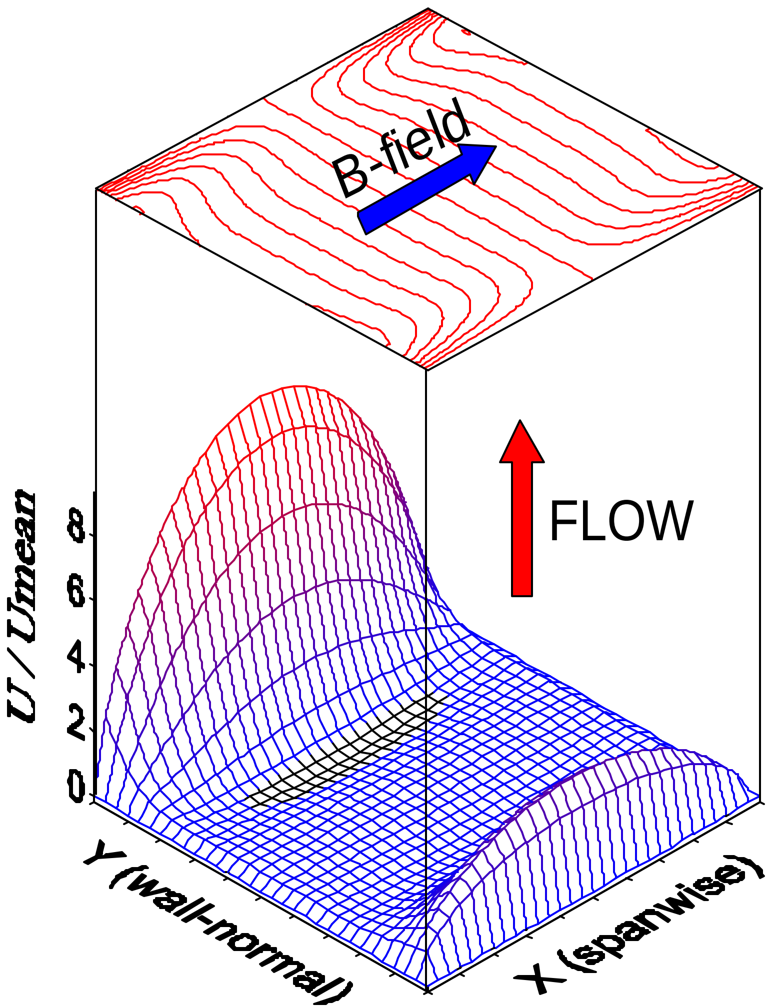


Conceptual illustration of experimental observation of burst-interface interactions - From Rashidi, Physics of Fluids, No.9, November 1997.

- **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.**

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

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**

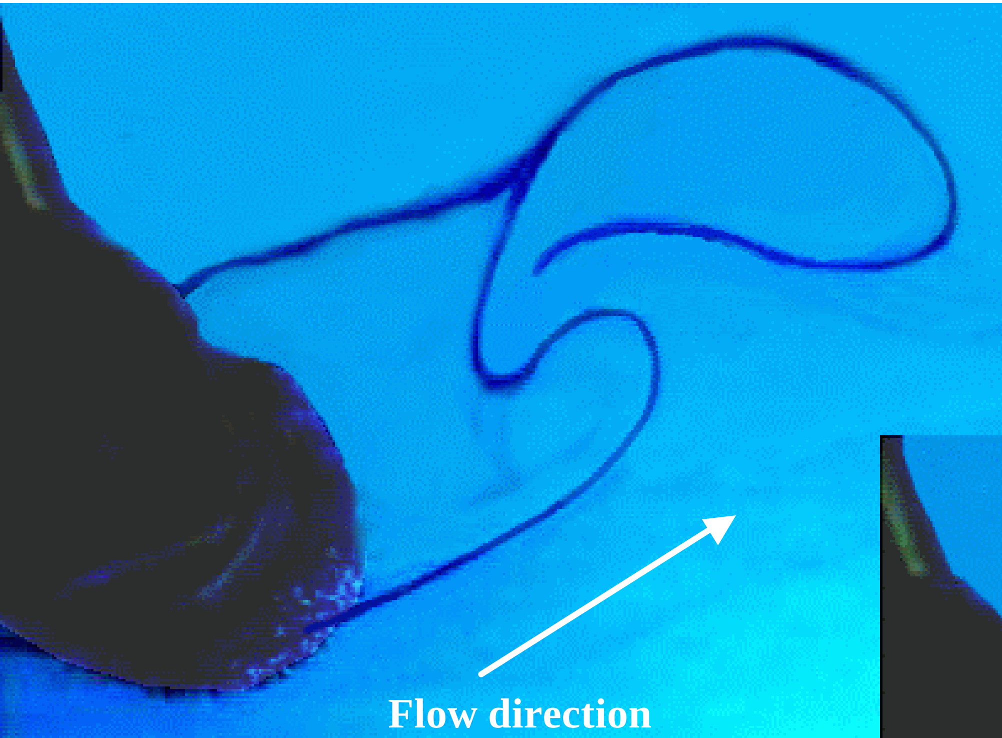
Computational Challenge Li flow in a chute in a transverse field with: b=0.1 m (half-width); B_0=12 T (field)

