# Merits & Issues for Liquid Wall Concepts Based on the APEX Study

*Handout to Aid Snowmass Discussions*

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# Liquid Walls
# Offer an Exciting Opportunity to HELP
# Develop a New VISION for Fusion with:

1) More Attractive and Competitive Fusion Power

2) Lower Cost, Faster R&D Path

# The Challenges in Free-Surface Liquid Research Present Excellent Opportunities for:

(1) Greater contributions to Engineering Sciences

(2) Direct coupling and outreach to other fields (e.g. Oceanography, Metallurgy, Rocket Engines)

(3) Intellectual synergism between Plasma Physicists and Fusion Engineers.

# Plasma Chamber Technology

- All Components from the Edge of the Plasma to the Magnet (i.e. First Wall / Blanket / Divertor / Vacuum Vessel)

- Functions

  - Provide Vacuum
  - Exhaust Plasma Burn Products
  - Power Extraction from Plasma Particles and Radiation (Surface Heat Load)
  - Power Extraction from Neutrons and Gamma-Rays (Bulk Heating)
  - Tritium Breeding
  - Radiation Protection

## Fundamentals of Economics Show That:

1. Attractive Vision Requires JOINT Physics and Technology Efforts
2. Technology is Critical

**Need High Power Density**
- High-Performance Plasma
- Power Extraction Technology

**Need Low Failure Rate**

$$COE = \frac{C \cdot i + \boxed{\text{replacement cost}} + O\,\&\,M}{P_{fusion} \cdot \boxed{\text{Availability}} \cdot M \cdot \eta_{th}}$$

Energy Multiplication

**Need High Temp. Energy Extraction**

$$\frac{(1/\text{failure rate})}{1/\text{failure rate} + \text{replacement time}}$$

- **Need Low Failure Rate:**
  - Innovative Power Extraction Technology
- **Need Short Maintenance Time:**
  - Simple Configuration Confinement
  - Easier to Maintain In-Vessel Technology

# APEX

## Objective

Identify and explore novel, possibly revolutionary, concepts for the Plasma Chamber that have the potential to:

(1) Substantially improve the vision for an attractive fusion energy system; and

(2) Lower the cost and time for R&D.

## Primary Criteria (to measure progress toward goals)

1. High Power Density Capability (main driver)
   Neutron Wall Load > 10 $MW/m^2$
   Surface Heat Flux > 2 $MW/m^2$

2. High Power Conversion Efficiency ( > 40% net)
3. Low Failure Rates
   MTBF > 43 MTTR
4. Faster Maintenance
5. Simpler Technological and Material Constraints

# APEX APPROACH

1) Foster an Environment conducive to innovation
    - Encourage innovative ideas
    - Opportunities for talented young scientists/engineers

2) Understand and Advance the underlying Engineering Sciences

3) Utilize a multidisciplinary, multi-institution integrated TEAM to foster collaboration, pool talents, and expand expert and specialty input. Organizations: UCLA, ANL, ORNL, SNL, LLNL, PPPL, GA, LANL, UW, UCSD, INEL

4) Provide for Open Competitive Solicitation in 1999

5) Close Coupling to the Plasma Community
    - Plasma Interface Group
    - Joint Physics-Technology Workshops

6) Direct Participation of Material Scientists and System Design Groups

7) Direct Coupling to IFE Chamber Technology Community

8) Encourage International Collaboration
    - Current participation from Germany and Japan

# Two Classes of Concepts
# Have Emerged From APEX as Very Promising

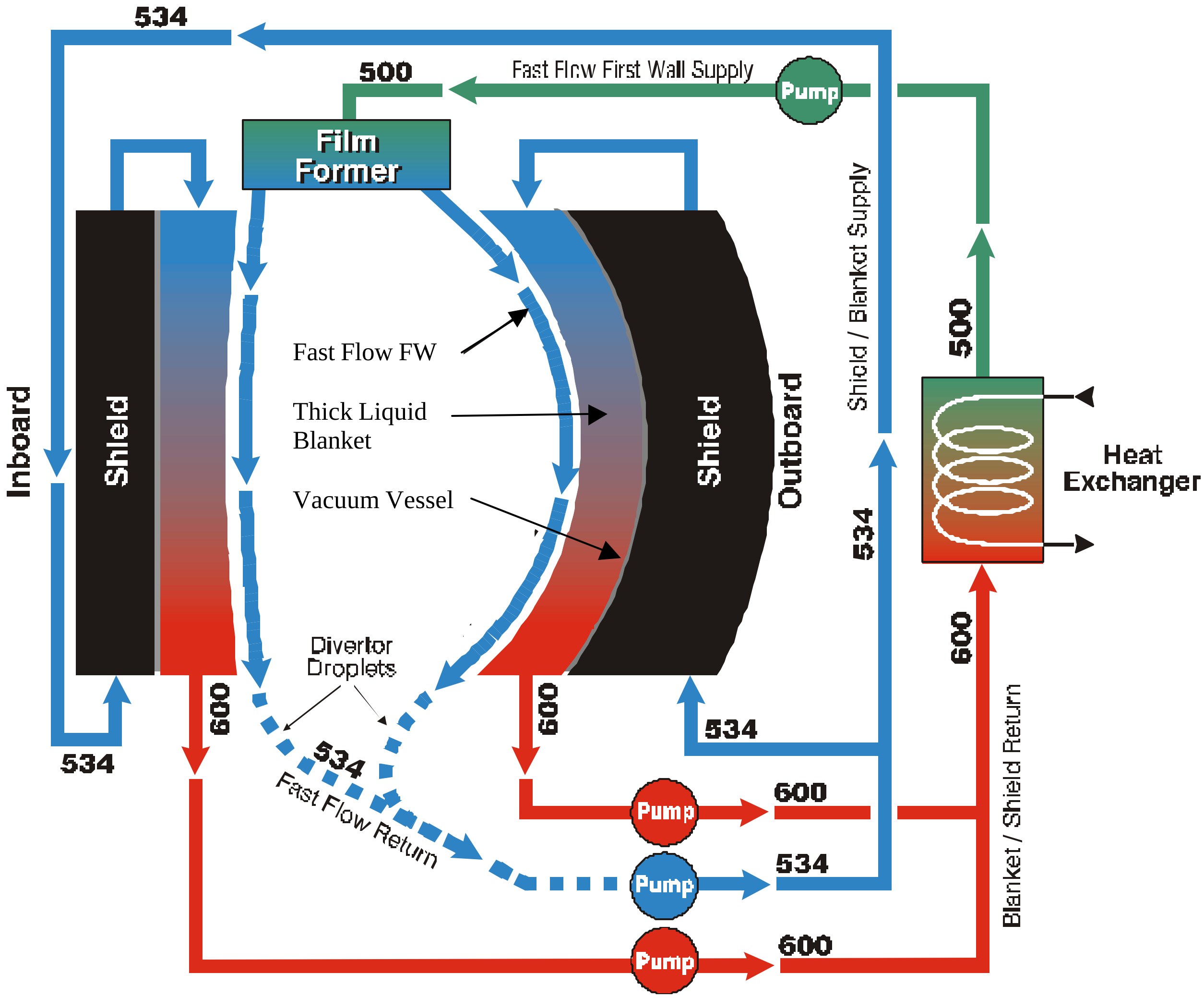
1. **Liquid Walls** (Revolutionary)

   - High Power Density, "true" low activation, reduce material problems, lower failure rate, easier maintenance
   - Candidate liquids: Li, Sn-Li, Flibe
   - Design Options:
     - CLIFF
     - Gravity-Momentum-Driven (with and without rotation)
     - Electromagnetically Restrained (Lithium Only)

2. **High-Temperature Refractory Alloy** (Evolutionary)

   - High-Temperature, High-Power Density Capability
   - Candidate Structure: W alloys (Nb, T-111, TZM)
   - Design Options:
     - Helium Cooling (high pressure)
     - EVOLVE (Two-Phase Lithium Flow)

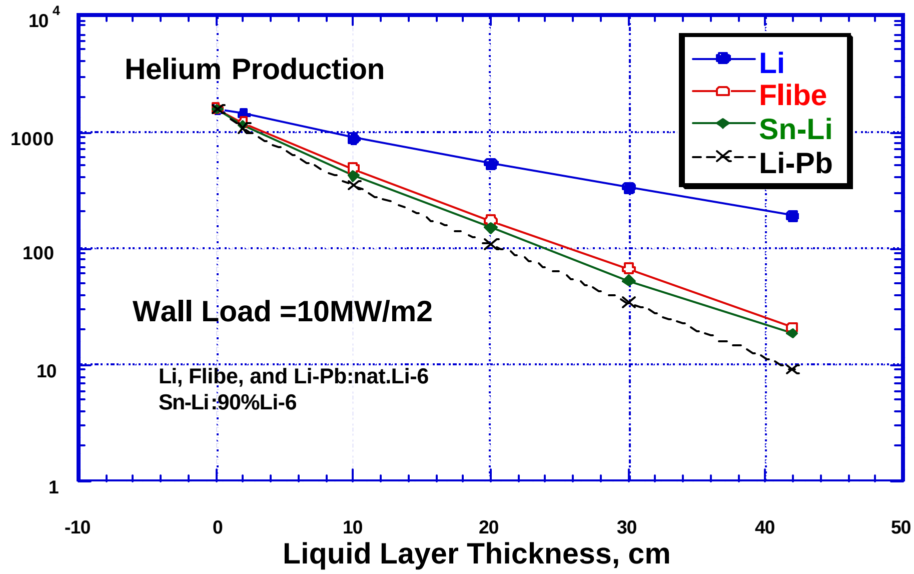
# Potential Attractiveness for an ALL-LIQUID FW/Blanket

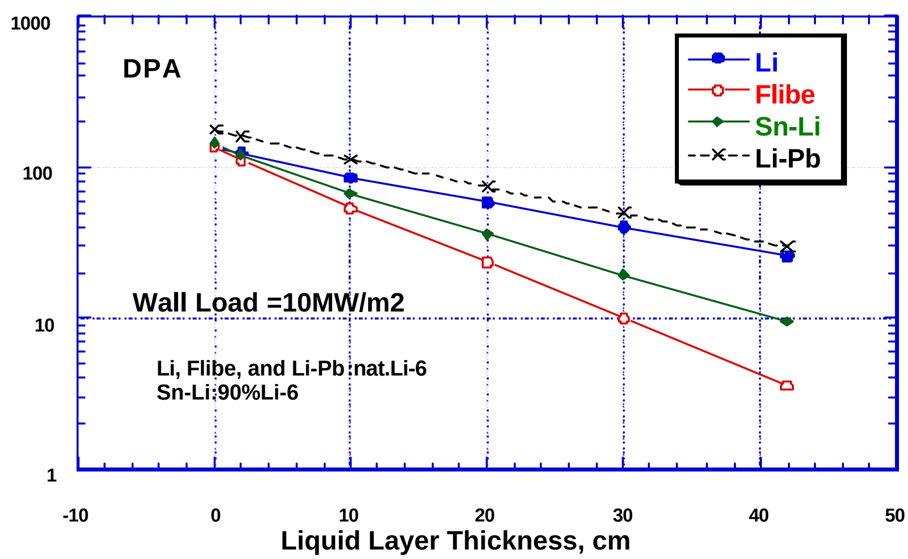



- **High Power Density**
- **High Thermal Conversion Efficiency** Dramatic **Reduction in Radiation Damage and Activation**
- **Higher Availability – Lower Failure Rates – Faster Maintenance**

* Temperatures shown in figure are for Flibe

# Liquid Walls Dramatically Increase Lifetime of Structure




## Conclusions

- An Order of Magnitude reduction in He for:
  - Flibe: 20 cm
  - Lithium: 45 cm
- For sufficiently thick liquid: Lifetime can be greater than plant lifetime

## Liquid Walls Have the Potential to Substantially Reduce the Radwaste Volume

- The total volume of the FW/Blanket, Shield and Magnet is inversely proportional to the NWL
  - Higher Power Density reduces readwaste volume
  - Example: If NWL goes from 4 to 10 $MW/m^2$, the total radwaste volume is reduced by a factor of 2

- Liquid walls Concepts have the potential to reduce the volume of radioactive waste materials in the high flux region of the FW/Blanket by a factor of 50 to 100.

