Experimental Results for Thin and Thick Liquid Walls

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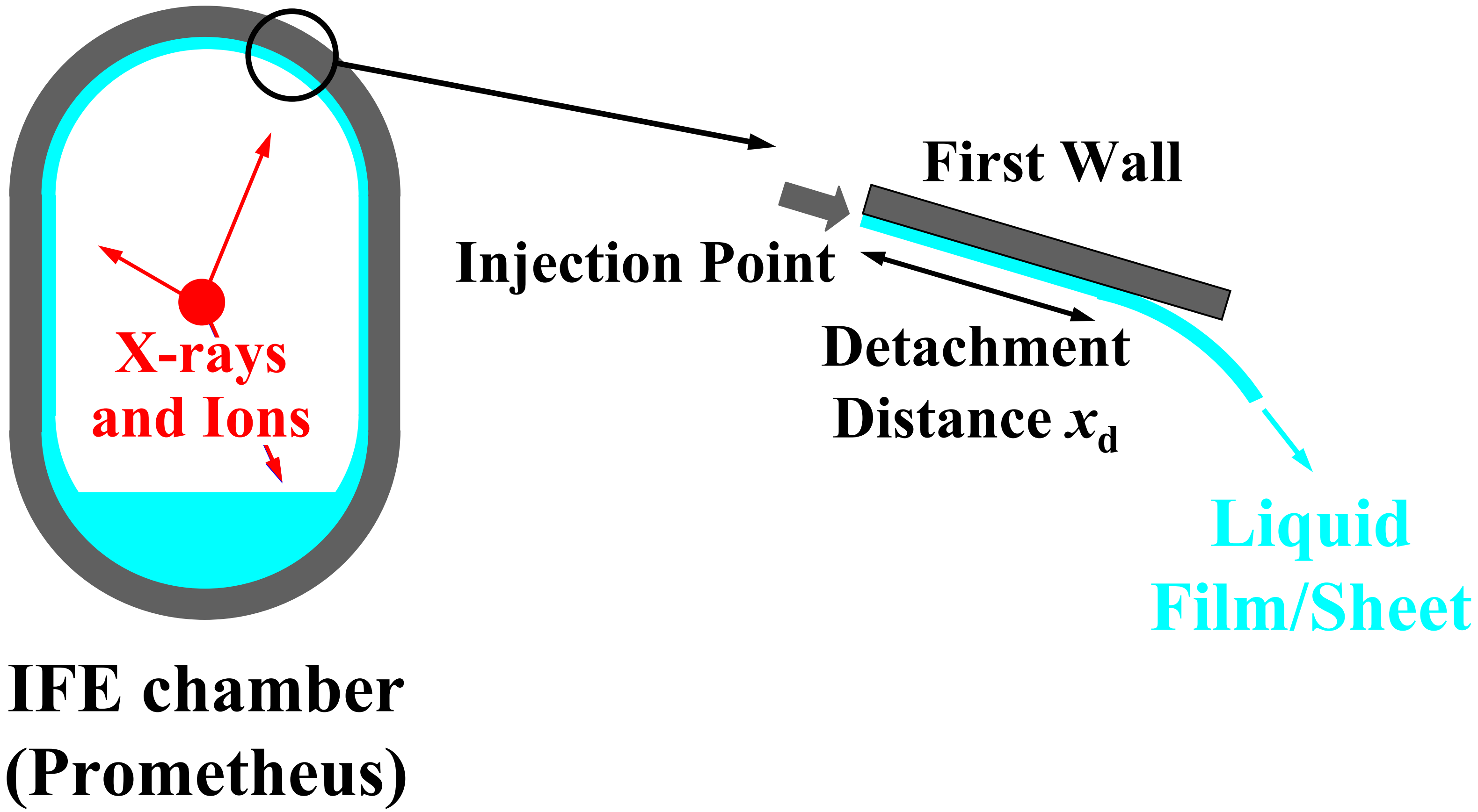
Overview

- Thin liquid protection: Experimental study of high-speed thin liquid films on downward-facing surfaces around cylindrical dams [*J. Anderson, D. Sadowski*]
  - Ports for beam entry and target injection
  - Effect of surface wettability
- Thick liquid protection: Experimental studies of turbulent liquid sheets [*S. Durbin, J. Reperant, D. Sadowski*]
  - Quantify surface smoothness of stationary liquid sheets using planar laser-induced fluorescence (PLIF) technique
  - Impact of initial conditions: nozzle geometry, flow straightener design, flow straightener blockage

