Liquid Walls
Innovative High Power Density Concepts

(Based on the APEX Study)

http://www.fusion.ucla.edu/APEX/

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Outline

- **Background on APEX**

- **Liquid Walls**
  - **Motivation**
  - **Scientific Principles**
  - **Examples of Concepts**
  - **Analysis and Issues of Liquid Walls**

APEX
(Advanced Power Extraction Study)

Objectives

Identify and explore NOVEL, possibly revolutionary, concepts for the Chamber Technology that can:

1. **Improve the vision for an attractive fusion energy system**
2. **Lower the cost and time for R&D**

- **APEX was initiated in November 1997 as part of the US Restructured Fusion Program Strategy to enhance innovation**
- **Natural Questions:**

  Are there new concepts that may make fusion better?

Primary 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%)**

3. **High Availability**

   -Lower Failure Rate

   MTBF > 43 MTTR

   -Faster Maintenance

4. **Simpler Technological and Material Constraints**

APEX APPROACH

1) Emphasize Innovation

2) Understand and Advance the underlying Engineering Sciences

3) Utilize a multidisciplinary, multi-institution integrated TEAM

4) Provide for Open Competitive Solicitations

5) Close Coupling to the Plasma Community

6) Direct Participation of Material Scientists and System Design Groups

7) Direct Coupling to IFE Chamber Technology Community

8) Encourage International Collaboration

APEX TEAM

Organizations

UCLA	ANL	PPPL
ORNL	LLNL	SNL
GA	UW	UCSD
INEL	LANL	U. Texas

Contributions from International Organizations

- FZK (Dr. S. Malang)
- Japanese Universities
  - Profs. Kunugi, Satake, Uchimoto and others
  - Joint Workshops on APEX/HPD
- Russia
  - University of St. Petersburg (Prof. S. Smolentsev)

Three Classes of Concepts Emerged from APEX as Very Promising

1. **Thick Liquid Walls**
   -Several Design Ideas
2. **Thin Liquid Walls**
   -CLIFF
3. **High-Temperature Refractory Solid Wall**
   -EVOLVE (Two-Phase Lithium Flow)
   -Helium Cooling

Notes

- EVOLVE was invented by Dr. S. Malang (FZK)
  The APEX work on EVOLVE was presented by the Concept Leader, Dr. R. Mattas, on Monday

This presentation is devoted to liquid walls

EVOLVE Concept

Elevation Section of
Lithium Trays + First Wall Tubes

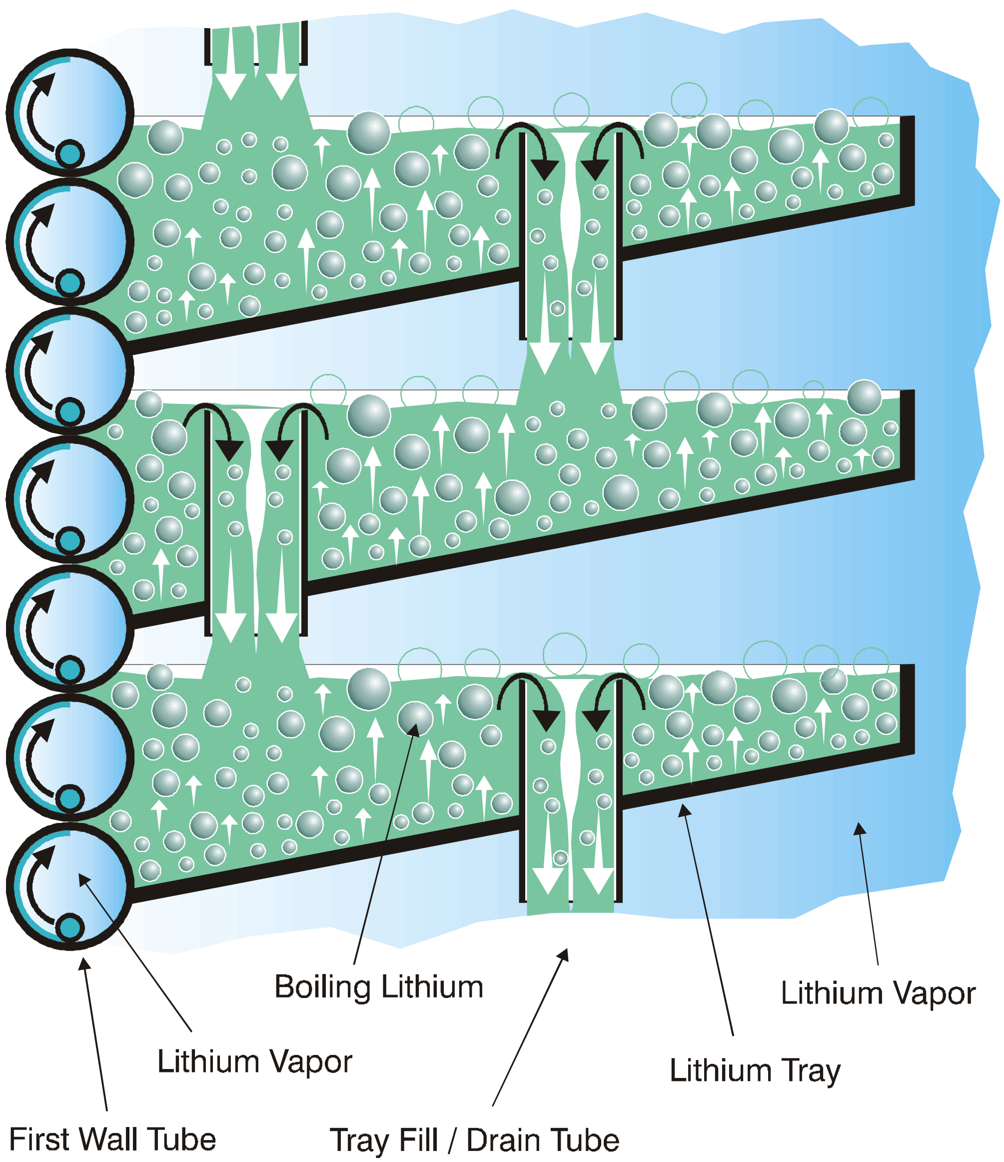
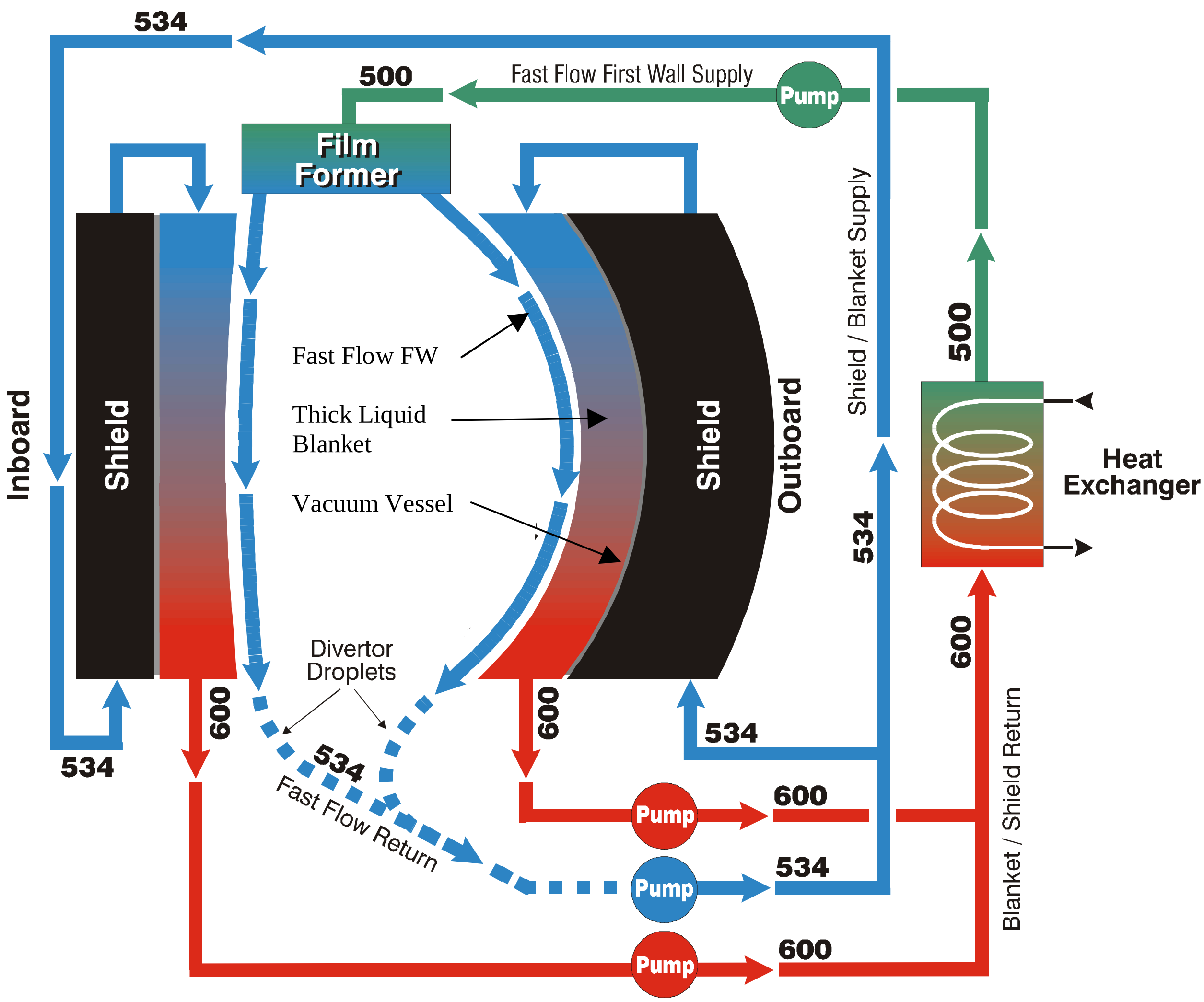


Illustration of Liquid Walls



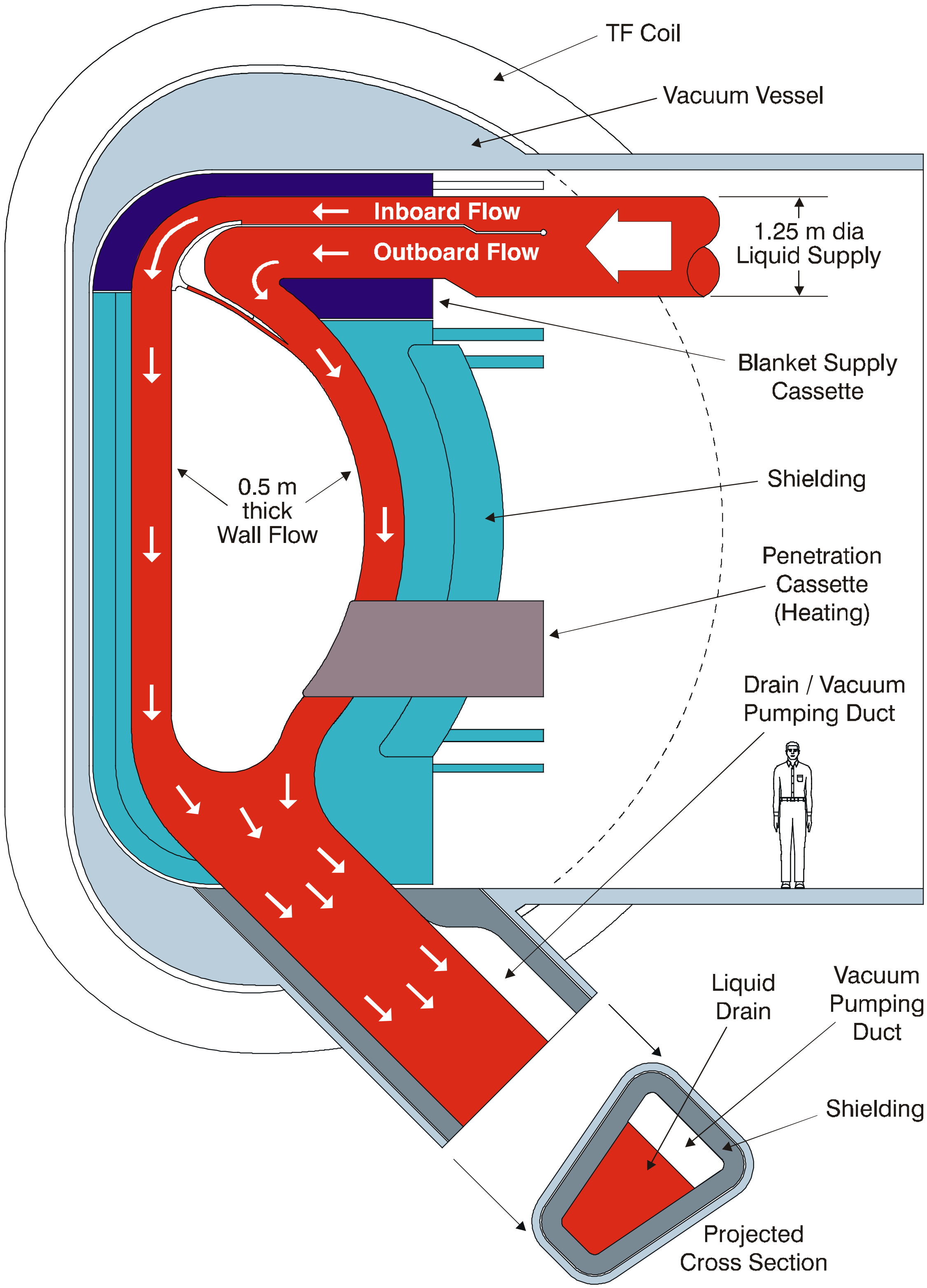
* Temperatures shown in figure are for Flibe

Thin Liquid Wall

- Thin (1-2 cm) of liquid flowing on the plasma-side of First Wall

Thick Liquid Wall

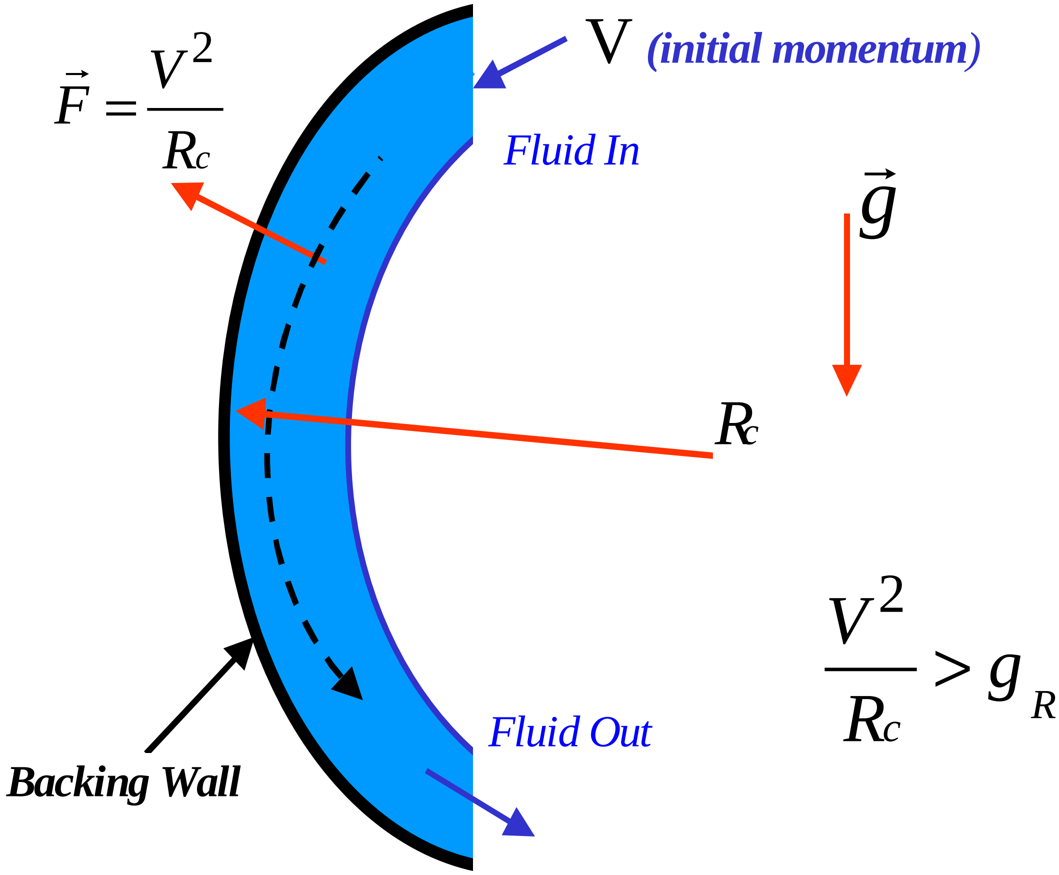
- Fast moving liquid as first wall
- Slowly moving thick liquid as the blanket