# <u>Liquid Concepts Currently Being Explored in APEX</u>

1. Liquid First Wall (CLIFF)
   - 1 cm liquid removes all the surface heat
   - Near-Term Applications in Plasma Devices

2. Thick Liquid FW/Blanket
   - Highest Potential but Most Challenging
     - A. Electromagnetically-Restrained Thick Lithium
     - B. Contiguous Gravity-Momentum-Rotational Flow
     - C. Separate Liquid FW and Liquid Blanket

<u>Candidate Liquids</u>
- Lithium
- Sn-Li
- Flibe

# Challenging Issues for Liquid Walls

## 1. Plasma-Wall Interaction

A. Surface Interactions

- What is the Allowable Temperature of the Liquid Surface Facing the Plasma?

B. "Bulk" Interactions

- Requirements on Field Penetration, Field Error, etc.
- Plasma Disruptions

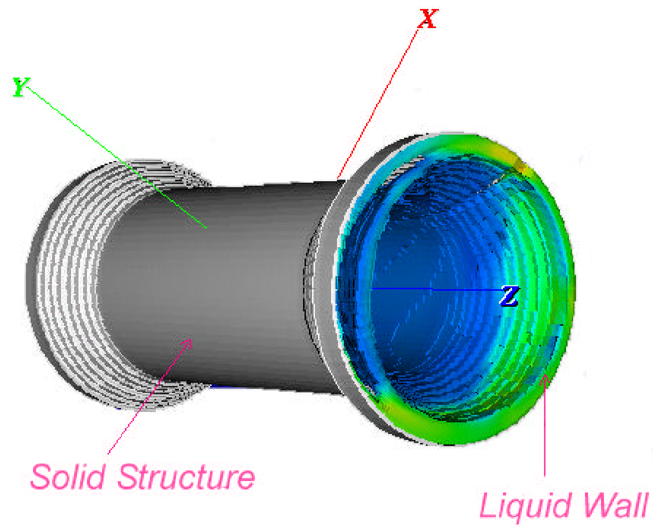
## 2. Temperature Control

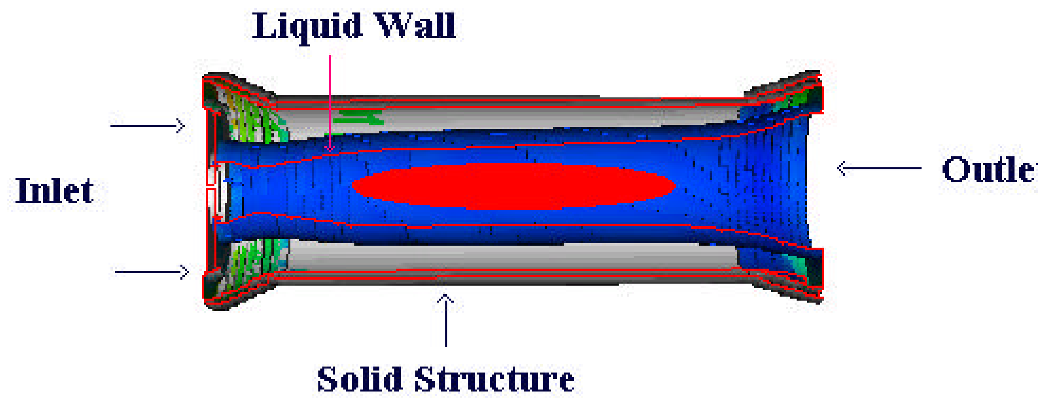
- How to Achieve Low Surface Temperature and High Bulk Temperature?

## 3. Hydrodynamic Configuration

- How to Form and Maintain the liquid FW/Blanket?

# Swirling Thick Liquid Walls for High Power Density FRC

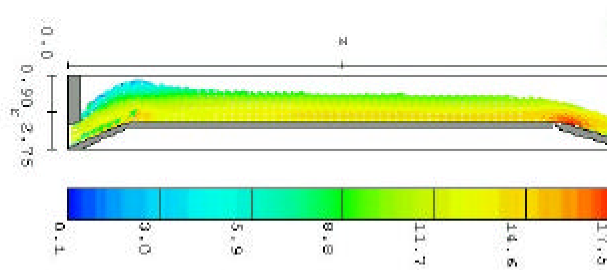


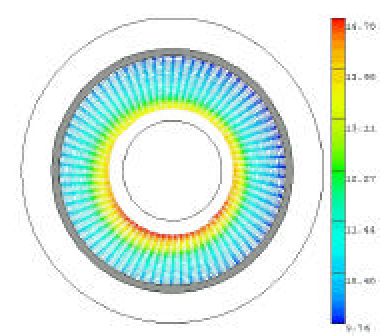




- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

- *Computer Simulation*: **3-D time-dependent Navier-Stokes Equations solved with RNG turbulence model and Volume of Fluid algorithm for free surface tracking**

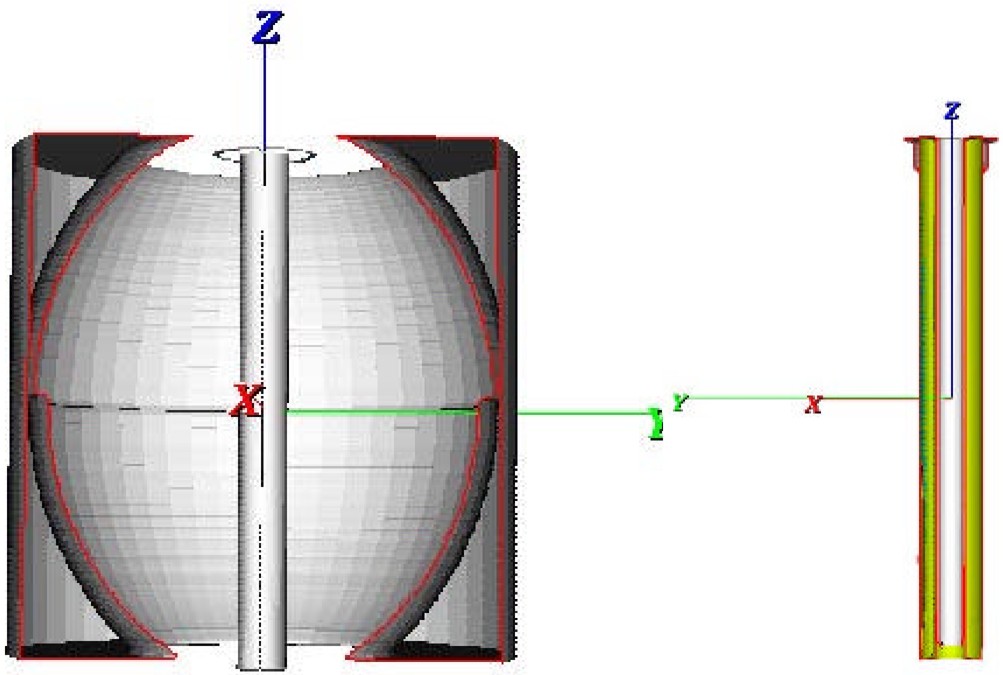
- **Results:** Adhesion and liquid thickness uniformity (> 50 cm) met with a flow of $V_{axial}$ = 10 m/s, $V_{q,ave}$ = 11 m/s

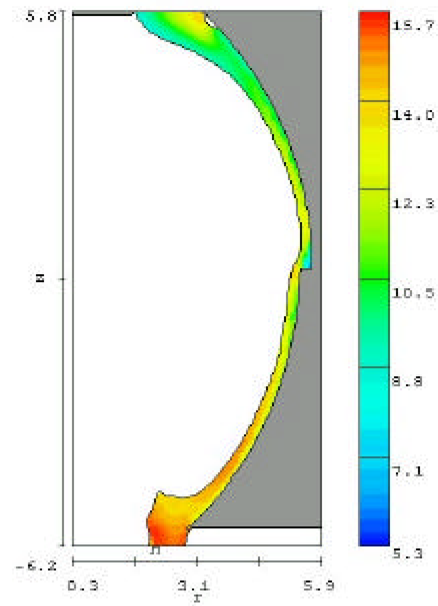




Calculated velocity and surface depth

# Toroidally Rotating Thick Liquid Wall for the ST




## Design Concept:

- Thick liquid flow from reactor top
- *Outboard:* Fluid remains attached to outer wall due to centrifugal acceleration from the toroidal liquid velocity
- *Inboard:* Fast annular liquid jet

## Simulation Results:

- Step in outboard vacuum vessel topology helps maintain liquid thickness > 30 cm
- Calculated outboard inlet velocity, $V_{poloidal} = 4.5$ m/s, $V_{toroidal,ave} = 12$ m/s
- Inboard jet $V_z = 15$ m/s is high to prevent excessive thinning, < 30%

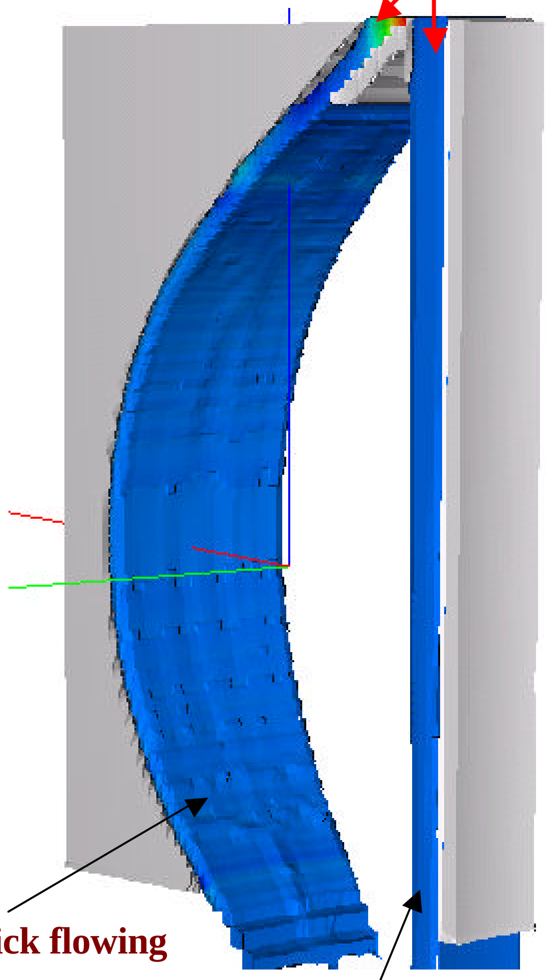
# Advanced Tokamak

## 3-D Hydrodynamics Calculation Indicates that a Stable Thick Flibe-Liquid Wall can be Established in an Advanced Tokamak Configuration

