Hydrodynamics of Liquid Protection schemes for IFE Reactor Chambers

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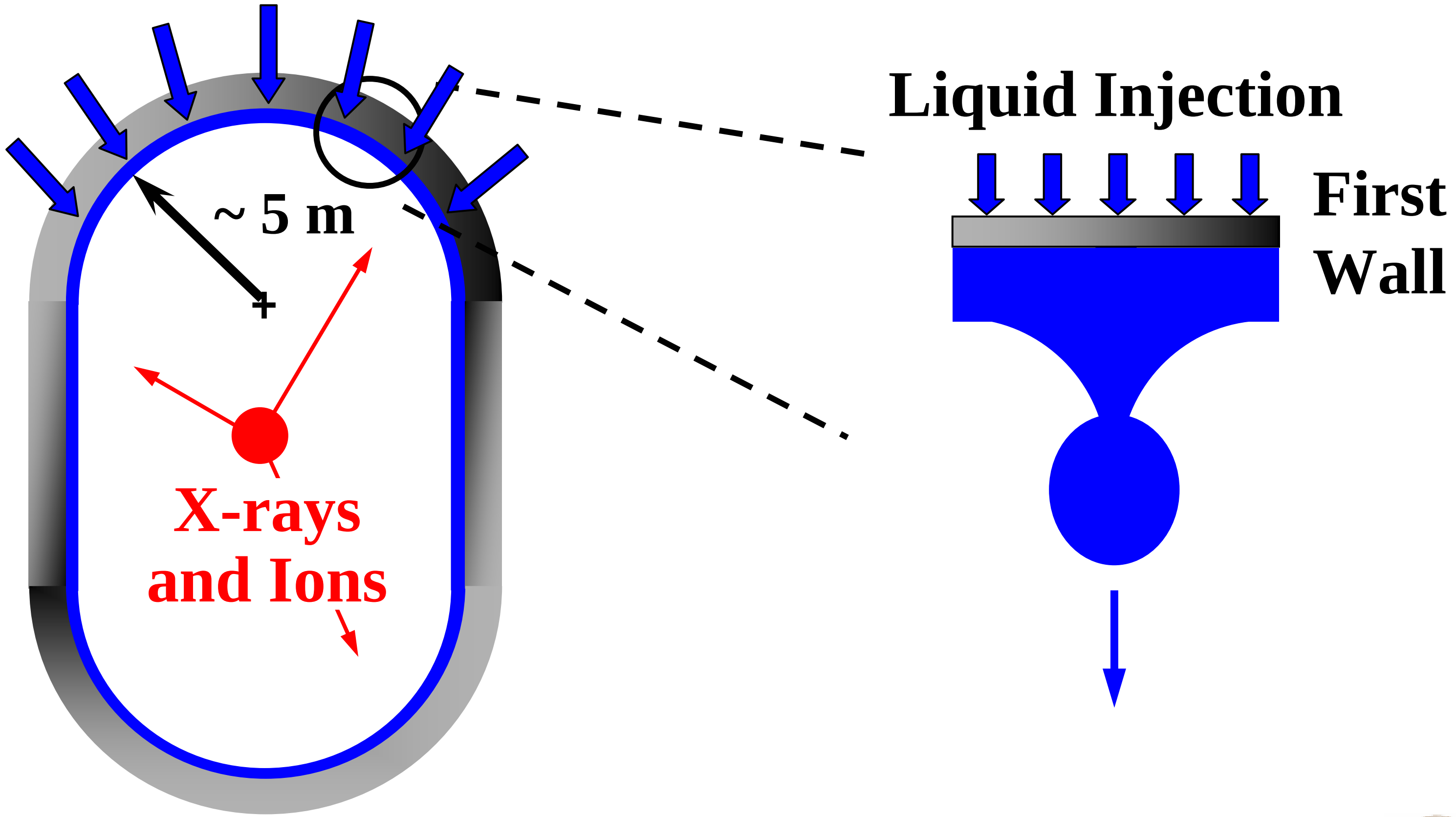
OUTLINE

- **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**

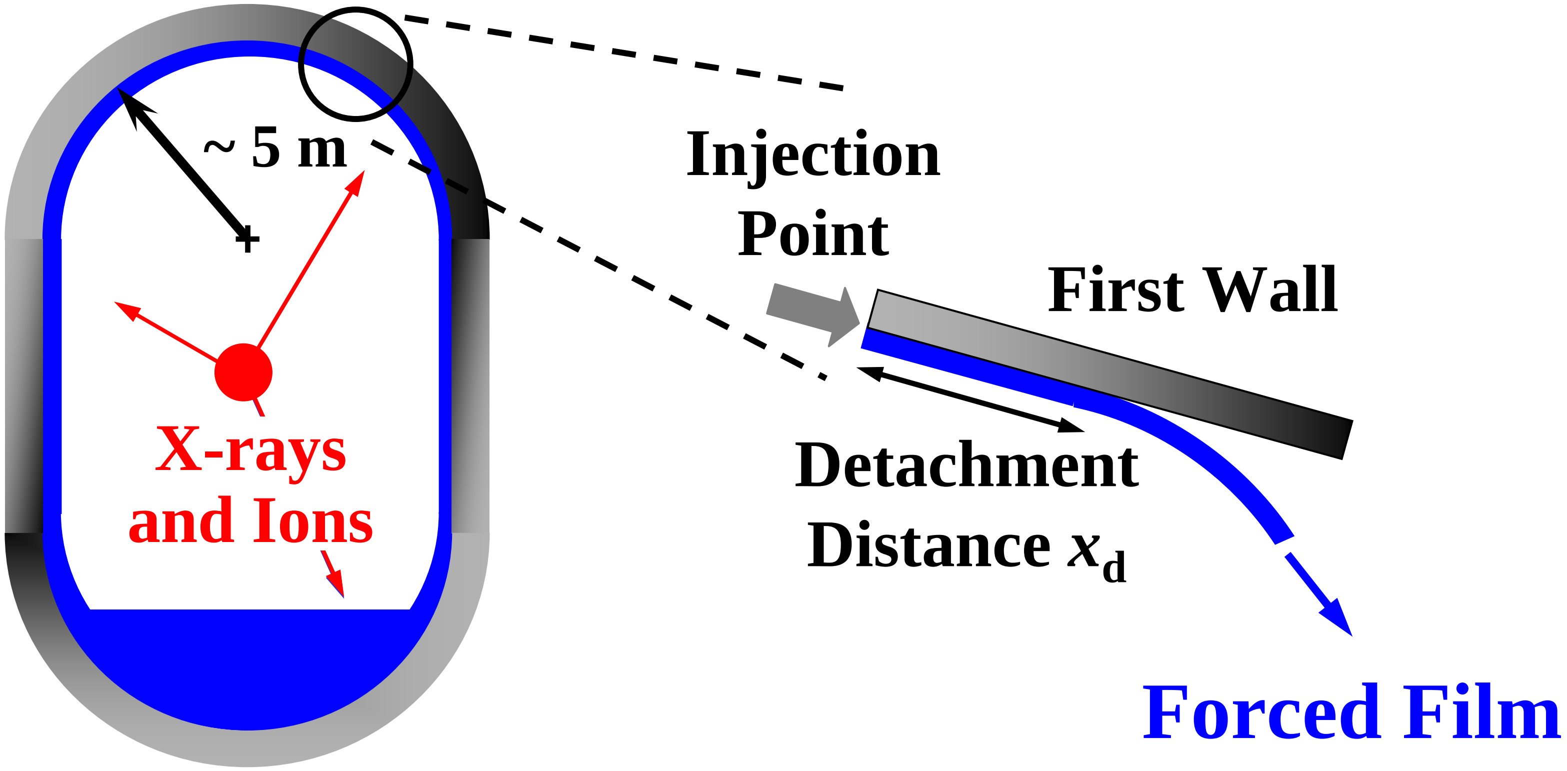
Wetted Wall Concept--*Problem Definition*

