An Overview of the Fluid Dynamics Aspects of Liquid Protection schemes for IFE Reactor Chambers

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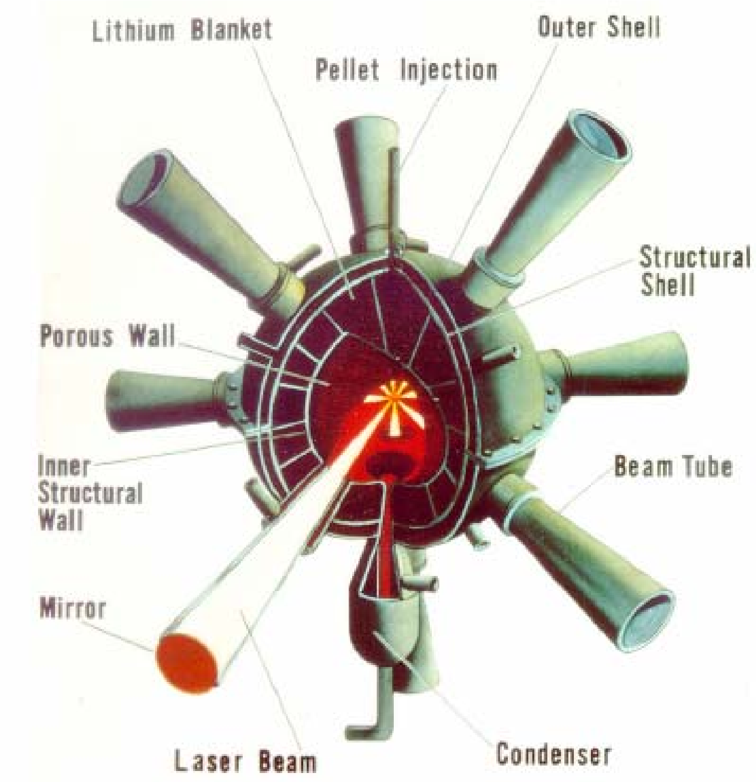
OUTLINE

- **Introduction – Problem Definition**
  - Description of Liquid Protection Concept
- **The Wetted Wall Concept**
  - Numerical Studies
  - Experimental Verification
- **Forced Liquid Film Concept**
- **Thick Oscillating Slab Jets (HYLIFE) Concept**

Inertial Fusion – Problem Definition
Wall Protection



- Target yield (10^2-10^3 MJ)
  - ~5% X-rays (~10ns)
  - ~20% Ions (~1μs)
  - ~75% Neutrons
- Soft X-rays and Ions Deposit their energy in very thin surface layer
- Can cause significant wall erosion due to
  - Evaporation
  - Spallation
  - Macroscopic erosion due to shock wave destruction, high thermal stress

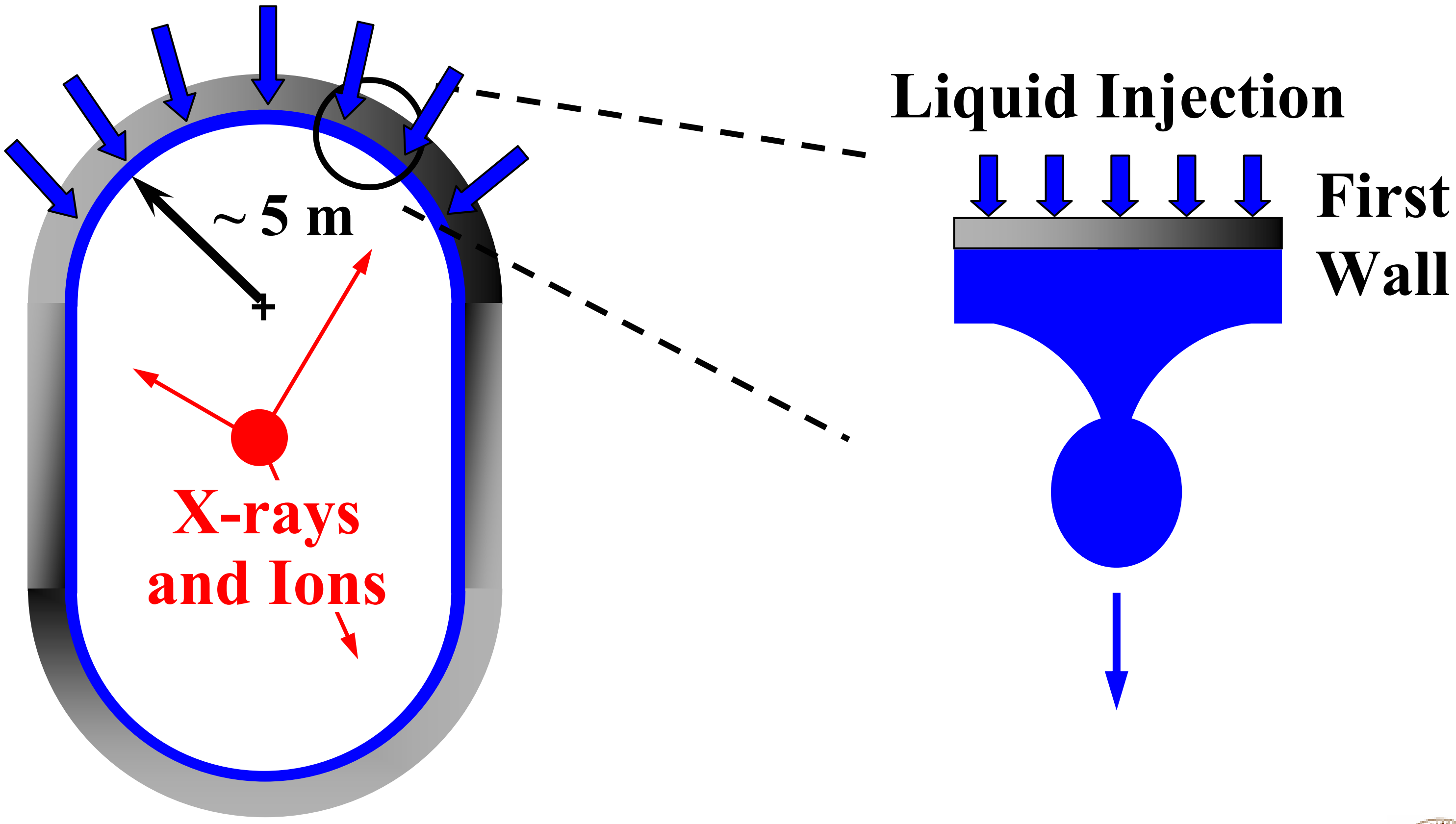
∴ Wall must be protected to assure reactor chamber survival at practical sizes

Inertial Fusion – Problem Definition
Liquid Protection Concepts

- **Wetted Wall Concept**
- **Forced Thin Film Concept**
- **Thick Oscillating Jets (HYLIFE Design)**

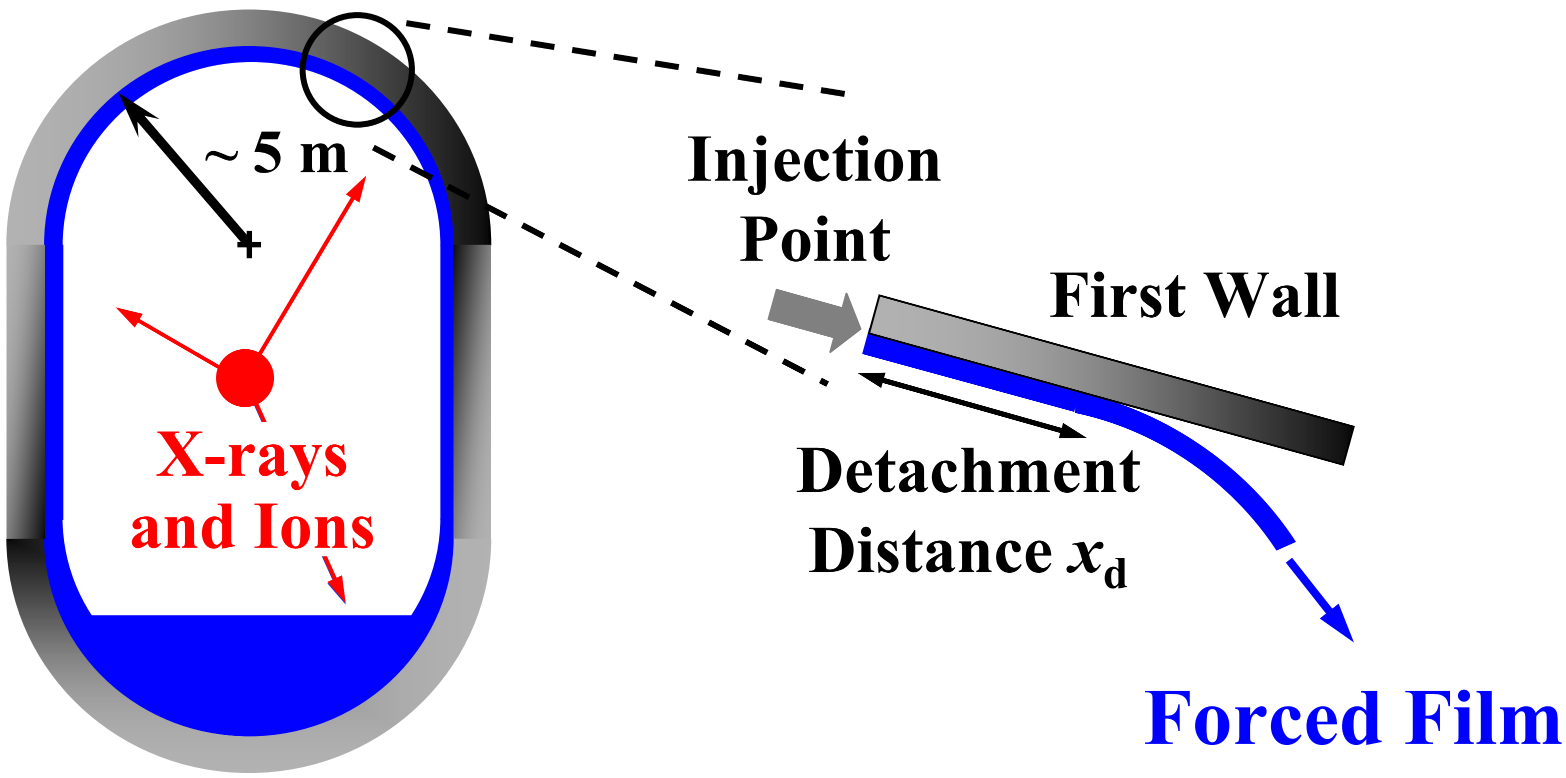
Wetted Wall Concept--*Problem Definition*

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

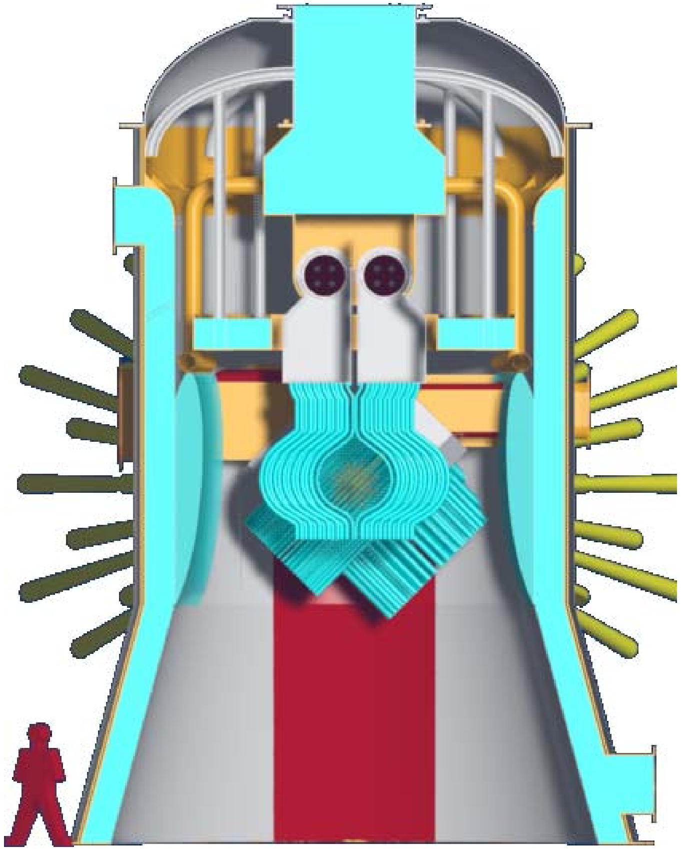


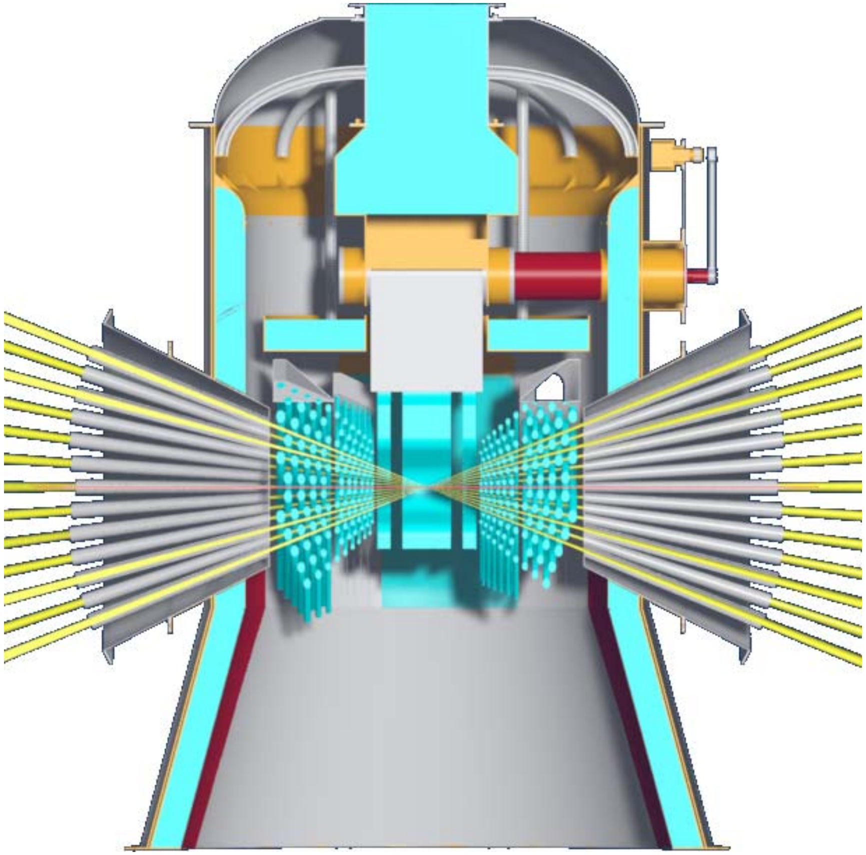
Forced Film Concept -- *Problem Definition*

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



Thick Oscillating Jets (HYLIFE)
-- *Problem Definition*



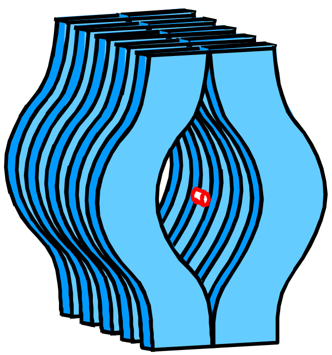


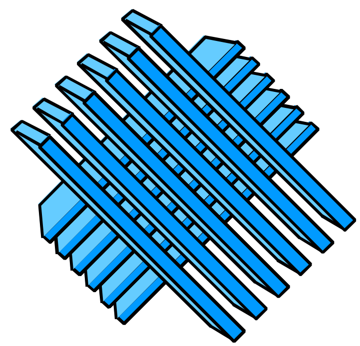
Pictures courtesy of Ryan Abbott (LLNL)

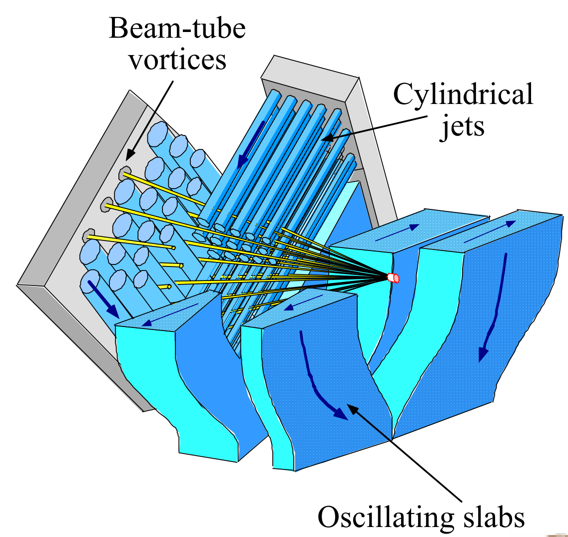
Turbulent Liquid Sheets

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

Thin Liquid Protection

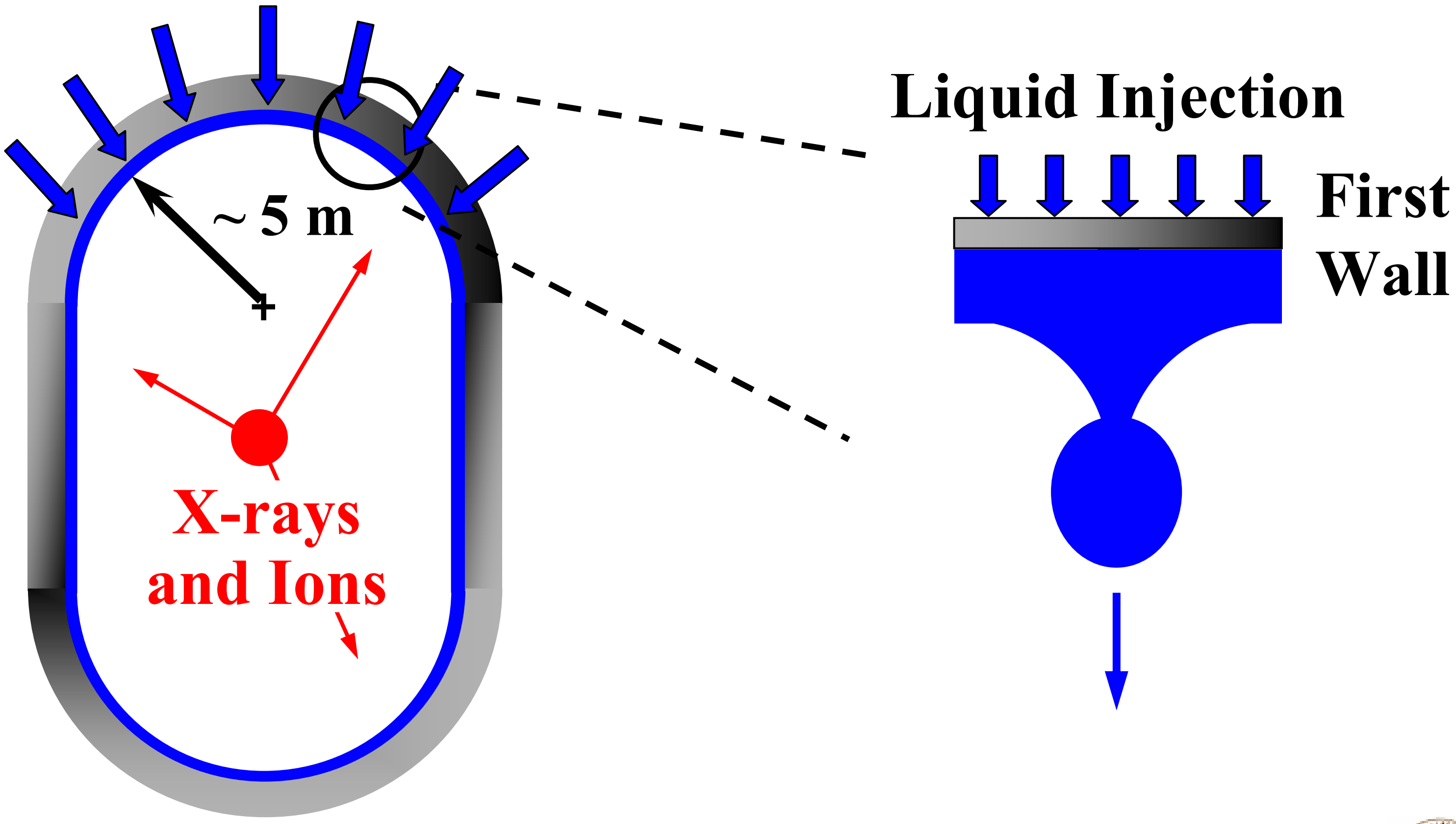
Major Design Questions

- Can a stable liquid film be maintained over the entire surface of the reactor cavity?
- Can the film be re-established over the entire cavity surface prior to the next target explosion?
- Can a minimum film thickness be maintained to provide adequate protection over subsequent target explosions?

