IFE Chamber Research Program Overview

University of California, Los Angeles

Faculty: M. Abdou, N. Ghoniem

Researchers: K. Gulec, N. Morley, T. Sketchley, S. Smolentsev, A. Ying, M. Youssef

Students: A. Konkachbaev, D. Lucero, S. Quan, J. Williams

IFE Chamber Technology Planning Meeting
Pleasanton, California
March 18-19, 1999

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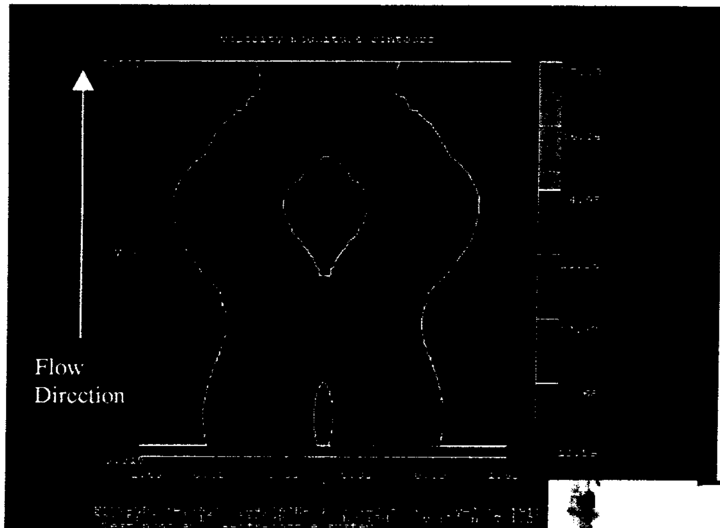
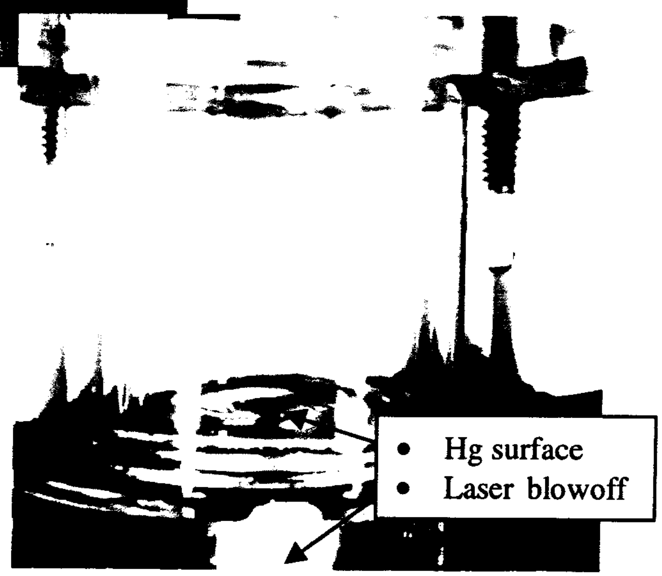
Inertial Fusion Research Program UCLA

Basic Chamber Research

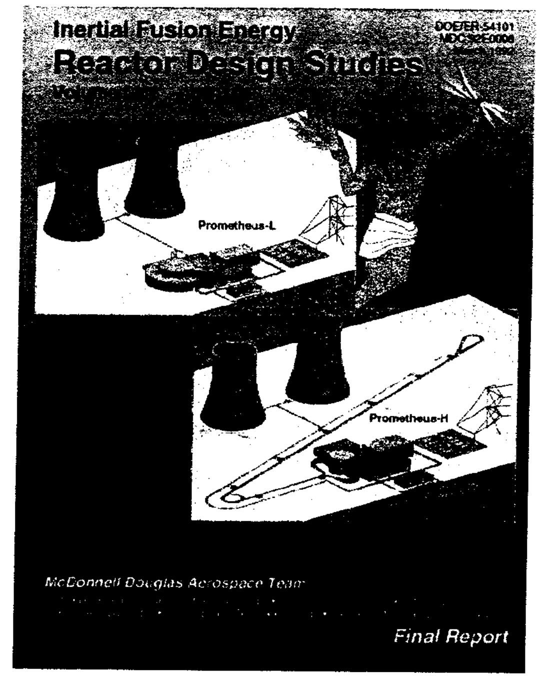


3D Liquid Pocket Simulation



Liquid Fracture Experiment

Design Studies and Program Guidance



Prometheus Design Study

UCLA Capabilities for IFE Chamber Technology

- Experimental Facilities
  - **Liquid Metal Flow Loop** and Discharge Jets
  - Large Working Volume (1 m^3) **Magnetic Field System**
  - 1-J, Nanosecond pulse, **Nd-Yag Laser** and Laser Diagnostics (collaboration with V. Gupta)
  - **Beryllium** and **ceramic oxide handling** and **heat transfer** test facilities
  - Engineering IV Laboratories (1st and 4th Floor)
  - STRB Building for large experimental apparatus (Power Supplies, Magnetic Yoke, Overhead Crane, etc.). Home of Electric Tokamak facility

- Simulation Tools
  - **3-D Navier-Stokes Simulations** for Incompressible and Compressible Flow
    - Free Surface
    - Phase Change
    - MHD Flow
    - Turbulence simulation
  - **3-D Heat Transfer** and Mechanics
  - **Magnetic Field Simulations**
  - **Neutron and Photon Transport** in Condensed Matter, Activation and Radioactivity

- MAE Department Faculty in Fluid Mechanics, Solid Mechanics, and Heat Transfer. (More than 15 Senior Professors with relevant research programs and experimental facilities)

- Physics and IPFR Research in Plasma Science, Laser Science, and Pulsed Power

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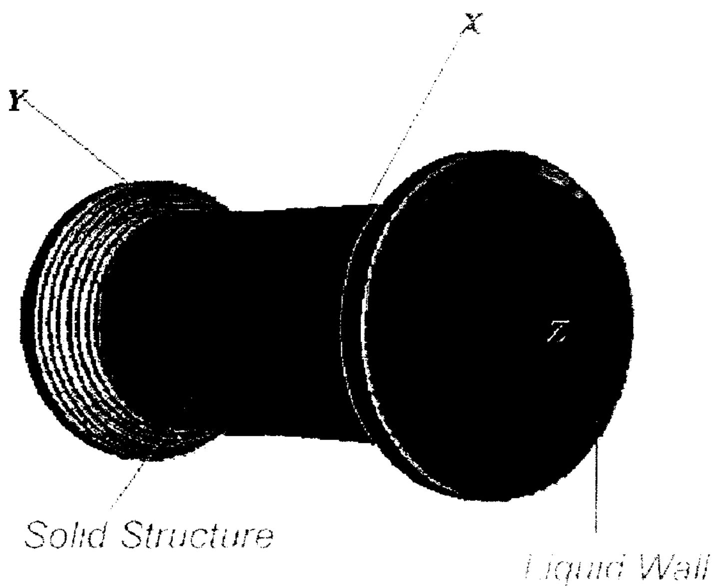
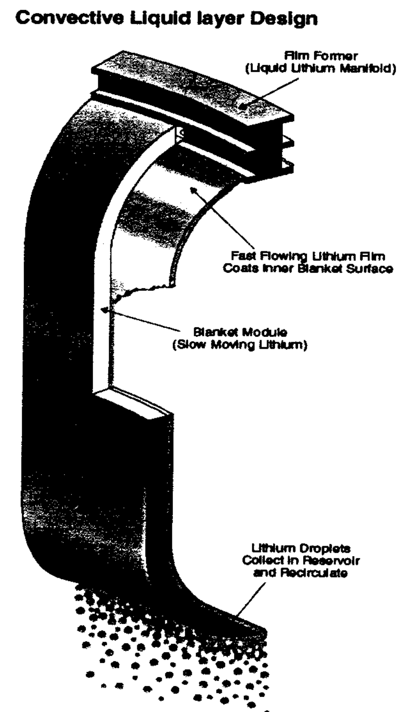
APEX Program Overlap with IFE Interests

The APEX program requires High Neutron Wall Load and High Surface Heat Flux Capabilities. Many innovative concepts under investigation

- Thick and Thin Liquid Wall Concepts



Cylindrical FRC similar to Vortex Flow IFE Chamber



Thin Liquid Layer Flow applicable to IFE Chamber

- High Power Density Drywall Concepts

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Current Chamber Research Activities at UCLA

- Simulation and Experimental Modeling of Free Liquid Jet Flows
- Simulation of Liquid Vortex Flows
- High Strain Rate Fracture of Liquid Layers and Jets
- Scoping Experiments for Grazing Incident Liquid Metal Mirror
- Analysis and Experimental Development of Ionized Vapor Condensation Experiment

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Wetted Wall and Vortex Chamber Issues

University of California, Los Angeles

Chamber IFE Programs

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Wetted and Thin Film

Chamber Wall Protection

Use a renewable thin film of liquid facing the target to absorb X-ray and target debris without damage to solid structures

- Surface heat is removed by a combination of conduction to the main coolant channel, vaporized material transport to droplet condenser streams, convection by film flow
- Neutrons are transmitted through the FW and nuclear heat is removed by bulk coolant
- Radius of the chamber is large enough so no fracture of the free surface will occur
- Recent Examples: Prometheus-L&H, Osirus, Hiball

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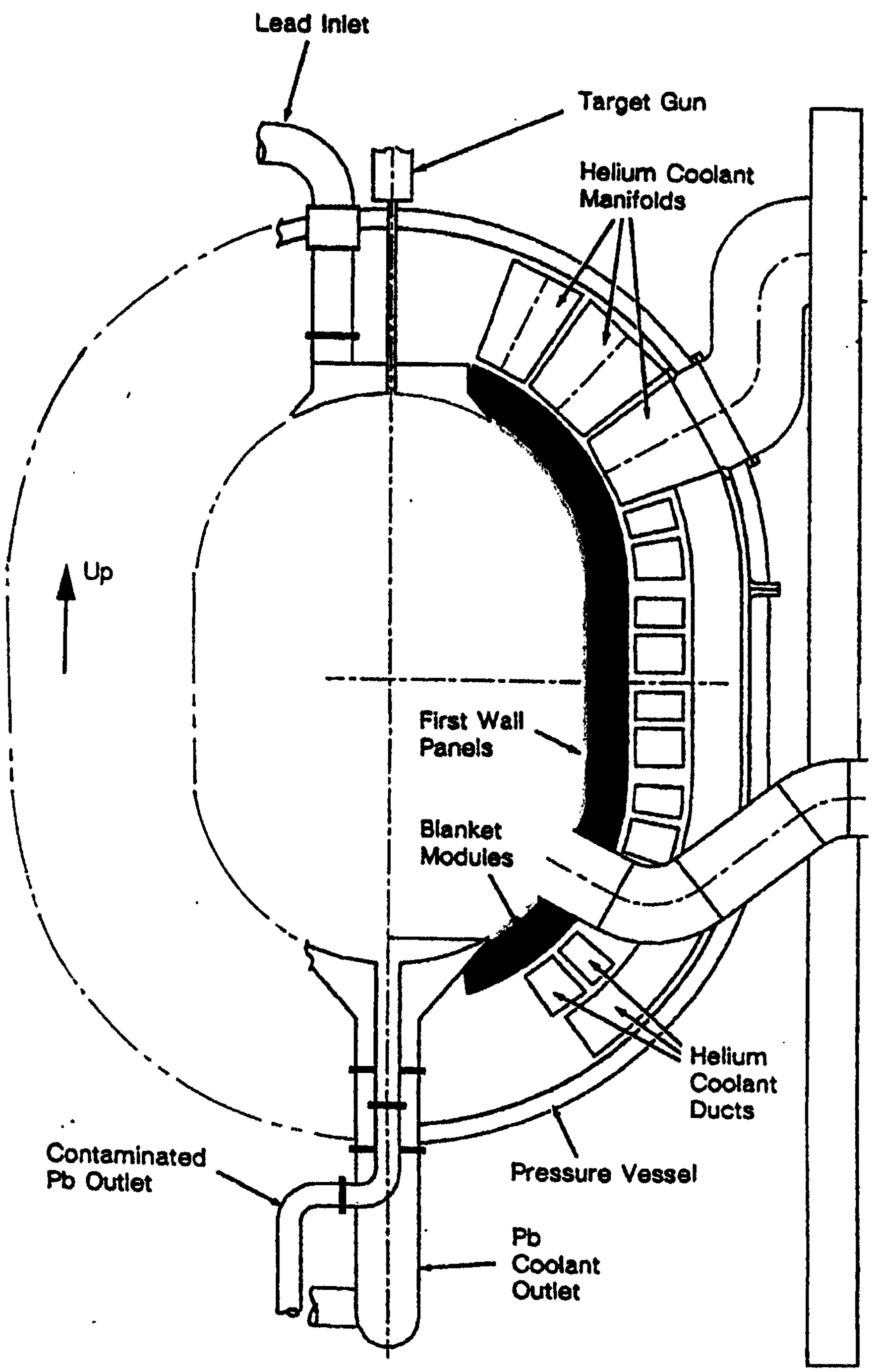
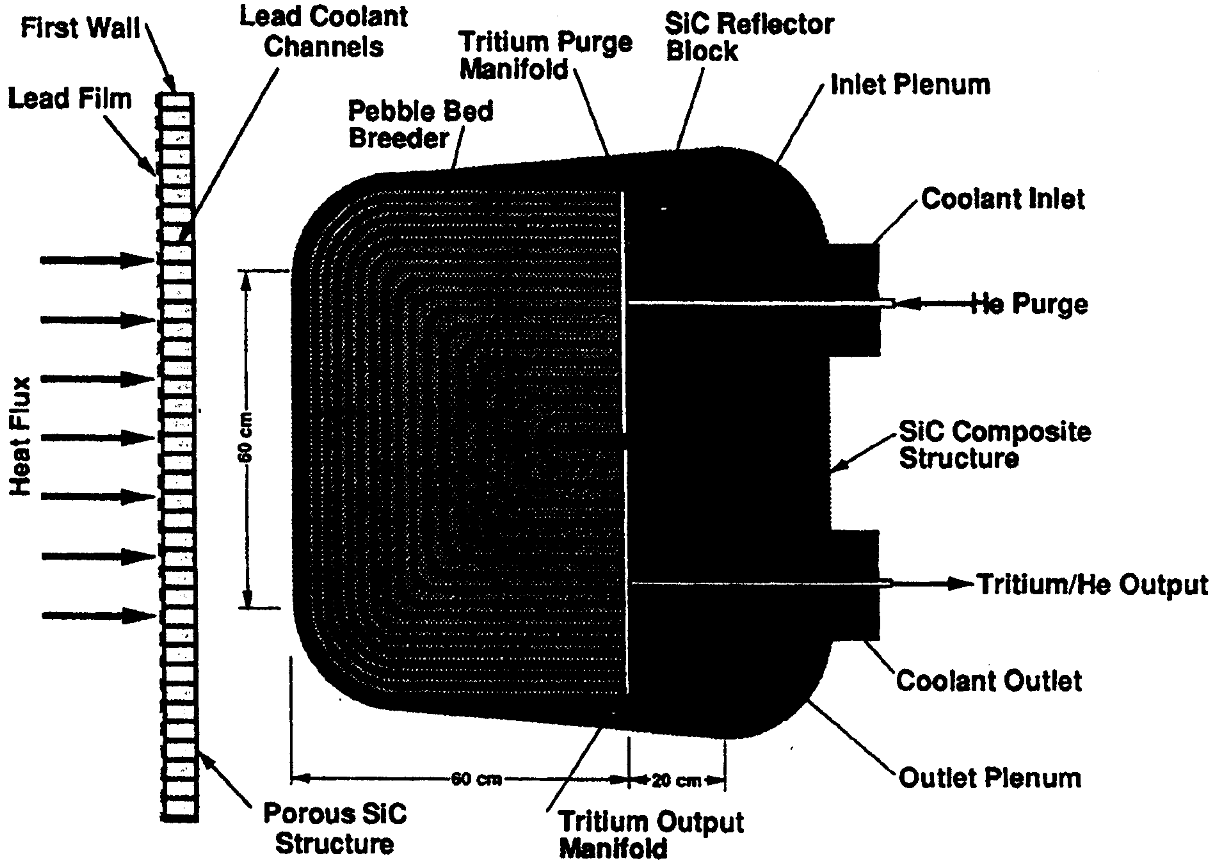
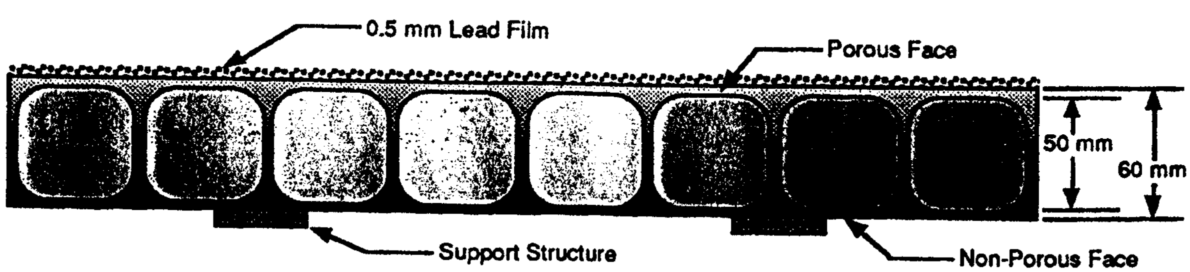
Prometheus-L&H Chamber Design