**ARIES-RS Geometric Configuration**
**(major radius 5.52 m)**

**Inlet velocity = 15 m/s;**
**Initial outboard and inboard thickness = 50 cm**

**Area expansion**
**Toroidal width = 61 cm Corresponding to 10$^{o}$ sector**



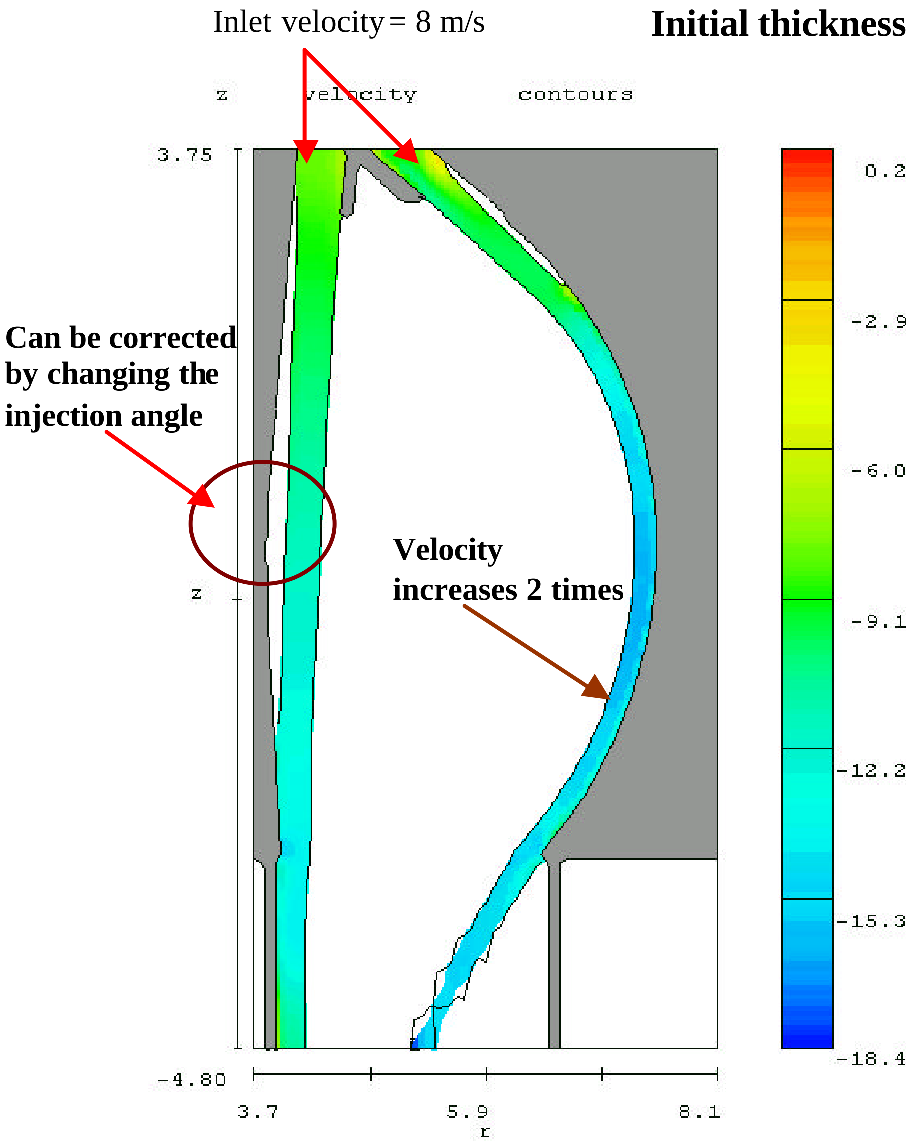

### *The thick liquid layer:*

- ***is injected at the top of the reactor chamber with an angle tangential to the structural wall***
- ***adheres to structural wall by means of centrifugal and inertial forces***

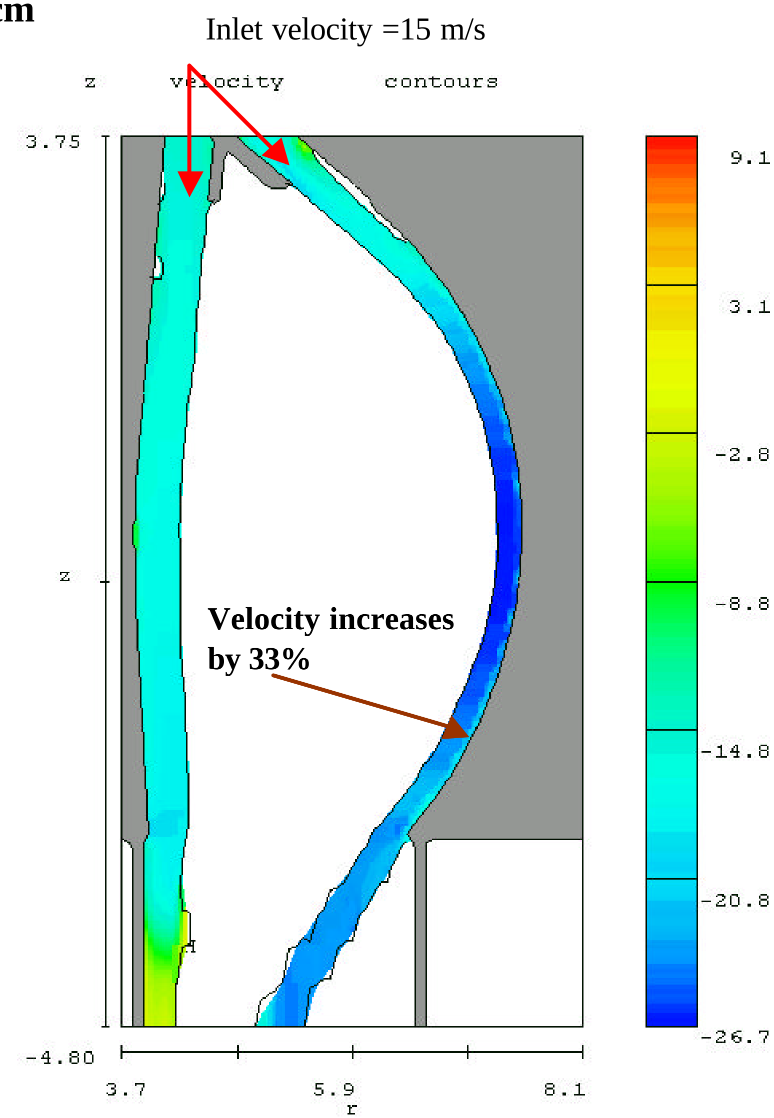
# Some amount of thinning was observed along the poloidal path due to gravitational thinning and toroidal area expansion

## z-velocity components along the structural inner walls from 3-D hydrodynamics calculations

**Initial thickness = 50 cm**




**t/pass = 0.9 second**




**t/pass = 0.5 second**

# Optimum Hydrodynamic Configurations for ST and Advanced Tokamaks can be Different

ST: Poloidal Flow with TOROIDAL ROTATION

Typical $V_v = 5$ m/s $V_? = 11$ m/s

AT: Poloidal Flow (No Rotation)

## Reason

To Adhere to the wall: $U^2/R > g$

- ST is taller and has Higher Radius of Curvature (R) in the poloidal direction

$$R_{ST} \sim 2\, R_{AT} \qquad [U^2/R]_{AT} \sim 2[U^2/R]_{ST}$$

- But, ST has smaller radius of curvature in toroidal direction than in the poloidal direction
- Therefore, Toroidal Rotation of Flow in ST results in substantial increment in the centripetal acceleration towards the backwall and better adherence to backwall
- Also, since ST is taller, the increase in velocity due to gravitation acceleration (and thinning) is larger

