APEX Overview: Part I
Opportunities and Challenges in Free-Surface Liquid Wall Research

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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.

Outline

- Limitations of Solid Walls / Traditional Concepts
- APEX Objectives
- Potential of Liquid Walls
- Challenges of Liquid Walls
- Low-Cost R&D Path
- Current Research Problems

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. Plasma Chamber Technology is Critical

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

Need Low Failure Rate

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

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

Traditional (Evolutionary) Concepts (Solid First Wall, etc.) Have Very Limited Potential

A) Limited Performance/Economic Potential

1) Low Power Density: Neutron Wall Load ≤ 3 MW/m^2
Factor of 200 Lower than LMFBR and 80 Lower than LWR

2) Low Conversion Efficiency: Exit Coolant Temperature < 400-600°C

3) Short Mean Time Between Failure: MTBF < 0.5 year

4) Long Mean Time to Recover: MTTR > 0.25 year
- Traditional Concepts: MTBF ~ 2 MTTR
- What is Needed: MTBF > 43 MTTR

B) Nuclear Environment is Dominant: Activation and Material Problems

C) High Cost, Long Time for R&D

Need Revolutionary Concepts with Much Greater Potential

APEX

Objective

Identify and explore novel, possibly revolutionary, concepts for the Plasma Chamber that can: 1 - substantially improve the vision for an attractive fusion energy system; and 2 - Lower the cost and time for R&D.

Primary Criteria

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

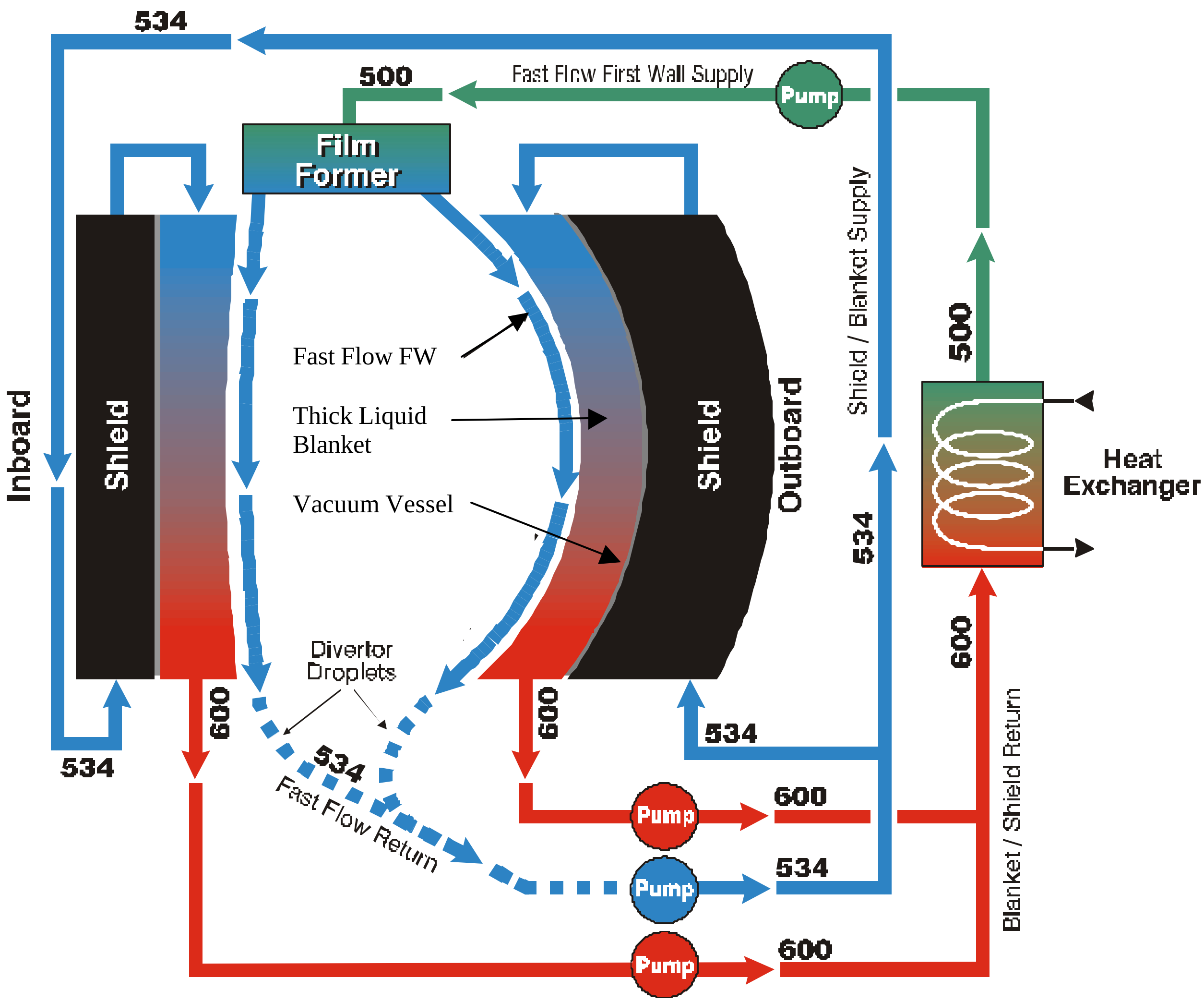
1. **Liquid Walls** (Revolutionary)

   - 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)

APEX Results Show Great Potential for an ALL-LIQUID FW/Blanket



- **High Power Density** (P_{NW} up to 30MW/m2)
- **High Thermal Conversion Efficiency** (> 40%)
- 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

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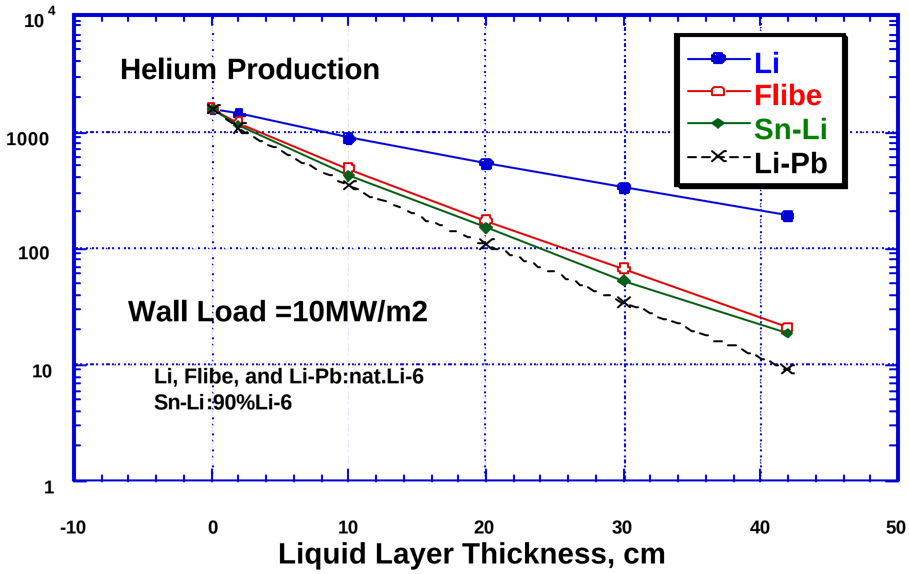