Prometheus-L&H
FW and Blanket Design



Schematic of a Blanket Module



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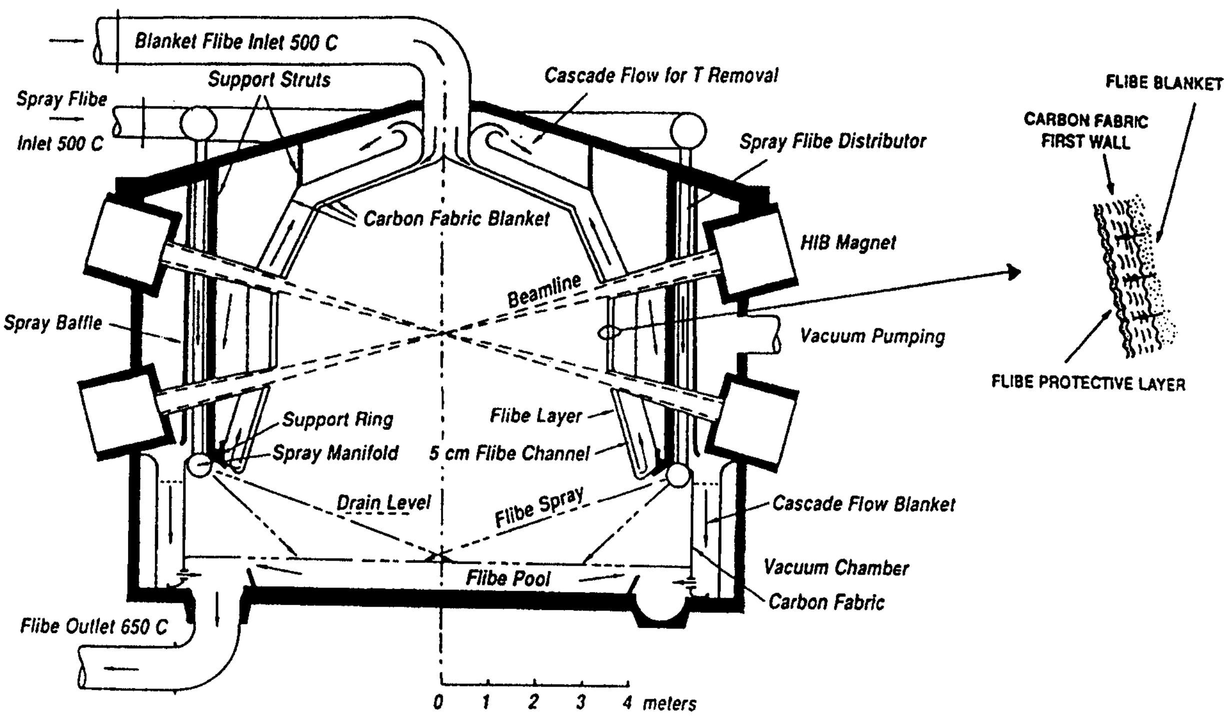
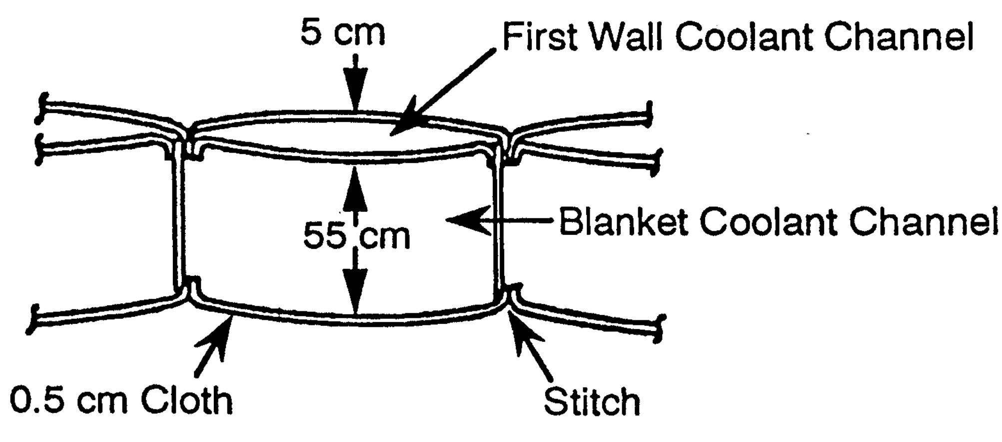
Osirus Chamber Design





Feasibility Issues for

Wetted Wall / Film Flow Schemes

- Control of liquid flows
  - through porous media,
  - on inverted surfaces, and
  - around beamline penetrations

- Droplet formation due to
  - compressible liquid response to rapid heating
  - vibration of underlying structure from impulse loading
  - in-flight condensation of superheated gas

- Rapid clearing of vaporized wall material before the next shot

- Propagation of driver beams and targets through residual chamber vapor

Thick Vortice Flow Chamber Protection

Use swirling motion to create thick liquid blanket facing the target explosion

- Surface heat penetrates into the bulk flow by turbulent convection. Neutrons are deposited volumetrically in the bulk flow, which also provides shielding for the first structural surfaces

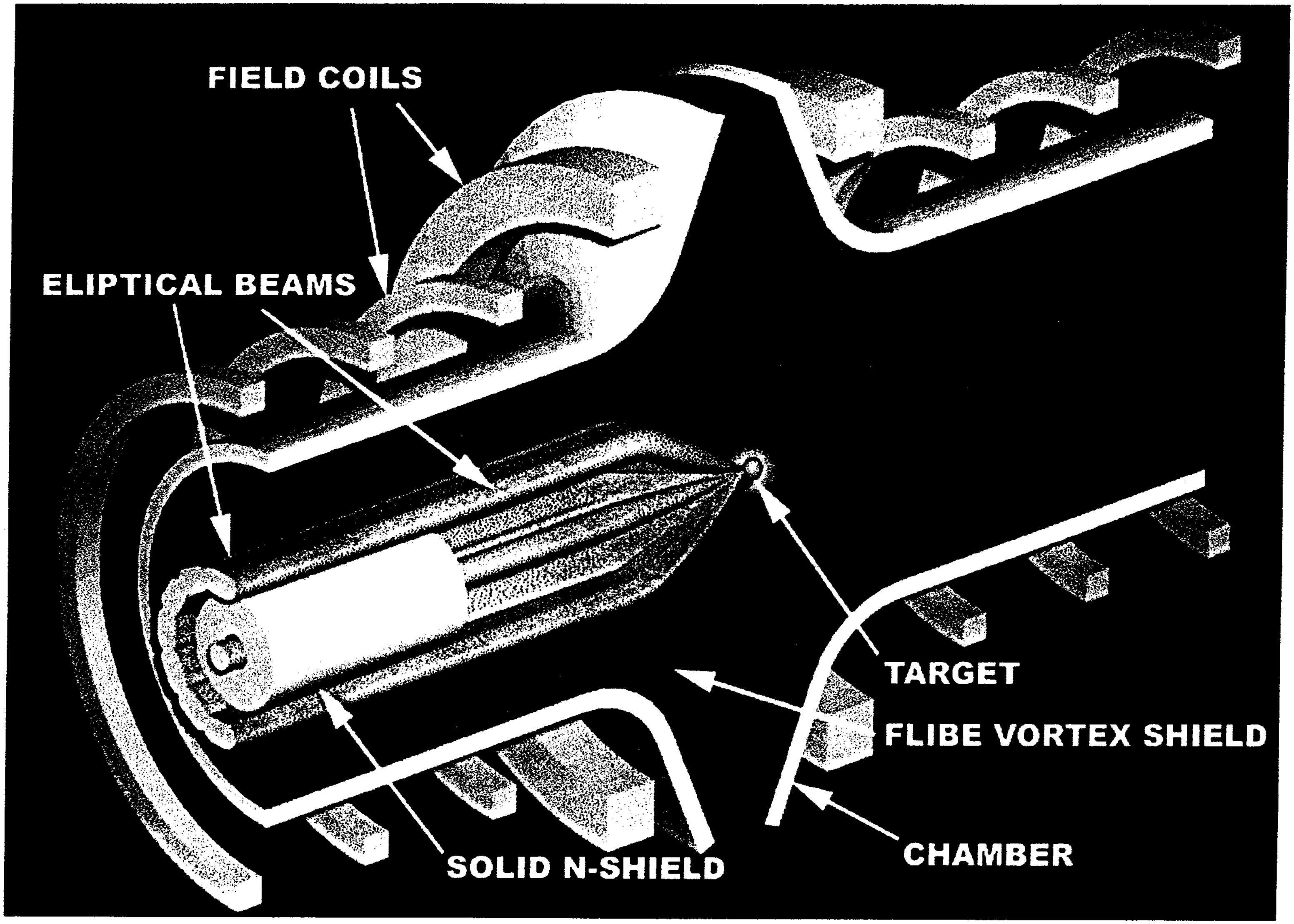
- Radius of the chamber is large enough and target yield low enough so that no fracture of the free surface will occur due to X-ray deposition and isochoric nuclear heating

- Ablation is minimized by guiding ionized debris along axial magnetic field and increasing the time scale for energy deposition in FW. This theoretically allows faster chamber clearing and increased rep-rate capability.

- Entrained bubbles in bulk flow ameliorates impulse loading of the first structural surface

Recent Example: NOVEL HIF CHAMBER by Grant Logan

Concept for a liquid-vortex chamber



NOVEL HIF CHAMBER WITH CUSP MAGNETIC FOCUSING FIELD AND SWIRLING LIQUID FIRST WALL

by

N. B. Morley, G. Logan, K. Gulec

Abstract Submitted to ISFNT-5, Rome, Italy

We have adapted an idea of swirling vortex liquid walls for MFE [Ralph Moir "Liquid first walls for magnetic fusion energy configurations", Nuclear Fusion Vol 37, No. 4, April 1997, p 557] to a heavy ion inertial fusion chamber using a cusp-shaped swirling liquid Flibe wall to absorb the neutrons, in a geometry synergistic with a cusp magnetic field to guide and focus heavy ions onto the target. A single magnetic cusp field in the chamber center commonly focuses an annular array of heavy-ion beams in order to reduce the effective standoff distance of the final focusing system, thus allowing smaller target spot sizes. New low yield, high gain, close-coupled HIF target designs could then be utilized with driver energies as low as 1 MJ [D. Callahan, LLNL, private communication], allowing smaller IFE plant sizes. The magnetic field also guides ionized target debris axially along the solenoidal length, distributing the heat and reducing vaporization from the surface. Utilization of swirling thick liquid walls allows for a continually replenished liquid surface facing the target. A cusp-like liquid surface is obtained by driving a swirling liquid vortex into the interior of cylindrical structural shell from both sides, with an azimuthally symmetric outlet in the magnetic cusp region so that the liquid streams are ejected by their own centrifugal acceleration. The radius of the first liquid surface is chosen large enough so that liquid fracture due to neutron isochoric heating is avoided, and the thickness of the liquid flow is chosen so damage in structural materials is reduced to an acceptable level. The reduction of vaporized and spalled wall material allows for faster chamber clearing and increased repetition rate. This paper discusses the underlying heavy ion beam and target physics requirements, and liquid wall hydrodynamics issues, associated with this novel HIF chamber and focusing concept. The scheme relies on ballistic focusing of pre-stripped heavy-ions with current and space-charge-neutralization in a sufficiently high density ambient target debris plasma ($\sim 10^{15}$-10^{17} cm^{-3}). The plasma temperature and conductivity must be high enough before each beam pulse to prevent uncontrollable beam-self-pinching and filamentation. The hydrodynamics aspects related to formation of liquid cusp are explored using numerical hydrodynamic code called Flow3d, a 3-D time-dependent Navier-Stokes Equation solver with a volume of fluid (VOF) free surface tracking algorithm. Relevant analysis on hydrodynamics and stability of swirling flows for novel MFE confinement schemes are also discussed [K. Gulec et al., "Hydrodynamic Feasibility of Swirling Liquid Blanket For Innovative Confinement Concepts FRC, ST", In these proceedings].