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

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



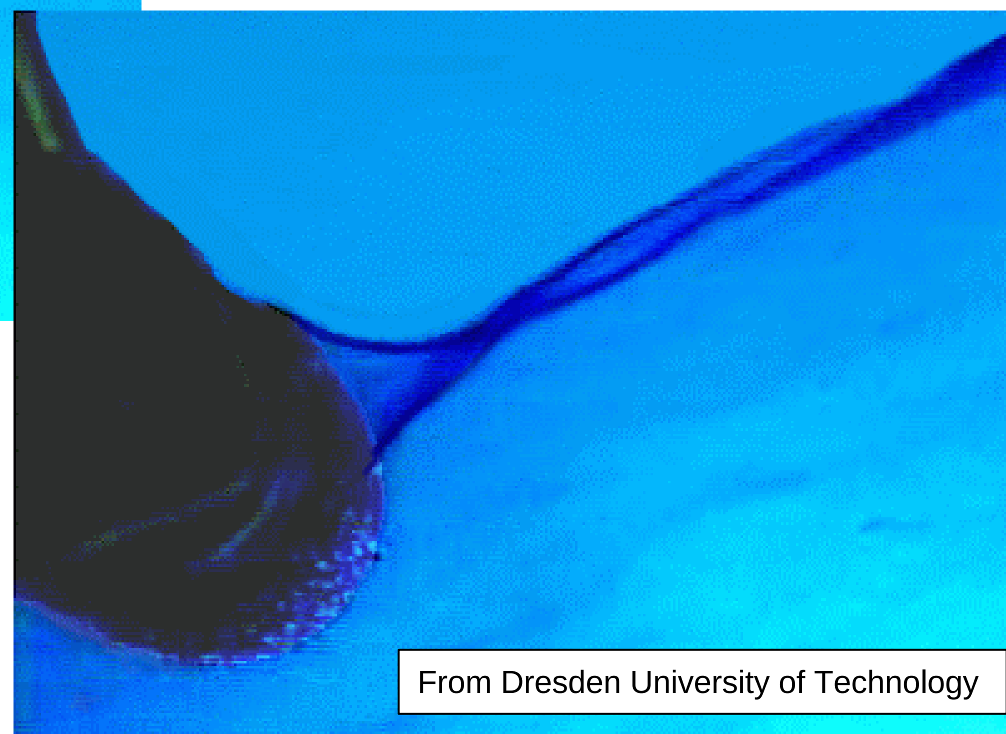
•Applied Lorentz forces act mainly in the fluid regions near the walls where they can prevent flow separation or reduce friction drag by changing the flow structure.

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

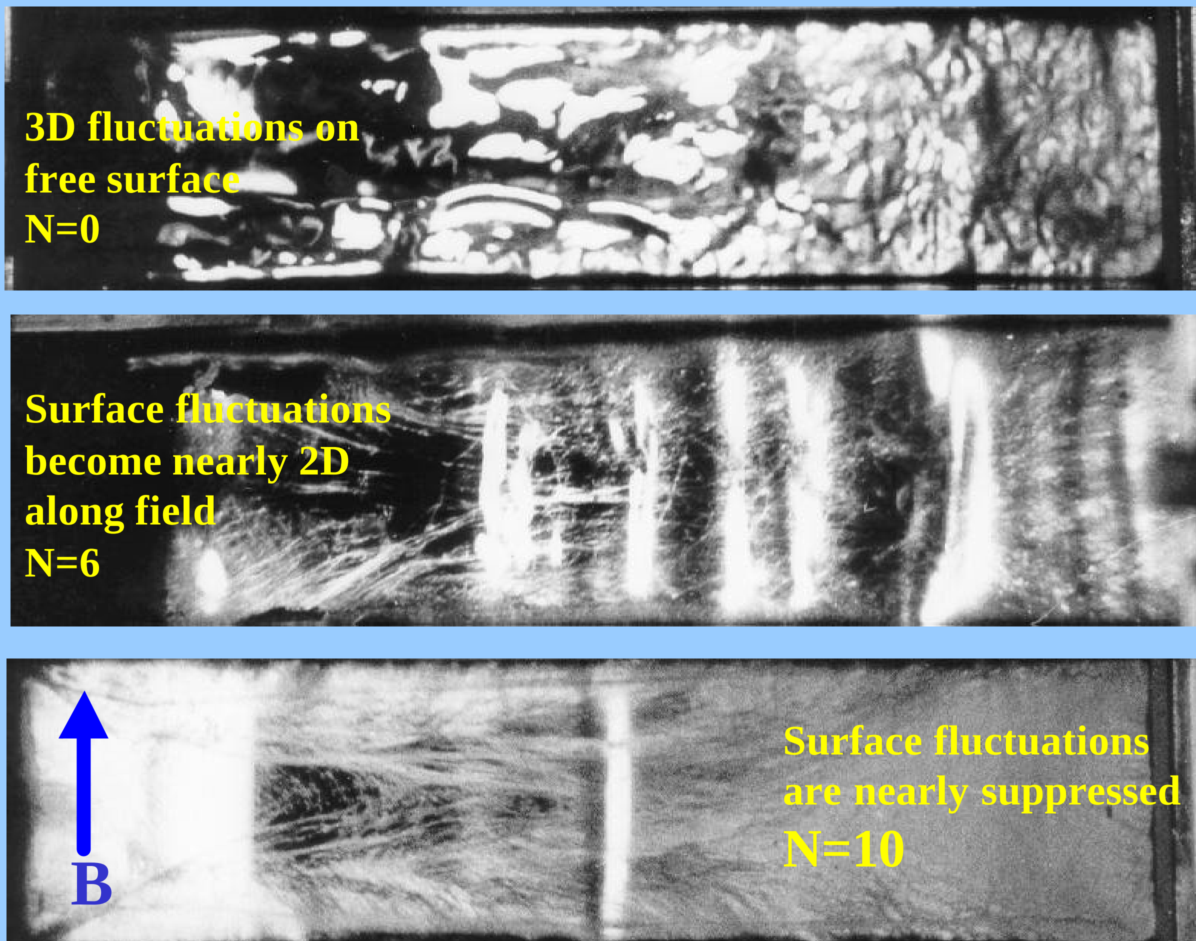
Experimental control of flow separation by a magnetic field:

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

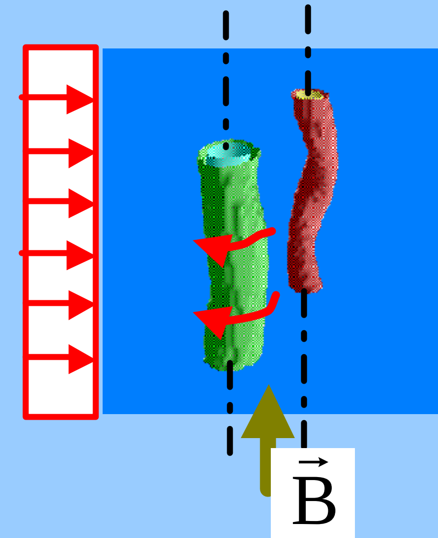
with a magnetic field (right)



NEW PHENOMENA IN LM-MHD FLOW
2D Turbulence



LM free surface images with motion from left to right - Latvian Academy of Science Data



SOME PROPERTIES OF 2-D MHD TURBULENCE:

- Inverse energy cascade;
- Large energy containing vortices;
- Low Joule and Viscous dissipation;
- Insignificant effect on the hydraulic drag.

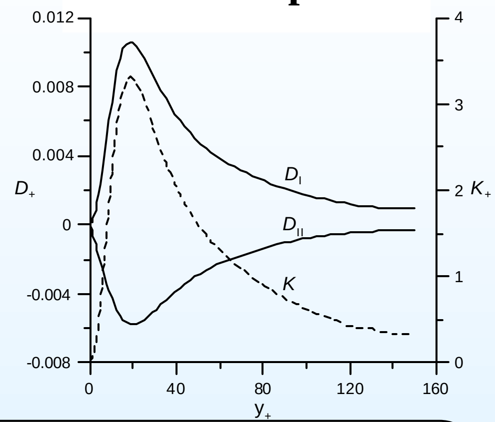
2-D turbulence could be very useful as a mean of intensifying heat transfer.

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

Joule Dissipation



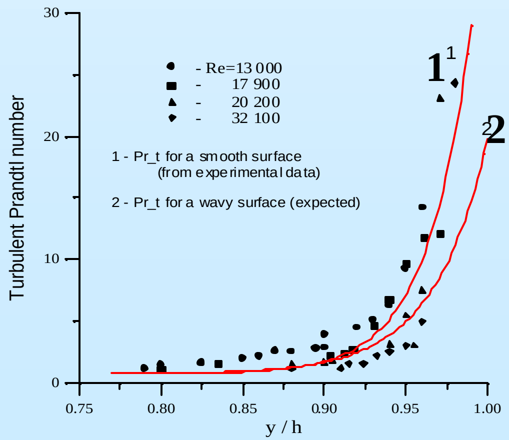
DNS and Experimental data are used at UCLA for characterizing free surface MHD turbulence phenomena and developing closures in RANS models

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

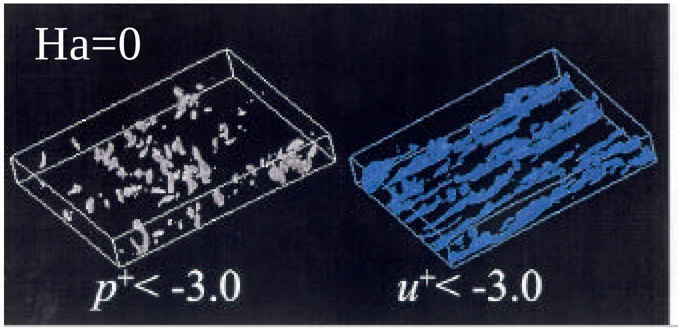


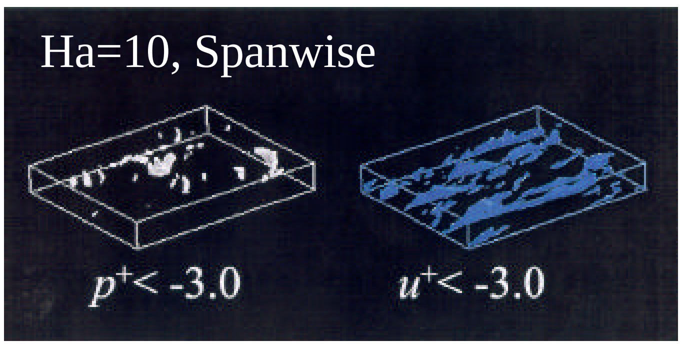
Turbulent Prandtl Number

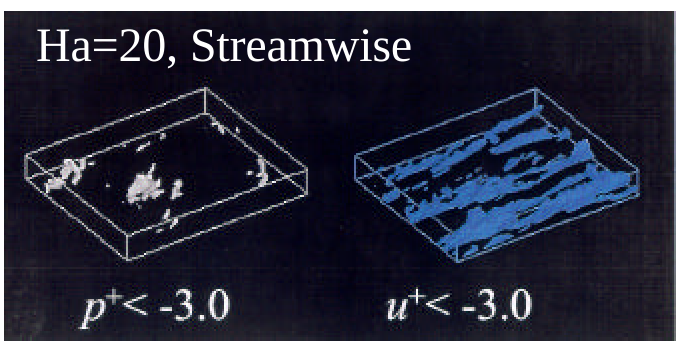
Curve1: Available Experimental Data
- Missing 0.95-1 and restricted to smooth surface, non-MHD flows

