## **Liquid Walls**

## **Innovative Concepts for First Walls and Blankets**

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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<sup>2</sup>

Surface Heat Flux > 2 MW/m<sup>2</sup>

- 2. High Power Conversion Efficiency (> 40%)
- 3. High Availability
  - -Lower Failure Rate

 $\mathbf{MTBF} > 43 \ \mathbf{MTTR}$ 

-Faster Maintenance

4. Simpler Technological and Material Constraints

# **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)

# 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

# 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  $\vec{F} = \vec{J} \times \vec{B}$



Fluid Out

- 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.



## **Liquid Wall Options**

Thickness	<ul> <li>Thin (~ 2cm)</li> <li>Moderately Thick (~ 15 cm)</li> <li>Thick (&gt; 40 cm)</li> </ul>
Working Liquid	<ul><li>Lithium</li><li>Sn-Li</li><li>Flibe</li></ul>
Hydrodynamic Driving / Restraining Force	<ul> <li>Gravity-Momentum Driven (GMD)</li> <li>GMD with Swirl Flow</li> <li>Electromagnetically Restrained</li> <li>Magnetic Propulsion</li> </ul>
Liquid Structure	<ul> <li>Singe, contiguous, stream</li> <li>Two streams (fast flowing thin layer on the plasma side and slowly flowing bulk stream)</li> </ul>

# **Motivation for Liquid Wall Research**

What may be realized if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement Enable high β, stable physics regimes if liquid metals are used
- High Power Density Capability
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials -Makes difficult structural materials more problems tractable
- Potential for Higher Availability -Increased lifetime and reduced failure rates -Faster maintenance

# Flowing LM Walls may Improve Plasma Stability and Confinement

Several possible mechanisms identified at Snowmass...

**Presence of conductor close to plasma boundary (Kotschenreuther) -** Case considered 4 cm lithium with a SOL 20% of minor radius

- Plasma Elongation  $\kappa > 3$  possible with  $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
- Size of plasma devices and power plants can be substantially reduced

### **High Poloidal Flow Velocity (Kotschenreuther)**

- LM transit time < resistive wall time, about  $\frac{1}{2}$  s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and E×B shearing rates (transport barriers)

### Hydroden Gettering at Plasma Edge (Zakharov)

- Low edge density gives flatter temperature profiles, reduces anomalous energy transport
- Flattened or hollow current density reduces ballooning modes and allowing high  $\beta$



#### **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 Reduce the Volume of Radioactive Waste

### Basis of Calculations

- 30-yr plant lifetime
- Structure life =  $20 \text{ MW} \cdot \text{y}/\text{m}^2$
- 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)



# **Scientific Issues for Liquid Walls**

- Effects of Liquid Walls on Core Plasma including:
  - Discharge evolution (startup, fueling, transport, beneficial effects of low recycling)
  - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma-Liquid Surface Interactions
- Turbulence Modifications At and Near Free-Surfaces
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, 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,  $V_{\theta,ave} = 11$  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,  $V_{poloidal} = 4.5 \text{ m/s}, V_{toroidal,ave} = 12 \text{ m/s}$
- 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**



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

Toroidal width = 61 cm Corresponding to 10° 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)

<sup>–</sup>Inboard thick flowing liquid wall

## **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 Interactions Affect both the Core Plasma and the Liquid Walls

- Multi-faceted plasma-edge modelling has started (Ronglien et al.)
- Experiments have started (in PISCES, DIII-D and CDX-U)





Liquid lithium limiter in CDX-U

### **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



# Flibe Free Surface Temperature Magnitude Highly Depends on the Turbulent Activities near the Surface

Heat transfer degradation at Flibe free surface results from both the damping of the normal velocity component at the free surface and suppression of turbulence by the field.



## ESTABLISHING A TWO-STREAM FLOW USING SUBMERGED WALLS to IMPROVE HEAT TRANSFER





- MHD drag slows down liquid between submerged walls
- Free surface layer can accelerate to high velocity



### 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 SIDEOF THE PORTZ

- A stream of rising fluid is diverted to the sides surrounding the penetration due to the obstruction of flow path.
  - (144 m<sup>3</sup> 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



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



Modified back wall topology surrounding the penetration.

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

# **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