Thick Liquid Blanket Concept

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.*

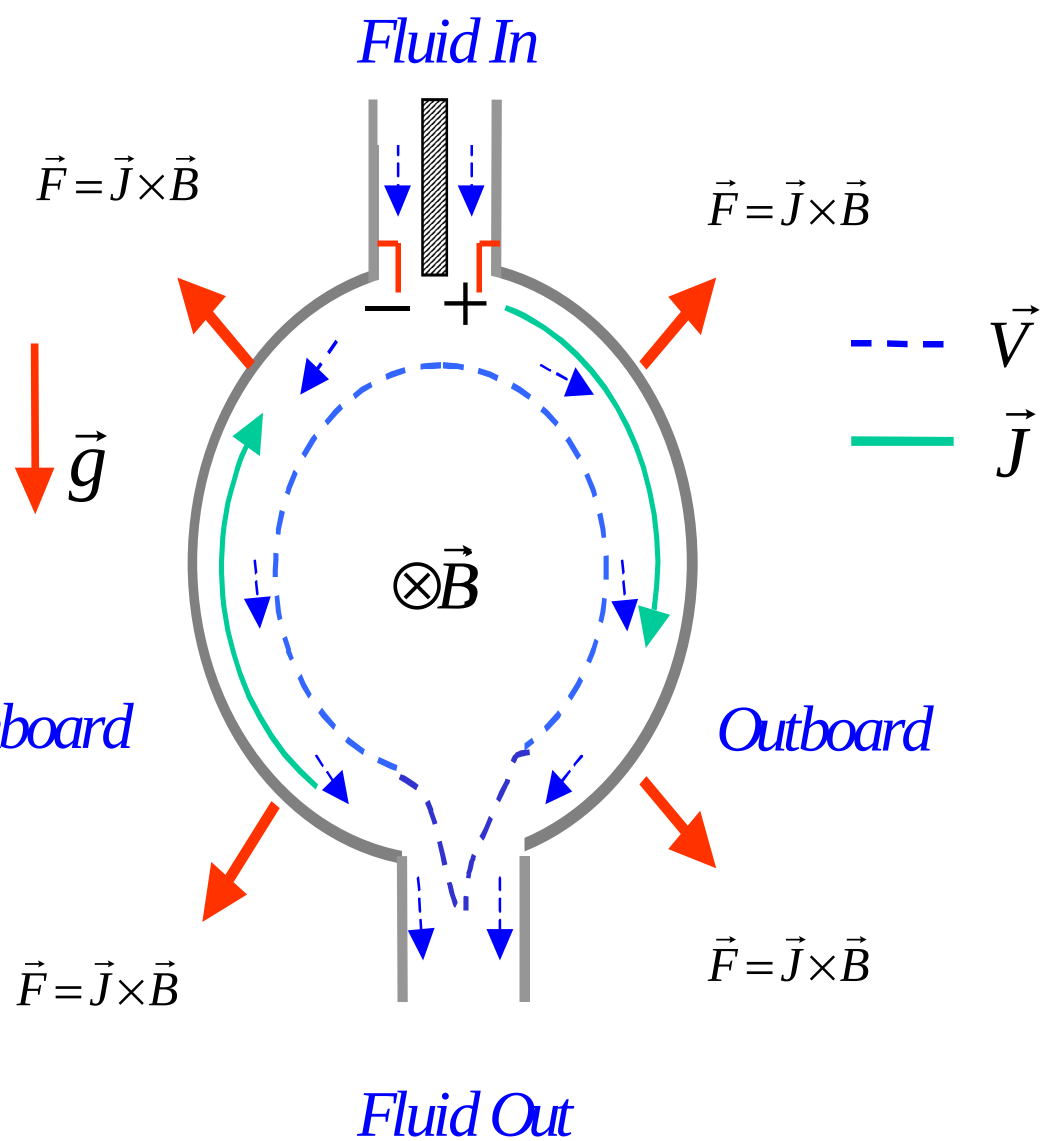
- ***GMD with Swirl Flow***

- *Add rotation.*

- ***Electromagnetically Restrained LM Wall***

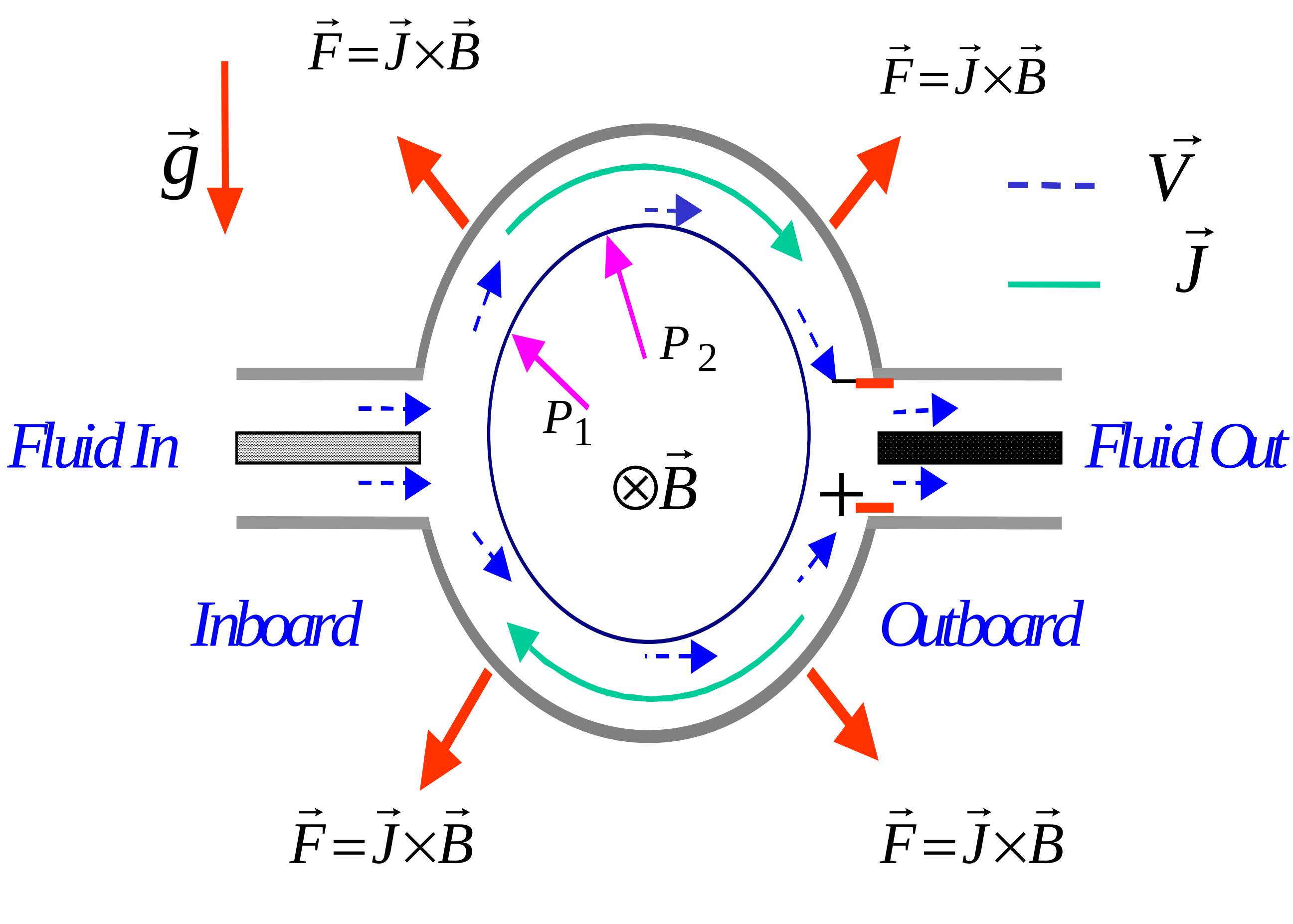
- *Externally driven current ($\vec{J}$) through the liquid stream.*

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



- *Magnetic Propulsion Liquid Metal Wall*

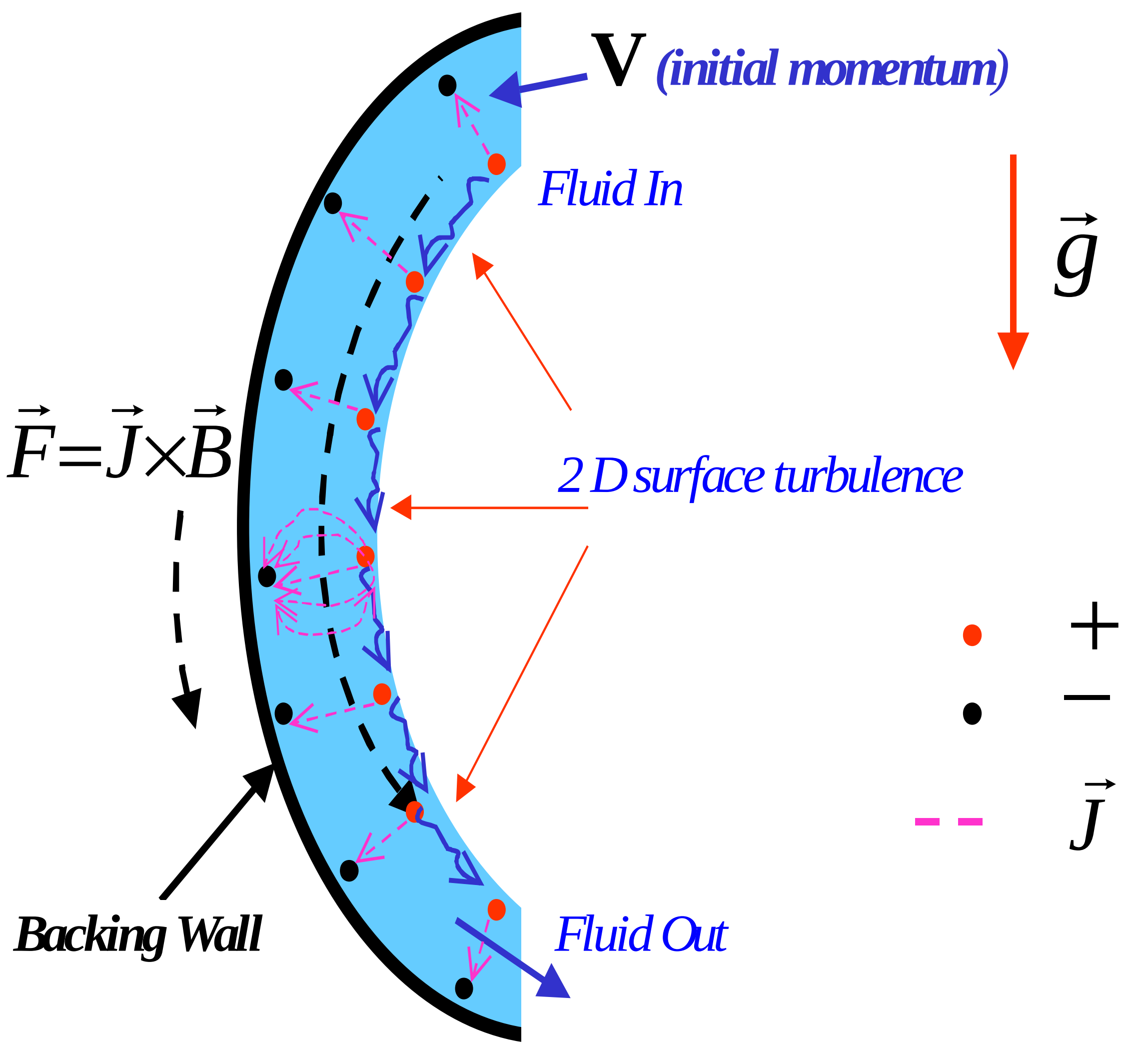
  - *Adheres to the wall by* $\vec{F} = \vec{J} \times \vec{B}$
  - *Utilizes 1/R variation in* $\vec{F} = \vec{J} \times \vec{B}$ *to drive the liquid metal from inboard to the outboard.*



$\vec{V}$ *is driven by* ΔP

- ***Poloidal Pumping***

- $\vec{F} = \vec{J} \times \vec{B}$ *flow poloidal direction*
- *Enhance surface heat transfer with 2 D turbulence*



Motivation for Liquid Walls

What may be realized if we can develop good liquid wall designs:

- Improvements in Plasma Stability and Confinement

  Enable high β, stable physics regimes if liquid metals are used

- High Power Density Capability

  -Eliminate thermal stress and wall erosion as limiting factors

  -Results in smaller and lower cost components (chambers, shield, vacuum vessel, magnets)

- Increased Potential for Disruption Survivability

- Reduced Volume of Radioactive Waste

- Reduced Radioactive Hazard from Accidental Releases

- Reduced Radiation Damage in Structural Materials

  -Makes difficult structural materials more tractable

- Potential for Higher Availability

  -Increased Lifetime and reduced failure rates

  -Faster maintenance (design-dependent)

Flowing LM Walls may Improve Plasma Stability and Confinement

Several possible mechanisms identified at Snowmass…

Presence of conductor close to plasma boundary (Kotchenreuther)

- Plasma Elongation $\kappa > 3$ possible – with $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
  (The closer the better, requires toroidal continuity, case considered 4 cm lithium with a SOL 20% of minor radius)

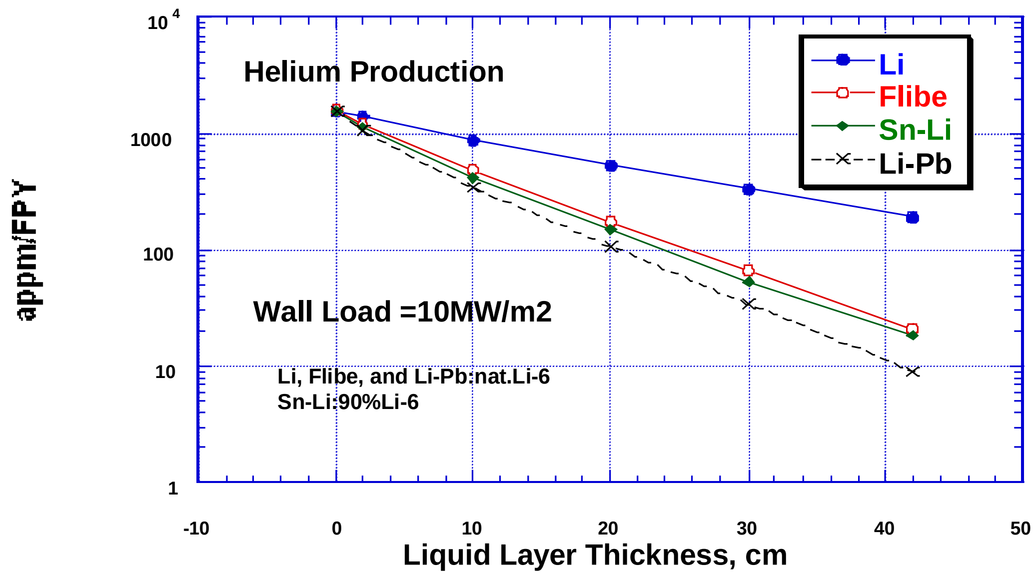
High Poloidal Flow Velocity (Kotchenreuther)