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

Wetted Wall Concept--*Problem Definition*

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



Numerical Simulation of Porous Wetted Walls
Summary of Results

Quantify effects of

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

on

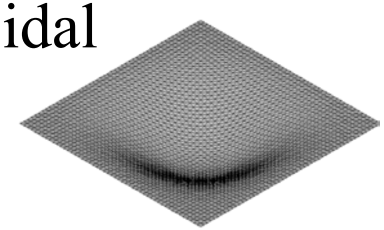
- Droplet detachment time
- Equivalent droplet diameter
- Minimum film thickness prior to detachment

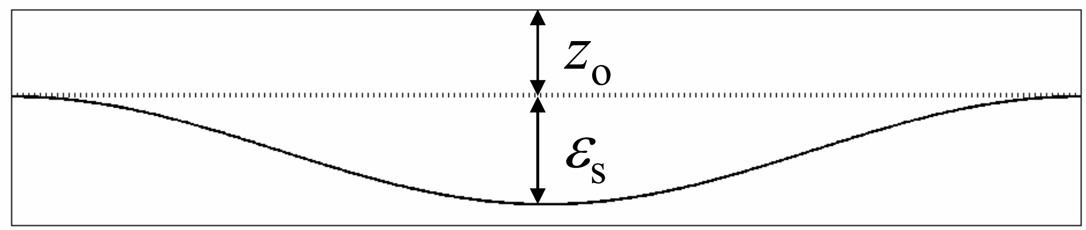
Obtain Generalized Charts for dependent variables as functions of the Governing non-dimensional parameters

Numerical Simulation of Porous Wetted Walls
Effect of Initial Perturbation

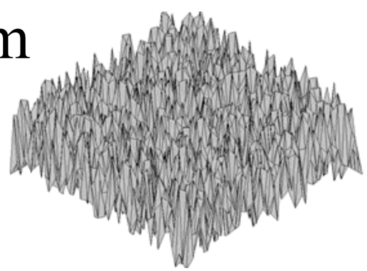
- Initial Perturbation Geometries

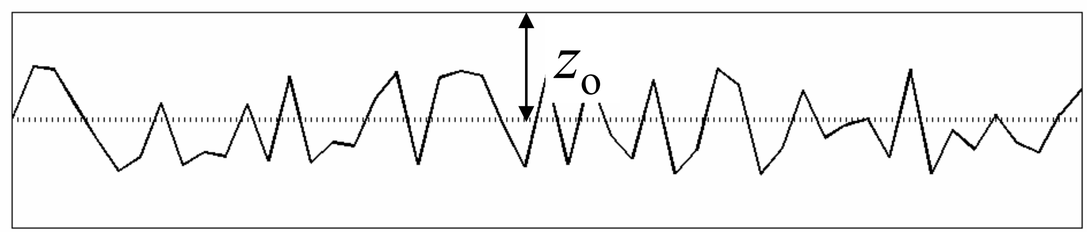
Sinusoidal



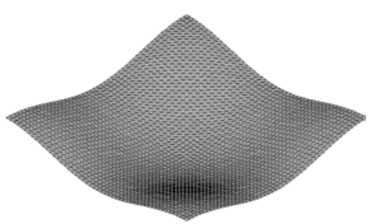


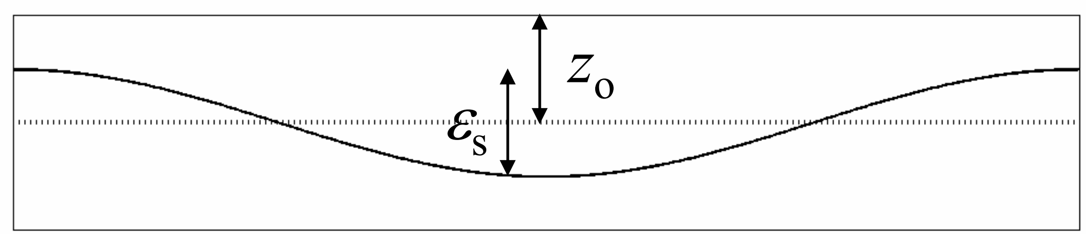
Random





Saddle





Numerical Simulation of Porous Wetted Walls
Effect of Initial Perturbation

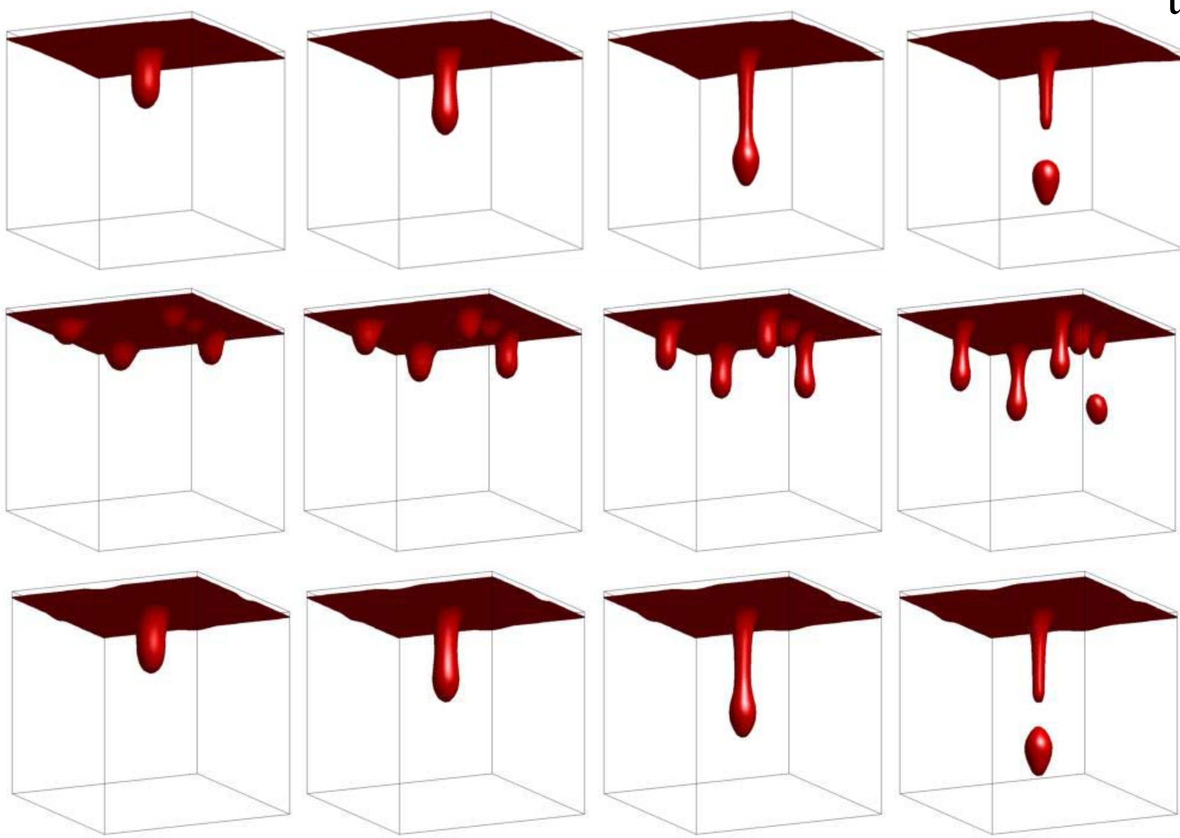
Pb at 700K

Detachment time τ (s)

Sinusoidal
z_o, ε_s = 0.5 mm
w_{in} = 1 mm/s

Random
w_{in} = 1 mm/s

Saddle
w_{in} = 1 mm/s



0.31

0.38

0.30

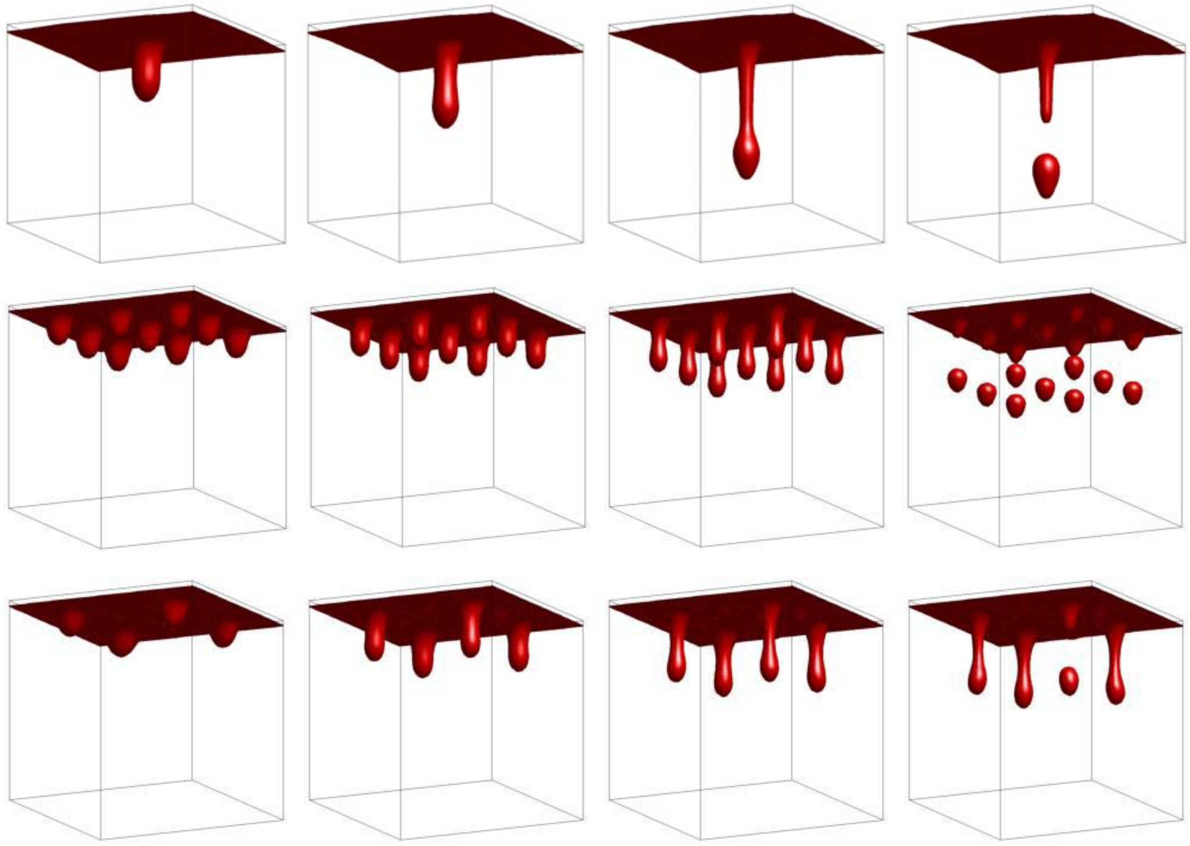
Numerical Simulation of Porous Wetted Walls
Effect of Disturbance Mode Number

- z_o=0.0005m, ε_s=0.0005m, w_{in}=0.001m/s

mode #1 — t=0.31

mode #3 — t=0.36

mode #4 — t=0.49



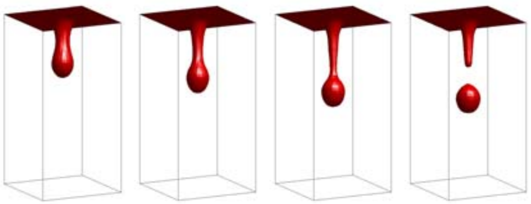
Numerical Simulation of Porous Wetted Walls

Effect of Evaporation/Condensation at Interface

- $z_o^*=0.1$, $w_{in}^*=0.01$, Re=2000

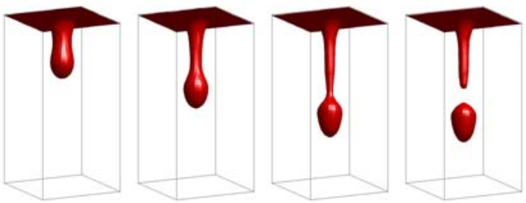
$m_f^+=-0.005$

(Evaporation)



$\tau^*=31.35$

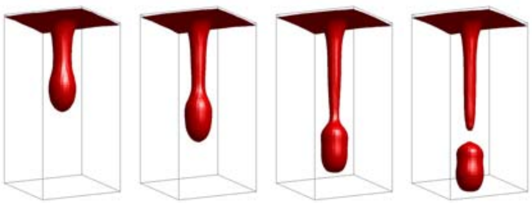
$m_f^+=0.0$



$\tau^*=27.69$

$m_f^+=0.01$

(Condensation)



$\tau^*=25.90$

Numerical Simulation of Porous Wetted Walls
Wetted Wall Parameters

- Length, velocity, and time scales :

$$l = \sqrt{\sigma / [g(\rho_L - \rho_G)]} \qquad U_o = \sqrt{g\,l} \qquad t_o = l / U_o$$

- Nondimensional drop detachment time : $\tau^* \equiv t_d / t_o$

- Nondimensional minimum film thickness : $\delta^*_{min} \equiv \delta_{min} / l$

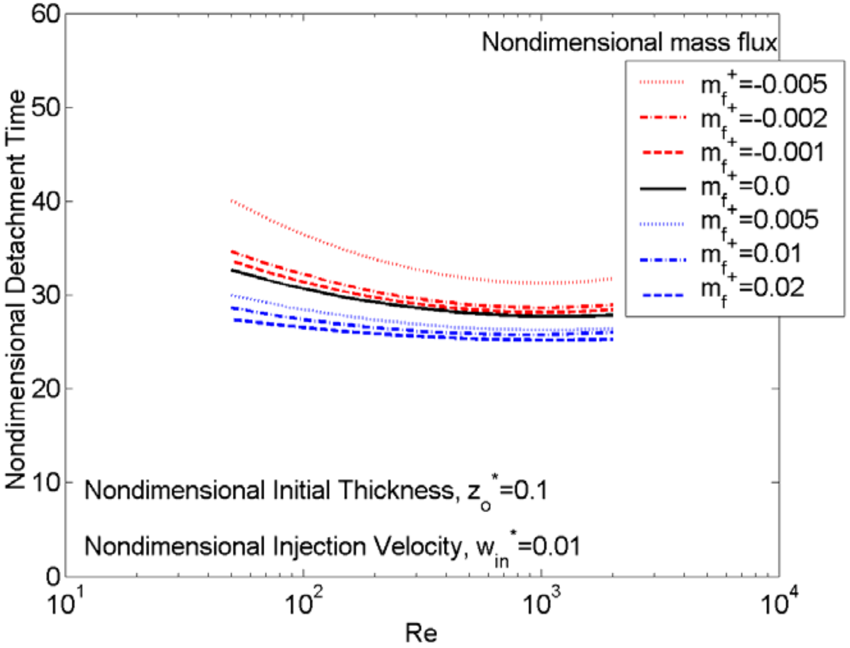
- Nondimensional initial film thickness : $z^*_o \equiv z_o / l$

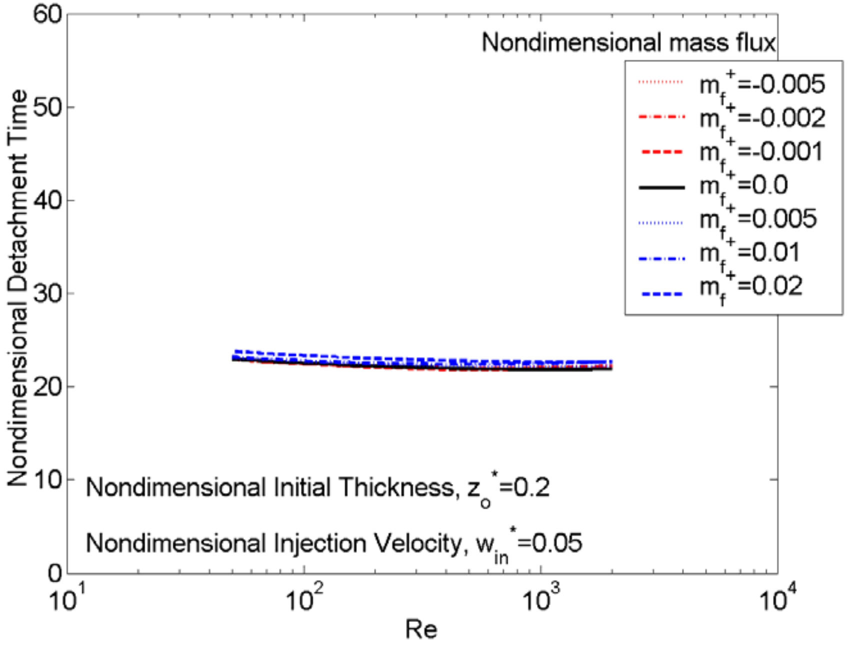
- Nondimensional injection velocity : $w^*_{in} \equiv w_{in} / U_o$

Numerical Simulation of Porous Wetted Walls
Non-Dimensional Parameters For Various Coolants

	Water		Lead		Lithium		Flibe		
T **(K)**	**293**	**323**	**700**	**800**	**523**	**723**	**773**	**873**	**973**
l **(mm)**	2.73	2.65	2.14	2.12	8.25	7.99	3.35	3.22	3.17
U_0 **(mm/s)**	163.5	161.2	144.7	144.2	284.4	280.0	181.4	177.8	176.4
t_0 **(ms)**	16.7	16.4	14.8	14.7	29.0	28.6	18.5	18.1	18.0
Re	445	771.2	1618	1831	1546	1775	81.80	130.8	195.3

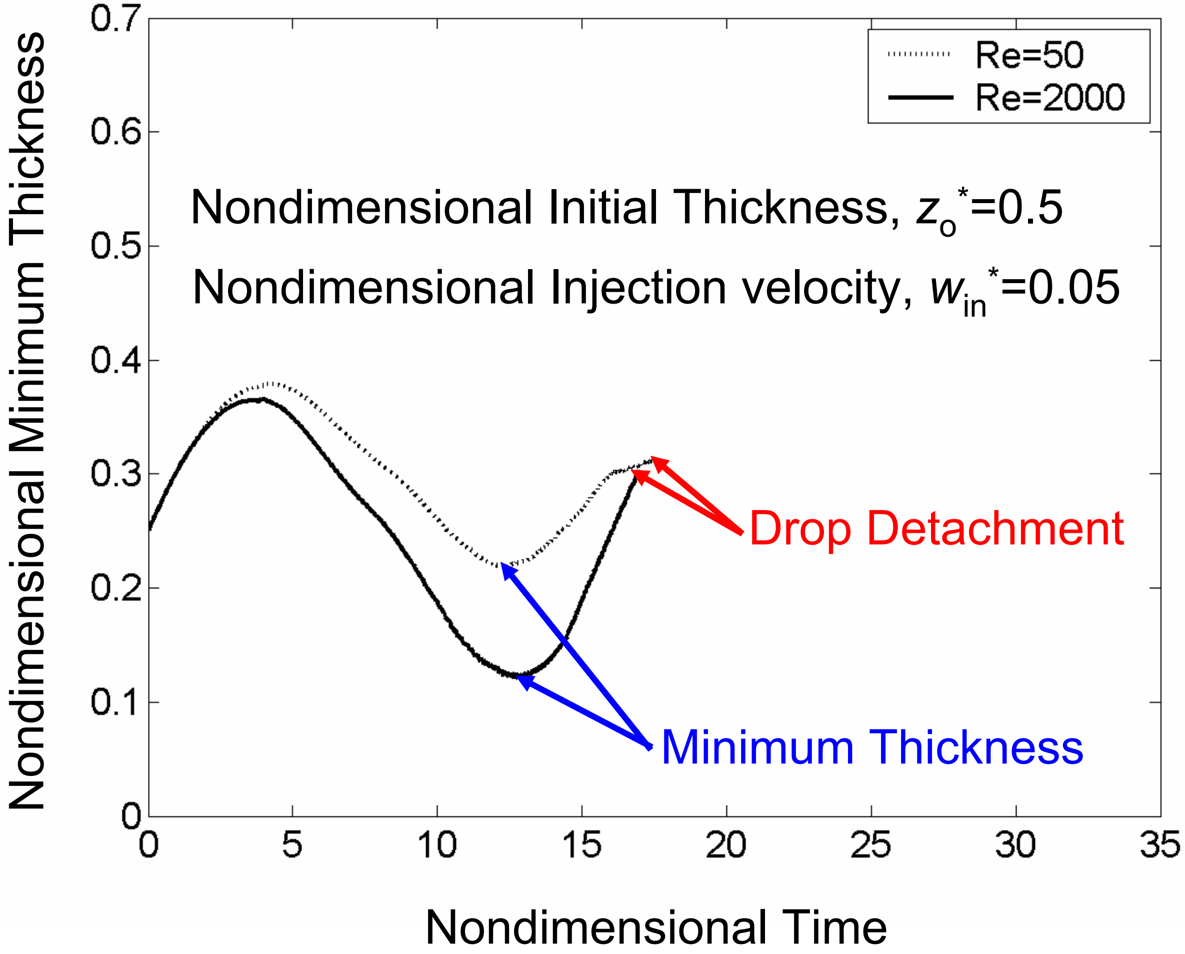
Numerical Simulation of Porous Wetted Walls
Drop Detachment Time





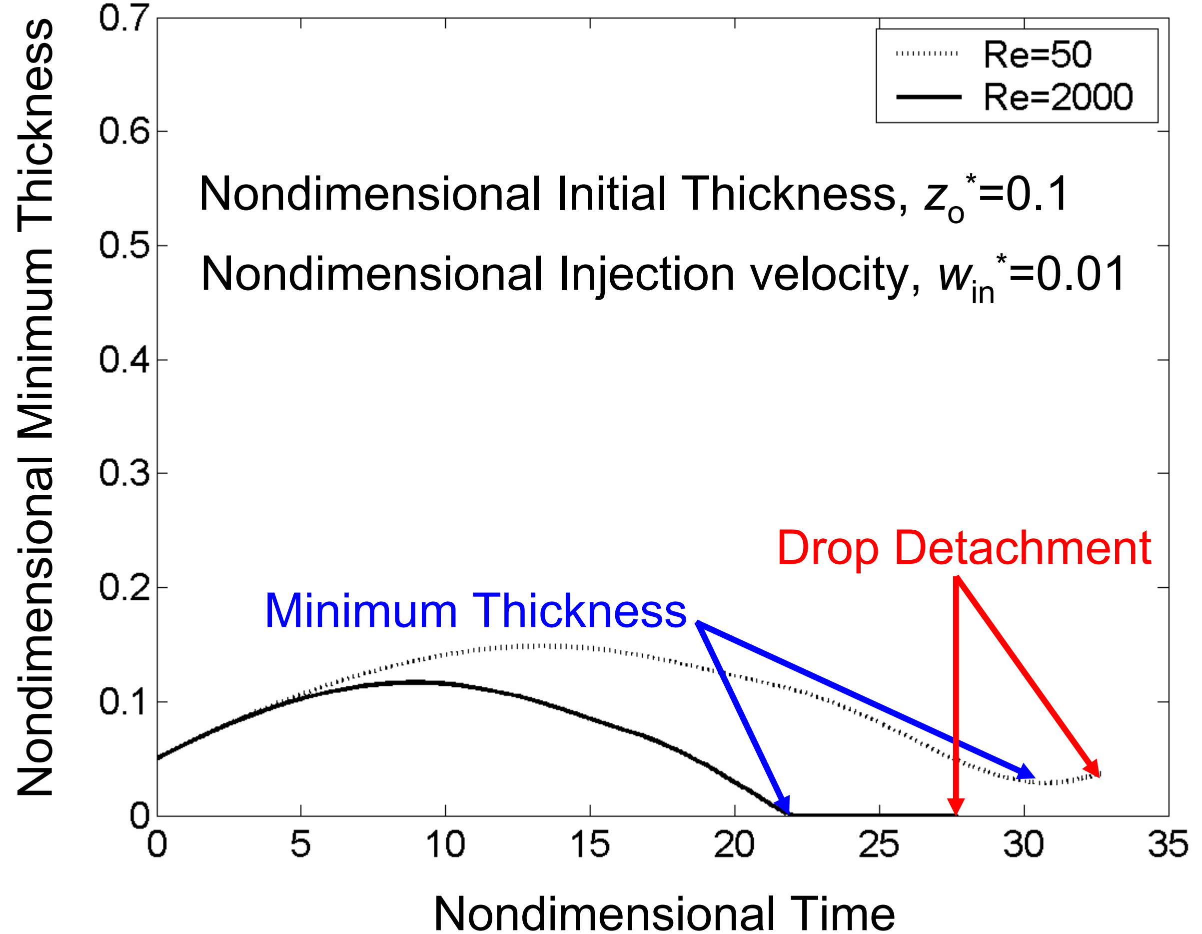
Numerical Simulation of Porous Wetted Walls