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



Forced Film Concept -- *Problem Definition*

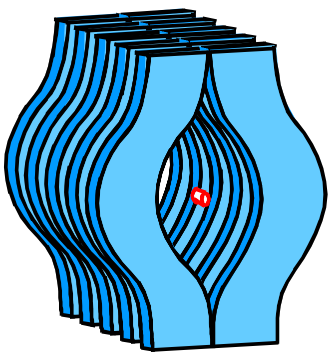
Prometheus: Few mm thick Pb "forced film" injected tangentially at >7 m/s over upper endcap

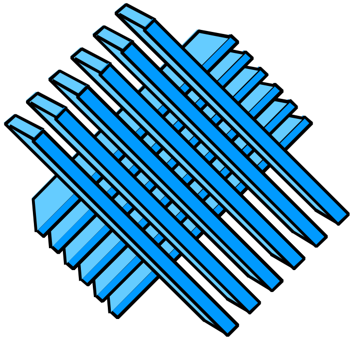


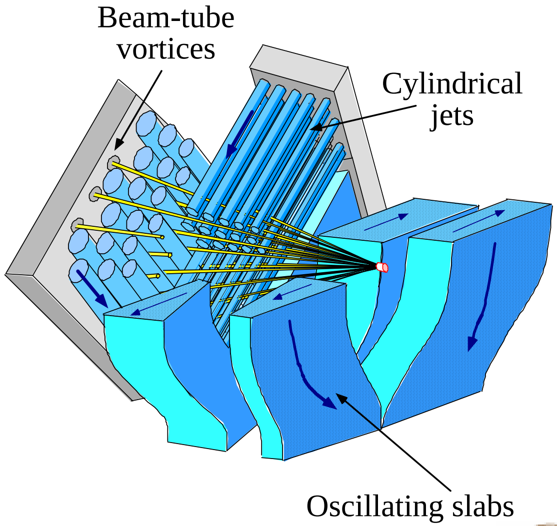
Turbulent Liquid Sheets

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

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

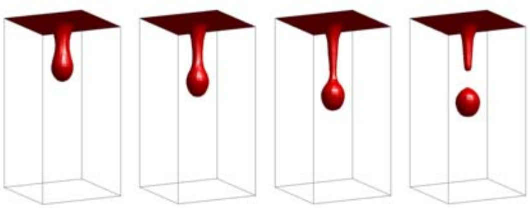
- Droplet detachment time
- Equivalent droplet diameter
- Minimum film thickness prior to detachment

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

Numerical Simulation of Porous Wetted Walls
Effect of Evaporation/Condensation at Interface

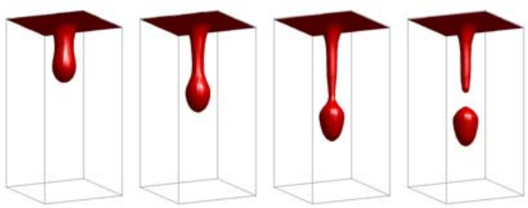
- $z_o^*=0.1$, $w_{in}^*=0.01$, Re=2000

$m_f^+=-0.005$
(Evaporation)



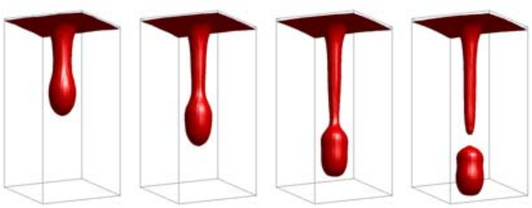
$\tau^*=31.35$

$m_f^+=0.0$



$\tau^*=27.69$

$m_f^+=0.01$
(Condensation)



$\tau^*=25.90$

Numerical Simulation of Porous Wetted Walls
Wetted Wall Parameters

- Length, velocity, and time scales :

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

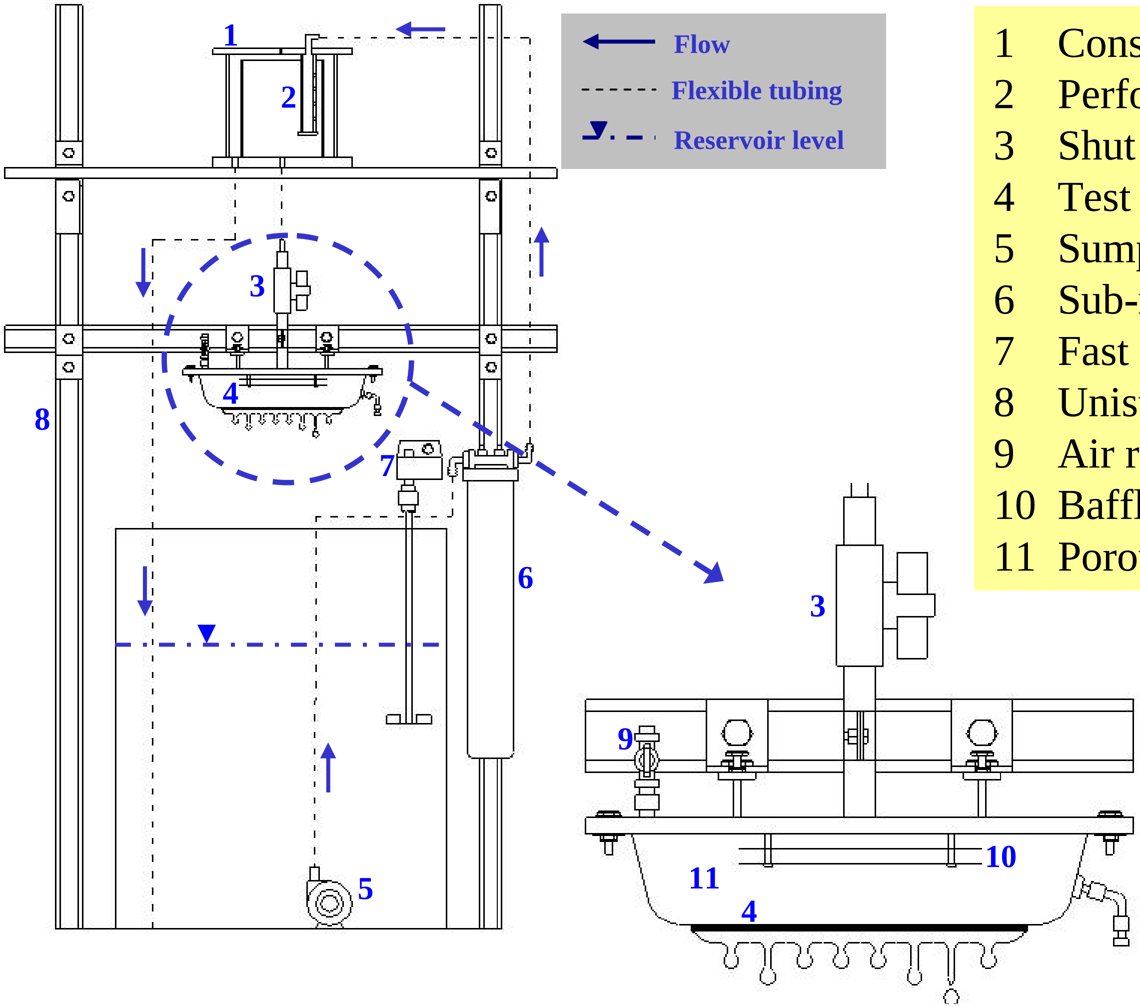
- Nondimensional drop detachment time : $\tau^* \equiv t_d / t_o$