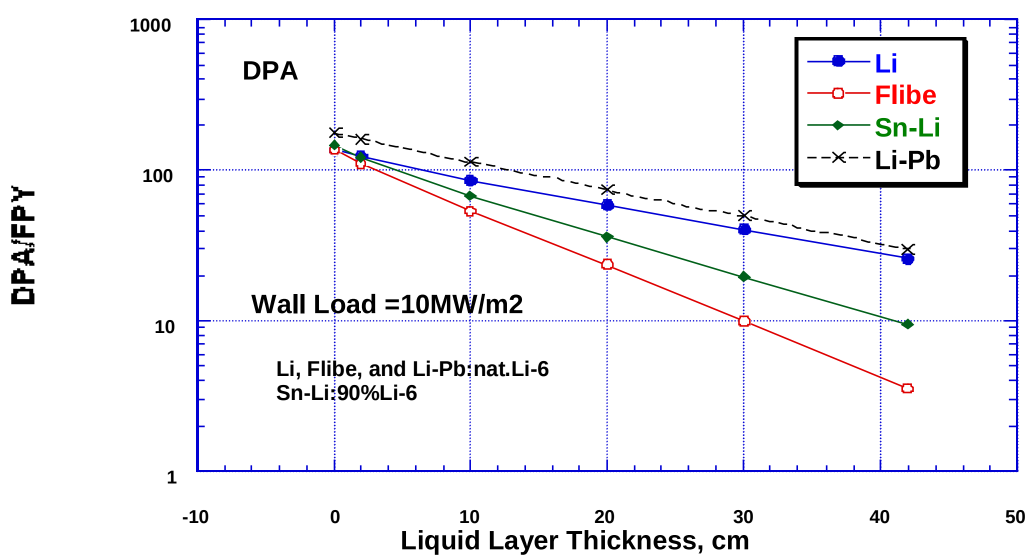
- LM transit time < resistive wall time, about ½ s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and $E \times B$ shearing rates (transport barriers)

Hydroden Gettering at Plasma Edge (Zakharov)

- Flattened average ion temperature profiles reducing anomalous energy transport
- Flattened or hollow current density reducing ballooning modes and allowing high β

Liquid Walls
Increase Lifetime of Structure





<u>Conclusions</u>

- 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 Reduce the Volume of Radioactive Waste

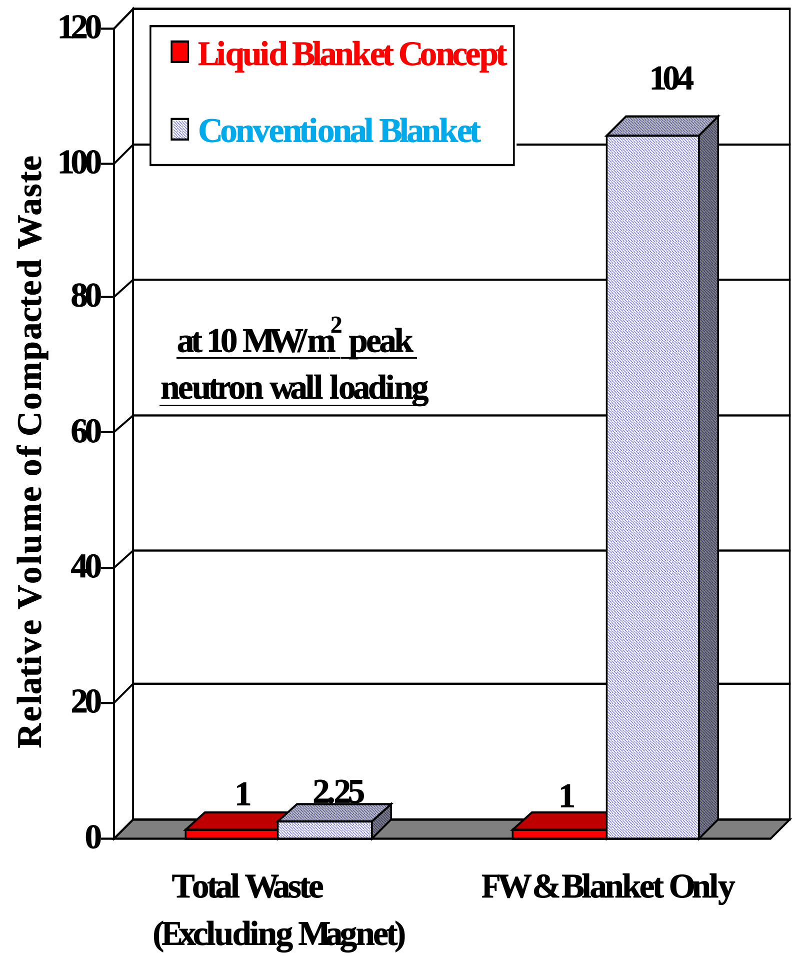
Basis of Calculations

- 30-yr plant lifetime
- Structure life = 20 MW • y / m^2
- Liquid blanket is 52 cm of liquid followed by 4-cm backing wall
- Conventional blanket is self-cooled liquid with 2 cm FW, 48 cm of 90% liquid plus 10% structure
- Results are design-dependent

Conclusions

- **Relative to Conventional Blankets, Liquid Walls reduce the waste over the plant lifetime by:**
  - **Two orders of magnitude for FW/Blanket waste**
  - **More than a factor of 2 for total waste**

Waste Volume (Relative)



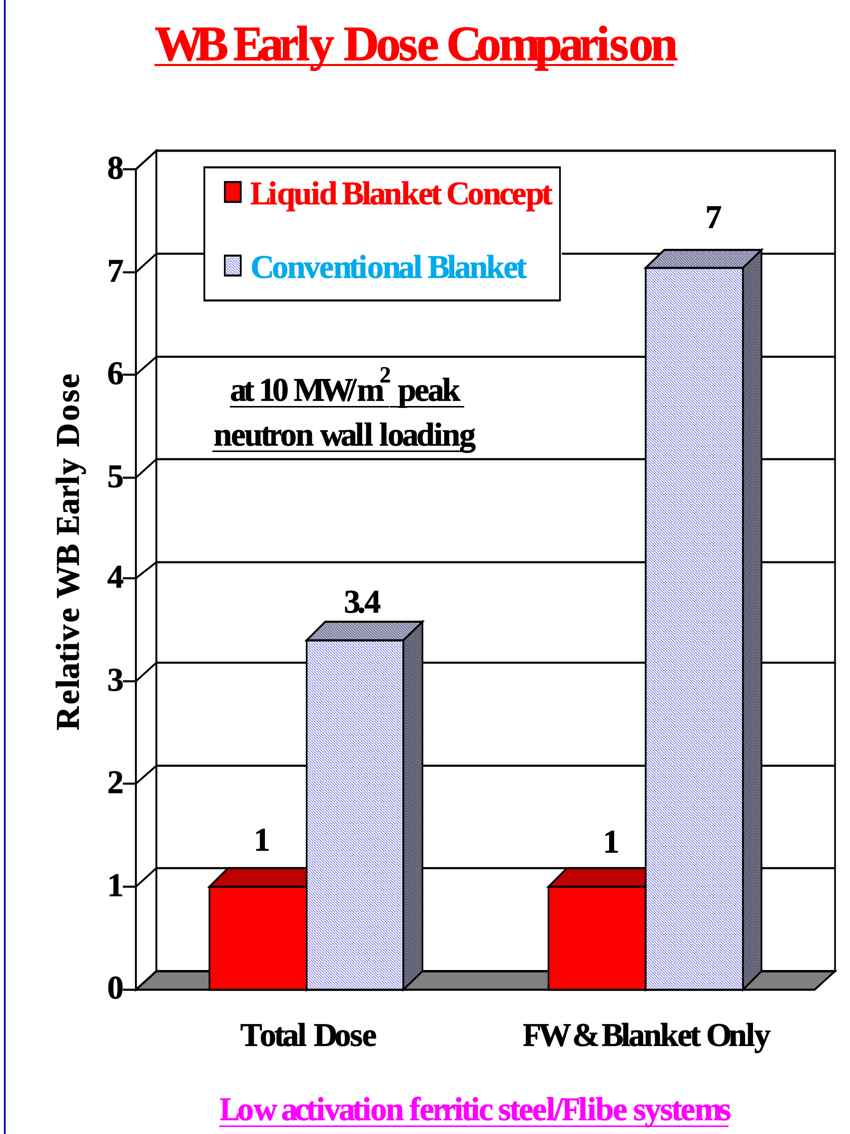
Low activation ferritic steel/Flibe systems

Whole Body Early Dose (due to 100 % release of radioactive inventories)

- Early Dose within one week after accident at site boundary (1 km) for ground release
- A power plant utilizing a conventional blanket generates more than three times the total amount of whole body early dose generated in a similar power plant utilizing a liquid blanket.
- The whole body early dose generated by the conventional first wall and blanket is a factor of seven higher than the dose generated by a liquid blanket.

Main Point

- **Liquid Walls can provide fusion with a substantial margin in satisfying the "No Evacuation Criteria"**



Challenging Issues for Liquid Walls

1. Plasma-Wall Interaction

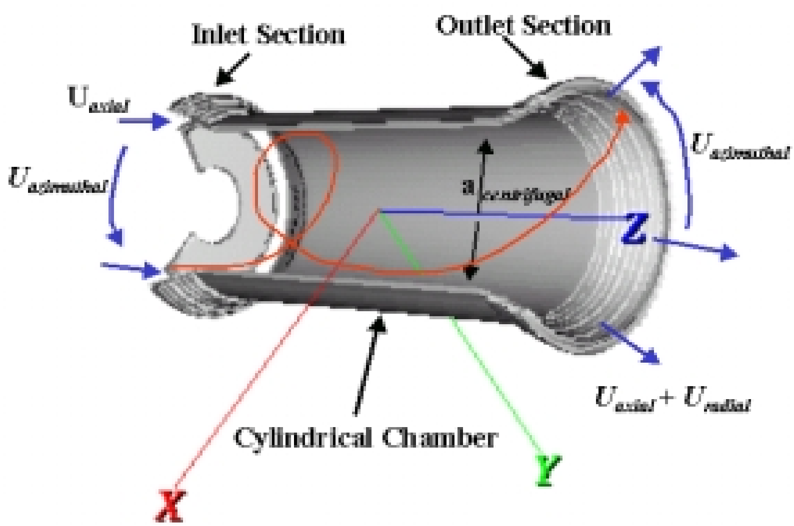
A. Surface Interactions
- What is the Allowable Temperature of the Liquid Surface Facing the Plasma?

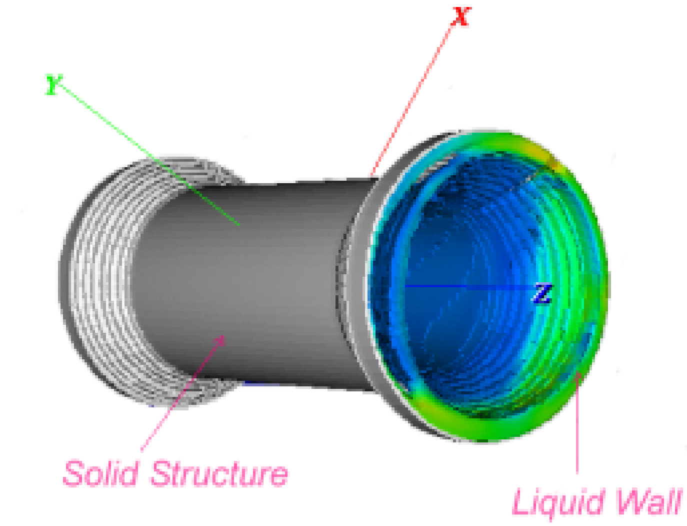
B. "Bulk" Interactions
- Requirements on Field Penetration, Field Error, etc.
- Plasma Disruptions

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

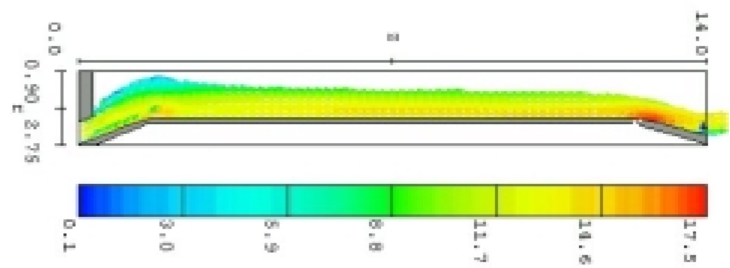


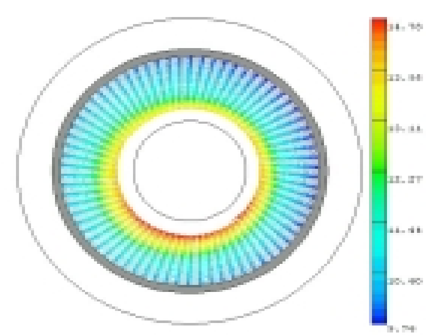


- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

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

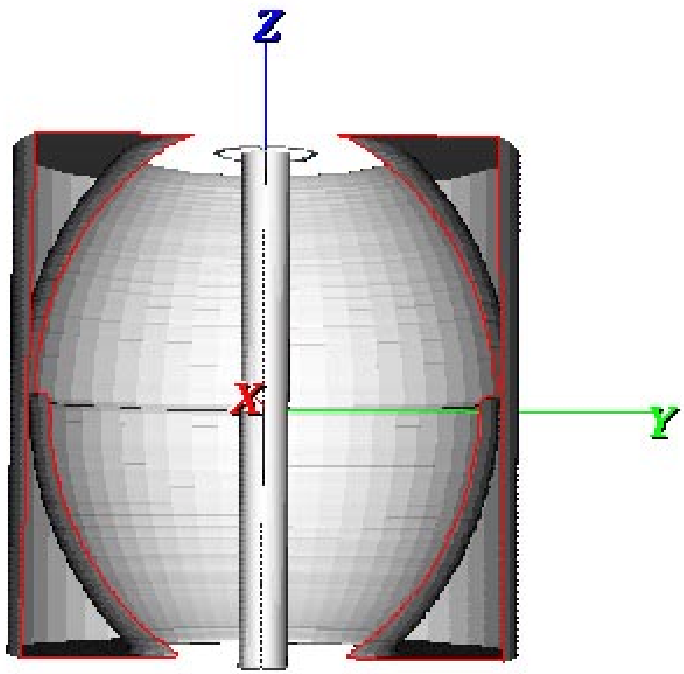
- **Results:** Adhesion and liquid thickness uniformity (> 50 cm) met with a flow of V_{axial} = 10 m/s, $V_{\theta,ave}$ = 11 m/s