# 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

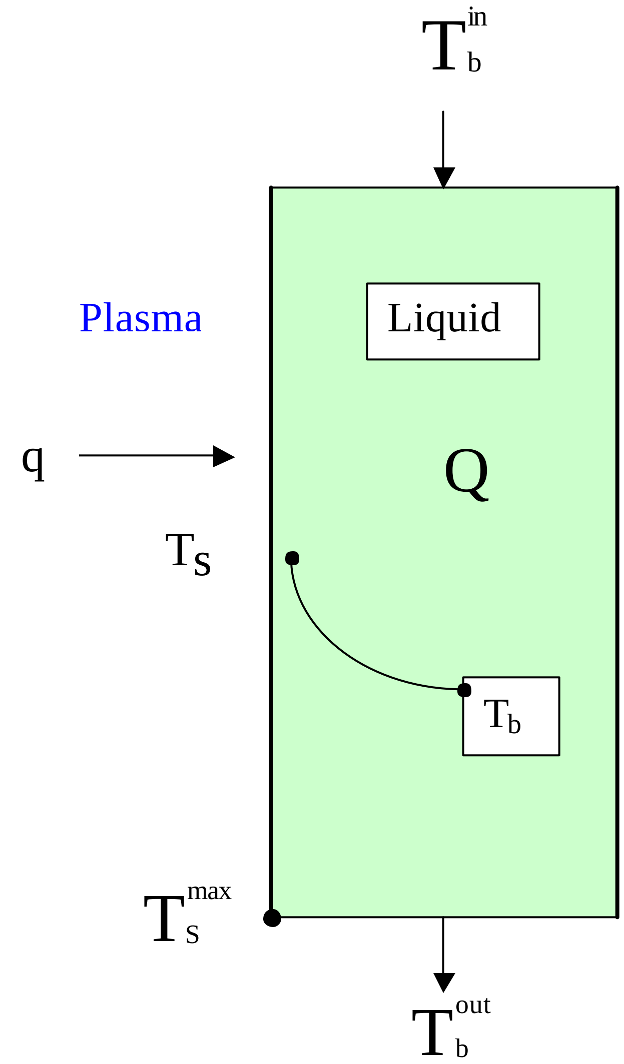
   $V^2/R > g$

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

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



# What is the Maximum Allowable Surface Temperature?

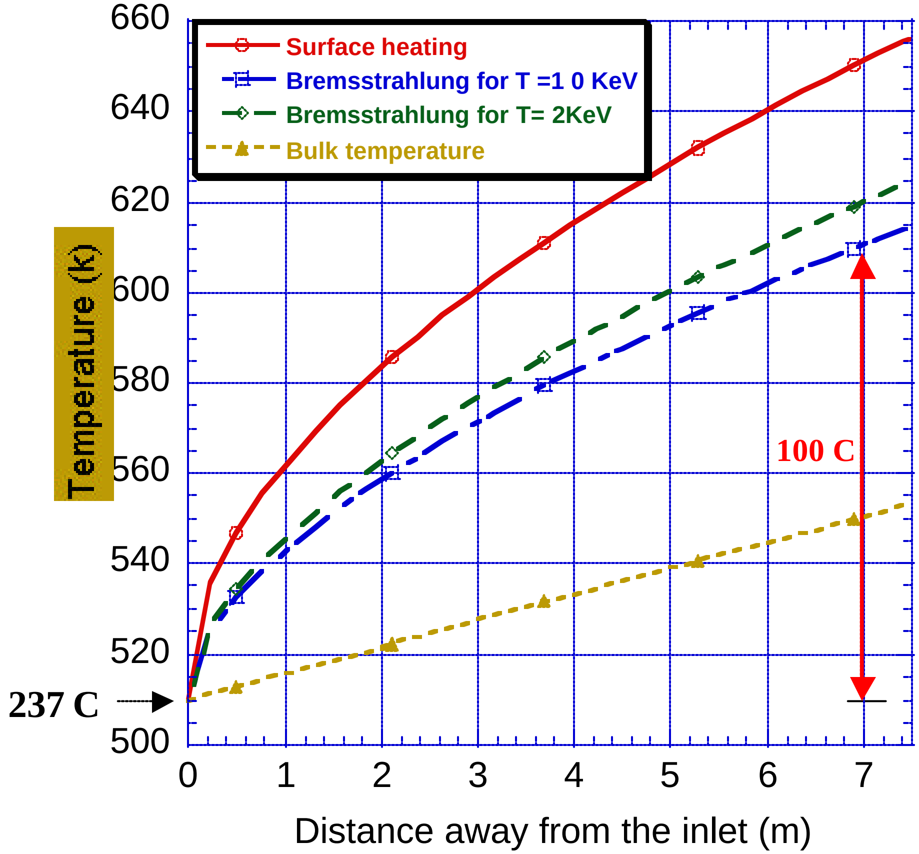
- An Edge Modelling Group for ALPS/APEX has been formed that involves a number of experts from the Physics community
  - J. Brooks, Coordinator
  - T. Rognlien responsible specifically for liquid walls (APEX)
- Reliable Answer requires:
  - extensive modelling
  - plasma experiments with liquid surfaces
- Current "Best Guess" on $T_s$ from plasma impurity limit:

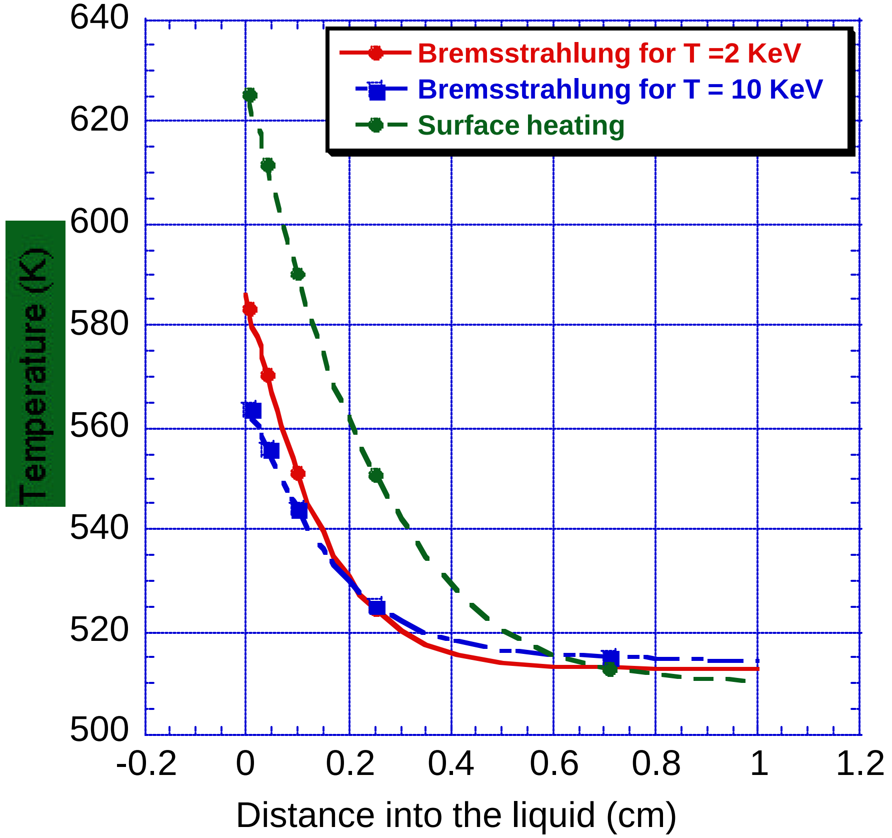
| | |
|---|---|
| Lithium: | $T_s \sim 490^oC$ |
| Flibe: | $T_s \sim 560^oC$ |
| Sn-Li: | $T_s \sim 820^oC$ (low vapor pressure) |

# 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

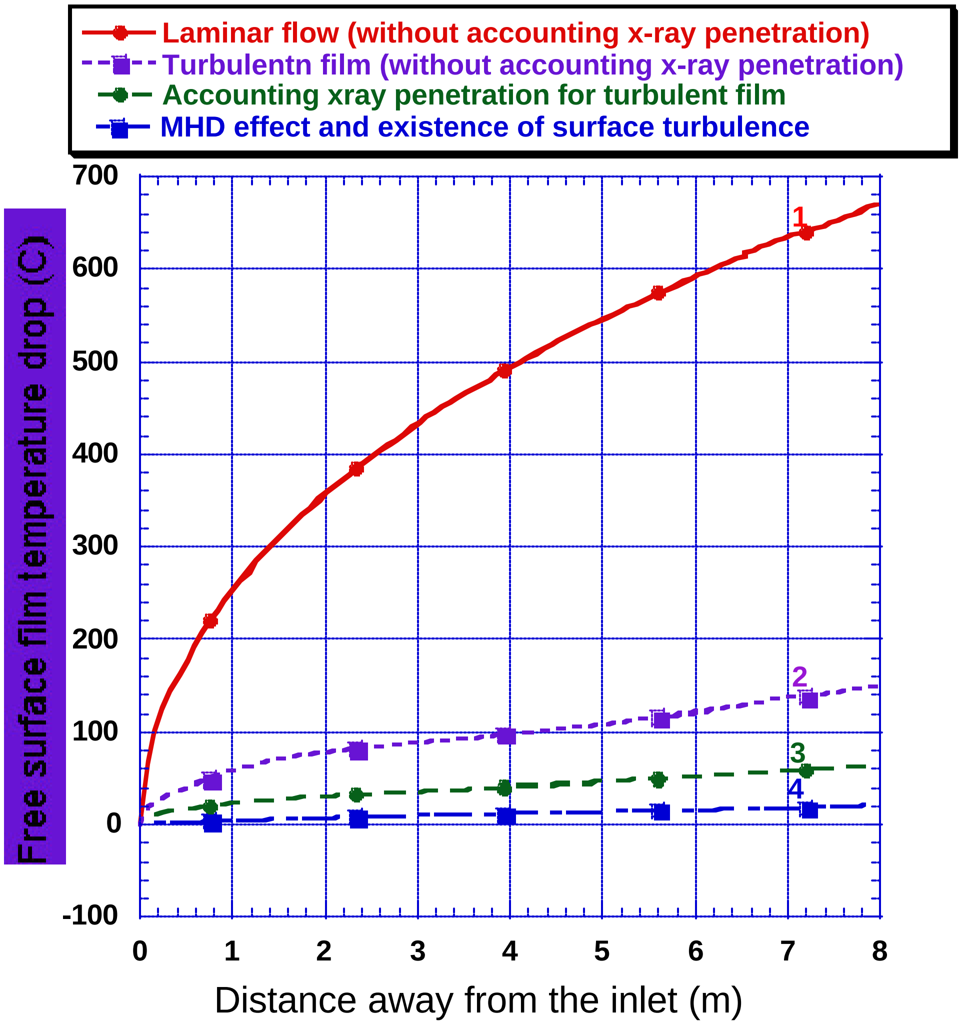
Li velocity = 20 m/s
Surface heat load = 2 $MW/m^2$



# Effect of Different Heat Transfer Mechanisms on Flibe Free Surface Temperature

- If the Flibe flow is laminarized, the Flibe free surface can be overly heated. The film temperature drop can reach 700 $^oC$ at the bottom of ARIES-RS under APEX 2 MW/m$^2$ surface heat load (curve 1).
- Turbulent heat transfer considerably reduces Flibe free-surface temperature drop (curve 2).
- Accounting for Bremsstrahlung radiation penetration further reduces surface temperature by about 90 $^oC$ (curve 3).
- Heat transfer at the vacuum/free surface interface can be significantly enhanced by the existence of surface turbulence (Smolentsev, curve 4)
- Initial calculation based on k-e model indicates that turbulence suppression due to MHD can be neglected at the current parameters of interest (Smolentsev, curve 4)



# Impact of Temperature Control on Hydrodynamic Configuration

- Thermal Efficiency Depends on Outlet Temperature

  To attain ? (net) > 40% need $T_{out} > 600°C$

**Lithium**

- The maximum allowable surface temperature is probably < 500ºC
- Therefore two coolant streams are necessary

**Flibe**

- Allowable surface temperature probably in the range 550 to 650ºC
- For > 650ºC: One Coolant Stream Possible
- For < 550ºC: Two Coolant Streams Needed

**Two Coolant Streams**

- Fast moving thin liquid jet as low-temperature FW
- Slow moving thick liquid as high-temperature blanket
- Several Design Options Exist for Hydrodynamic Configurations

# Several Innovative schemes have been proposed in APEX to ensure compatibility of free-surface liquids with plasma operation while attaining High Thermal Efficiency

These include

**Design innovation:**

1. Fast flowing liquid jet, separate from slow moving liquid blanket, to keep surface temperature of the liquid (and hence evaporation rate) low, while the slow moving blanket has high outlet temperature
2. New Schemes to promote controlled surface mixing and wave formation to eliminate surface thermal boundary layer