Thin Liquid Protection

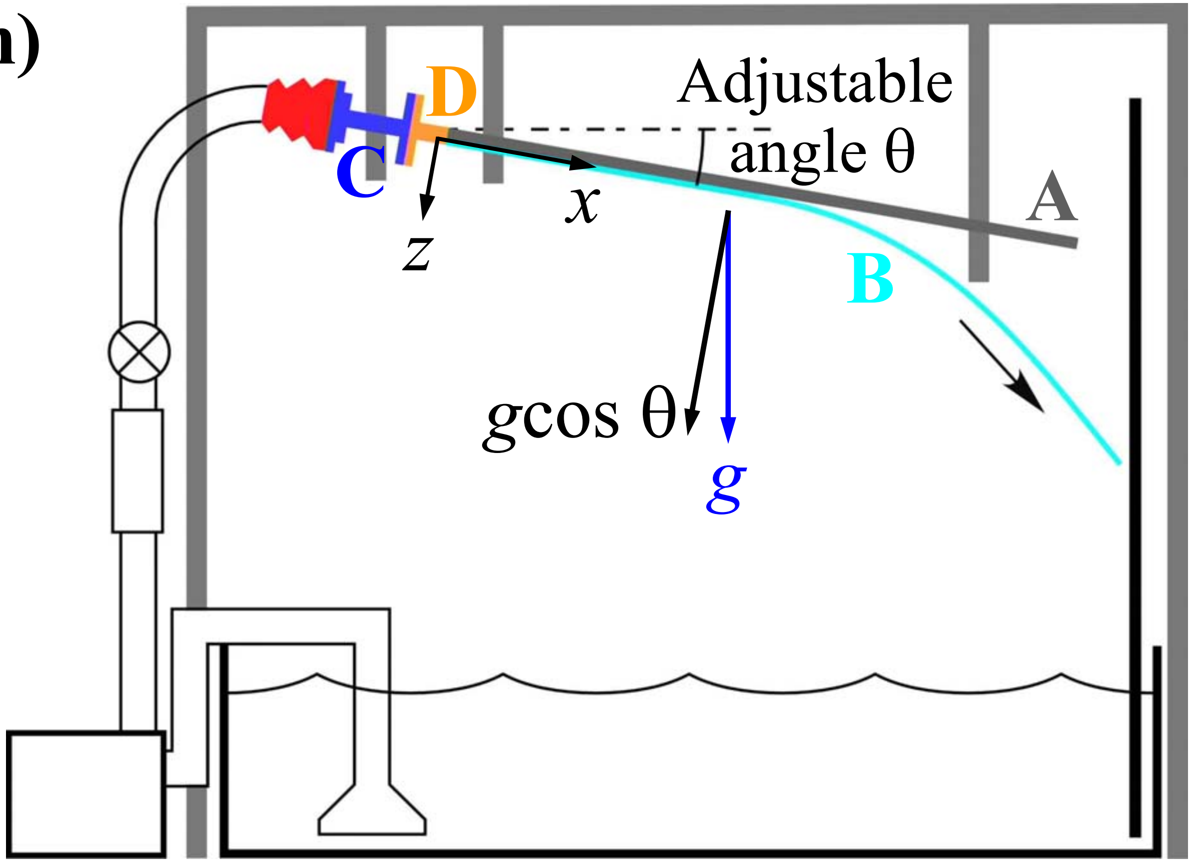


Objectives

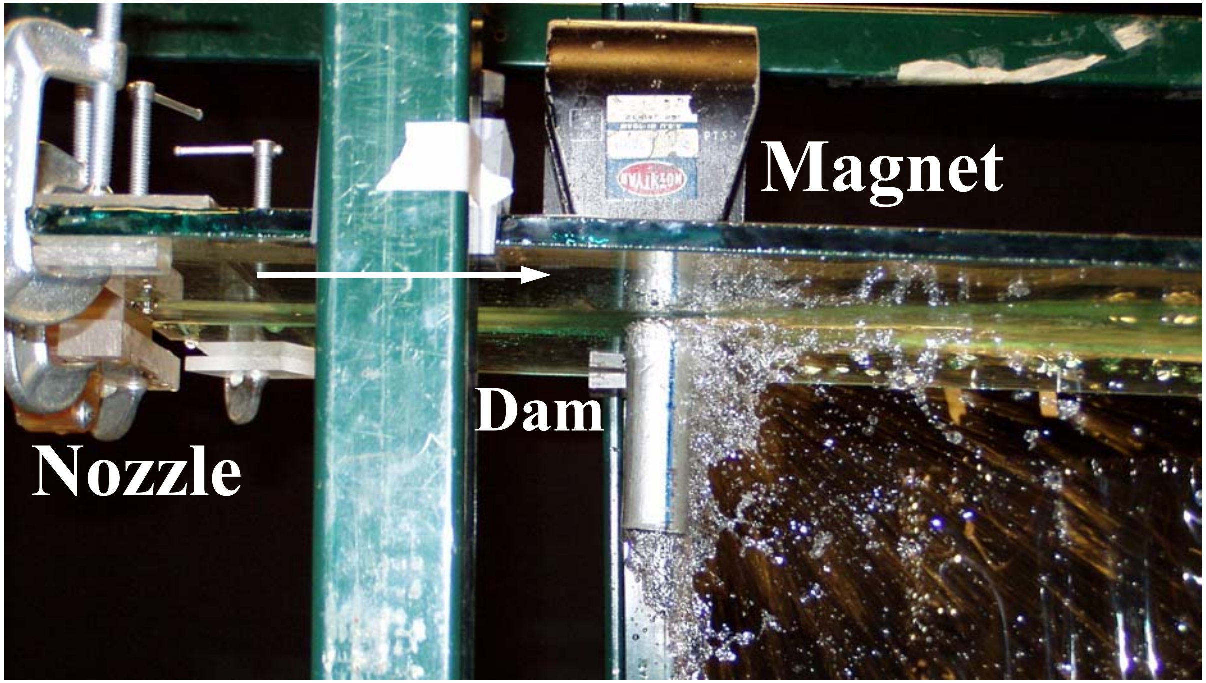
- Determine “design windows” for high-speed liquid films proposed for thin liquid protection of IFE reactor chamber first wall
- In the absence of film dryout, films most likely to detach on downward-facing surfaces on top endcap
  - Chamber curvature probably negligible: chamber radius ~6.5 m, *vs.* film radius of curvature at detachment point *O*(1 cm)
- How does film flow around cylindrical obstructions, or dams (*e.g.* beam ports)?

Experimental Apparatus

- **A Glass plate (1.52 × 0.40 m)**
- **B Liquid film**
- **C Flow straightener**
- **D Film nozzle**



Cylindrical Obstructions



How does high-speed film flow around obstructions (*e.g.* beam ports)?

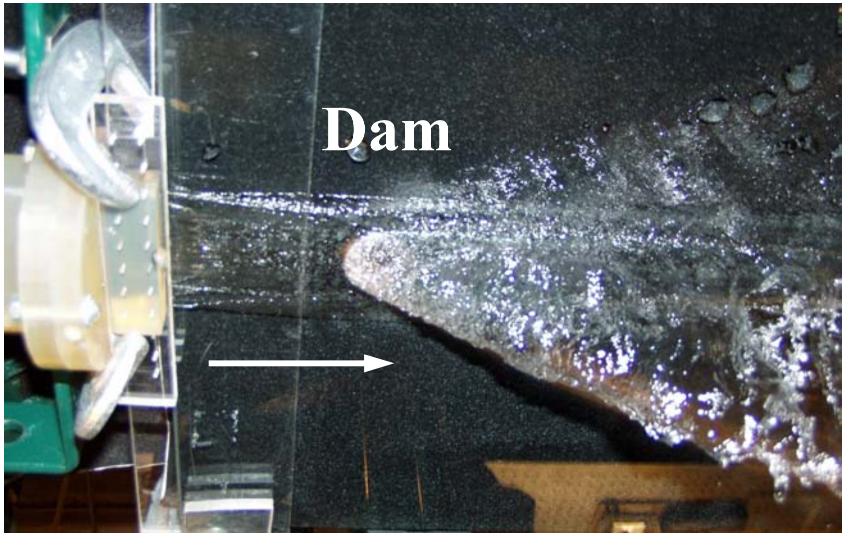
- Cylindrical dam/obstruction at x = 7.6–9 cm from nozzle exit
  - Held in place by permanent rare-earth magnet above glass plate
- Vary cylindrical dam height H and diameter D
  - Height (axial dimension) $H \sim \delta$

Experimental Parameters

- Nozzle exit thickness (*z*-dimension) δ = 0.1, 0.15, 0.2 cm
- Average speed at nozzle exit U_0 = 1.9–5.1 m/s
- Jet injection angle θ = 0°, 30°
- Cylindrical dam outer diameter D = 1.58, 2.54 cm
- Cylindrical dam height H = 0.051, 0.12, 0.24 cm

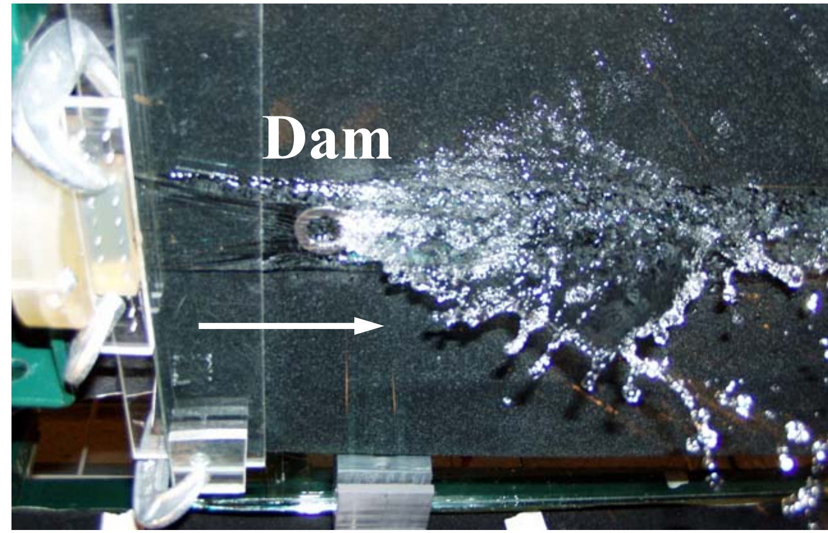
– Reynolds number $Re = U_0\,\delta/\nu$ = 3800–9800
– Froude number $Fr = U_0 / [(g \cos\theta)\,\delta]^{1/2}$ = 15–55
– Weber number $We = \rho U_0^2\,\delta/\sigma$ = 100–700
– Cylindrical dam aspect ratio $AR = H/D$ = 0.02–0.093
– Film nozzle aspect ratio AR_f = (5 cm)/δ = 25–50

Results



Detachment Type I

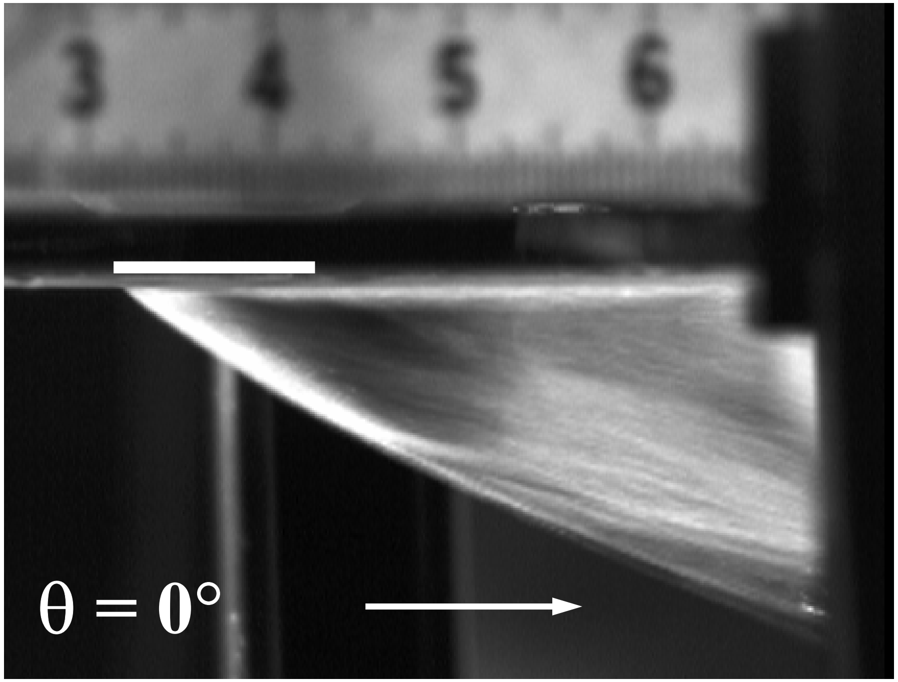
- $\delta = 0.15$ cm
- $Re = 7600$
- $H = 0.24$ cm
- $D = 2.54$ cm
- $AR = 0.093$