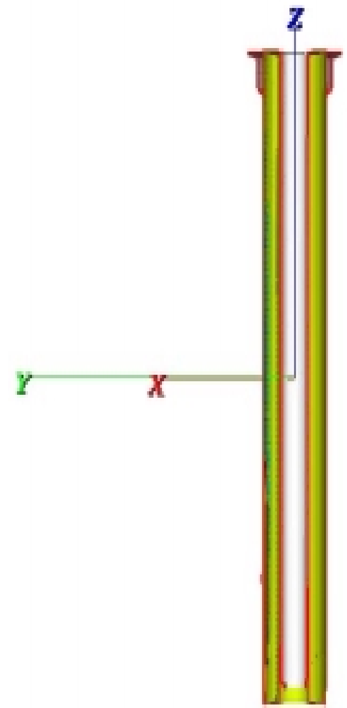


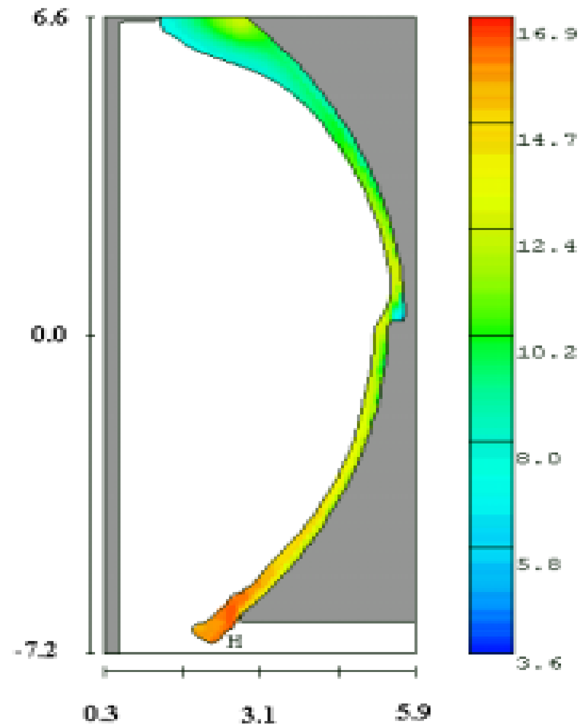


Calculated velocity and surface depth

Toroidally Rotating Thick Liquid Wall for the ST







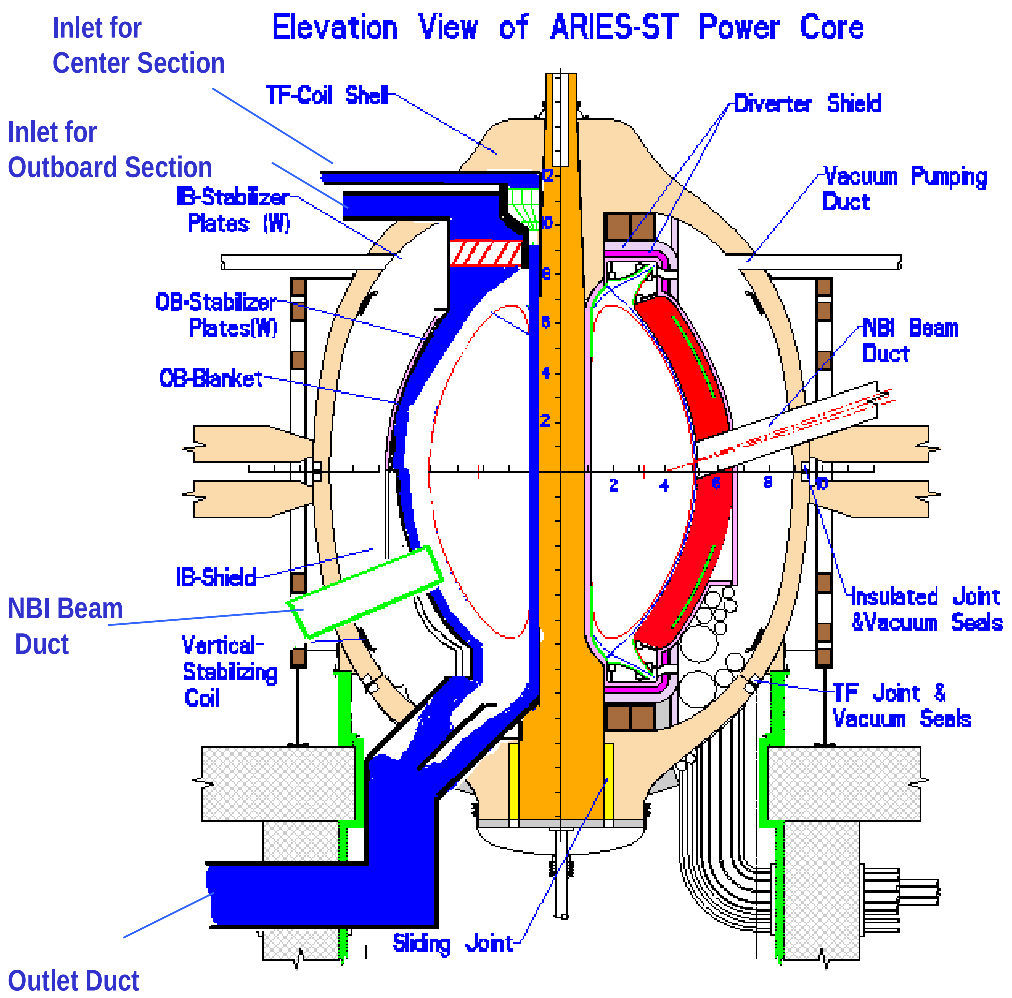
Design Concept:

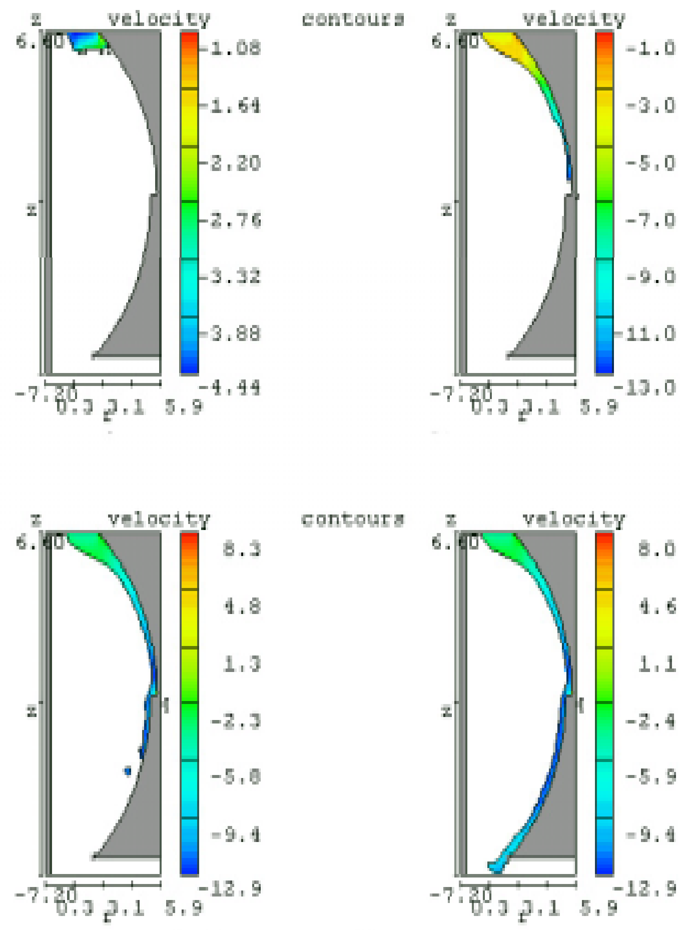
- Thick liquid flow from reactor top
- *Outboard:* Fluid remains attached to outer wall due to centrifugal acceleration from the toroidal liquid velocity
- *Inboard:* Fast annular liquid layer

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%

ST
DESIGN HIGHLIGTHS OF SWIRL CONCEPT



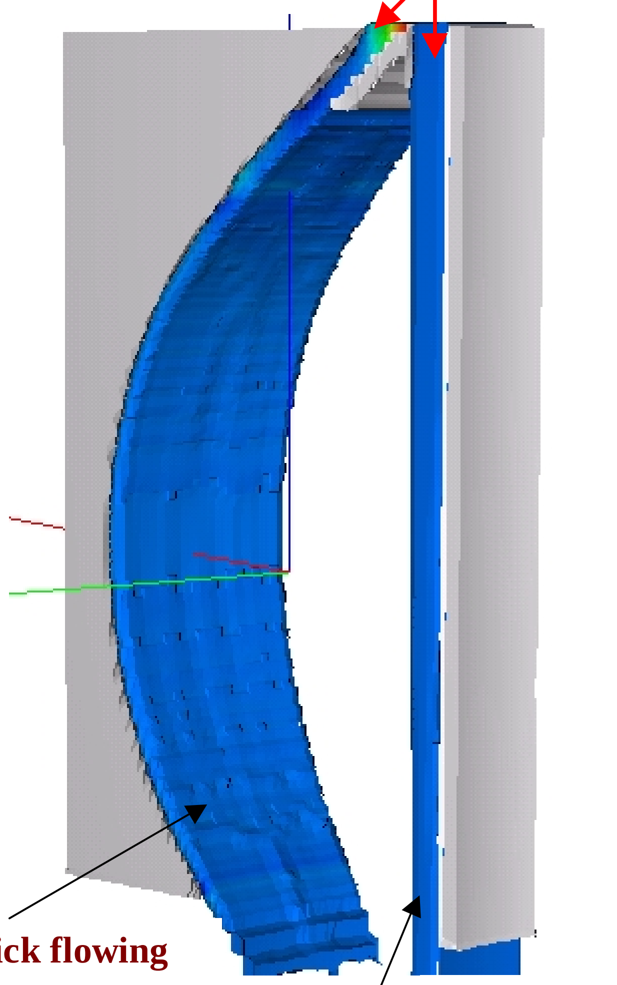


Z-Velocity Contour on a r-z plane at an arbitrary azimuthal location.

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

- **Toroidal width = 61 cm Corresponding to 10^{o} sector**
- **Area expansion included in the analysis**

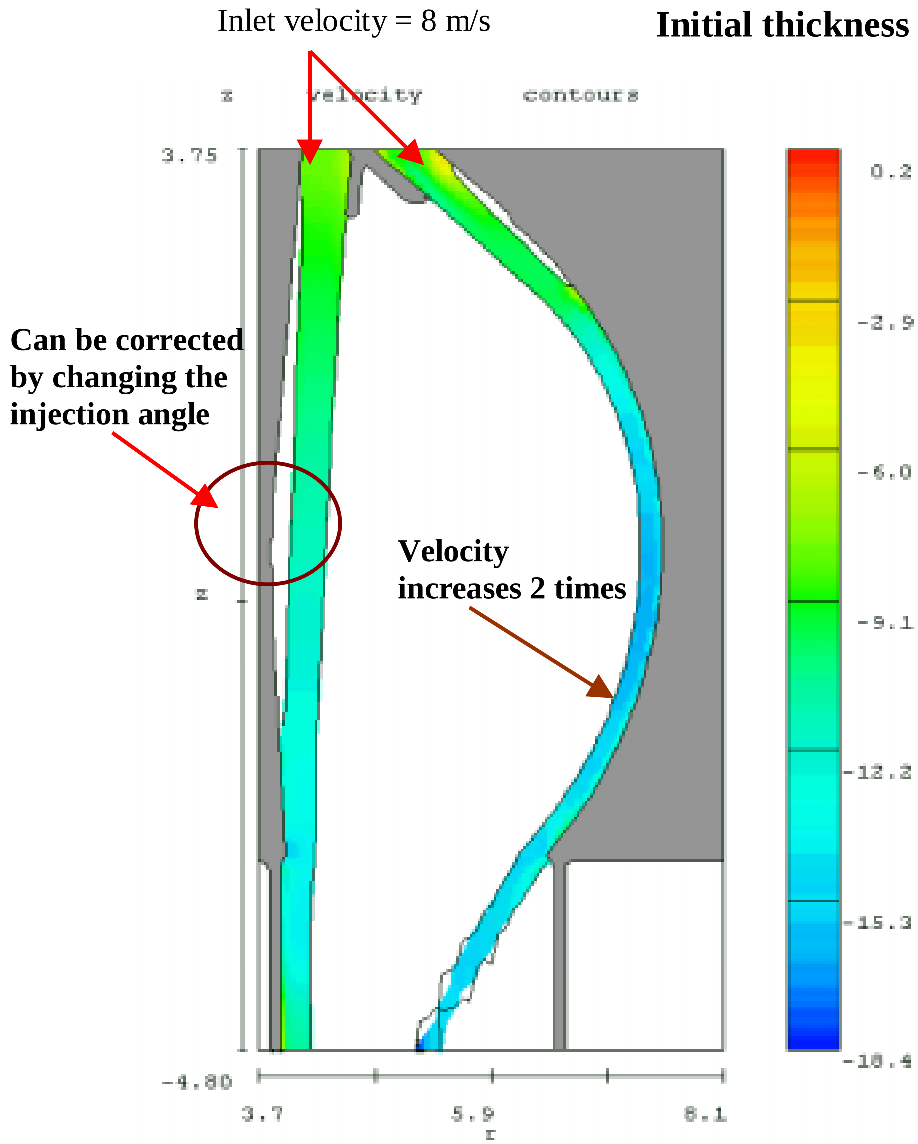
The thick liquid layer:

- ***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***
- ***is collected and drained at the bottom of the reactor (under design)***

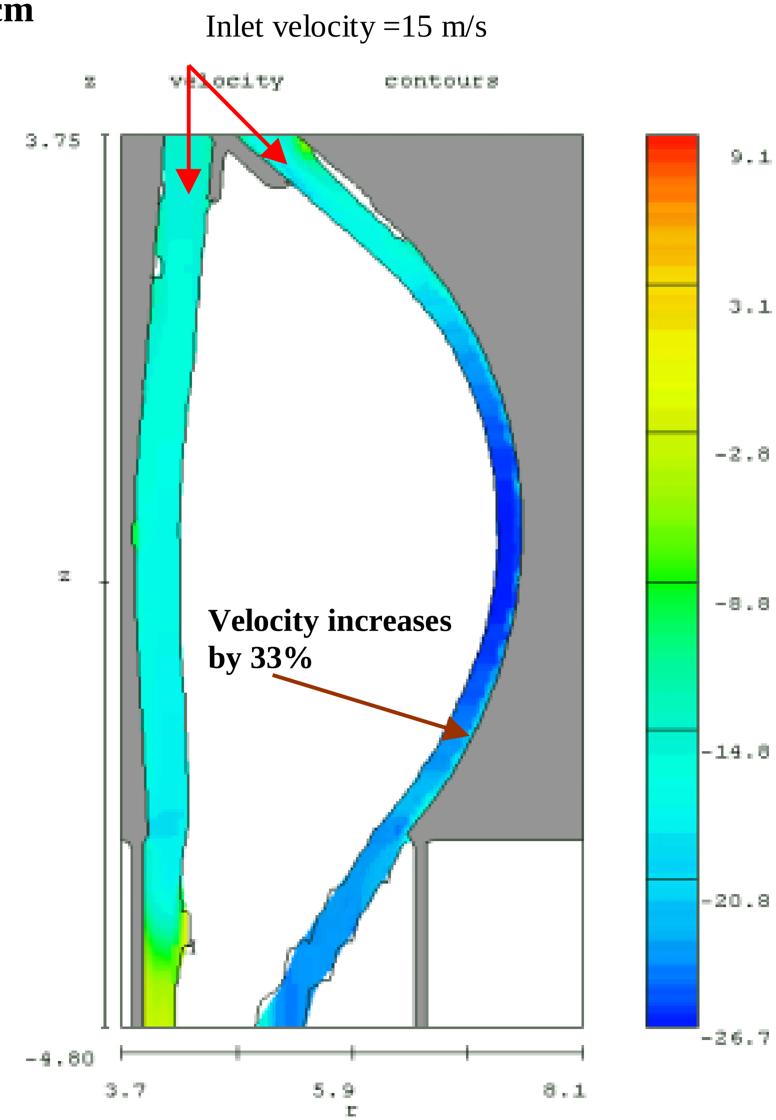
Some amount of thinning was observed along the poloidal path due to gravitational thinning and toroidal area expansion

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

Initial thickness = 50 cm



t/pass = 0.9 second



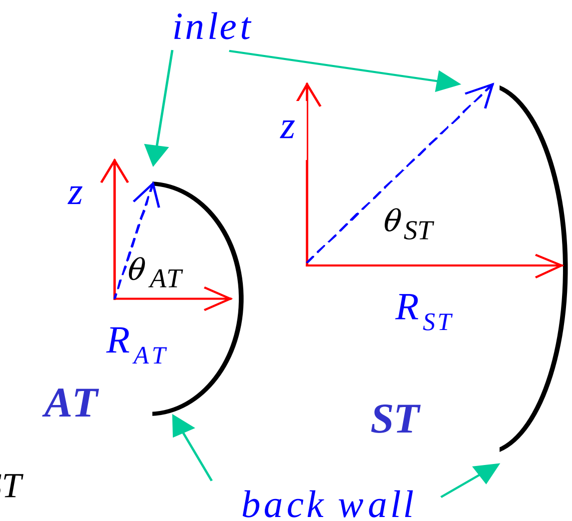
t/pass = 0.5 second

Optimum Hydrodynamic Configurations for ST and Advanced Tokamak can be Different

ST: Poloidal Flow with toroidal ROTATION

Initial Velocity: U= 5 m/s (poloidal direction),
V = 11 m/s (azimuthal direction),