Evolution of Minimum Film Thickness (High Injection/Thick Films)



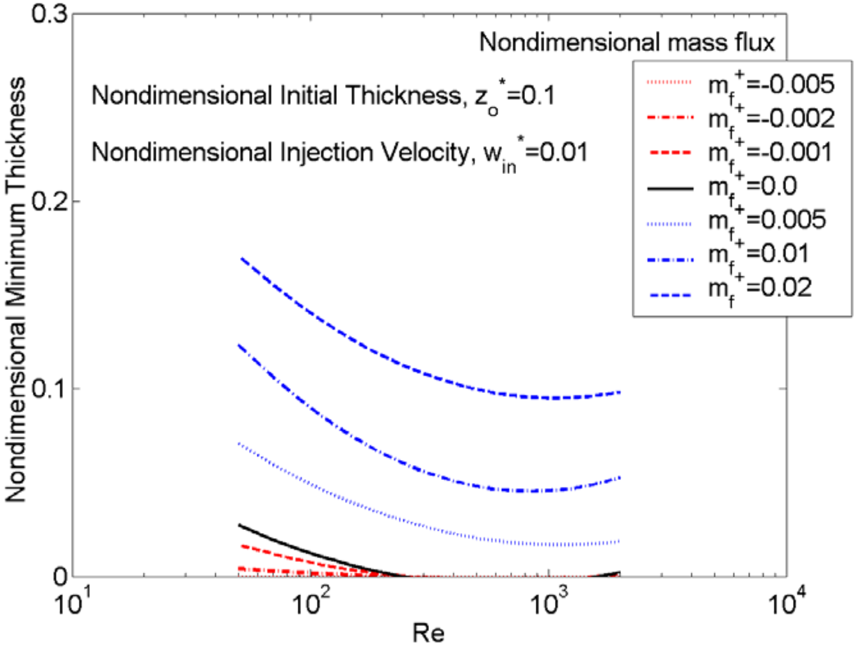
Numerical Simulation of Porous Wetted Walls

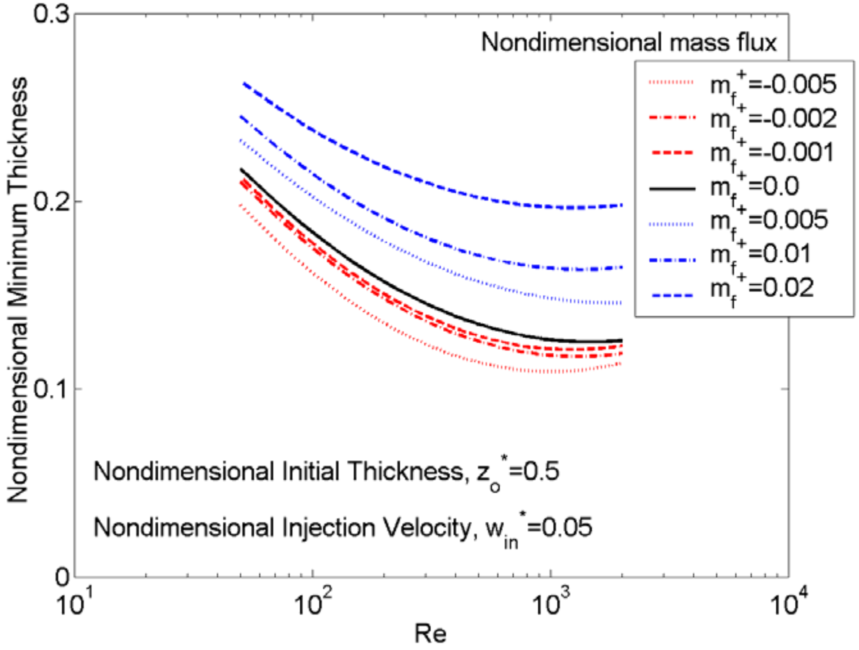
Evolution of Minimum Film Thickness (Low Injection/Thin Films)



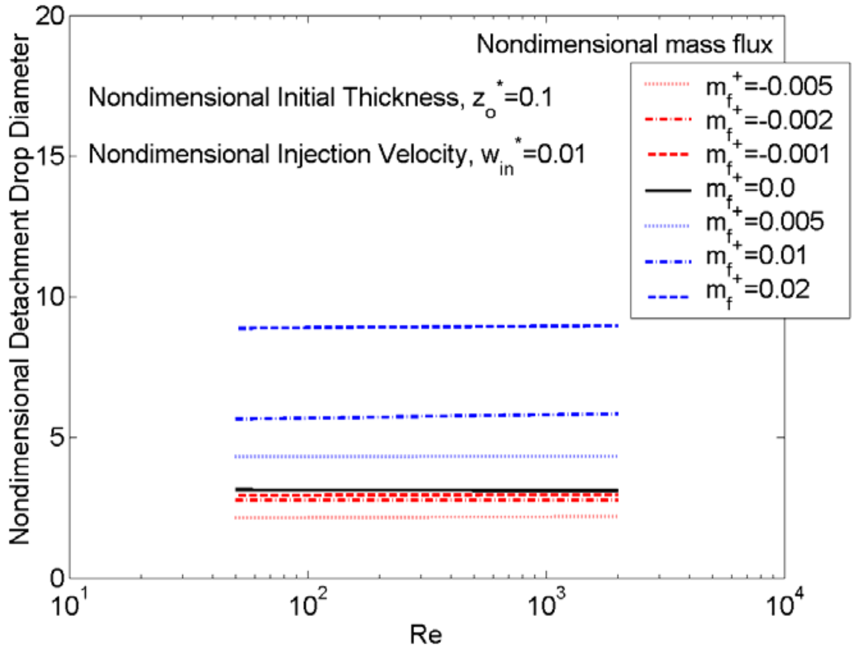
Numerical Simulation of Porous Wetted Walls

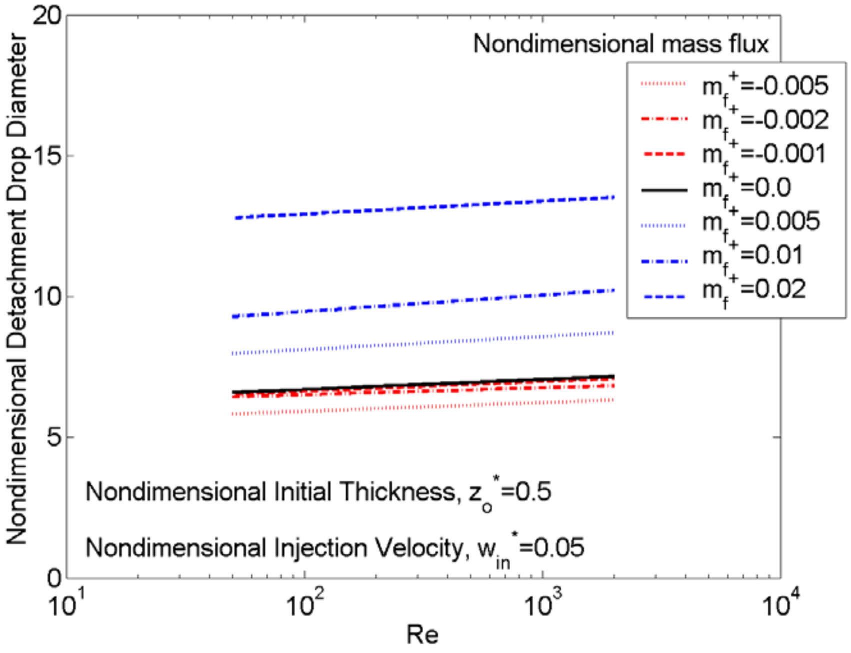
Minimum Film Thickness



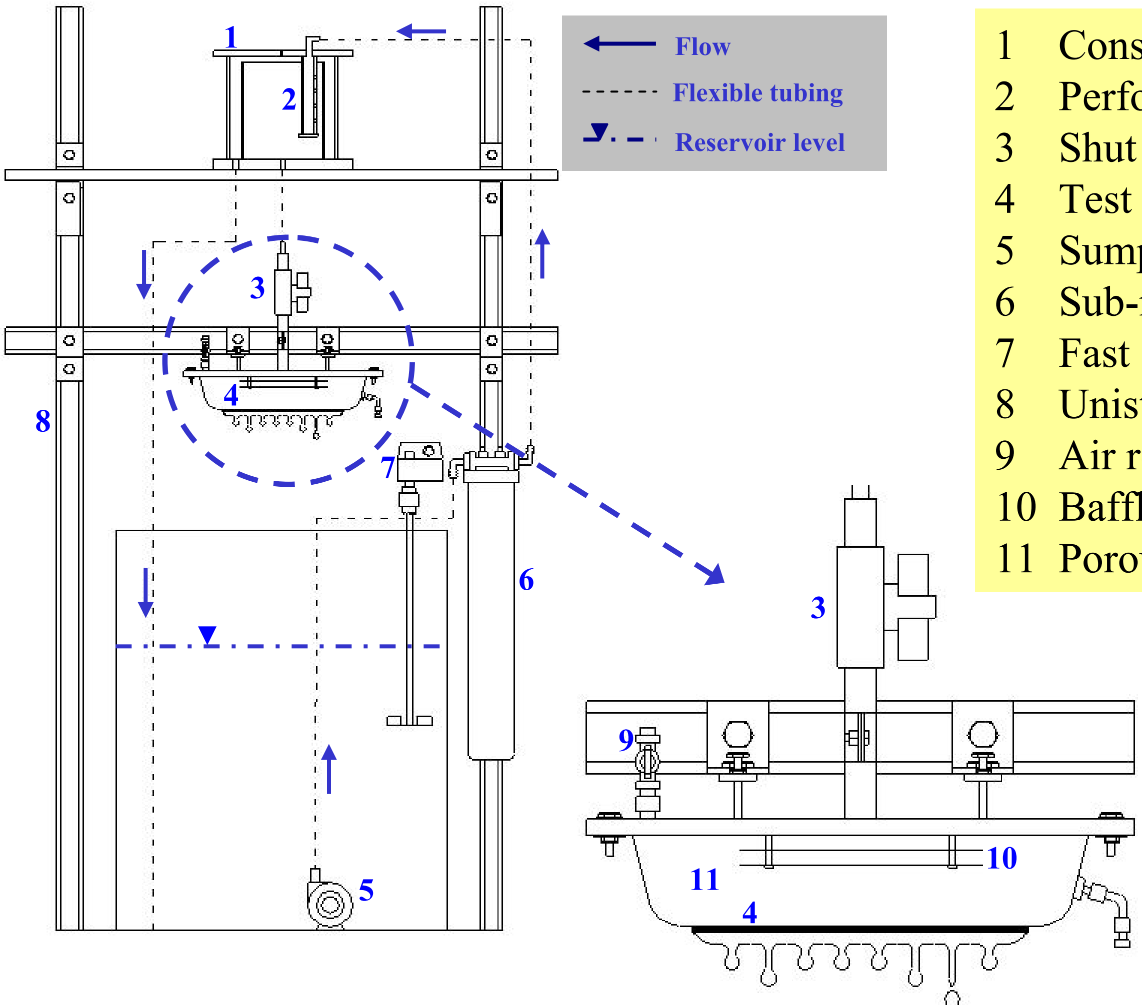


Numerical Simulation of Porous Wetted Walls
Equivalent Detachment Diameter



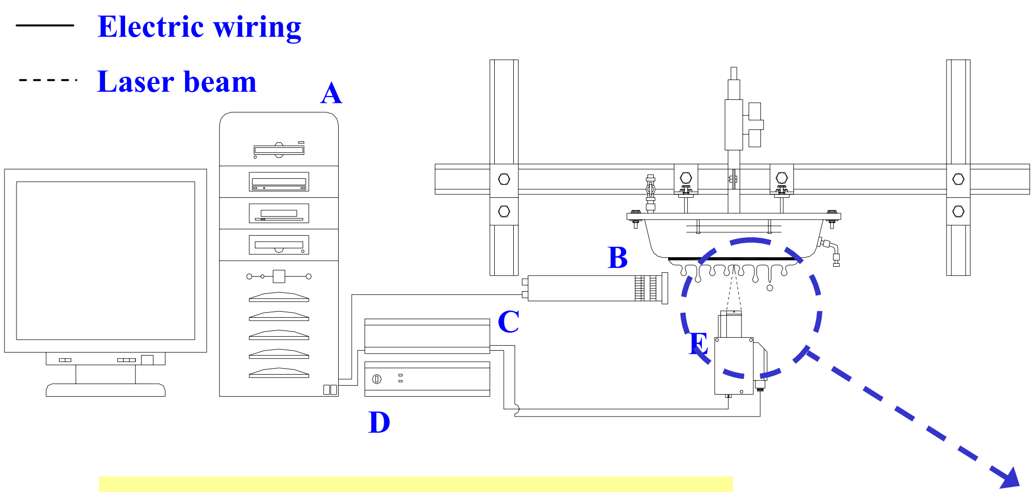


Experimental Validations



1	Constant-head supply tank w/var. height
2	Perforated tube
3	Shut off valve
4	Test section porous plate, 316L SS
5	Sump pump
6	Sub-micron filter
7	Fast stirrer
8	Unistrut frame
9	Air relief valve
10	Baffles
11	Porous plate plenum

Experimental Measurement
-- *"Unperturbed" Film Thickness*



A	Workstation PC
B	CCD camera
C	Laser camera unit
D	Laser controller
E	Laser sensor head

Laser Confocal Displacement Meter
KEYENCE CORPORATION OF AMERICA, Model # : LT-8110

Experimental Variables

Experimental Variables

- Plate porosity
- Plate inclination angle θ
- Differential pressure
- Fluid properties

