An Overview of the Fluid Dynamics Aspects of Liquid Protection Schemes for Fusion Reactors

S. I. Abdel-Khalik and M. Yoda

TOFE-16 Meeting - Madison (September 2004)

**G. W. Woodruff School of
Mechanical Engineering
Atlanta, GA 30332–0405 USA**

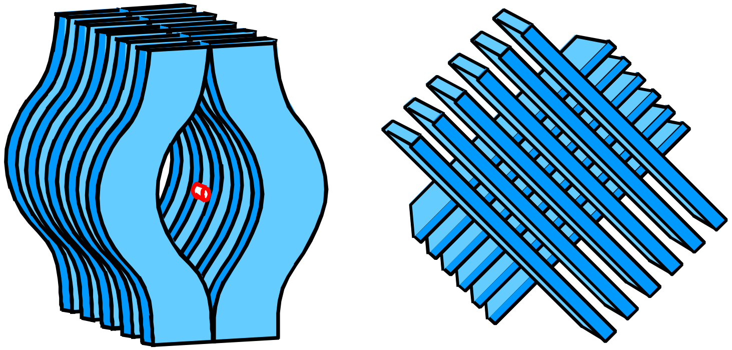
OUTLINE

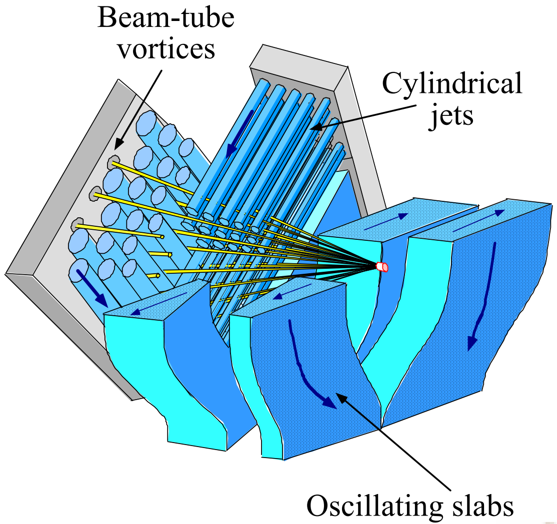
- **Thick Liquid Protection (HYLIFE-II)**
- **Thin Liquid Protection (Prometheus)**
  - Wetted Wall Concept
  - Forced Liquid Film Concept
- **Liquid-Surface-Protected PFCs**

Thick Liquid Protection

HYLIFE-II: Use slab jets or liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles.

- Oscillating sheets create protective pocket to shield chamber side walls
- Lattice of stationary sheets (or cylindrical jets) shield front/back walls while allowing beam propagation and target injection





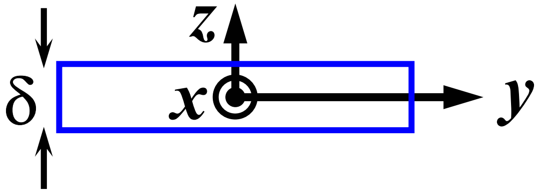
Pictures courtesy P.F. Peterson, UCB

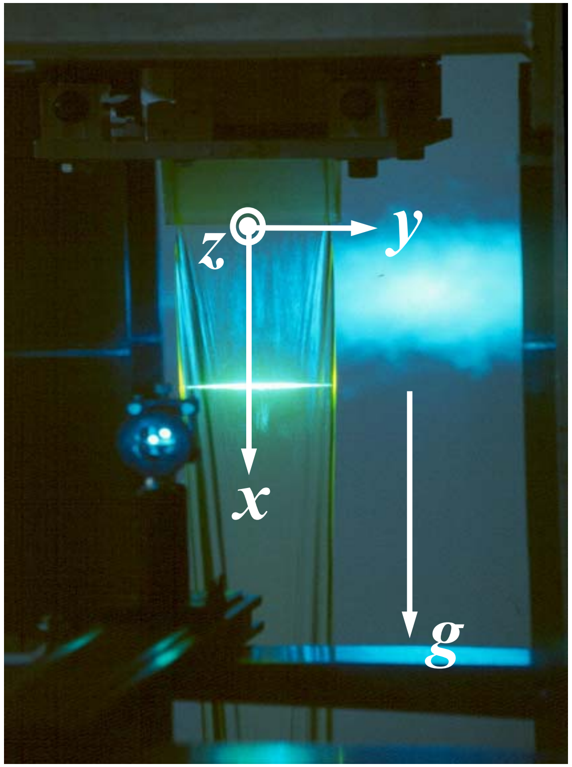
Thick Liquid Protection

Problems Addressed:

- Is it possible to create "smooth" prototypical turbulent liquid sheets to allow beam propagation through the lattice?
  - ❑ Small (~5 mm) clearance between driver beam & sheet free surface in protective lattice ⇒ > 30 year lifetime for final focus magnets
- How much "fog" is created in the chamber?
  - ❑ Primary turbulent breakup – the "hydrodynamic source term"
  - ❑ Limits dictated by beam propagation and target delivery requirements

