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

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OUTLINE

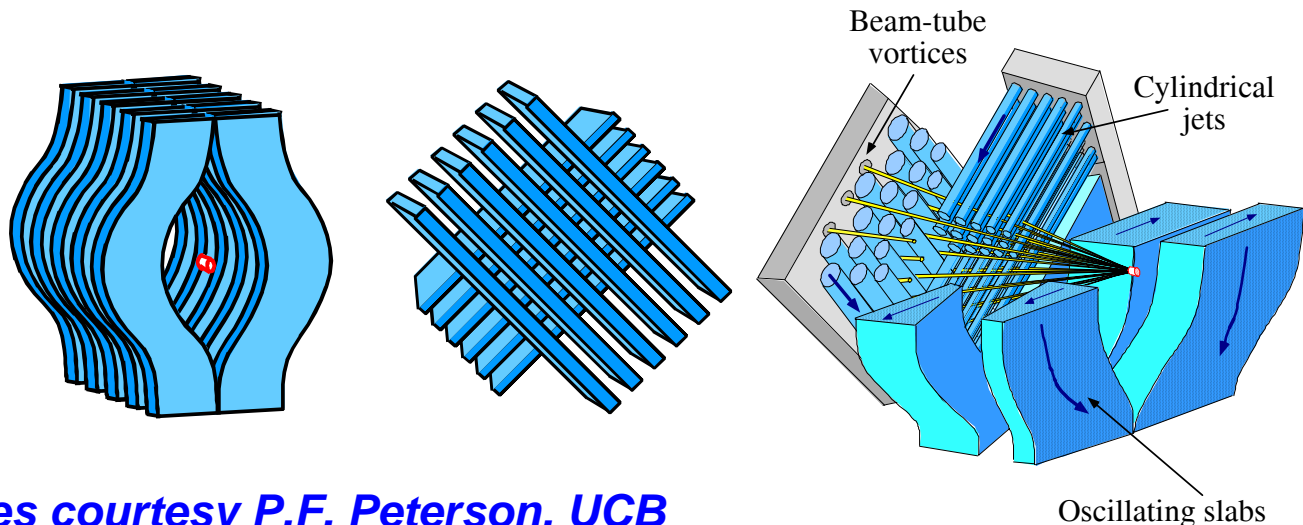
- **Thick Liquid Protection (HYLIFE-II)**
- **Thin Liquid Protection (Prometheus)**
 - Wetted Wall Concept
 - Forced Liquid Film Concept
- **Liquid-Surface-Protected PFCs**



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



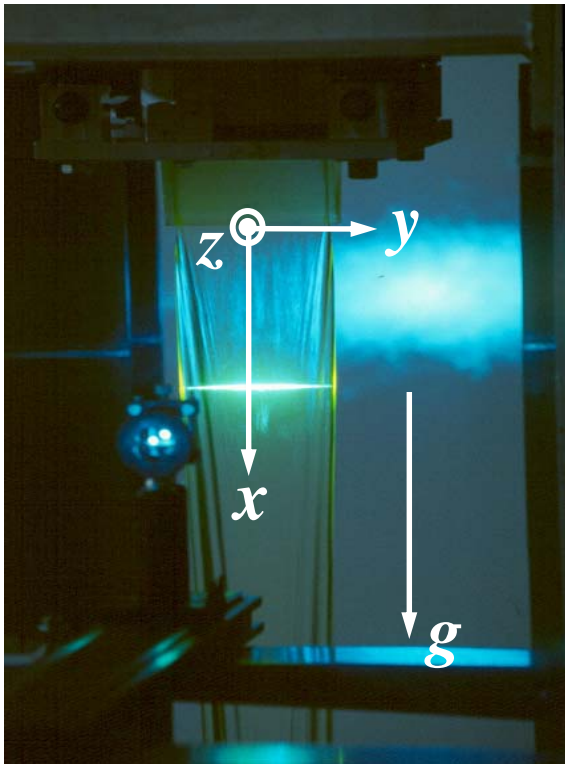
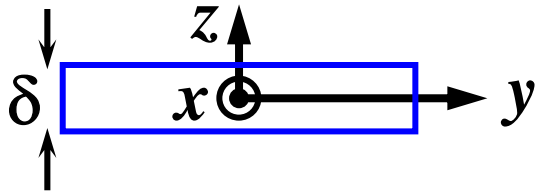
Thick Liquid Protection

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 \Rightarrow > 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