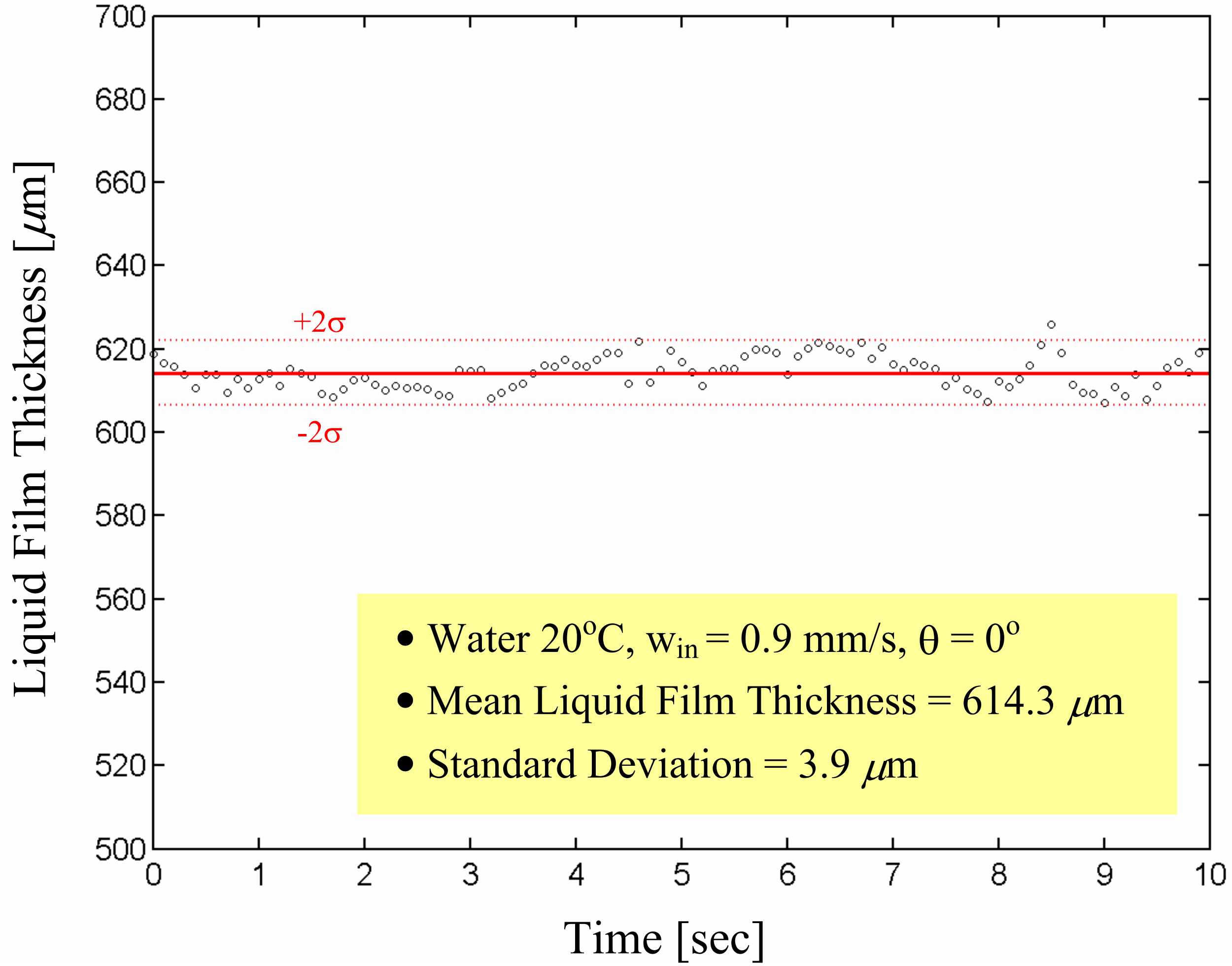
Independent Parameters

- Injection velocity, w_{in}
- "Unperturbed" film thickness, z_o

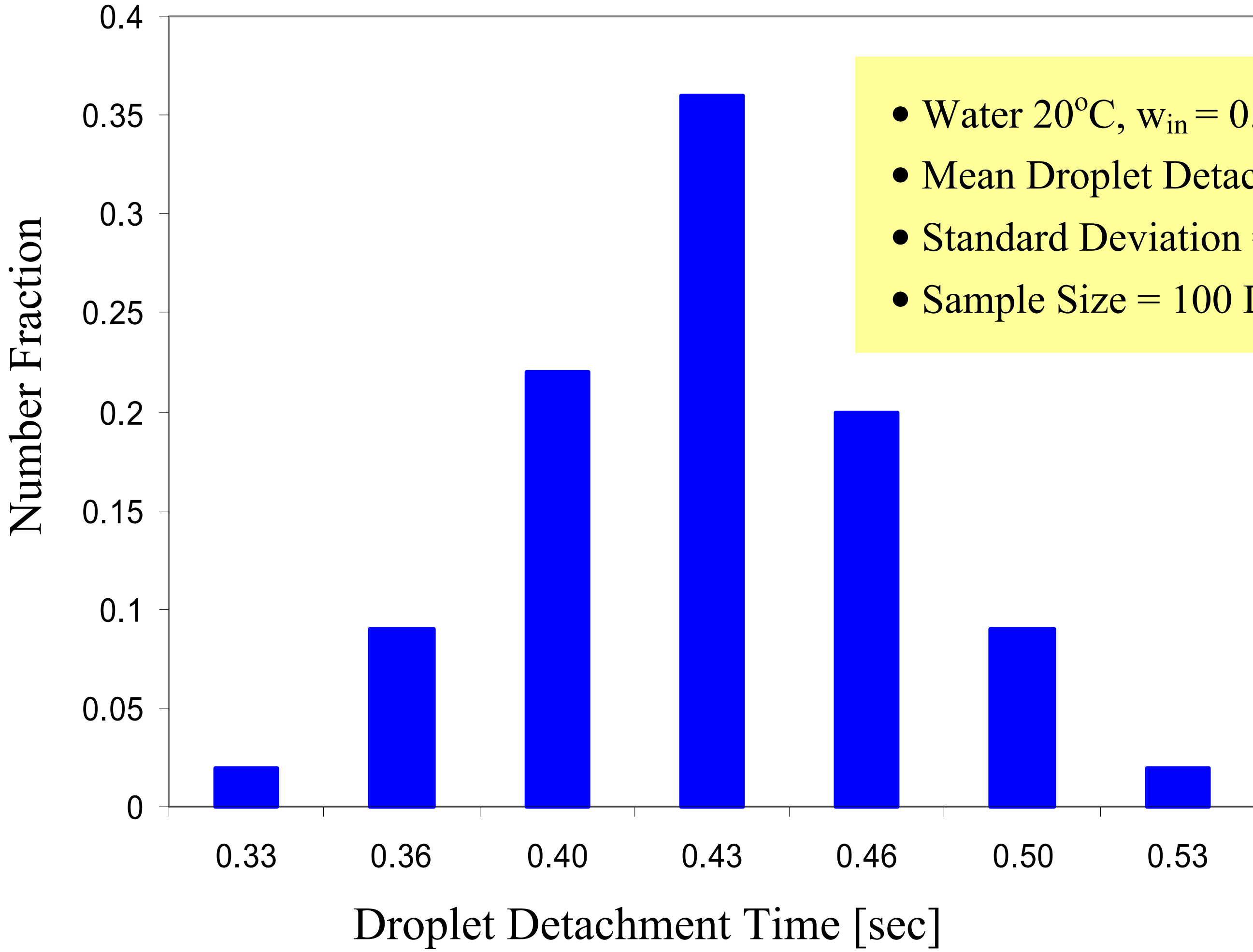
Dependent Variables

- Detachment time
- Detachment diameter
- Maximum penetration depth

Experiment #W090 -- *"Unperturbed" Film Thickness*

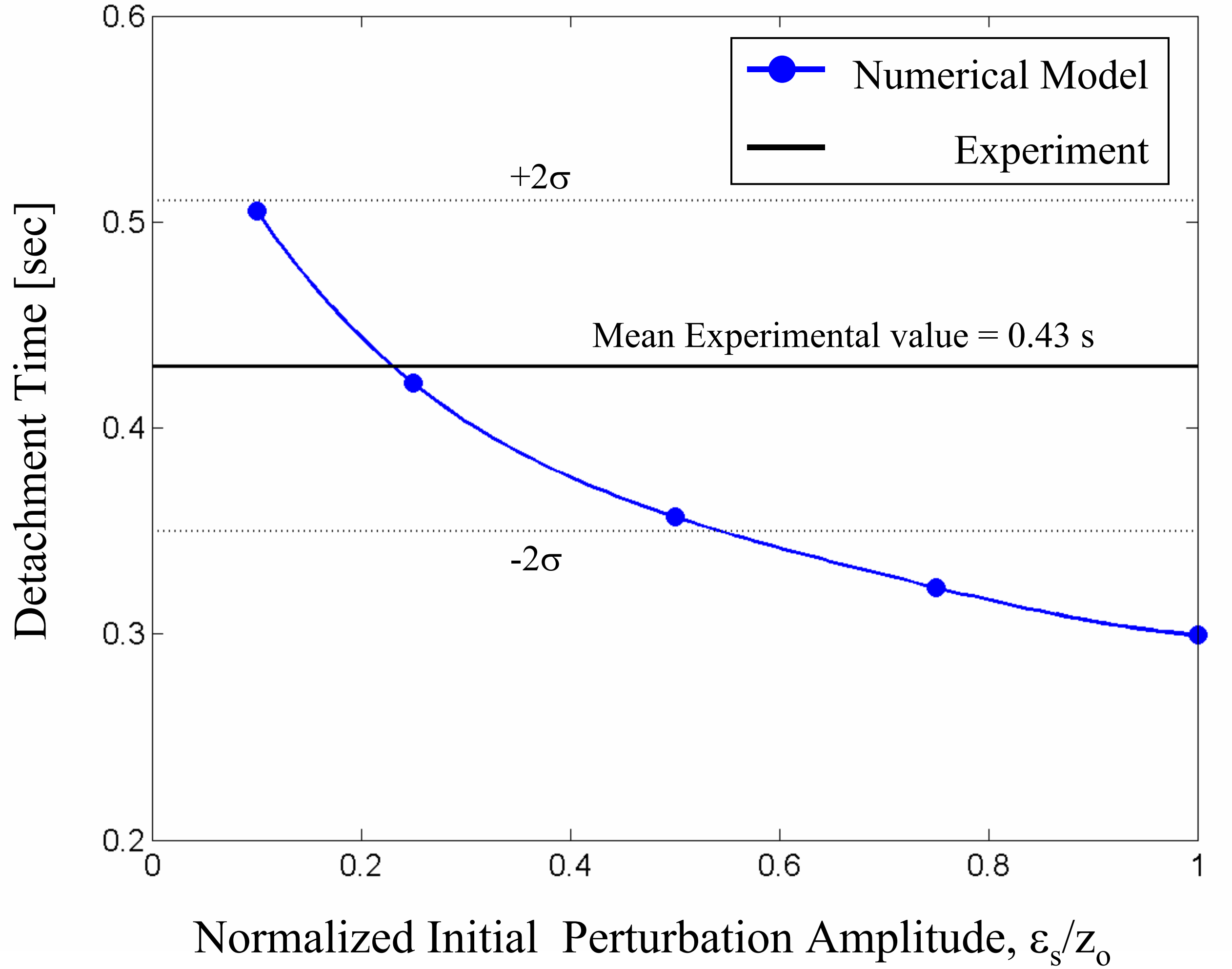


Experiment #W090 -- *Droplet Detachment Time*

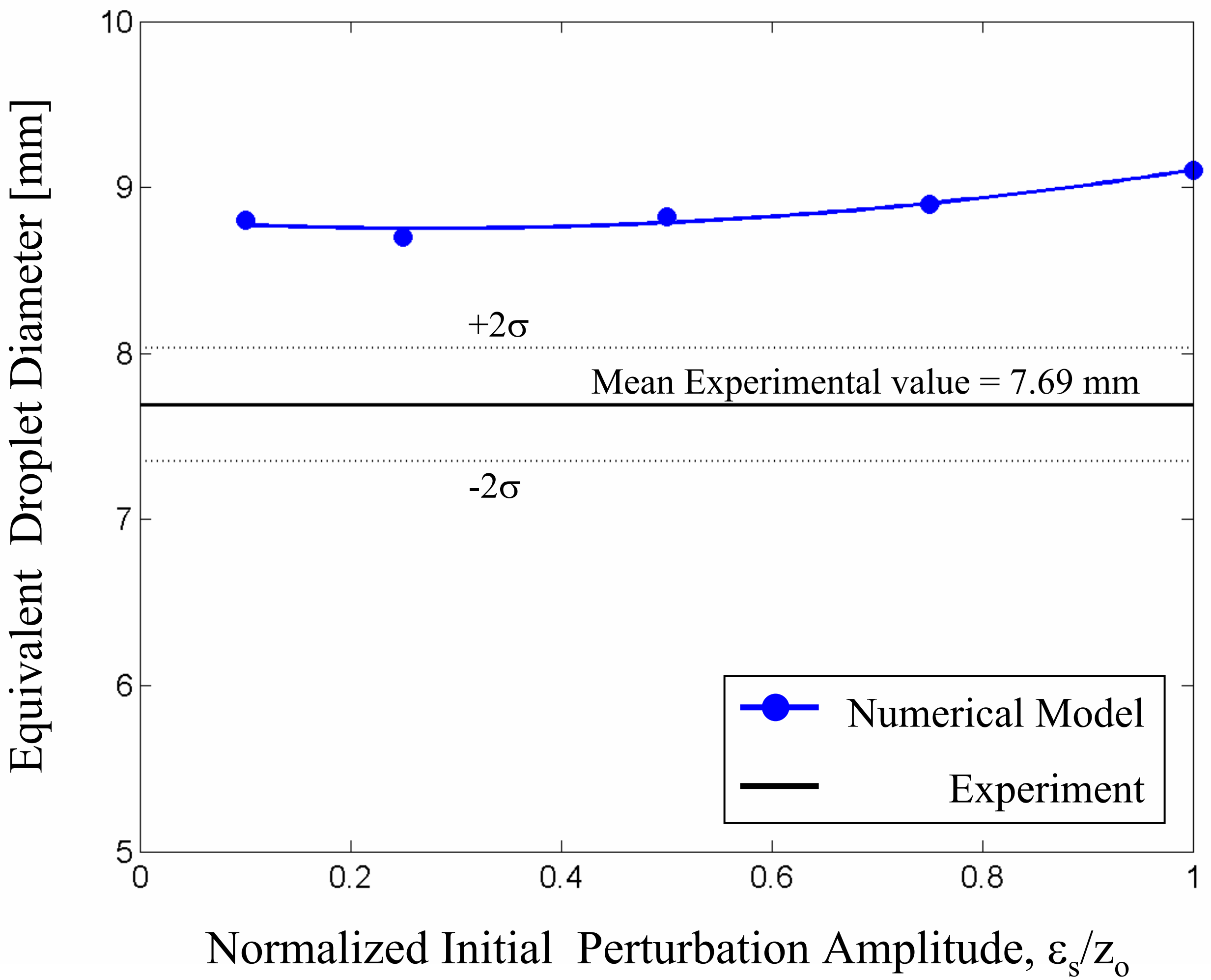


- Water 20°C, w_{in} = 0.9 mm/s, $\theta = 0^{o}$
- Mean Droplet Detachment Time = 0.43 s
- Standard Deviation = 0.04 s
- Sample Size = 100 Droplets

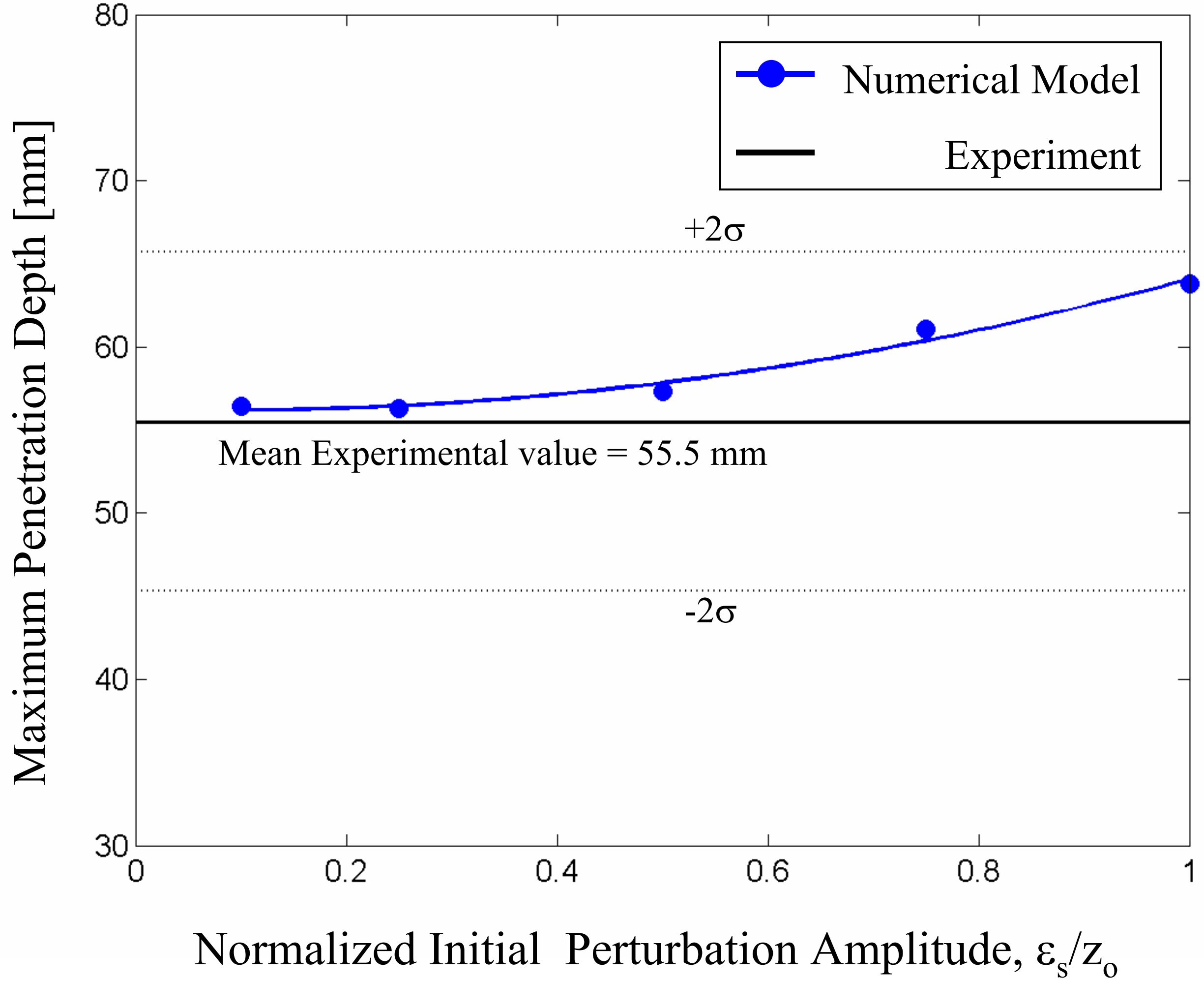
Experiment #W090
-- *Calculated Detachment Time*



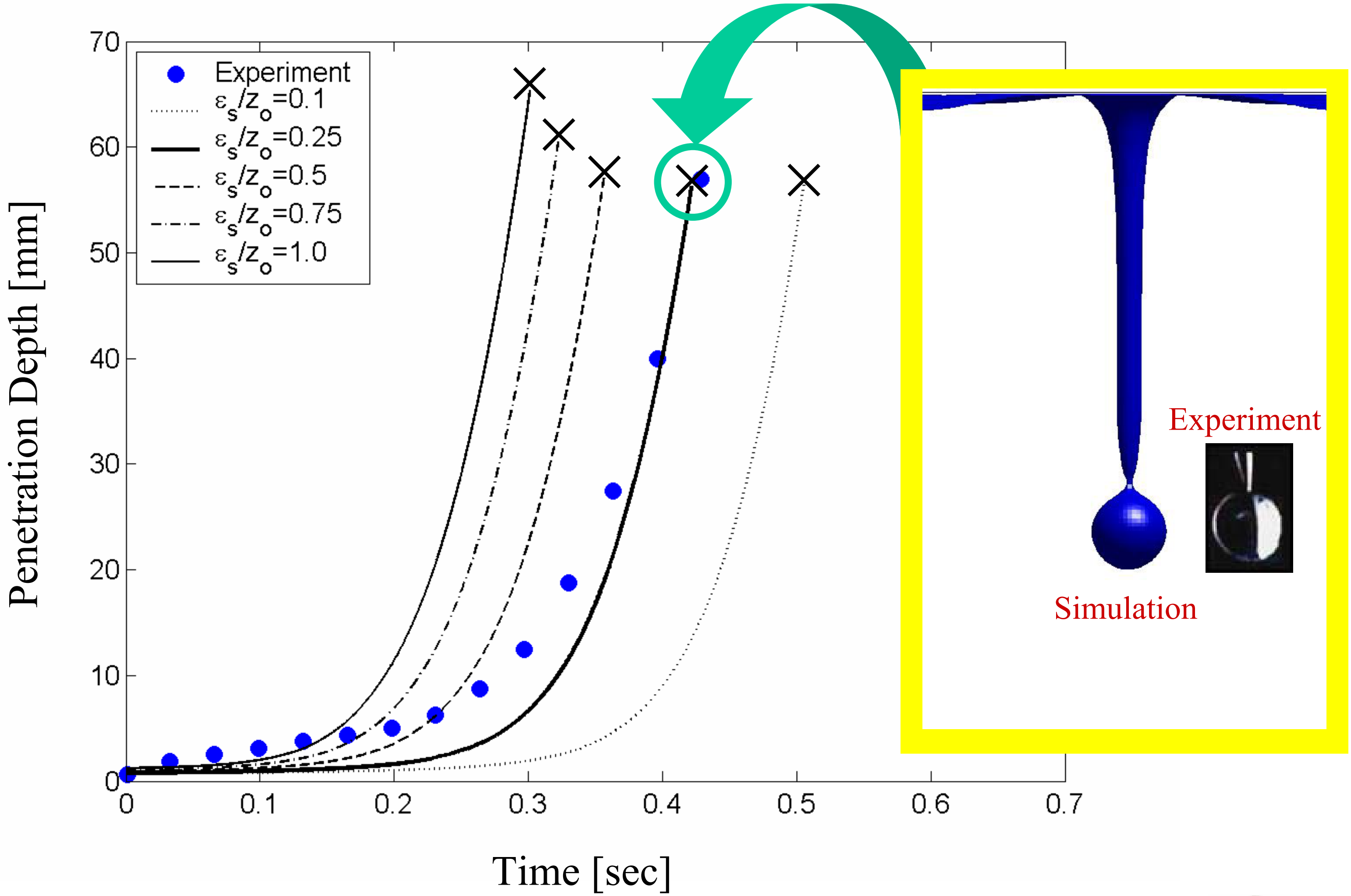
Experiment #W090 – *Equivalent Detachment Diameter*



Experiment #W090 --
Calculated Penetration Distance



Experiment #W090 --
Evolution of Maximum Penetration Distance

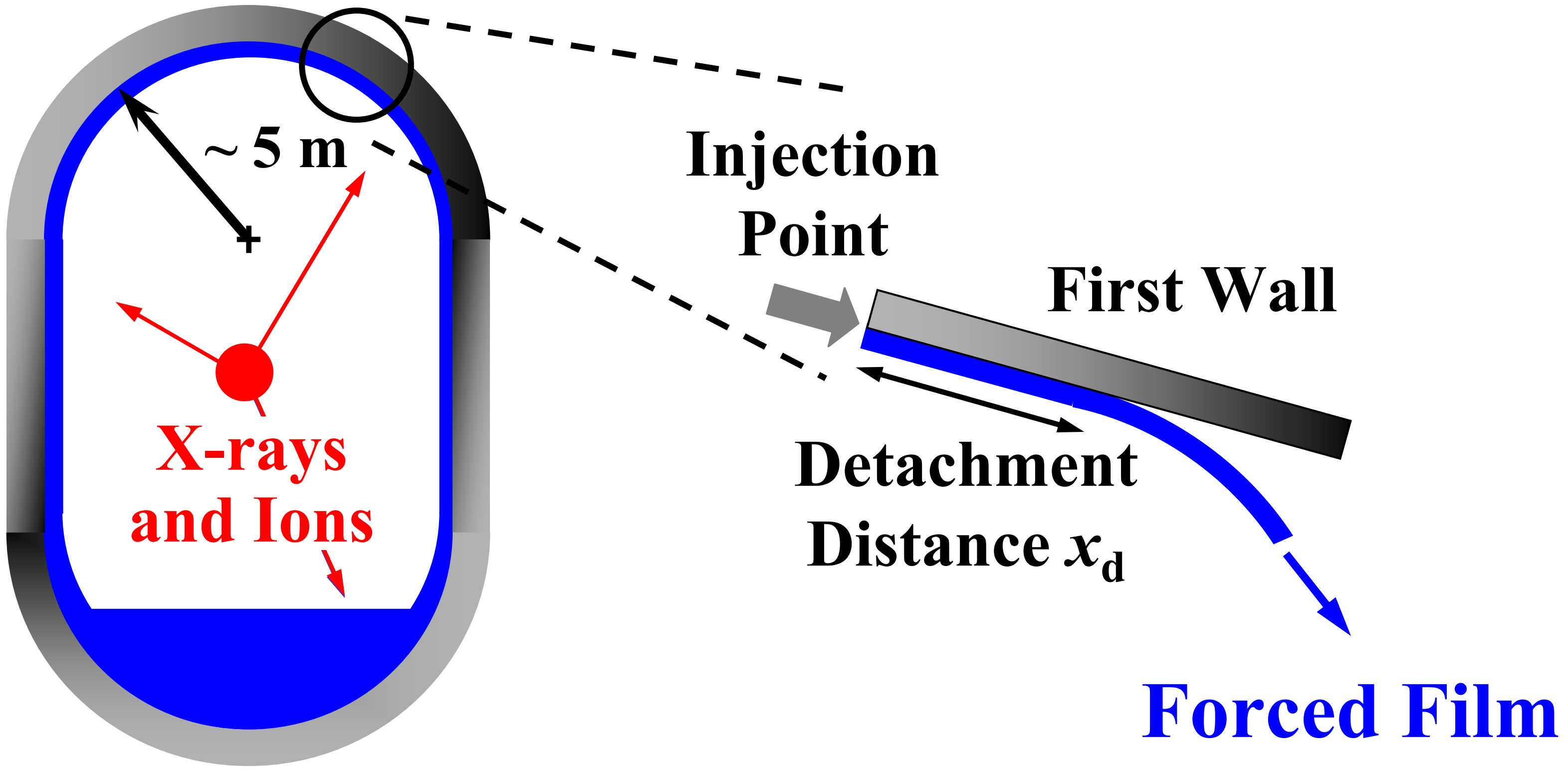


Wetted Wall Summary

- Developed general 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

Forced Film Concept
-- *Problem Definition*

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



Forced Film Parameters

- Weber number We
  - Liquid density ρ
  - Liquid-gas surface tension σ
  - Initial film thickness δ
  - Average injection speed U

$$We \equiv \frac{\rho U^2 \delta}{\sigma}$$

- Froude number Fr
  - Surface orientation θ ($\theta = 0° \Rightarrow$ horizontal surface)