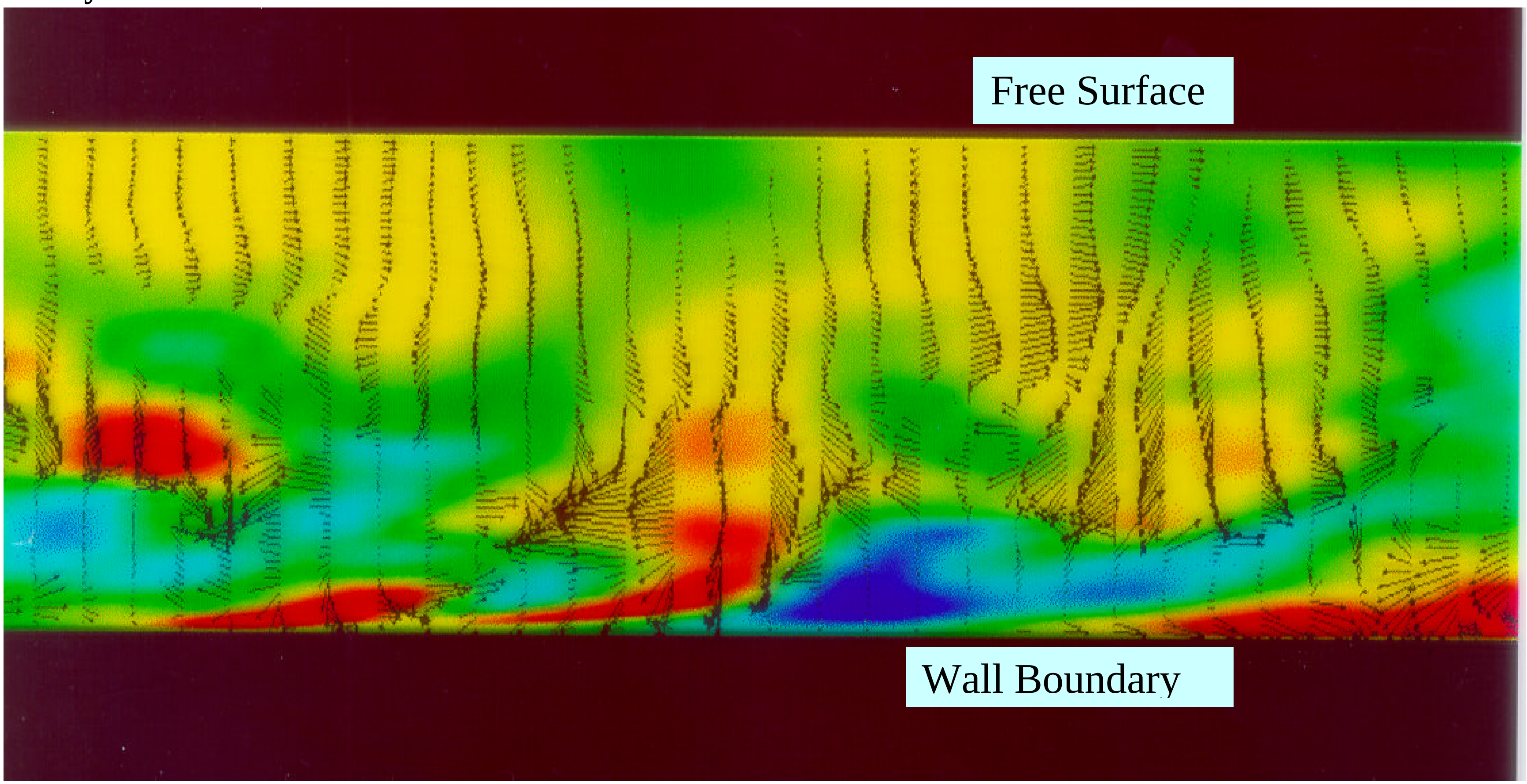
**Material innovation:** discovery of a new lithium-containing material (SnLi) that has low vapor pressure at elevated temperatures

**Accounting for hard Bremsstrahlung radiation penetration:** the surface heat load can be deposited deeper in the liquid; this significantly reduces the liquid jet surface temperature

**APEX Modeling of Free-Surface Flow is A Challenging Engineering Science Problem and is Attracting Outstanding International Experts**

(UCLA/Toyama/Tokai University Collaboration- Professors Satake and Kunugi)

**Reynolds number ~ 5000**



# Challenge: How to Accommodate Void Penetrations (For Heating, Fueling, etc.) in Liquid Walls?

<u>APEX Approach to Problems</u>

1. Understand the Problem and the Underlying Sciences

2. Search for “Innovative Solutions”
   Our Job is “How to Make Things Work”

3. Do good Analysis using the best engineering sciences tool available

4. Confirm by “low-cost and fast” experiments

<u>Penetration Analysis</u>

- Calculations were performed for Elliptical Penetrations solving 3-D, time-dependent Navier-Stokes equations using the best computational tools

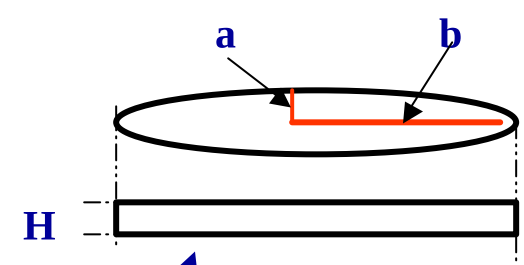
- Results are Very Interesting and Encouraging. Solutions are being developed to overcome problems revealed by the calculations

# INITIAL REFERENCE PENETRATION CASE FOR 3-D TIME DEPENDENT FLUID FLOW CALCULATIONS

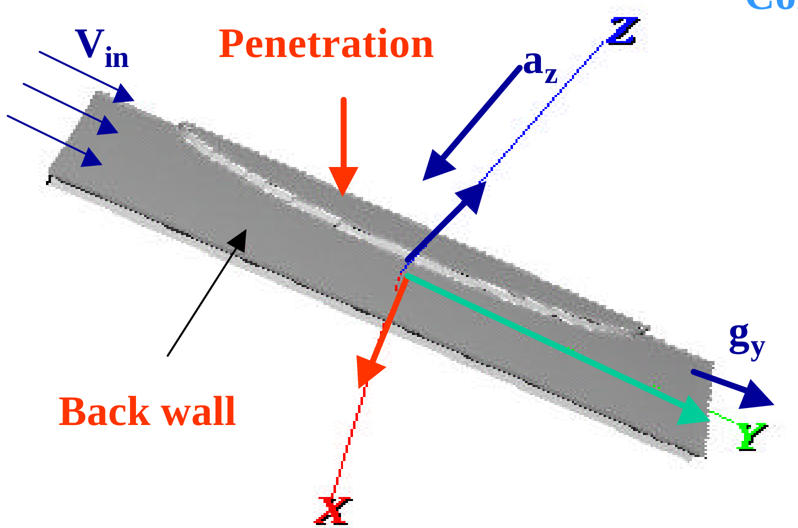
## REFERENCE CASE PARAMTERS

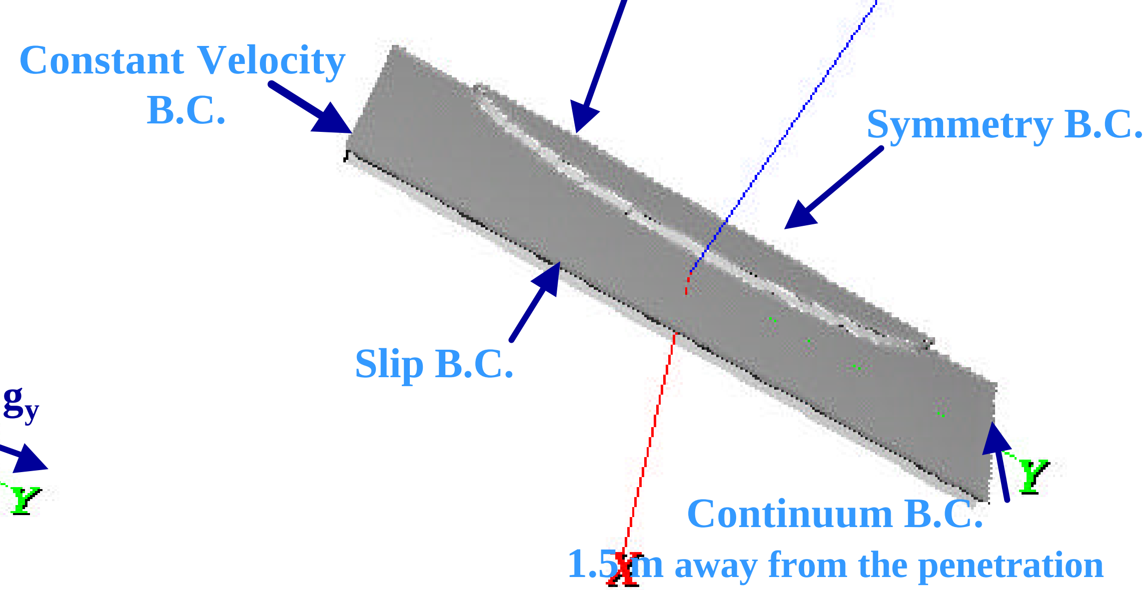
| | | | |
|---|---|---|---|
| $V_{in}$ (m/s) | 10.0 | | |
| $a_z$ ($m^2$/s) | 25.0 | | |
| $g_y$ ($m^2$/s) | 9.8 | | |
| Wall Roughness (m) | $10^{-5}$ | | |
| Fluid-Wall Contact Angle | 0.0 | | |
| Penetration Dimensions (m) | a | b | H |
| | .1 | .45 | 0.02 |

Flibe at 550 ºC is used as a working fluid.



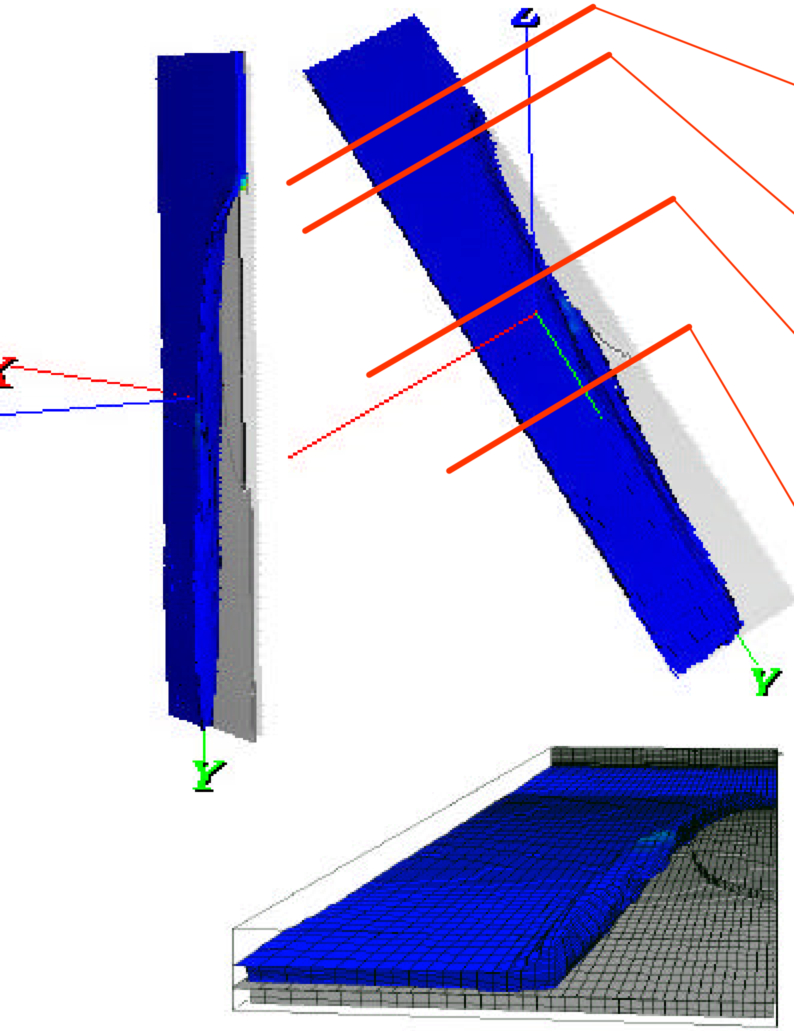

Fluid Wets the Structure.