Feasibility Issues for Vortice Blanket Schemes

- Establishment of cusp-flow vortice hydrodynamic configuration
- Eliminate droplet formation due to
  - compressible liquid response to rapid heating
  - vibration of underlying structure from impulse loading
  - in-flight condensation of superheated gas
  - axial velocity stagnation point in cusp region
- Heat transport into bulk flow with minimal ablation
- Rapid clearing of vaporized wall material before the next shot
- Propagation of driver beams and targets through residual chamber vapor

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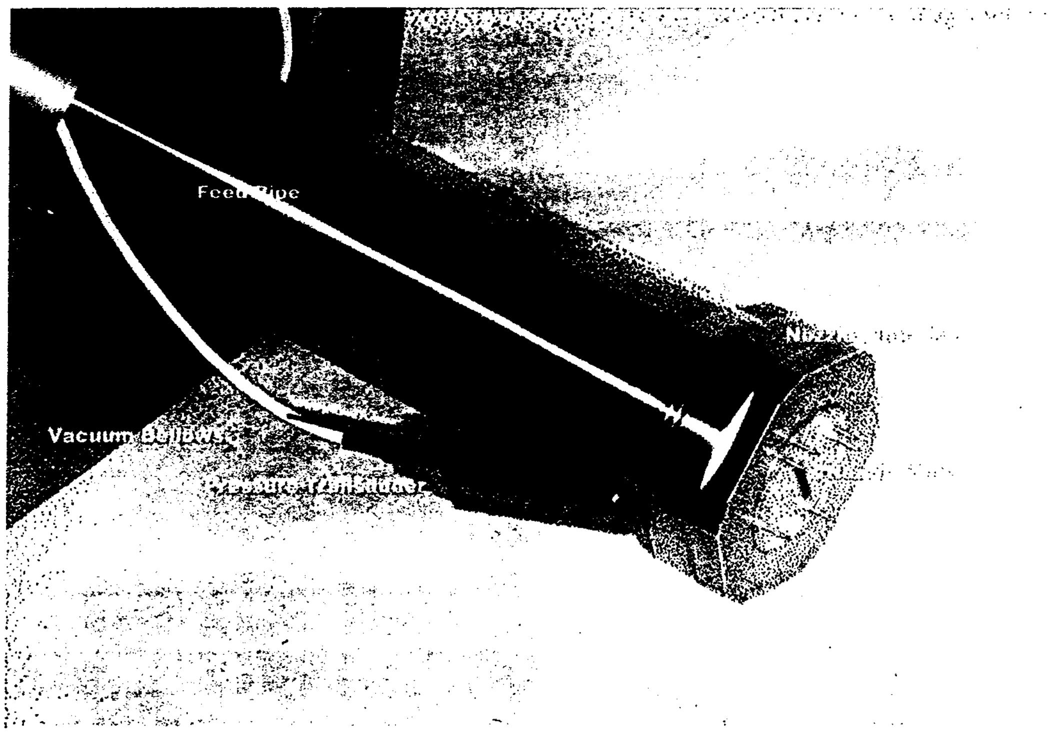
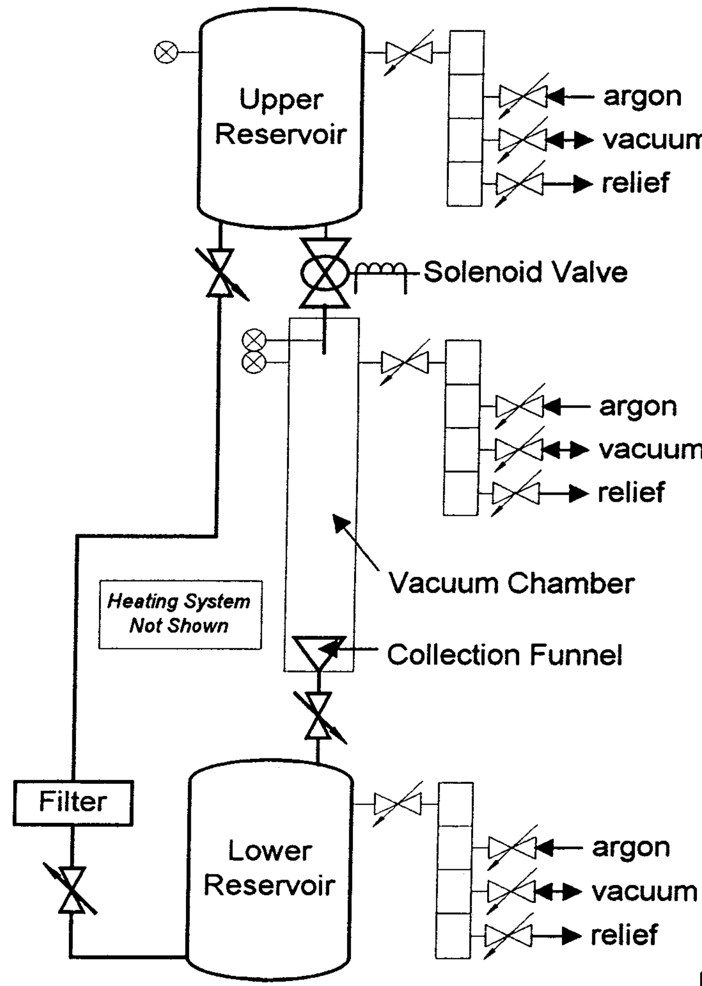
"MeSO Jet" - Turbulent Slab Jet Experiments

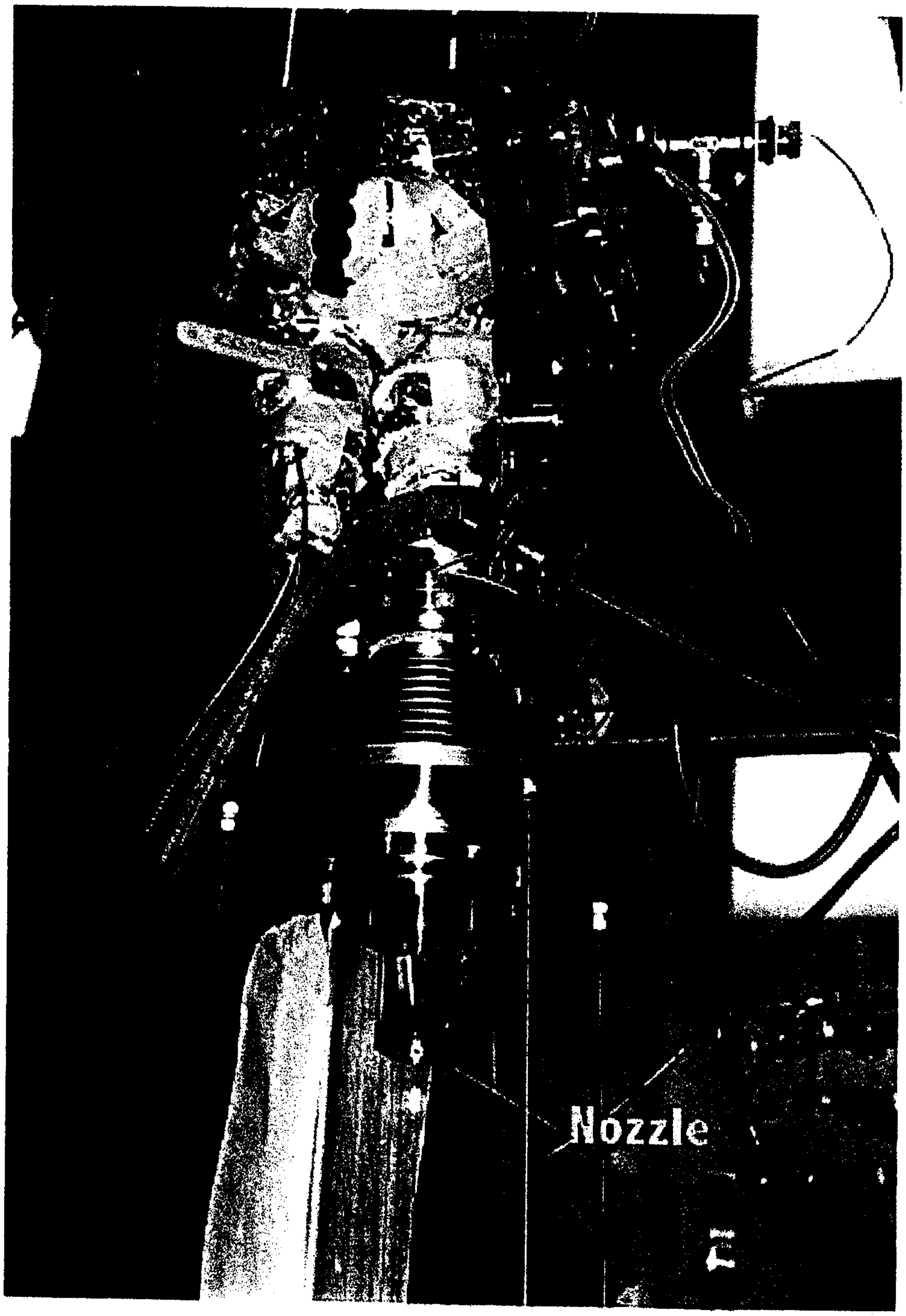
Goal: *to determine surface wave character, slab contraction length, and ultimate breakup length of stationary and oscillating liquid slab jets and optimize nozzle design for IFE applications*

- Low volatility liquid metal is driven through interchangeable nozzle assembly into transparent vacuum chamber by variable pressurization of upper reservoir
- Jet image is recorded with high speed digital camera
- Photographs are analyzed with analysis software





MeSO-Jet Experimental Apparatus



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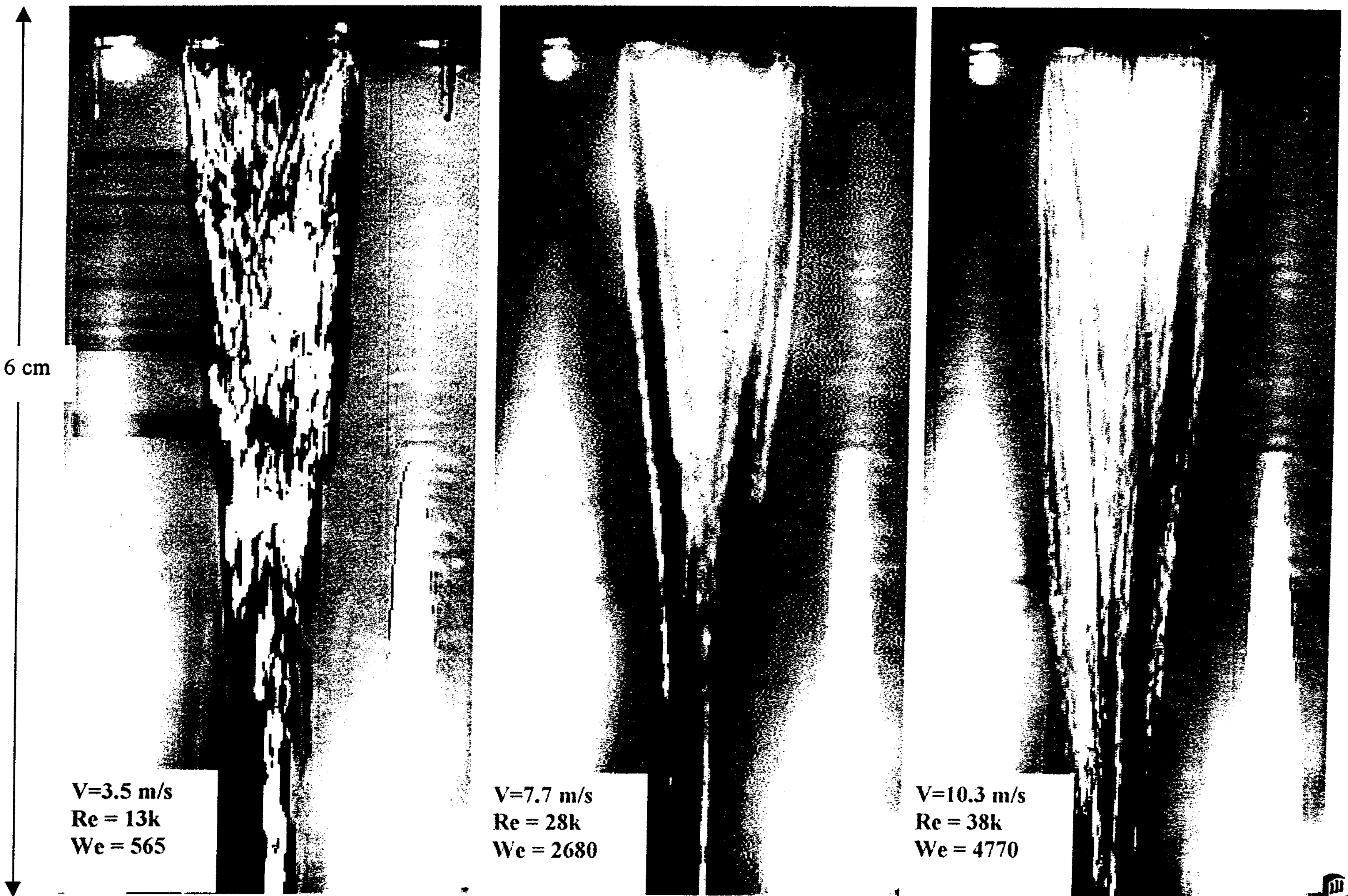
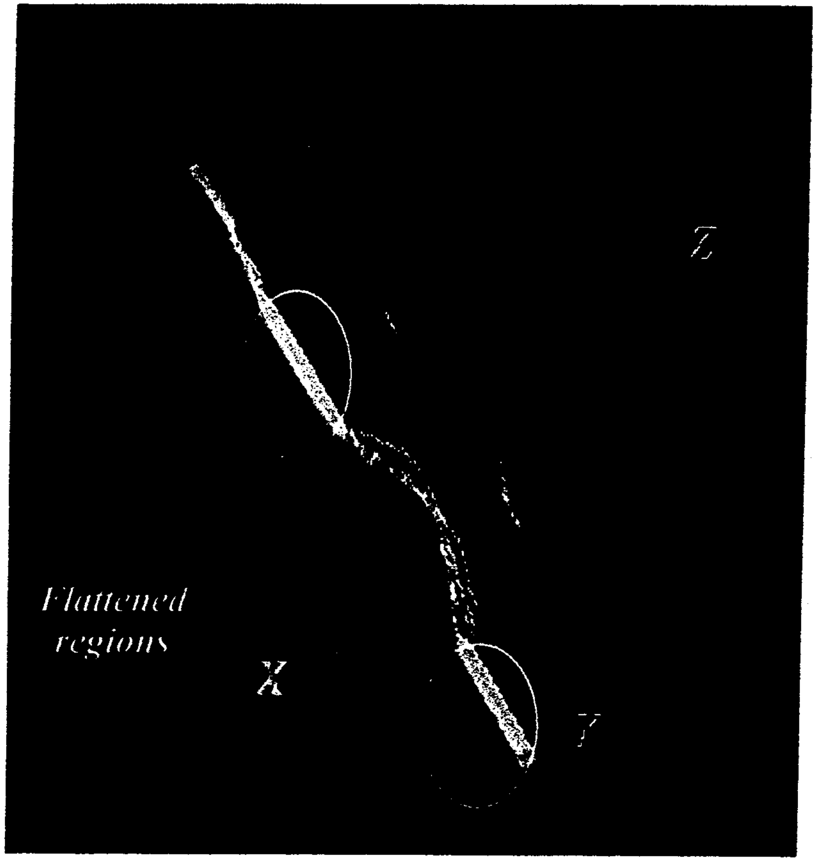
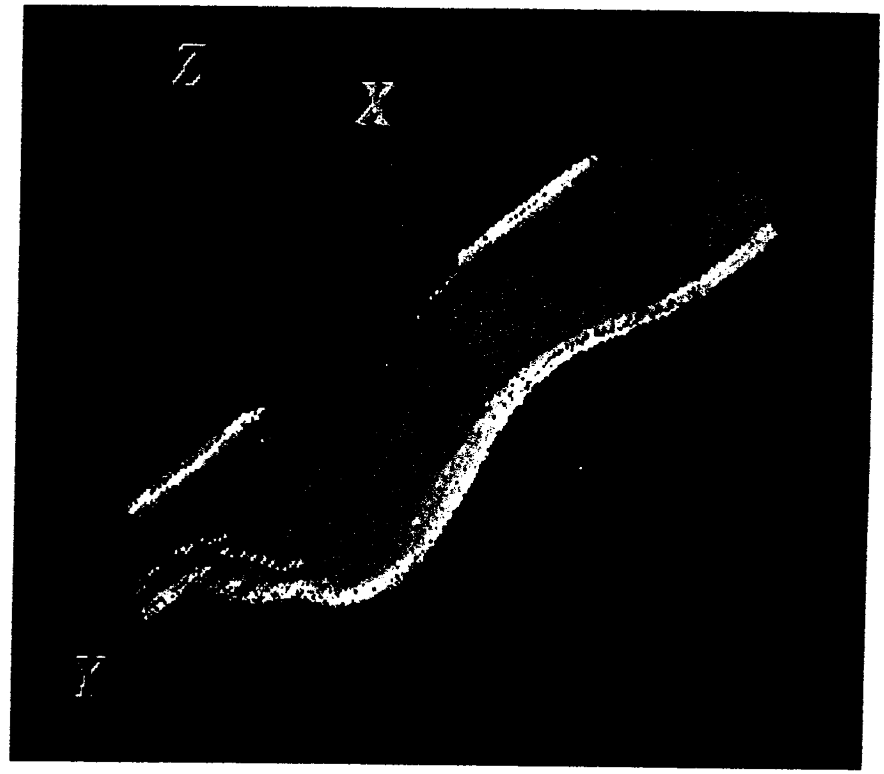
MeSO-Jet Data: 2x10 mm Slot Nozzle, Area contraction 25x)

