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

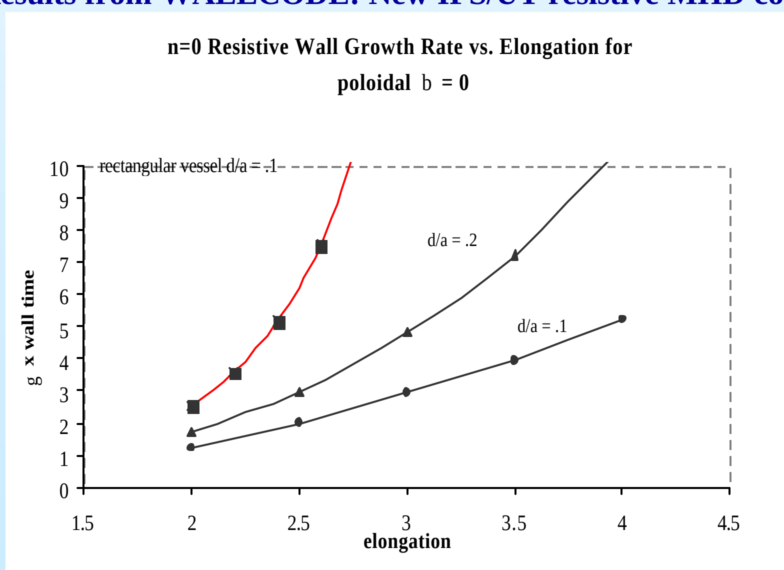
- **Initial Results: Liquid metals can be used as conducting walls that offer a means for stabilizing plasma MHD modes**

Utilization of Liquid Metals for a Conducting Shell May Allow Higher Power Density Tokamak Plasma

APEX

- **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

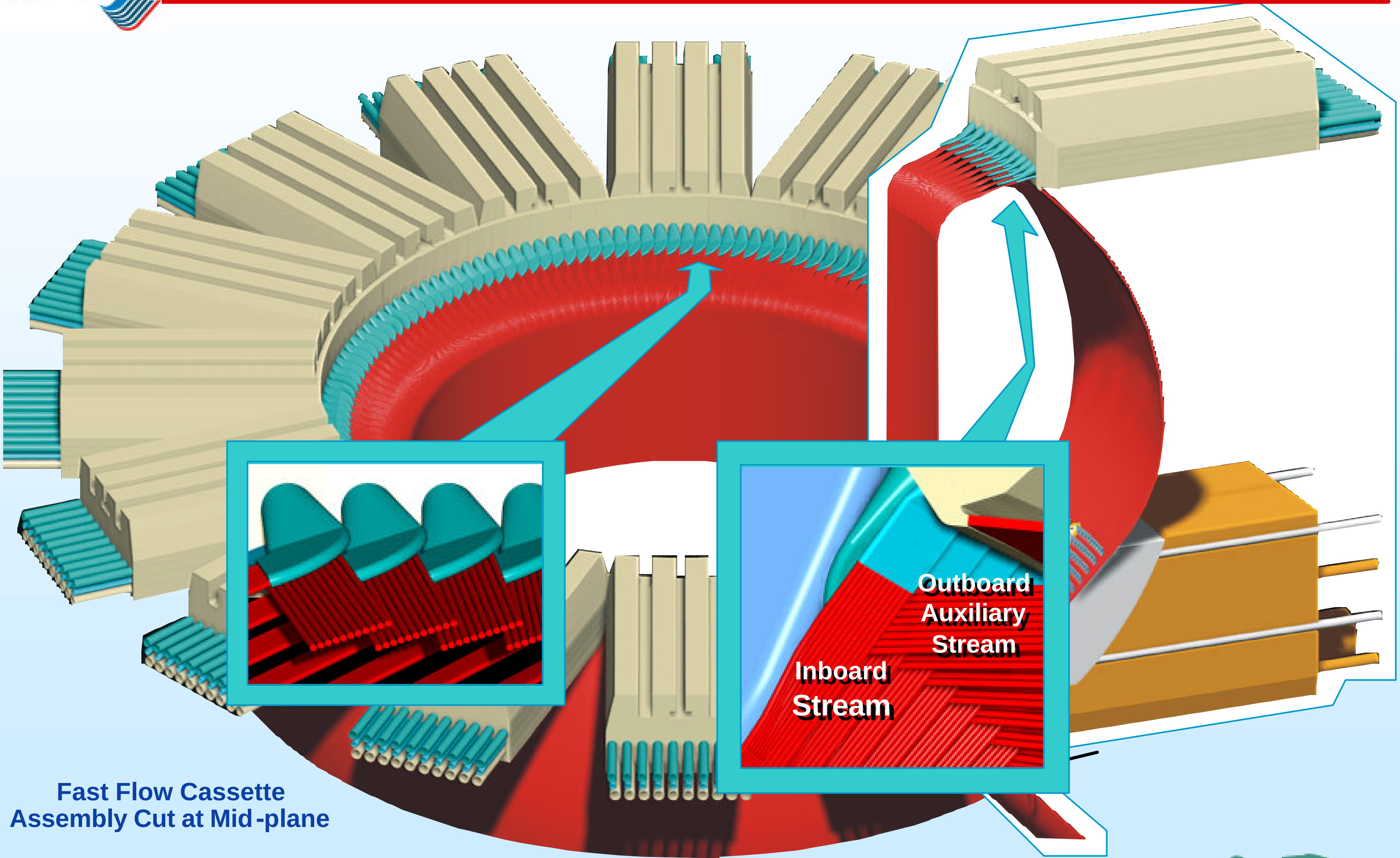
- Search for Innovative Solutions: Our job is "to make things work"