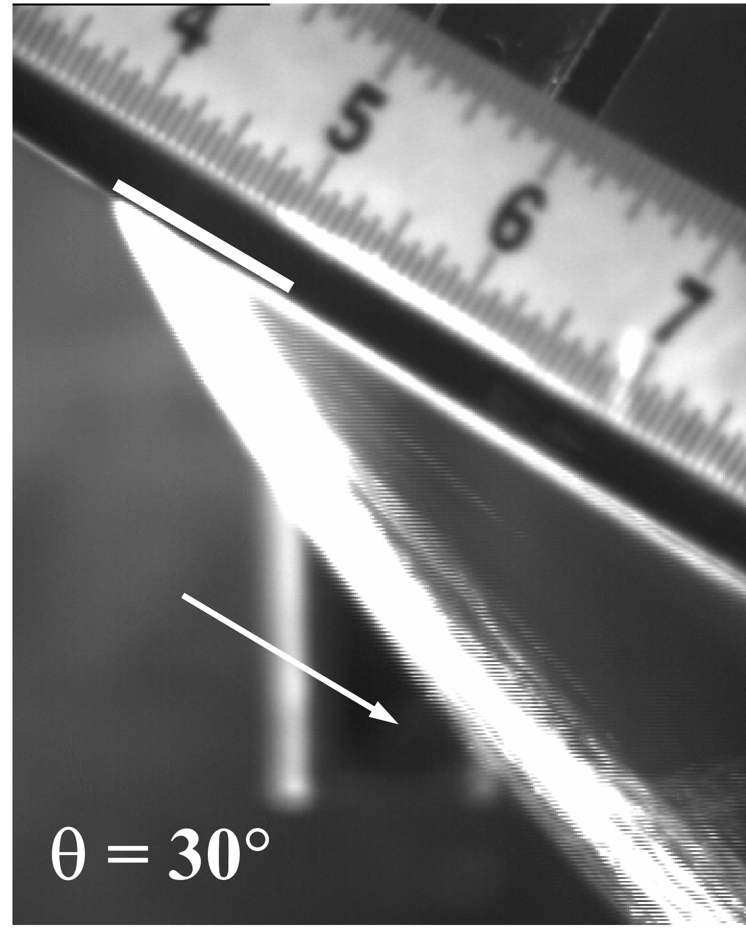


Detachment Type II

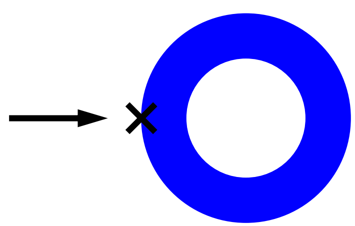
- $\delta = 0.15$ cm
- $Re = 3800$
- $H = 0.24$ cm
- $D = 2.54$ cm
- $AR = 0.093$