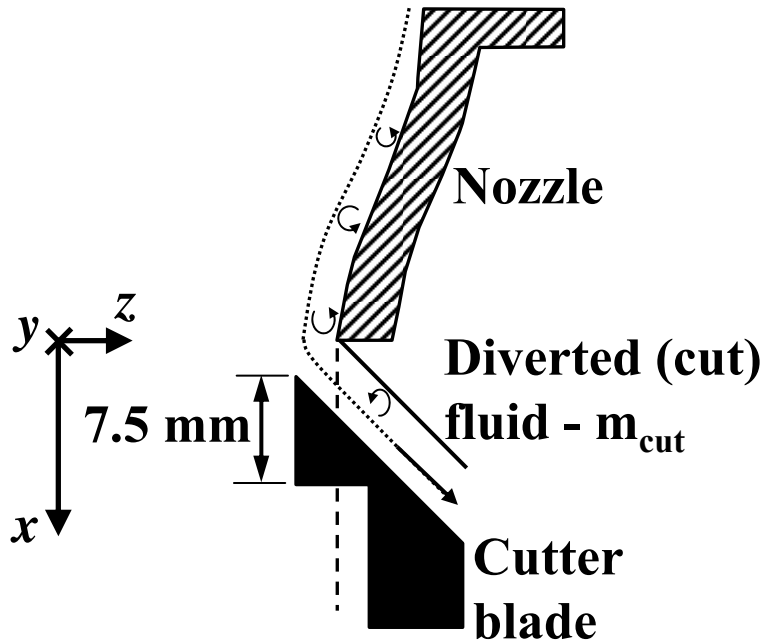
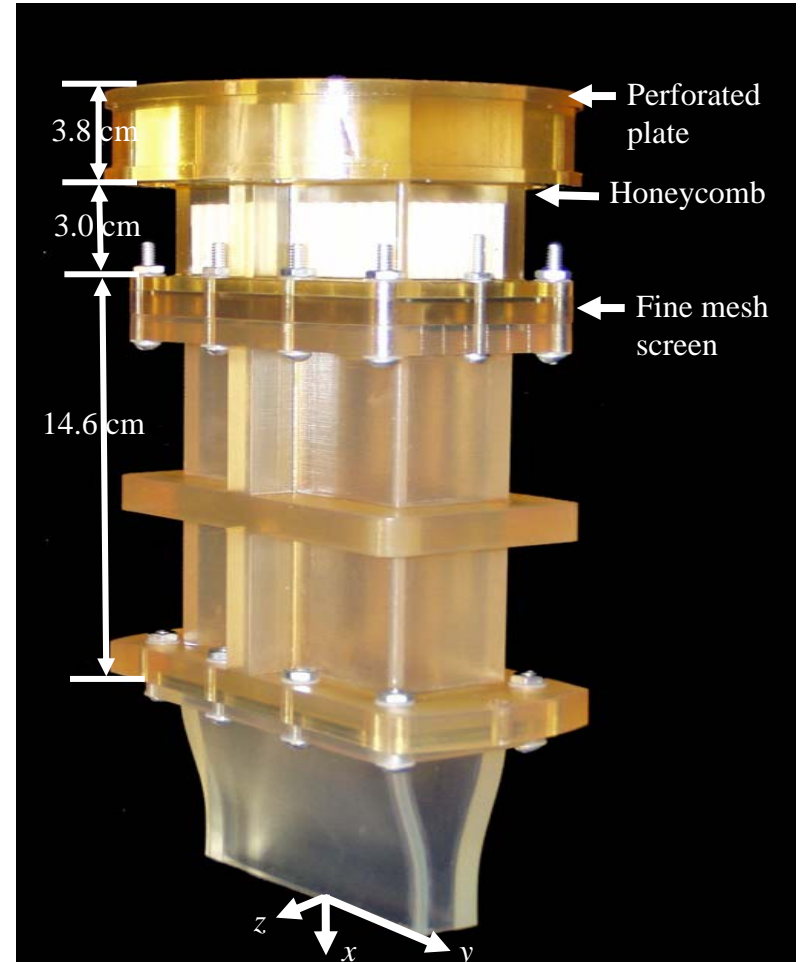
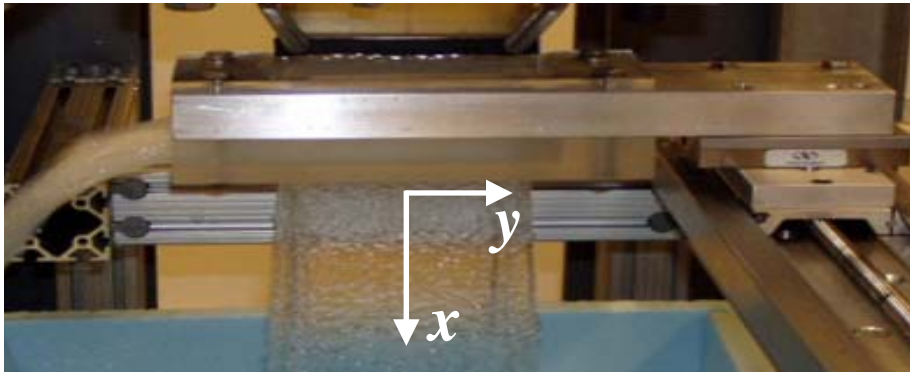
Surface Smoothness