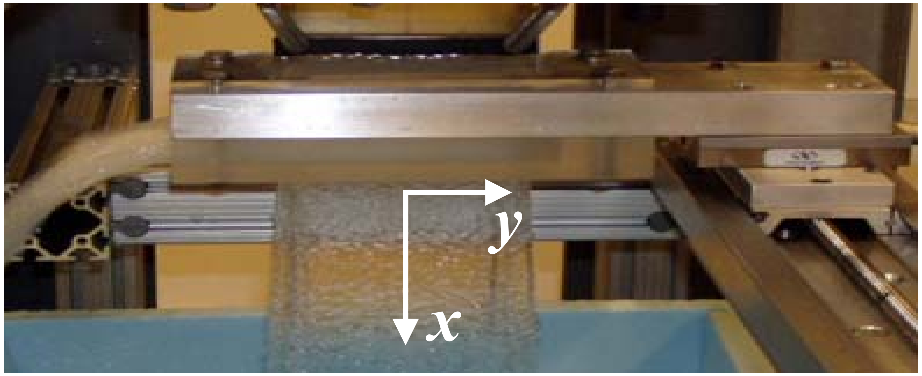
Surface Smoothness

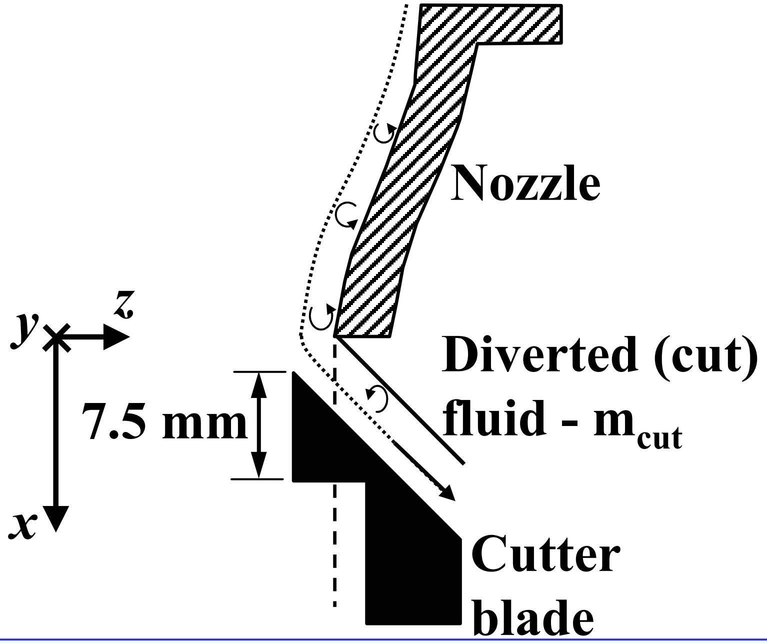




- **Used Planar Laser Induced Fluorescence (PLIF) to characterize the jet free surface at near prototypical conditions**
- **Examine effects of nozzle design, flow conditioning, and boundary layer cutting on surface ripple**
- **Measure standard deviation of free surface *z*-location (σ_z)**
  - Characteristic length scale $\delta = 1$ cm
  - $Re = U_o \delta / \nu \lesssim 130{,}000$
  - $We = \rho_L U_o^2 \delta / \sigma \lesssim 19{,}000$
  - Near field $x / \delta \lesssim 25$
  - Boundary layer cutter removal rate $\dot{m}_{cut} / \dot{m}_{flow} = 0.0 - 1.9\%$