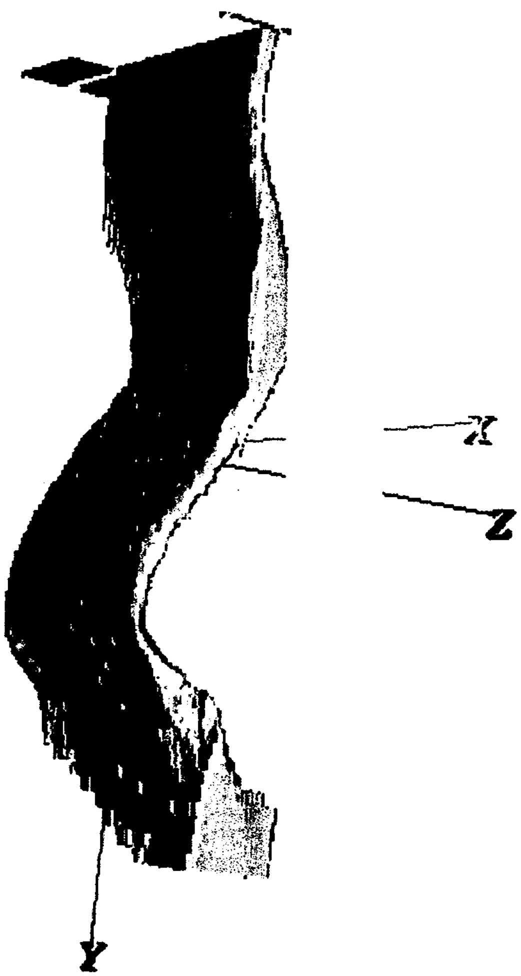


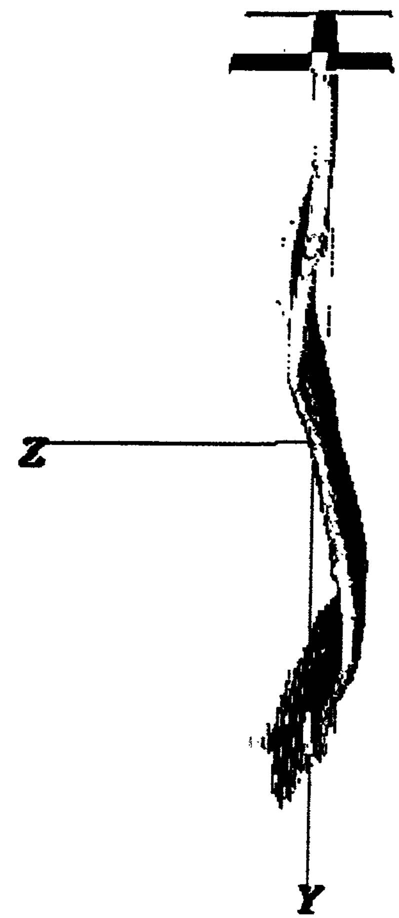
3D Simulation of Oscillating HYLIFE-II Jet





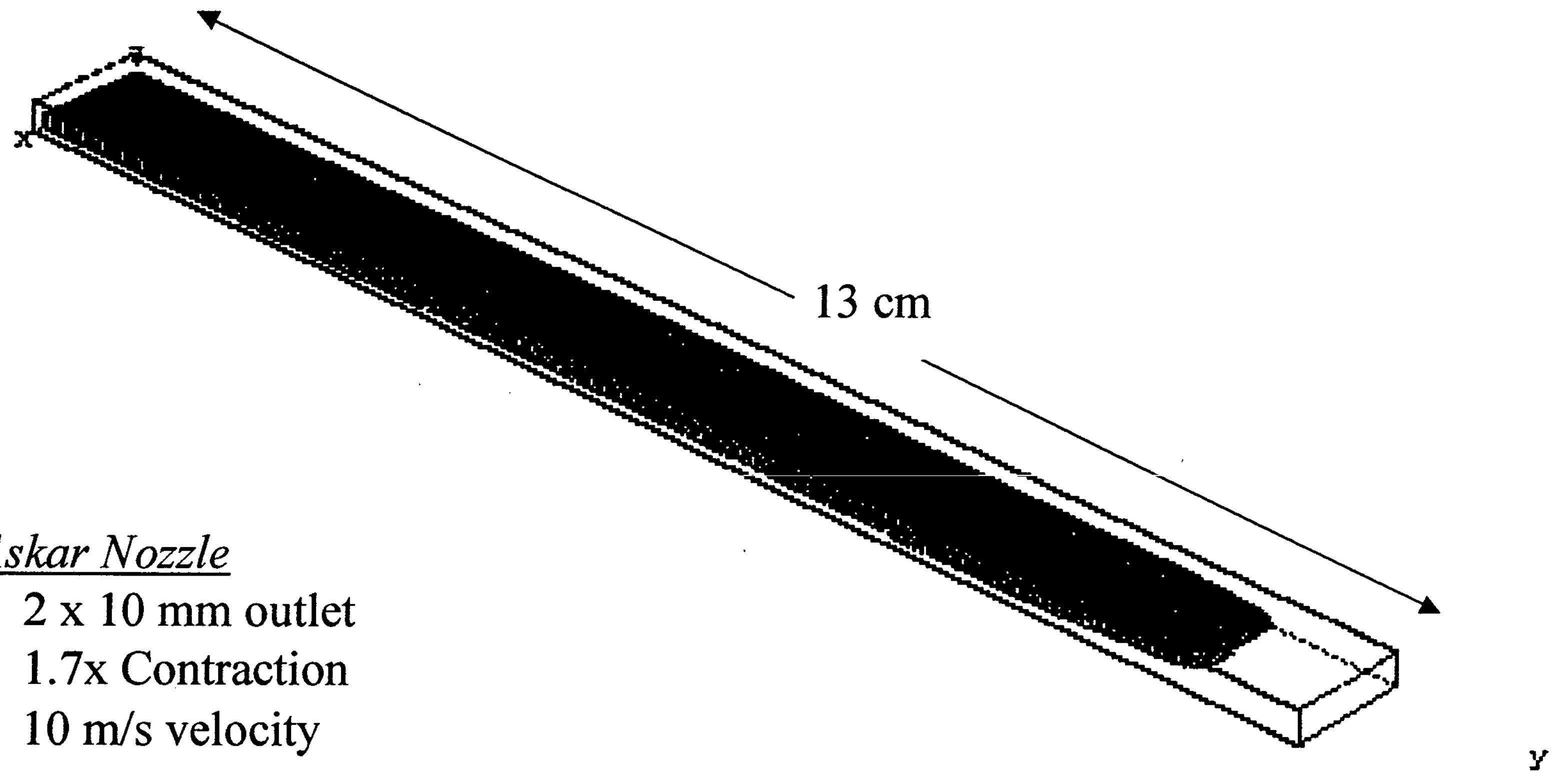
Initial oscillation velocity parallel to free surface plane *t=.6000*





Initial oscillation velocity at 30° to free surface plane

Current MeSO-Jet Nozzle Simulation



Askar Nozzle

- 2 x 10 mm outlet
- 1.7x Contraction
- 10 m/s velocity

"Popoff" – Liquid Fracture Strength Experiment

Goal: To measure tensile strength properties of various liquids as candidates for IFE chamber wall protection

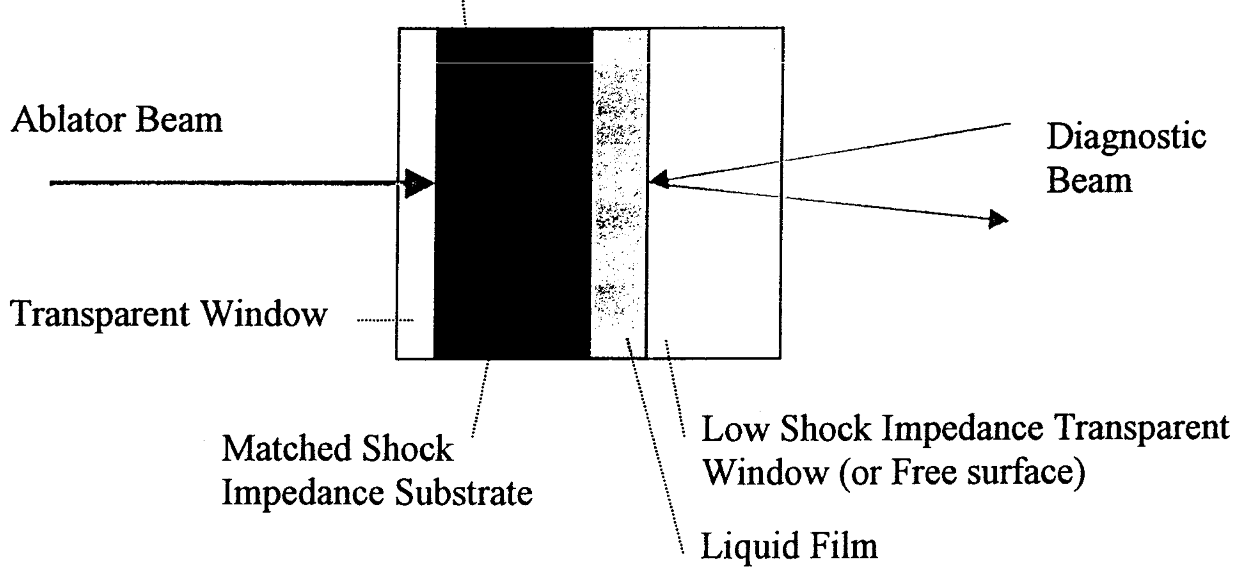
Method: Simulate fast "tensile" waves resulting from X-ray ablation shock reflection and neutron isochoric heating by using pulsed laser to initiate pressure shock

Liquids of interest:
Flibe, Li, Pb, Pb-Li, Sn-Li, and Hg

Facility:

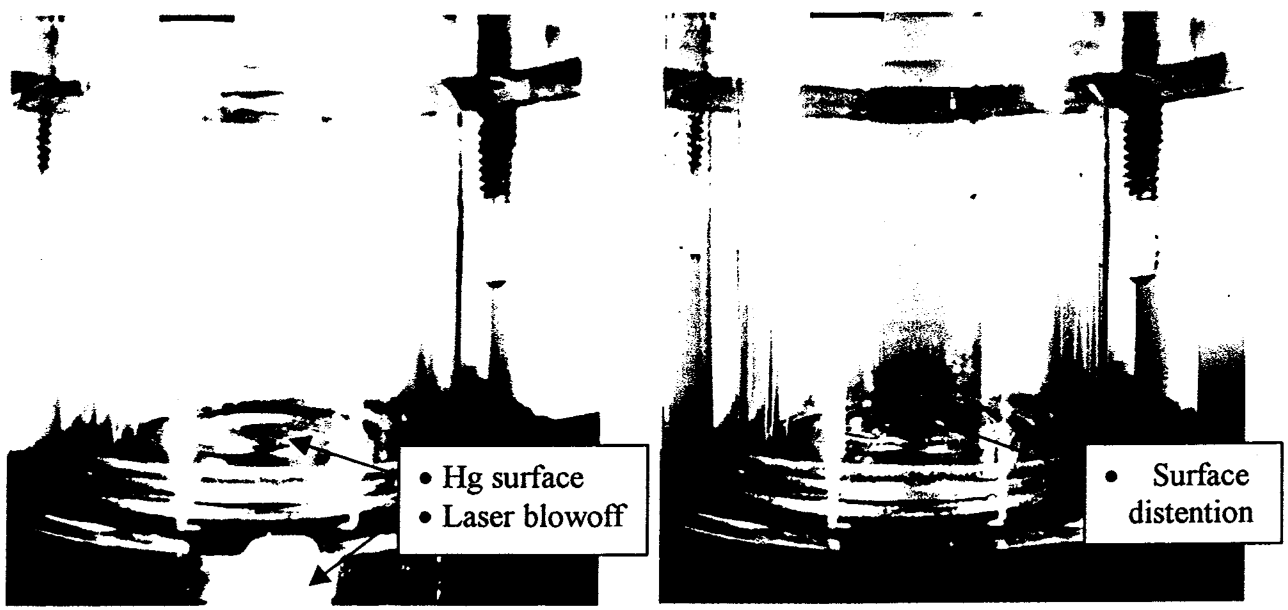
- 1 Joule, 3 ns, 1.06 μm, Nd:Yag laser
- Velocity or displacement interferometer (1 ns, 1000 m/s, 1 μm)
- High temperature furnace (1000 C)

Induced shock travels into the liquid film and reflects from surface as a tensile wave. Liquid fractures in bulk as wave gains strength

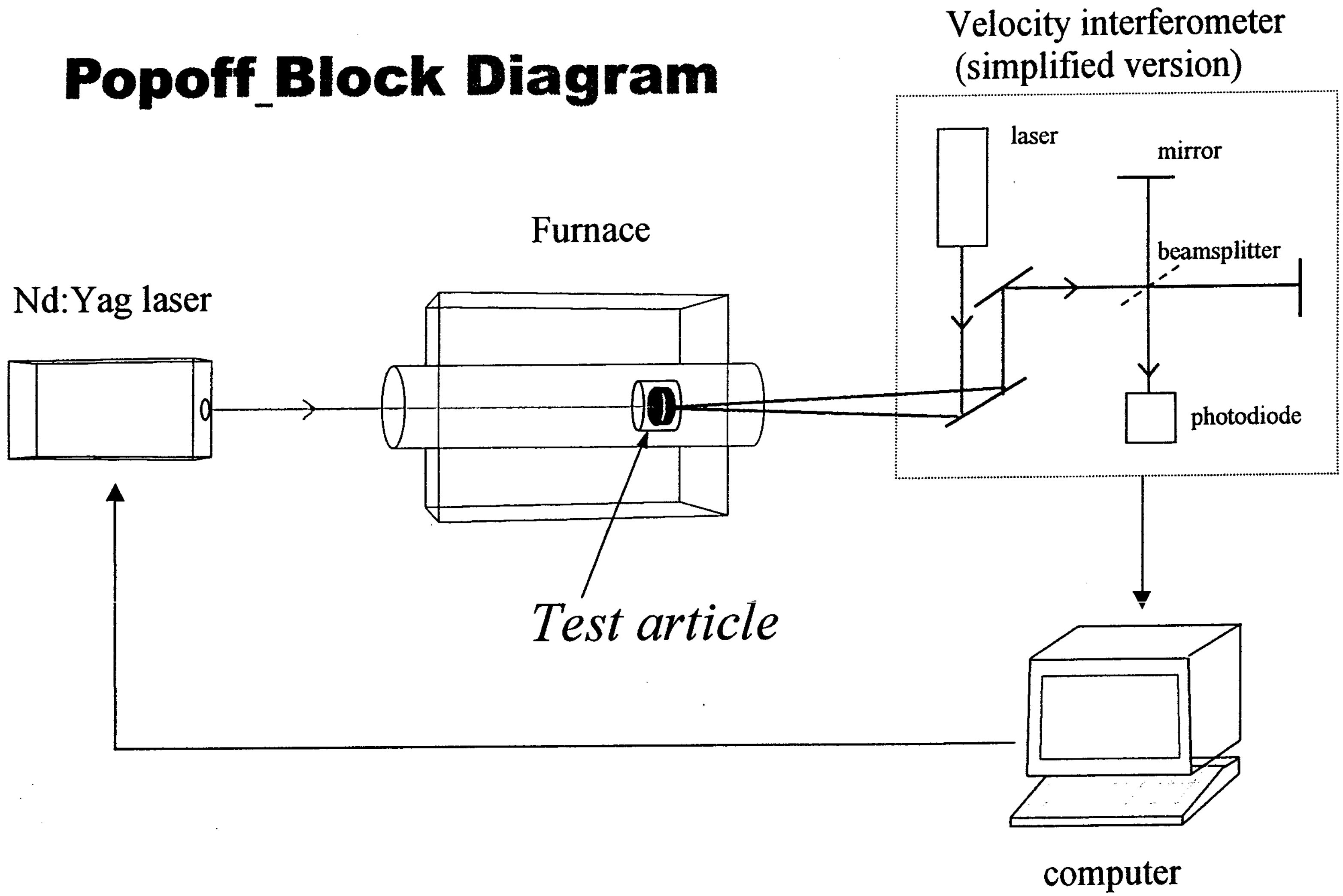


Initial Popoff Experiments

- Surface distention of >0.5 mm at approximately 3.5 ms after laser impact indicates liquid fracture beneath the surface.
- Some shots without camera showed small Hg droplets scattered around inside of test article