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

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

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

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 Variables

Experimental Variables

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

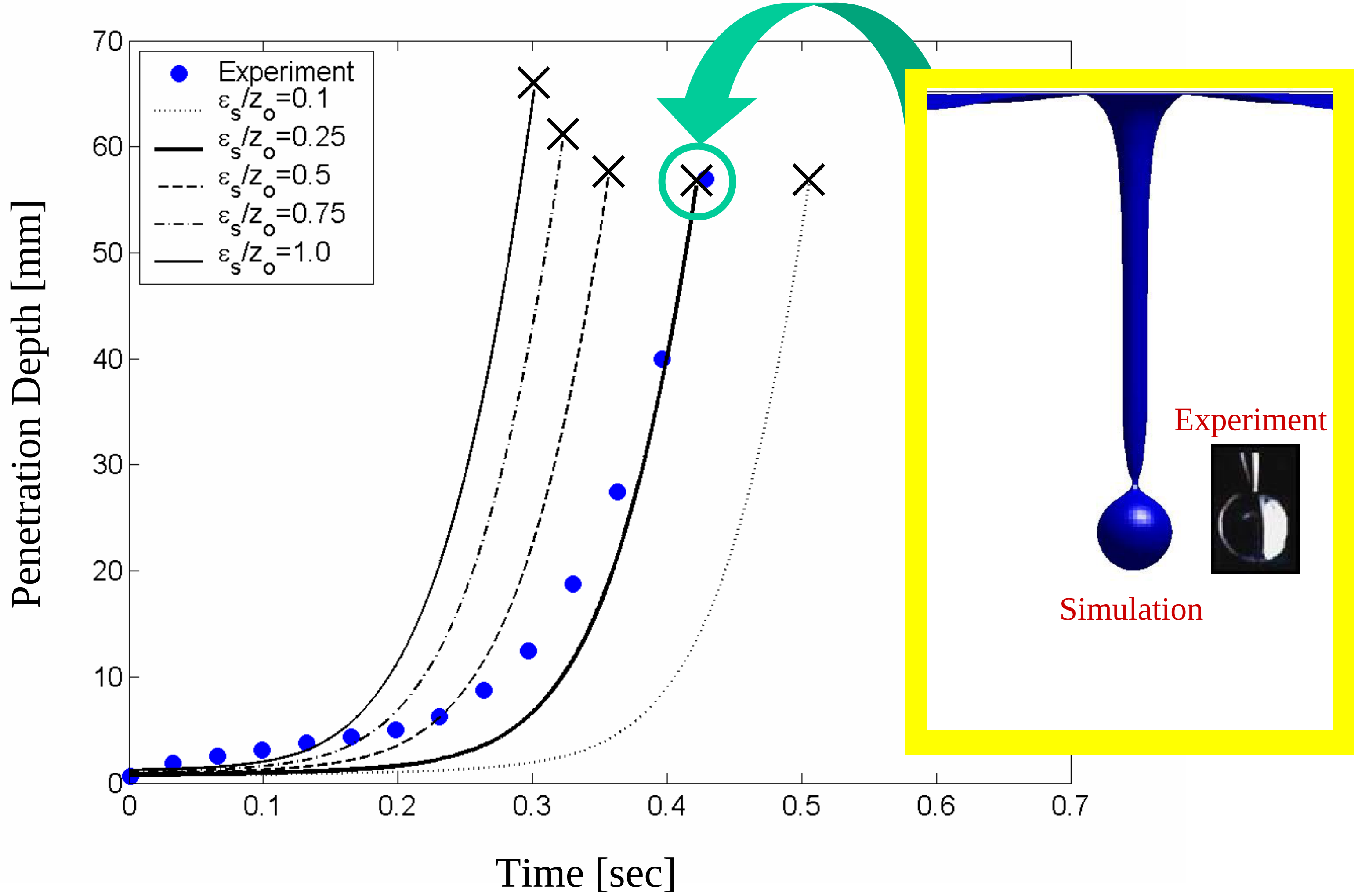
Independent Parameters

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

Dependent Variables

- Detachment time
- Detachment diameter
- Maximum penetration depth

Experiment #W090 --
Evolution of Maximum Penetration Distance



Wetted Wall Summary

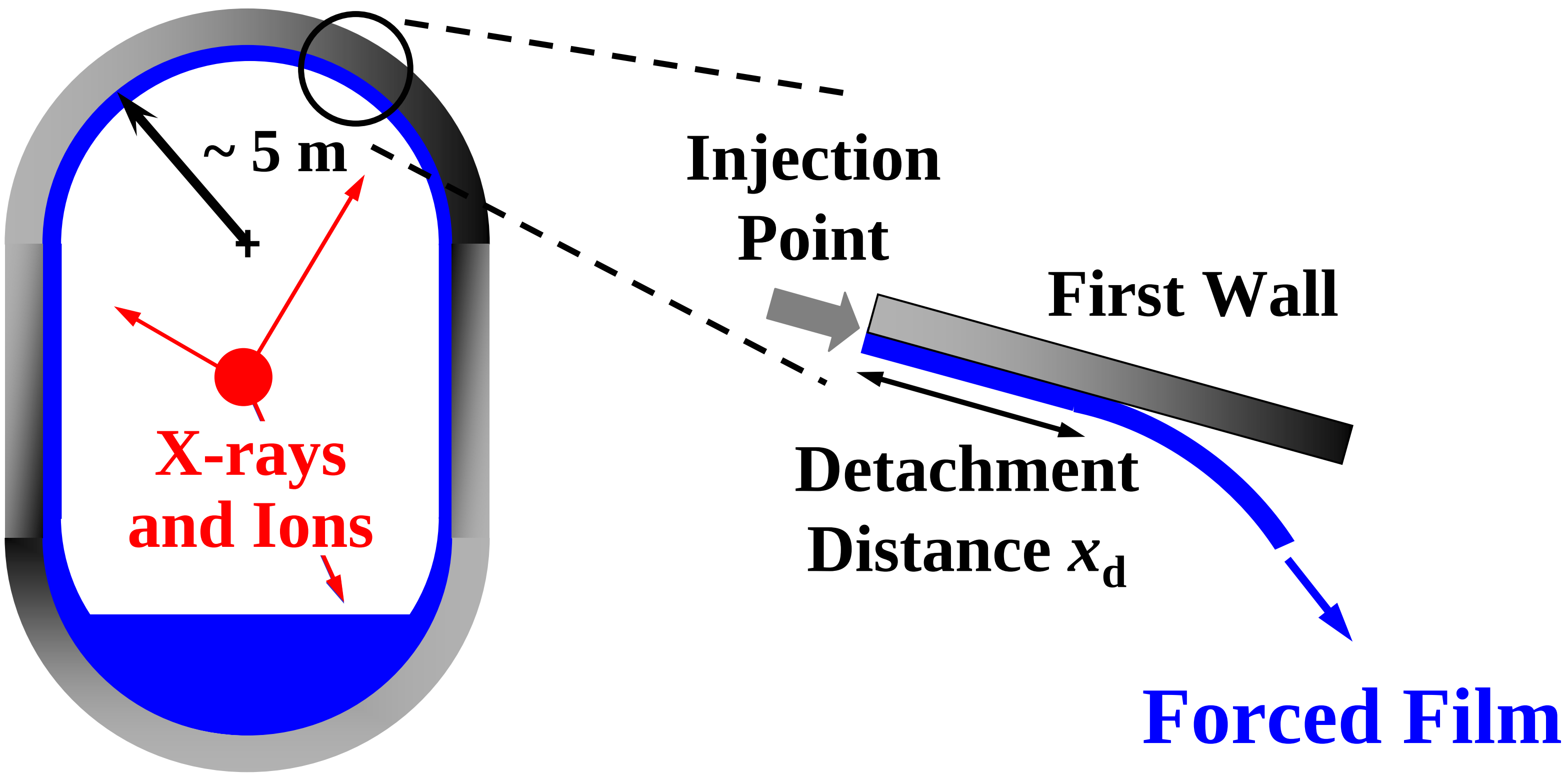
- Developed general non-dimensional charts applicable to a wide variety of candidate coolants and operating conditions

- 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*

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

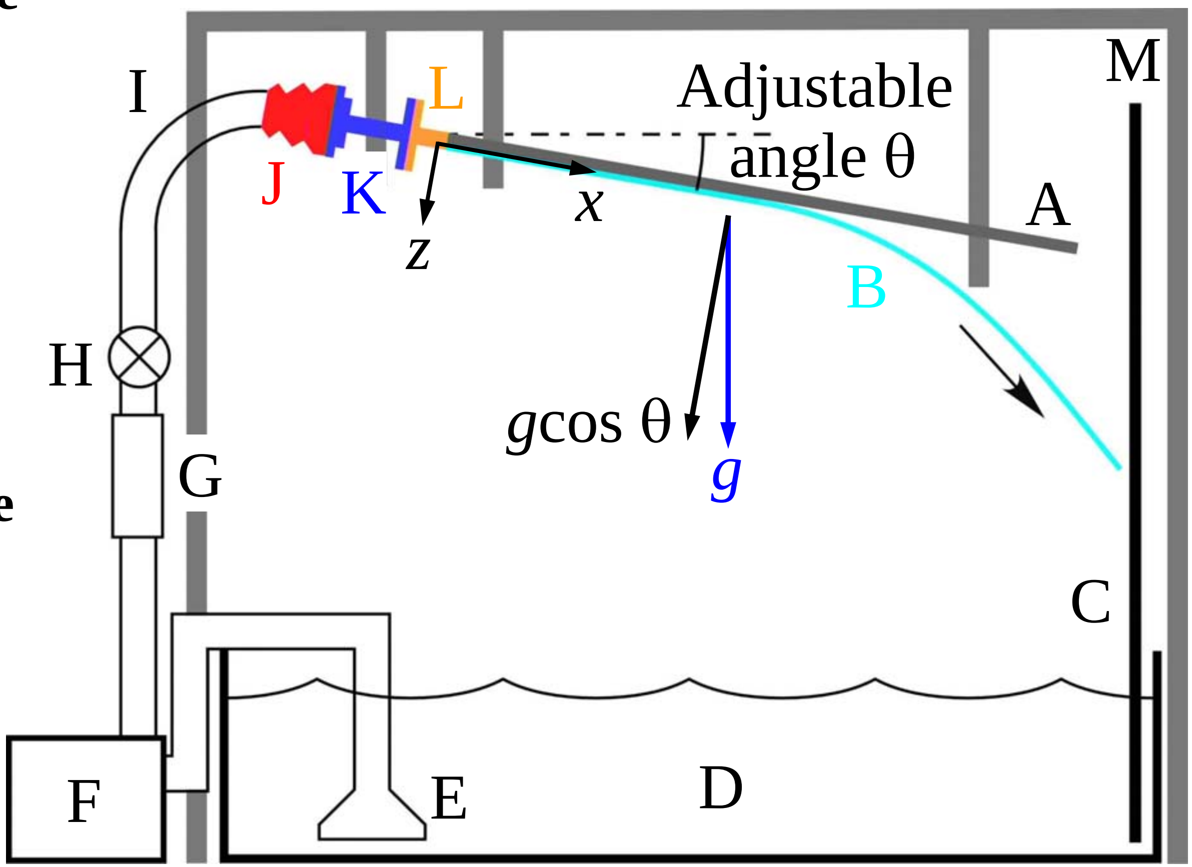
$$\boldsymbol{Fr} \equiv \frac{\boldsymbol{U}}{\sqrt{\boldsymbol{g}(\cos\theta)\delta}}$$

- Froude number *Fr*
  - Surface orientation θ (θ = 0° ⇒ horizontal surface)
- 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 θ = 0 – 45°, *Fr* = 100 – 680 over nonwetting surface (α_{LS} = 90°)