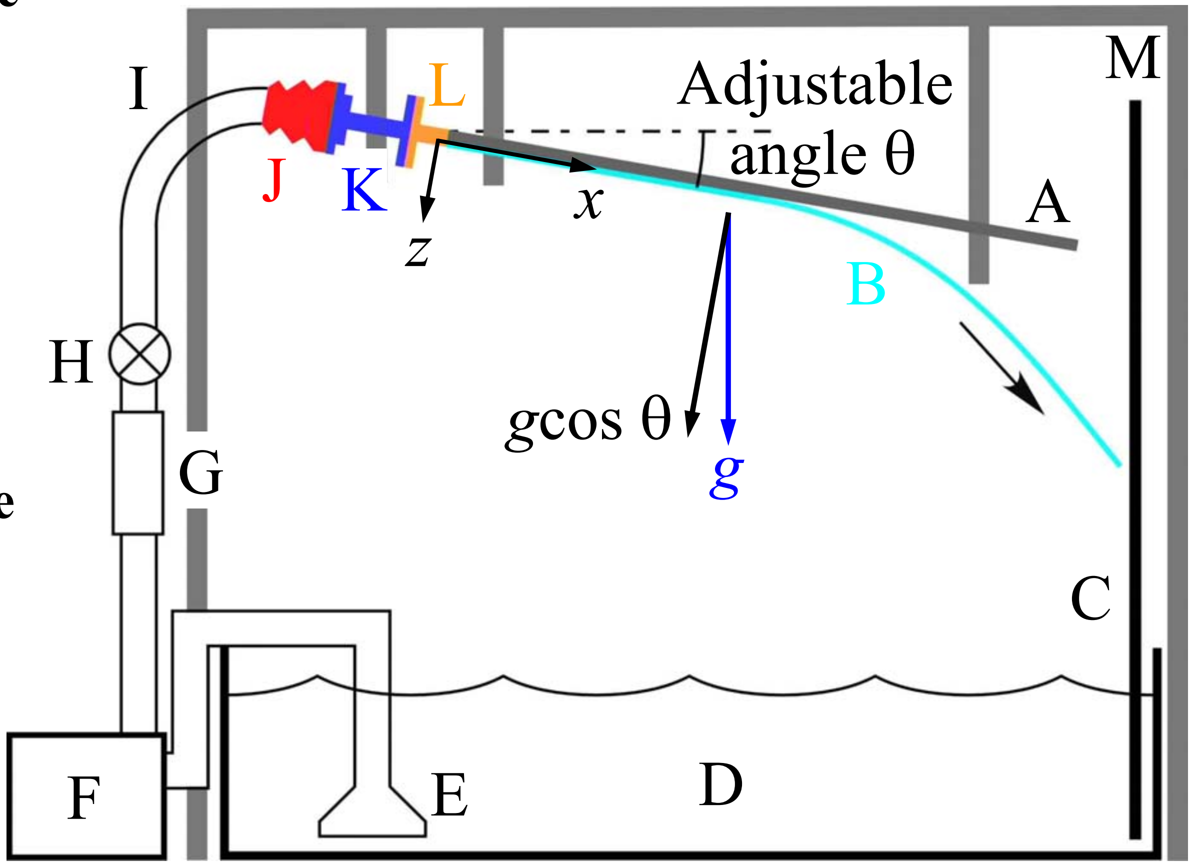
$$Fr \equiv \frac{U}{\sqrt{g(\cos\theta)\delta}}$$

- Mean detachment length from injection point x_d
- Mean lateral extent W
- Surface radius of curvature $R = 5$ m
- Surface wettability: liquid-solid contact angle α_{LS}
- In Prometheus: for $\theta = 0 – 45°$, $Fr = 100 – 680$ over nonwetting surface ($\alpha_{LS} = 90°$)

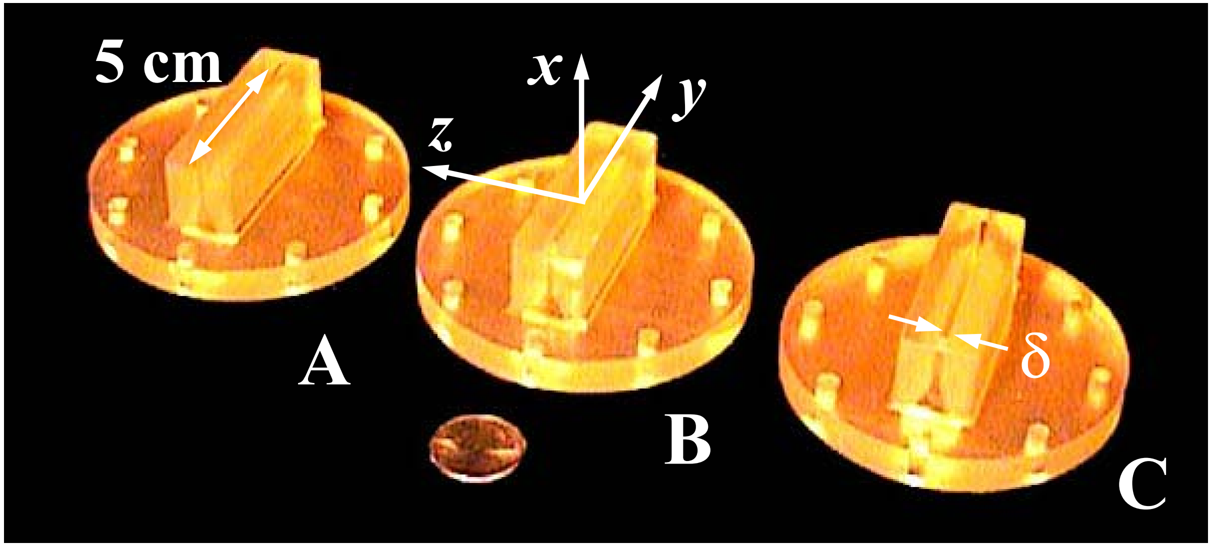
Contact Angle, α_{LS}
Glass : 25°
Coated Glass : 85°
Stainless Steel : 50°
Plexiglas : 75°

Experimental Apparatus

- **A** **Flat or Curved plate (1.52×0.40 m)**
- **B** **Liquid film**
- **C** **Splash guard**
- **D** **Trough (1250 L)**
- **E** **Pump inlet w/ filter**
- **F** **Pump**
- **G** **Flowmeter**
- **H** **Flow metering valve**
- **I** **Long-radius elbow**
- **J** **Flexible connector**
- **K** **Flow straightener**
- **L** **Film nozzle**
- **M** **Support frame**



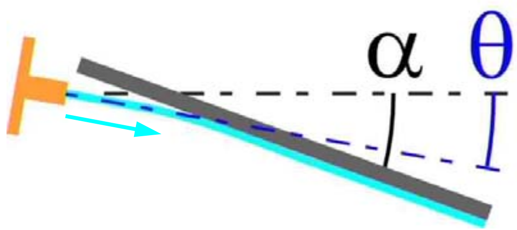
Liquid Film Nozzles



- Fabricated with stereolithography rapid prototyping
- $\delta_A = 0.1$ cm; $\delta_B = 0.15$ cm; $\delta_C = 0.2$ cm
- 2D 5th order polynomial contraction along z from 1.5 cm to δ
- Straight channel (1 cm along x) downstream of contraction

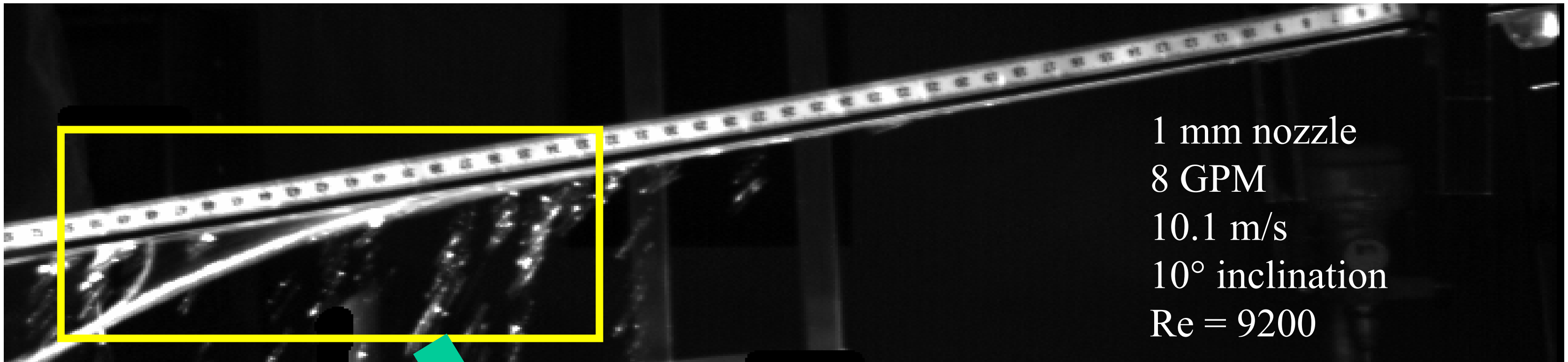
Experimental Parameters

- **Independent Variables**
  - Film nozzle exit dimension $\delta = 0.1$–0.2 cm
  - Film nozzle exit average speed $U_0 = 1.9 - 11.4$ m/s
  - Jet injection angle $\theta = 0°, 10°, 30°$ and $45°$
  - Surface inclination angle α ($\alpha = \theta$)
  - Surface curvature (flat or 5m radius)
  - Surface material (wettability)

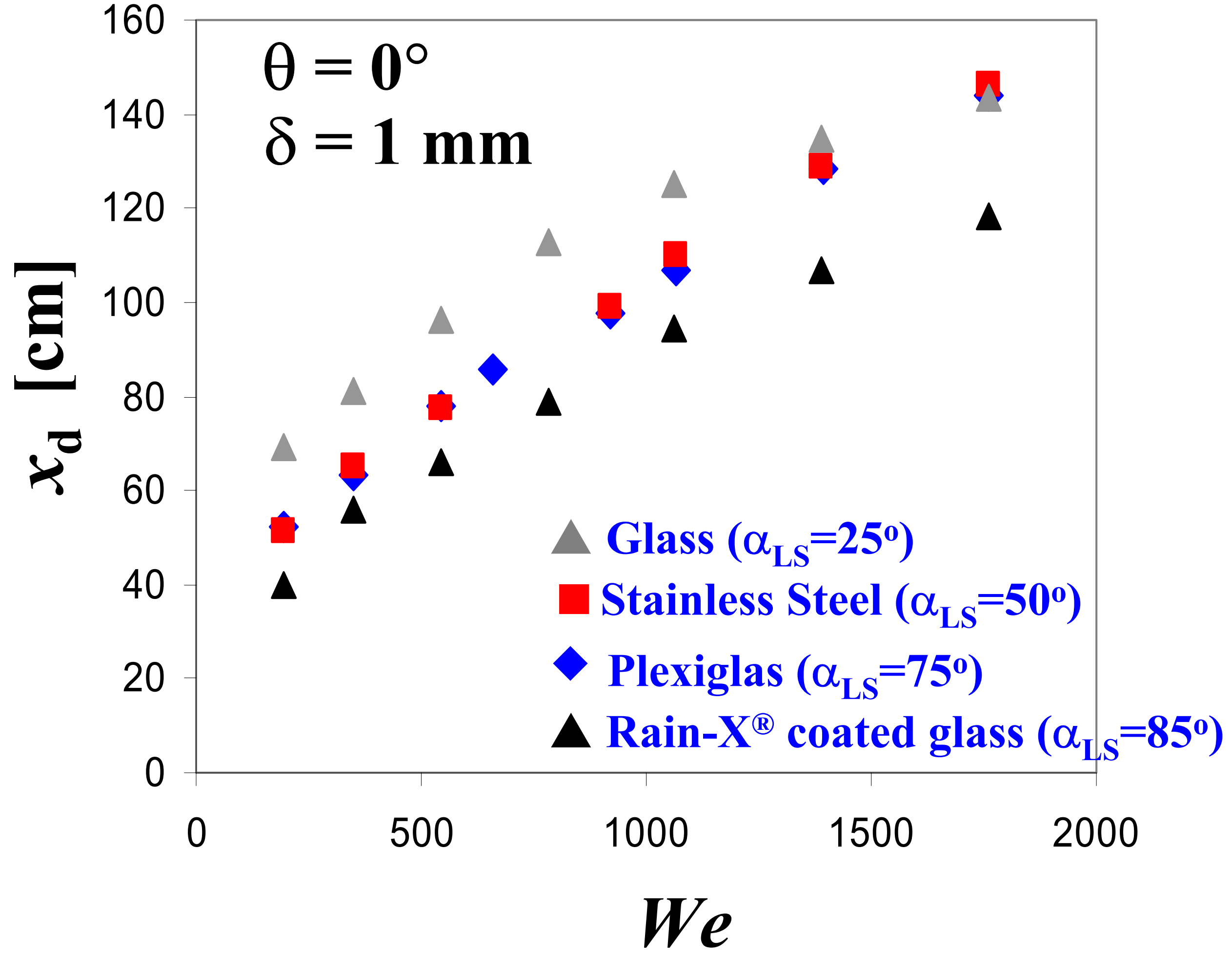


- **Dependent Variables**
  - Film width and thickness $W(x)$, $t(x)$
  - Detachment distance x_d
  - Location for drop formation on free surface

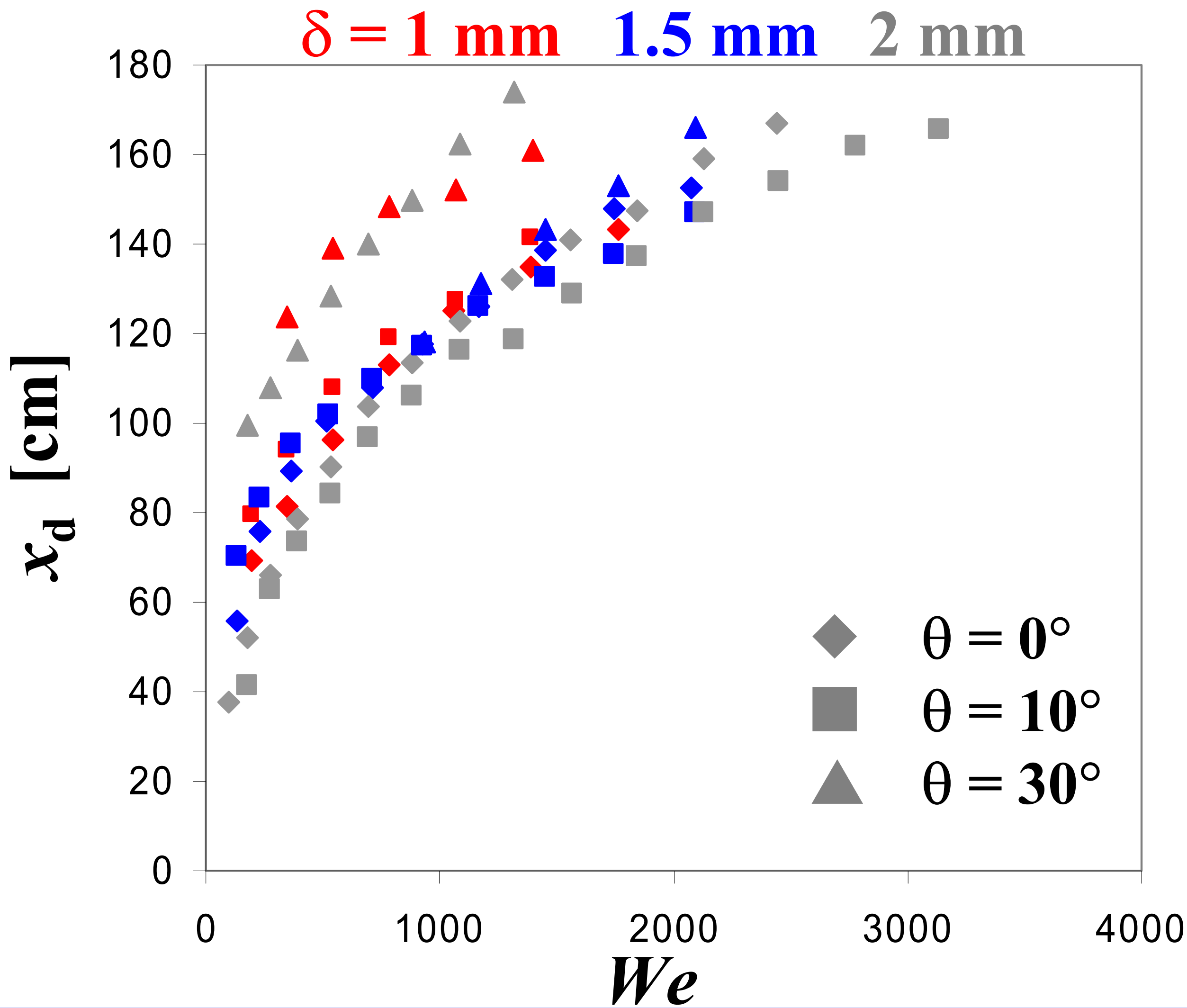
Detachment Distance



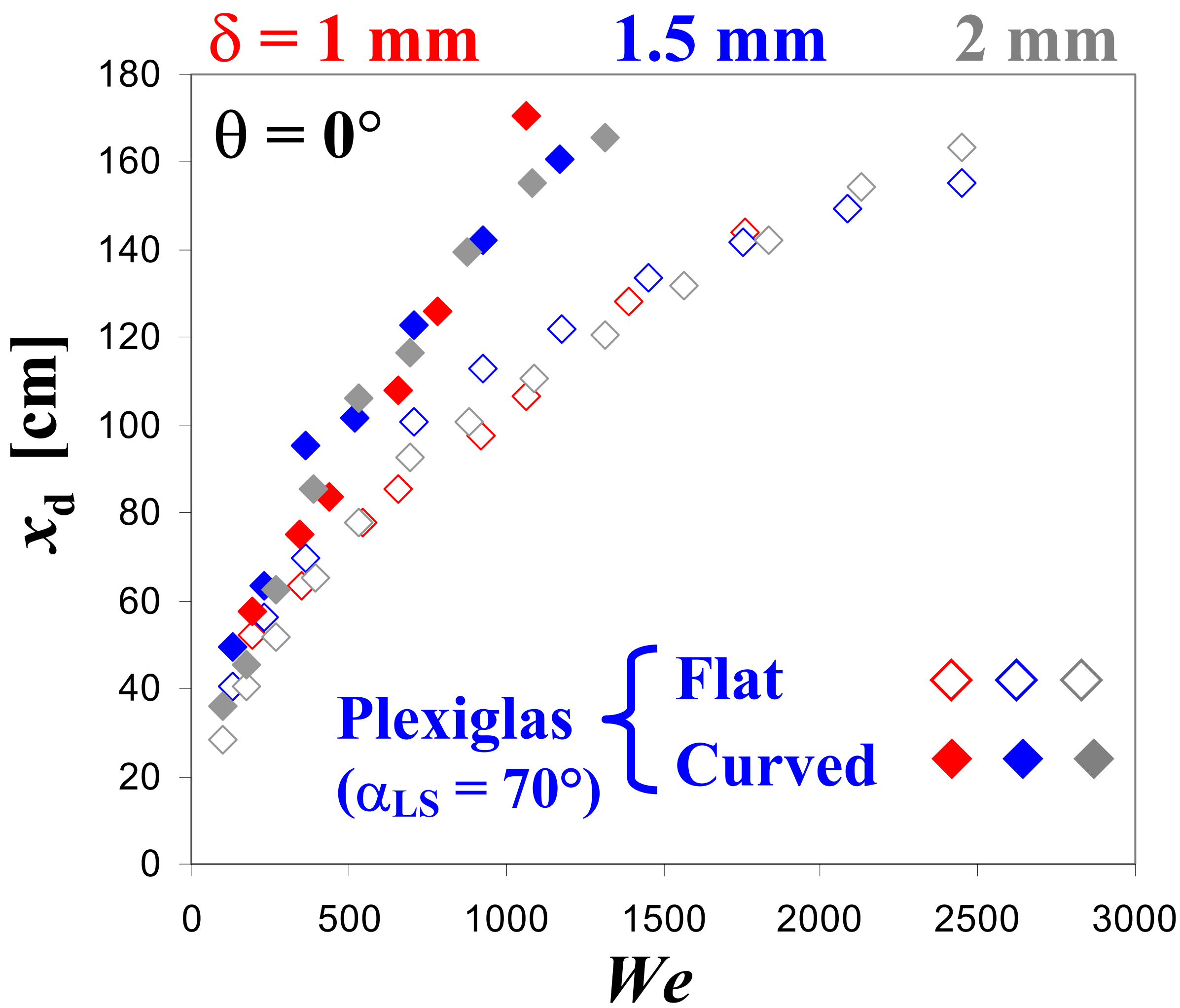
Detachment Distance Vs. Weber Number



Effect of Inclination Angle
(Flat Glass Plate)

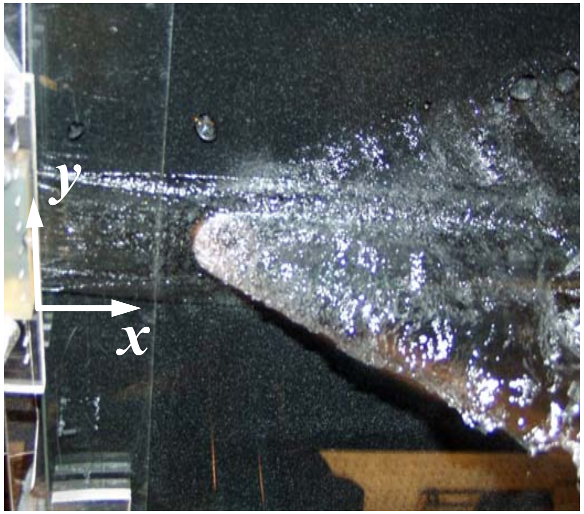


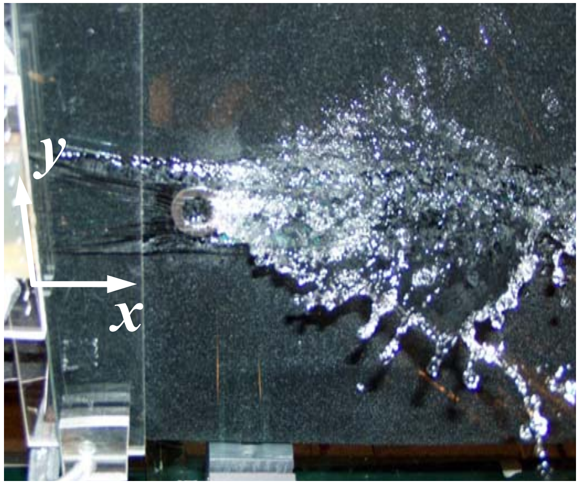
Effect of Weber Number on Detachment Distance (Flat and Curved Surfaces, Zero Inclination)