AT: Poloidal Flow (no rotation).



$$\theta_{AT} > \theta_{ST}$$

$$g \sin\theta_{AT} > g \sin\theta_{ST}$$

$$R_{ST\ poloidal} \sim 2R_{AT\ poloidal}$$

$$R_{ST\ poloidal} > R_{ST\ toroidal}$$

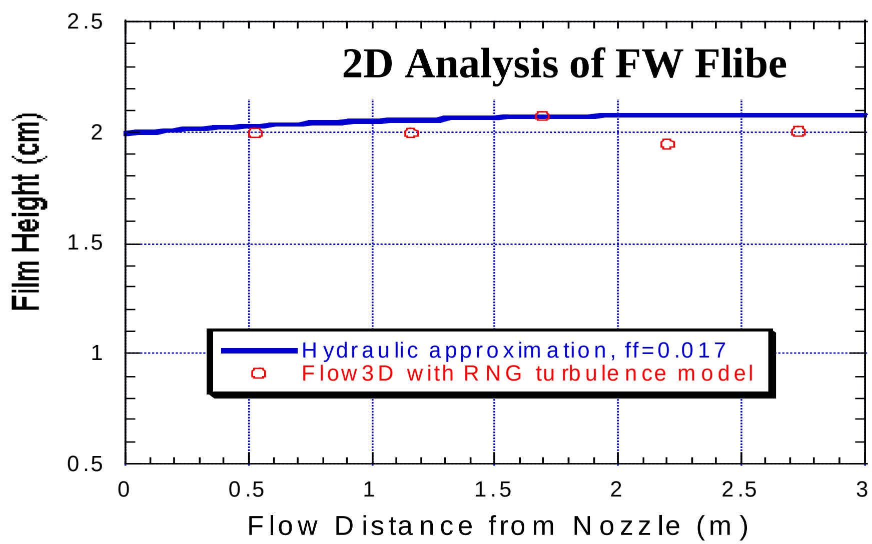
<u>REASONS</u>

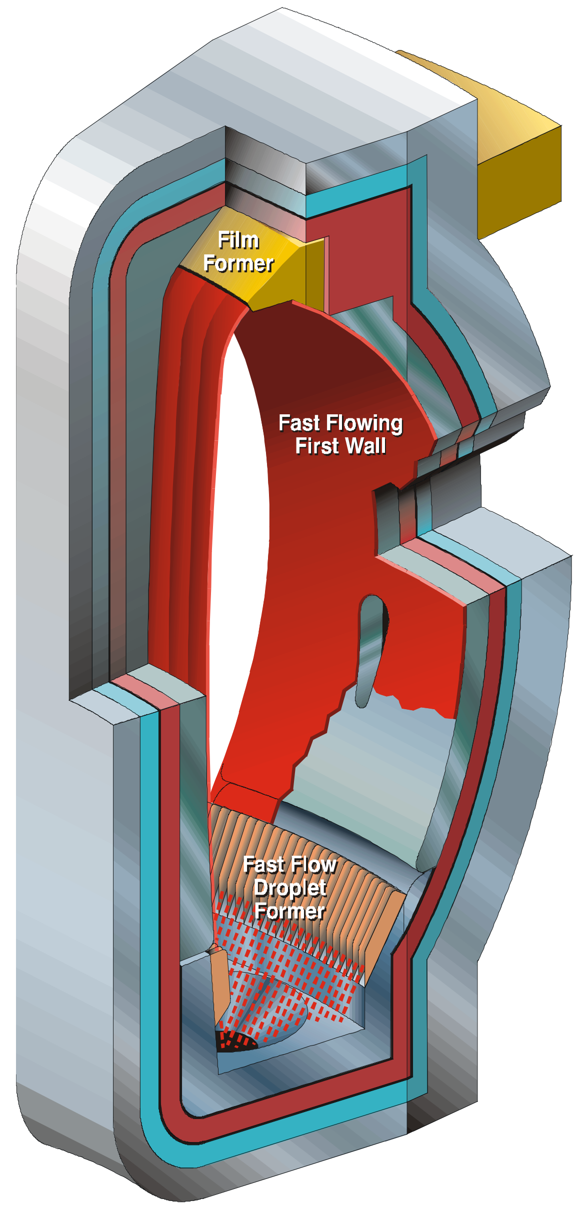
- ST is more elongated, therefore, ST has less "adherence to the wall" constraint at the inlet
- ST is taller, the increase in velocity due to gravitational acceleration (and thinning) is larger.
- Liquid layer thinning in ST can be prevented using obstacles in the flow path at mid plane where gravitational acceleration effect on the liquid layer is maximum.
- Toroidal Rotation of the flow in ST results in substantial increment in the centrifugal force towards the backwall and better adherence to the backwall at the mid plane.

$$F_{centrigual\ ST} \propto [U^2 / R_{ST\ poloidal}] + [V^2 / R_{ST\ toroidal}]$$

Convective Liquid Flow First Wall (CLIFF)

- **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**
- **Hydrodynamics calculations indicate near equilibrium flow for Flibe at 2 cm depth and 10 m/s velocity (below).** Some contradiction between different turbulence models needs to be resolved.





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

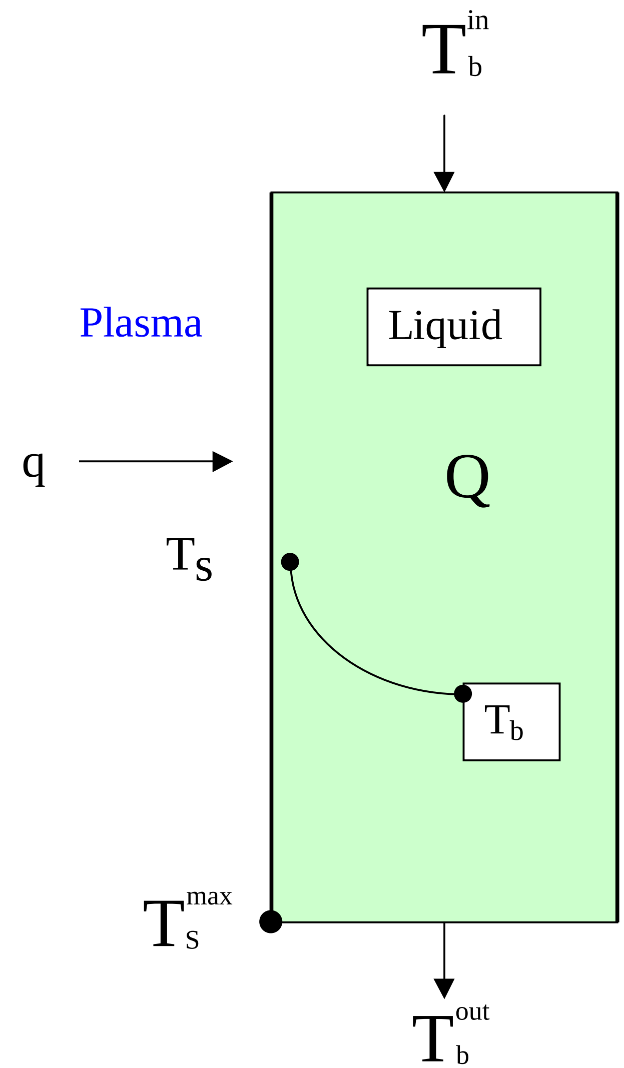
   $V^2/R > g$

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

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

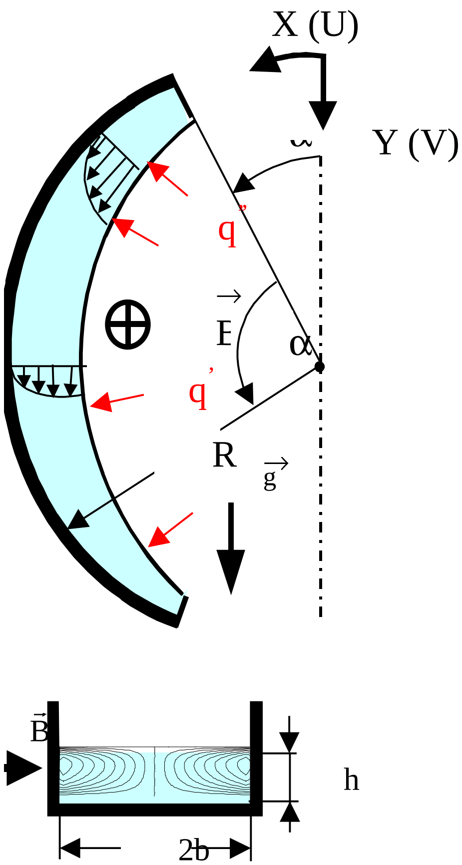


What is the Maximum Allowable Surface Temperature?

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

MODELING OF MAGNETOHYDRODYNAMICS AND HEAT TRANSFER FOR APEX



1. Momentum equation

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=\underbrace{\frac{1}{Fr}\{\cos(\alpha+\alpha_0)\frac{\partial h}{\partial x}+\sin(\alpha+\alpha_0)\}}_{\text{gravitational force}}-\underbrace{\chi\frac{\partial}{\partial x}(\int_y^h U^2dy)}_{\text{centrifugal force}}-\underbrace{\beta^2\frac{Ha}{Re}U}_{\text{MHD force}}+\underbrace{\frac{1}{We}\frac{\partial^3 h}{\partial x^3}}_{\text{capillar force}}+\underbrace{\frac{1}{Re}\frac{\partial}{\partial y}[1+\nu_t\frac{\partial U}{\partial y}]}_{\text{turbulent diffusion}}$$

2. Continuity equation

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0$$

3. Free surface kinematic condition

$$\frac{\partial h}{\partial t}=V_s-U_s\frac{\partial h}{\partial x}$$

4. Eddy viscosity

$$\nu_t=C_Df_D\,Re^2\frac{k^2}{\varepsilon}$$

5. "k" (turbulent kinetic energy) equation

$$\frac{\partial k}{\partial t}+U\frac{\partial k}{\partial x}+V\frac{\partial k}{\partial y}=\underbrace{\frac{1}{Re}\frac{\partial}{\partial y}[(1+\frac{\nu_t}{\sigma_k})\frac{\partial k}{\partial y}]}_{\text{diffusion}}+\underbrace{\frac{1}{Re}\nu_t(\frac{\partial U}{\partial y})^2}_{\text{production}}-\underbrace{\frac{\varepsilon}{Re}}_{\text{dissipation}}-\frac{2}{Re}(\frac{\partial\sqrt{k}}{\partial y})^2-\underbrace{C_3\beta^2Nk}_{\text{Joule dissipation}}$$

6. "Epsilon" (dissipation rate) equation

$$\frac{\partial \varepsilon}{\partial t}+U\frac{\partial \varepsilon}{\partial x}+V\frac{\partial \varepsilon}{\partial y}=\frac{1}{Re}\frac{\partial}{\partial y}[(1+\frac{\nu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial y}]+\frac{f_1}{Re}C_1\nu_t\frac{\varepsilon}{k}(\frac{\partial U}{\partial y})^2-\frac{f_2}{Re}C_2\frac{\varepsilon^2}{k}+\frac{2}{Re}\nu_t(\frac{\partial^2 U}{\partial y^2})^2-C_4\beta^2N\varepsilon$$

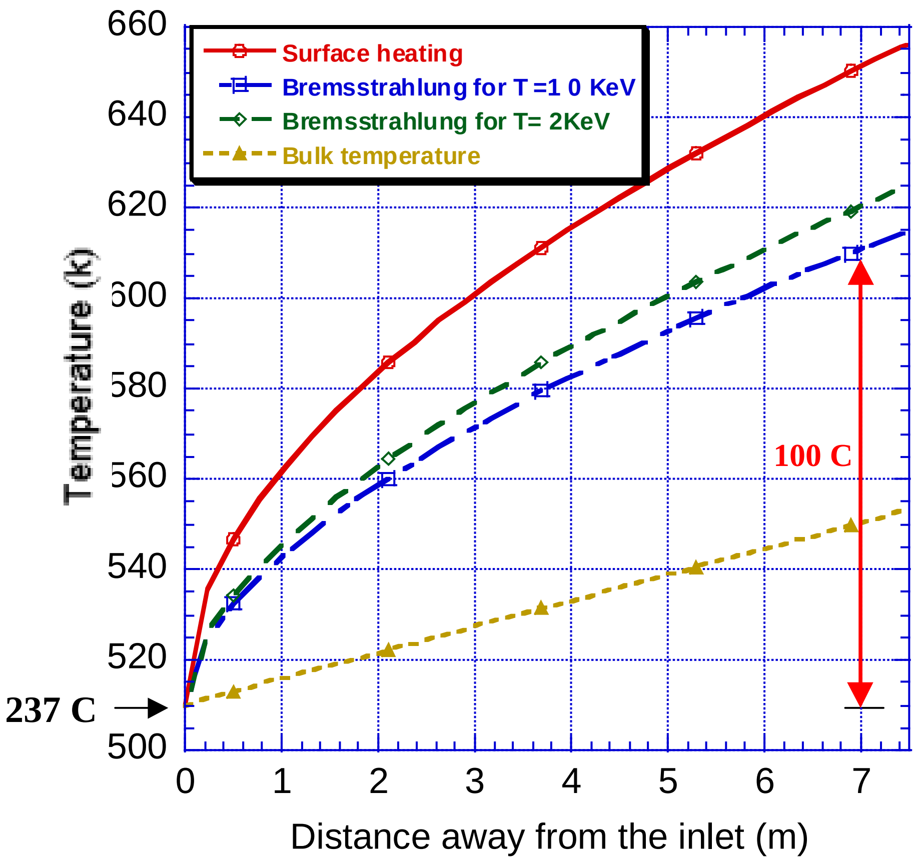
7. Energy equation

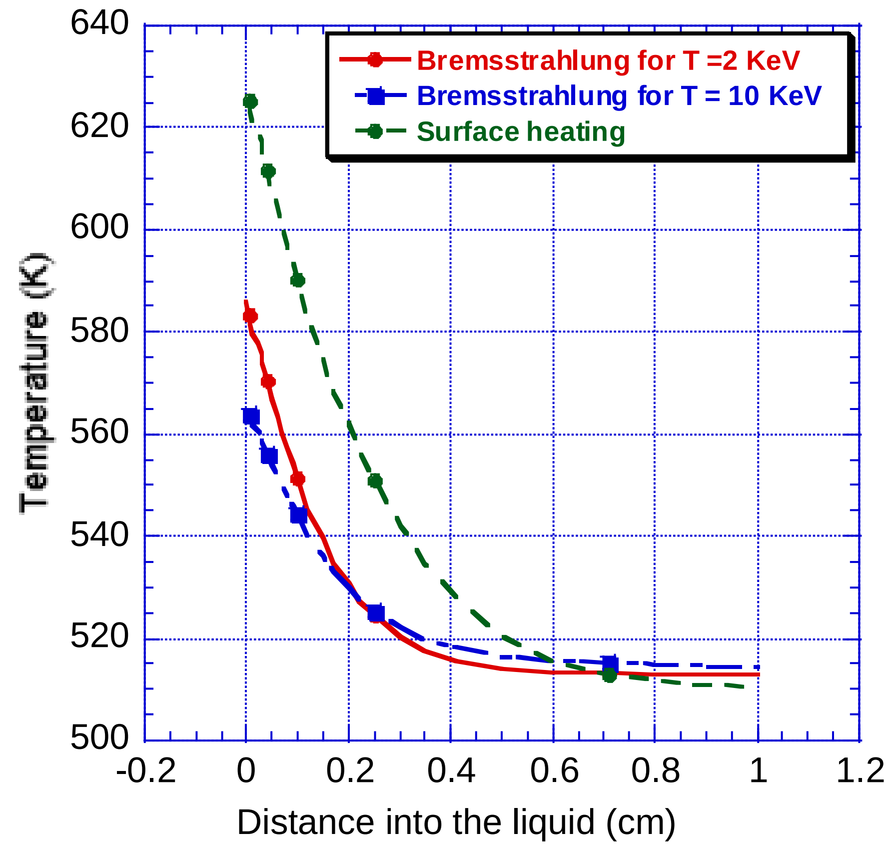
$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}=\frac{1}{Pe}\frac{\partial}{\partial y}[(1+\frac{\nu_t}{\sigma_T}Pr)\frac{\partial T}{\partial y}]+q_v$$