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

APEX

MHD K- e TURBULENCE MODEL

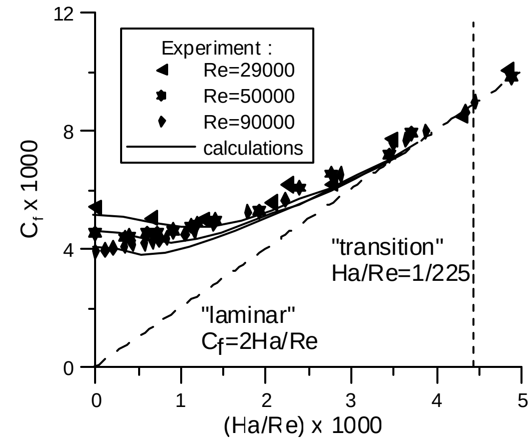
$$\frac{\partial K}{\partial t}+\left\langle v_j\right\rangle\frac{\partial K}{\partial x_j}=\underbrace{n_t\left(\frac{\partial v_i}{\partial x_j}\right)^2}_{\text{Pr oduction}}+\underbrace{\frac{\partial}{\partial x_j}[(n+\frac{n_t}{s_K})\frac{\partial K}{\partial x_j}]}_{Diffusion}-\underbrace{e-e^K_{em}}_{Dissipatio\ n};$$

$$\frac{\partial e}{\partial t}+\left\langle v_j\right\rangle\frac{\partial e}{\partial x_j}=C_1\frac{e}{K}n_t\left(\frac{\partial v_i}{\partial x_j}\right)^2+\frac{\partial}{\partial x_j}[(n+\frac{n_t}{s_e})\frac{\partial e}{\partial x_j}]-C_2\frac{e}{K}e-e^e_{em}.$$

$$q_t=-rC_p<t'v_n'>=-rC_p\frac{n_t}{\Pr_t}\frac{\partial T}{\partial n};\quad \Pr_t=n_t/a_t$$

MHD DEPENDENT TURBULENCE CLOSURES

Magnetic field direction	e^K_{em}	e^e_{em}	C_3	C_4
Streamwise	$C_3\frac{s}{r}B_0^2K$	$C_4\frac{s}{r}B_0^2e$	0.02	0.015
Wall-normal	$C_3\frac{s}{r}B_0^2K$	$C_4\frac{s}{r}B_0^2e$	$1.9\exp\{-1.0N\}$	$1.9\exp\{-2.0N\}$
Spanwise	$C_3\frac{s}{r}B_0^2K$	$C_4\frac{s}{r}B_0^2e$	$1.9\exp\{-1.0N\}$	$1.9\exp\{-2.0N\}$



Comparison of UCLA model to experimental data

1.5-D MHD K-e 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

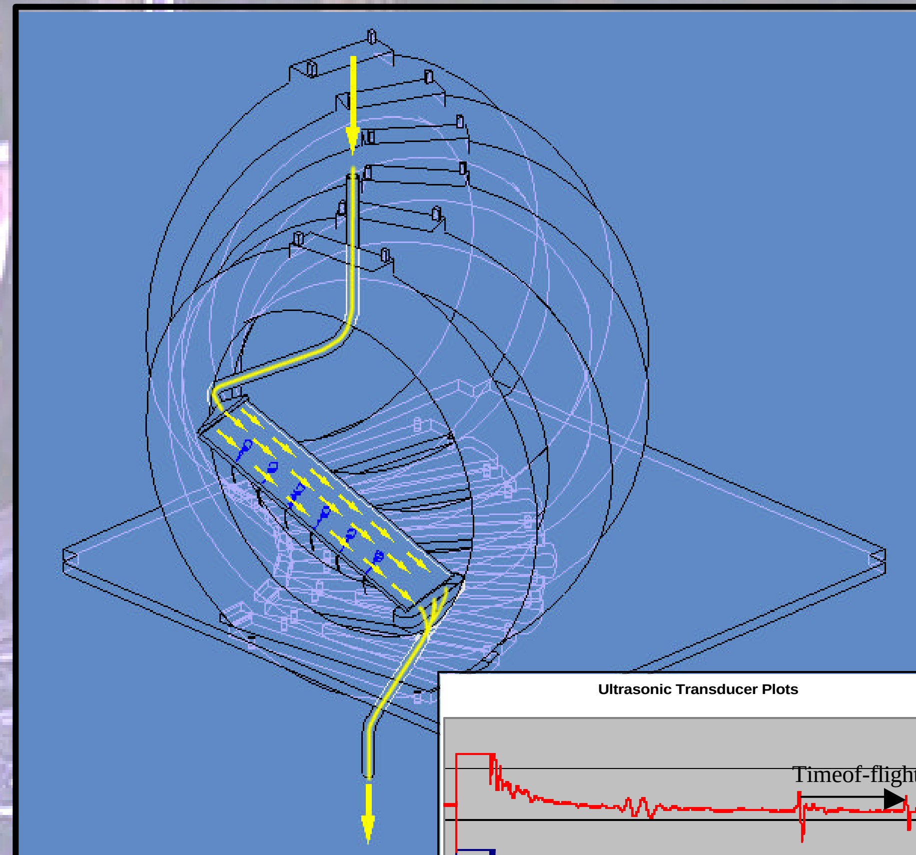
•Study toroidal field and gradient effects: Free surface flows are very sensitive to drag from toroidal field 1/R gradient, and surface-normal fields

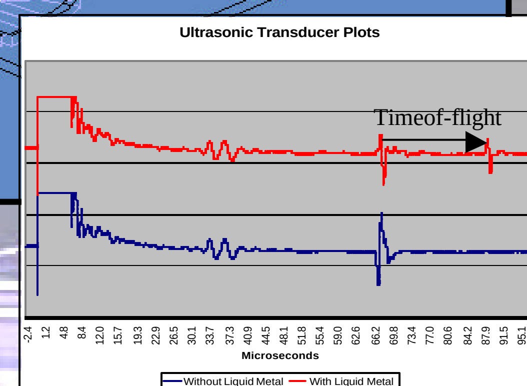
•3-component field effects on drag and stability: Complex stability issues arise with field gradients, 3-component magnetic fields, and applied electric currents