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

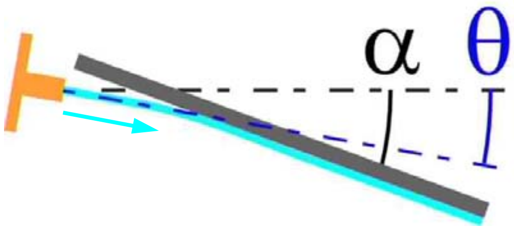
Experimental Apparatus

- **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**



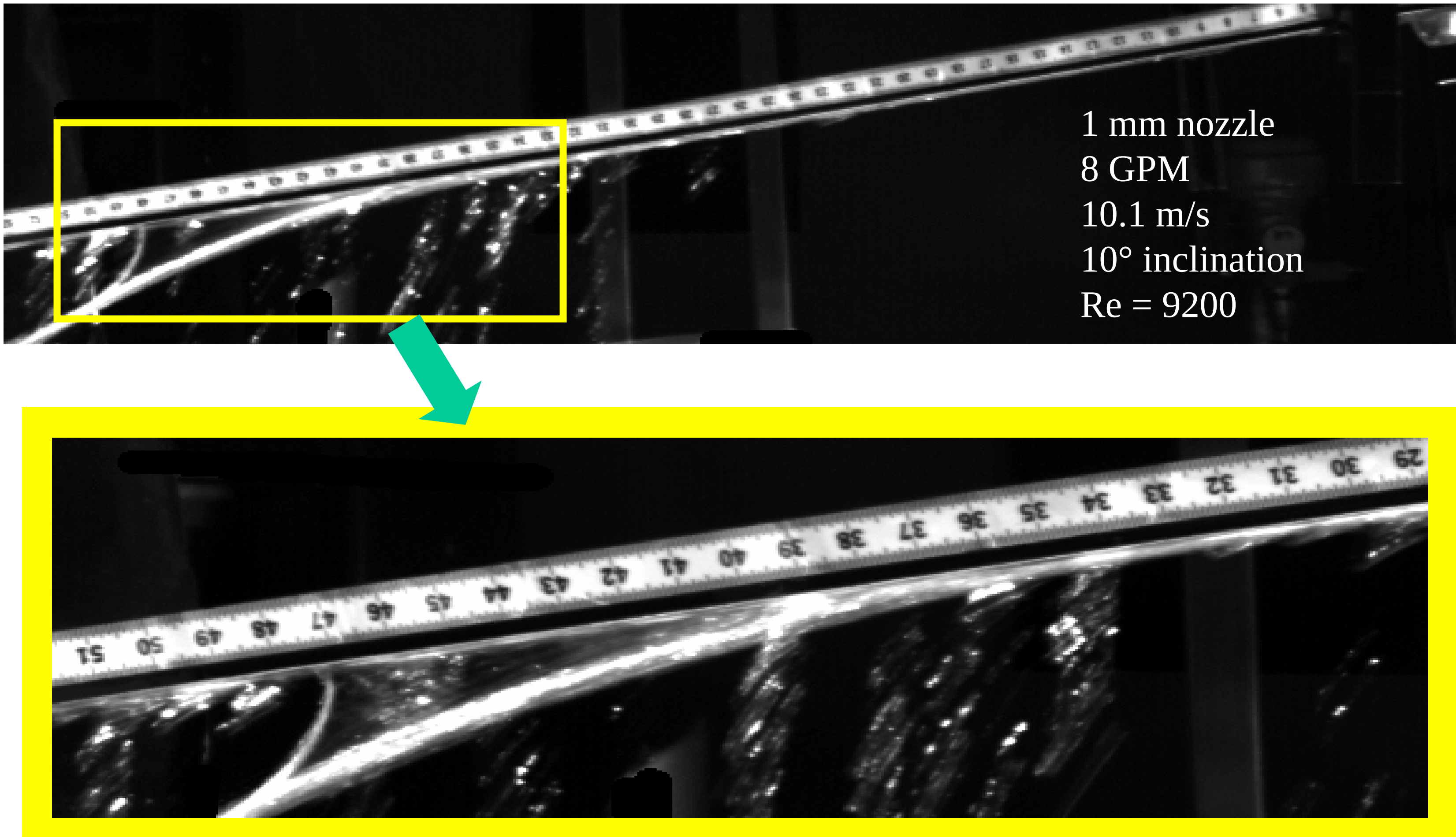
Experimental Parameters

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

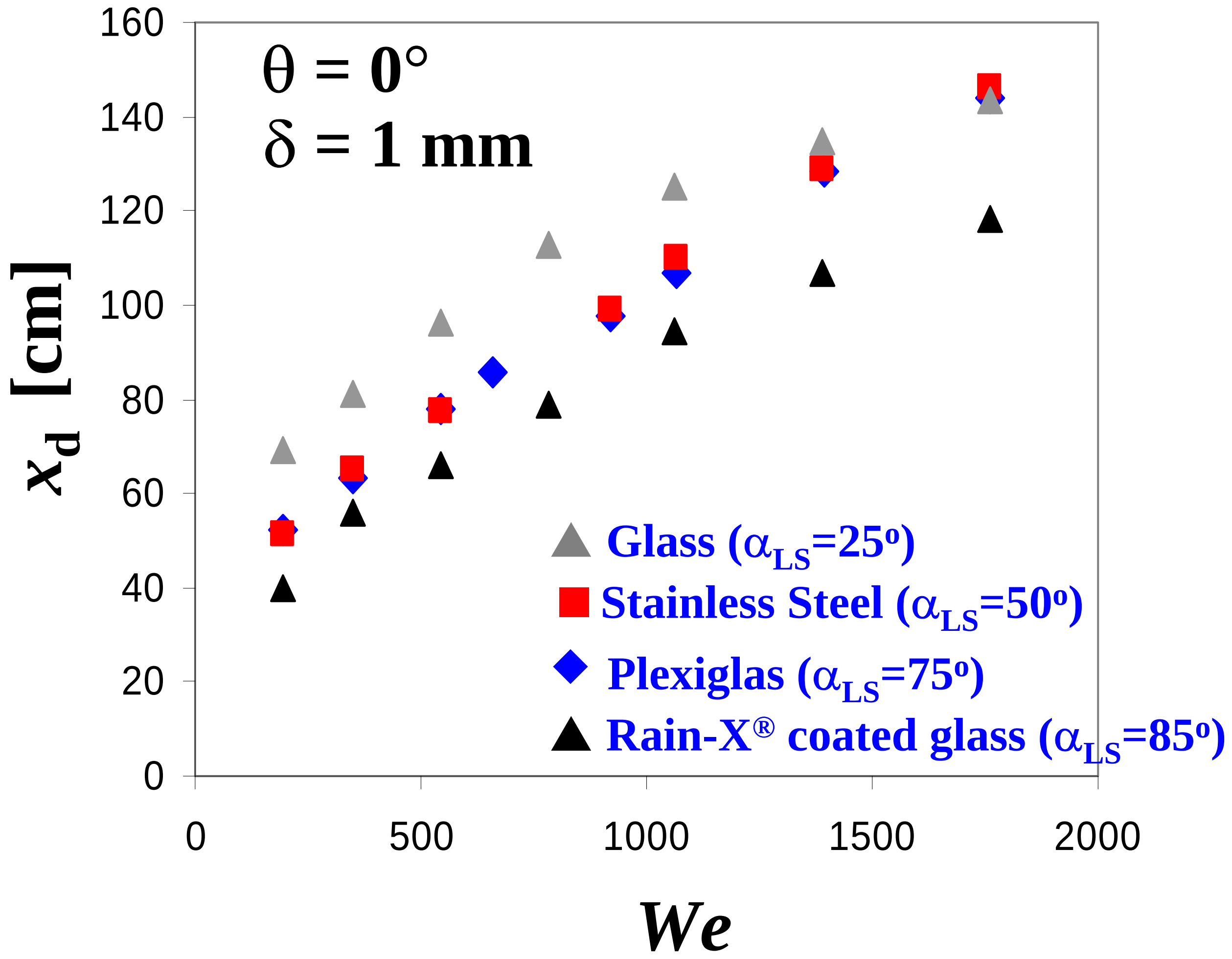


- **Dependent Variables**
  - Film width and thickness $W(x)$, $t(x)$
  - Detachment distance x_d
  - Location for drop formation on free surface