Detachment Type I: $H > \delta$

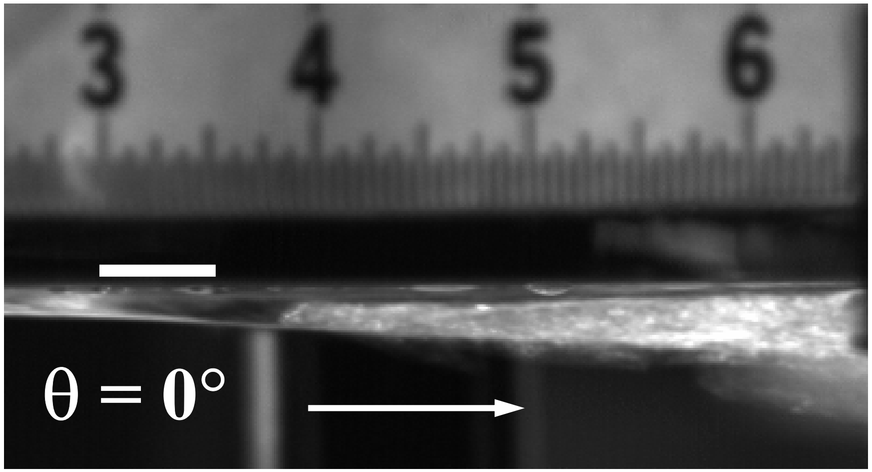


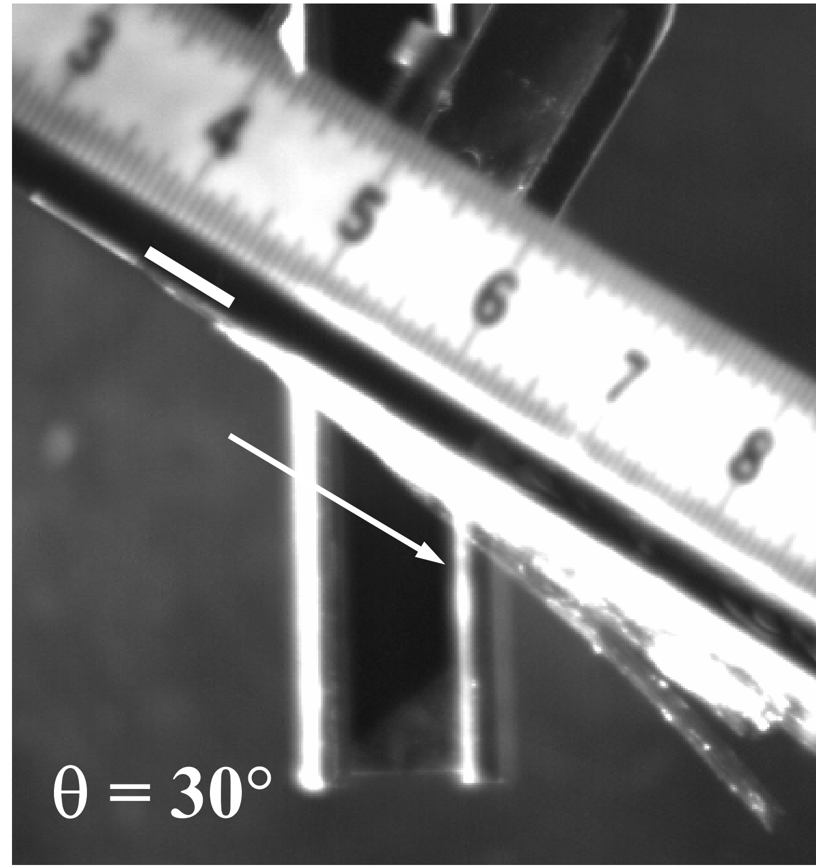


- $\delta = 0.1$ cm
- $Re = 3800$
- $H = 0.12$ cm
- $D = 2.54$ cm
- $AR = 0.047$

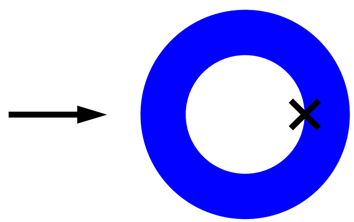


Detachment Type II: $H > \delta$

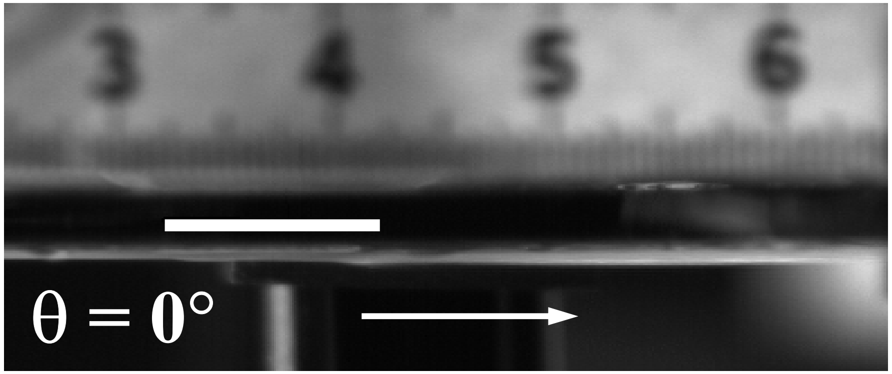


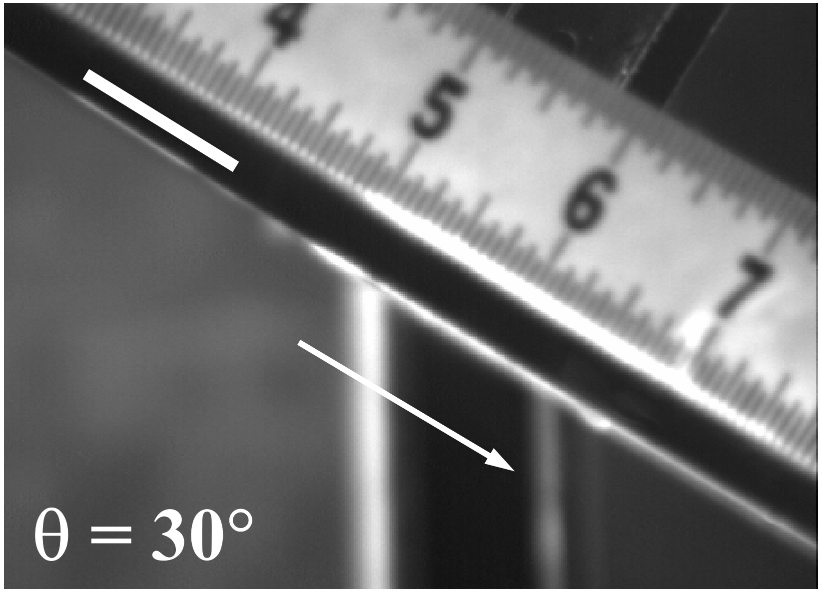


- $\delta = 0.2$ cm
- $Re = 3800$
- $H = 0.24$ cm
- $D = 1.59$ cm
- $AR = 0.15$



Flow Over Dam: $H < \delta$



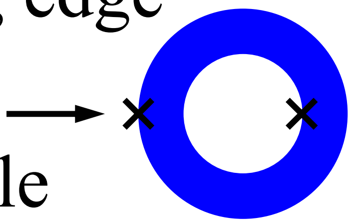


- $\delta = 0.1$ cm
- $Re = 3800$
- $H = 0.051$ cm $< \delta$
- $D = 2.54$ cm
- $AR = 0.02$

Summary: Obstructions

For all cases studied, film flow on downward-facing surfaces either:

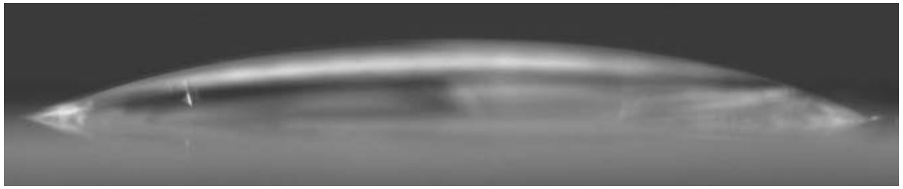
- ***H*** $> \delta$: Detaches around cylindrical obstructions at outer leading edge (Type I) or inner trailing edge (Type II)



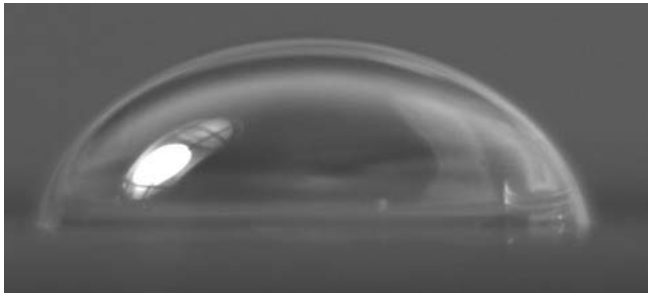
- ***H*** $< \delta$: Flows over obstruction, blocking hole
- Occurs at lowest speeds (and *Re*)
- Cylindrical beam ports incompatible with wet wall concept
  – “Streamlined” fairings?
  – No beam ports on upper endcap ⇒ fewer beams?

Surface Wettability

- Compare film average detachment length x_d, lateral spread W for water on two surfaces with very different contact angles/wettability
  - Water on glass: contact angle ≈ 30°
  - Water on glass coated with Rain-X®: contact angle ≈ 85°



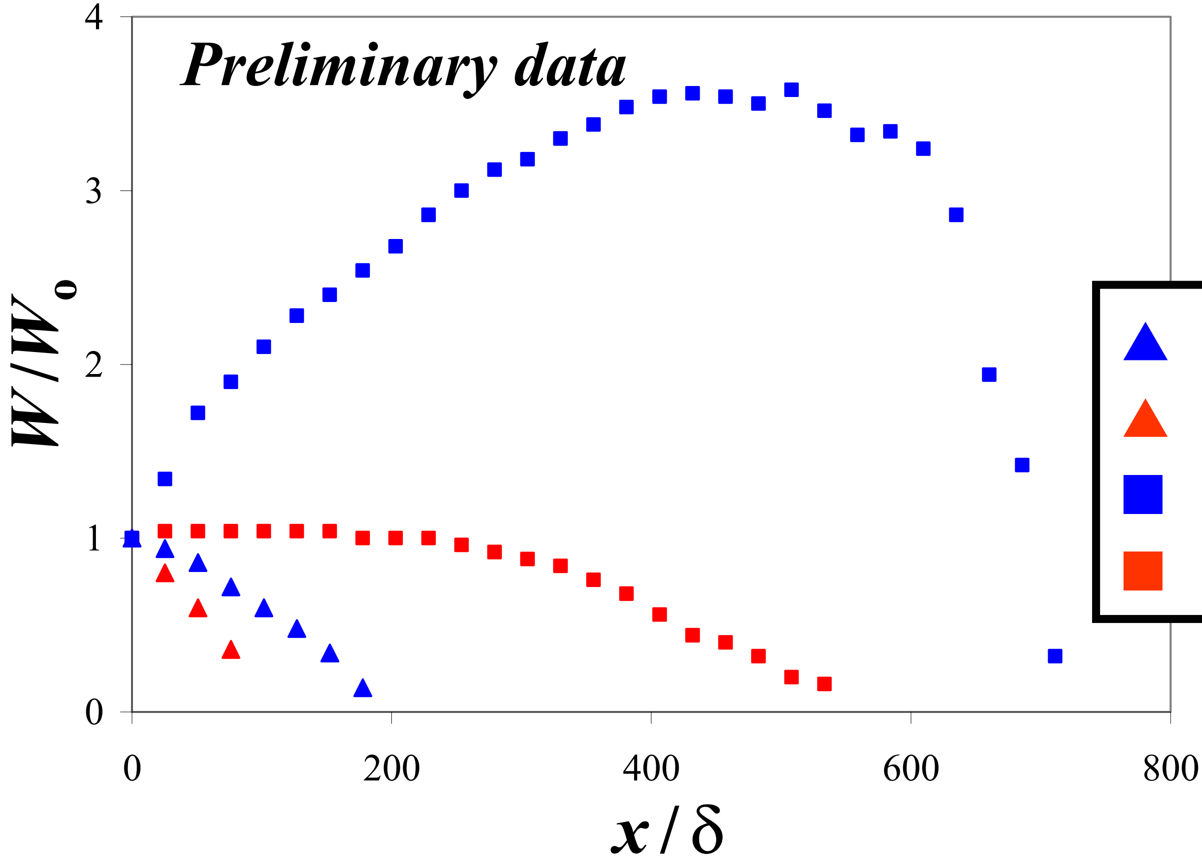
Water on glass (drop diameter ~5 mm; volume 0.4 mL)



Water on glass w/Rain-X (drop dia. ~4 mm; vol. 0.4 mL)

Wettability Effects

- At *Re* = 3800, $x_d / \delta \approx$ **100** for Rain-X surface; **180** for glass
- At *Re* = 14700, $x_d / \delta \approx$ **550** for Rain-X surface; **700** for glass

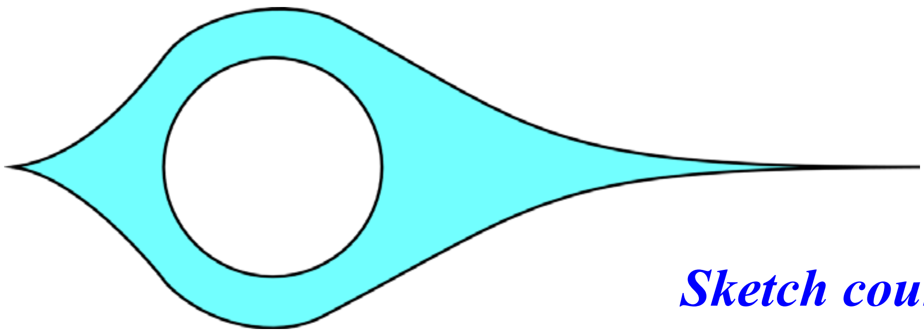


Non-wetting surface ⇒ Earlier detachment

- $\delta = 0.2$ cm
- $\theta = 0°$

Future Work

- Streamlined beam ports

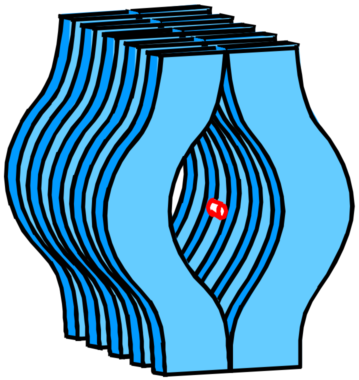


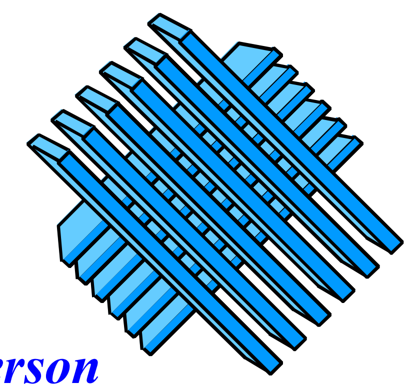
Sketch courtesy L. Waganer

- Examine effect of surface wettability/contact angle
  - Non-wetting surfaces (a la Prometheus) **worse**: earlier detachment, smaller lateral spread
- Measure film thickness with ultrasonic probes
- Measure lateral (*y*) velocity profile across film using laser-Doppler velocimetry (LDV)