•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





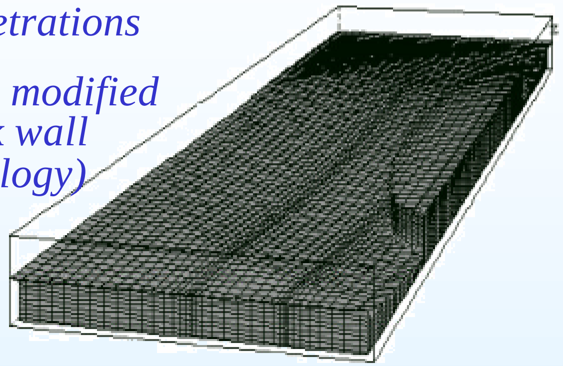
MTOR Magnetic Torus and LM Flowloop: Designed in collaboration between UCLA, PPPL and ORNL

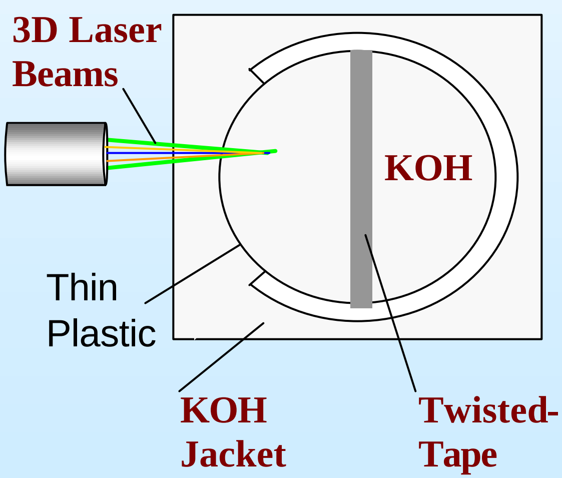
FLIHY is a flexible facility that serves many needs for Free-Surface Flows

Flow Control

Penetrations

(e.g. modified back wall topology)

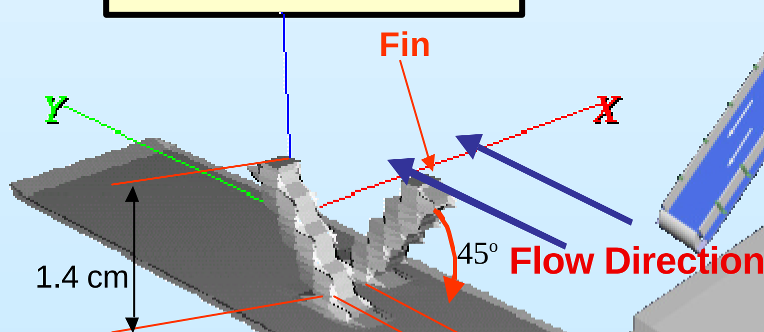




JUPITER-II

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**



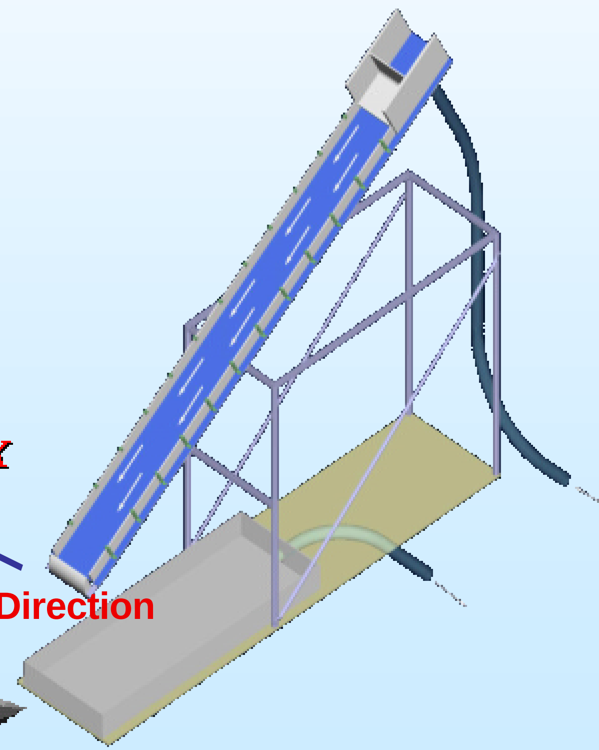
Surface Renewal

(e.g. Delta-Wing" tests)