Detachment Distance



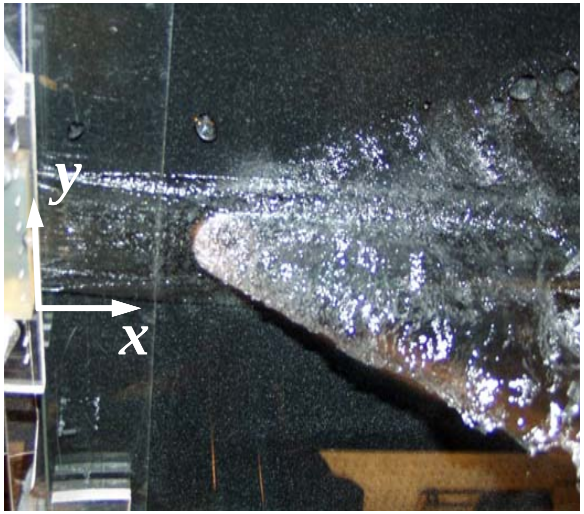
Detachment Distance Vs. Weber Number

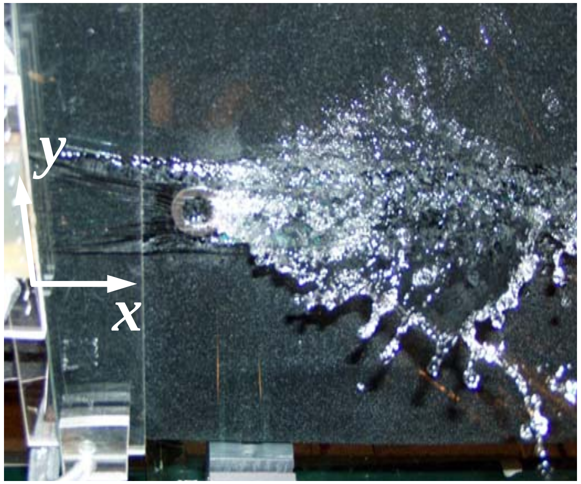


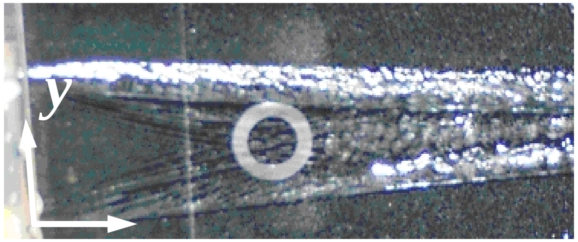
Penetrations and Beam Ports

- Cylindrical obstructions modeling protective dams around penetrations and beam ports incompatible with forced films

- Film either detaches from, or flows over, dam







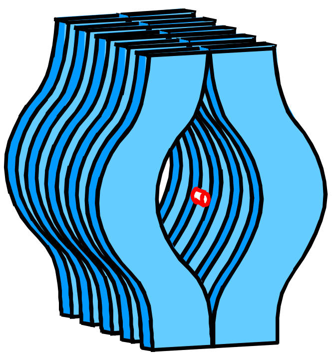
Forced Film Summary

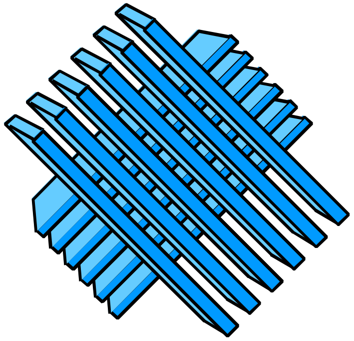
- Design windows for streamwise (longitudinal) spacing of injection/coolant removal slots to maintain attached protective film
  - Detachment length increases w/Weber and Froude numbers
- Wetting chamber first wall surface requires fewer injection slots than nonwetting surface $\Rightarrow$ wetting surface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