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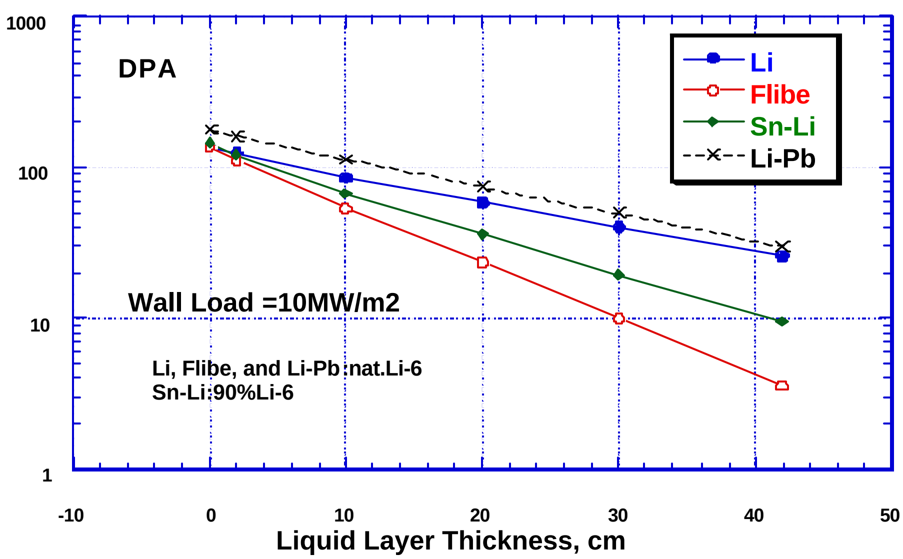
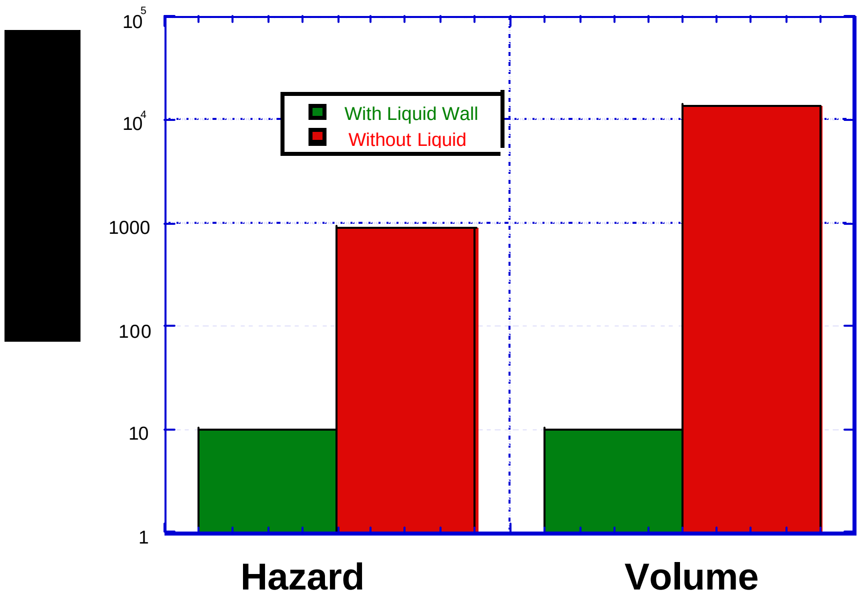


Conclusions

- 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 Provide a Good Low Activation Solution by Reducing Both Hazard and Volume in First Wall/ Blanket



<u>What 40 cm of Flibe in front of structure can do</u>

<u>Activation Hazard</u>

- Lower by two orders of magnitude
  (reduction in flux; soften the spectrum)

<u>Activation Volume</u>

- Accumulated Radwaste Volume Lower by THREE orders of magnitude
  - High Wall Load capability (a factor of 10)
  - Volume of the structure is a factor of 20 lower
    (area • thickness)
  - Replacement due to FW end of life is less by a factor of ten (100 x 1/10)
  - Replacement due to “unscheduled” FAILURES is lower by at least a factor of 10

<u>Low Level Waste</u> (Shield, magnets, etc.)

- Will be lower because of smaller size (high power density)

Liquid Concepts Being Explored

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

Candidate Liquids

- 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?

Hydrodynamic Configuration
Can Liquid Walls be Formed and Maintained?

Ultimate Vision

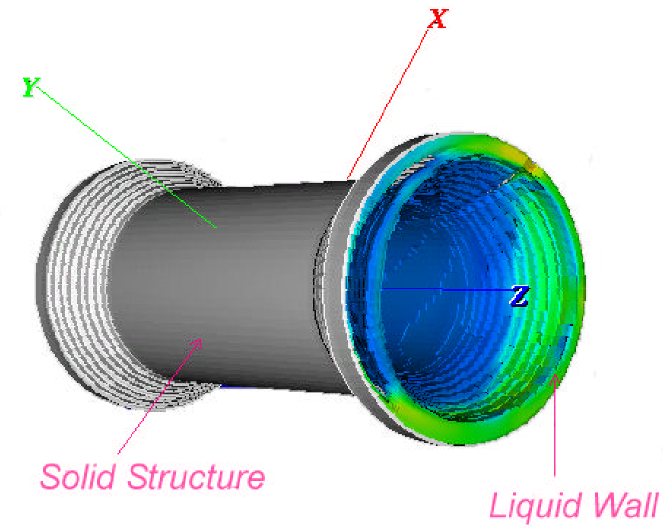
SMART LIQUIDS

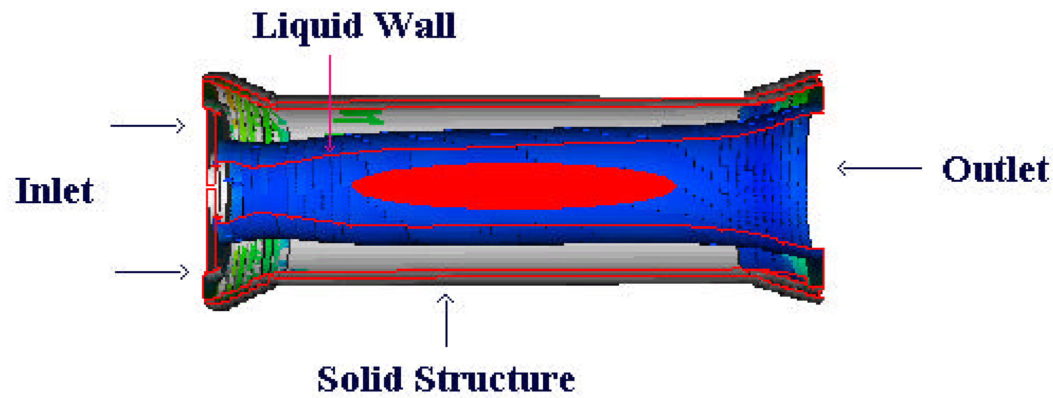
For Now: 1) EM Restrained 2) Gravity-Momentum Driven

With Some Ingenuity from Young Researchers:

- The answer is YES
- Confirmed by Solving 3-D Navier Stokes Equations
- Optimum Flow Configurations are somewhat different for magnetic confinement concepts (FRC, ST, Advanced Tokamaks, etc.)