- 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

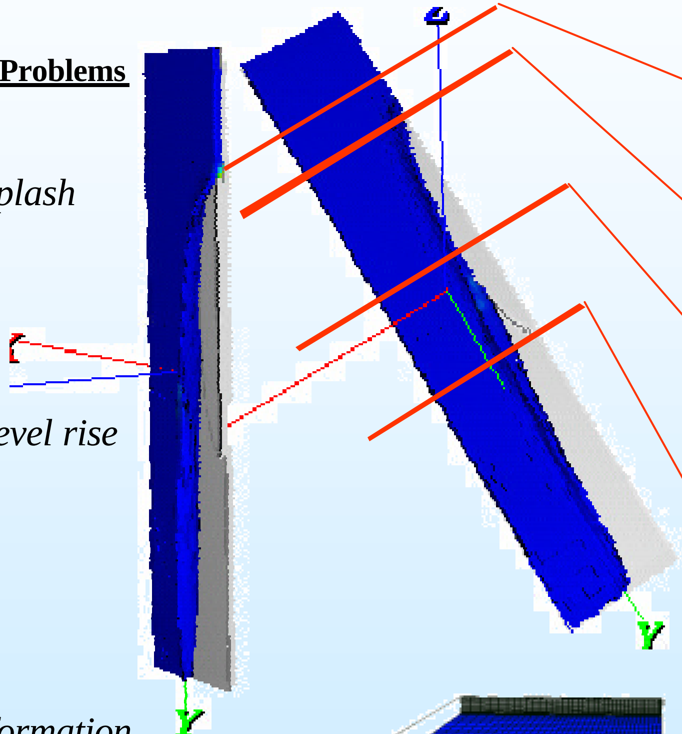
STATE-OF-THE-ART 3-D TIME DEPENDENT FLOW 3-D CALCULATIONS WAS KEY TO UNDERSTANDING PENETRATION PROBLEMS

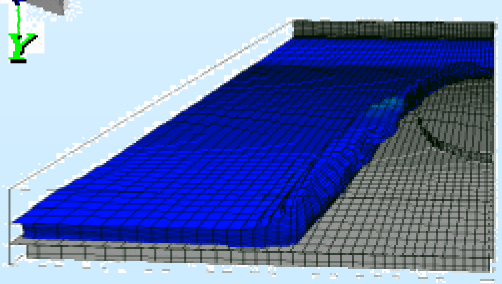
3-D CFD Simulation Results

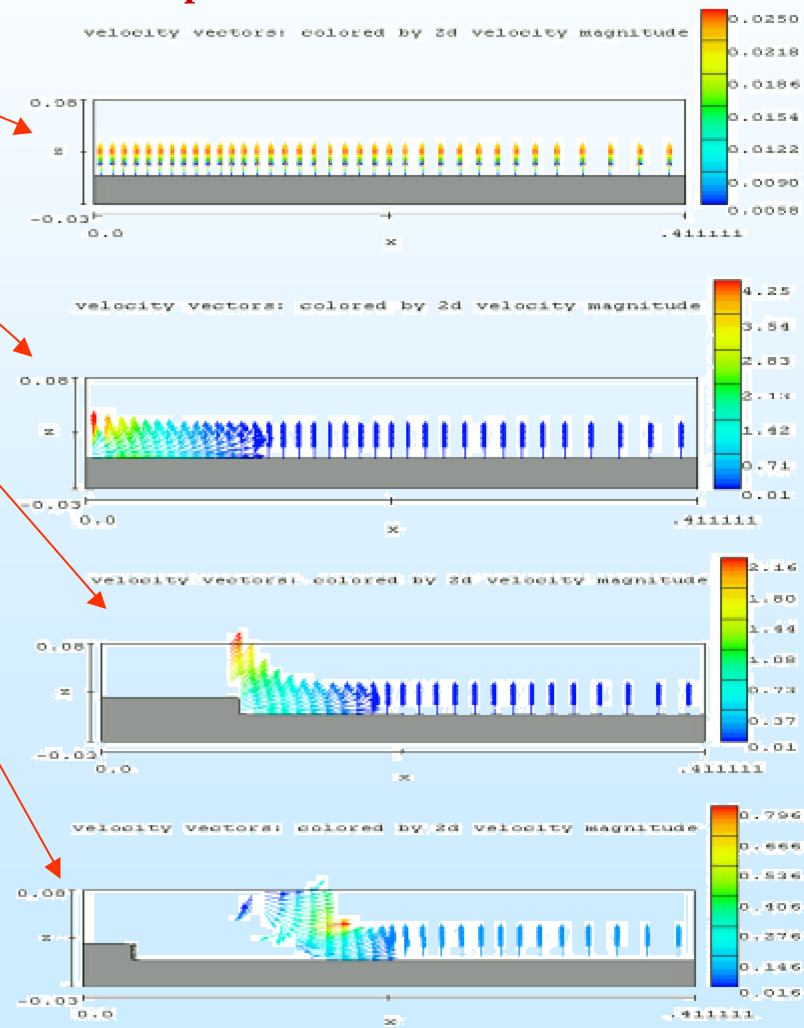
2-D Velocity Magnitude in Planes Perpendicular to the Flow Direction