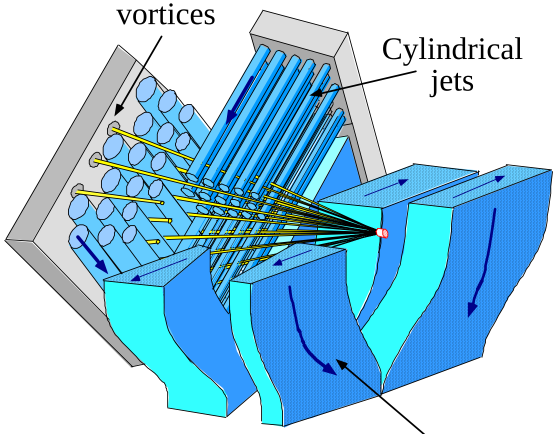
Turbulent Liquid Sheets

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

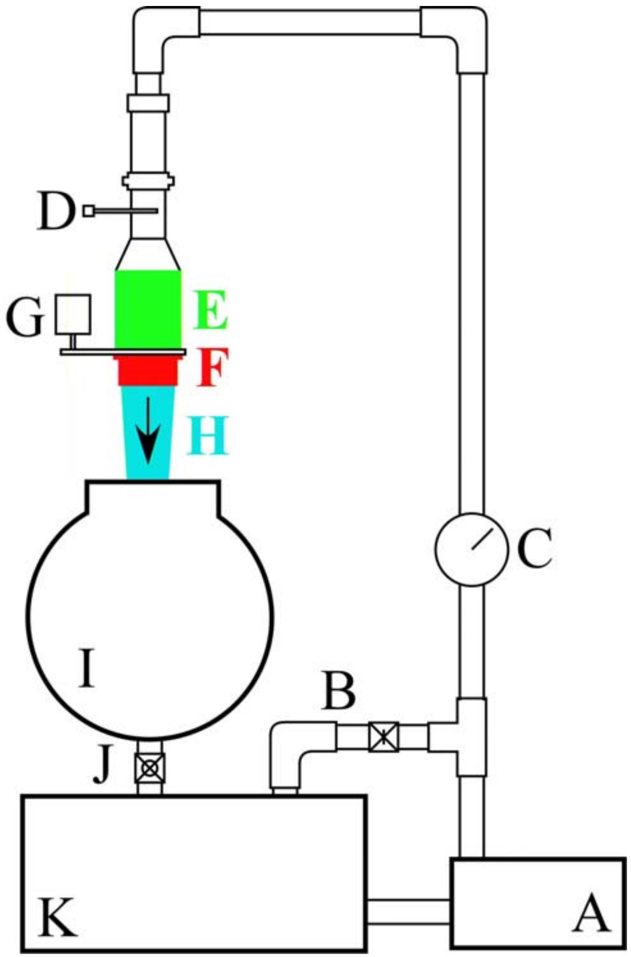
Major Design Questions

- 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

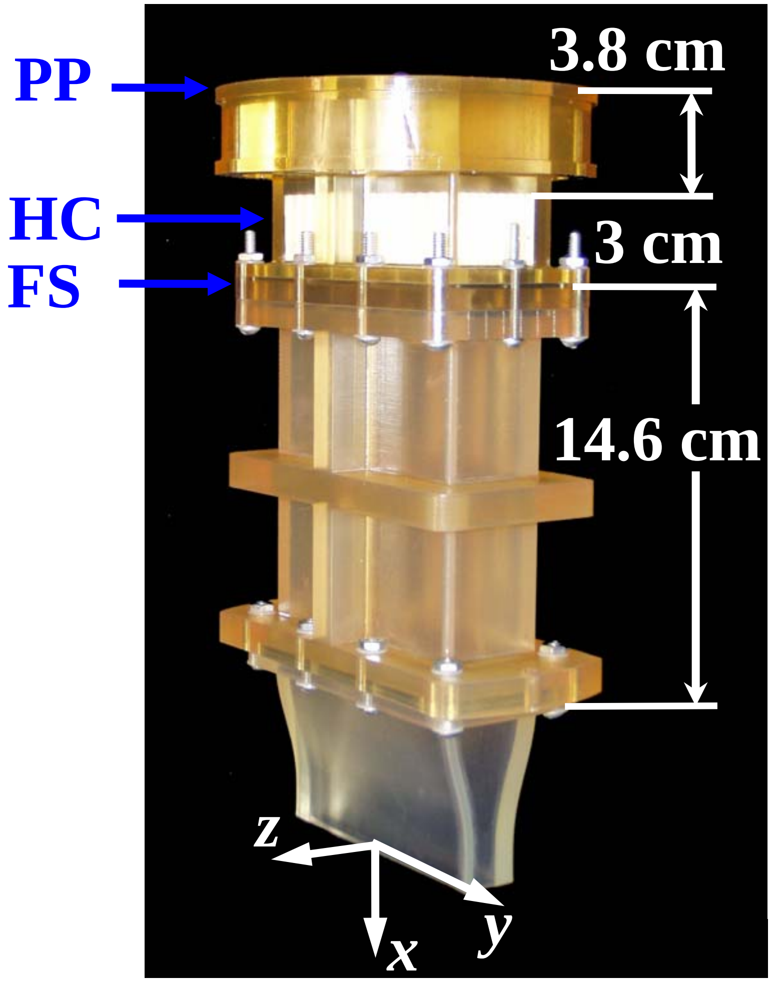
Flow Loop



- 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