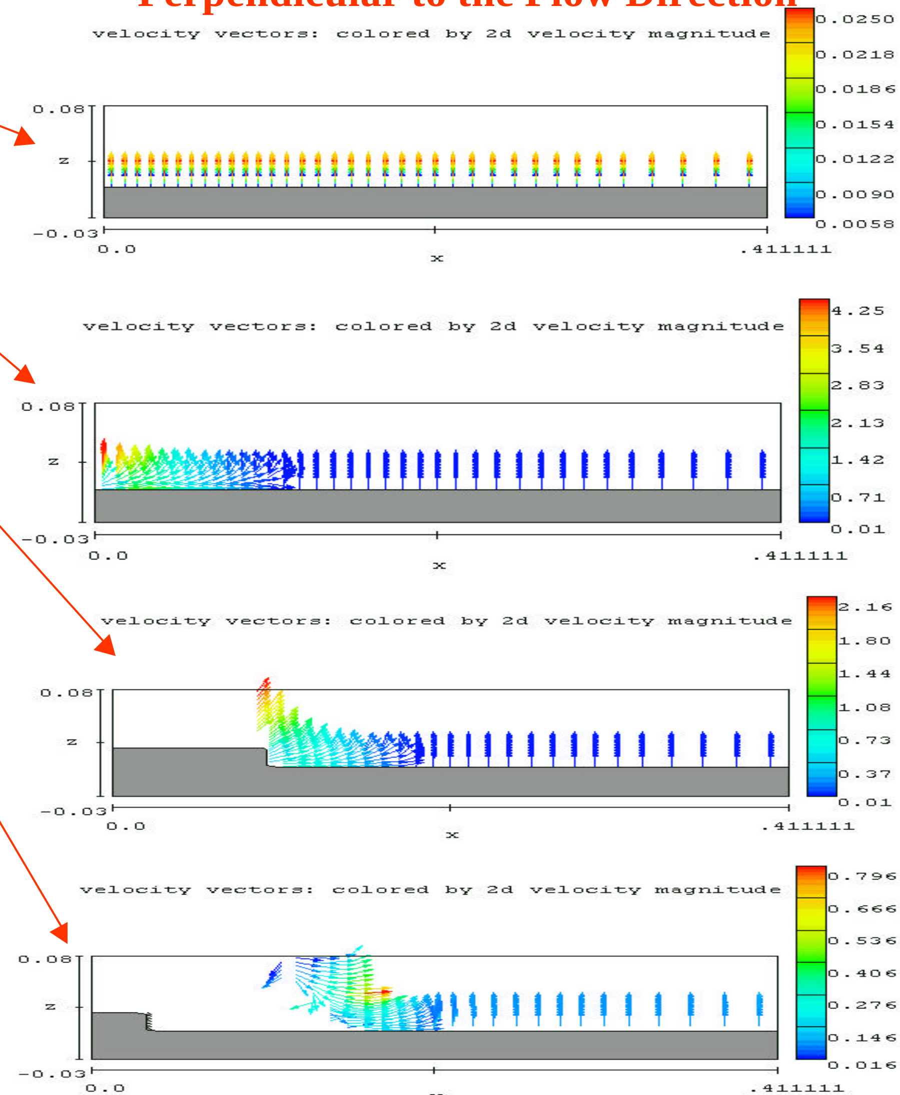



# RESULTS OF 3-D TIME DEPENDENT CALCULATIONS FOR FLUID FLOW AROUND PENETRATIONS (For Initial Case)

**3-D CFD Simulation Results**




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




**3-D View of the Wake Following the Penetration.**

# POTENTIAL CHALANGES 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.

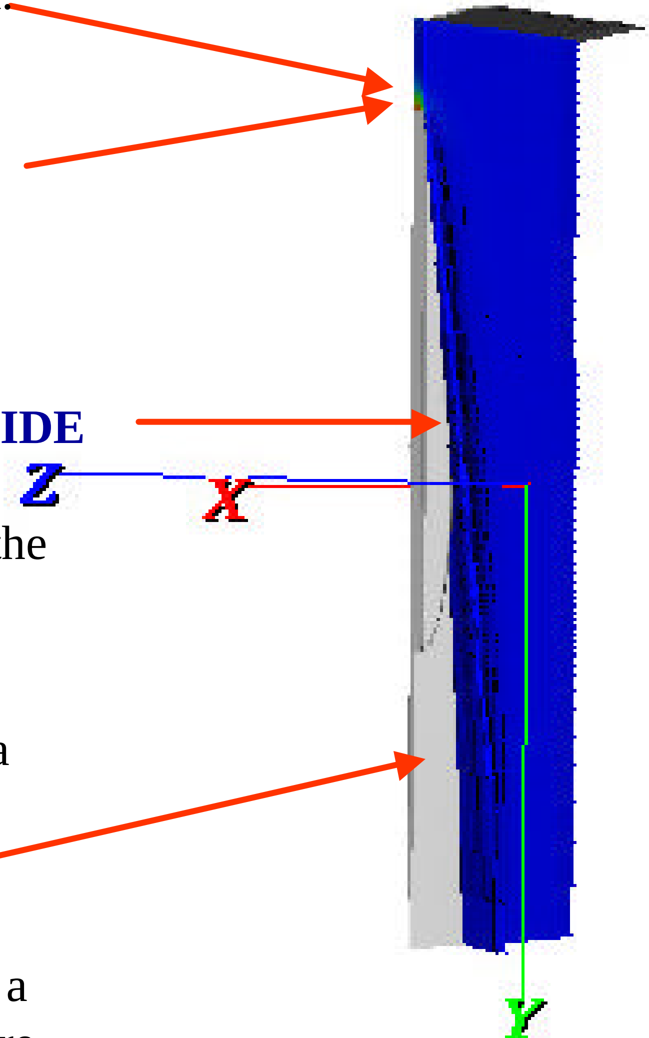
**FLUID LEVEL RISE SURROUNDINDG THE FRONT SIDE OF THE PORT**

- A stream of rising fluid is diverted to the sides surrounding the penetration due to the obstruction of flow path.

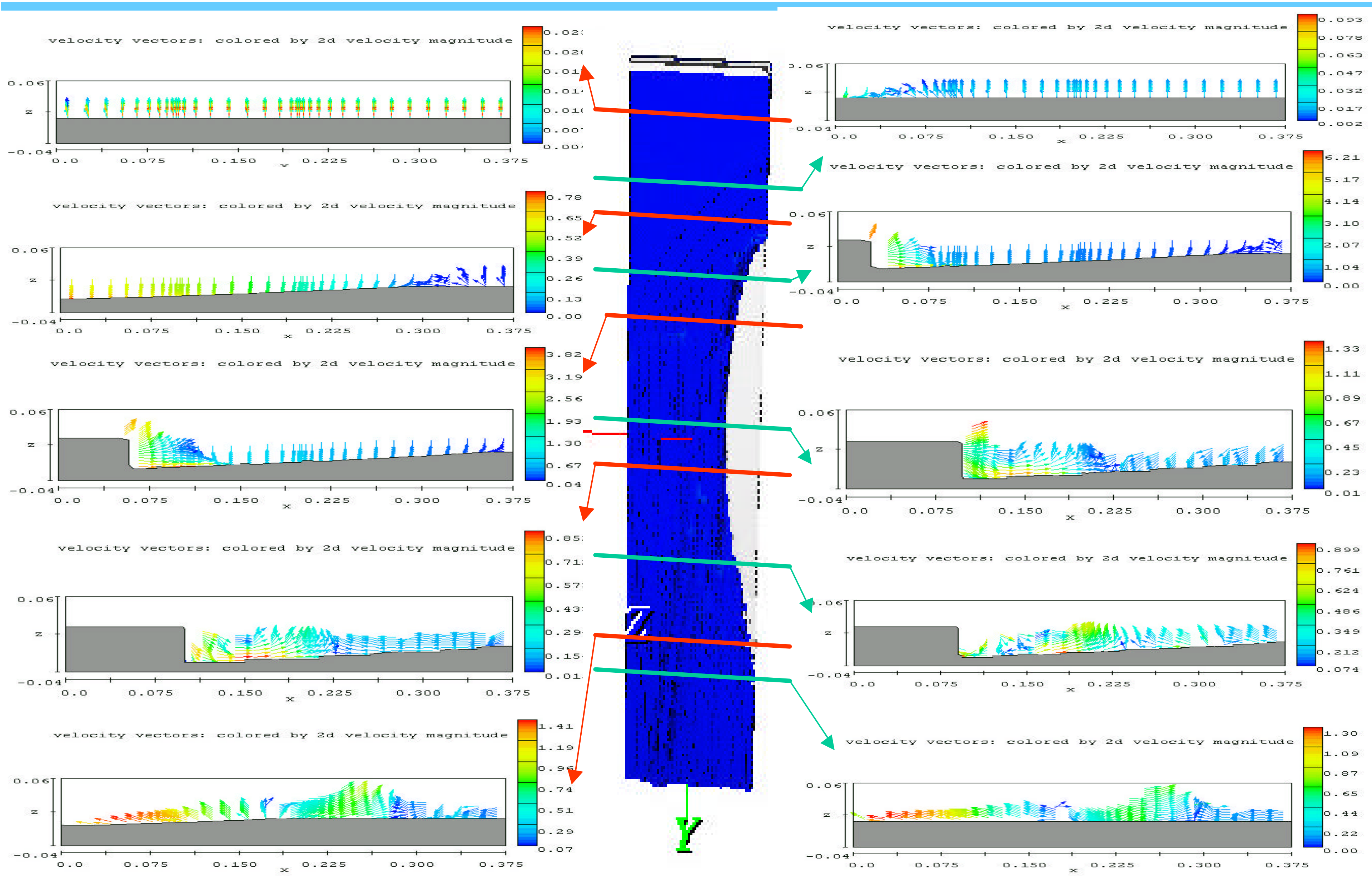
(144 $m^3$ of fluid per hour is displaced for a 20 cm wide (in the flow direction) penetration for the CLIFF concept with a base velocity of 10 m/s.)

**WAKE FORMATION**

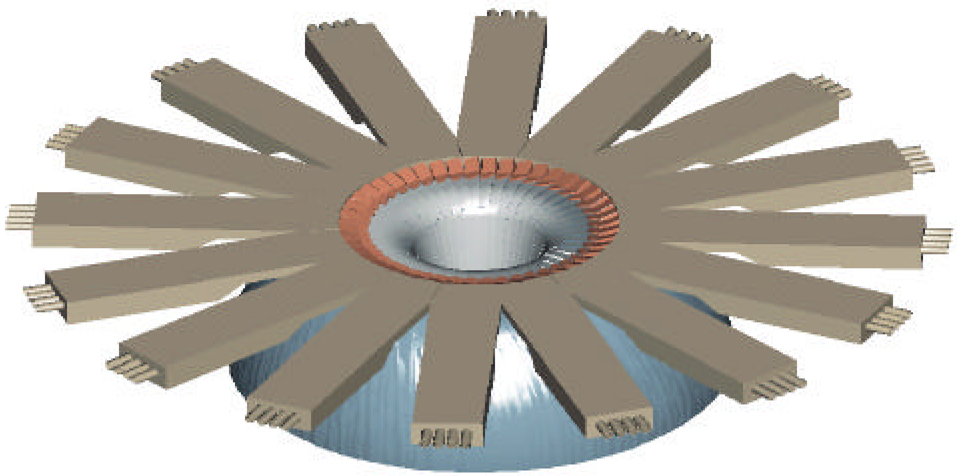
- The wake formation at the end section of the penetration, as a result of deflection of streamlines by the penetration structure.