<u>**Potential Problems**</u>

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

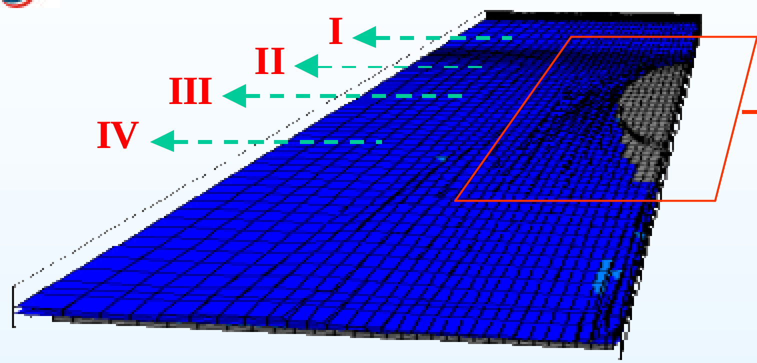




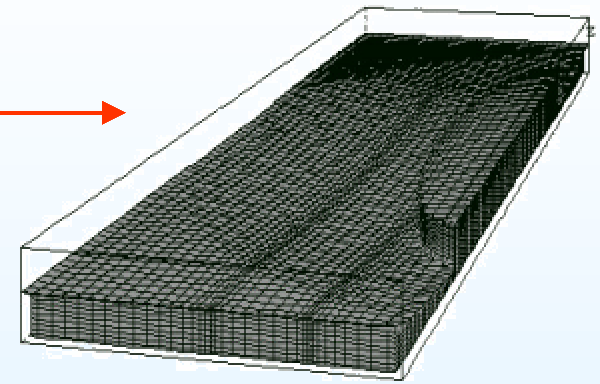


3-D View of the Wake Following the Penetration.

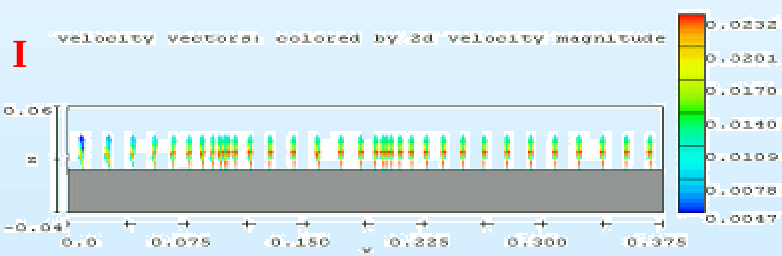
Innovative Solutions Found and Confirmed by FLOW-3D Calculations (experiments also planned)

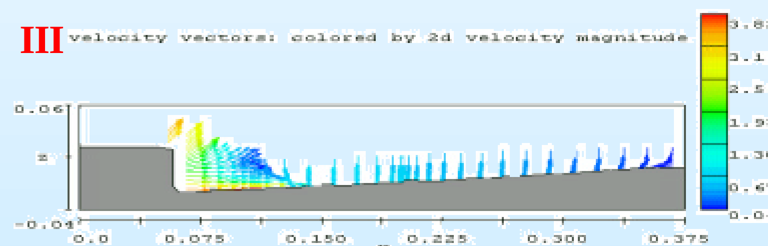


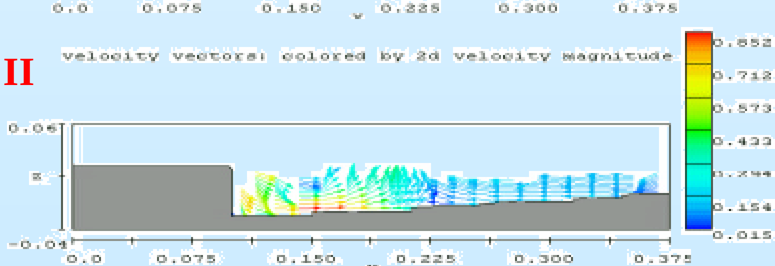
3-D Hydrodynamic simulation of penetration accommodation when the back wall topology surrounding the penetration is modified.

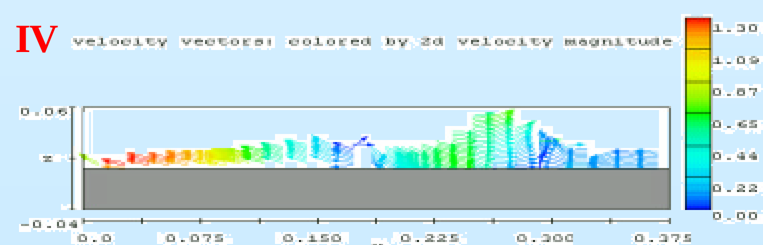


Modified back wall topology surrounding the penetration.