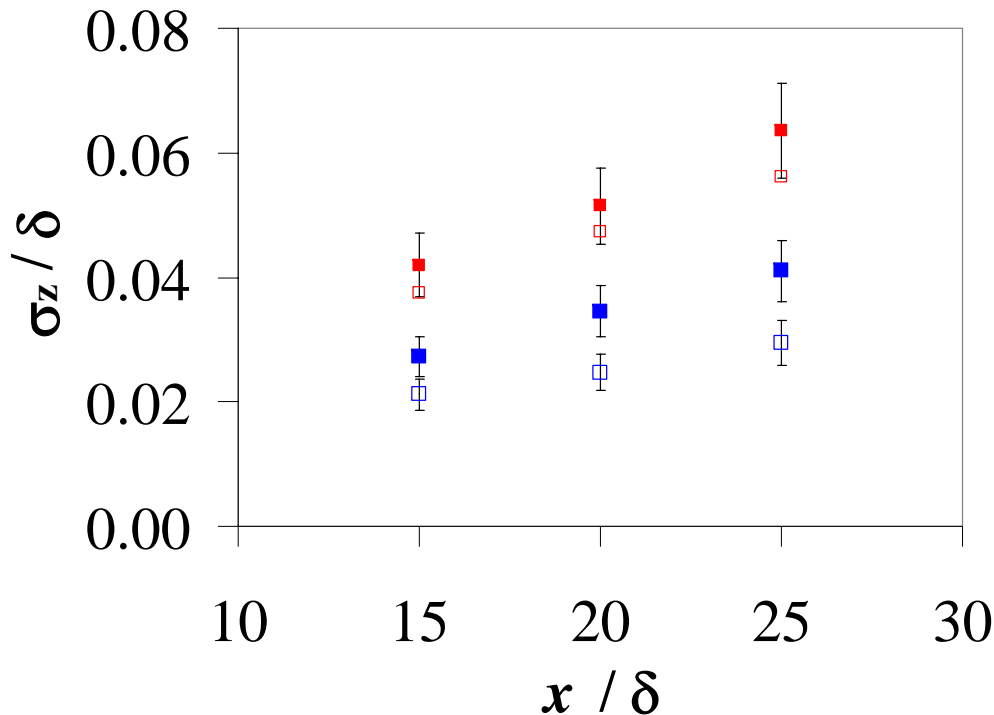
- Used Planar Laser Induced Fluorescence (PLIF) to characterize the jet free surface at near prototypical conditions
- Examine effects of nozzle design, flow conditioning, and boundary layer cutting on surface ripple
- Measure standard deviation of free surface z -location (σ_z)
 - Characteristic length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



Flow Conditioning and Boundary Layer Cutting



Surface Smoothness (PLIF Results)