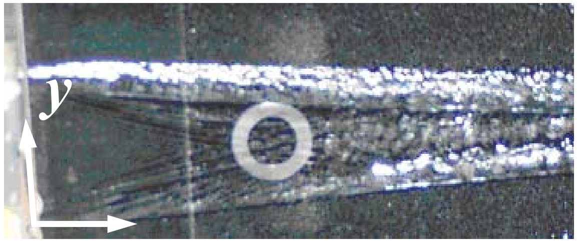


Penetrations and Beam Ports

- Cylindrical obstructions modeling protective dams around penetrations and beam ports incompatible with forced films
- Film either detaches from, or flows over, dam

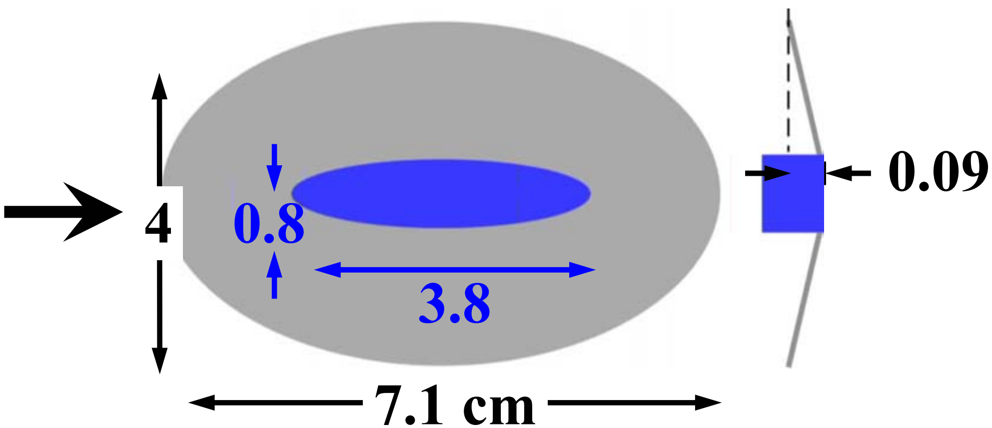


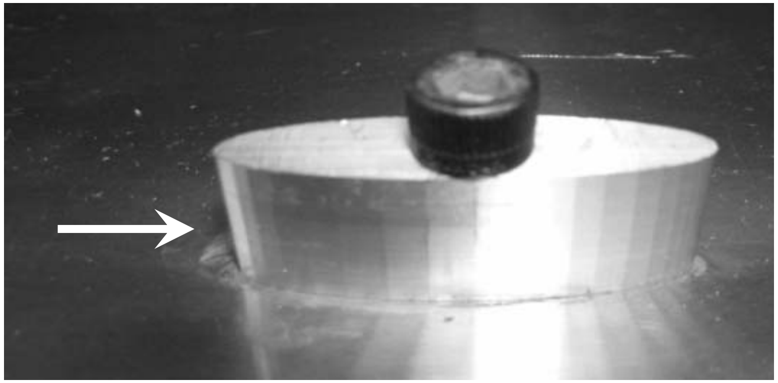




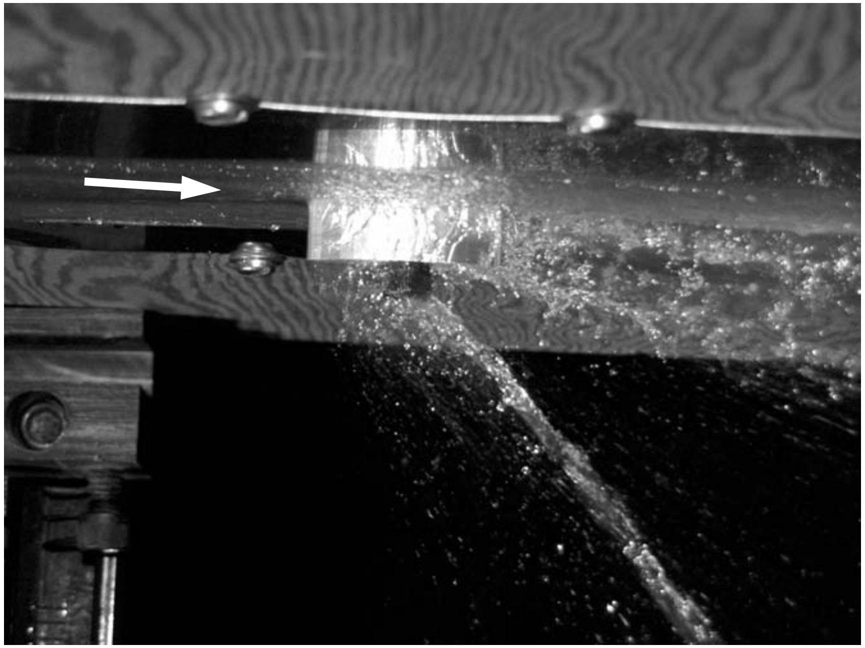
Hydrodynamically Shaped Penetration With Back wall Modification

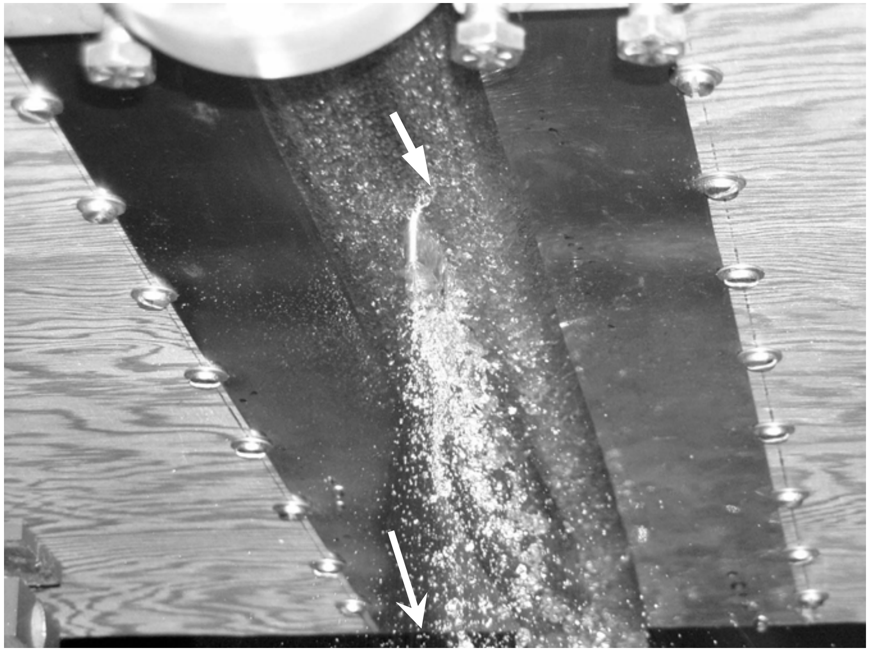
- **Scaled penetration/back wall geometry shown in APEX study to ensure fluid closure downstream of penetration**
  - Simulations for perfectly wetting fluid (0° contact angle)
  - Leading edge x = 16.4 cm from nozzle exit
- **Downward and upward-facing flat surfaces**
  - No centrifugal acceleration





Initial Results





- **Water on stainless steel (contact angle ~50°)**
- ***Re* = 10,000; *We* = 1,000 (APEX: *Re* = 860,000; *We* = 305,000)**
- **Similar results for horizontal upward-facing surface**

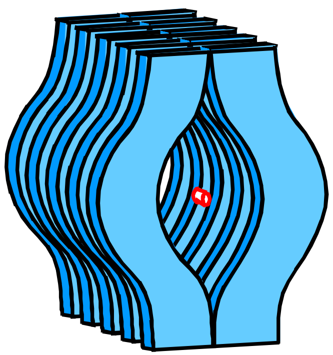
Forced Film Summary

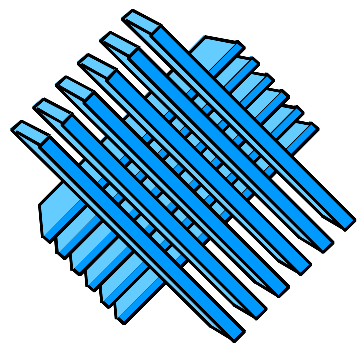
- Design windows for streamwise (longitudinal) spacing of injection/coolant removal slots to maintain attached protective film
  - Detachment length increases w/Weber and Froude numbers
- Wetting chamber first wall surface requires fewer injection slots than nonwetting surface $\Rightarrow$ wetting surface more desirable
- Cylindrical protective dams around chamber penetrations incompatible with effective forced film protection
  - "Hydrodynamically tailored" protective dam shapes may also fail

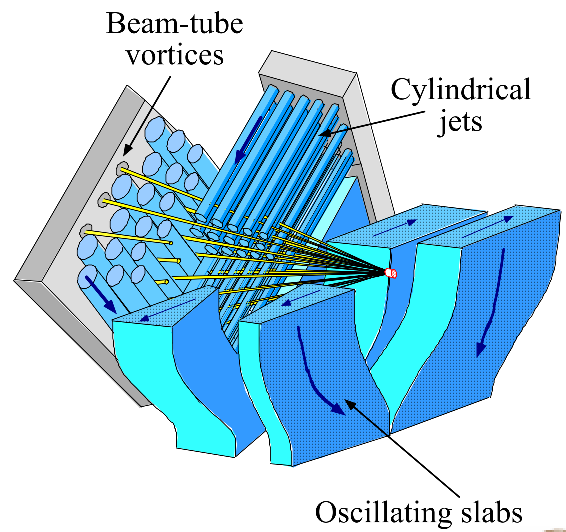
Turbulent Liquid Sheets

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

Major Design Questions

- Is it possible to create "smooth" prototypical turbulent liquid sheets?
  - 5 mm clearance between driver beam, sheet free surface in protective lattice $\Rightarrow$ > 30 year lifetime for final focus magnets

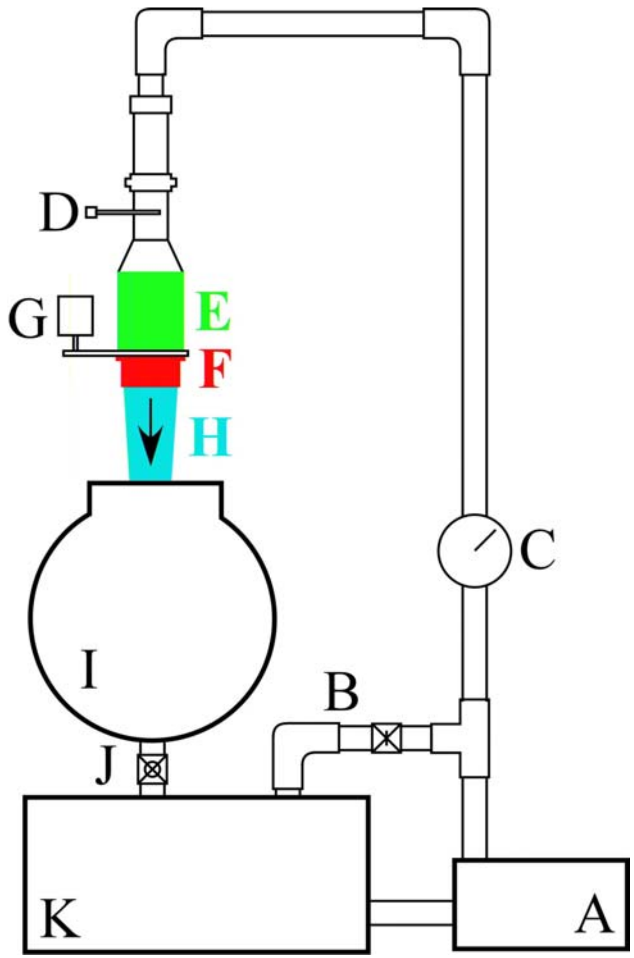
- Can adjacent sheets, once they collide, separate and re-establish themselves before the next fusion event?

- Can the flow be re-established prior to the next fusion event?
  - Chamber clearing
  - Hydrodynamic source term – Beam propagation requirements

Liquid Sheets Parameters

- Length scale δ = initial sheet thickness, Velocity scale U_o = mean speed at nozzle
- Reynolds number, $\boldsymbol{Re} \equiv \boldsymbol{U}_o \delta / \nu_L$
  - HYLIFE-II: $Re \approx 200{,}000$
- Nondimensional distance downstream of nozzle x / δ
  - Measured from nozzle
  - HYLIFE-II: $x / \delta < 30$ over protective pocket
- Nozzle dimensions $W_o \times \delta$
  - $W_o = 10$ cm; $\delta = 1$ cm $\Rightarrow$ aspect ratio $AR = 10$

Flow Loop

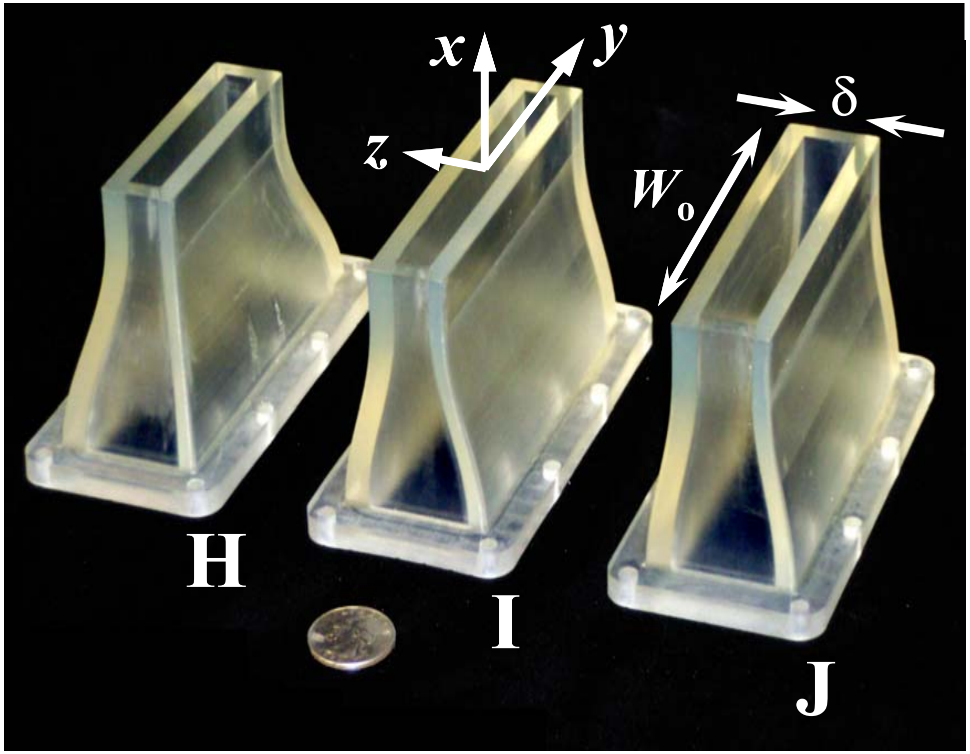


- Pump-driven recirculating flow loop
- Test section height ~1 m
- Overall height ~5.5 m

A	Pump	B	Bypass line
C	Flow meter	D	Pressure gage
E	Flow straightener		
F	Nozzle	G	Oscillator (Not used)
H	Sheet	I	400 gal tank
J	Butterfly valve	K	700 gal tank

Nozzle Geometries

- Rapid prototyped in DSM® Somos WaterClear™
- 5th order polynomial contractions with inlet cross-section 10 cm × 3 cm ($y \times z$)
- Straight channel at nozzle exit (1 cm x-extent)
- Three different nozzles

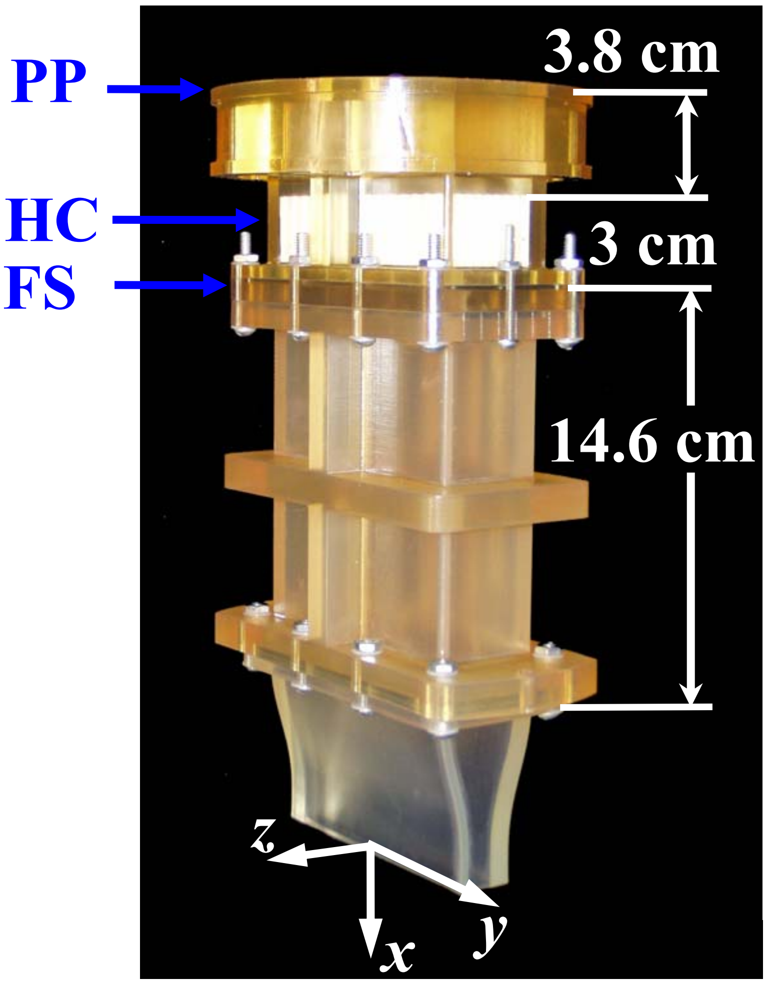


H 3D contraction: exit aspect ratio $AR = 6.7$; $W_o = 6.7$ cm × $\delta = 1$ cm ($y \times z$)

I 2D contraction: $AR = 10$; $W_o = 10$ cm × $\delta = 1$ cm ($y \times z$)

J 2D contraction: $AR = 6.7$; $W_o = 10$ cm × $\delta = 1.5$ cm ($y \times z$)

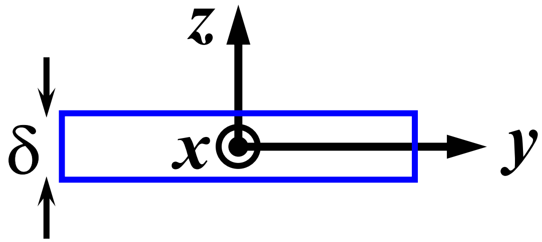
Flow Conditioning



- Round inlet (12.7 cm ID) to rectangular cross-section 10 cm × 3 cm ($y \times z$)
- Perforated plate (PP)
  - Open area ratio 50% with staggered 4.8 mm dia. holes
- Honeycomb (HC)
  - 3.2 mm dia. × 25.4 mm staggered circular cells
- Fine mesh screen (FS)
  - Open area ratio 37.1%
  - 0.33 mm dia. wires woven w/ open cell width of 0.51 mm (mesh size 30 × 30)
- 5^{th} order contracting nozzle
  - Contraction ratio = 3
- Note: No BL trimming

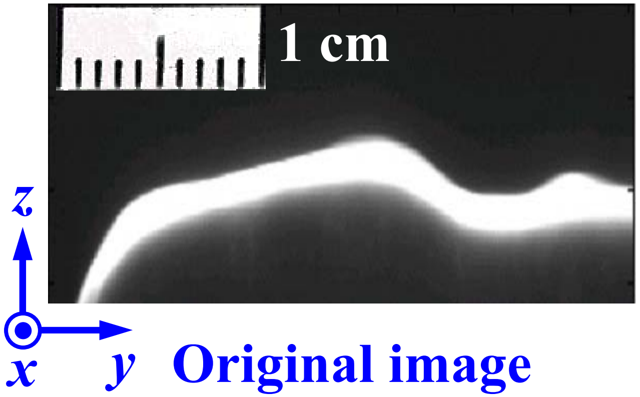
Experimental Parameters

- δ = 1 cm; aspect ratio $AR = 10$
- **Reynolds number** Re **= 130,000** [U_o average speed; ν liquid kinematic viscosity]
- **Weber number** We **= 19,000** [ρ_L liquid density; σ surface tension]
- **Froude number** Fr **= 1,400**
- **Fluid density ratio** ρ_L / ρ_G **= 850** [ρ_G gas density]
- **Near-field:** $x / \delta \leq 25$



Surface Ripple Measurements

- Free surface ⇒ interface between fluorescing water and air
  - Planar laser-induced fluorescence (PLIF)
- Free surface found w/edge detection
  - Threshold individual images
- σ_z = standard deviation of free surface *z*-position spatially averaged over central 7.5 cm of flow