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

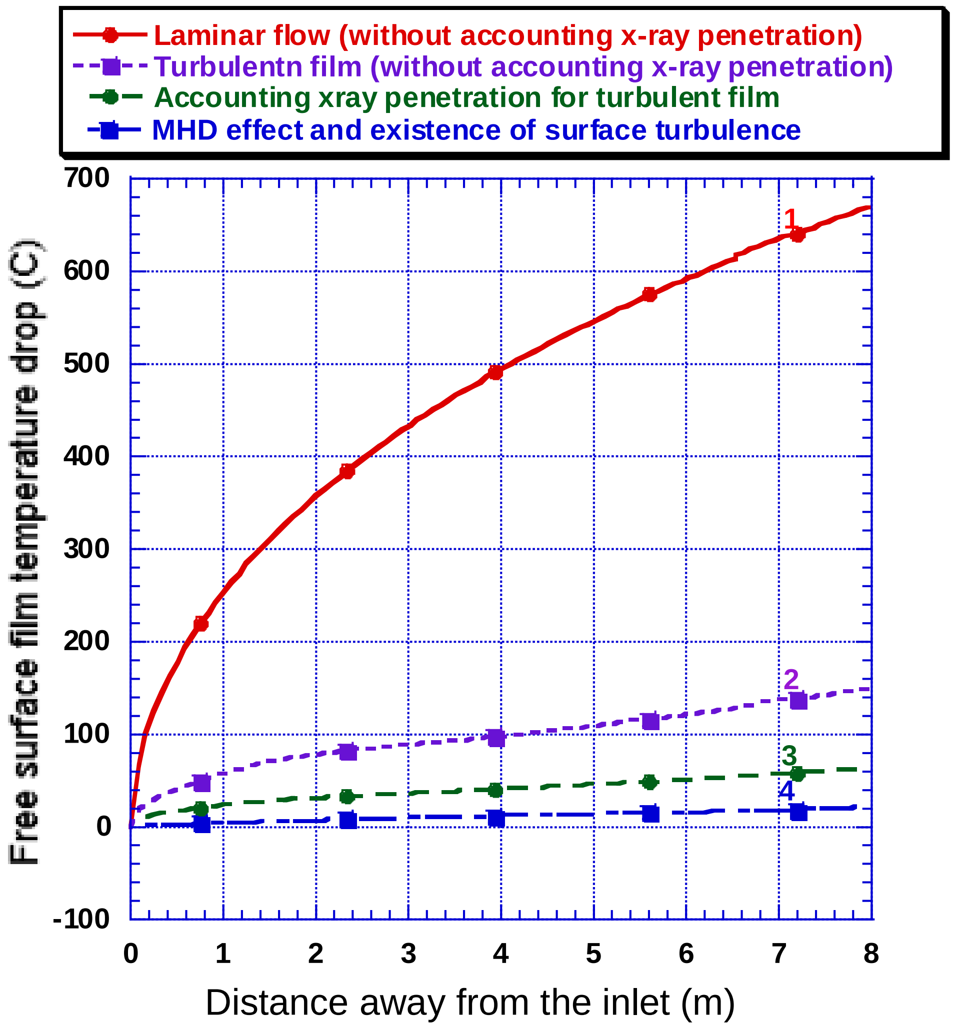
Li velocity = 20 m/s
Surface heat load = 2 MW/m^2





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 η (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:

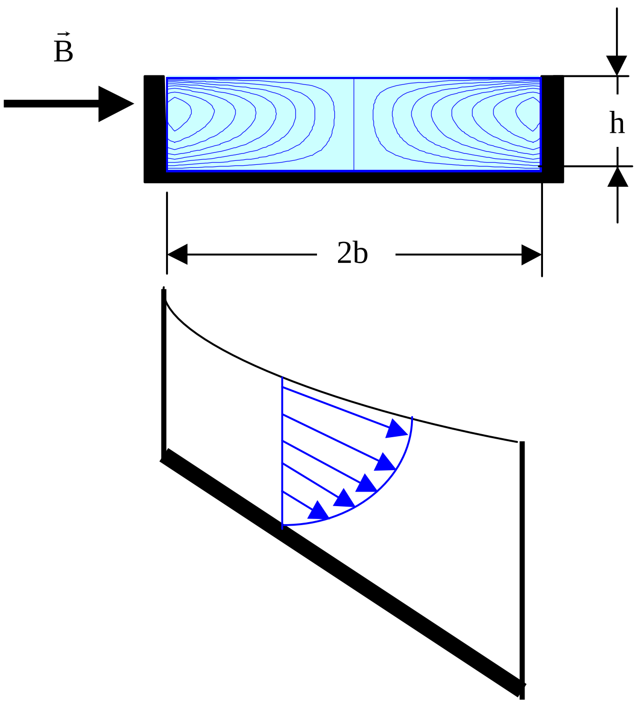
1. Fast flowing liquid jet, separate from slow moving liquid blanket, to keep surface temperature of the liquid (and hence evaporation rate) low, while the slow moving blanket has high outlet temperature
2. New Schemes to promote controlled surface mixing and wave formation to eliminate surface thermal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

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

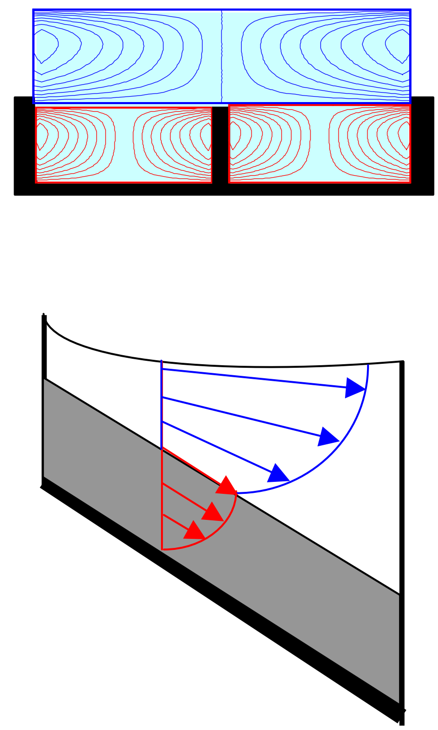
Accounting for hard Bremsstrahlung radiation penetration: the surface heat load can be deposited deeper in the liquid; this significantly reduces the liquid jet surface temperature

Realization of two-streem flow using a submerged wall

a) without a submerged wall

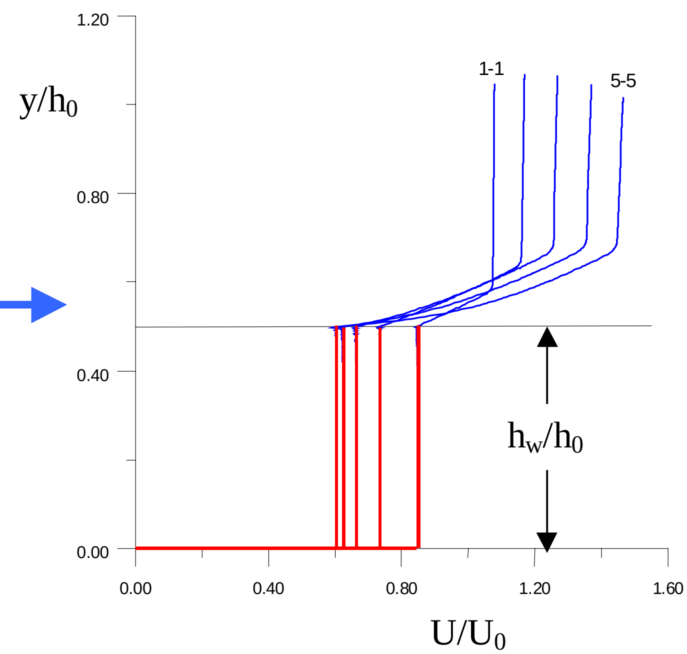


b) with a submerged wall



Calculated velocity profiles in the two-stream flow : $h_w/h_0=0.5$

$X_{1\text{-}1}=1.7$ m; $X_{2\text{-}2}=3.4$ m; $X_{3\text{-}3}=5.1$ m; $X_{4\text{-}4}=6.8$ m; $X_{5\text{-}5}=8.3$ m



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

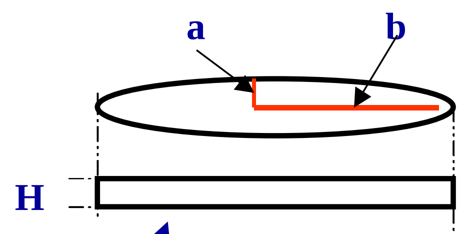
- Results are Very Interesting and Encouraging. Solutions are being developed to overcome problems revealed by the calculations

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

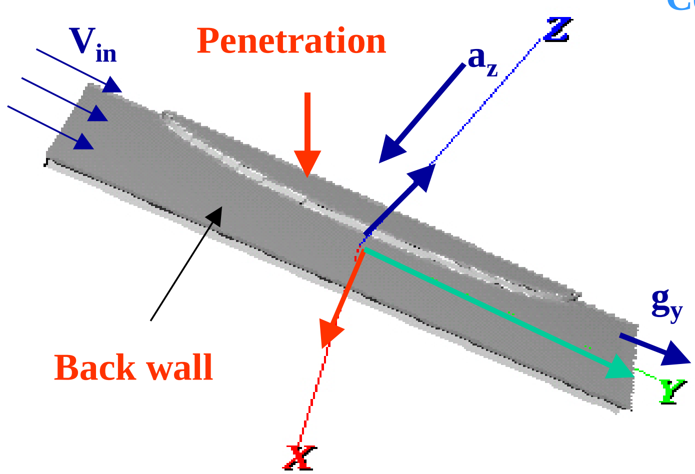
REFERENCE CASE PARAMTERS

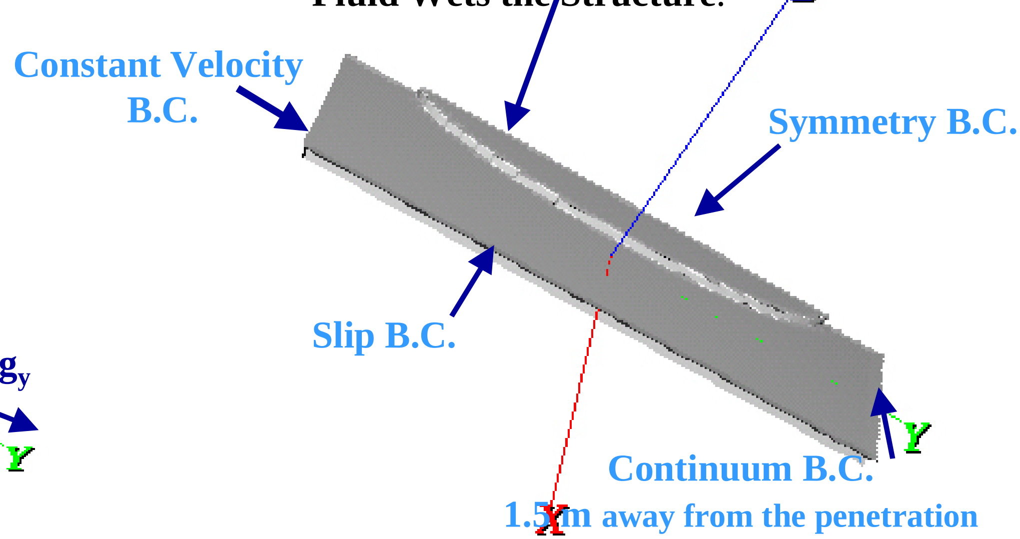
V_{in} (m/s)	10.0		
a_z (m^2/s)	25.0		
g_y (m^2/s)	9.8		
Wall Roughness (m)	10^{-5}		
Fluid-Wall Contact Angle	0.0		
Penetration Dimensions (m)	a	b	H
	.1	.45	0.02

Flibe at 550 ºC is used as a working fluid.



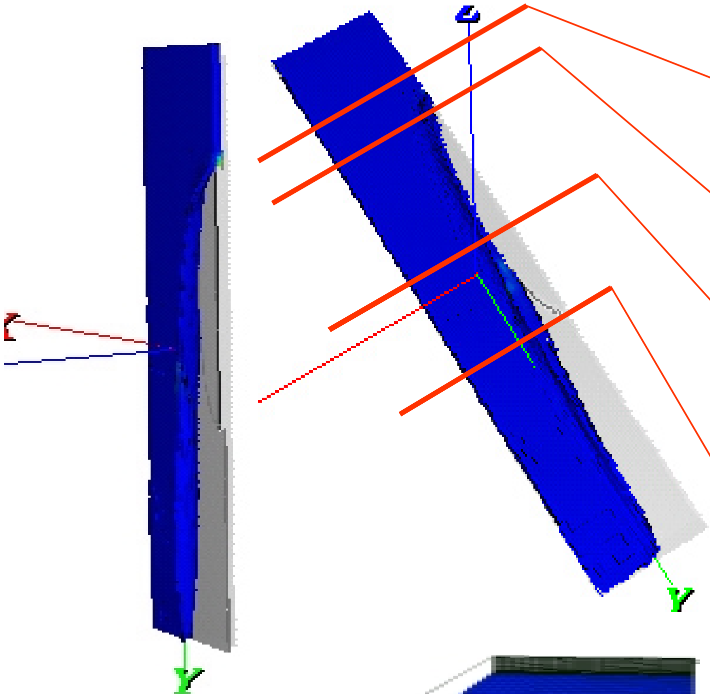
Fluid Wets the Structure.

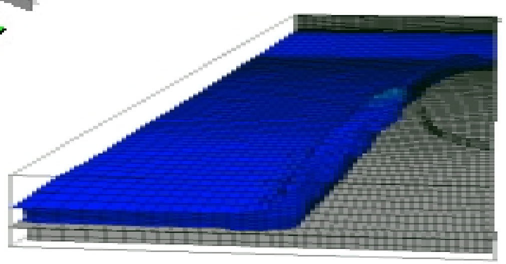




RESULTS OF 3-D TIME DEPENDENT CALCULATIONS FOR FLUID FLOW AROUND PENETRATIONS (For Initial Case)

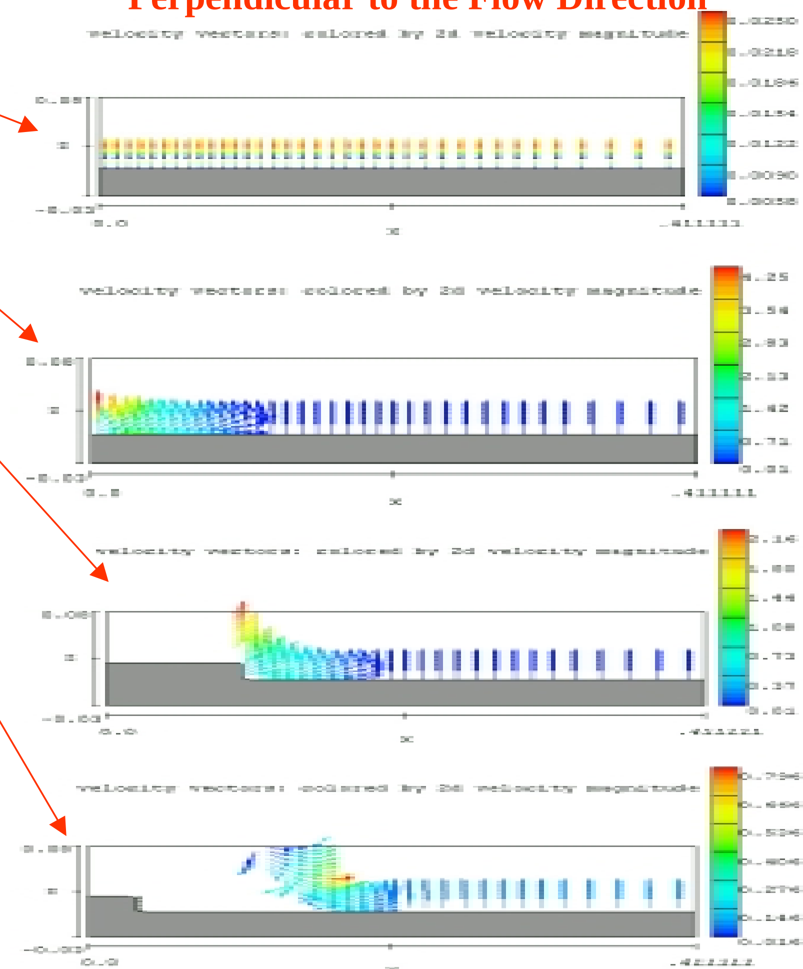
3-D CFD Simulation Results





3-D View of the Wake Following the Penetration.