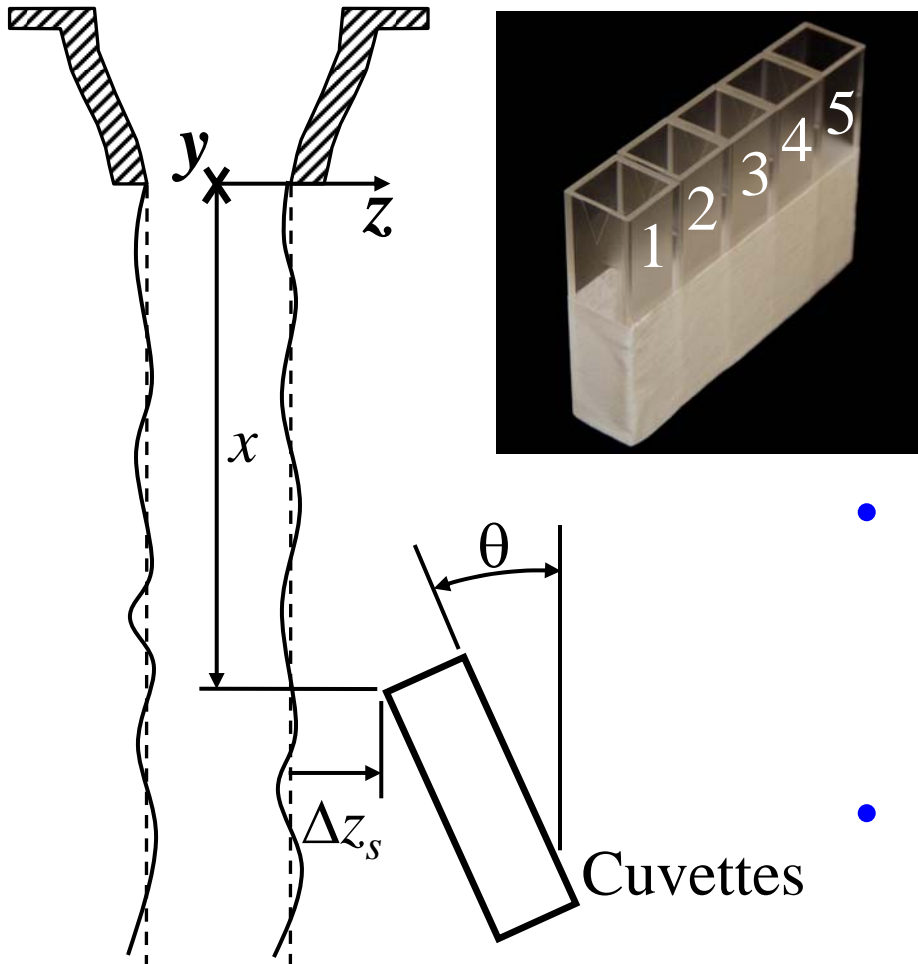


Standard Design ■ - No cutting
No Fine Screen □ - 1.9% cut

- Surface ripple increases by $\sim 50\%$ when fine screen removed
- BL cutting reduces σ_z by $\sim 33\%$ 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)**



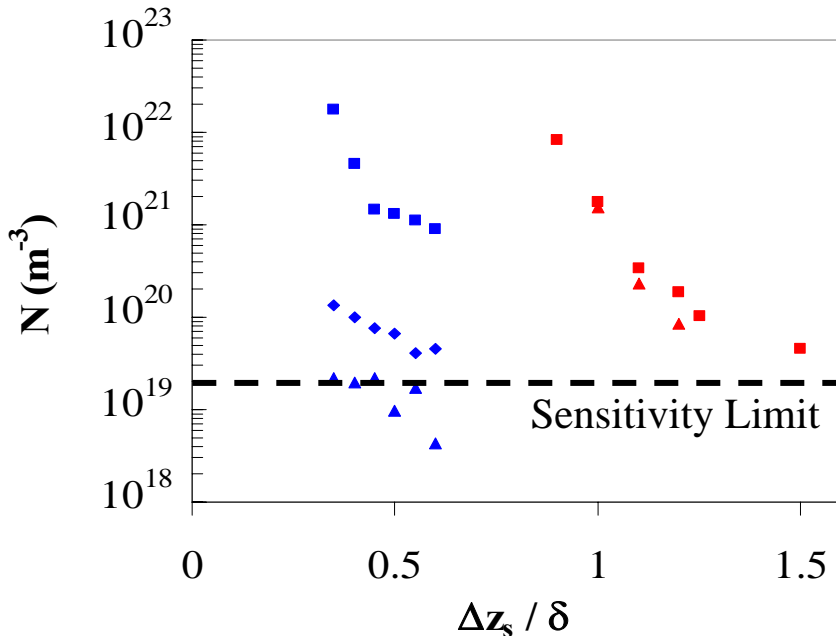
The “Hydrodynamic Source Term”



- 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 ($x / \delta = 25$)



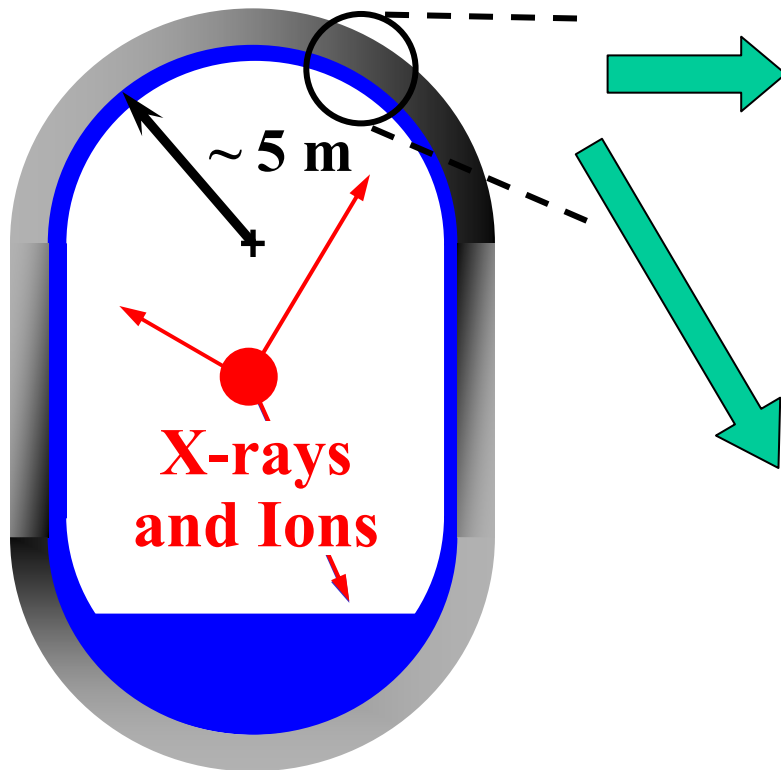
- Droplet mass flux values for jets produced by nozzles with optimized flow conditioners is $\sim 3-4$ orders of magnitude lower than predictions of empirical correlation
 - Droplets ejected form sparse aerosol around jet
- Removing fine screen increases range and number density of droplets
- **Boundary 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%