Thick Liquid Protection

- Protect IFE reactor chamber first walls by using molten salt or liquid metal "curtain" to absorb neutrons, X-rays, ions and target debris from fusion events
- HYLIFE-II conceptual design based on turbulent liquid sheets as "building block"
  - Oscillating slab jets, or liquid sheets, create protective pocket to shield chamber sides
  - Lattice of stationary liquid sheets shield front and back of chamber while allowing beam propagation, target injection





Sketches courtesy P.F. Peterson

Design Issues

- ***Effective* protection** ⇒ minimize clearance between liquid sheet free surface and driver beams, or minimize surface ripple
  - Irradiation of final focus magnets
  - Interferes with target injection, beam propagation
  - How do various jet (nozzle, flow straightener) designs impact the free-surface geometry and its fluctuations?
- ***Robust* protection** ⇒ thick liquid protection system must withstand occasional disturbances
  - How does partial blockage of the flow straightener (due, for example, to debris) affect the free-surface geometry and hence surface ripple?

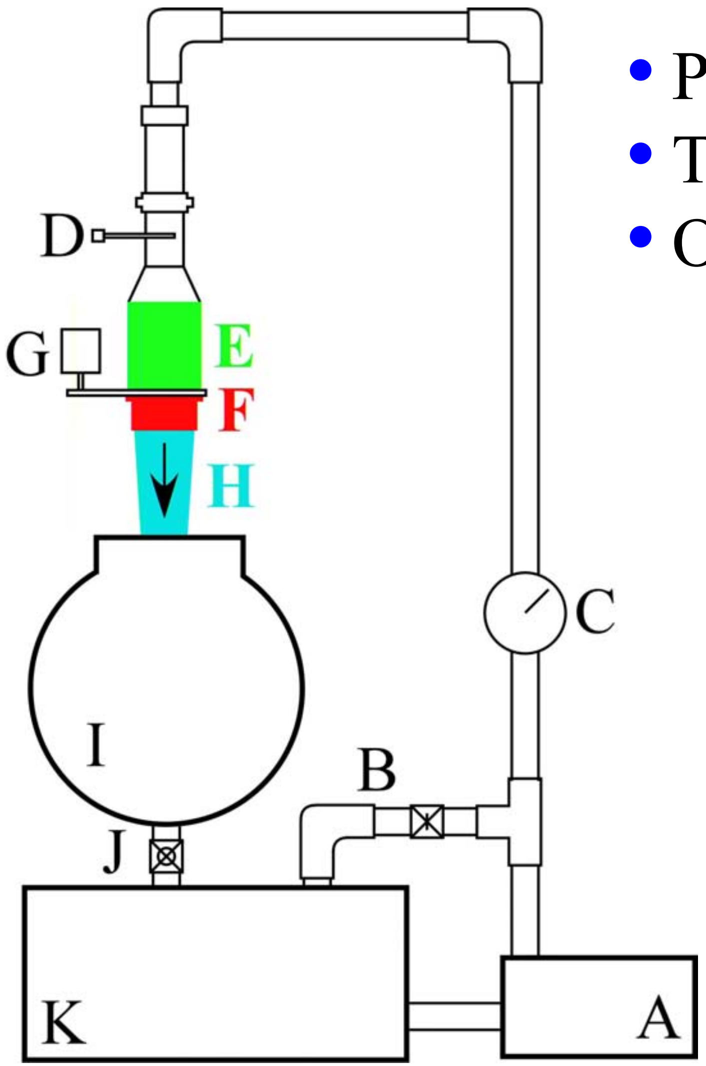
Objectives

Quantify impact of nozzle designs and blockage on surface ripple in liquid sheets typical of HYLIFE-II

- Liquid probability distribution (LPD): probability of finding liquid at any given spatial location
- Mean surface ripple σ_z: Average standard deviation of the z-position of the free surface
- Study turbulent vertical sheets of water issuing downwards into atmospheric pressure air at Reynolds numbers $Re = U_o\delta/\nu$ = 53,000–130,000 (prototypical Re = 200,000)

  U_o average speed at nozzle exit; δ nozzle thickness (short dimension); ν fluid kinematic viscosity

Experimental Apparatus

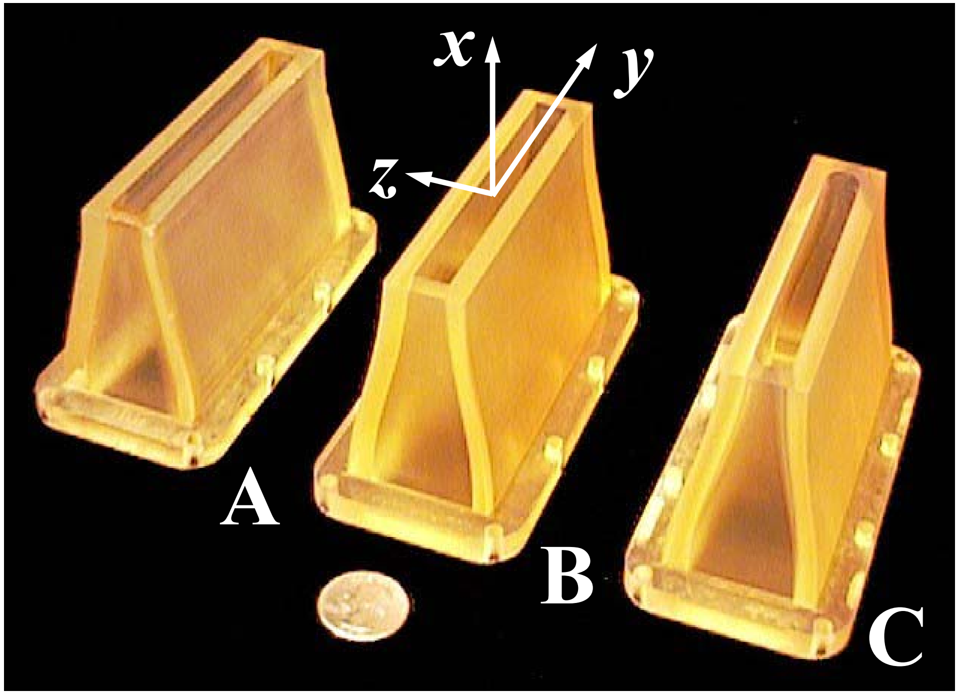


- Pump-driven recirculating flow loop
- Test section height ~1 m
- Overall height ~5.5 m

A Pump	B Bypass line
C Flow meter	D Pitot tube
E Flow straightener	
F Nozzle	G Oscillator
H Sheet	I 400 gal tank
J Butterfly valve	K 350 gal tank

Nozzle Geometries

- Fabricated with stereolithography rapid prototyping
- Nozzle exit dimensions 1 cm (δ) × 10 cm
- 2D contractions: nozzle *z*-dimension contracts from 3 cm to 1 cm at exit
- Three different nozzles
  - **A** Matched circular-arc contraction