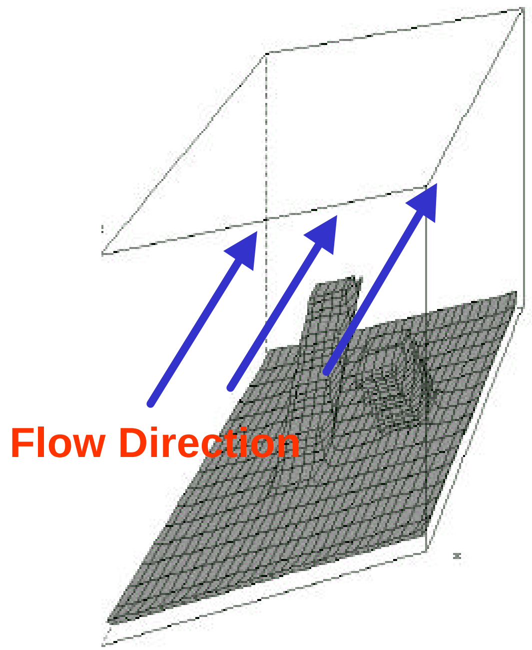


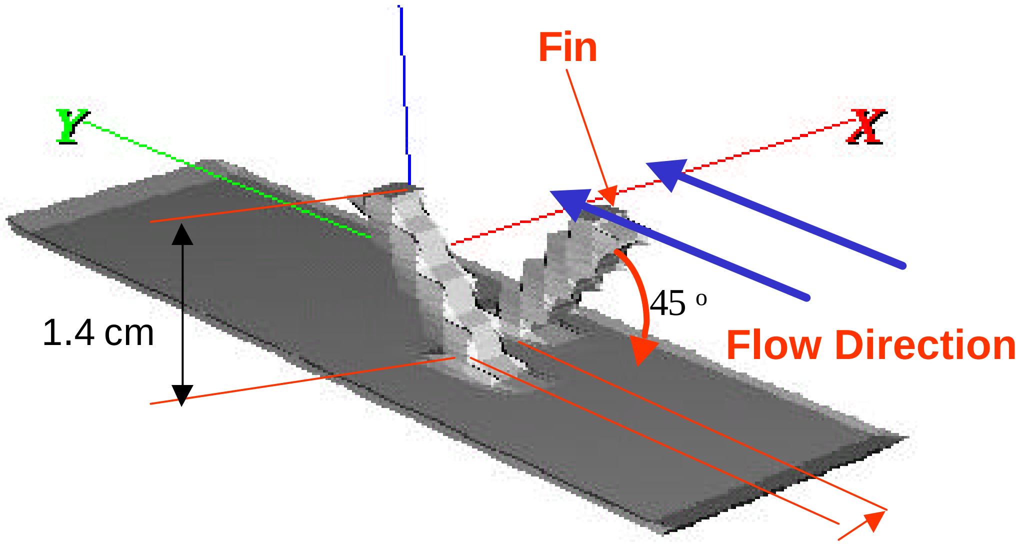


2-D Velocity magnitude in planes perpendicular to the flow direction

Finding innovative surface renewal methods to improve heat transfer

- IDEA: Promote streamwise vortex production by "delta-wing" backwall structures
- Long-lived vortices should renew surface and transport heat to the bulk flow.
- Technique borrowed from aerospace applications



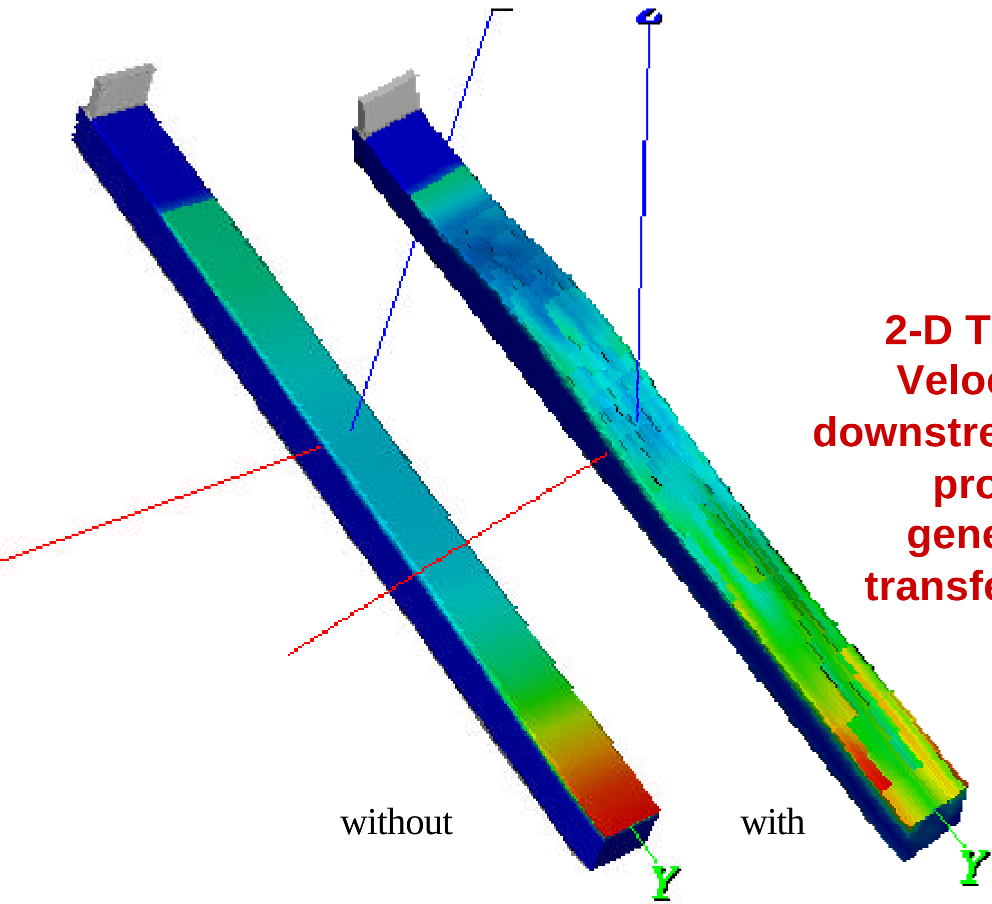


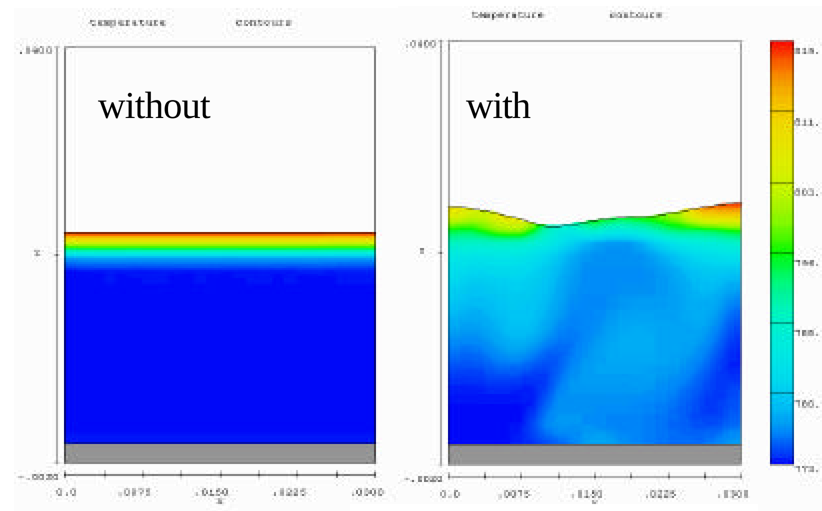
Case Analyzed to Assess Effect

Liquid Layer Velocity	**: 1.5 m/s**
Liquid Layer Height	**: 2.0 cm**
Fin Height	**: 1.4 cm**
Fin Width	**: 0.5 cm**
Spacing Between Fins	**: 0.5 cm**