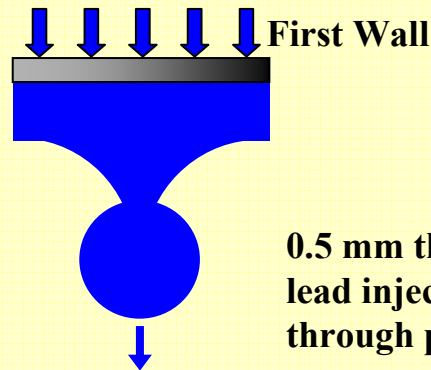


Thin Liquid Protection



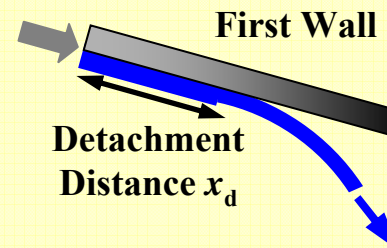
Wetted Wall

Liquid Injection



Forced Film

Injection Point



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

Forced Film



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

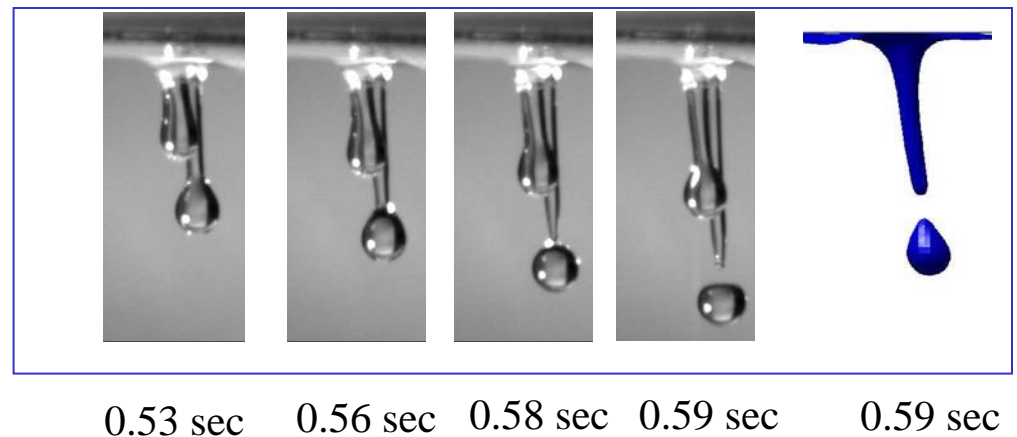
Quantify effects of

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

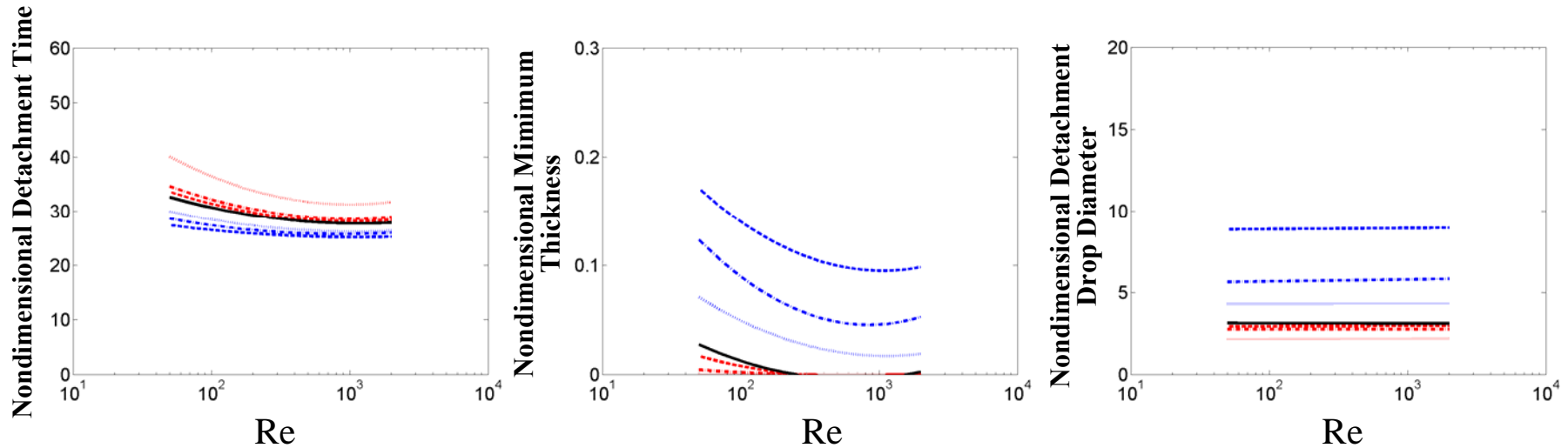
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- Droplet detachment time, Droplet size, and minimum film thickness prior to detachment