Free Surface Interfacial Transport

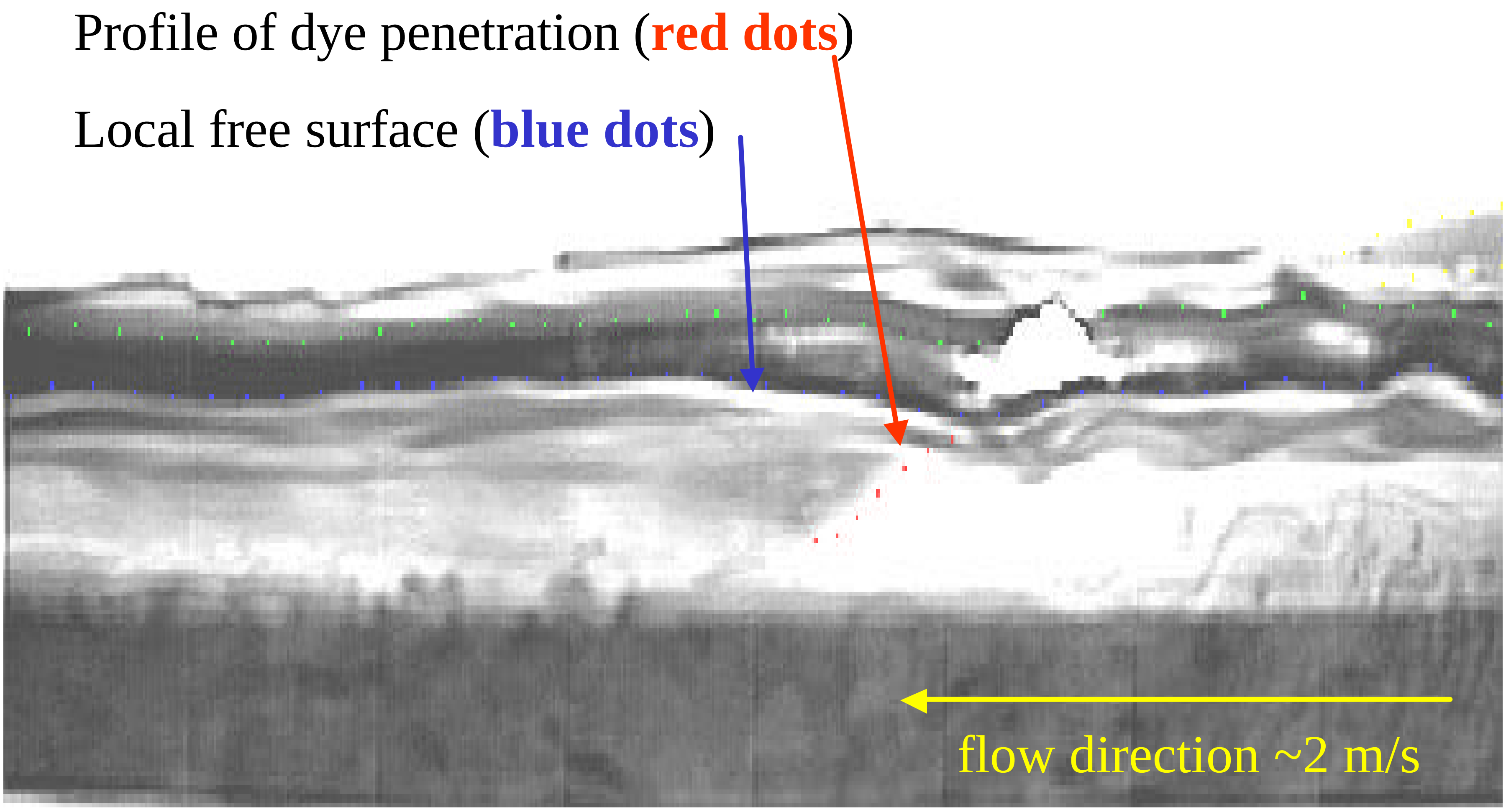
- Turbulence at free surface

- Novel Surface Renewal Schemes



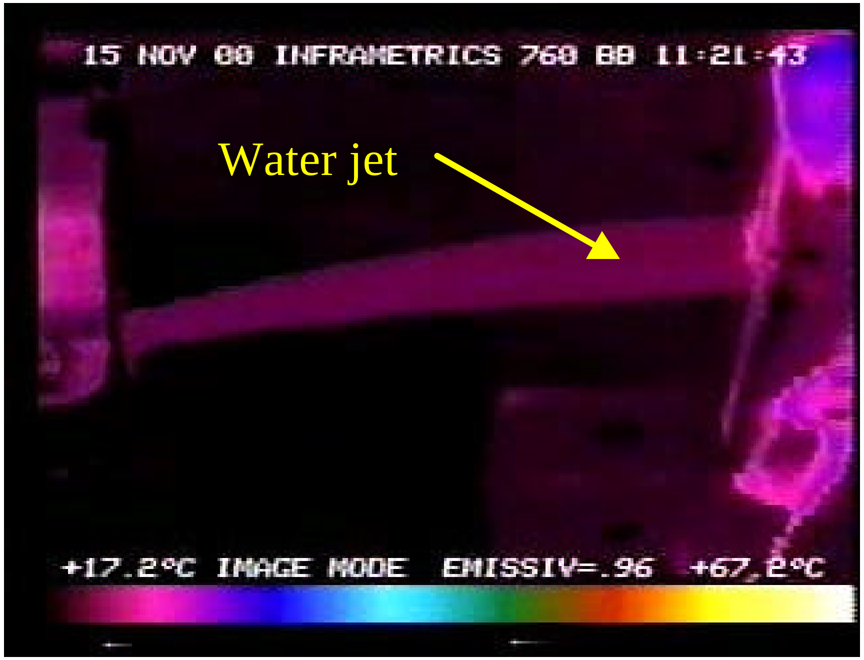
Interfacial Transport Test section length = 4 m

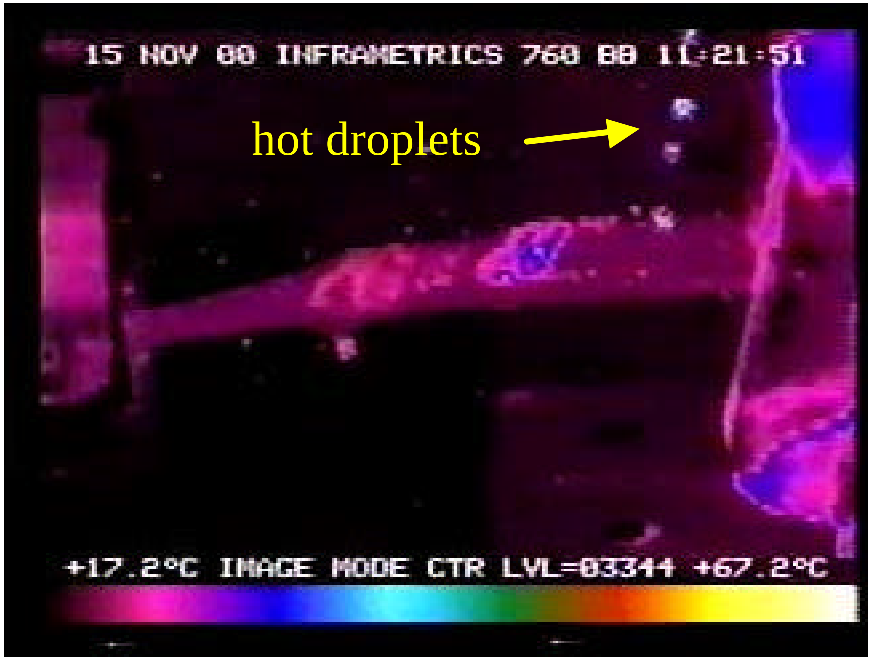
Dye Diagnostics for Interfacial Mass Transport Measurements