Flow Conditioning and Boundary Layer Cutting



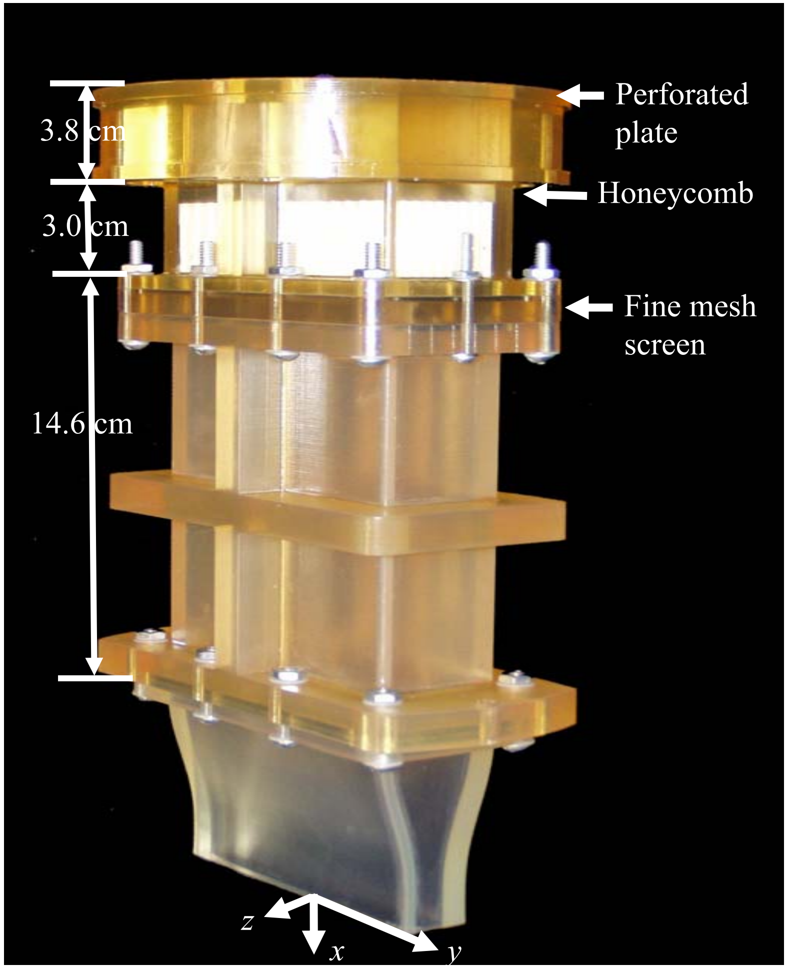


Nozzle

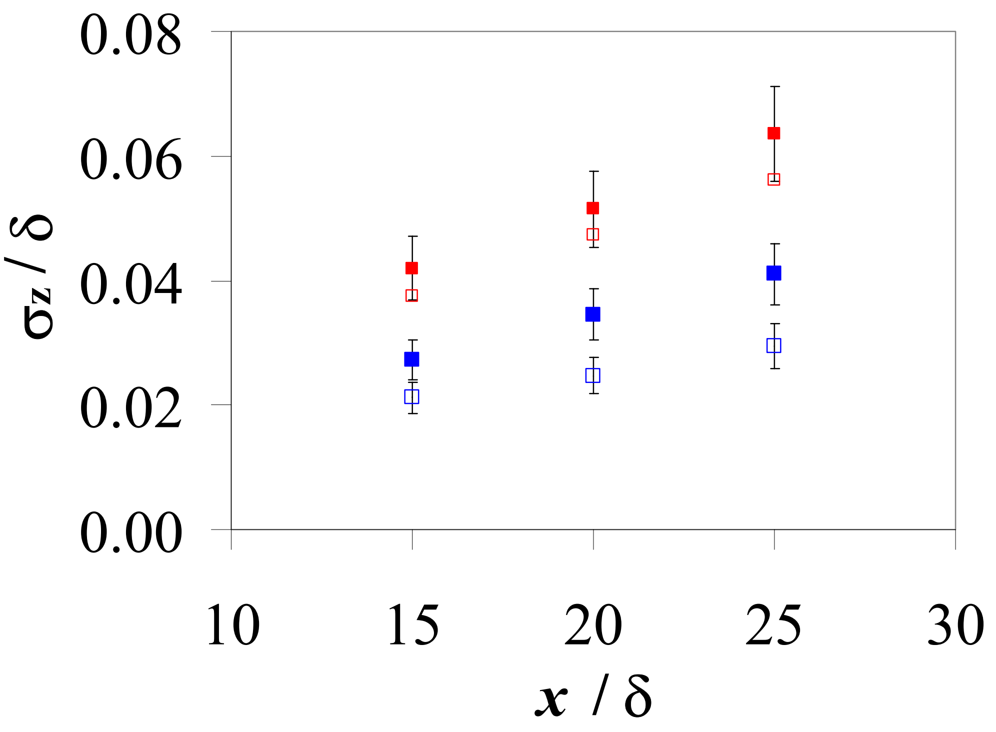
Diverted (cut) fluid - m_{cut}

7.5 mm

Cutter blade



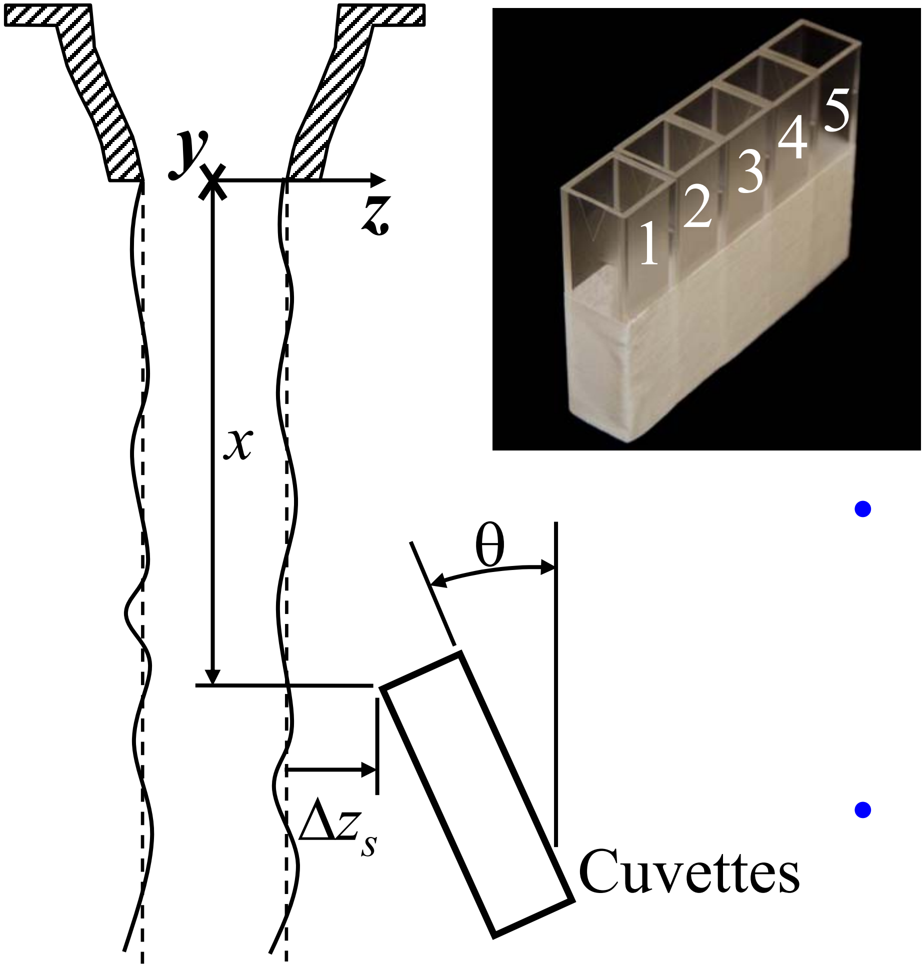
Surface Smoothness (PLIF Results)

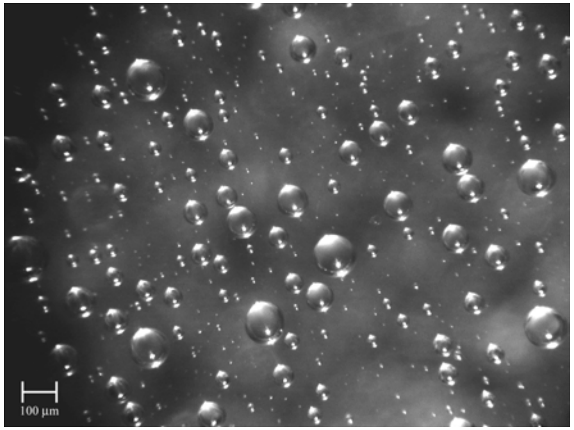


Standard Design ■ - **No cutting**
No Fine Screen □ - **1.9% cut**

- Surface ripple increases by ~50% when fine screen removed
- BL cutting reduces σ_z by ~33% for standard flow conditioner design
- $\sigma_z \downarrow$ as $\dot{m}_{cut} \uparrow$; Cutting as little as 0.6% significantly improves surface smoothness
- **Proper flow conditioning and boundary layer cutting can reduce surface ripple well below the maximum value specified for HYLIFE-II (0.07 δ)**