Swirling Thick Liquid Walls for High Power Density FRC

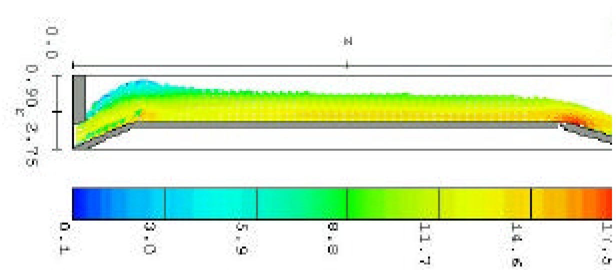


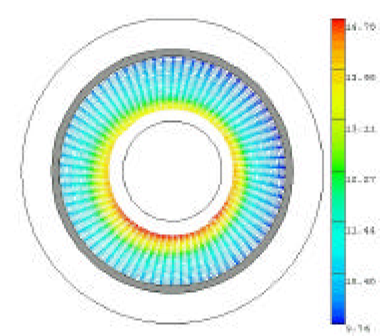


- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

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

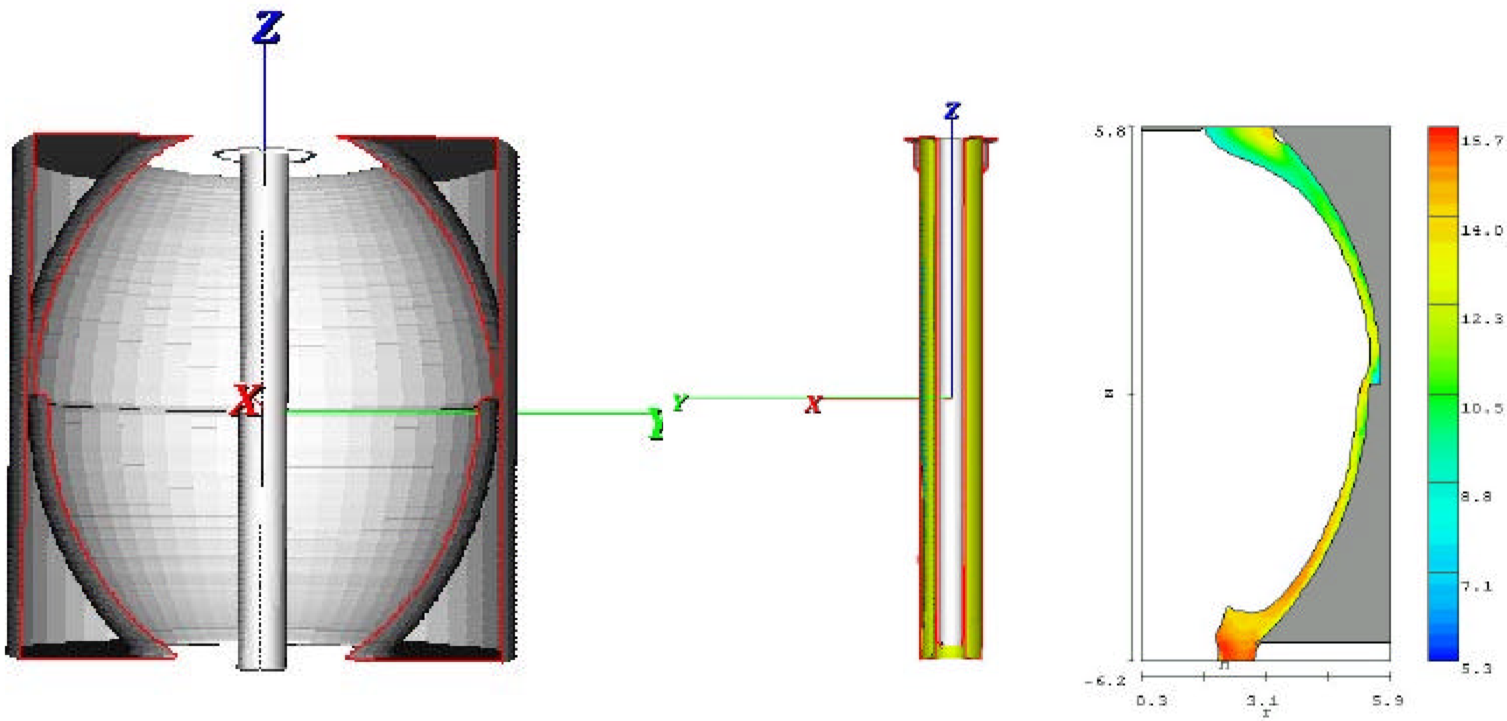
- **Results:** Adhesion and liquid thickness uniformity (> 50 cm) met with a flow of V_{axial} = 10 m/s, $V_{q,ave}$ = 11 m/s





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

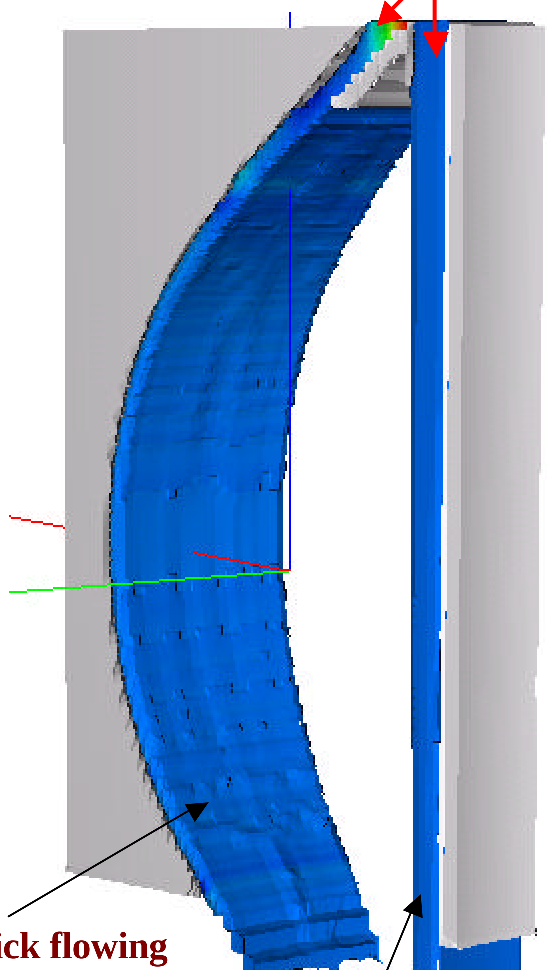
Simulation Results:

- 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)



Area expansion
Toroidal width = 61 cm Corresponding to 10° 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

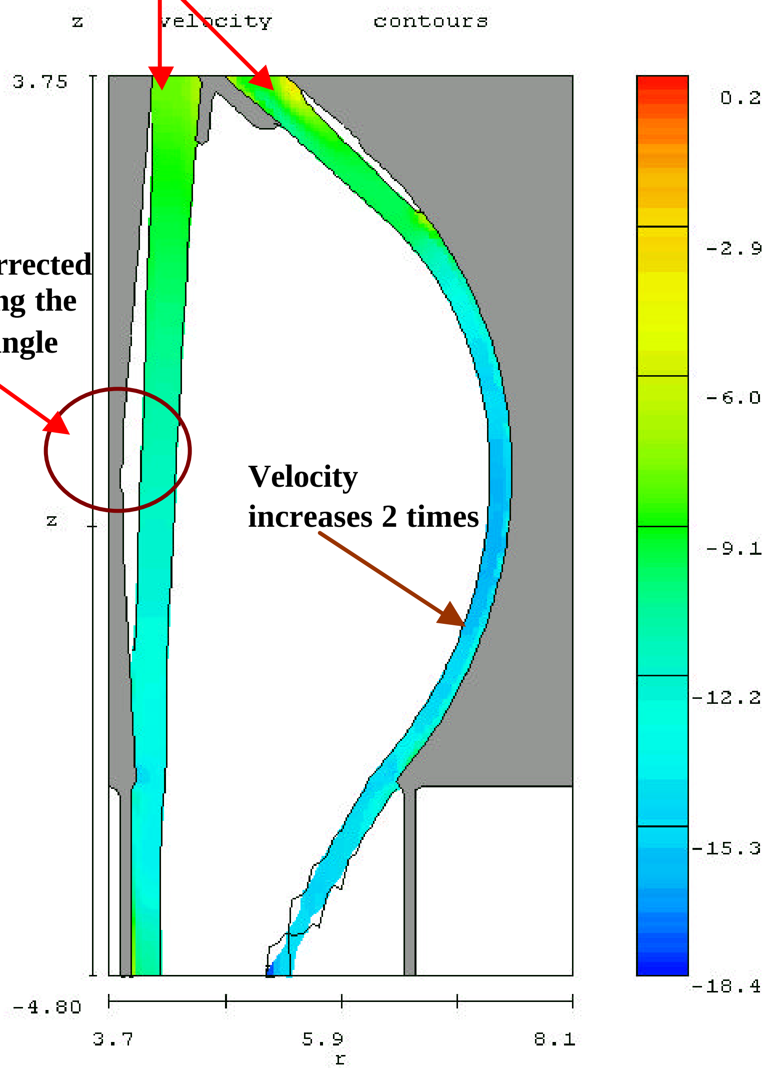
z-velocity components along the structural inner walls from 3-D hydrodynamics calculations