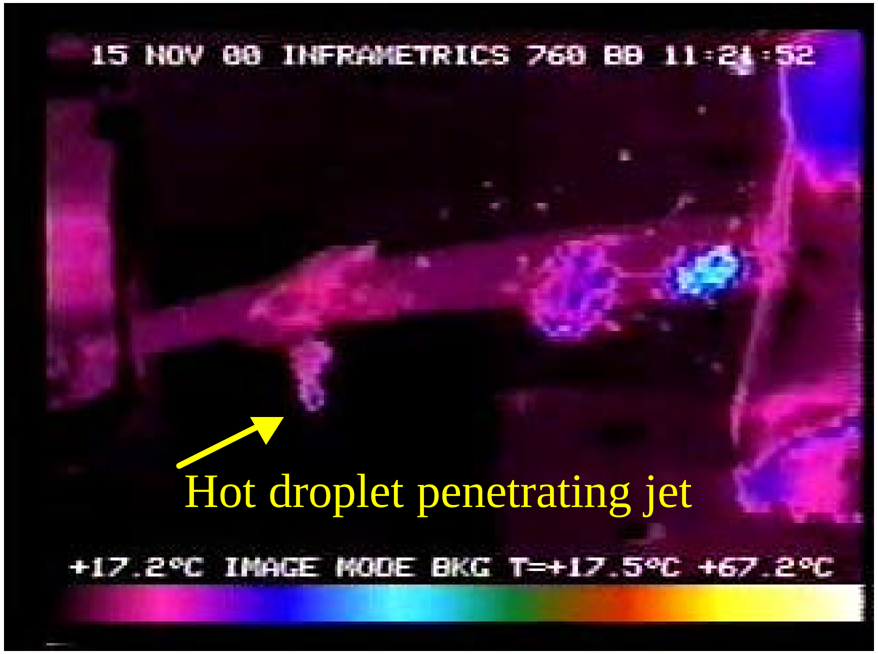


Dynamic Infrared measurements of jet surface temperature

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



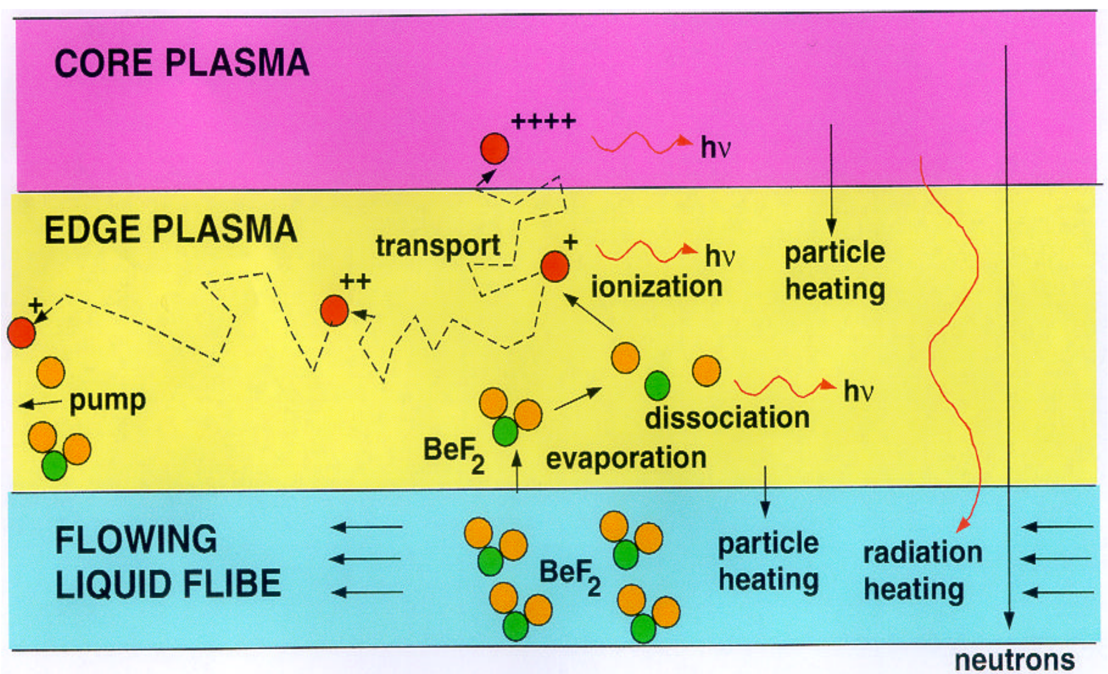


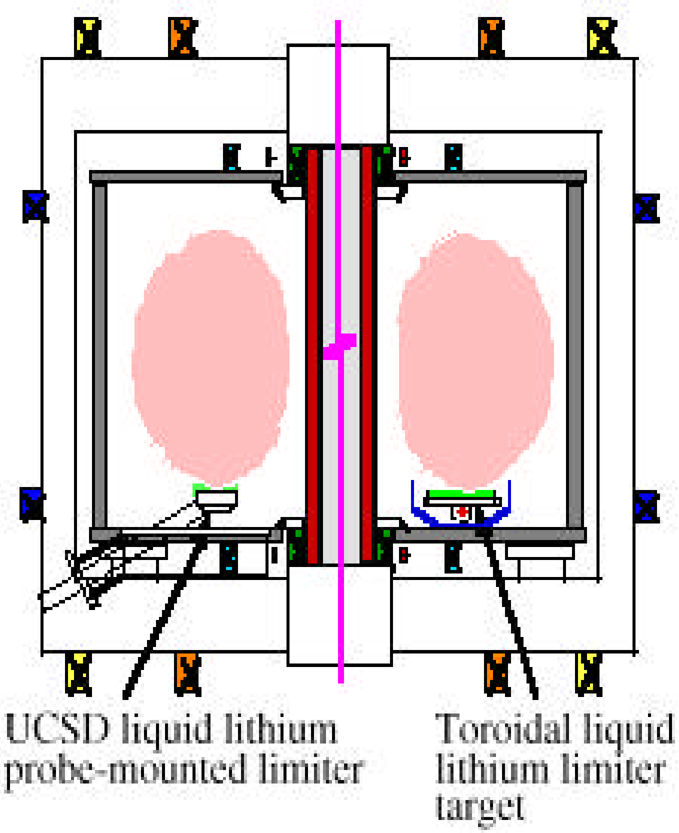


Plasma-Liquid Surface Interactions

- 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





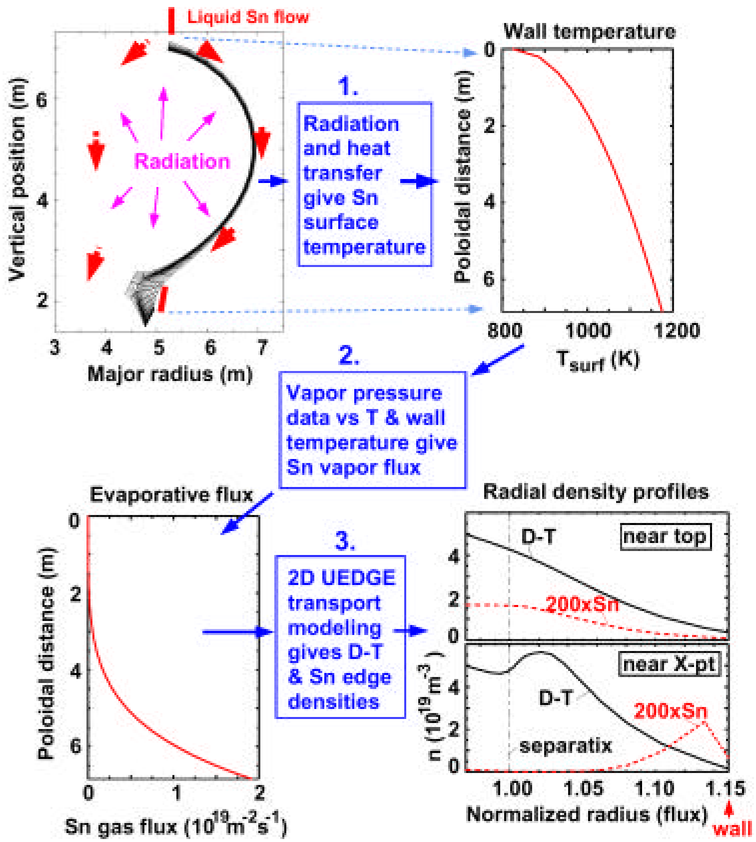
Liquid lithium limiter in CDX-U

Validated Plasma Edge Models were extended to predict the Physics Limits on LW Surface Temperature

APEX

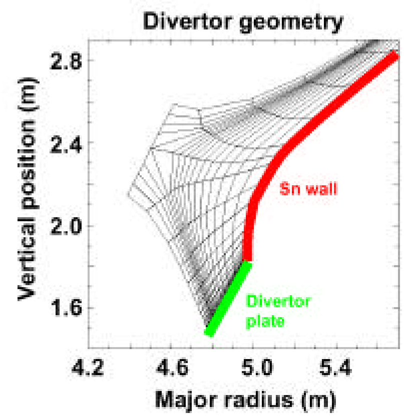