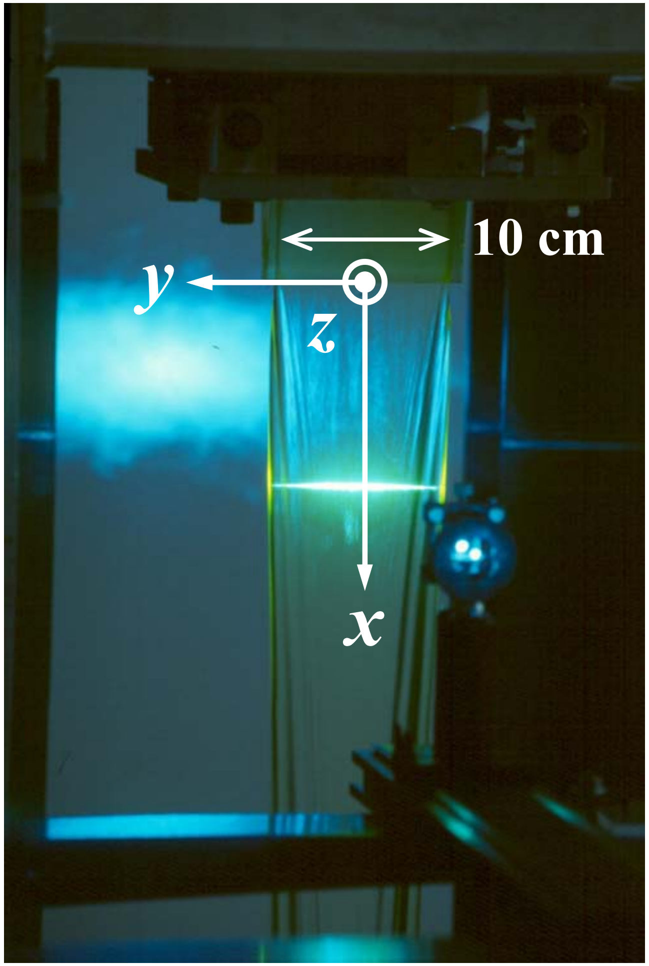
B 5th order polynomial contraction

C B with rounded corners

PLIF Technique

Visualize free surface as interface between fluorescing (white) water and (black) air

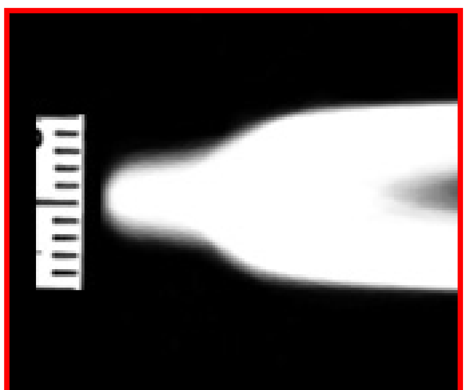
- Water dyed with fluorescein
- Jet illuminated by Ar^+ laser light sheet at 514 nm
- Free surface imaged obliquely from below by CCD camera
- 100 (1008 × 1008 pixel) consecutive images acquired at 30 Hz over 3.3 s for $x \leq 25$ cm
- Image exposure $5\tau = 4.3–11.2$ ms, where $\tau = \delta/U_o$



Liquid Prob. Distribution

- Threshold individual images
  - Grayscale > threshold ⇒ liquid; < threshold ⇒ air
- Average over 100 images ⇒ LPD; assemble composite LPD over half the flow by overlapping side, edge sections
- Probability of finding liquid inside 50% contour ≥ 50%
- Distance between contours measure of surface ripple

LPD (edge view)



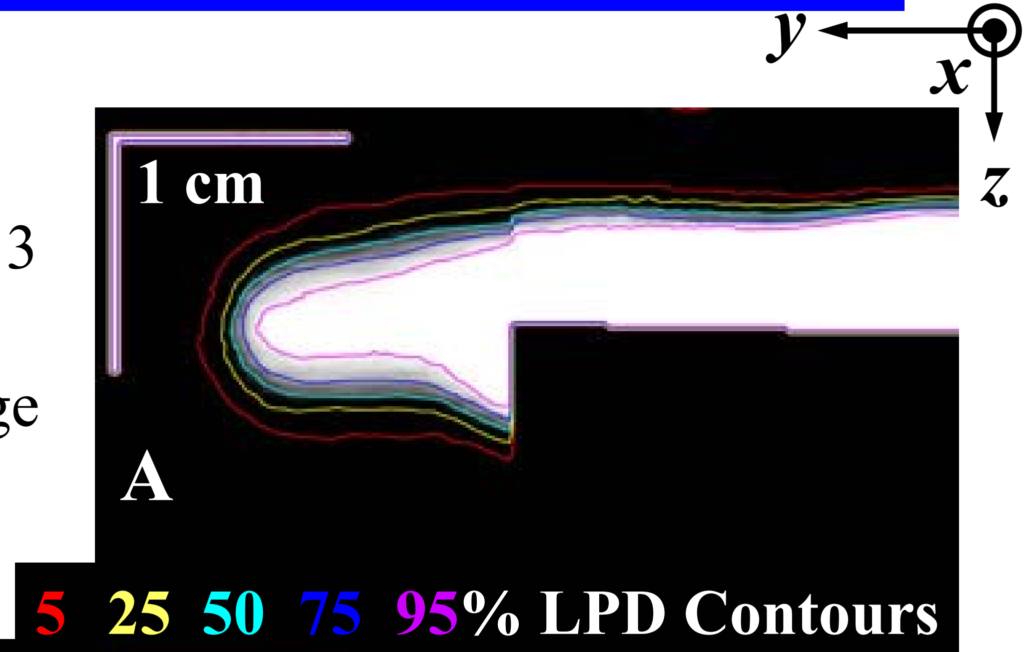
LPD (part of side view)

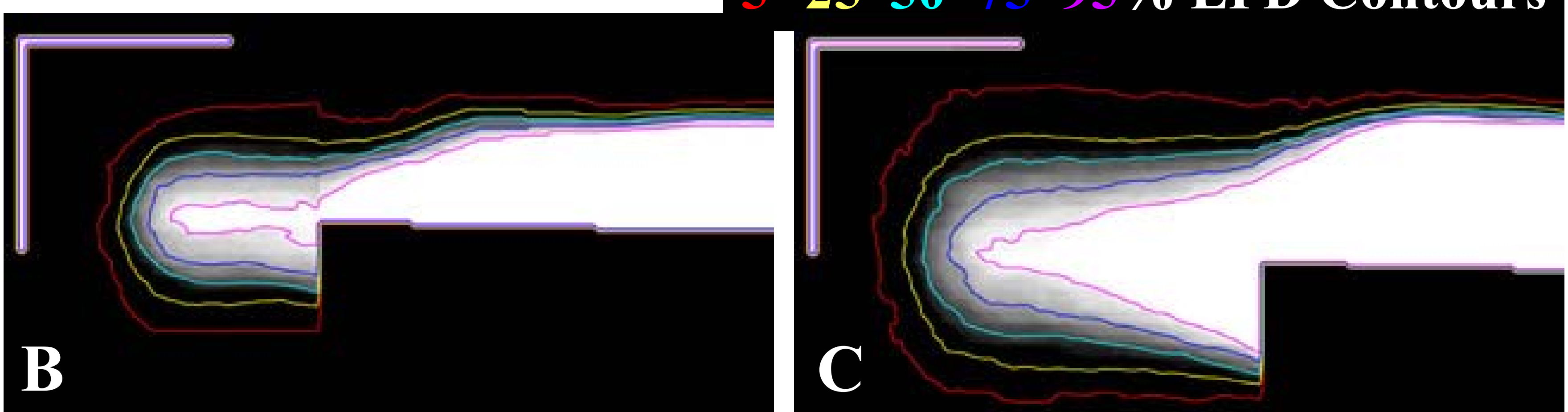
Nozzle Geometry Effects

LPDs for nozzles A, B, C:

Re = 130,000; *x* = 25 cm

- Surface ripple similar for all 3 nozzles
- Surface ripple greatest at edge
- C has largest surface ripple
- B "best" nozzle