Initial thickness = 50 cm

Inlet velocity = 8 m/s

Can be corrected by changing the injection angle

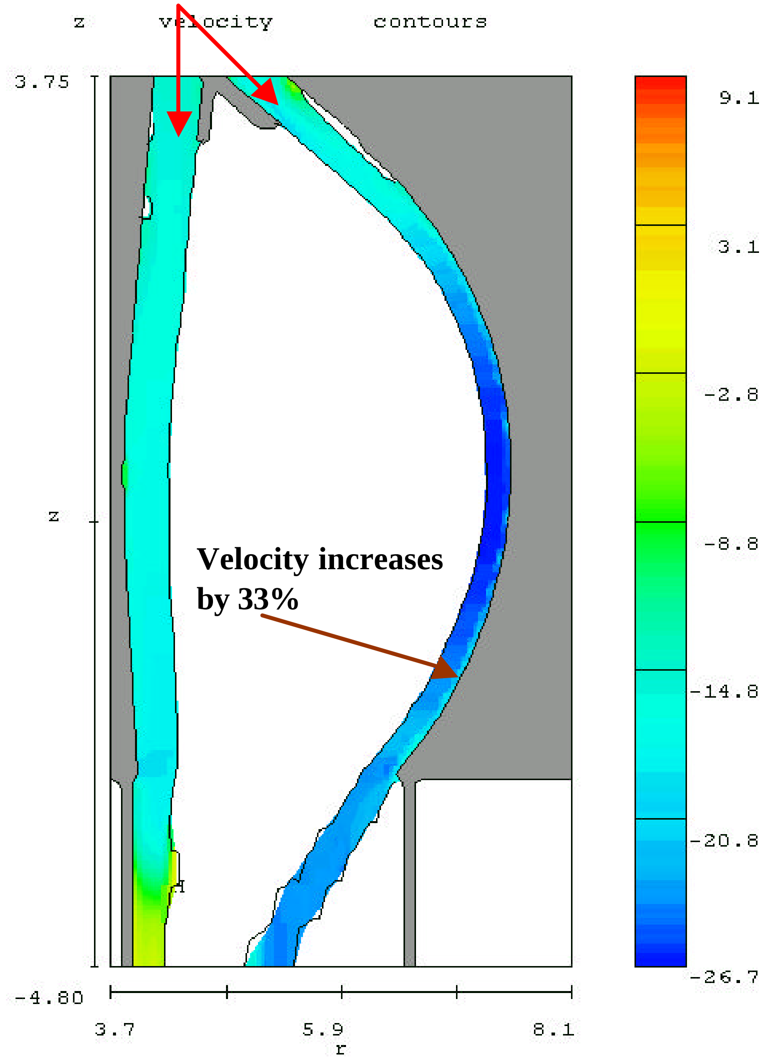
Velocity increases 2 times



t/pass = 0.9 second

Inlet velocity =15 m/s

Velocity increases by 33%



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

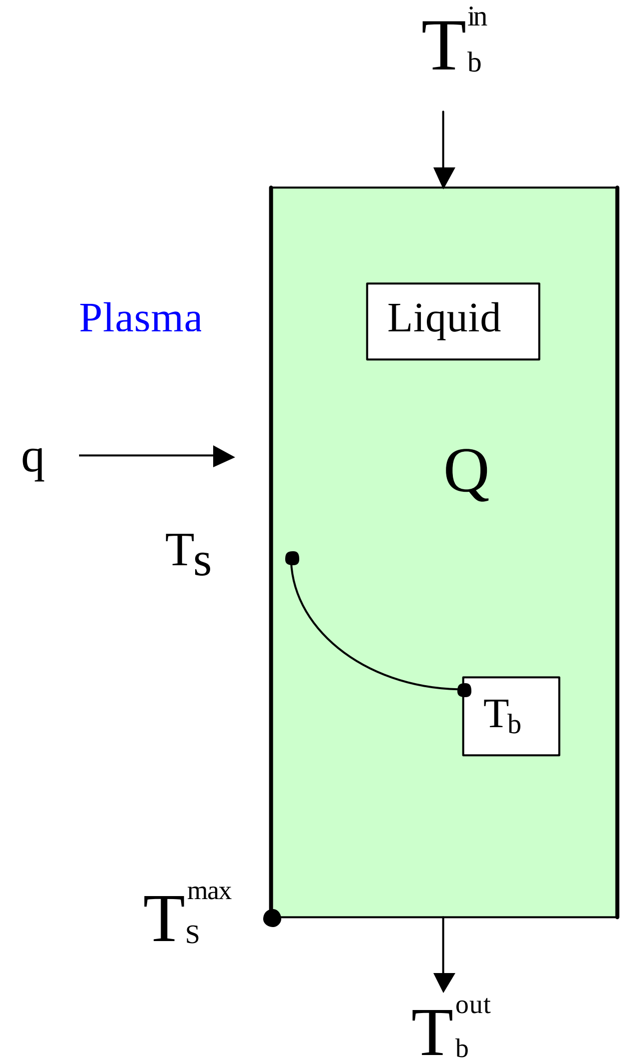
   $V^2/R > g$

5. Overcome Thinning

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

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

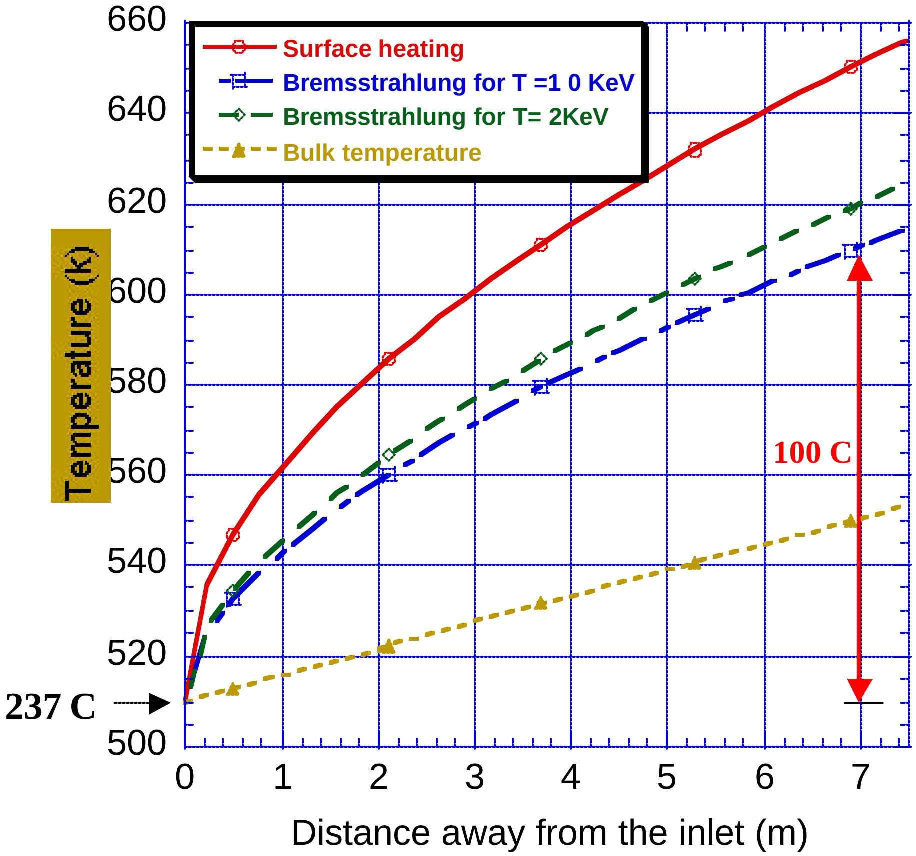
- Current “Best Guess” on T_s from plasma impurity limit:

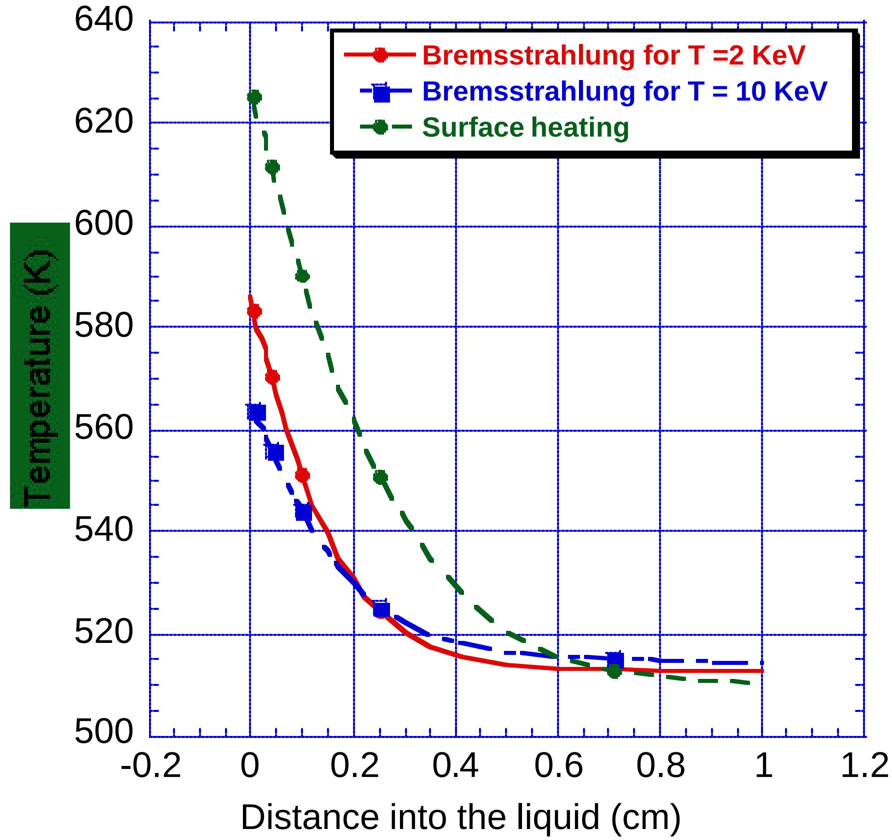
Lithium:	$T_s \sim 490^{o}C$
Flibe:	$T_s \sim 560^{o}C$
Sn-Li:	$T_s \sim 820^{o}C$ (low vapor pressure)

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

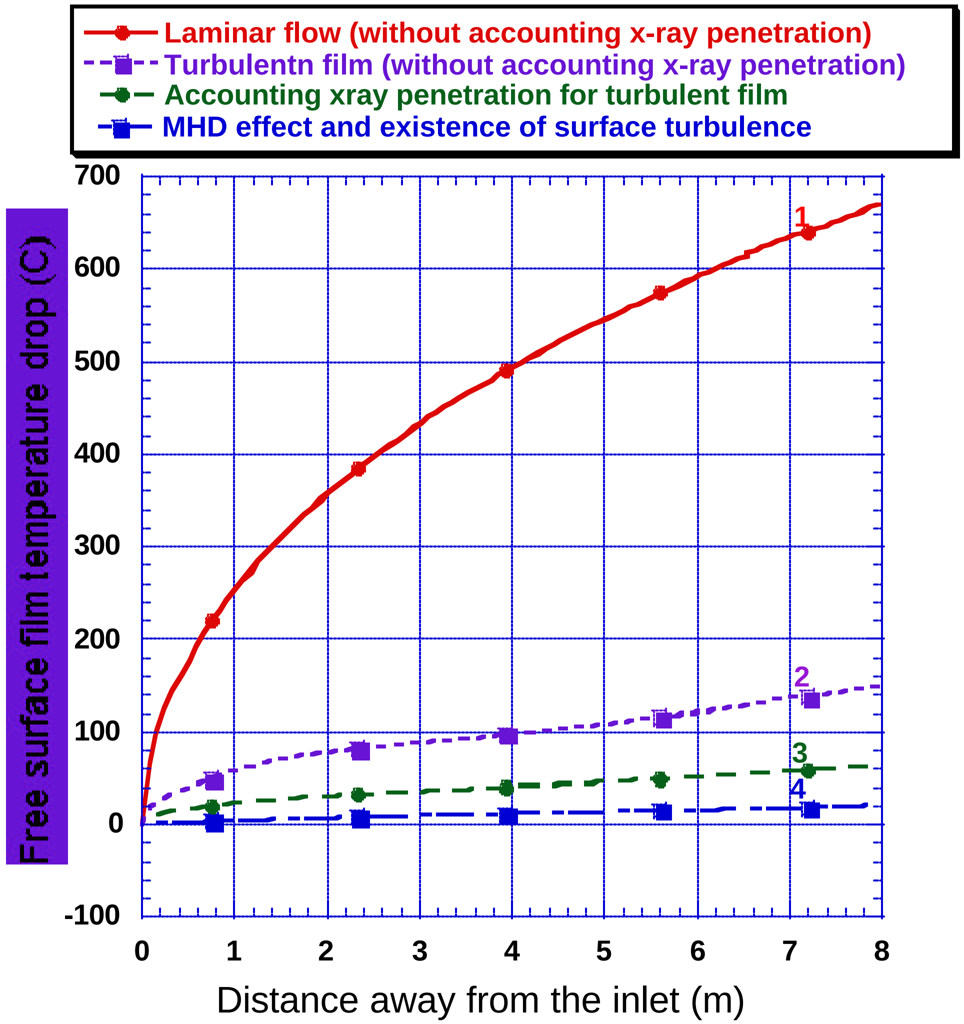
- If the Flibe flow is laminarized, the Flibe free surface can be overly heated. The film temperature drop can reach 700 ^{o}C at the bottom of ARIES-RS under APEX 2 MW/m^{2} surface heat load (curve 1).

- Turbulent heat transfer considerably reduces Flibe free-surface temperature drop (curve 2).

- Accounting for Bremsstrahlung radiation penetration further reduces surface temperature by about 90 ^{o}C (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 $T_{out} > 600$ºC