A systematic set of steps predicts the core impurity level from liquid walls

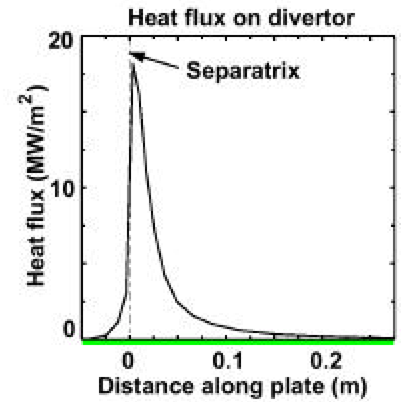
An acceptable core Sn level is obtained for ARIES case:

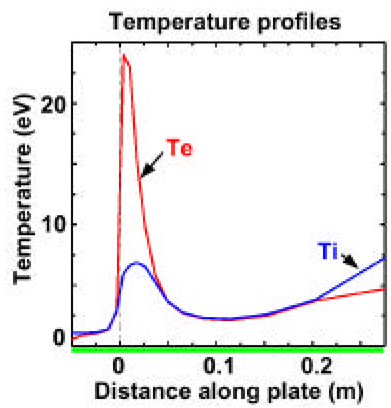


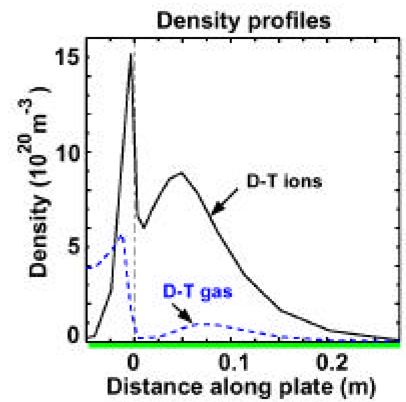
Global edge plasma/neutral transport modeling used to aid divertor design

- Designing divertor-region hardware is a critical element
- Validated 2D UEDGE predicts divertor plasma conditions









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 $\kappa > 3$ 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