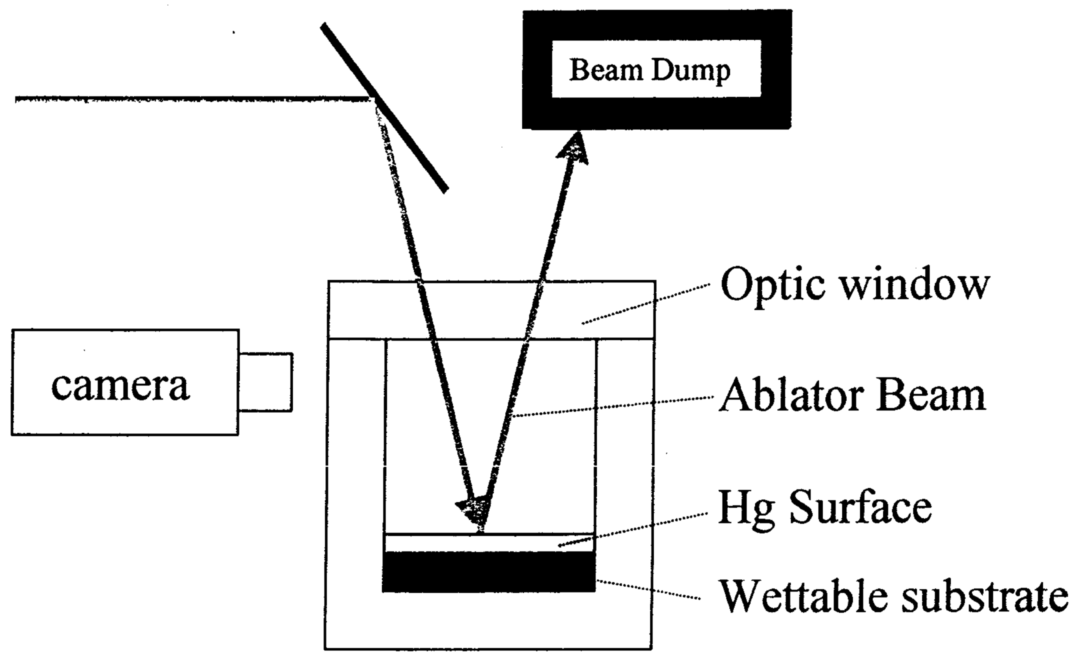
Popoff_Block Diagram



Popoff Procedure

- Design high-temperature test article/furnace to test liquid samples of Flibe, Li, Pb-Sn, Pb, etc.
- Measure surface velocity as a function of time with high speed laser velocity interferometer (VISAR or equivalent)
- Compare experimental data to sophisticated numerical simulations assuming no liquid fracture (CFDLIB-99, LANL)
- Use discrepancies in surface velocity profile to determine physical location and peak tensile stress at the failure point

Grazing Incidence Liquid Metal Mirror Test



Feasibility Exploration of Vapor Clearing Rates for IFE Liquid Chambers

Presented by

Alice Ying

UCLA

Contributors

Mohamed Abdou, Karani Gulec, Neil Morley, Tom Sketchley

Additional Technical Consultants

Mohamed Bourham – electrothermal plasma source

Mac Toth – Flibe handling/manufacturing

Shahram Sharafat- material/plasma energy source

Ken Moses – plasma energy source

IFE Chamber Technology Planning Meeting

Pleasanton, California

March 18-19, 1999

Vapor Condensation Experiments

Key Technical Issues:

- ❑ Ablation, dissociation, ionization and chemical recombination
- ❑ Vapor venting
- ❑ Transient pressure response/ Pressure relaxation
- ❑ Vapor condensation/Spray assisted

Goals:

- **Generate fundamental vapor clearing data used for modeling development and benchmark**
- **Determine the dynamical effects that affect the condensation of vaporized materials back onto the first wall and droplets spray**
- **Provide chamber design guidance based on clearing requirements**

Table taken from Dr. John Scott' s Ph. D. Thesis (UCB).

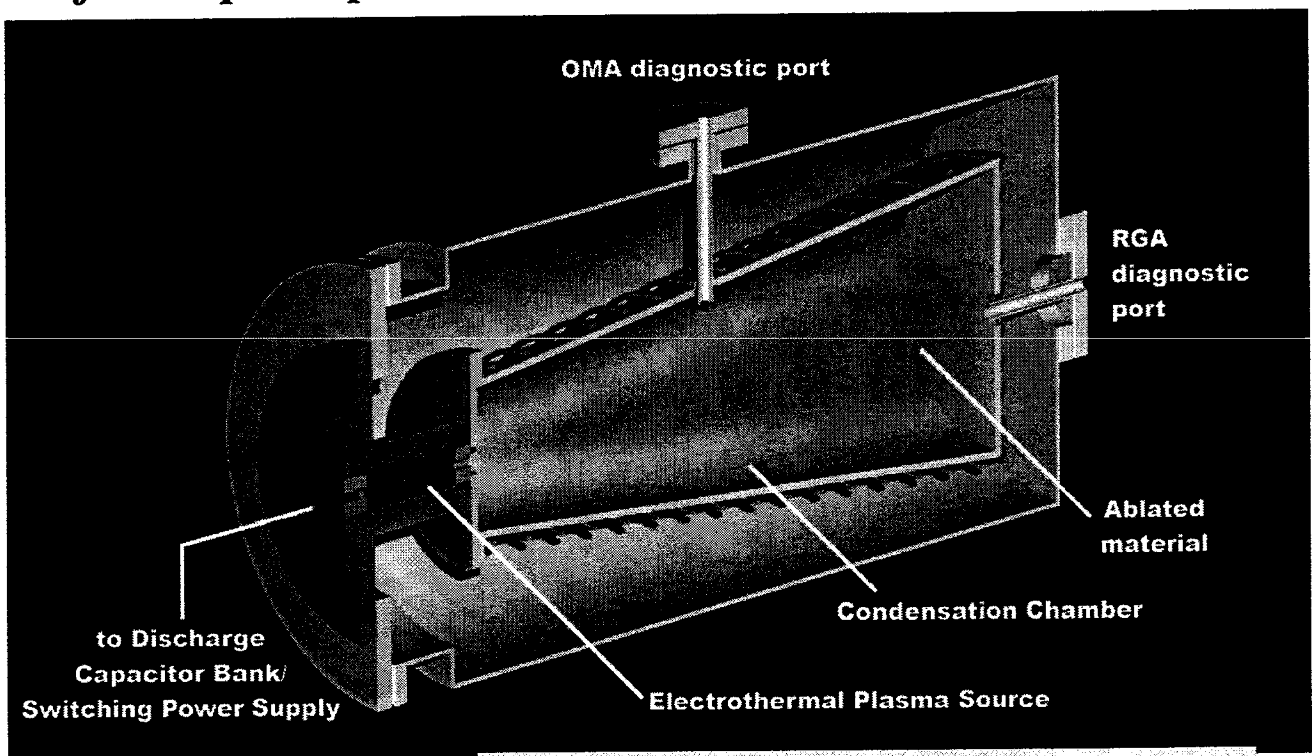
Table 2.2--History of Events in HYLIFE-II reactor (Moir, 1991)

Time	Event
-60×10^{-3} s	Fuel pellet enters chamber at 3-m. radius at 50 m/s/
-15×10^{-9} s	Driver beams begin interaction with target.
0×10^{-12} s	Fusion burn begins.
10×10^{-12} s	Fusion burn ends releasing 350 MJ.
2×10^{-9} s	X rays vaporize inner surfaces of innermost FLiBe jets
10×10^{-9} s	Neutrons begin volumetrically heating inner jets.
20×10^{-9} s	Isochoric heating of FLiBe jets by neutrons finishes.
11×10^{-6} s	Inner jets begin to break up as a result of isochoric heating.
$20\text{-}30 \times 10^{-6}$ s	Vaporized, partially dissociated and ionized, jet material reaches chamber center, stagnates, radiates energy (causing secondary ablation), and expands.
$10\text{-}30 \times 10^{-6}$ s	Vapor expanding from center of chamber reaches vicinity of jets, re-thermalizes as it impacts the slower vapor near jets, and begins two-phase shock propagation through jet structure.
0.1×10^{-3} s	Major vapor propagation through jet fragments imparts outward momentum in addition to the momentum from isochoric heating and X-ray ablation momentum.
$0.1\text{-}0.2 \times 10^{-3}$ s	First vapor blast penetrates jet curtain.
0.3×10^{-3} s	Vapor impacts first wall disturbing the existing condensation-spray jets.
$1\text{-}2 \times 10^{-3}$ s	Uniform vapor pressure established in chamber. Condensation of vapor begins.
2.5×10^{-3} s	Uninhibited condensation jet spray begins to enter chamber.
20×10^{-3} s	Jet fragments consolidate to form a thick annular two-phase mass.
0.05-0.1 s	Critical time period for chemical kinetics to affect vapor condensation.
0.2-0.3 s	Two-phase mass hits and loads the first wall of the chamber near the bottom.
0.065 s	Clearing is completed along the path for the next pellet to enter chamber.
0.1 s	Vapor condensation is sufficient to allow for a driver pulse.
0.125 s	New FLiBe jets are established and driver beam path is clear. Next fusion burn begins.

Partially Ionized Flibe Plasma can be formed by the **Ablation** of a Flibe Liner with a large current discharge

Requirements

- ***A pulsed energy source that simulates the pellet explosion for rapid vapor generation***
- ***A practical size chamber that is representative of an IFE liquid protection chamber for vapor clearing***
- ***Diagnostics – fast response pressure transducers, temperature measurements, etc.***



Tube-shaped Flibe samples [redacted]

The pulsed –plasma facility will be constructed from the existing assembled components originally for a theta pinch plasma device:
A high voltage capacitor bank with rail gap switching system and 2 charging power supplies

Operational Capability

Discharge Voltage	±25 kV max.
Peak Current	1 MA
Discharge Period	~ 10 μs
Capacitor Bank	40 (Maxwell C-type, 33007)
Maximum Energy Storage	100 kJ
Operation Mode	Bipolar
Operating range	24 to 50 kV
Bank Capacitance	~ 88.5 μF

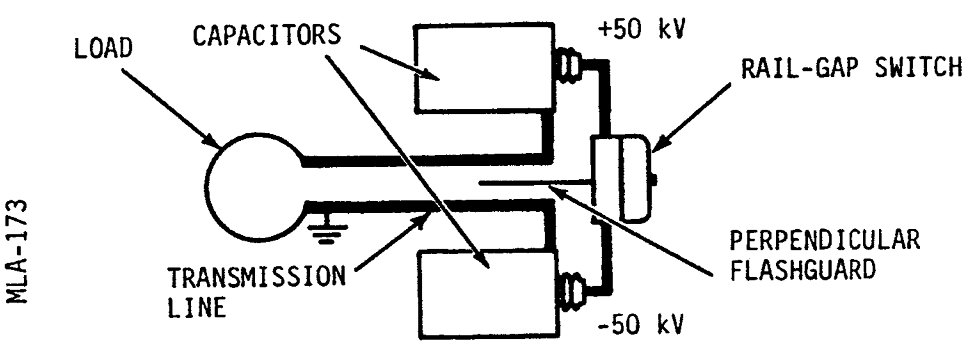
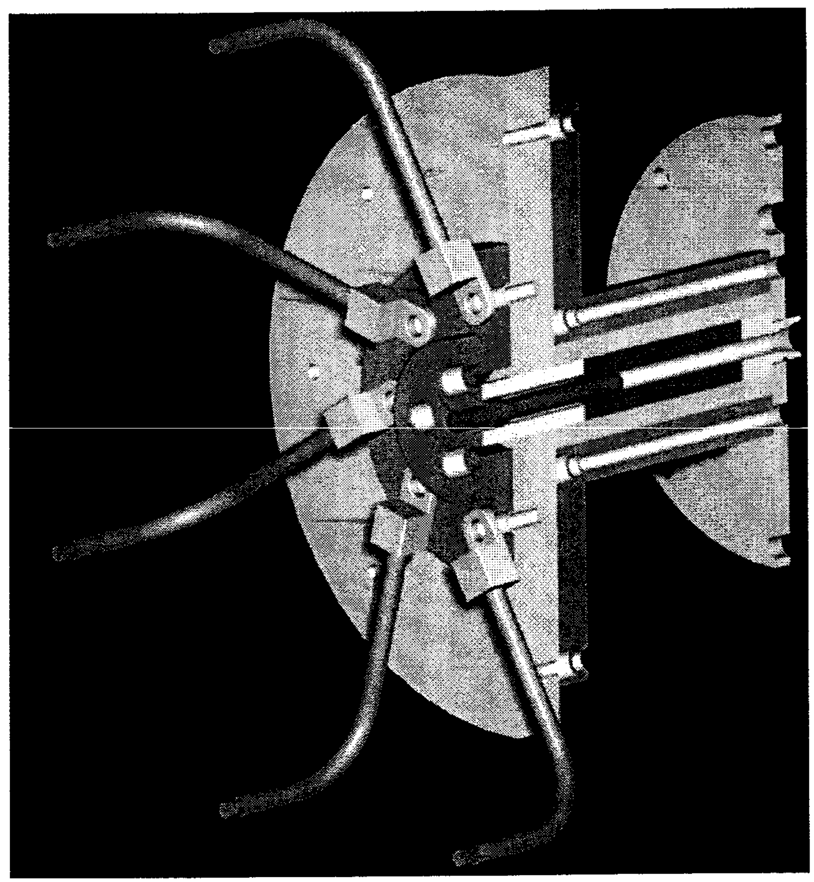


Figure 2. Perpendicular flashguard (bipolar or balanced mode)