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



Typical Non-Dimensional Charts – Porous Wetted Walls



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

Nondimensional mass flux

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

.....	$\dot{m}_f^* = -0.005$	$\dot{m}_f^* = 0.005$
- . - .	$= -0.002$	- . - .	$= 0.01$
- - - -	$= -0.001$	- - - -	$= 0.02$
————	$= 0$		



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



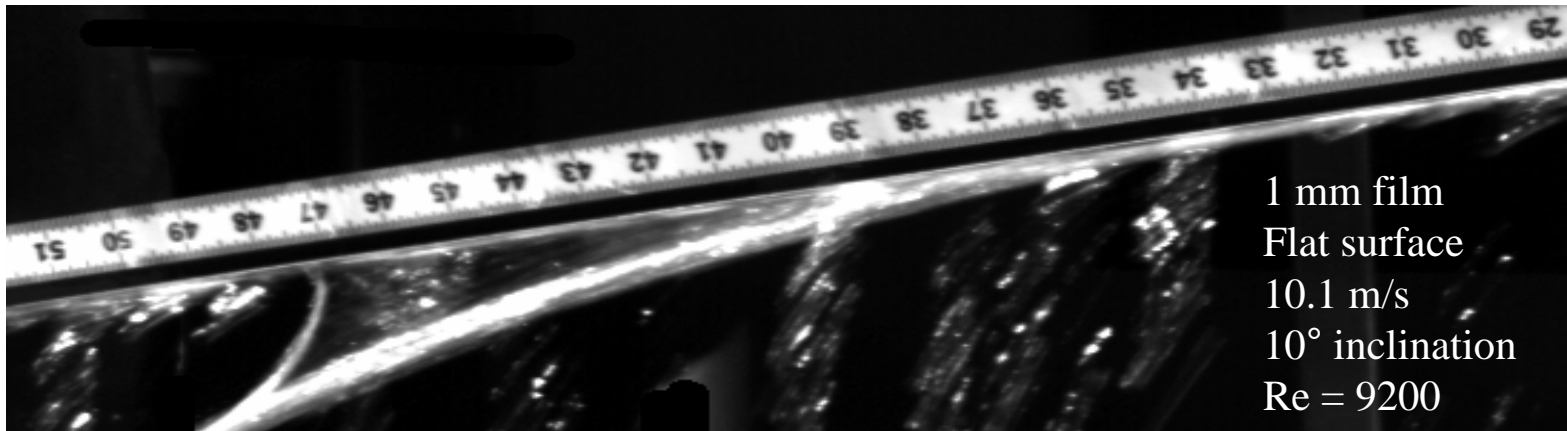
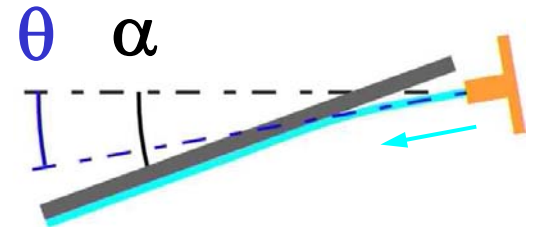
Experimental Study of Forced Liquid Films