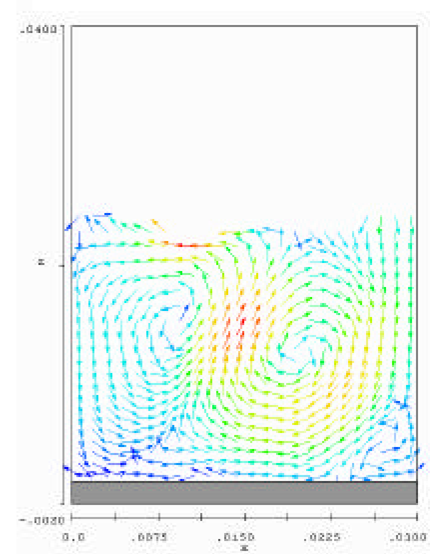
3D Thermofluid Simulations Confirm Heat Transfer Enhancement

Free surface temperature distribution of a Flibe flow over a plane wall, without (left) and with (right) vortex promoters

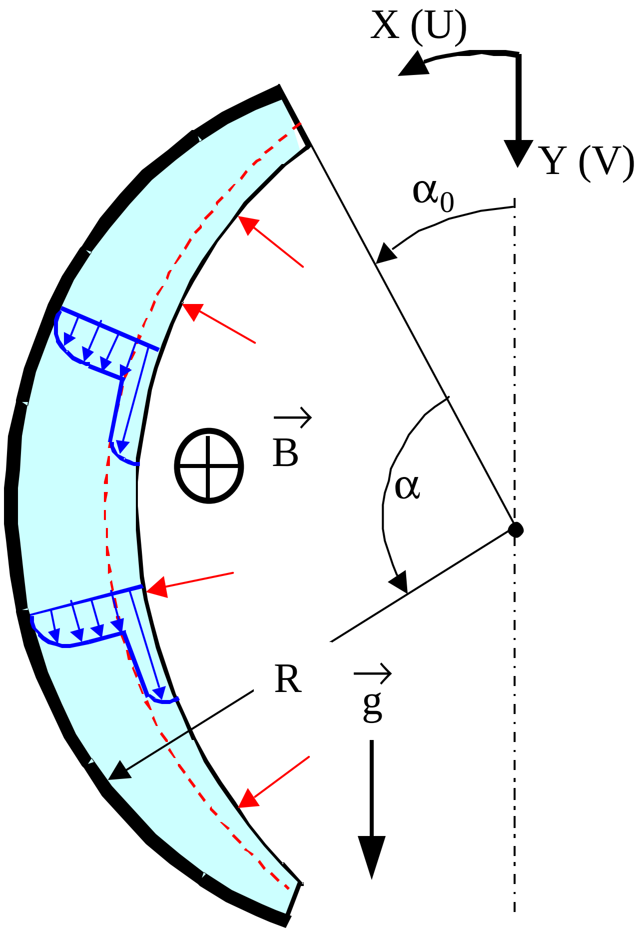




2-D Temperature and Velocity Distribution downstream from vortex promoters - vortex generation and heat transfer enhancement clearly evident.



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

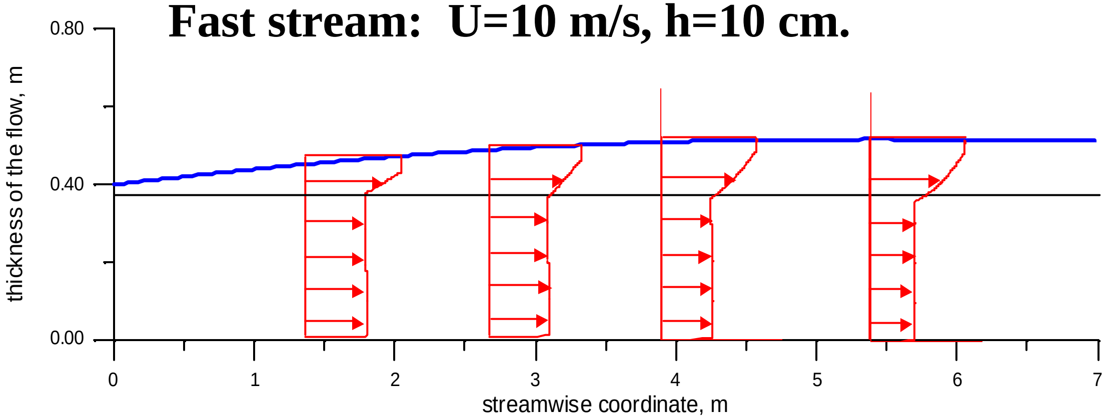
CFD-MHD Calculations Show the Potential for Practical Realization of the TWO-STREAM Idea

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.

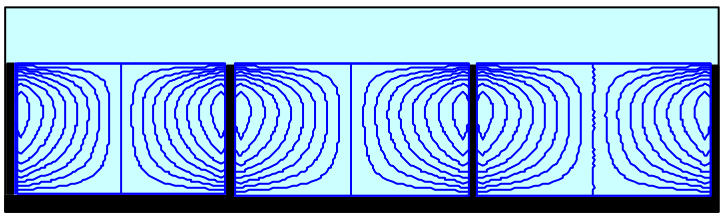
Downstream development of the two-stream flow produced with the submerged walls.