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

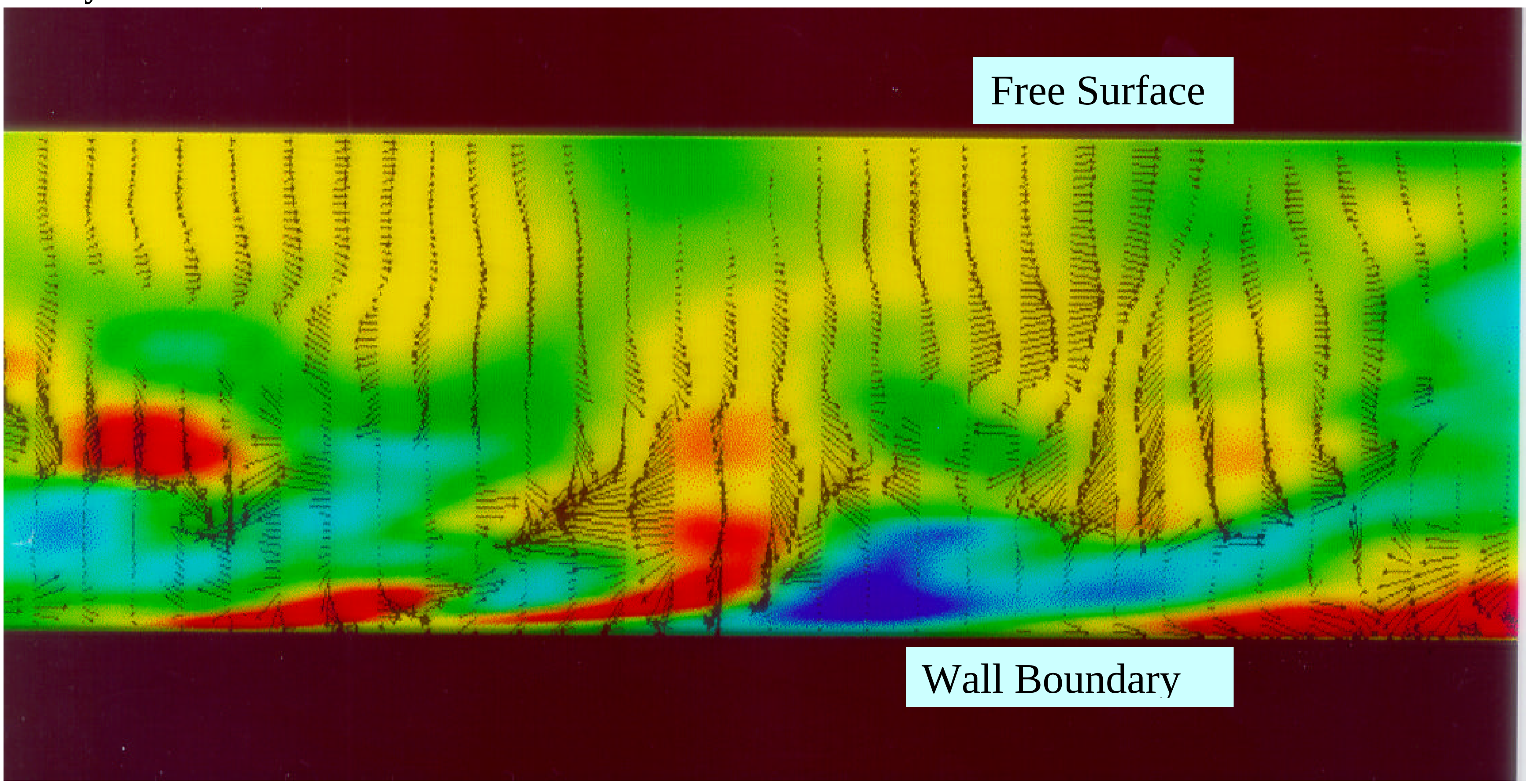
Material innovation: discovery of a new lithium-containing material (SnLi) that has low vapor pressure at elevated temperatures

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?

APEX Approach to Problems

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

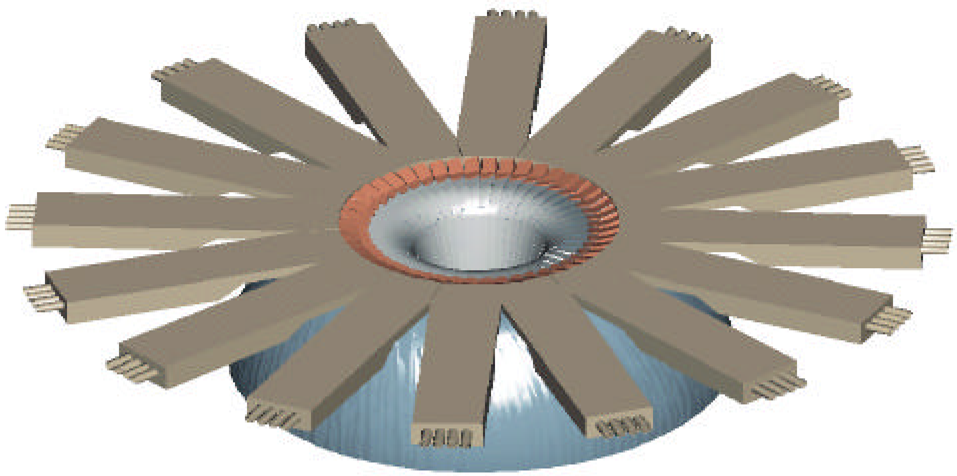
4. Confirm by "low-cost and fast" experiments

Penetration Analysis

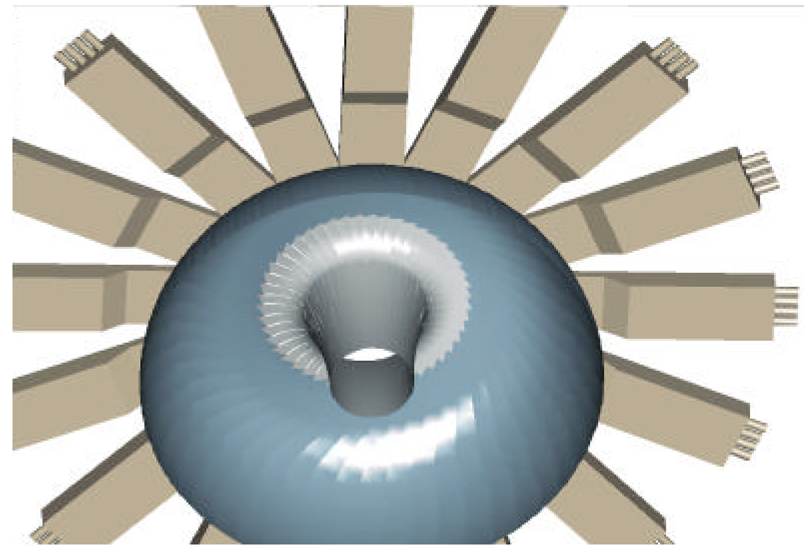
- Calculations were performed for Elliptical Penetrations solving 3-D, time-dependent Navier-Stokes equations using the best computational tools

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

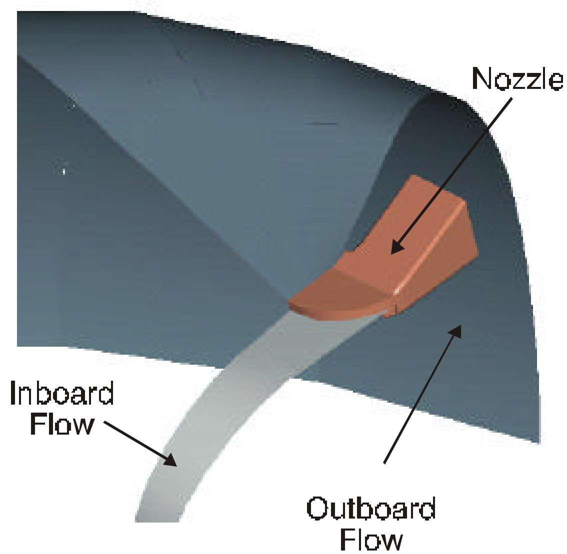
Convective Layer Forming Device



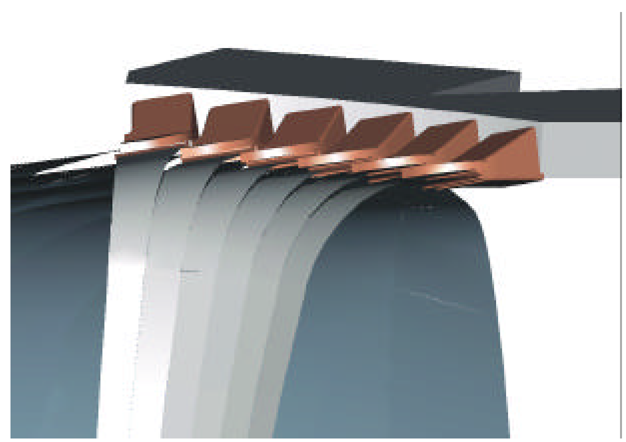
Top view of convective layer forming device array