Quantify Effects of

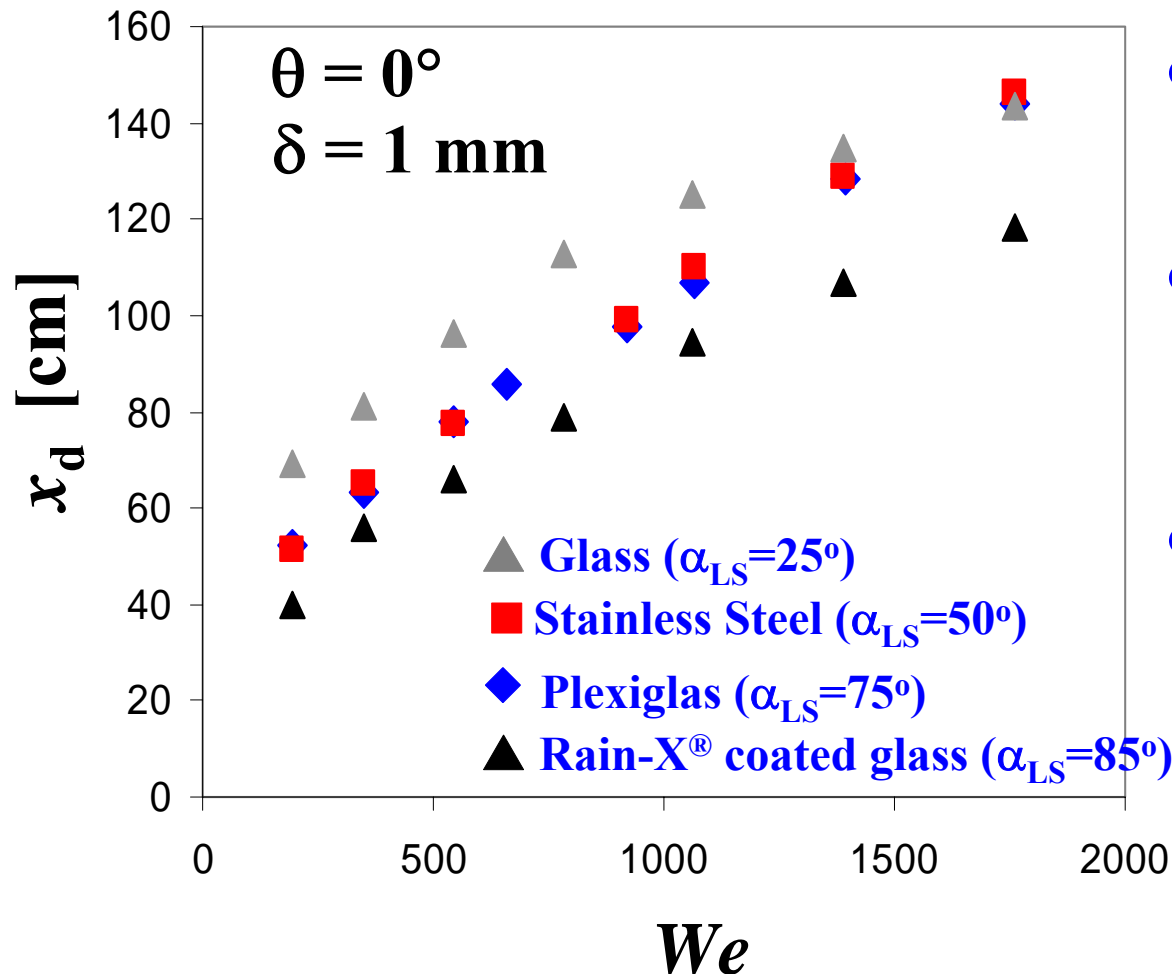
- Film thickness, injection velocity, surface inclination, surface curvature, injection angle, and surface material wettability

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



Detachment Distance Vs. Weber Number

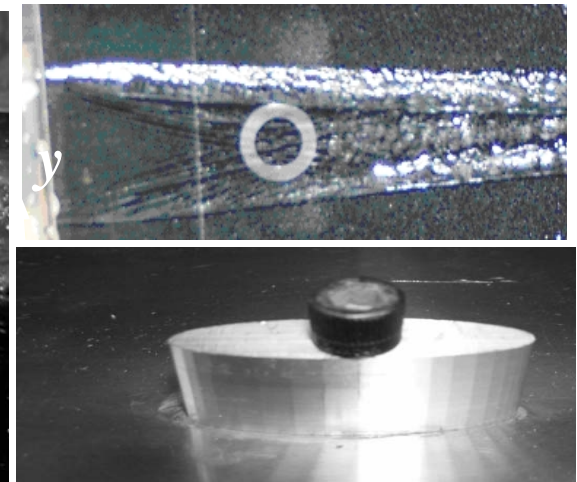
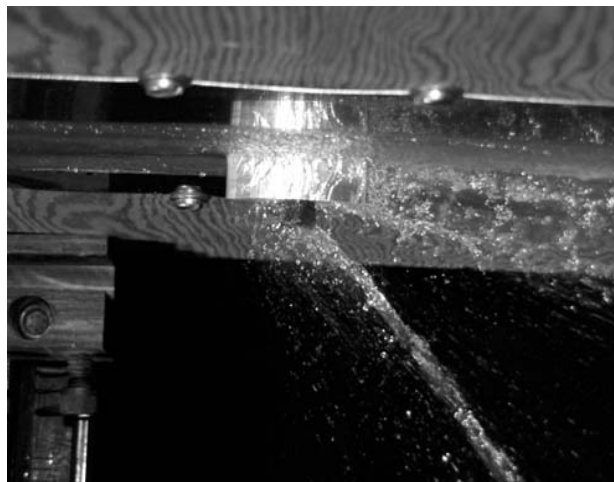
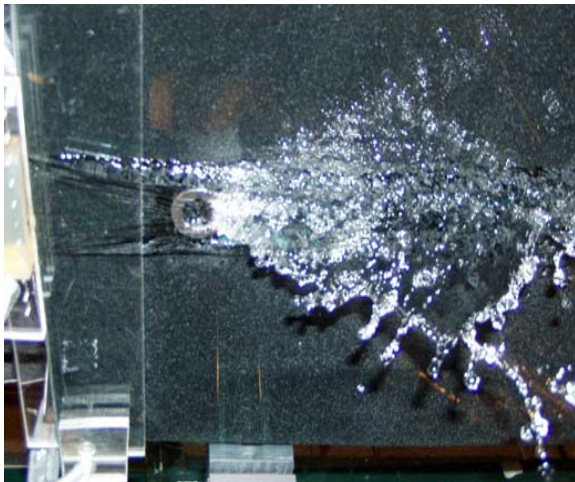