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

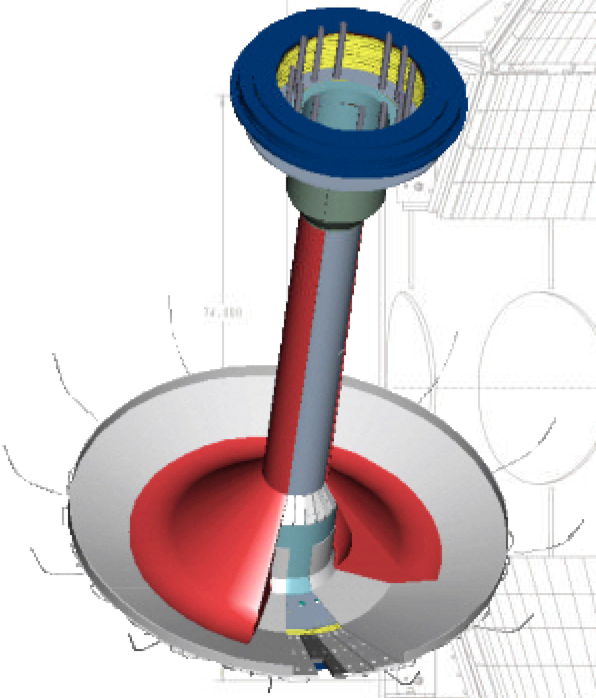


Sketch of the induced current in the cross-sectional area.

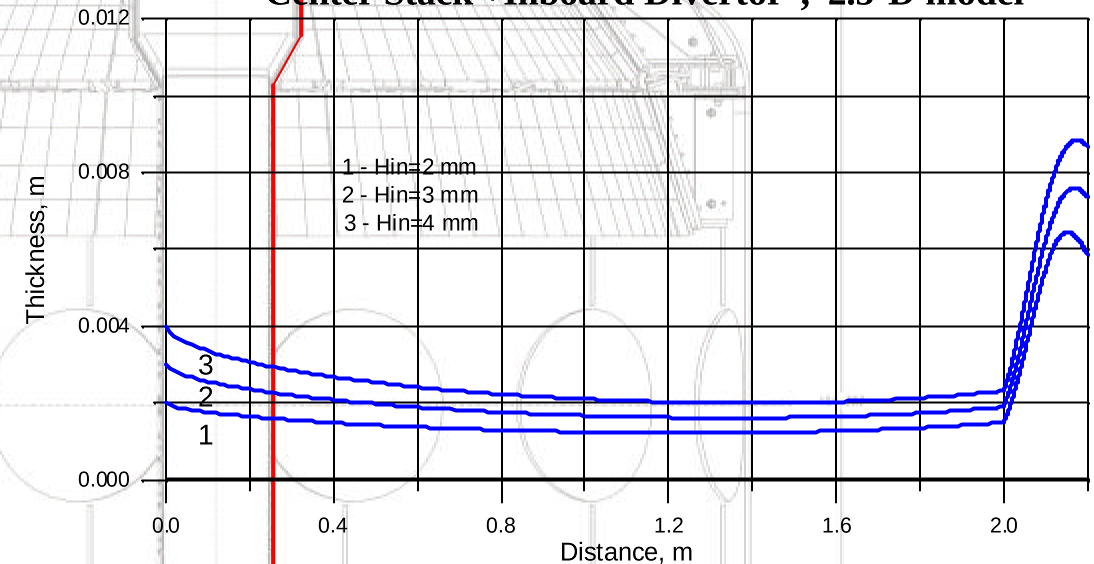
The submerged walls are slightly conducting: $c_w=2\times10^{-6}$.



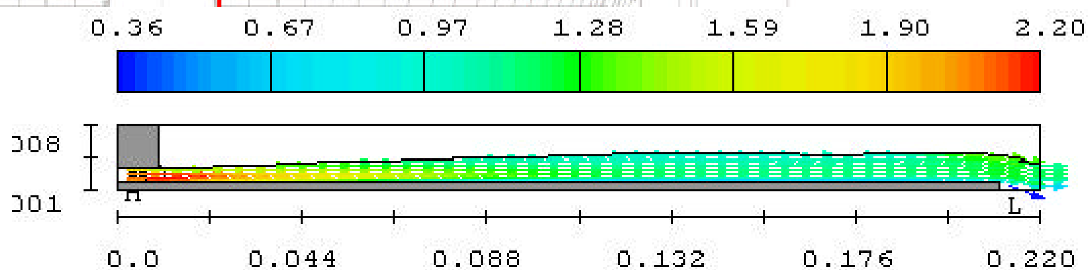
Simulations of Flowing Lithium in NSTX using Newly Developed MHD Free Surface Tools



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



“Inboard Divertor”, Flow3D-M



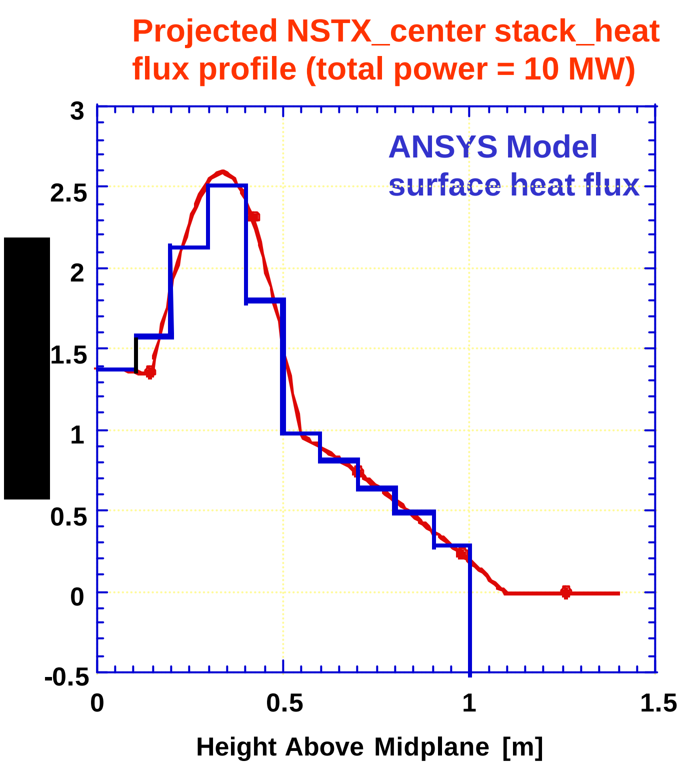
- **Flow3D code was extended to include MHD effects (Flow3D-M)**