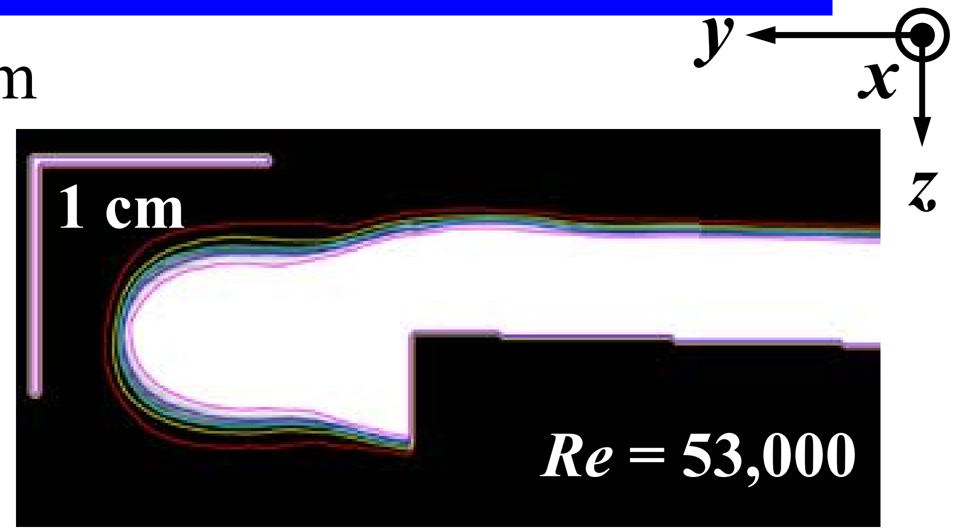


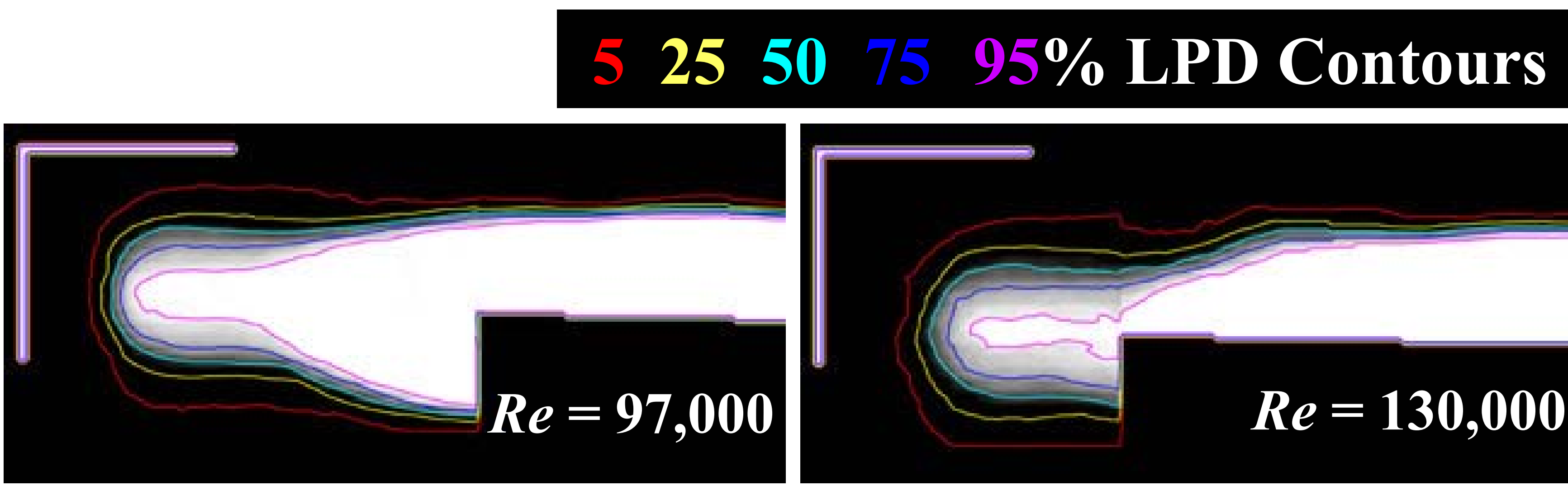


Reynolds Number Effects

LPDs for Nozzle B: $x = 25$ cm

- Side and edge fluctuations increase with *Re*



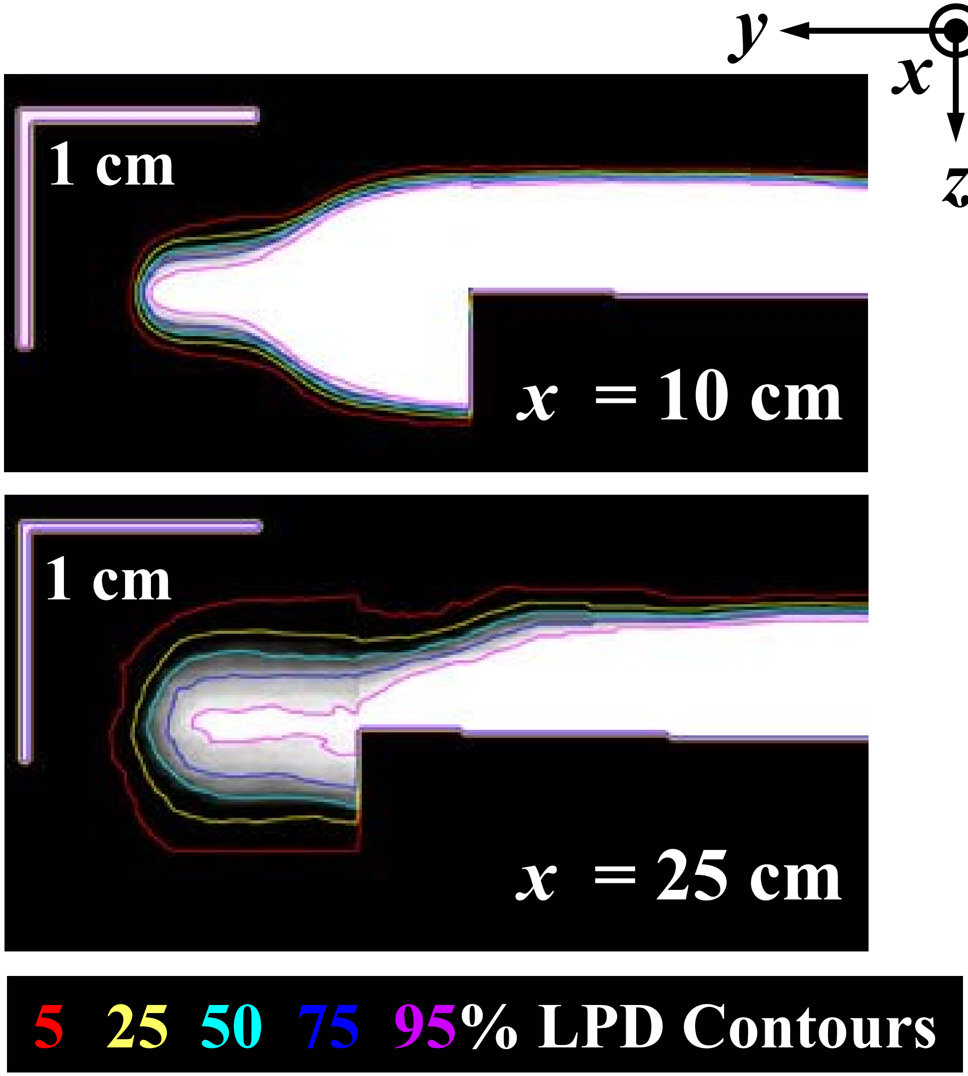


Mean Standard Deviation

LPDs for Nozzle B:
$Re = 130{,}000$

- Edge, side fluctuations increase with x
- $\sigma_z = 0.10$ mm at $x = 10$ cm from nozzle exit
- $\sigma_z = 0.19$ mm at $x = 25$ cm [scaled HYLIFE-II pocket: $x \leq 30$ cm]

*⇒ **Max. surface ripple for HYLIFE-II 1.4 mm***



Flow Straightener

Perforated Plate (PP)

- Open area ratio 50% with staggered 4.8 mm dia. holes

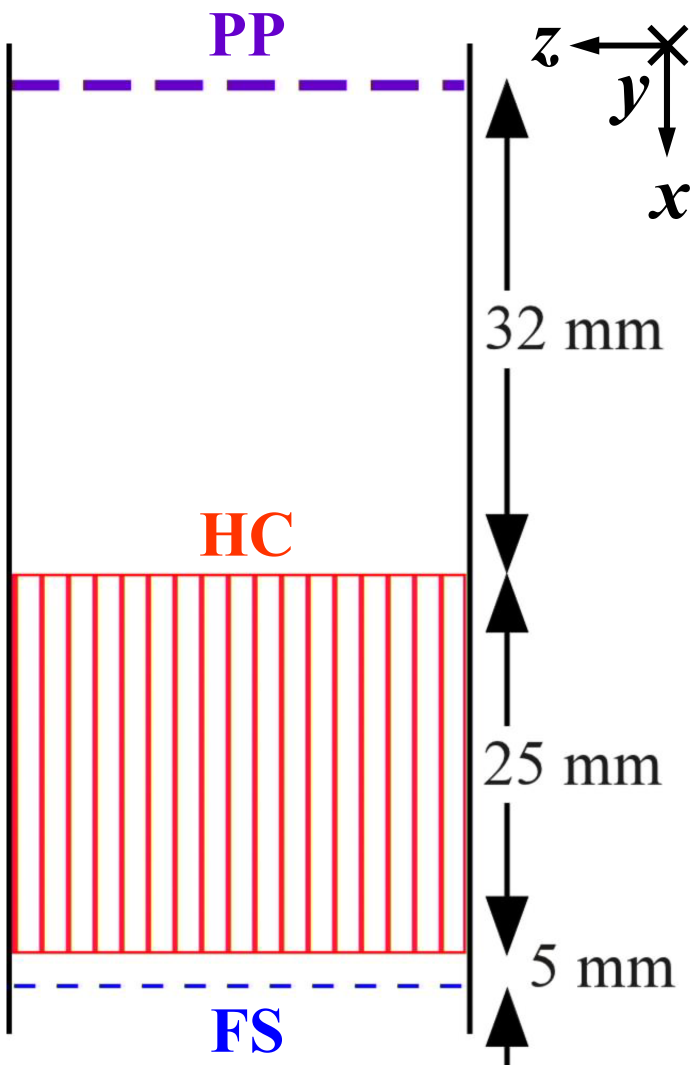
Honeycomb (HC)