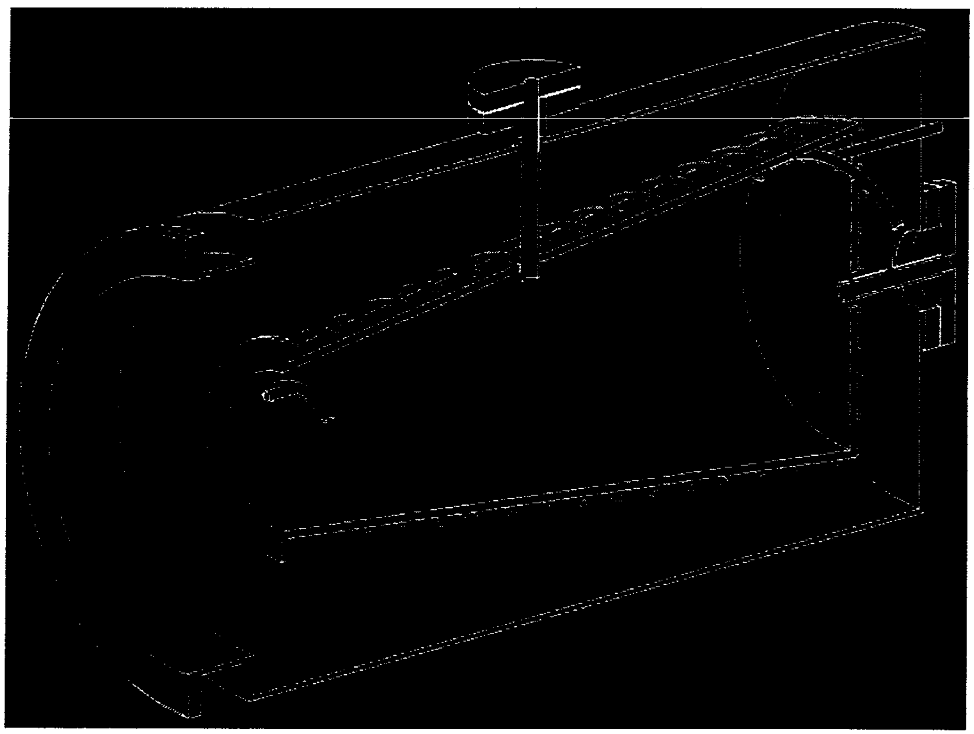


Extremely High Heat Flux Capability from the Pulsed Plasma Source Allows the Use of A Large Size Chamber to Simulate Different Vapor/Liquid Interactions

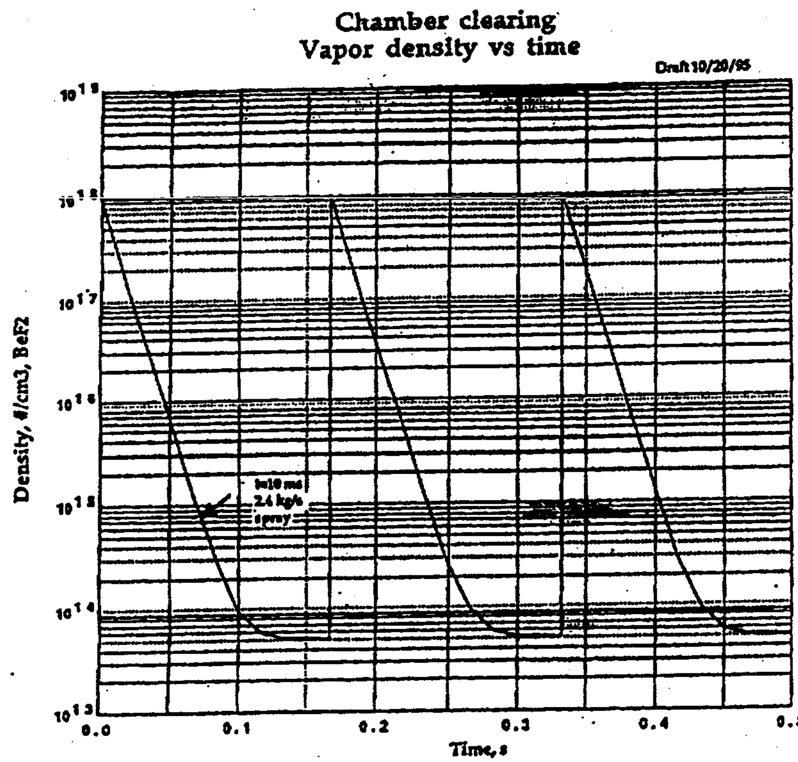
- ❑ **The liquid jets can be incorporated into the chamber to study the interaction of the blast with the jets.**
- ❑ **Well characterized spray coolant droplets could be injected into the back surface of the chamber for clearing enhancement evaluation.**
- ❑ **Diagnostics:**

Base- Fast response pressure transducers to detect the induced pressure history
Conductivity probes/thermocouples for temperatures
Post processing for condensate

Upgrade- Mass spectroscopy to measure the composition of the ablated materials



A Flibe vapor density of 10^{18} /cc can be formed in a chamber size of about 5 liters at a discharge energy density of 4.49 MJ/m^2 (assuming a low transmission factor)



R.Y. Bai and V.E. Schrock, "An Approximate method for analyzing transient condensation on spray in HYLIFE-II," Fus. Tech. 19 (1991) 732-739.

Schedule and Milestones

Nov. 98

Conceptual design and request for NOVA surplus

Feb. 99

- ❑ **Acquired Flibe handling/manufacturing knowledge**
- ❑ **Acquired large capacitor bank, power supply and rail-gap switch**
- ❑ **Engineering design of pulsed plasma source**
- ❑ **Engineering design of condensation chamber**

Jul. 99

- ♦ **Construction of base condensation chamber**
- ♦ **Installation of pulsed plasma source facility**
- ♦ **Acquire basic diagnostics equipment**

Dec. 99

- **Facility shakedown**
- **Benchmark test**
- **Begin to take data**

HYDRODYNAMIC ANALYSIS OF NOVEL HIF CHAMBER WITH SWIRLING LIQUID WALL

University of California, Los Angeles

Faculty: M. Abdou, N. Ghoniem
Researchers: K. Gulec, N. Morley, T. Sketchley, S. Smoletsev, A. Ying, M. Youssef
Students: A. Konkachbaev, D. Lucero, S. Quan, J. Williams

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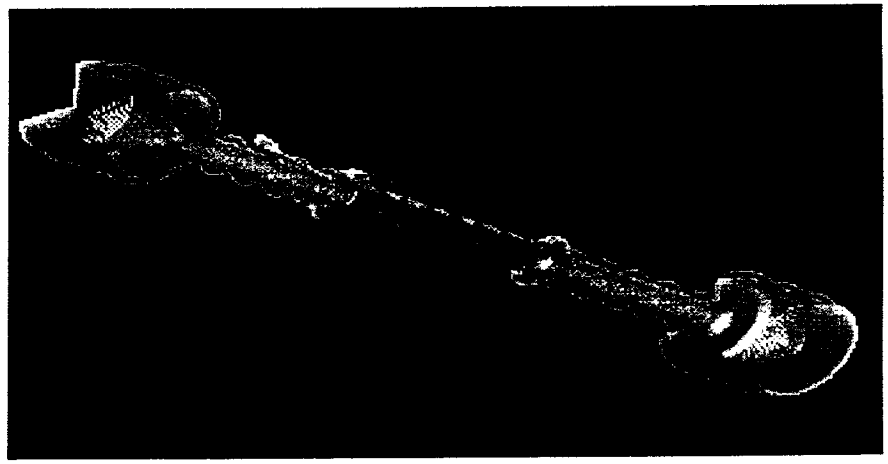
SWIRLING LIQUID WALL CONCEPT (I)

* A concept of swirling liquid wall for MFE utilized during *APEX* study (for FRC configuration) has been adapted, modified and developed for heavy ion inertial chamber design.



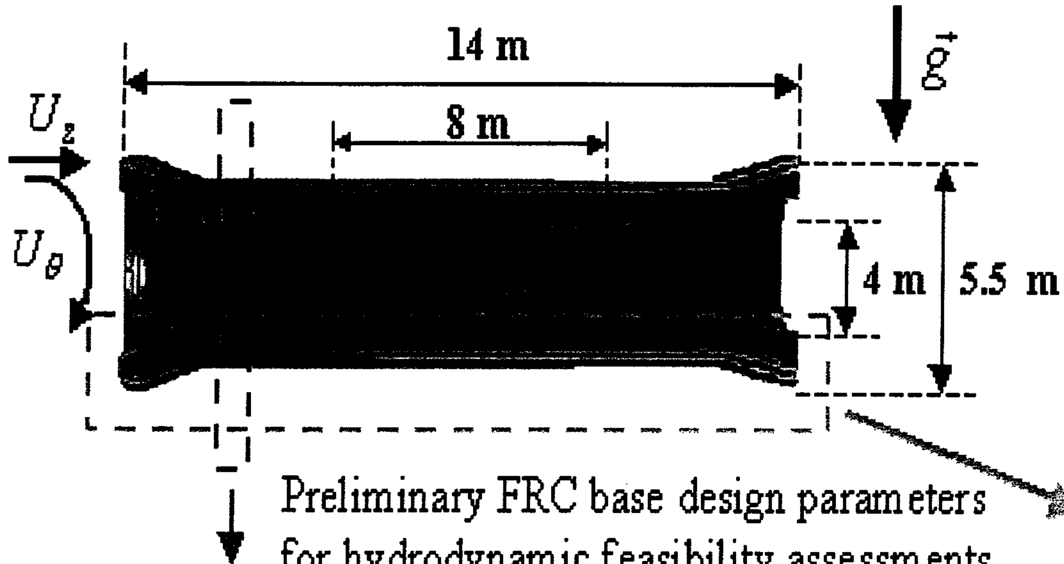
SWIRLING LIQUID WALL CONCEPT:

* The liquid layer is injected at one of the circular vacuum chamber from an swirl flow generating intake with an axial and azimuthal velocity components.

* Liquid layer adheres to the circular structure by means of centrifugal acceleration (>~ 3.2 g) as a result of its high azimuthal velocity (> 8 m/s) and cylindrical structure's small radius of curvature (< 2 m).

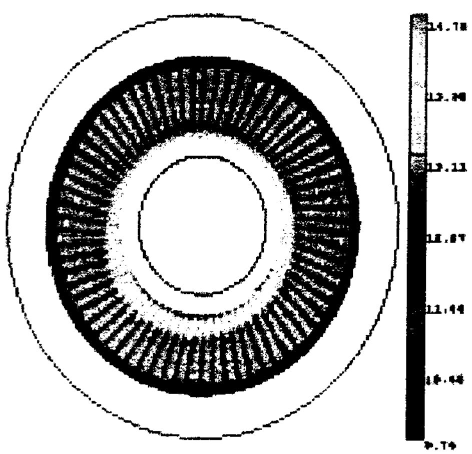
* The cylindrical shaped structural is protected from thermal stress and radiation damage.

SWIRLING LIQUID WALL CONCEPT (II)

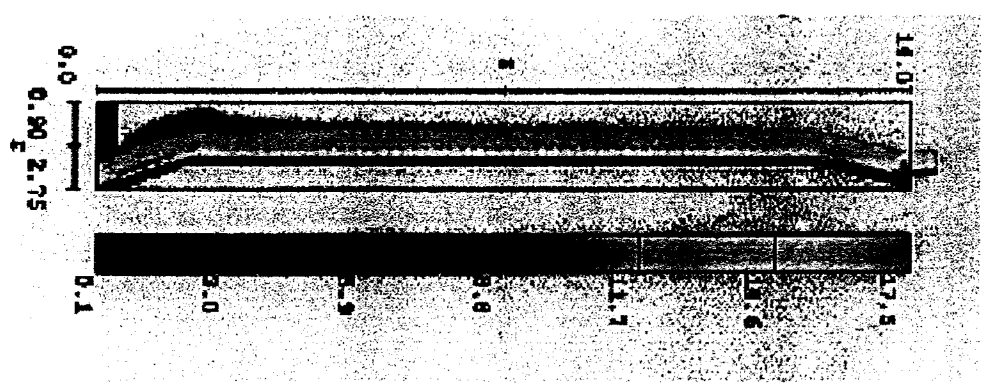


Preliminary FRC base design parameters for hydrodynamic feasibility assessments.

3-D time dependent Navier-Stokes Equations were solved using Flibe for incompressible flows using the Volume of Fluid (VOF) algorithm for free surface flows (with a constant axial and rotational velocity boundary condition at a converging inlet).



Velocity distribution in the plane (r-theta) perpendicular to the flow direction.

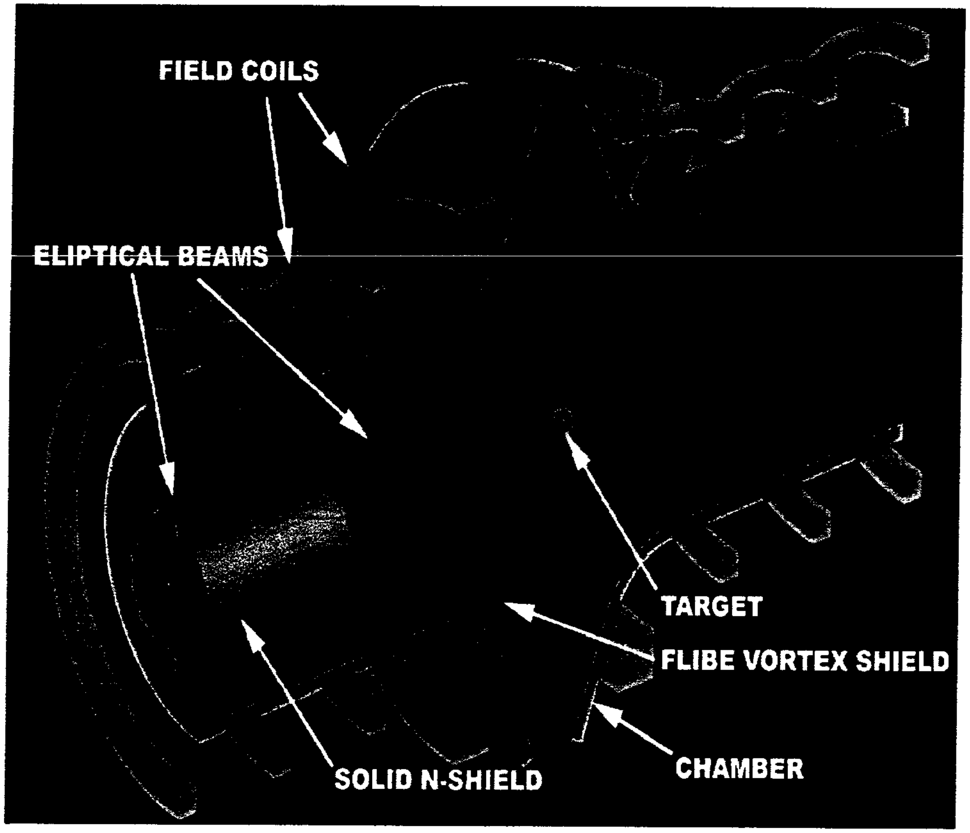


Velocity distribution in the plane (r-z) parallel to the flow direction.

SWIRLING LIQUID WALL CONCEPT FOR HIF

* Cusp-like liquid surface is obtained by driving a swirling liquid vortex into the interior of cylindrical structural shell from both sides with a an azimuthally symmetric outlet in the magnetic cusp region so that the liquid streams are ejected by their own centrifugal acceleration.

* Utilization of swirling thick liquid walls allows for continually replenished liquid surface facing the target.