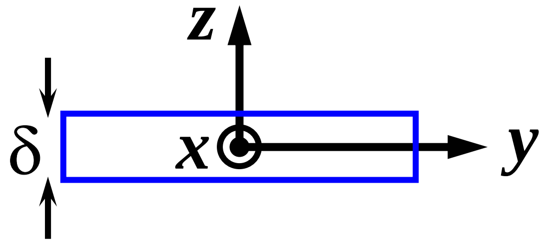
Flow Conditioning



- 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

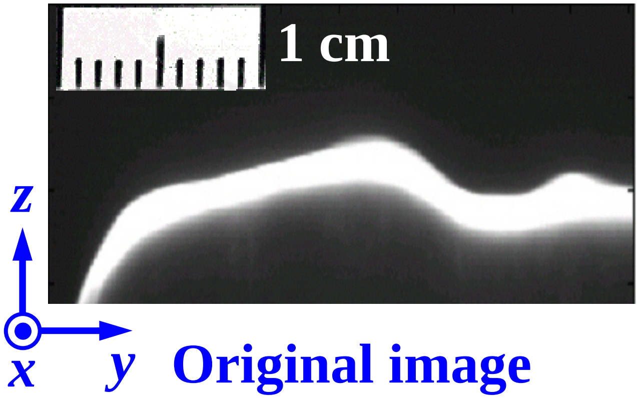
Experimental Parameters

- **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

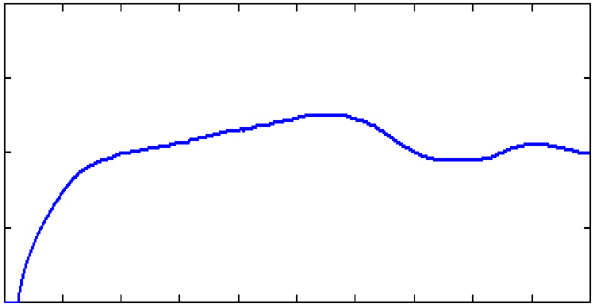
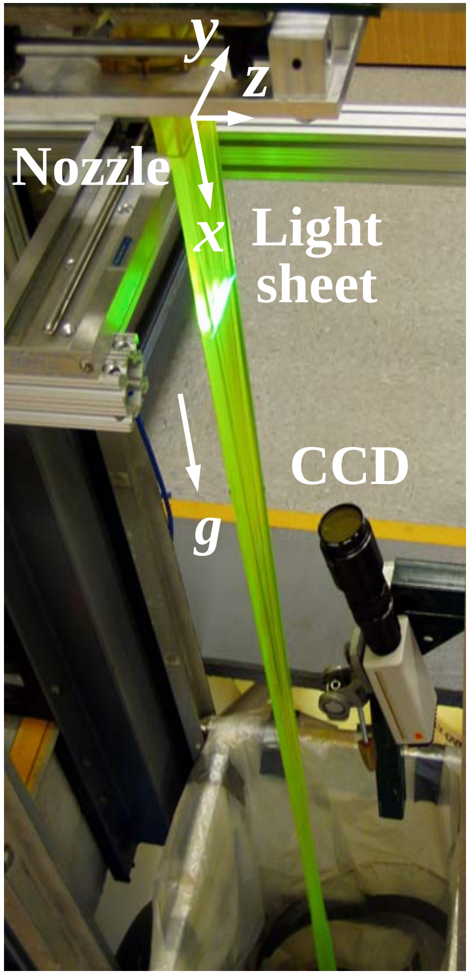
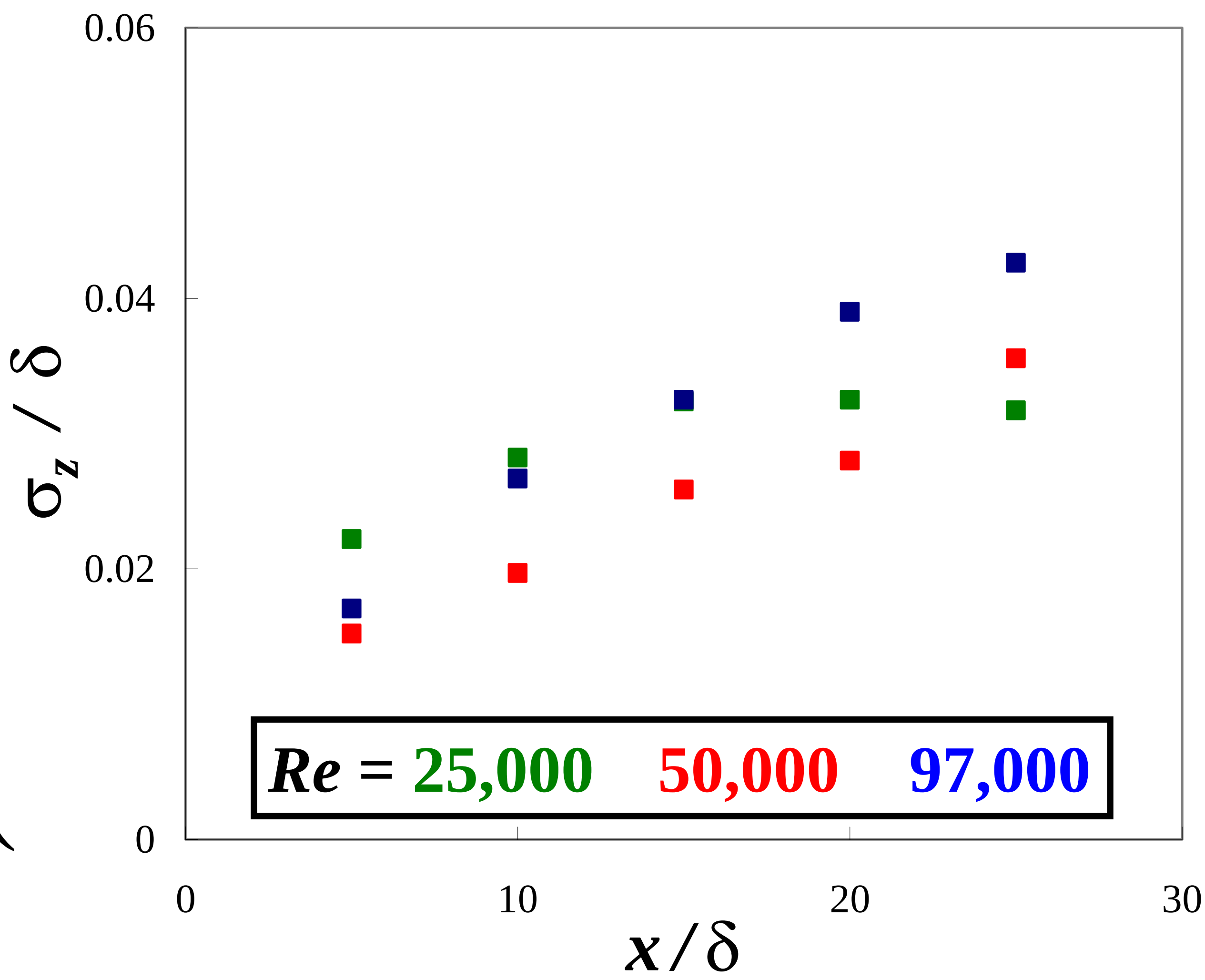