- 3.2 mm dia. hexagonal cells

Fine Screen (FS)

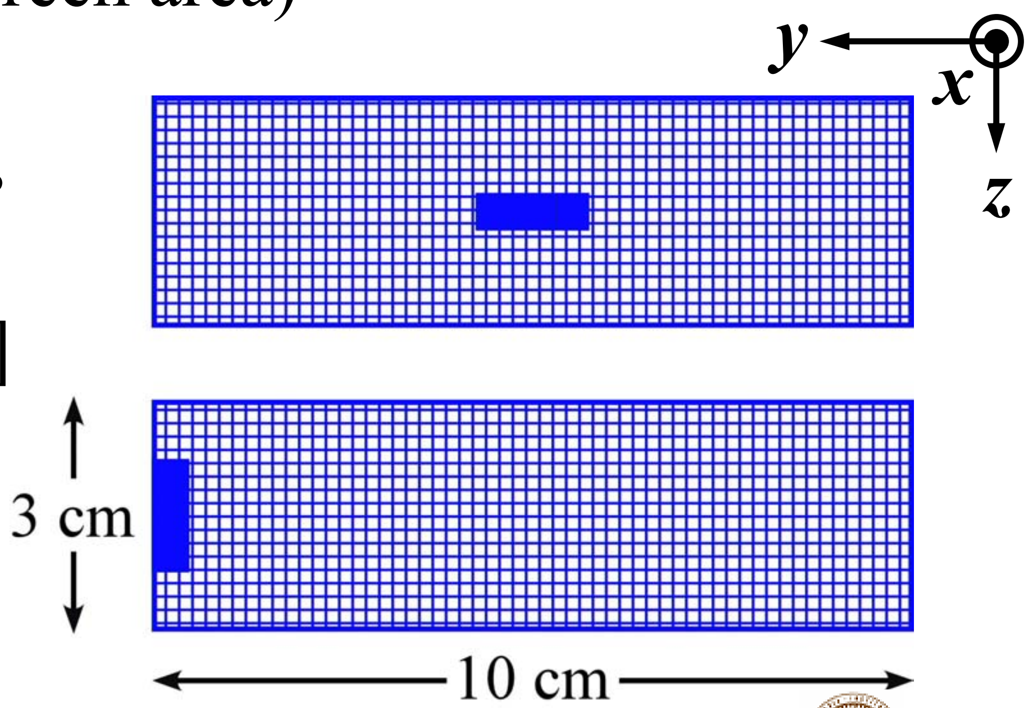
- Open area ratio 37.1%
- 0.33 mm dia. wires woven with open cell width of 0.51 mm
- 195 mm from FS to nozzle exit

All elements stainless steel



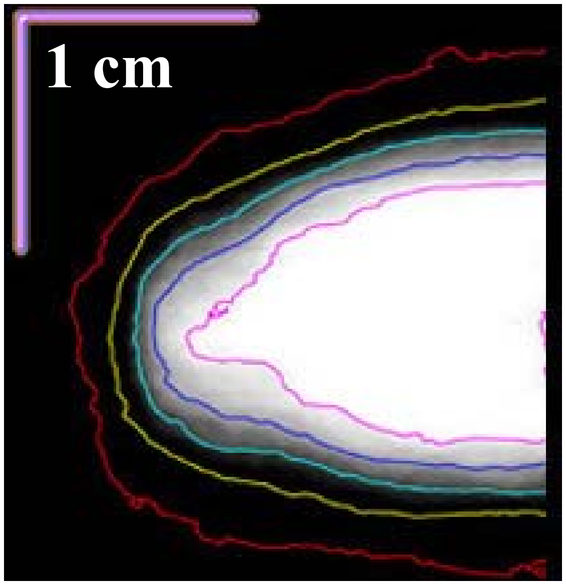
Flow Straightener Blockage

- Flow straightener blocked just upstream of fine mesh screen (element most likely to trap debris)
- "Blockage" = 1.5 cm × 0.5 cm rectangle (blockage area = 2.5% of total screen area)
- Studied blockage at two different locations
  - Centered along *y*, *z* ["center blockage"]
  - On right edge centered along *z* ["edge blockage"]



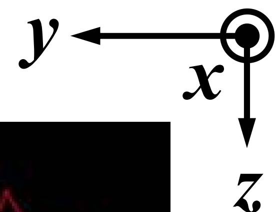
Blockage Effects

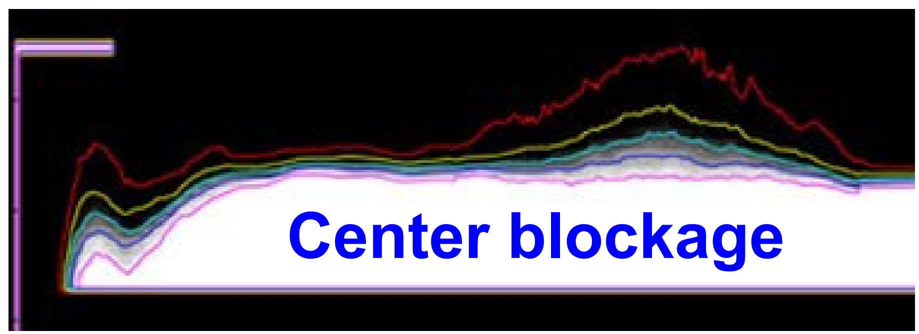
Edge Blockage

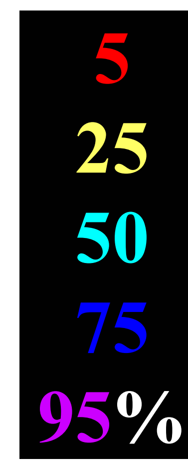


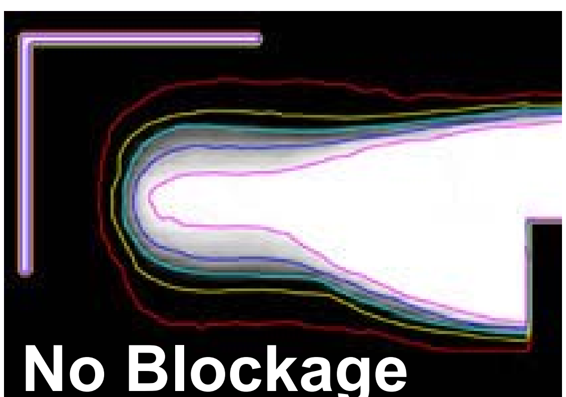
LPDs for Nozzle B: $Re = 97{,}000$; $x = 25$ cm

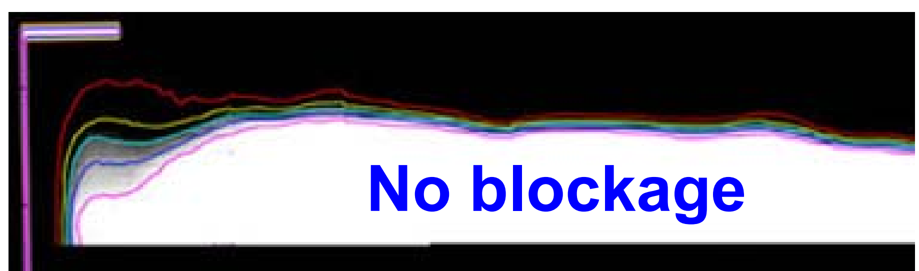
- 2.5% area blockage 19.5 cm upstream of nozzle











Summary: Thick Liq. Prot.

Results at 2/3 the prototypical *Re* imply:

- Standard deviation of side free-surface geometry ~1.4 mm at bottom of lattice typical of HYLIFE-II
- At higher *Re* and *x*, free surface ripple on sheet side AND edge can "clip" driver beams
- Surface ripple appears relatively insensitive to small changes in nozzle geometry (circular-arc, *vs.* 5th order polynomial, contraction)
- Rounding nozzle corners ($\rightarrow$ elliptical nozzle) does <u>not</u> reduce surface ripple
- Blockage of flow straightener (due to debris, for example) will drastically increase surface ripple $\Rightarrow$ filtration required

What remains to be done?

All concepts:

- ***Chamber clearing***
- ***Droplet formation/ejection***

High-speed film/Wet wall:

- ***Beam port designs compatible with film flow*** [GT]
- ***Surface wettability*** [GT]
- Surface curvature [GT]

Porous wall/Wetted wall:

- ***How does heat transfer affect film stability?***

Thick liquid protection:

- ***Vacuum effects (We) on sheet breakup***
- Oscillating sheets at high *Re*