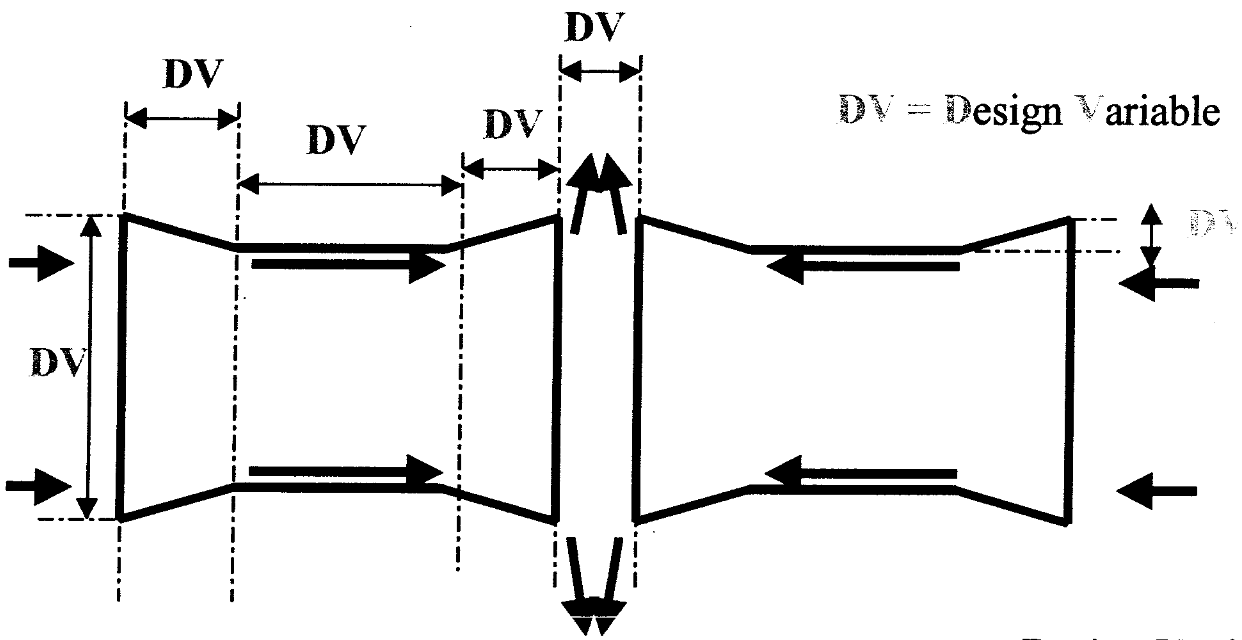
FOCUS

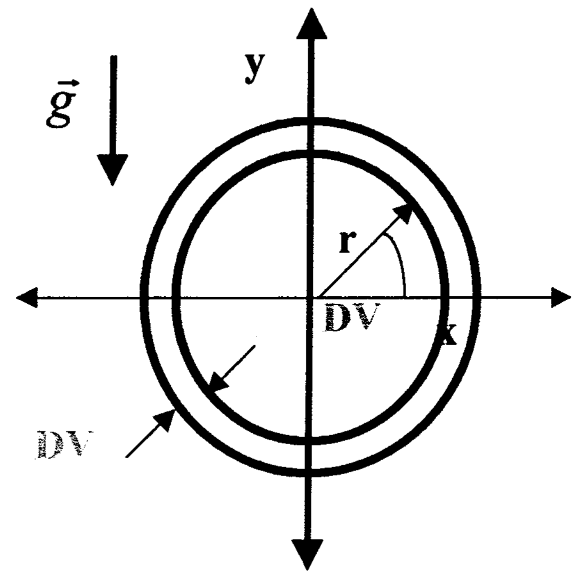
* Simulation of swirling flow configuration for HIF. (3-D, cylindrical geometry, free surface flow)

* Determination of the required conditions to obtain a stable swirling flow in cylindrical structure and liquid wall cusp formation at the outlet.

* Stability analysis of swirling flow a cylindrical structure.

DESIGN STUDY OF SWIRLING LIQUID WALL CONCEPT





Major Constraints For Preliminary Design Study:

* Liquid Blanket Thickness (> 45 cm)
* Axial Velocity at the Liquid Wall Surface Facing to the Plasma (>10 m/s).
* Displacements of the Liquid Wall Surface (+/- 2 cm).
* No Liquid Splash/Drip.
* Uniform Liquid Wall Thickness on Planes Perpendicular to Axial Flow Direction.
* Liquid Cusp Formation and Smooth Fluid Removal

Design Variables For Preliminary Design Study:

* Axial Inlet Velocity (z-direction)
* Azimuthal Inlet Velocity (theta-direction)
* Liquid Wall Thickness.
* Length and Radius of Cylindrical Structure.
* Lengths and Slope of Cusp Forming Outlet.
* Intake Design.
* Distance Between Two Main Cylindrical Section.

PRELIMINARY RESULTS (I)

Operation Parameters and Initial Conditions

Operating Fluid : Flibe

U_{axial} : 1.0 m/s

U_{theta} : 13.0 m/s

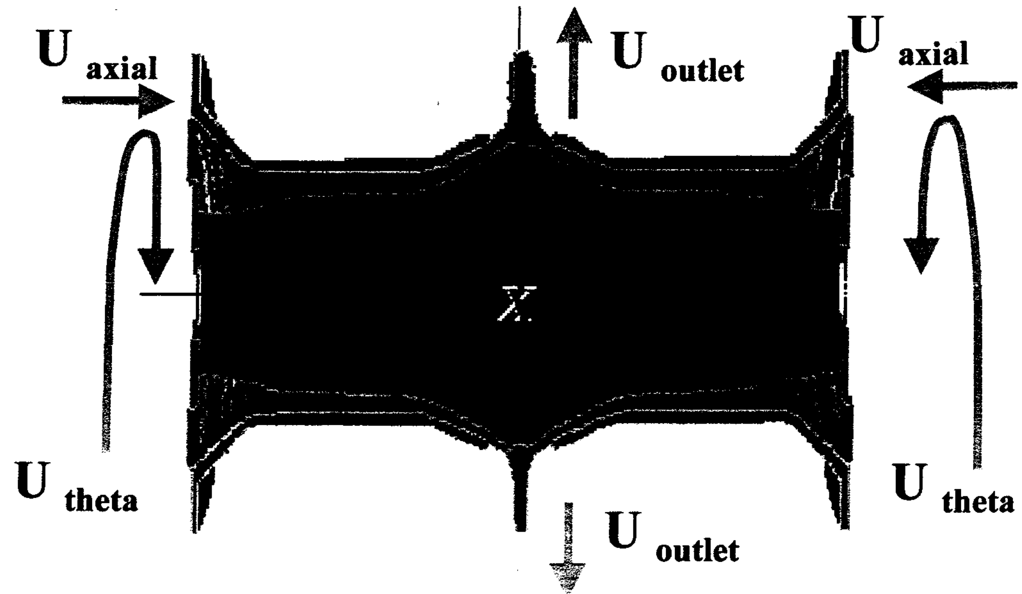
Radius : 2.0 m

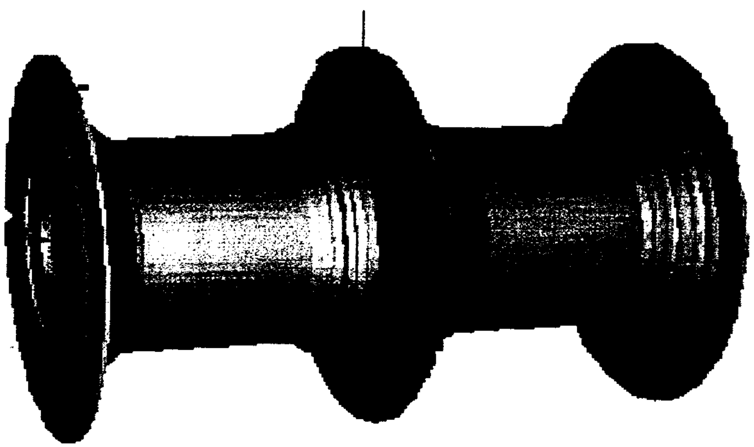
Length : 3.0 m

Diverging Outlet Angle : 25 °

Diverging Outlet Axial Length : 1.0 m

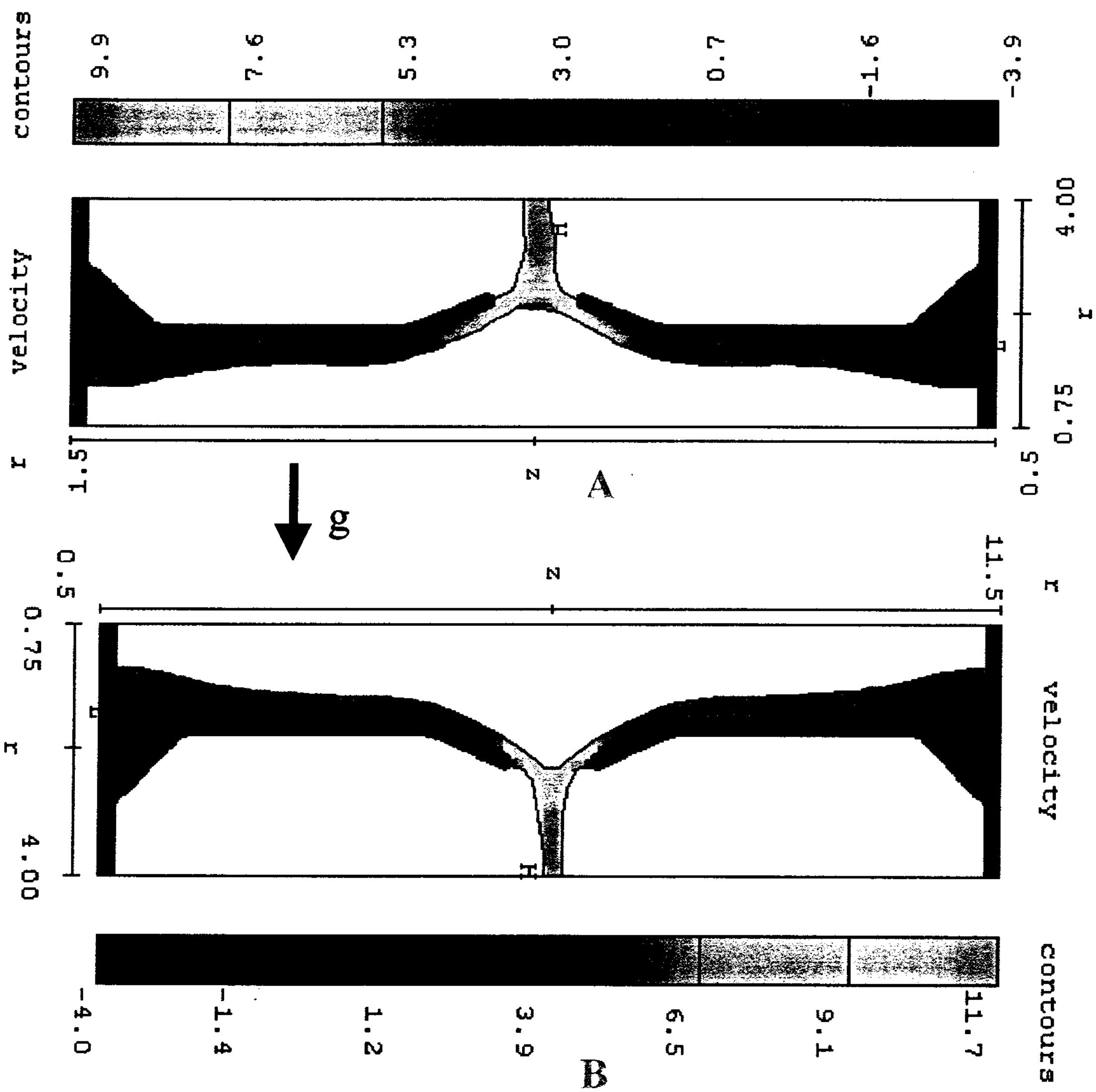
Distance Betw. Two Cylin. : 1.0 m





* Swirling liquid wall in the cylindrical and cusp shaped liquid wall at the outlet sections can be maintained.
* Formation of cusp is strongly dependent on rotational velocity component.
* The distance between two cylindrical section becomes lower and the fluid drip into to the target section may be eliminated when the initial axial inlet velocity is minimized.

PRELIMINARY RESULTS (II)



R-Velocity Contour A) Top Section, B) Bottom Section.

* There is an asymmetry in the cusp due to the effect of gravitational acceleration on the hydrodynamic behavior of the swirling liquid flow.

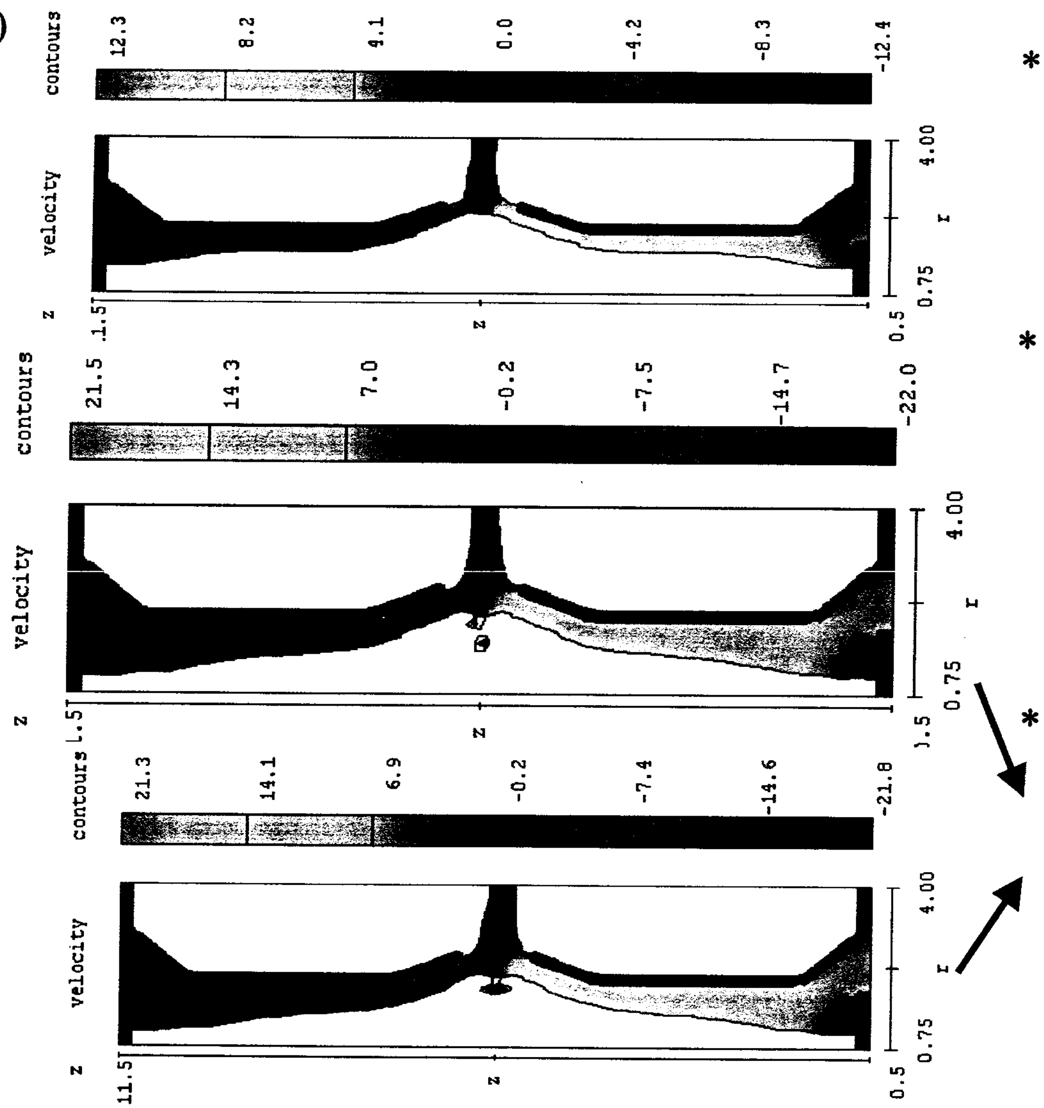
* The slope of the cusp is constant due to the structural constraint, however the thickness of the liquid wall on the diverging section varies due to the gravitational acceleration.

* This condition may be minimized by increasing the azimuthal flow velocity.