- Similar data for other angles, film thickness, and surface curvature
- Design Windows for stream-wise spacing of injection/removal slots to maintain attached film
- Wetting wall surface requires fewer injection slots (more desirable)



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.



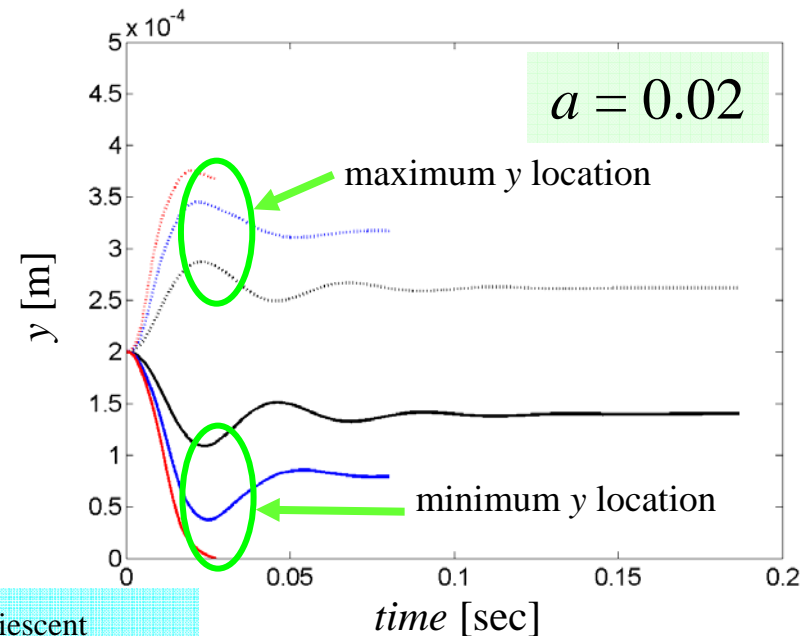
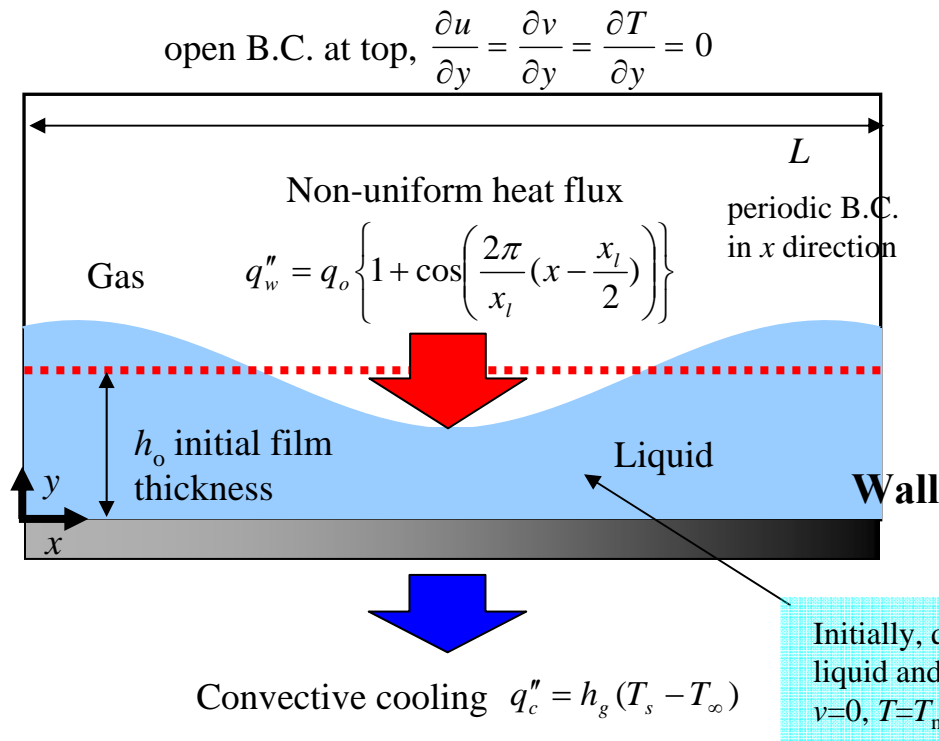
Liquid-Film-Protected Divertors

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



- 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

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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*