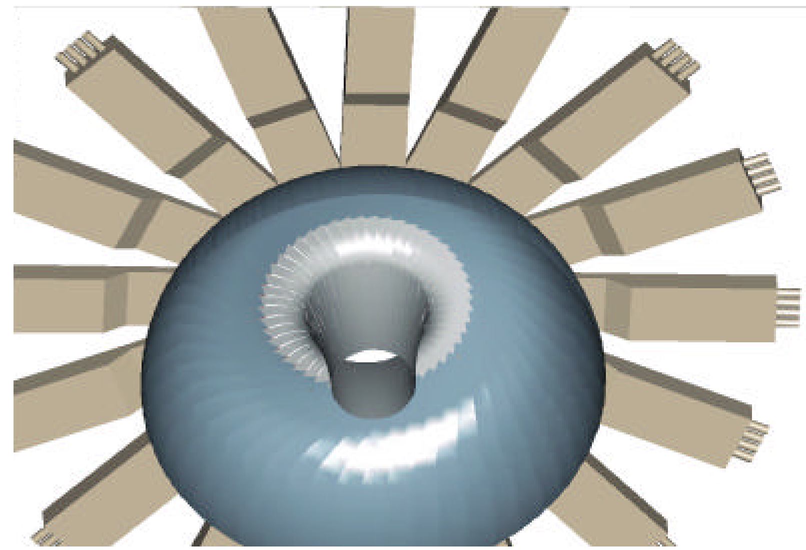
# DESIGN SOLUTIONS, SUCH AS MODIFICATIONS TO BACK WALL TOPOLOGY RESULT IN MORE ATTRACTIVE FLUID FLOW CHARACTERISTICS AROUND PENETRATIONS



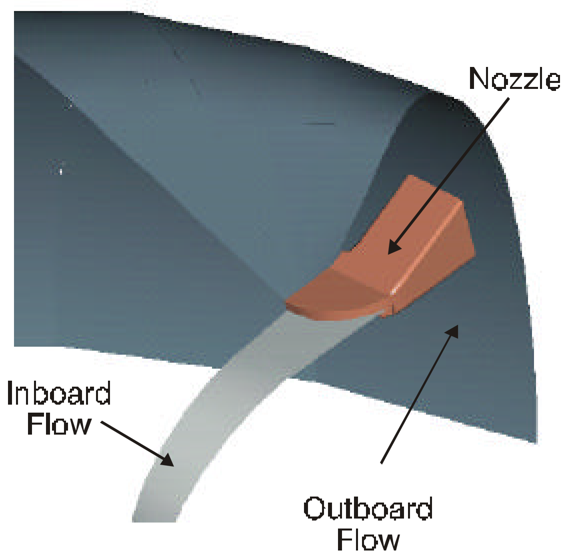
# Convective Layer Forming Device



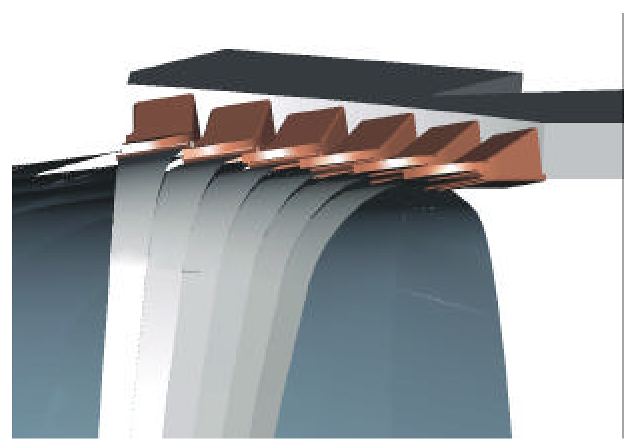
Top view of convective layer forming device array



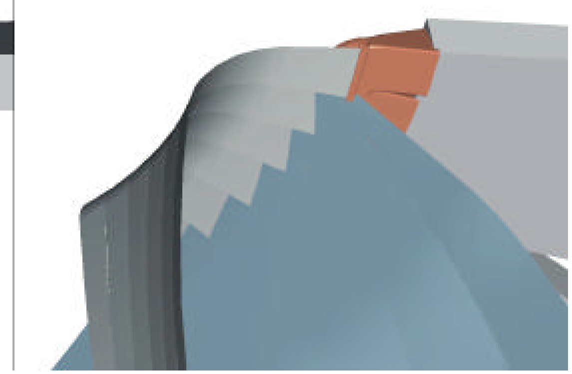
View looking up from inside the machine




View of convective layer forming device - single nozzle



View from centerline of machine showing inclination of nozzles

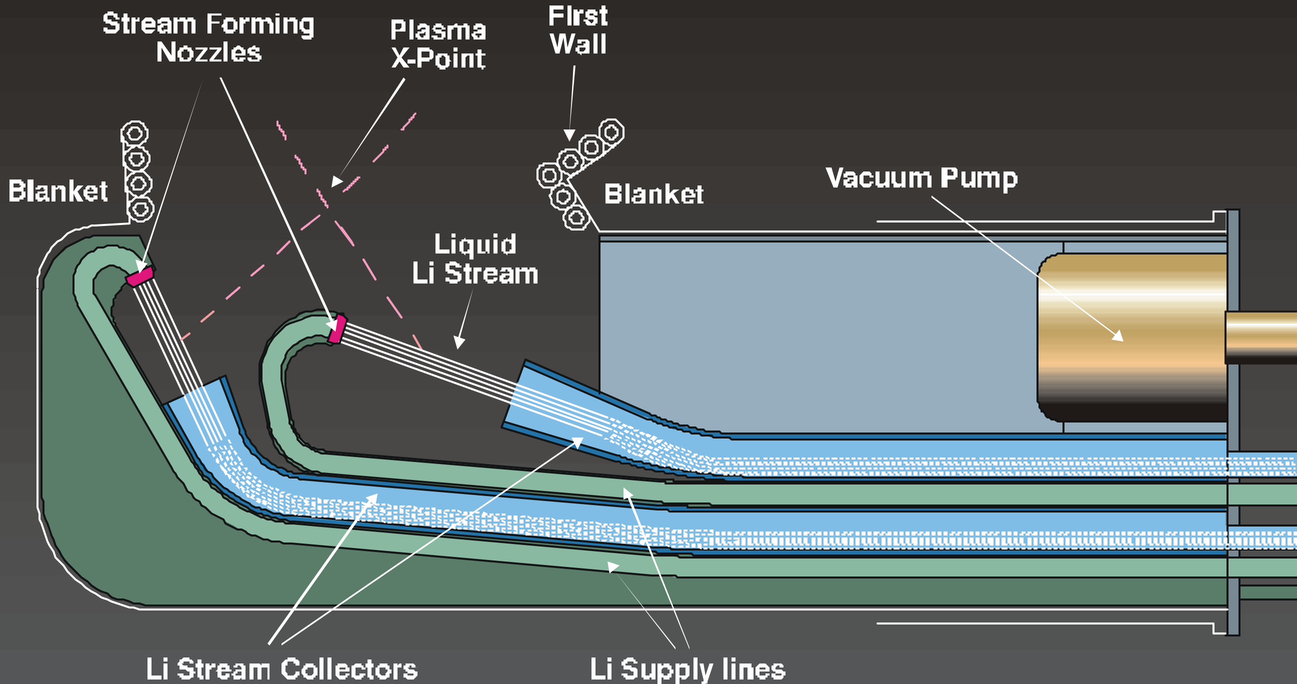


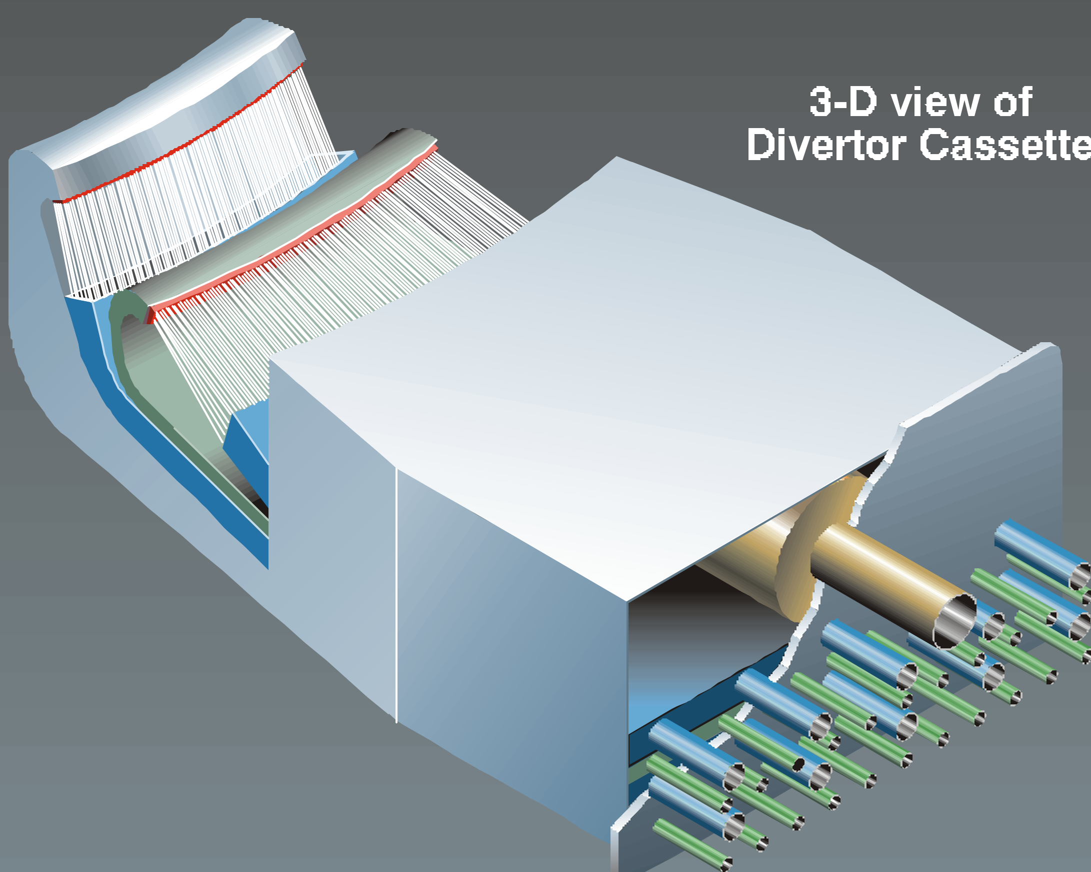
View from plasma looking up, nozzles are completely shielded

APEX

# Evolve Divertor Cassette

(Elevation View)