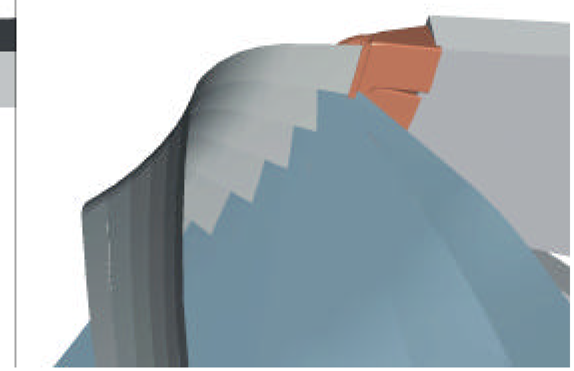
View looking up from inside the machine



View of convective layer forming device - single nozzle



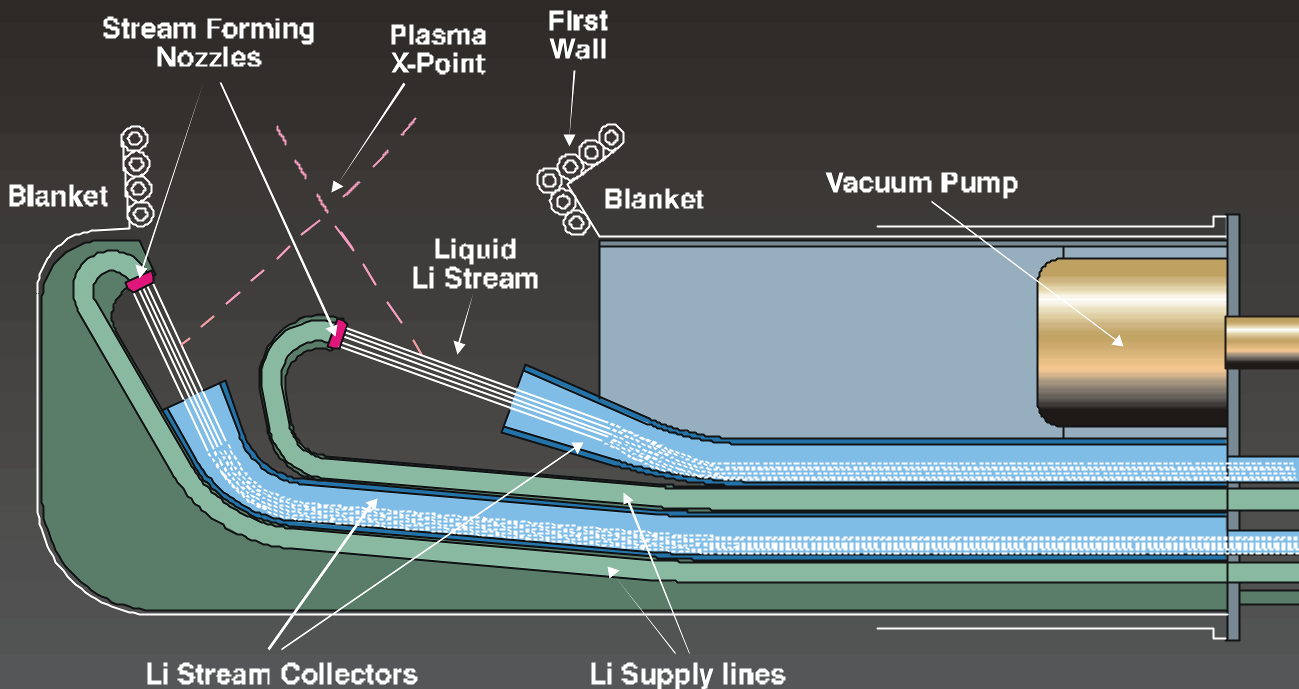
View from centerline of machine showing inclination of nozzles

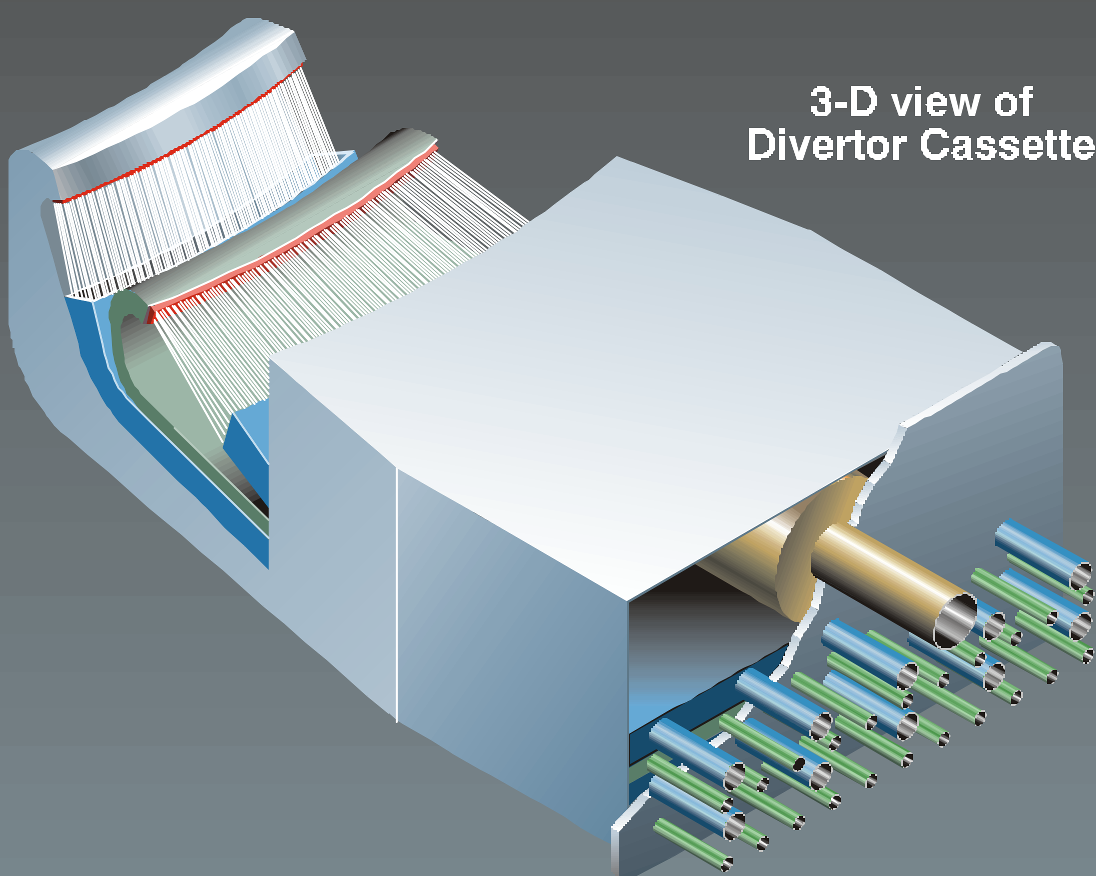


View from plasma looking up, nozzles are completely shielded

Evolve Divertor Cassette

(Elevation View)