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



POTENTIAL CHALANGES IN LIQUID WALL BEHAVIOR AROUND PENETRATIONS

STAGNATION

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

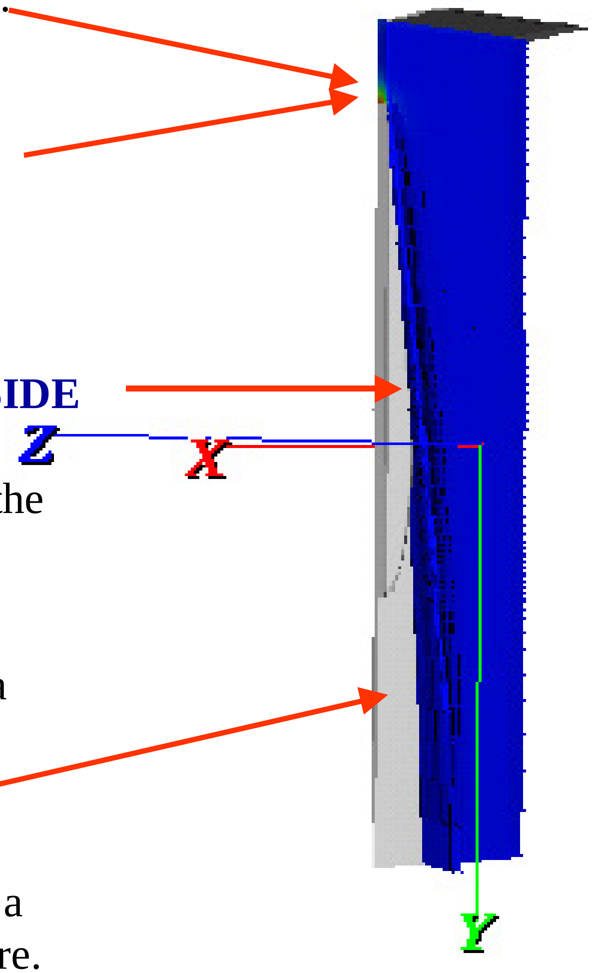
SPLASH OF THE FLUID AND DROPLET EJECTIONS

- 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.

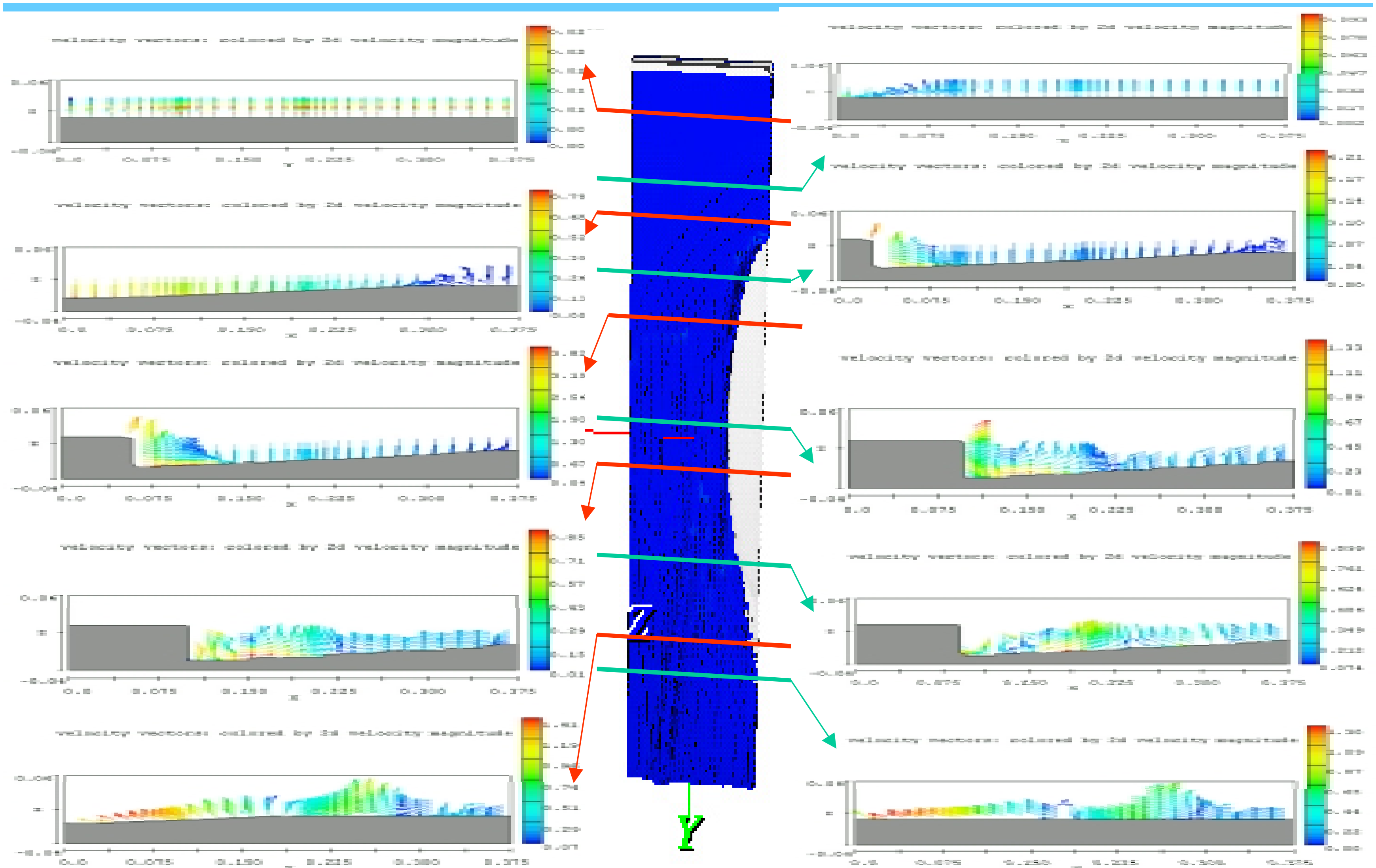
  (144 m^3 of fluid per hour is displaced for a 20 cm wide (in the flow direction) penetration for the CLIFF concept with a base velocity of 10 m/s.)



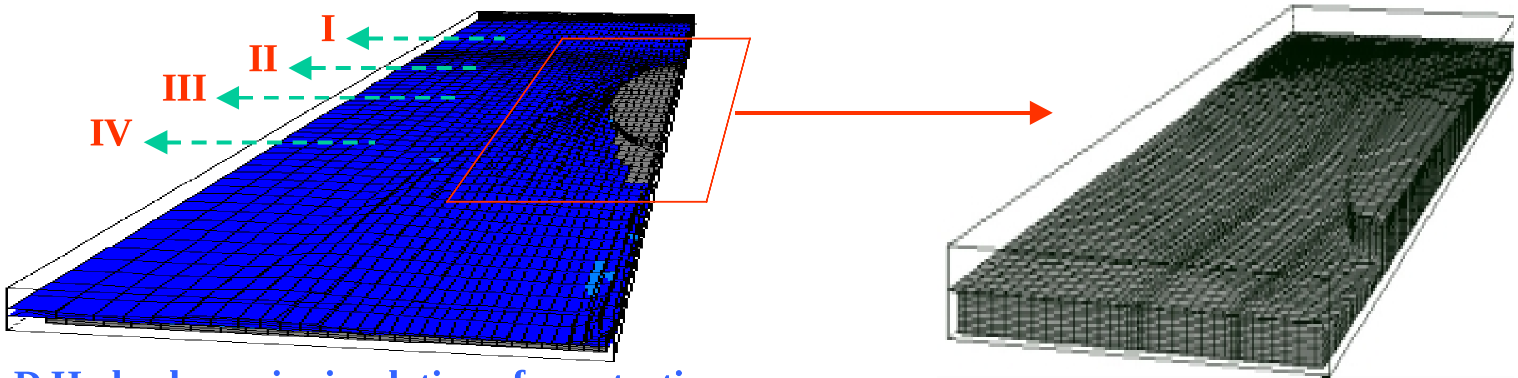
WAKE FORMATION

- 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

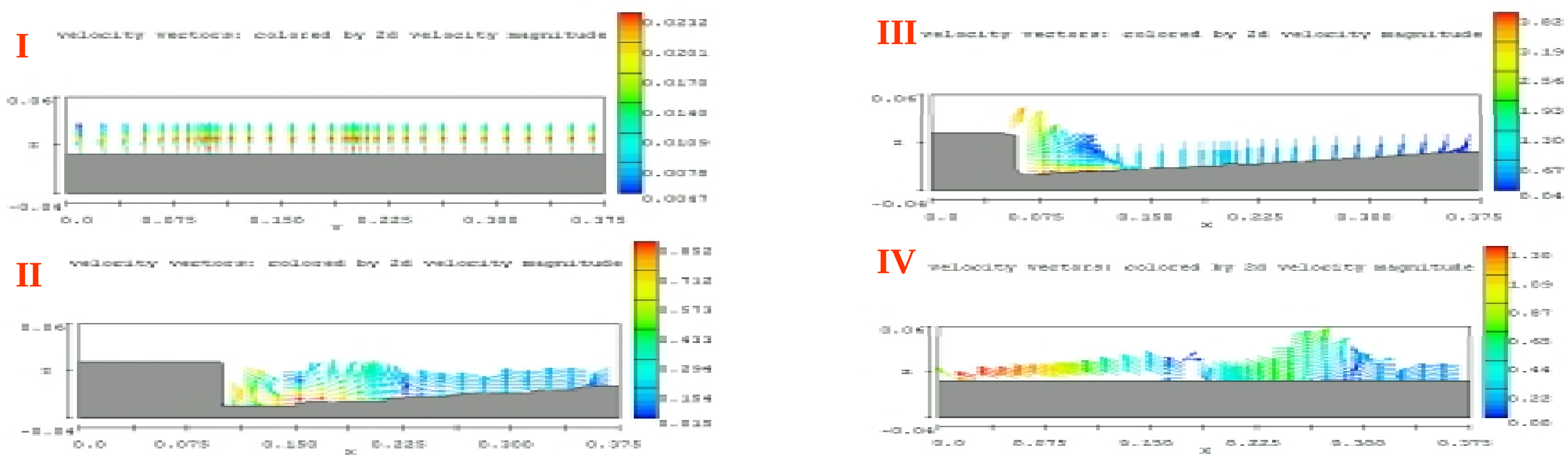


DESIGN SOLUTIONS, SUCH AS MODIFICATIONS TO BACK WALL TOPOLOGY RESULT IN MORE ATTRACTIVE FLUID FLOW CHARACTERISTICS AROUND PENETRATIONS



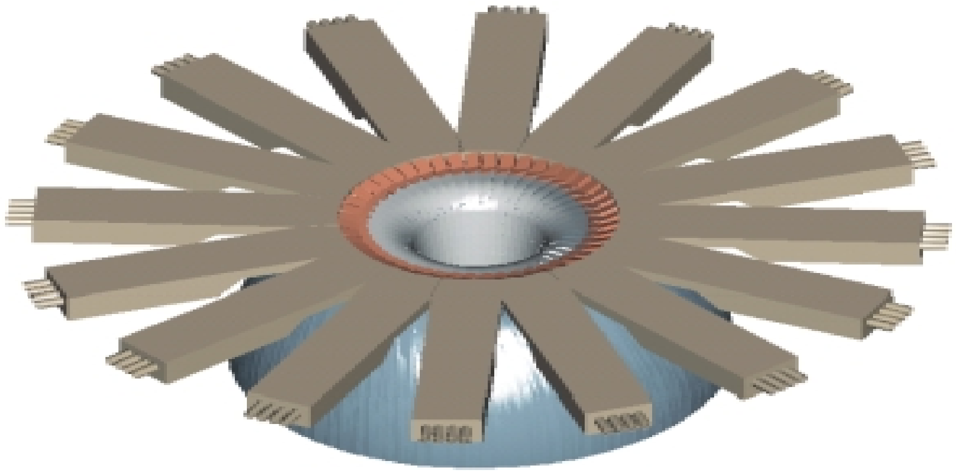
3-D Hydrodynamic simulation of penetration accommodation when the back wall topology surrounding the penetration is modified.

Modified back wall topology surrounding the penetration.

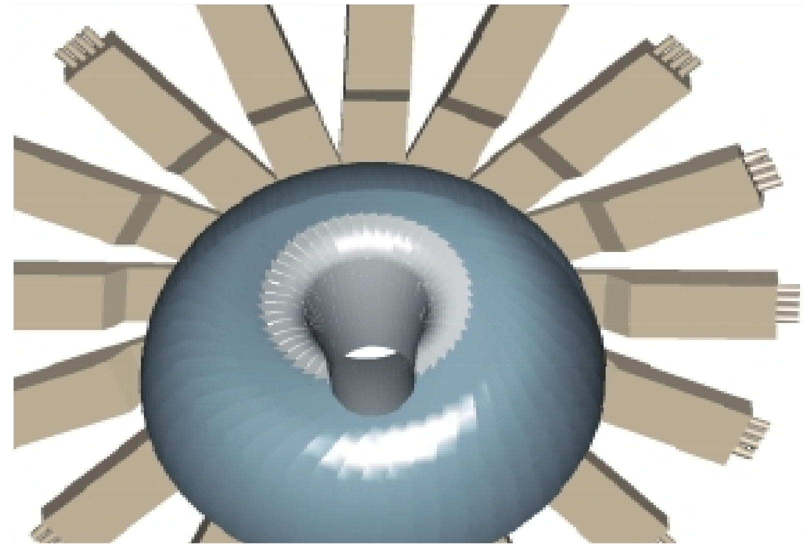


2-D Velocity magnitude in planes perpendicular to the flow direction

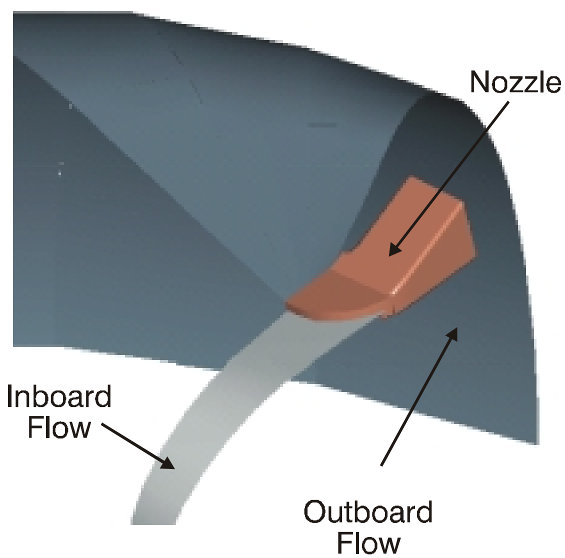
Convective Layer Forming Device



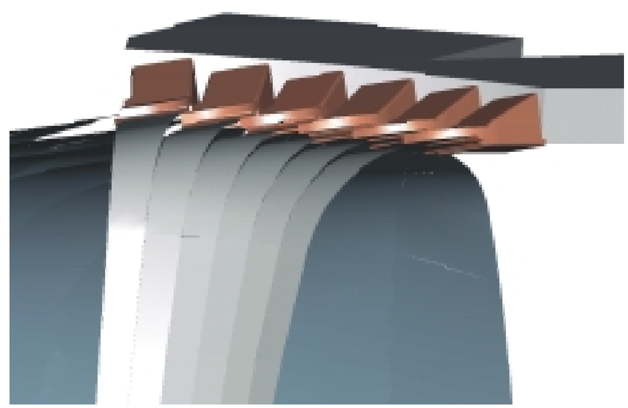
Top view of convective layer forming device array