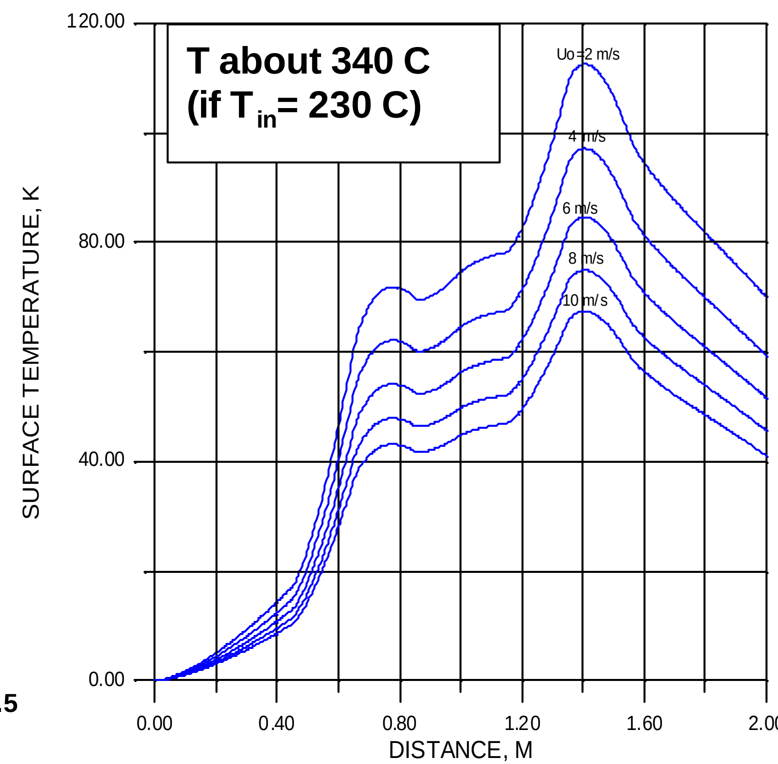
- **New 2.5-D model and computer code were developed to calculate MHD free surface flows in a multi-component magnetic field**

Stable Li film flow can be established over the center stack

NSTX: Heat flux can be removed with flowing lithium along the center stack with acceptable surface temperature (even with 4-mm film at 2m/s)

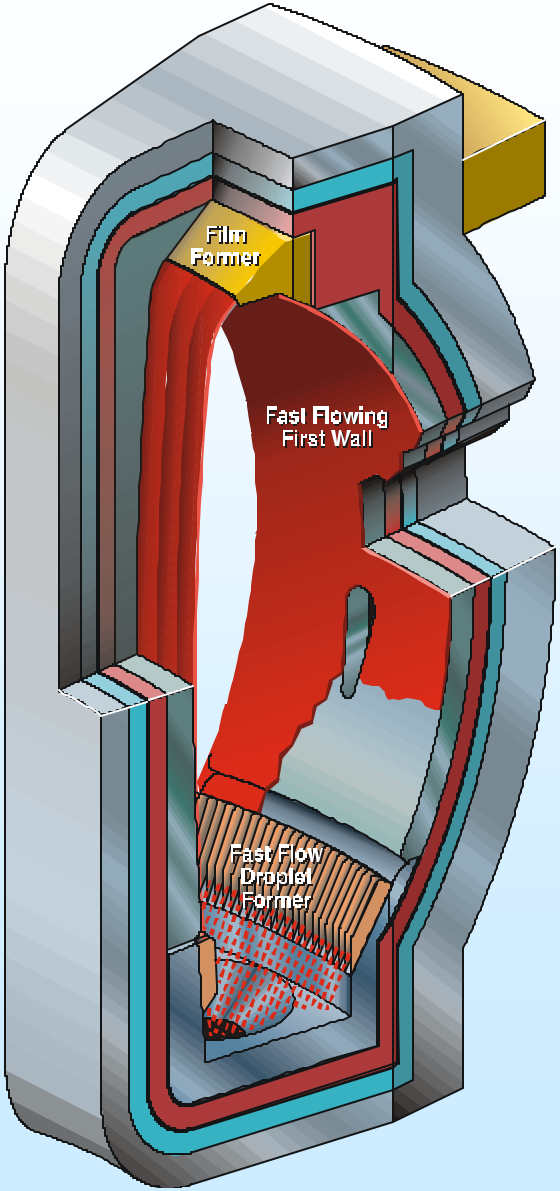
Results of Heat Transfer Calculations for NSTX Center Stack Flowing Lithium Film





- **Lithium surface temperature increases as flow proceeds downstream as a function of lithium inlet velocity**
- **Two local temperature peaks are related to local maximums in the heat flux profile**