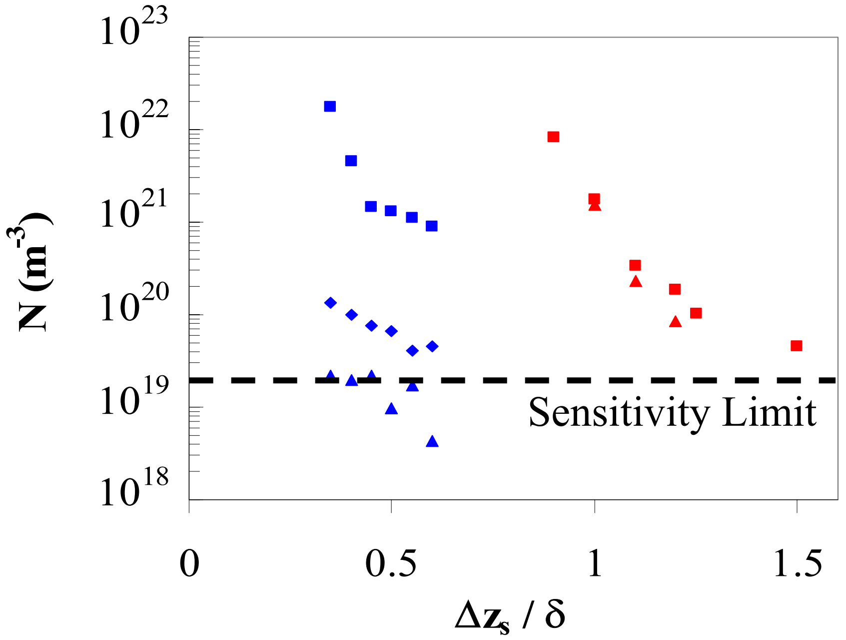
The "Hydrodynamic Source Term"





- Used simple mass collection system to measure mass flux of liquid droplets ejected from the free surface at different locations – estimated corresponding chamber number density
- Quantified effects of flow conditioning and boundary layer cutting– compared data vs. empirical primary turbulent breakup model w/o FC & BLC

Hydrodynamic Source Term - Equivalent Number Density ($x / \delta = 25$)



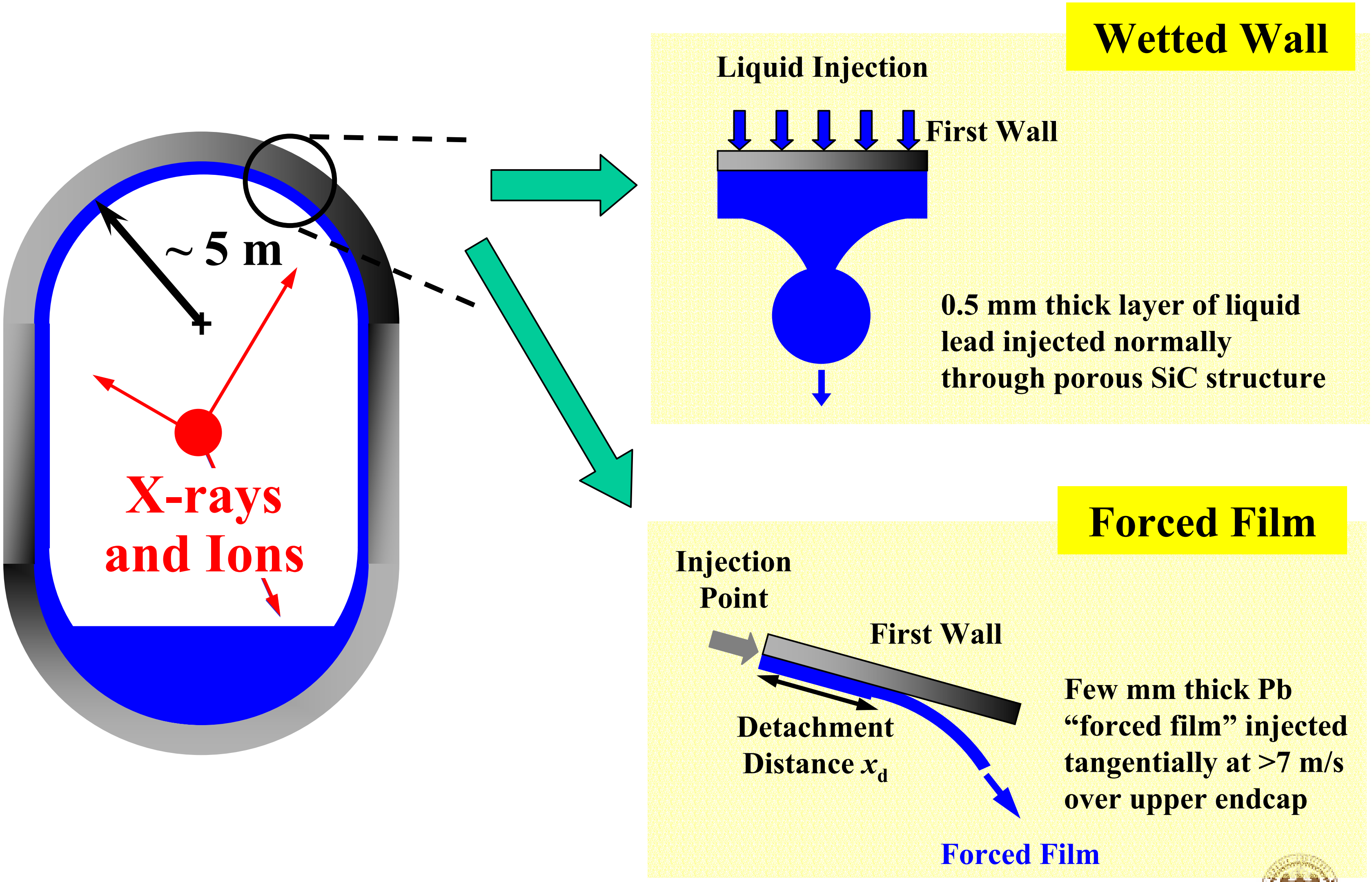
- Droplet mass flux values for jets produced by nozzles with optimized flow conditioners is ~3-4 orders of magnitude lower than predictions of empirical correlation
  - Droplets ejected form sparse aerosol around jet
- **Removing fine screen increases range and number density of droplets**
- **Boundary Layer cutting with modest mass removal rates effectively eliminates turbulent breakup for a well-conditioned jet.**

Standard Design
No Fine Screen

$\dot{m}_{cut} / \dot{m}_{flow}$

■ **0.0%** ◆ **1.0%** ▲ **1.9%**

Thin Liquid Protection



Wetted Wall

0.5 mm thick layer of liquid lead injected normally through porous SiC structure

Forced Film

Few mm thick Pb "forced film" injected tangentially at >7 m/s over upper endcap

Thin Liquid Protection

Problems Addressed (wetted wall/Forced Film):

- How frequently will the film "drip"? How large are the drops?
  - ☐ Constraints on the repetition rate to prevent interference with beam propagation and/or target injection
- Can a minimum film thickness be maintained to provide adequate protection over subsequent target explosions?
  - ☐ Constraints on minimum injection velocity
- How far will the film remain attached to the wall?
  - ☐ Constraints on "tile" size, i.e. spacing between injection and removal ports
- How much "fog" will be formed around the forced liquid film?
- How will the film behave around beam ports/penetrations?
  - ☐ Recommendations on beam port geometry/design.