Original image

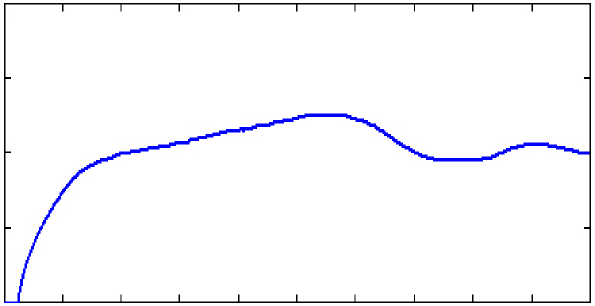
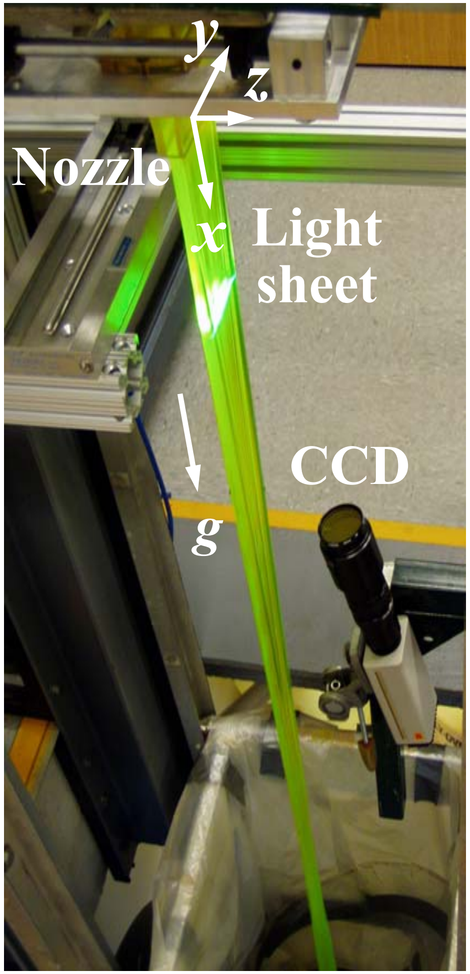
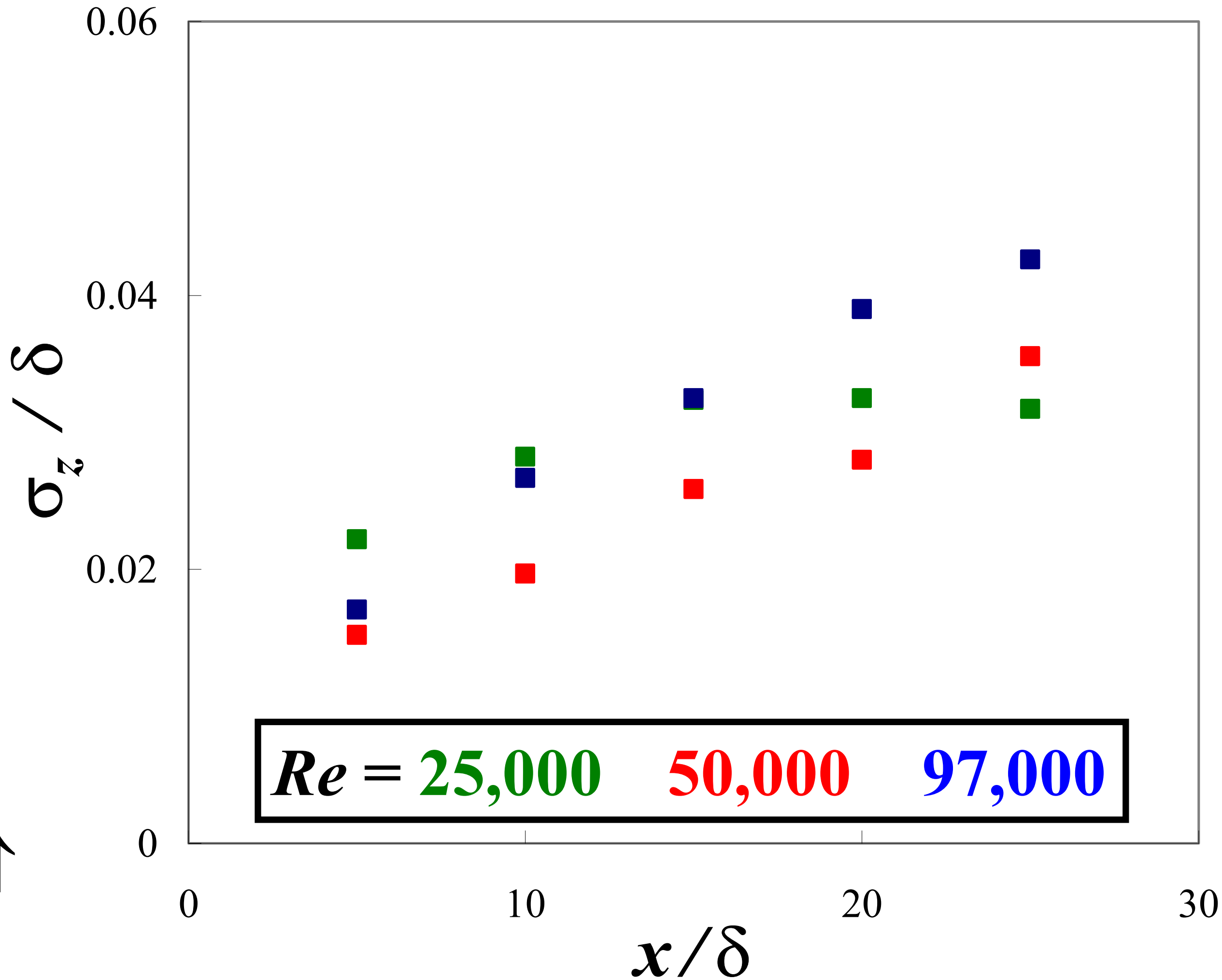


Image after thresholding, edge detection



Surface Ripple: Nozzle H

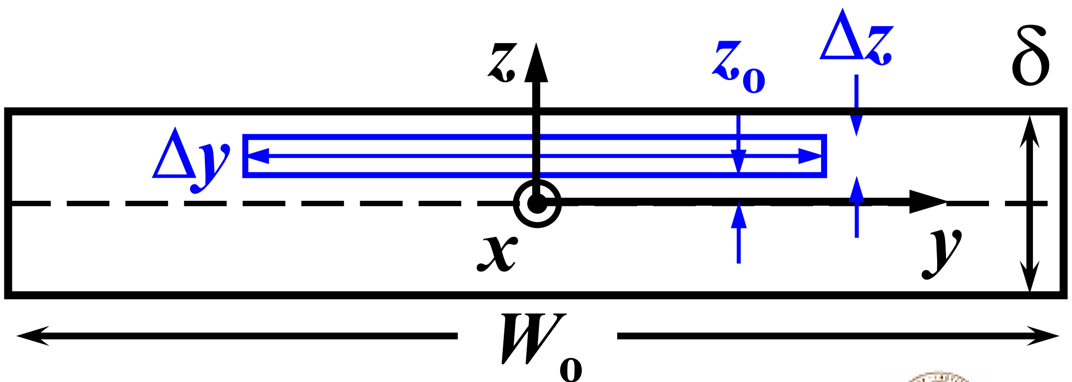
- σ_z measure of average surface ripple
- $\sigma_z / \delta < 4.3\%$ for $x / \delta < 25$
- σ_z essentially independent of *Re*
- $\sigma_z \uparrow$ slightly as $x \uparrow$



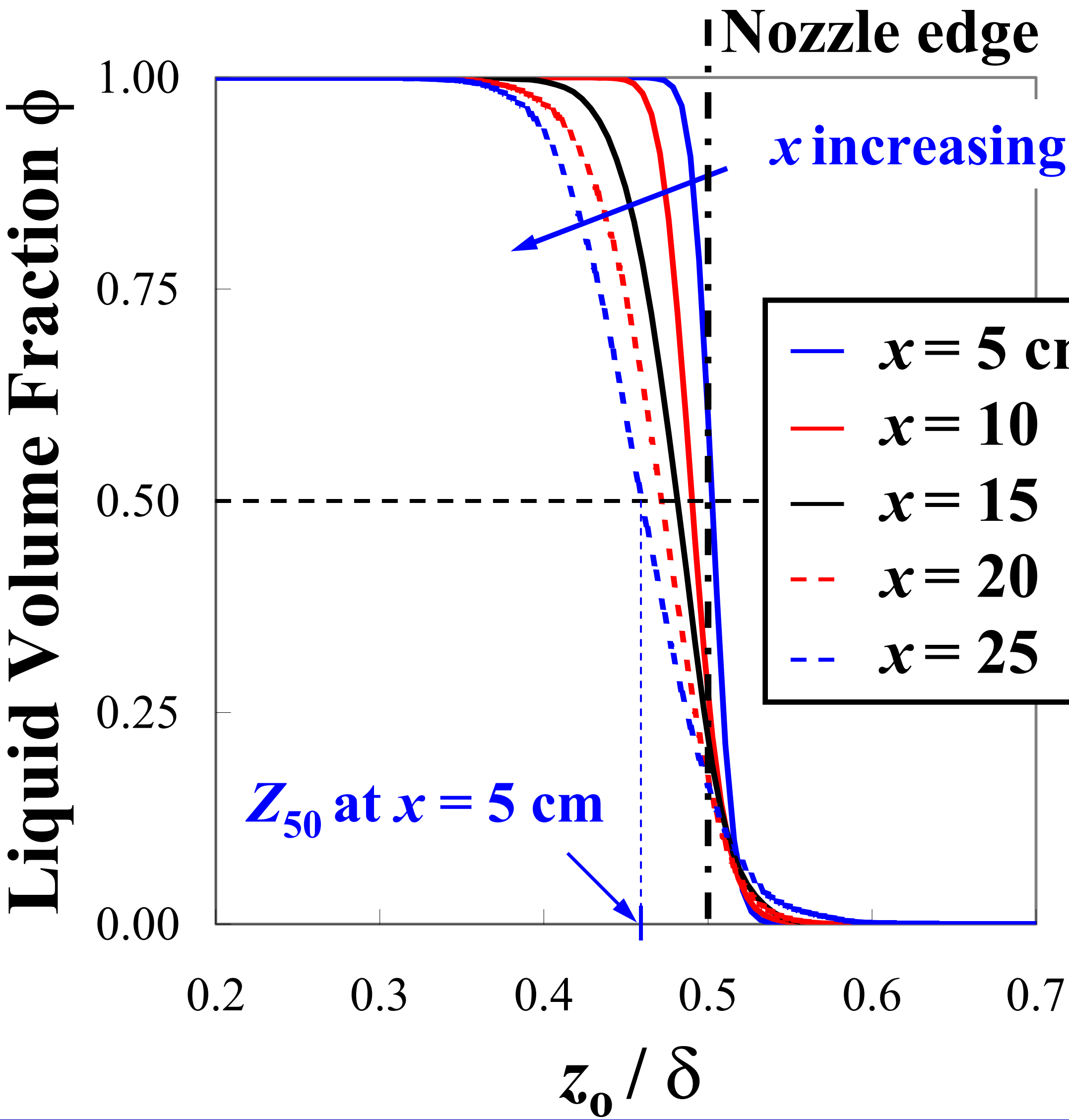
Liquid Cumulative Distribution Function

- Liquid cumulative distribution function (LCDF) = liquid volume fraction ϕ within a $\Delta y \times \Delta z$ "box" located at z at given x
  - Results for box at nozzle edge useful in neutronics calculations

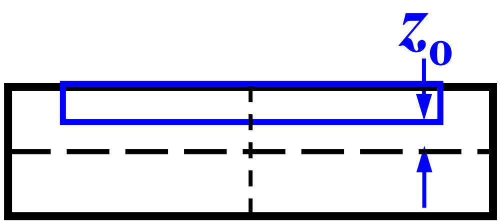
- Calculate liquid volume fraction in rectangular box at given x location: box spans $-0.5\Delta y \le y \le +0.5\Delta y$; $z_o \le z \le z_o + \Delta z$
  - $\Delta z / \delta = 0.01$
  - $\Delta y / W_o = 0.1 - 0.8$



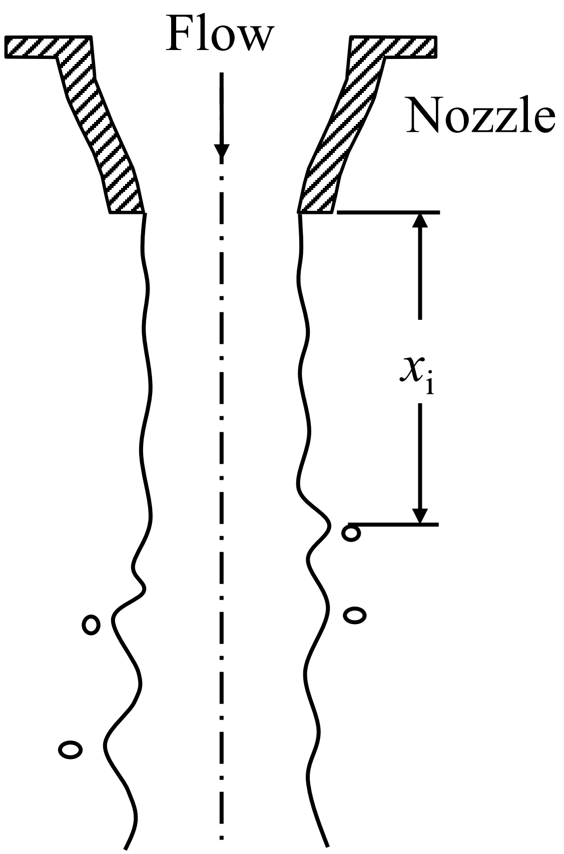
LCDF Results: *Re* = 130,000



- Z_{50}, or z-extent of $\phi = 0.5$ region, characterizes sheet "thickness" at each x
- Nozzle edge at $z_o / \delta = 0.5$
- Box size 0.01 cm × 6 cm



Turbulent Breakup



- **Turbulent primary breakup**
  - Formation of droplets along free surface: "hydrodynamic source term"
  - Due to vorticity imparted at nozzle exit
- **Onset of breakup, x_i**
  - Location of first observable droplets
  - $x_i \downarrow$ as Weber number $We \uparrow$

RPD-2002 Jet Layout

Row	R (cm)	D_j (cm)	Row	R (cm)	D_j (cm)
0	90	4.61	6	155.0	8.95
1	98.07	5.15	7	170.6	10.0
2	107.1	5.75	8	188.1	11.2
3	117.1	6.42	9	207.7	12.5
4	128.4	7.18	10	229.5	13.9
5	140.9	8.01	11	253.9	15.6

- Jet speeds >12 m/s
- 252 jets total
- 12 rows/quad

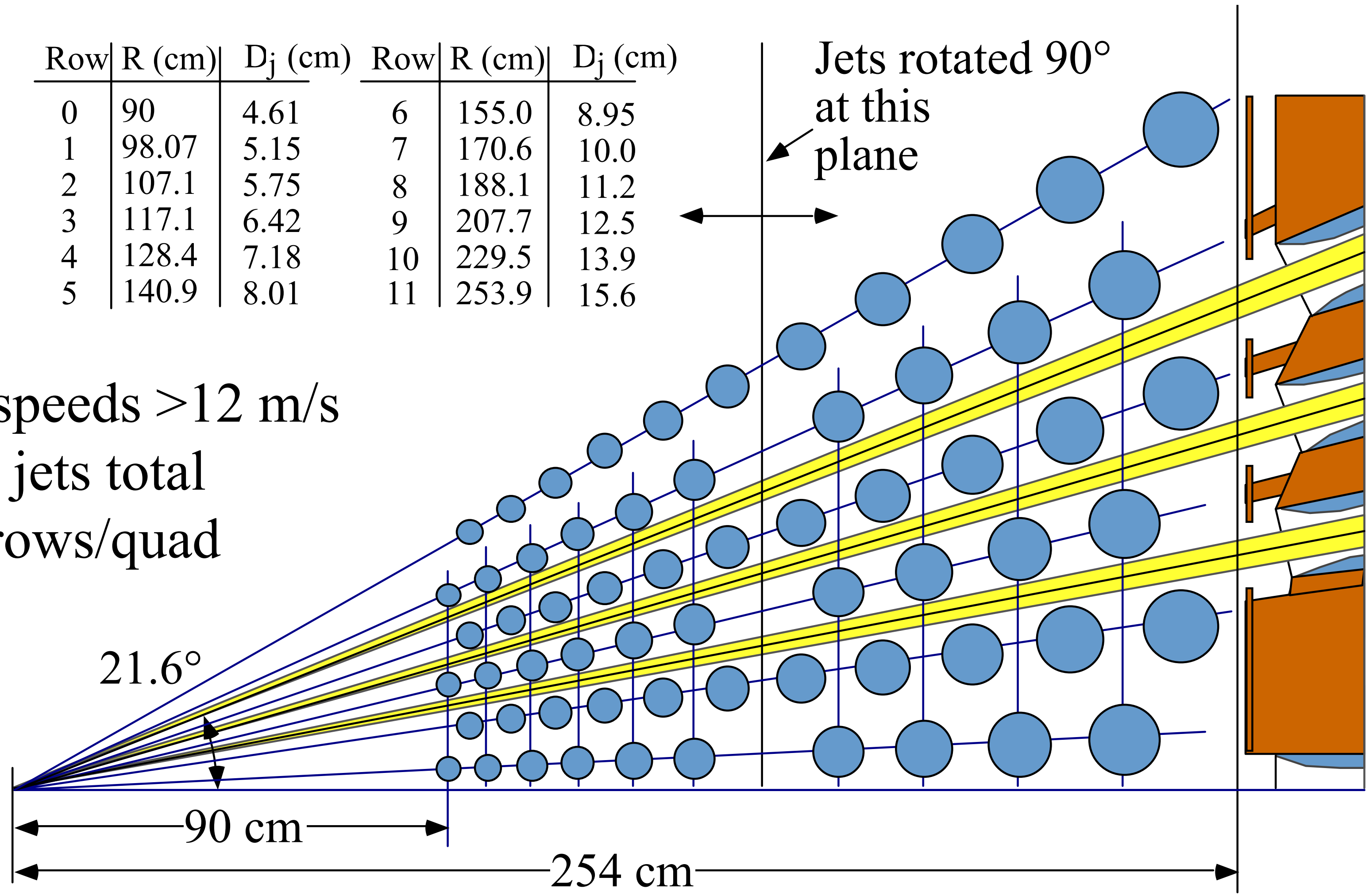


Diagram courtesy P.F. Peterson, UCB

RPD-2002 Correlation Results

[Sallam, Dai, & Faeth 2002]

- **Total droplet mass ejection rate ≈ 1300 kg/s**
  - Assumes $G(x = 1\ \text{m})$ over entire surface area of each respective jet (Mean value of predictions)
  - ~3% of total jet mass flow rate
- **Sauter mean dia. ≈ 5.7 mm for all jets at $x = 1$ m**
  - SMD at $x_i \approx 0.82 - 1.0$ mm for $d = 4.61 -$ 15.6 cm, respectively

Comments

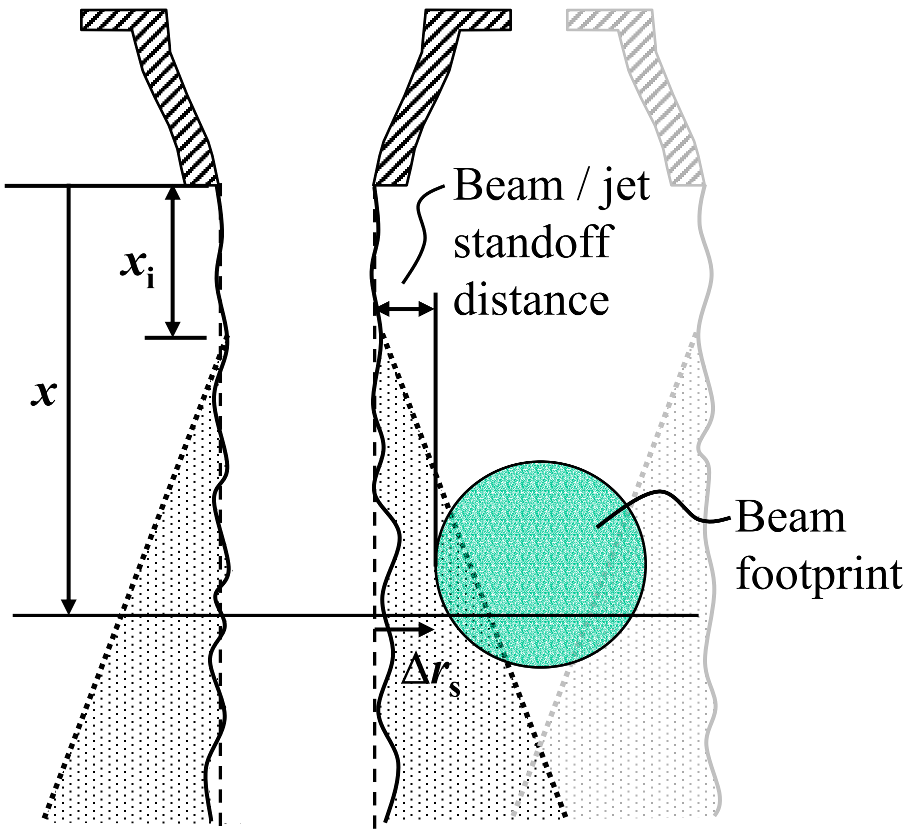
- **Evaporation rate due to target energy deposition assuming 6 Hz**

	Total (MJ)	X-rays and ions (MJ)	Mass rate (kg/s) *
NRL - DD	**154**	**45**	**37 - 51**
HIF - ID	**458**	**142**	**116 - 160**

* Saturated Flibe: $\Delta h = h_{fg} = 5.3$ MJ/kg
Subcooled Flibe: $\Delta h = 7.3$ MJ/kg

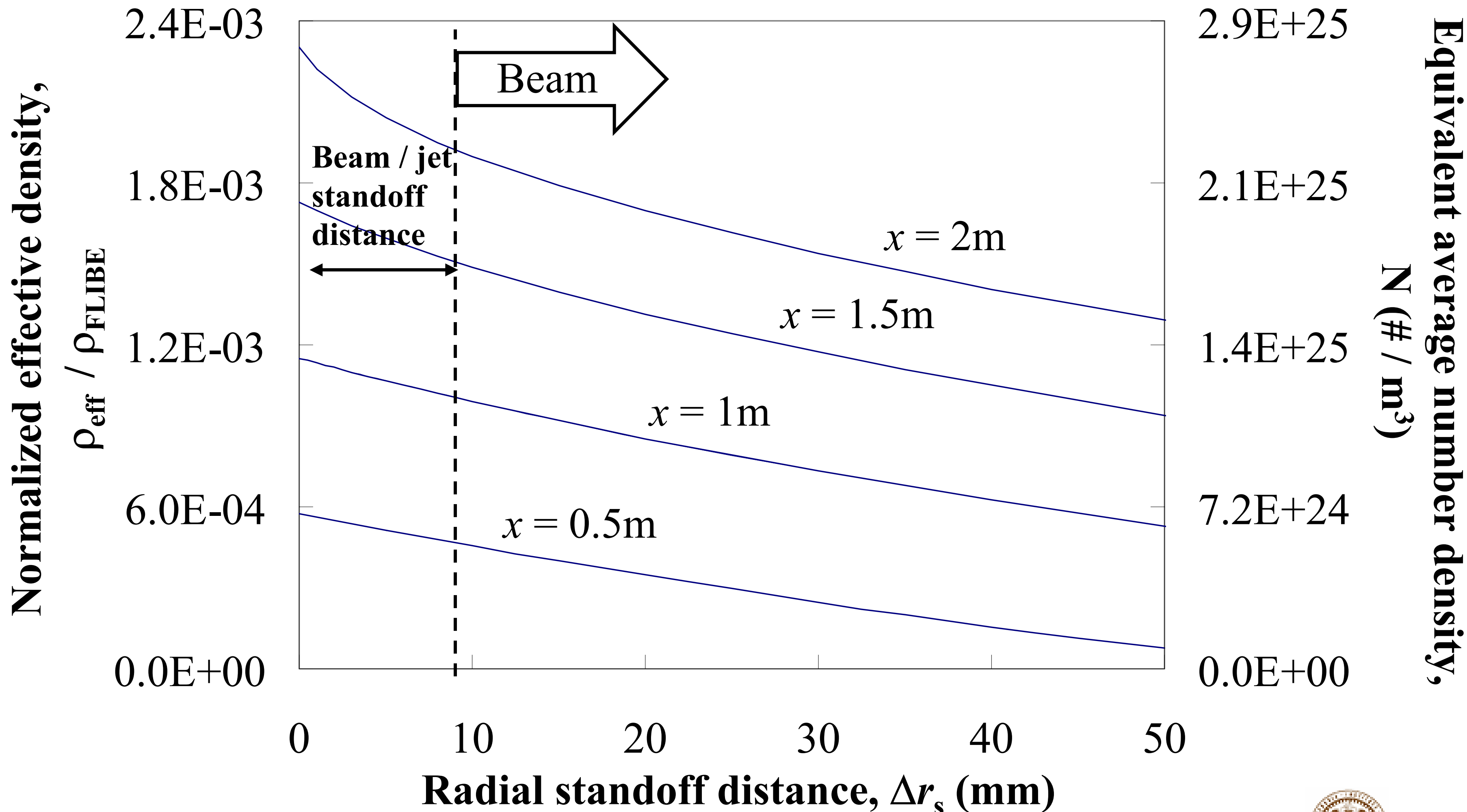
- **Hydrodynamic source term ~1300 kg/s !**
  - Must be reduced (flow conditioning, nozzle, BL cutting, etc.)