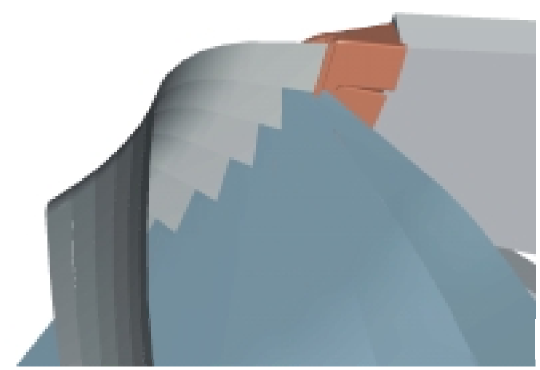
View looking up from inside the machine



View of convective layer forming device - single nozzle



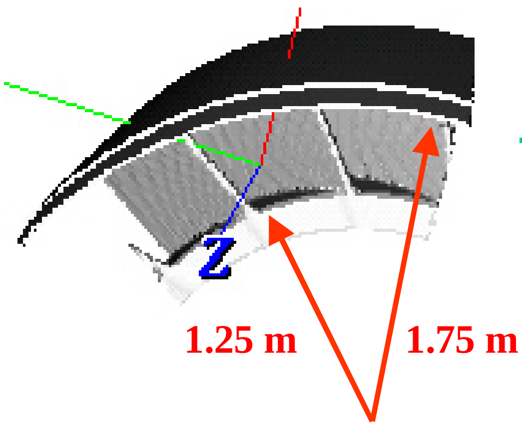
View from centerline of machine showing inclination of nozzles



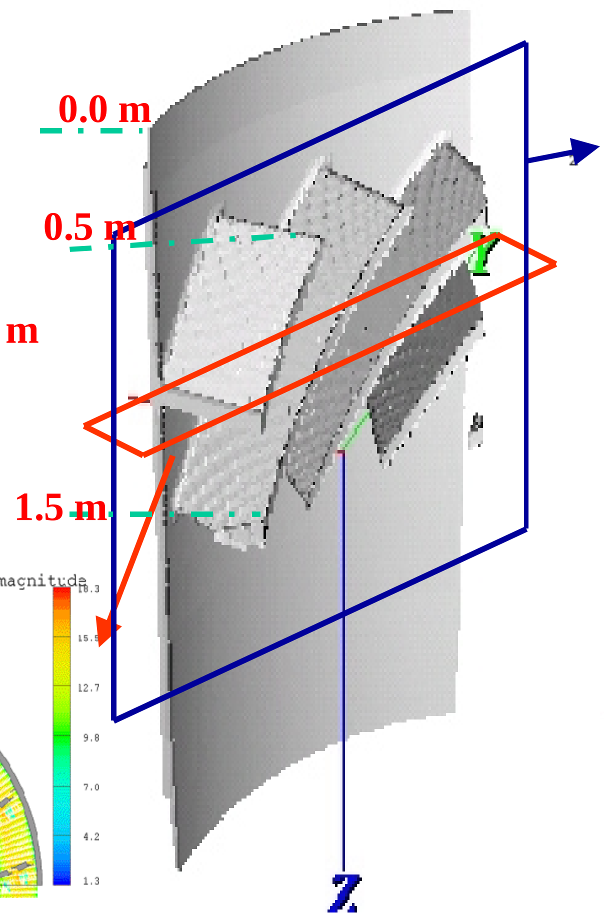
View from plasma looking up, nozzles are completely shielded

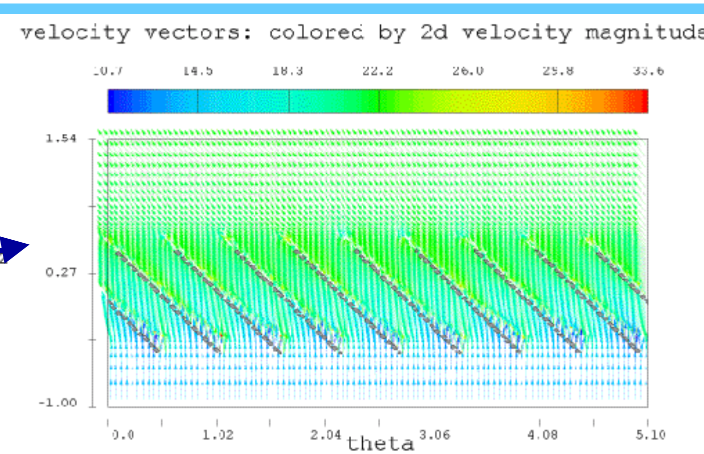
ST & FRC
INLET NOZZLE DESIGN FOR SWIRL FLOW

60 º Cross-section of Inlet

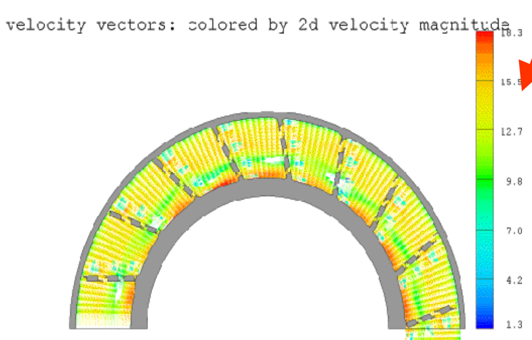


Top View

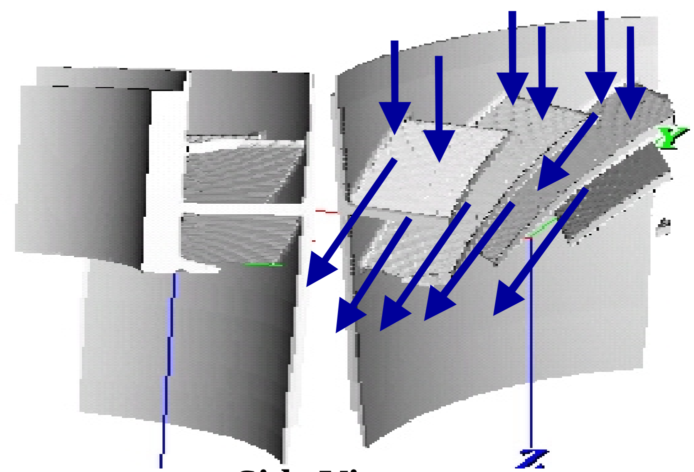




2-D Velocity Vector in z-theta plane at r = 1.6 m



2-D Velocity Vector in r-theta plane at z =0.7 m from the inlet



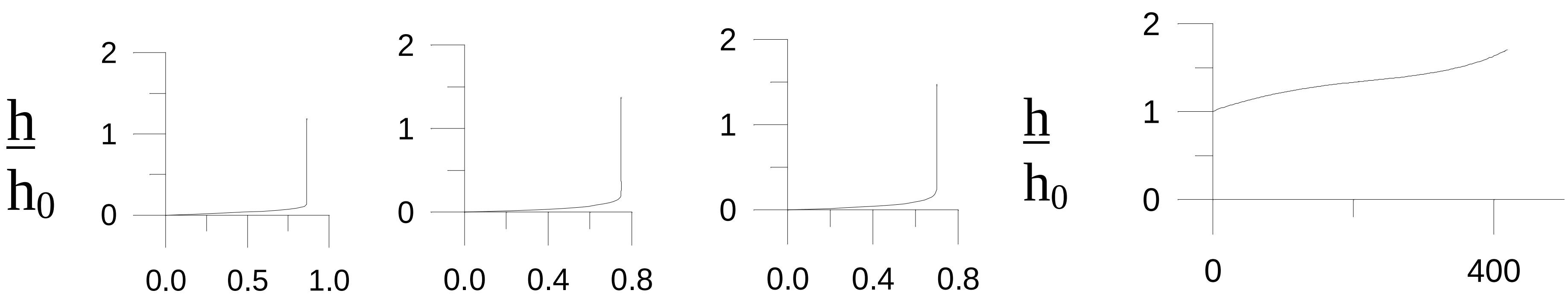
Side Views

Insulators Appear to be Required for Liquid Metal Walls

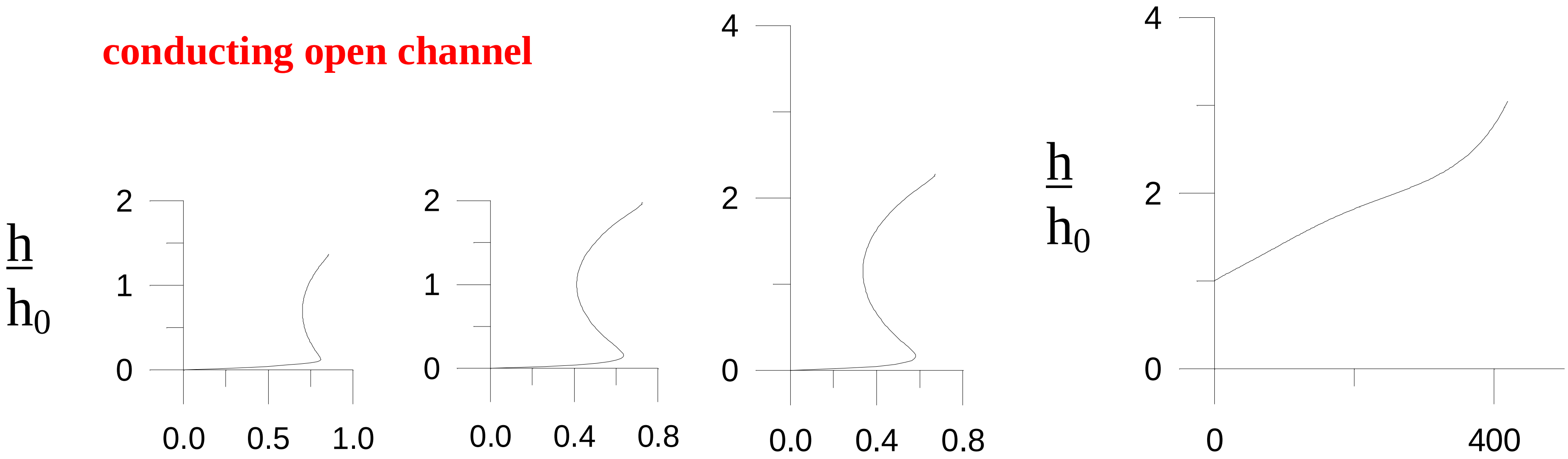
MHD Results of CLiFF Thin Lithium Layer

Dimensionless cross-sectional velocity profiles and film thickness evolution as flow proceeds downstream:

insulated open channel



conducting open channel



Summary Remarks on Liquid Walls

- **Liquid Walls appear to be Concept Rich. Options include:**
  - Thin Wall
  - Thick Blankets
  - Liquids: Flibe, Liquid Metals (Li, SnLi)
  - Hydrodynamics: GMD, Swirl GMD, EMR, MP
- **These options have some common as well as their own unique issues and advantages**
- **APEX will continue to explore and advance these options**
- **Some R&D on modelling and experiments have been initiated in various US organizations, but much more is needed**

  e.g.
  - Plasma-Wall Interactions
  - Free Surface Flow and Heat Transfer (including MHD)
  - Liquid data base

Summary Remarks (cont'd)

- **International Collaboration has already provided excellent contributions. More is encouraged**

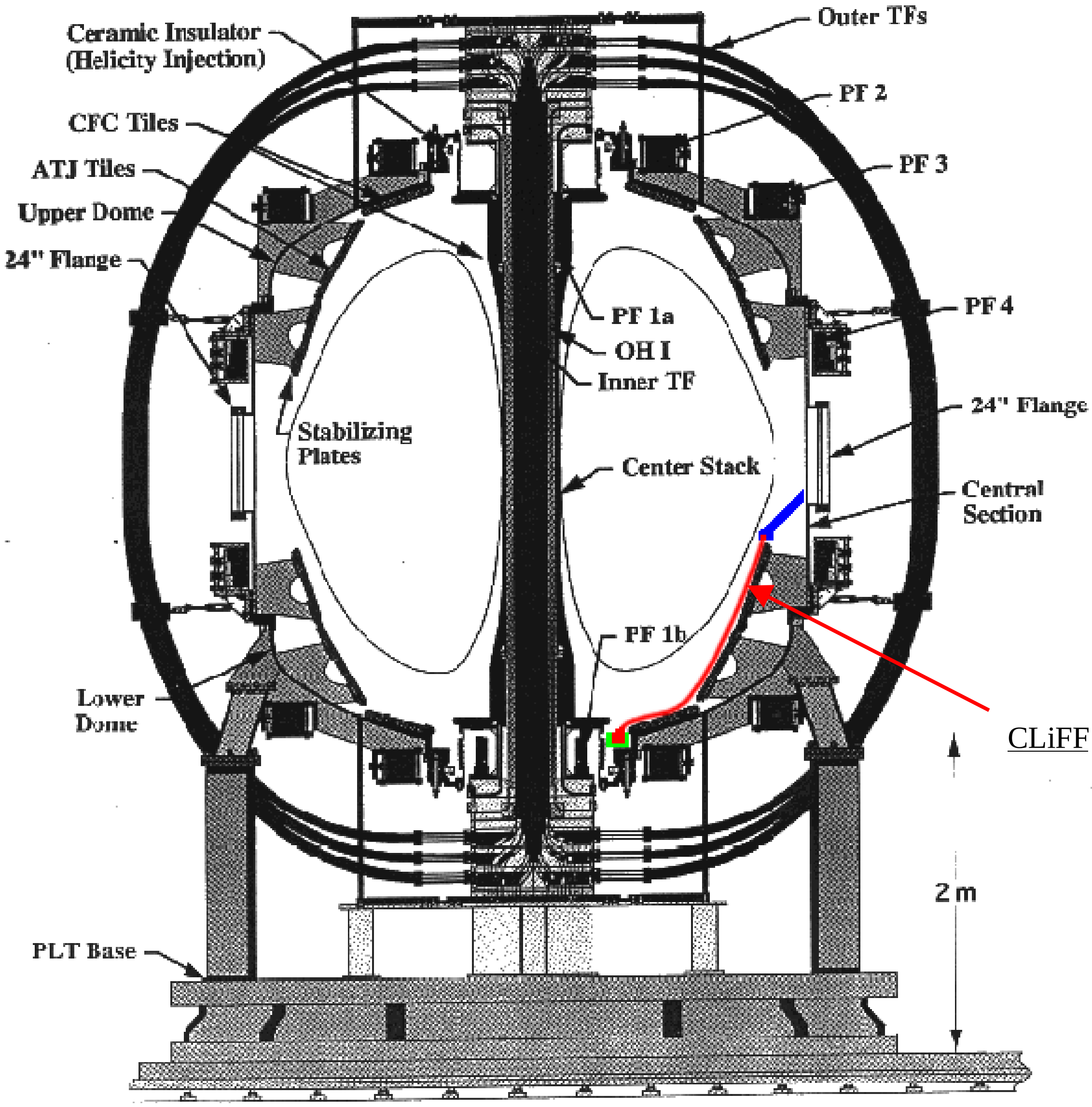
- **Snowmass Meeting Provided Important Input on Liquid Walls:**

- **Potential Improvements in Plasma Confinement and Stability (e.g. higher β)**

- **Enthusiasm among the physicists to test liquid walls (e.g. CDX-U, DIII-D, C-MOD)**

- **Challenge to put liquid walls in a large plasma device (e.g. NSTX) in 5 years**

Liquid Wall in NSTX Provides Exciting Opportunities



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

APEX