Study both wetted wall & forced film concepts over "worst case" of downward-facing surfaces

Experimental & Numerical Study of Porous Wetted Walls

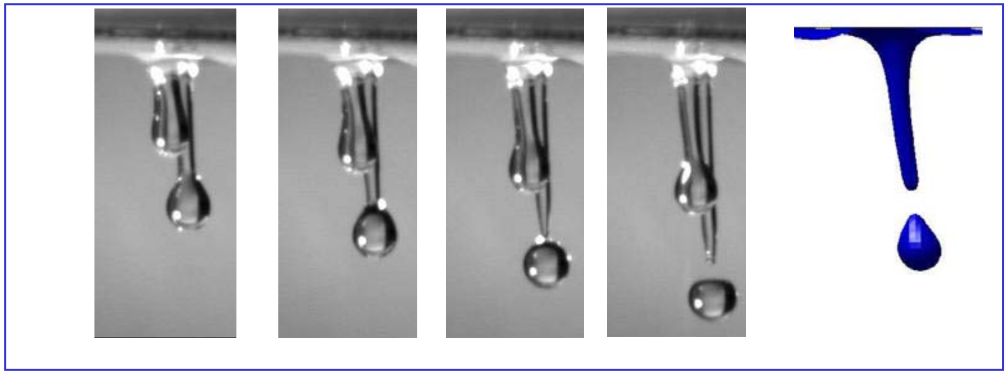
Quantify effects of

- injection velocity w_{in}, initial film thickness z_o, initial perturbation geometry& mode number, inclination angle θ, and Evaporation & Condensation at the interface

on

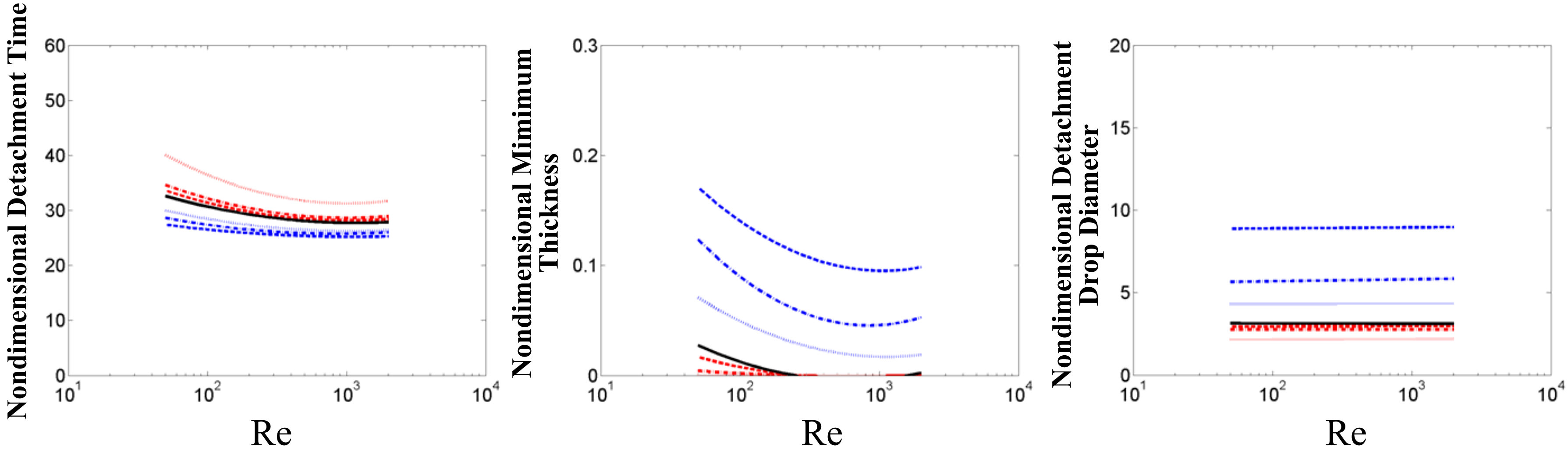
- Droplet detachment time, Droplet size, and minimum film thickness prior to detachment

Obtained generalized charts for dependent variables as functions of the governing non-dimensional parameters



0.53 sec 0.56 sec 0.58 sec 0.59 sec 0.59 sec

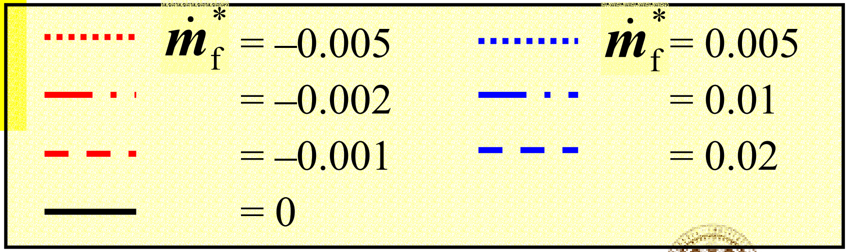
Typical Non-Dimensional Charts
– Porous Wetted Walls



- Nondimensional Initial Thickness z_o^*=0.1
- Nondimensional Injection Velocity w_{in}^*=0.01

Nondimensional mass flux

$$\dot{m}_f^* = \dot{m}_f / (\rho_L U_o)$$



Wetted Wall Summary

- Developed generalized non-dimensional charts applicable to a wide variety of candidate coolants and operating conditions

- Stability of liquid film imposes
  - Lower bound on repetition rate (or upper bound on time between shots) to avoid liquid dripping into reactor cavity between shots
  - Lower bound on liquid injection velocity to maintain minimum film thickness over entire reactor cavity required to provide adequate protection over subsequent fusion events