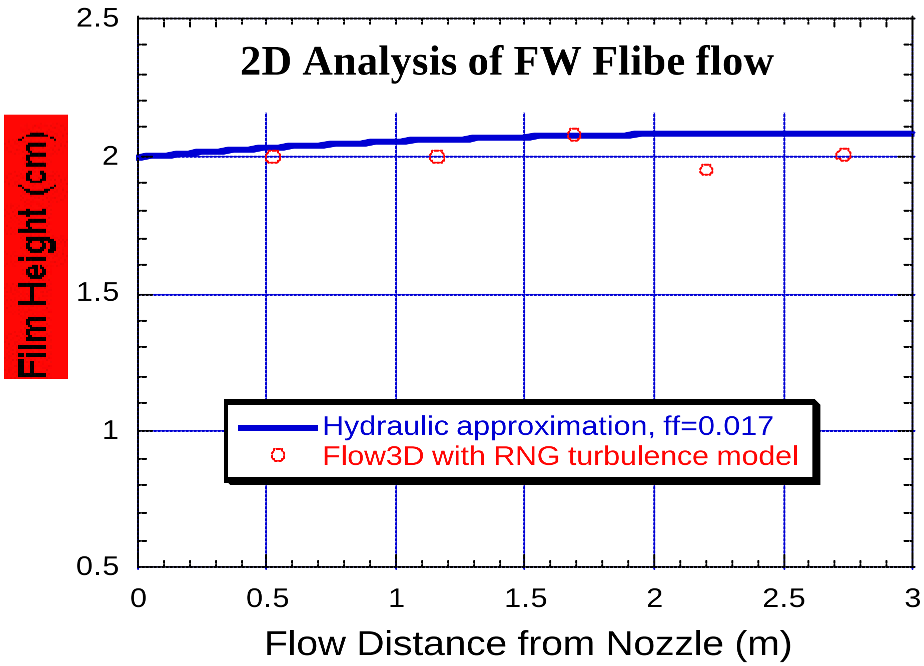


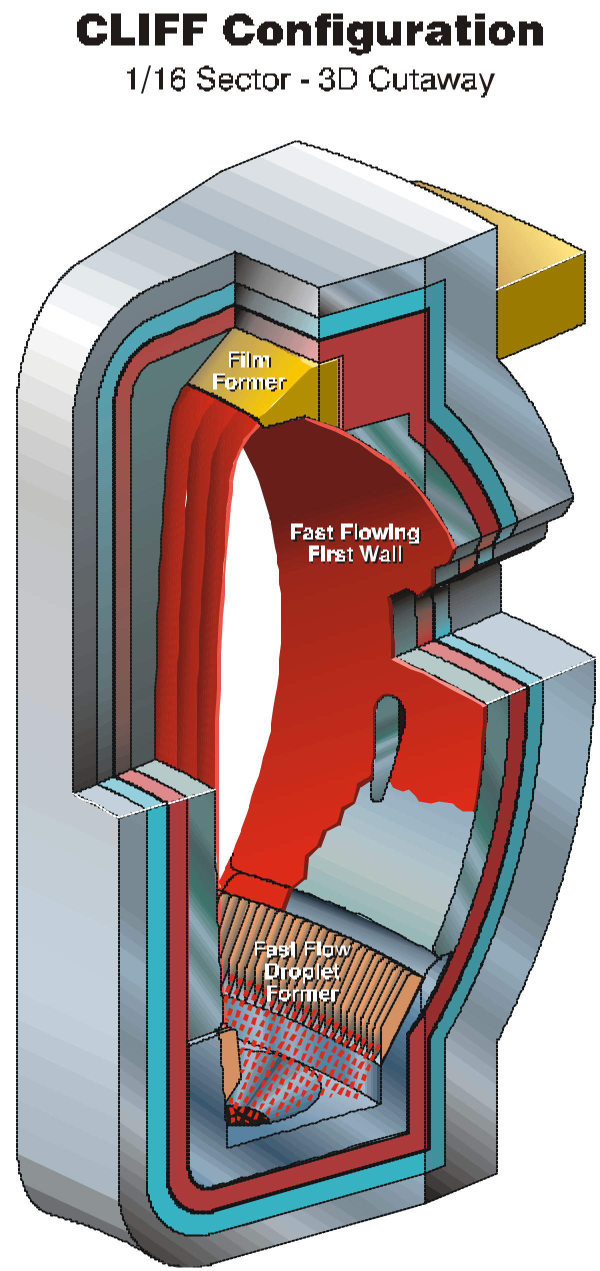



3-D view of Divertor Cassette

# *Convective Liquid Flow First Wall (CLIFF) Concepts*

- **Underlying structure protected by a fast moving layer of liquid, typically 1 to 2 cm thick at 10 to 20 m/s.**
- **Liquid adheres to structural walls by centrifugal force**
- **2D hydrodynamic calculations confirm near equilibrium flow for Flibe at 2 cm depth and 10 m/s velocity (below)**



# *Potential and Issues of CLIFF Concepts*

- **Potential:** Removal of surface heat loads (greater than 2 $MW/m^2$ possible). Local peaking and transients can be tolerated.
- **Potential:** FW surface protected from sputtering erosion and possibly disruption damage
- **Potential:** Elimination of high thermal stresses and pressures in solid FW components, having a potentially positive impact of FW/Blanket failure rates
- **Potential:** Possible reduction of structure-to-breeder material ratio in FW area, with breeder material facing virgin neutron flux
- **Potential:** Integrated divertor surface possible where CLiFF removes all $\alpha$ heat
- **Potential:** Complex tokamak D-shape and port penetration can be accommodated, implementation is straight-forward

- **Issue:** Hydrodynamics and heat transfer involve complicated MHD interaction between flow, geometry, and the magnetic field:
  - Suppression of turbulence and waves
  - LM-MHD drag thickening the flow and inhibiting drainage from chamber
  - MHD effects of spatially and temporally varying fields on LM surface stability
- **Issue:** Evaporated liquid can pollute core plasma, surface temperature limits unknown
- **Issue:** High mass flowrate requirement can result in low coolant $\Delta T$ or two coolant streams
- **Issue:** Effect of liquid choice on edge plasma gettering, tritium through-put, and tritium breeding
- **Issue:** Neutron damage in structure is only slightly reduced compared to standard blankets, frequent blanket change-out required for high power density operation

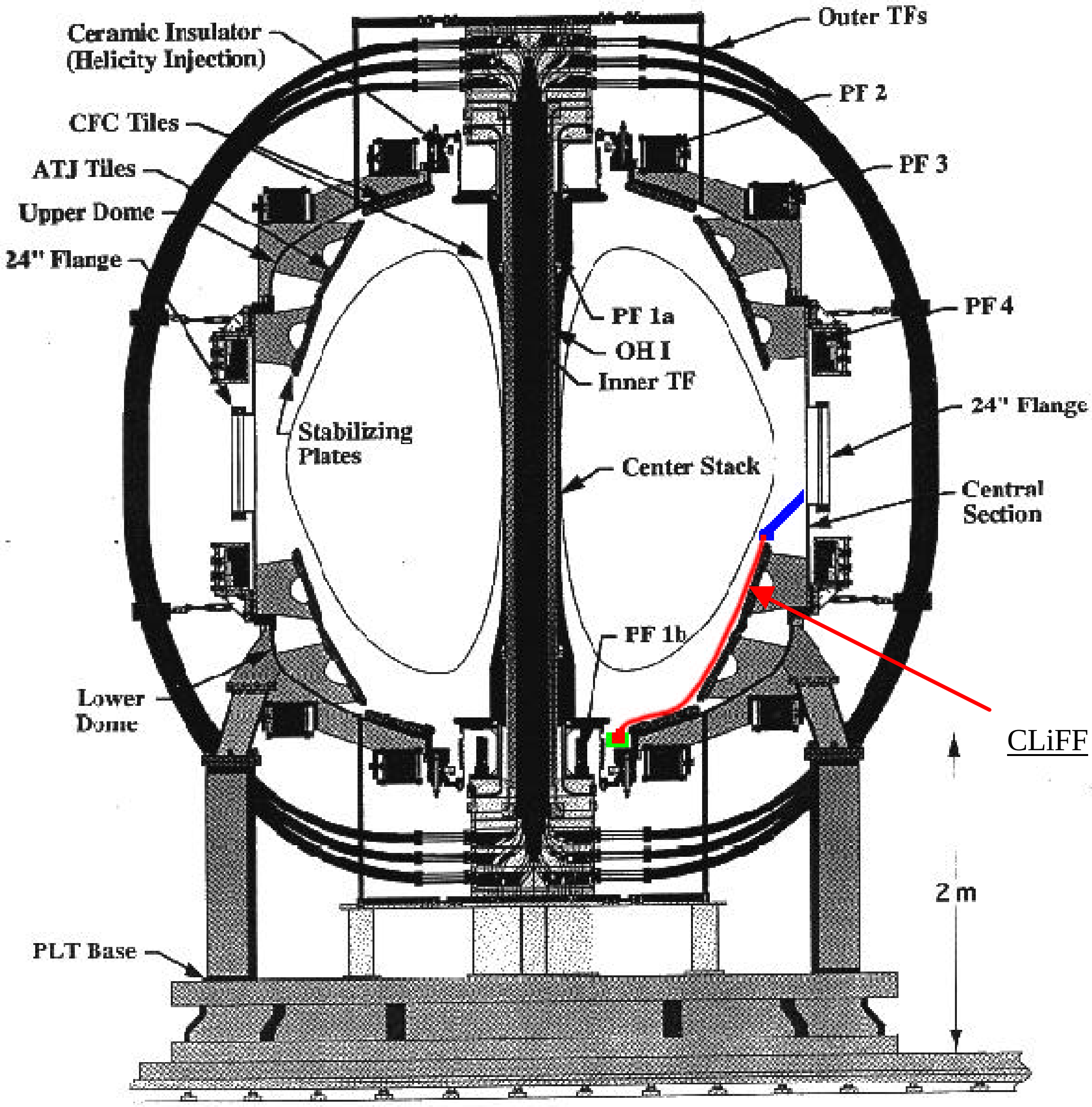
# Liquid Walls Can Substantially Reduce Time and Cost of Major Facilities Prior to DEMO

## Proof of Principle and Proof of Performance can be obtained with a combination of Computer Simulation and Laboratory Experiments

| | Major Facilities for: | |
|---|---|---|
| | **Solid Wall/Evolutionary** | **Liquid Wall/Revolutionary** |
| **Key Testing Environment** | **-NEUTRONS**<br>**-Surface heat flux** | **- Surface heat flux** |
| **Dominant Testing Effects** | **-Radiation Damage**<br>**-Failure Modes/Rates**<br>**-Maintenance Time** | **-Hydrodynamics/heat transfer** |
| **Capital Cost for a Major Facility** | **1) Component Testing (Facility) > $2B**<br>**2) IFMIF-type > $1B** | Thermofluid facility<br>~ $50 M |
| **Time to obtain test data** | **> 20 years** | **5 years** |
| **Operating Cost** | **> $2 B** | **$50 M** |
| **Total Cost** | **$5 Billion** | **$100 Million** |

- **Synergism between IFE and MFE will also SAVE MONEY**
- **Proof of Principle and Proof of Performance for Chamber Technology LIQUID WALL Concepts can be realized at a modest cost and in less than a decade (in sharp contrast to the case for solid walls/Evol. Concepts)**
- **Note: The cost of testing in fission reactors is comparable in both cases, and is not included. Extrapolation of fission data will be with more confidence in the case of liquid walls because the spectrum is much closer.**

# Liquid Wall in NSTX Provides Exciting Opportunities




- ❑ **It helps NSTX remove high heat flux**
- ❑ **It provides excellent data on plasma liquid interactions**

APEX