* The outlet velocity varies as the direction of gravitational acceleration with respect to axial flow direction changes.

PRELIMINARY RESULTS (III)

A) B)



* Axial velocity increases and the liquid wall gets thinner along the flow direction due to the centrifugal acceleration.

* The thinning of the liquid wall may be minimized/eliminated by modifying the cylindrical structure (placing a contraction in the flow direction).

* An increase in inlet axial velocity profile may generate a drip formation at the point where two swirling liquid wall in opposite direction meets each other.

Z-Velocity Contour A) V axial=2 m/s, B) V axial=5 m/s at different times (V azimuthal is same in all cases)

FUTURE WORK

*** Swirling flow and inlet:**

- Hydrodynamic stability of the boundary layer.
- Hydrodynamic stability of the main stream (Coriolis force and the axial velocity component to be included.)
- Various inlet designs currently being studied to be evaluated.

*** Liquid cusp:**

- An optimization analysis for diverging cusp section (angle, length) and liquid wall operating conditions to be performed to eliminate droplet formation, maximize heat transfer and maintain the wall thickness along the axial and azimuthal flow directions.

*** Determination of the turbulence intensity in the flow:**

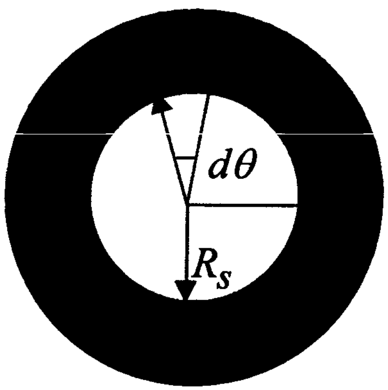
- Turbulence generation at the boundary layer (additional enhancement due to unstable nature of the concave boundary layer, Gortler, etc), in the swirling flow itself and in the inlet will be evaluated.
- The effect of generated turbulence intensity to the heat transfer characteristic at the liquid wall surface will be evaluated.

SWIRLING LIQUID WALL

* Minimum required azimuthal velocity for the liquid blanket to rotate without falling from the top section is function of radius of cylindrical flow section and the desired liquid wall thickness.

* The relationship for the minimum required liquid blanket thickness can be derived by assuming a fully developed potential flow in the azimuthal direction.

$$U_\theta = \frac{C \cdot R_s}{r} \qquad U_\theta = C \quad r = R_s$$



Force per unit length due to centripetal acceleration $\int_{R_s}^{R_b} \rho \frac{U_\theta^2(r)}{r} r\,dr\,d\theta$

$$\rho C^2 \cdot R_s^2 \left[\frac{1}{R_s} - \frac{1}{R_b} \right] d\theta$$

Force per unit length due to gravitational acceleration $\int_{R_s}^{R_b} \rho \cdot \vec{g} \cdot r\,dr\,d\theta$

$$\rho \cdot \vec{g} \frac{\left(R_b^2 - R_s^2\right)}{2} d\theta$$

$$C^2 = g \frac{\left(R_b + R_s\right)}{2} \frac{R_b}{R_s}$$

For a $d\theta$ in the neighborhood of 90^0, the force balance requires the minimum condition for the rotating fluid not to fall down.

$R_b = 2 \quad m \quad R_s = 1 \quad m \qquad C = 5.42 \quad m/s$

$R_b = 2 \quad m \quad R_s = 1.5 \quad m \qquad C = 4.78 \quad m/s$

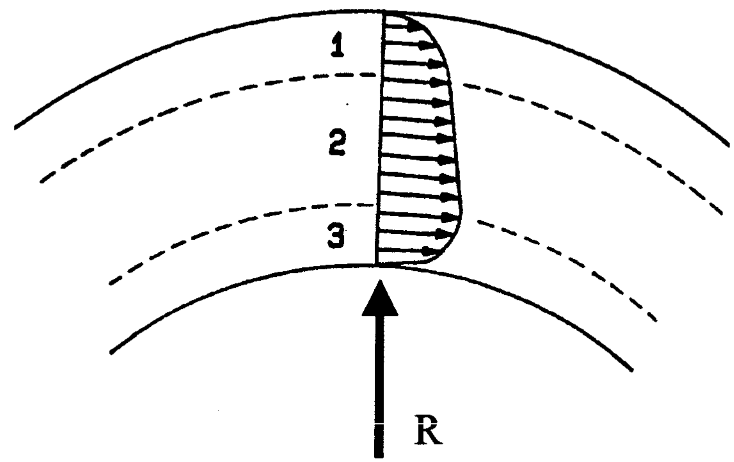
$R_b = 1 \quad m \quad R_s = 1.5 \quad m \qquad C = 4.28 \quad m/s$

LINEAR STABILITY ANALYSIS (I)

* The previous experimental results suggest that the azimuthal velocity profile in the free stream region of a flow over a concave surface can be expressed as irrotational flow.

* Previous experimental results suggest that, flow in a curved duct has three mechanism that effects its stability.

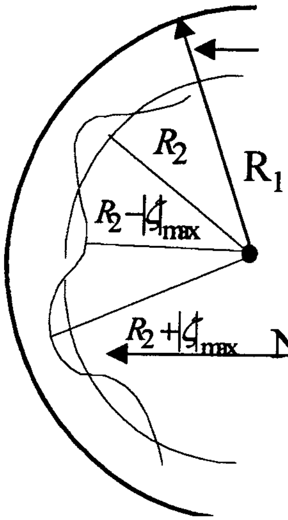
1. Concave boundary layer, d(Ur)/dr < 0, unstable, radial mixing is enhanced.
2. Free stream, irrotational, d(Ur)/dr=0, neutrally stable.
3. Convex boundary layer, d((Ur)/dr > 0, stable, radial mixing is suppressed.



* A 2-D (r-theta) linear stability analysis has been using irrotational velocity profile and modeling surface tension, varying gravitational acceleration and the centrifugal acceleration term using method of normal modes for swirl flow. Assumptions:

- The boundary layer thickness is small compared to the free stream thickness for such a high Reynolds number flow (Re> 700,000)
- Only azimuthal velocity component have been taken into account as an initial step.
- An initial infinitely small perturbation is introduced for surface displacement and velocity potential.

LINEAR STABILITY ANALYSIS (II)



* The fully-developed potential flow in cylindrical geometry is used. The velocity profile in the liquid lithium jet can be expressed as,

$$U(r) = U_s \frac{R_2}{r}$$

where R_2 is the radius nominal surface position and U_s is the azimuthal velocity at the flow surface.

* The velocity potential can be expressed as a function of θ such that,

$$\phi = V_{\text{int}} R_1 \theta$$

Boundary Conditions:

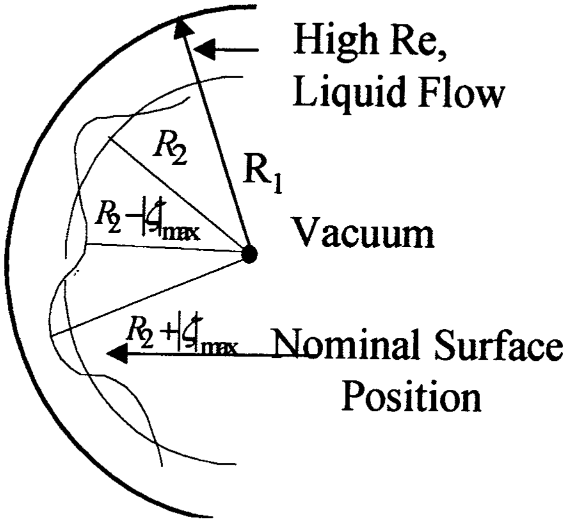
The boundary condition of zero velocity in the r- direction, at the wetted side of the back plate ($r=R_1$).

$$V = \frac{\partial \phi}{\partial r}\vec{r}_0 = 0, \qquad r = R_1.$$

The fluid particles at the interface must move with the interface. Therefore, the vertical velocity at the interface can be given by the substantial derivative of the surface elevation (Lamb, 1960) as:

$$\frac{\partial \phi}{\partial r} = \frac{\mathrm{D}\zeta}{\mathrm{Dt}} = \frac{\partial \zeta}{\partial t} + (\nabla \phi)_r \frac{\partial \zeta}{\partial r} + (\nabla \phi)_\theta \frac{1}{r}\frac{\partial \phi}{\partial \theta}$$

LINEAR STABILITY ANALYSIS (III)



System Equations :

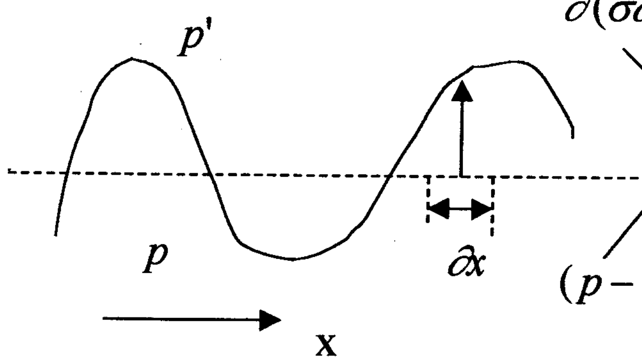
* Laplacian of the velocity potential should be zero.

$$\nabla^2\phi = 0$$

* The pressure equilibrium at the surface streamline can be expressed using Bernoulli Equation,

$$\frac{\partial\phi}{\partial t} + \frac{1}{2}(\nabla\phi)^2 + \frac{P}{\rho} + gz = C(t)$$

Modeling of Surface Tension:



$\partial(\sigma\partial\zeta/\partial x)$

$$p - p' + \sigma\frac{\partial^2\zeta}{\partial x^2} = 0$$

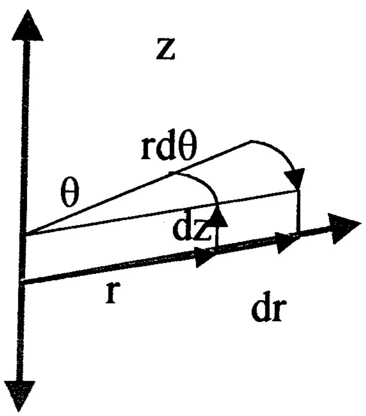
$(p-p')\partial x$

* The surface elevation is a function of θ, the pressure term for the streamline on the liquid lithium jet surface can be expressed as,

$$p = \sigma\left(\frac{1}{R_{initial}} - \frac{1}{r^2}\frac{d^2\zeta}{d\theta^2}\right), \qquad r = R_2.$$

LINEAR STABILITY ANALYSIS (IV)

Modeling of Centrifugal Acceleration Term:

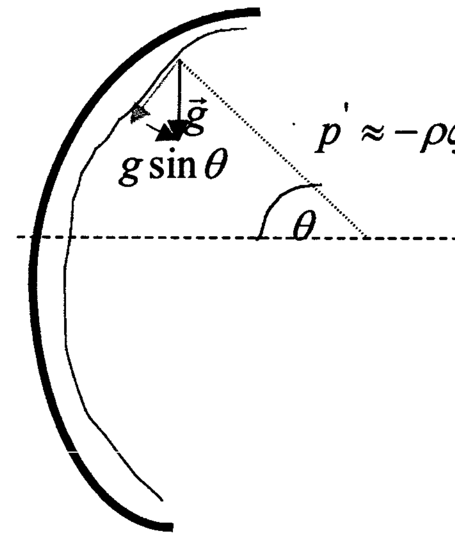


$$\frac{dp}{dr} = \rho\omega^2 r \rightarrow \omega = \frac{U_s}{R_2}$$

$$p' = \rho \frac{U_s^2}{R_2^2} \int_{R_2-\zeta}^{R_2} r\,dr \rightarrow p' = \frac{\rho}{2}\frac{U_s^2}{R_2^2}\left[R_2^2 - (R_2-\zeta)^2\right]$$

$$p' \approx \rho \frac{U_s^2}{R_2}\zeta$$

Modeling of Gravitational Acceleration Term:



$$p' \approx -\rho\zeta g \sin\theta$$

* The sets of partial differential equation with constant coefficients independent of time and θ. This permits the method of normal modes to be used where small arbitrary perturbations of the form,

$$\zeta, \phi' = (\hat{\zeta}, \hat{\phi}) e^{ik\theta + st}$$

STABILITY ANALYSIS (V)

* Linearization is performed by combining the steady-state and the perturbed parts of the velocity potential and neglecting the higher order perturbed velocity potential terms.

Linearized set of system equations

$$\nabla^2(V_{\text{int}} R_1\theta) + \nabla^2\phi' = 0 \Rightarrow \nabla^2\phi' = 0 \qquad \text{EQ-1}$$

$$\frac{\partial\phi_o}{\partial t} + \frac{\partial\phi'}{\partial t} + \frac{1}{2}(\nabla\phi_0)^2_\theta + (\nabla\phi_0\nabla\phi')_\theta = \frac{1}{\rho}\left(\rho g\sin\theta\zeta - \frac{\sigma}{R_2} + \frac{\sigma}{R_2{}^2}\frac{\partial^2\zeta}{\partial\theta^2} - \rho\frac{U_s^2\zeta}{R_2}\right)$$

$$\downarrow \qquad \downarrow \qquad \text{EQ-2}$$

$$\frac{\partial\phi'}{\partial t} + (\nabla\phi_0\nabla\phi')_\theta + = \frac{1}{\rho}\left(\rho g\sin\theta\zeta + \frac{\sigma}{R_2{}^2}\frac{\partial^2\zeta}{\partial\theta^2} - \rho\frac{U_s^2\zeta}{R_2}\right)$$

Linearized set of boundary conditions

$$\vec{r}_0\frac{\partial}{\partial r}(V_{\text{int}}R_1\theta) + \vec{r}_0\frac{\partial}{\partial r}\phi' = 0 \quad \Rightarrow \quad \vec{r}_0\frac{\partial\phi'}{\partial r} = 0 \quad . \qquad \text{BC-1}$$

$$\frac{\partial\phi}{\partial t} = \frac{D\zeta}{Dt} = \frac{\partial\zeta}{\partial t} + (\nabla\phi)_r\frac{\partial\zeta}{\partial t} + (\nabla\phi)_\theta\frac{1}{r}\frac{\partial\phi}{\partial\theta} \longrightarrow \frac{\partial\phi'}{\partial r} = \frac{\partial\zeta}{\partial t} + (V_{\text{int}}\frac{R_1}{R_2} + \frac{1}{r}\frac{\partial\phi'}{\partial\theta})\frac{1}{r}\frac{\partial\zeta}{\partial\theta}, \qquad r = R_2 \qquad \text{BC-2}$$

LINEAR STABILITY ANALYSIS (VI)

* Linearization is performed by combining the steady-state and the perturbed parts of the velocity potential and neglecting the higher order perturbed velocity potential terms.

Coefficient of time exponential expression of perturbations

$$s_{1,2} \cong \frac{U_s}{R_2} ik \pm i \sqrt{\frac{k}{R_2} \frac{1-\left(\frac{R_1}{R_2}\right)^{2k}}{1+\left(\frac{R_1}{R_2}\right)^{k}}} \sqrt{g\sin\theta - \frac{U_s^2}{R_2} - \frac{\sigma k^2}{R_2}}$$

Always Positive

High Velocity liquid layer is stable when gravitational acceleration, centripetal acceleration and surface tension is taken into account for

$$g\sin\theta < \frac{U_s^2}{R_2} + \frac{\sigma k^2}{R_2}$$

→ **Always stable since centrifugal acceleration should be more than gravitational acceleration for liquid layer to adhere to the wall.**

* **Gravitational acceleration has stabilizing and destabilizing effect on the flow depending on the direction of the flow with resect to direction of the gravitational acceleration.**
* **Surface tension has stabilizing effect for high wave number (short wave wavelength) as expected.**