- Model Predictions are closely matched by Experimental Data

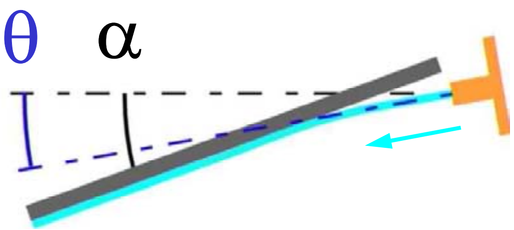
Experimental Study of Forced Liquid Films

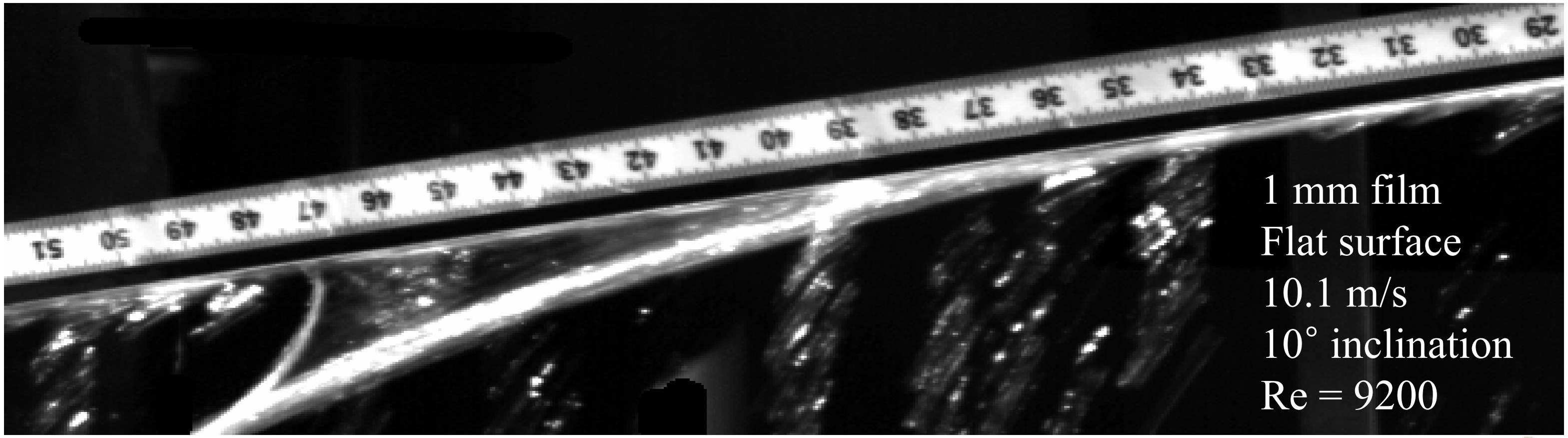
Quantify Effects of

- Film thickness, injection velocity, surface inclination, surface curvature, injection angle, and surface material wettability

On

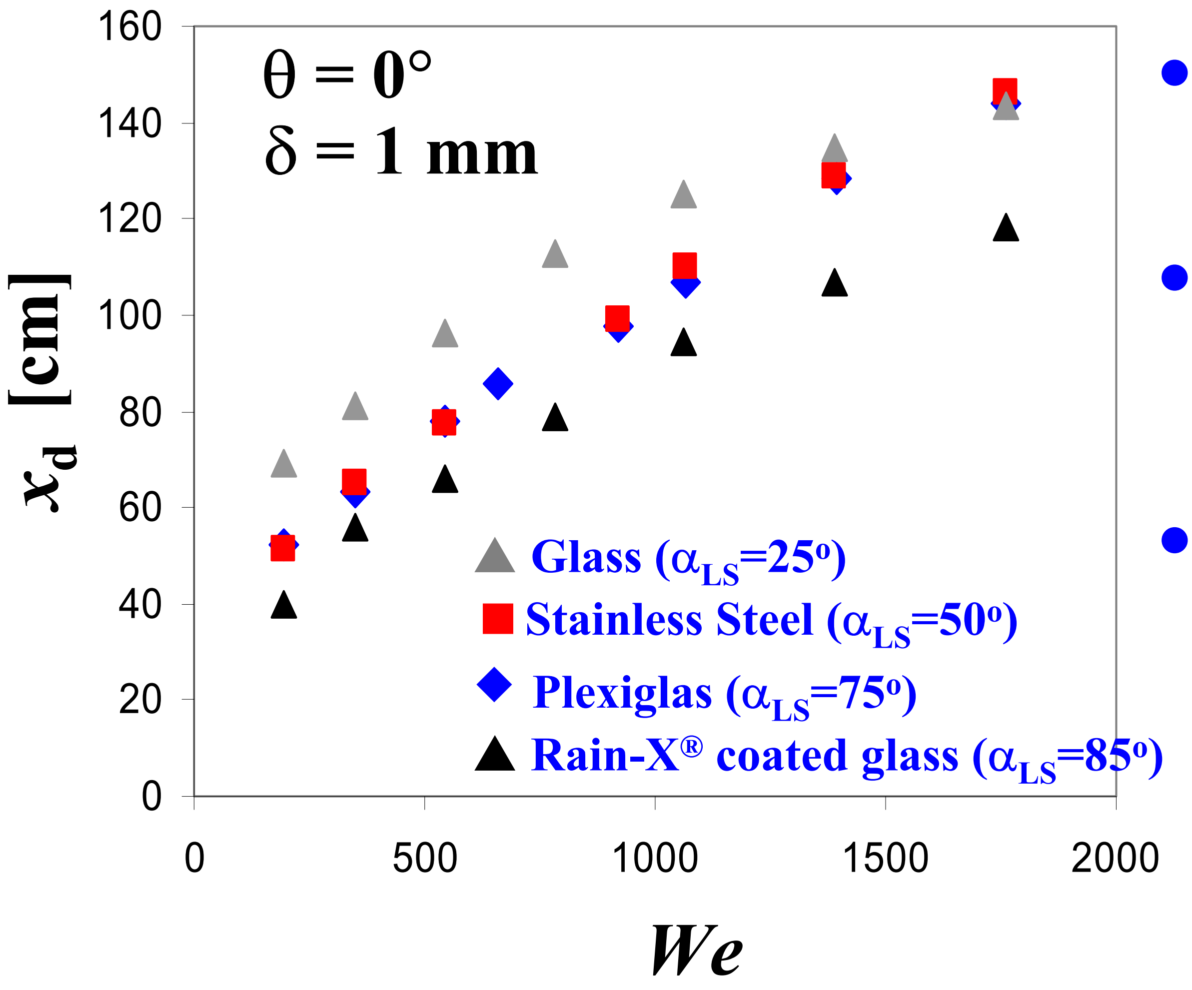
- Detachment distance, film width and thickness, and ejected droplet mass flux