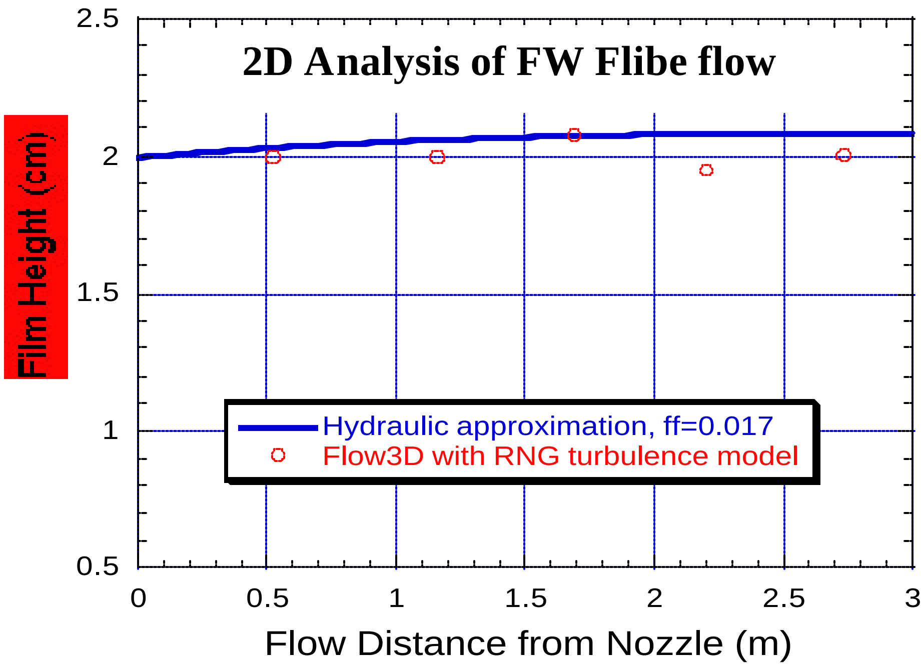




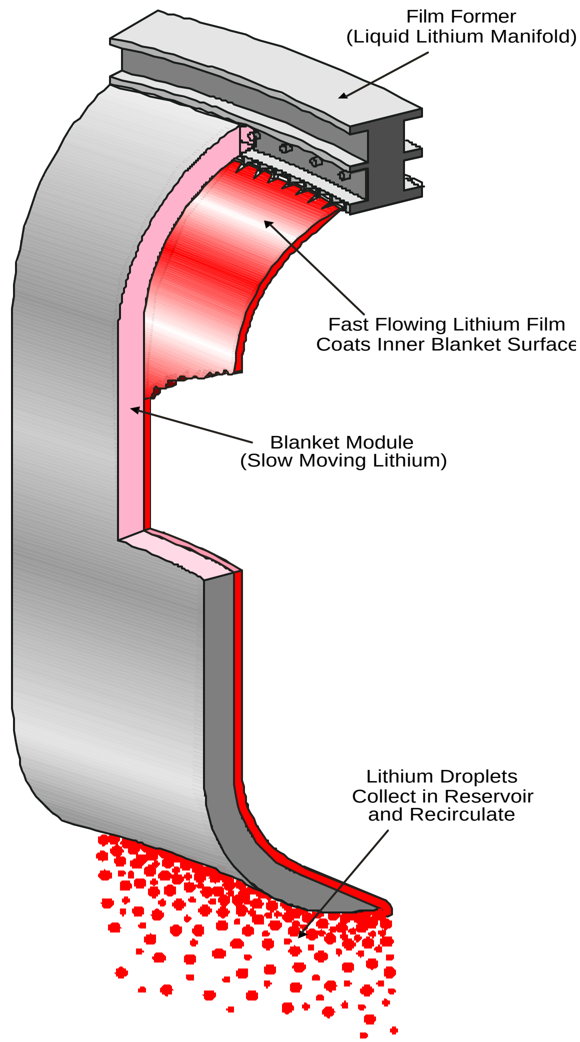
3-D view of Divertor Cassette

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 means of centrifugal force**
- **2D hydrodynamic calculations confirm near equilibrium flow for Flibe at 2 cm depth and 10 m/s velocity (below)**



Convective Liquid layer Design



The Thin Liquid Wall Concept (CLIFF) Has Near Term Applications

Advantages

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

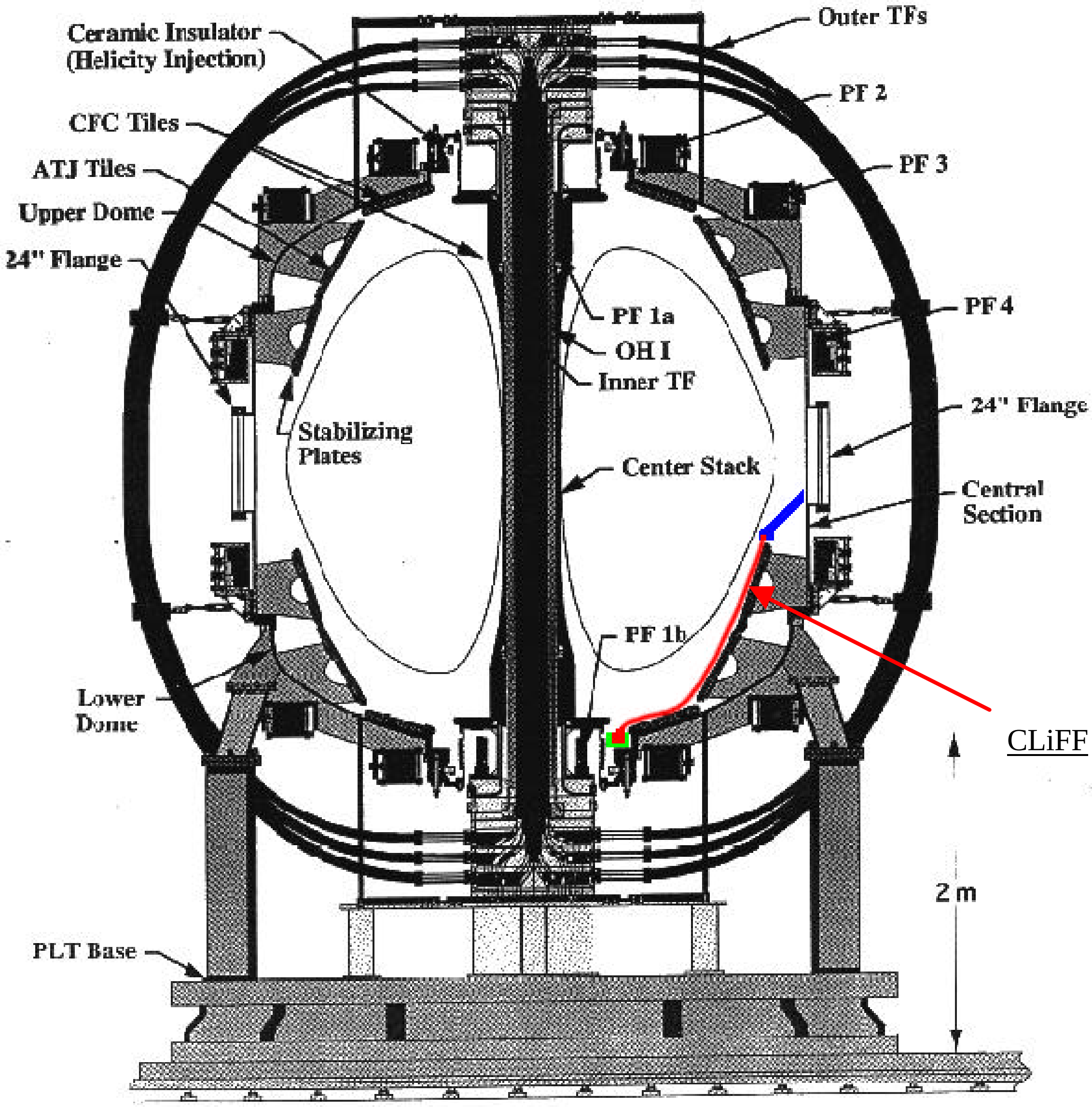
Liquid Walls Can Substantially Reduce Time and Cost of Major Facilities Prior to DEMO

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** **-Surface heat flux**	**- Surface heat flux**
Dominant Testing Effects	**-Radiation Damage** **-Failure Modes/Rates** **-Maintenance Time**	**-Hydrodynamics/heat transfer**
Capital Cost for a Major Facility	**1) Component Testing (Facility) > $2B** **2) IFMIF-type > $1B**	Thermofluid facility ~ $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)**

Liquid Wall in NSTX Provides Exciting Opportunities



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

APEX