Implications for Beam Propagation



- **Droplets enter into beam footprint**
- **Radial standoff, Δr_s**
  - Measured from nominal jet surface
- **Equivalent number density dependent on x and Δr_s**
  - Ignores jet-jet interactions

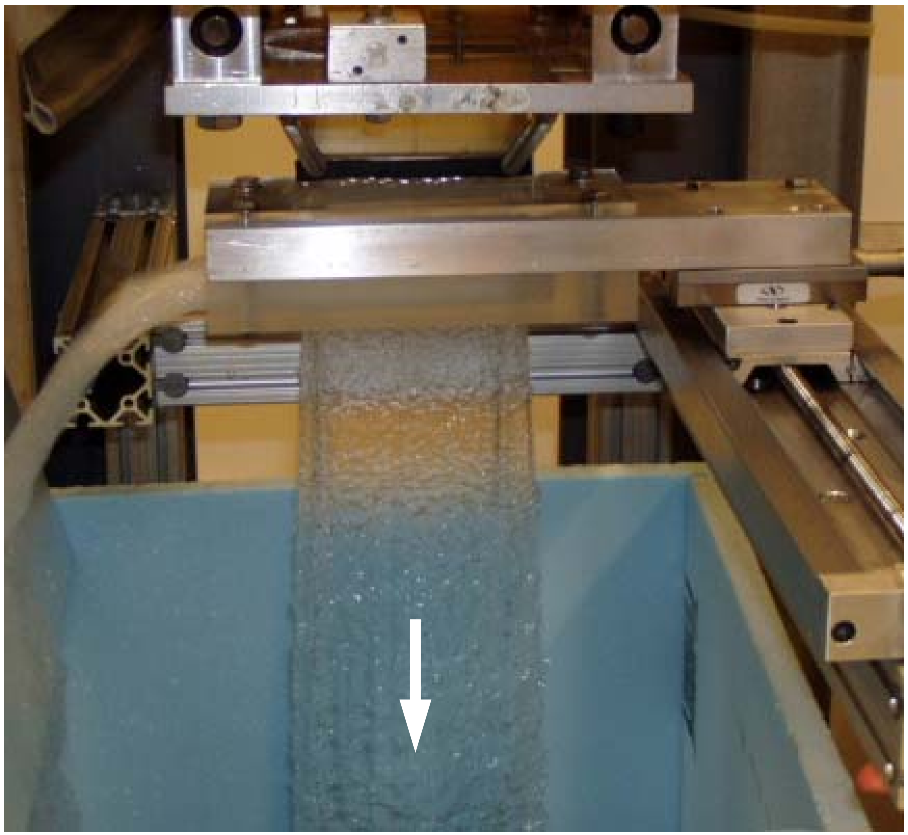
Implications for Typical RPD-2002 Jet: d = 4.61 cm (Row 0)



Beam Propagation Implications

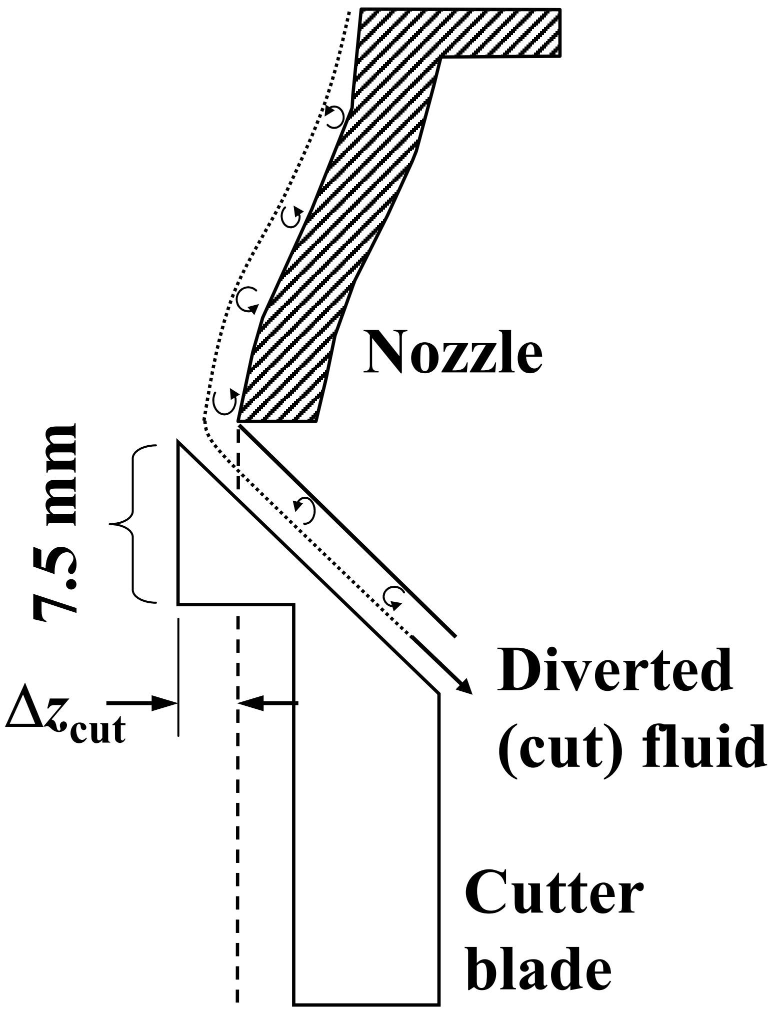
- **Model predictions imply protection concept is incompatible with beam propagation requirements**
- **However, model is based on :**
  - Fully developed turbulent pipe flow at exit
  - No flow conditioning, nozzle or BL cutting
- **Can nozzles / jets be designed to reduce these number densities to a level compatible with beam propagation requirements?**

Boundary Layer Cutter



- **"Cut" (remove BL fluid) on one side of liquid sheet**
- **Independently control:**
  - Cut depth, Δz_{cut}
  - Downstream location of cut, x
- **Removed liquid (~0.18 kg/s) diverted to side**

Cutter Details

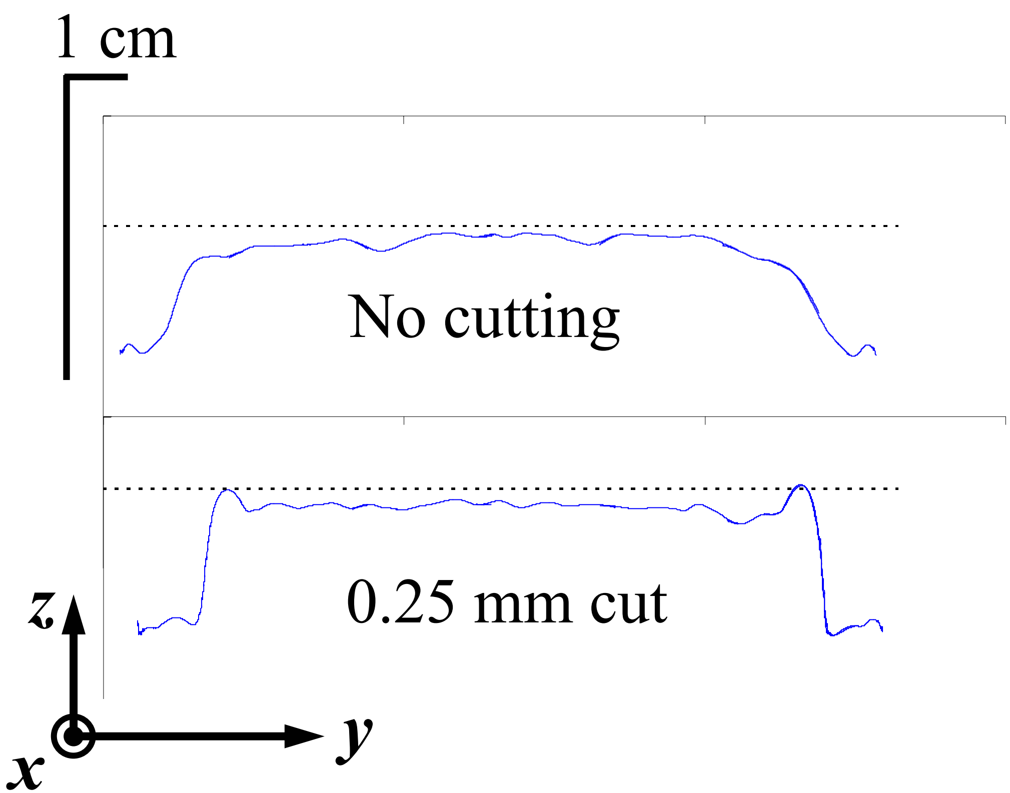


- **Aluminum blade inserted into flow**
  - Remove high vorticity / low momentum fluid near nozzle wall
  - Blade face tilted 0.4° from vertical
  - Blade width (*y*-extent) 12 cm
- **Relatively short reattachment length**
  - Nozzle contraction length 63 mm

Summary: BL Cutting

- **Reduces surface ripple by 17% for Δz_{cut} = 0.25 mm and standard flow conditioner**
  - Preliminary data suggest 48% reduction in surface ripple for $\Delta z_{cut} = 0.38$ mm ($Re = 97{,}000$; $x / \delta = 16$)
- **Re-emergence of "dog-bone" structures as seen at lower *Re***
- **Jet width (*y*-extent) decreased by ~6 mm at $x / \delta = 25$**

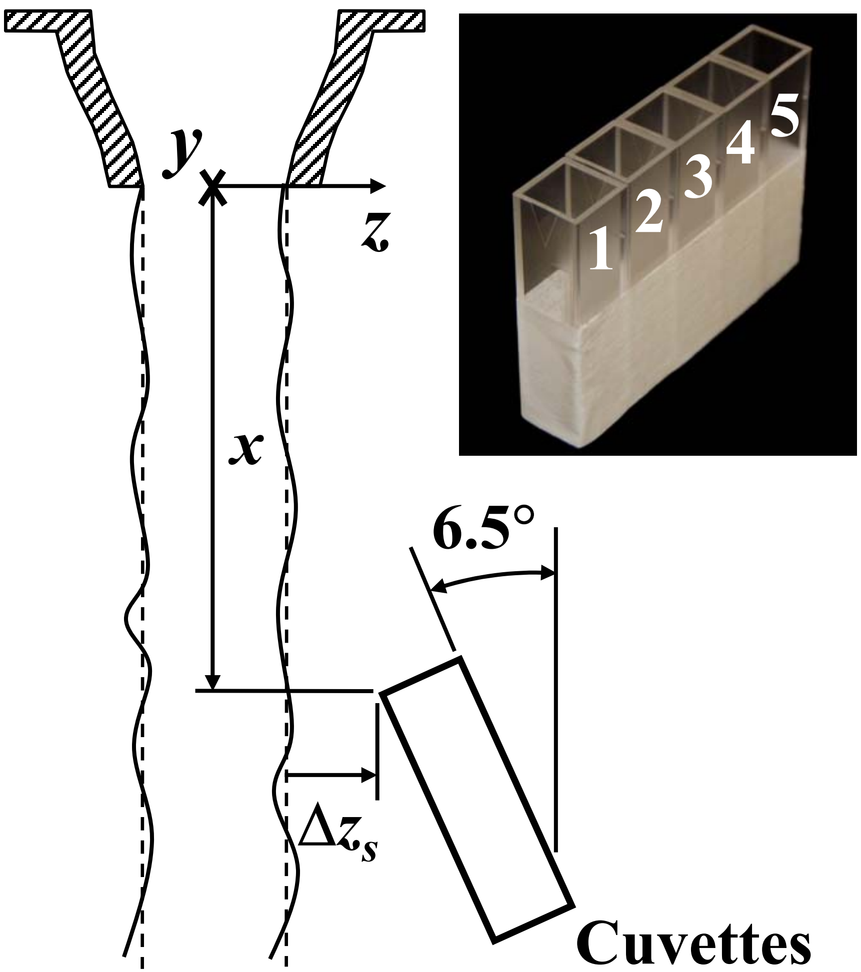
Jet Profiles
(x / δ = 15)



Note: Vertical axis at 5× magnification

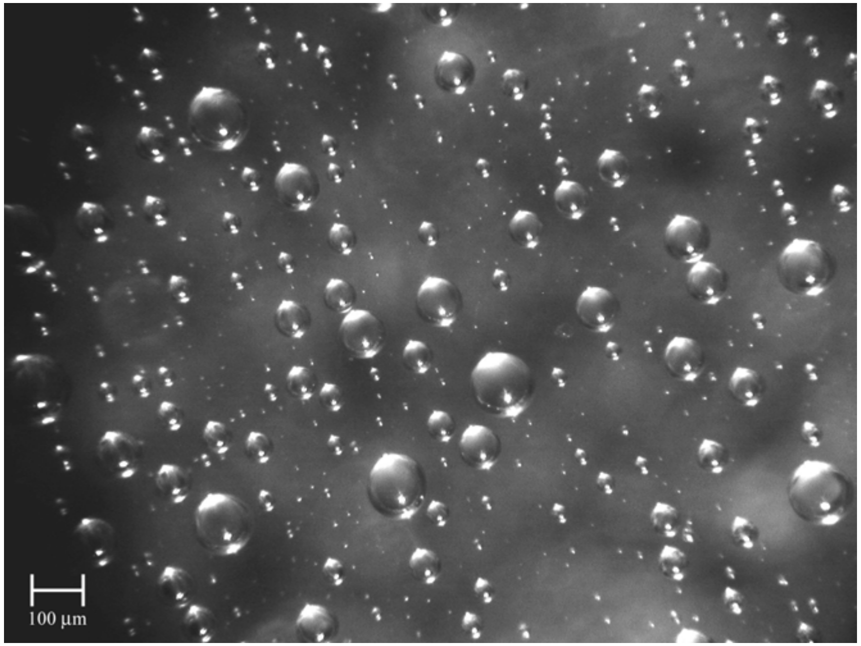
- Obtained from average of 130 images over 4.3 s
- Standard flow conditioning design
- Cut depth, Δz_{cut} = 0.25 mm
- Nominal free surface (jet nozzle) indicated by dashed lines
- BL cutting results in “dog-bone” structures near edges of jet

Mass Collection Procedure



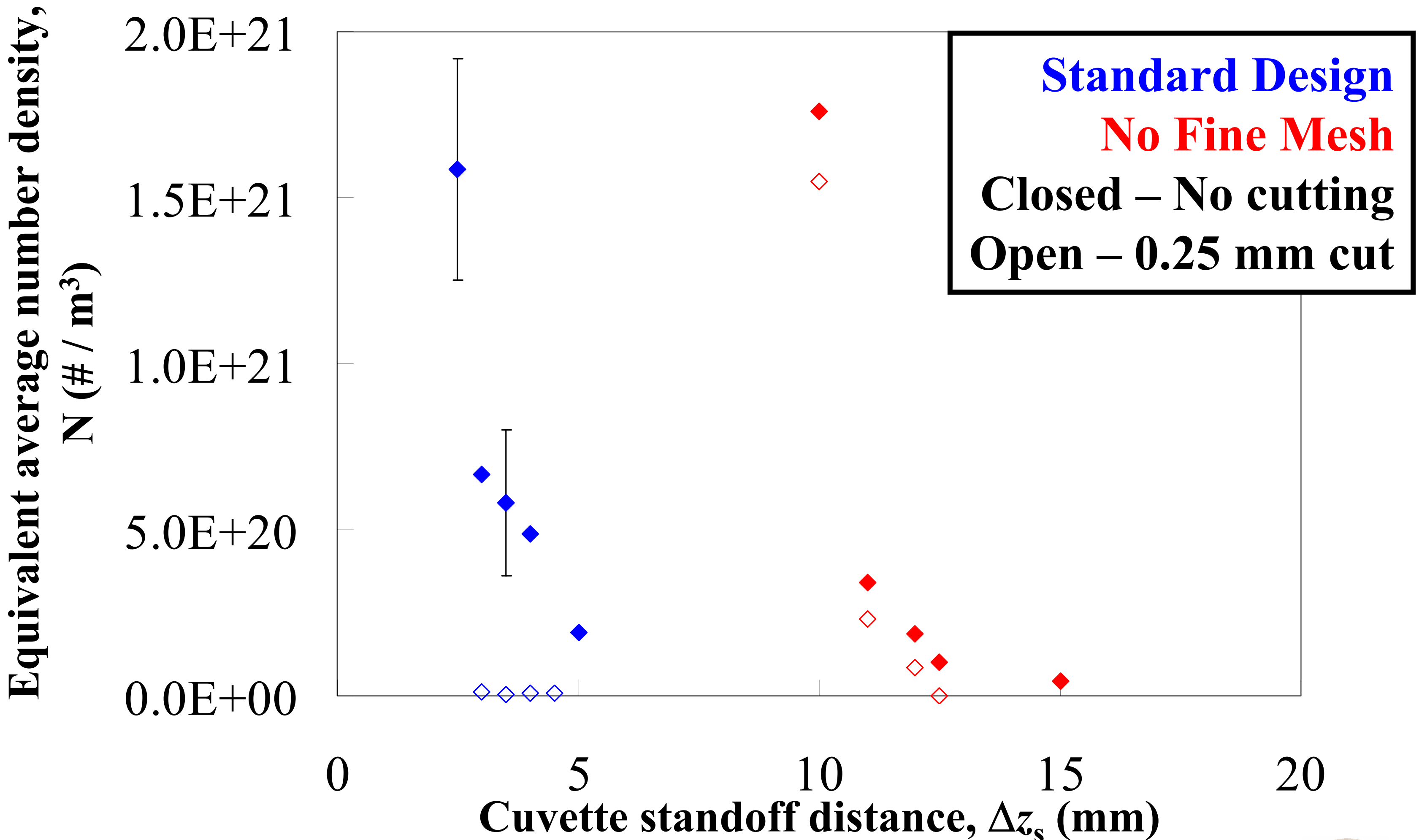
- **Cuvette opening = 1 cm × 1 cm w/0.9 mm wall thickness**
- **Five adjacent cuvettes**
  - Cuvette #3 centered at $y = 0$
- **Located at x, Δz_s away from nominal jet position**
  - $\Delta z_s \cong 2.5$–15 mm
  - Experiments repeated to determine uncertainty in data
- **Mass collected over 0.5–1 hr**

Droplet Visualizations



- **Droplets collected on coated microscope slide**
  - Standard flow conditioning
  - Re = 130,000; $x / \delta = 25$
  - Diameters O(1–100 µm)
- **Initial visualizations for no fine mesh suggest intermittent ejection of large (~1 mm dia.) drops**
- **Model predicts SMD = 0.6 – 1.3 mm**
  - No flow conditioning

Experimental Number Density
(x / δ = 25)



Summary: Mass Collection

- **Flow straightening and contracting nozzle significantly reduce ejected droplet mass (by 3–5 orders of magnitude) compared w/model**
- **BL cutting has considerable impact on collected droplet mass**
- **BUT: proper flow conditioning more important**
- **Flow conditioning and BL cutting reduce collected droplet mass by orders of magnitude (compared with model predictions)**

Conclusions

- **Hydrodynamic source term sensitive to initial conditions**
- **Jet geometry, surface ripple and breakup affected by flow conditioning**
- **Flow conditioning / converging nozzle reduces droplet mass flux (and number density) by 3–5 orders of magnitude over model predictions**
- **BL cutting appears to eliminate droplet ejection for a "well-conditioned" jet**
- **Preventing blockage of fine mesh screens major issue**

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