[redacted]

1 mm film
Flat surface
10.1 m/s
10° inclination
Re = 9200

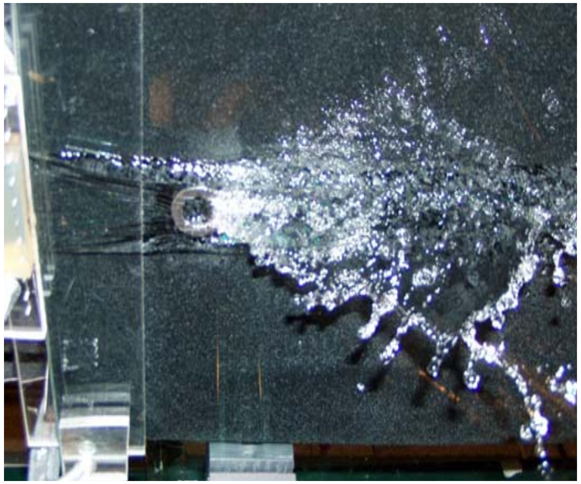
Detachment Distance Vs. Weber Number

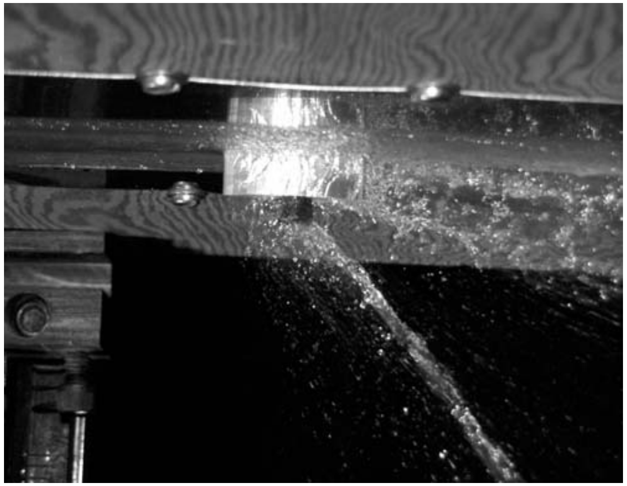


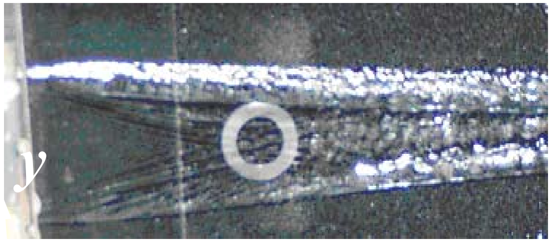
- Similar data for other angles, film thickness, and surface curvature
- Design Windows for stream-wise spacing of injection/removal slots to maintain attached film
- Wetting wall surface requires fewer injection slots (more desirable)

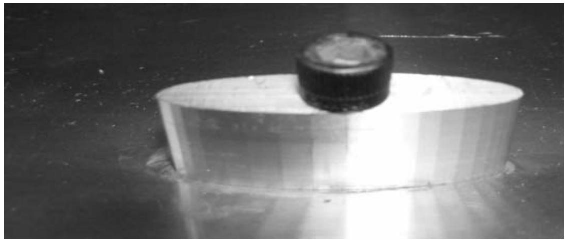
Penetrations and Beam Ports

- Cylindrical and hydrodynamically-tailored obstructions modeling protective dams around penetrations and beam ports result in film “breakup.”
- Penetrations will pose significant design challenge for forced film wall protection systems.









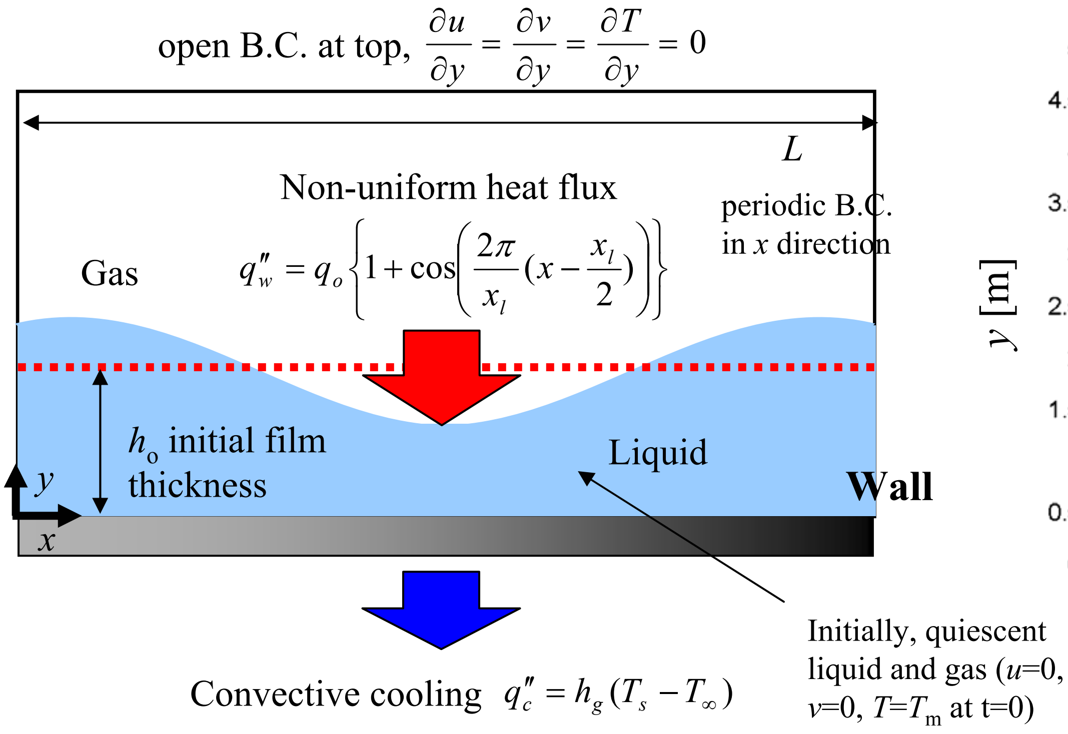
Liquid-Film-Protected Divertors

Problem Definition:

- **ALPS and APEX Programs established temperature limits for different liquids to limit plasma contamination by evaporation**

- **This work establishes limits for the maximum spatial temperature gradients (i.e. heat flux gradients)**
  - ☐ Spatial Variations in the wall and Liquid Surface Temperatures are expected due to variations in the wall loading
  - ☐ Thermocapillary forces created by such temperature gradients can lead to film rupture and dry spot formation in regions of elevated local temperatures
  - ☐ Initial Attention focused on Plasma Facing Components protected by a “non-flowing” thin liquid film (e.g. porous wetted wall)

Numerical Simulation - Film Rupture



open B.C. at top, $\frac{\partial u}{\partial y} = \frac{\partial v}{\partial y} = \frac{\partial T}{\partial y} = 0$

L

Non-uniform heat flux

Gas

$q''_w = q_o\left\{1+\cos\left(\frac{2\pi}{x_l}(x-\frac{x_l}{2})\right)\right\}$

periodic B.C. in x direction

h_o initial film thickness

Liquid

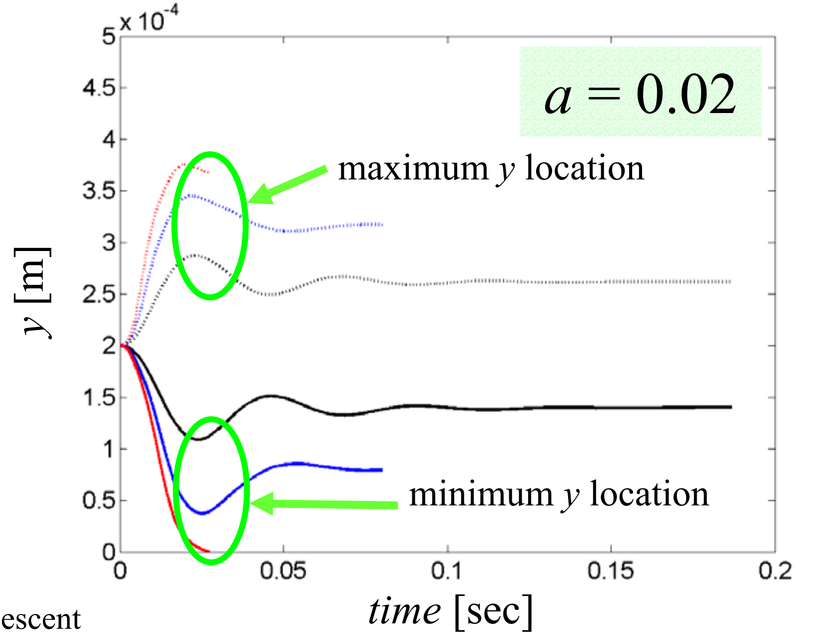
Wall

y

x

Convective cooling $q''_c = h_g(T_s - T_\infty)$

Initially, quiescent liquid and gas (u=0, v=0, T=T_m at t=0)



- Asymptotic solution for low aspect ratio with variable surface temperature or heat flux
- Film surface evolution also determined by Level Contour Reconstruction Method
- Generalized Charts for maximum allowable surface temperature (or heat flux) gradients

Maximum Heat Flux Gradients

Typical Results for h_o=1 mm & a(Nu)=1.0

Coolant	**Mean Temperature [K]**	**Maximum Allowable Heat Flux Gradient : $(Q''/L)_{max}$ [(MW/m^2)/cm]**				
		$a = 0.05$	$a = 0.02$	$a = 0.01$	$a = 0.005$	$a = 0.002$
Lithium	573	1.9×10^0	6.3×10^{-1}	3.1×10^{-1}	1.5×10^{-1}	6.1×10^{-2}
Lithium-Lead	673	1.2×10^1	4.9×10^0	2.4×10^0	1.2×10^0	4.9×10^{-1}
Flibe	673	1.7×10^{-1}	6.5×10^{-2}	3.2×10^{-2}	1.6×10^{-2}	6.4×10^{-3}
Tin	1273	1.7×10^1	6.8×10^0	3.4×10^0	1.7×10^0	6.8×10^{-1}
Ga	1073	5.0×10^1	1.9×10^1	9.7×10^0	4.8×10^0	1.9×10^0

CONCLUSIONS

Experimental & Numerical Studies:

- Provide fundamental understanding of “building block” type flows in liquid-protected systems
- Develop experimentally-validated numerical tools (codes/models) to analyze behavior of such flows
- Produce generalized charts and design guidelines to identify windows for successful operation of liquid wall protection systems

Acknowledgements

DOE, ARIES, and Georgia Tech

- **Research Faculty** : D. Sadowski and S. Shin
- **Students** : F. Abdelall, J. Anderson, J. Collins, S. Durbin, L. Elwell, T. Koehler, J. Reperant and B. Shellabarger, V. Novak, C. Dillon, D. Lascar

Additional Information -- See TOFE-16 Presentations:

1. P-11-33: S. Shin, et al., *Design Constraints for Liquid-Protected Divertors*

2. P-11-41: S. Durbin, et al., *Flow Conditioning Design in Thick Liquid Protection*

3. P-11-40: S. Durbin, et al., *Impact of Boundary Layer Cutting on Free Surface Behavior in Turbulent Liquid Sheets*

4. P-11-43: V. Novak, et al., *Experimental and Numerical Investigation of Mist Cooling for the Electra Hibachi*