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



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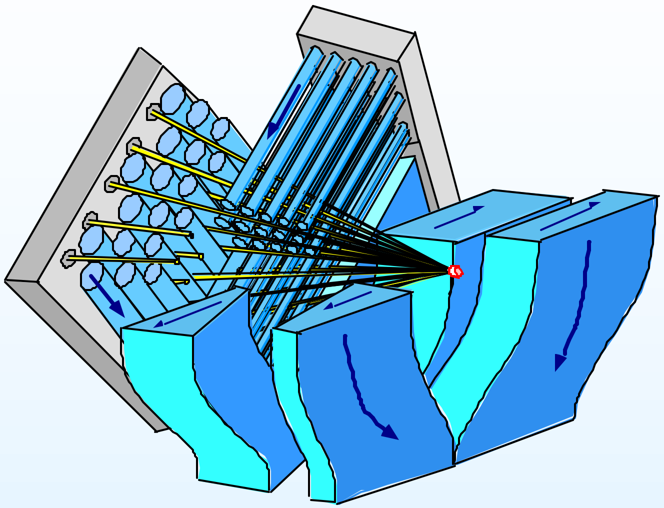
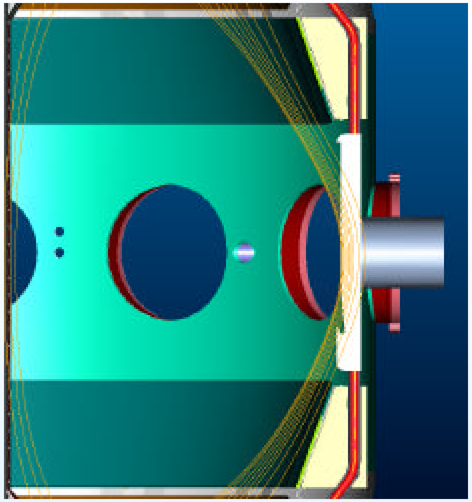
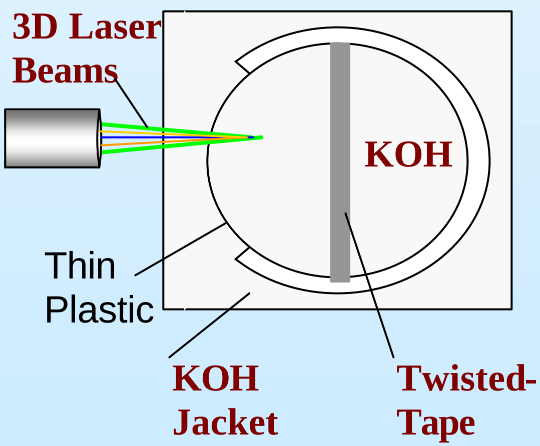


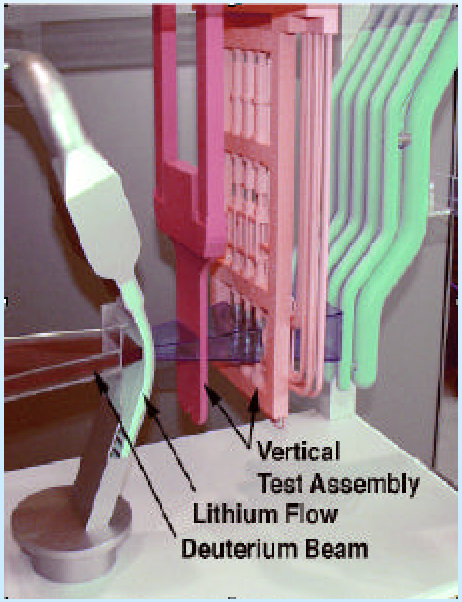
HYLIFE-II



NSTX Li module



JUPITER-II



IFMIF

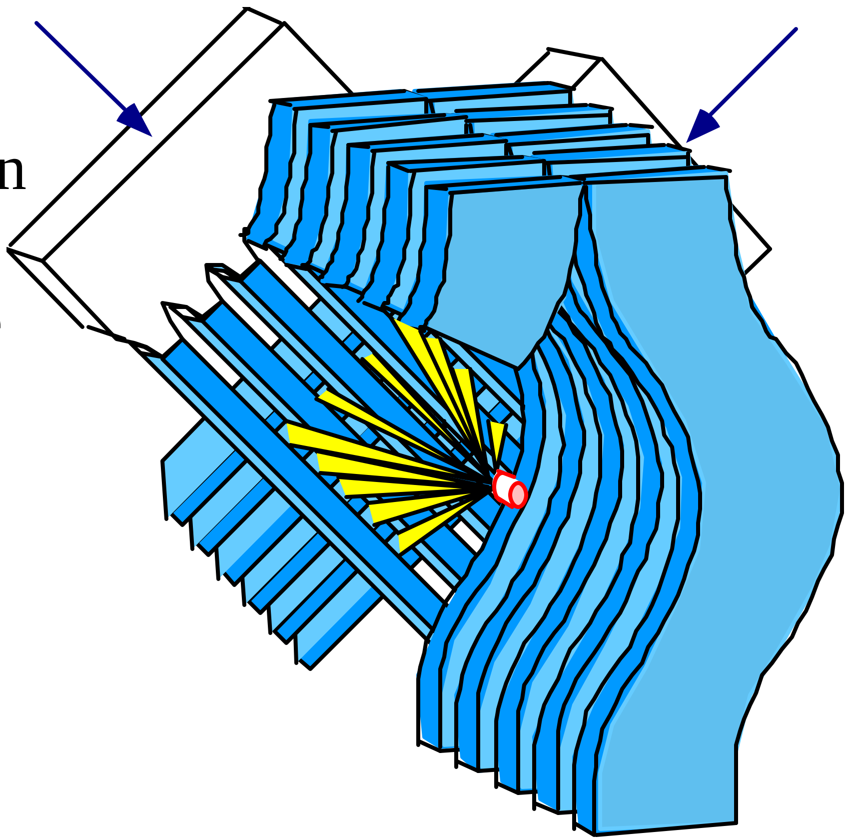
Liquid Jet Research for IFE Chambers

High-velocity, oscillating <u>jets for liquid "pocket"</u>

•flow trajectory and jet deformation
•primary breakup / droplet formation
•dissembly processes
•liquid debris interaction / clearance
•partial head recovery

High-velocity, low surface-ripple <u>jets for liquid "grid"</u>

•surface smoothness control
•pointing accuracy / vibration
•primary breakup / droplet ejection



Graphics from UCB

Oscillating IFE jet experiments and simulations

•**Single jet water experiments and numerical simulations demonstrate control of jet trajectory and liquid pocket formation at near prototypic Re**

Experimental Data from UCB