Image after thresholding, edge detection

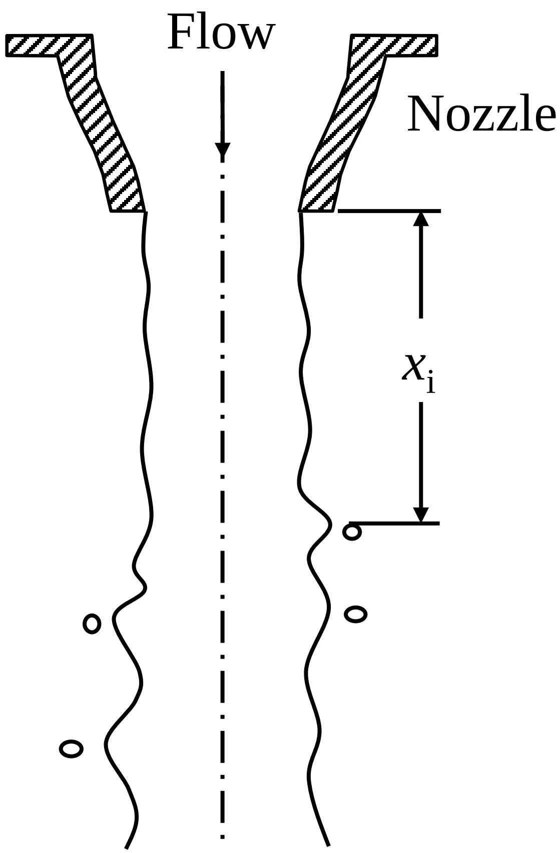


Surface Ripple: Nozzle H

- 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 $x \uparrow$



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 $We \uparrow$

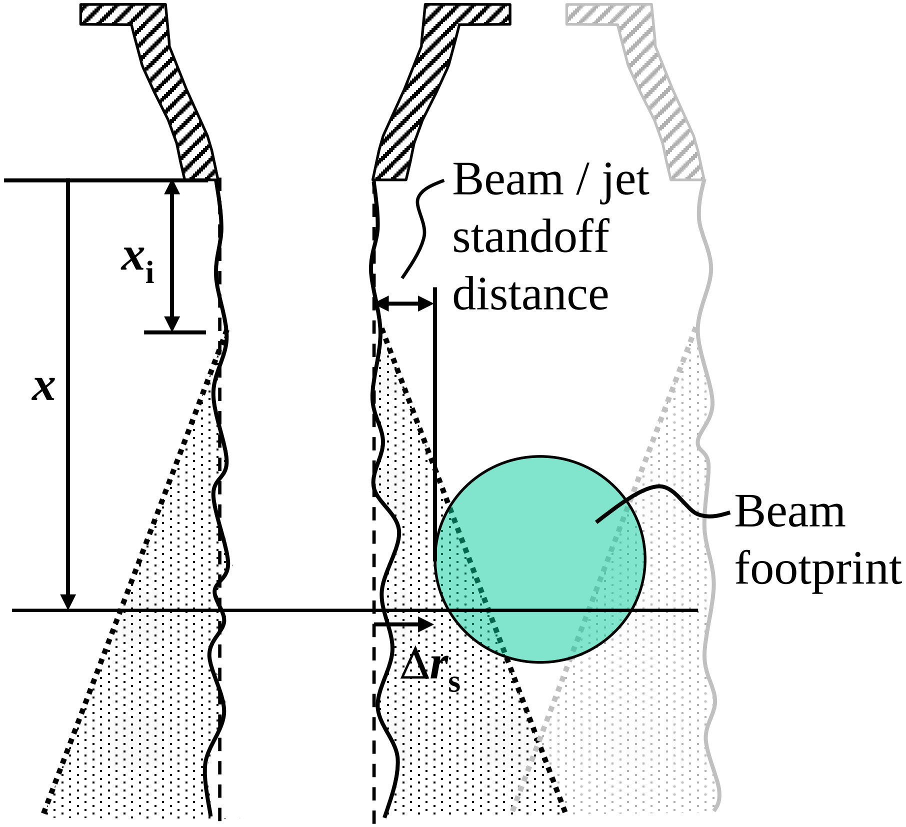
RPD-2002 Correlation Results

[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

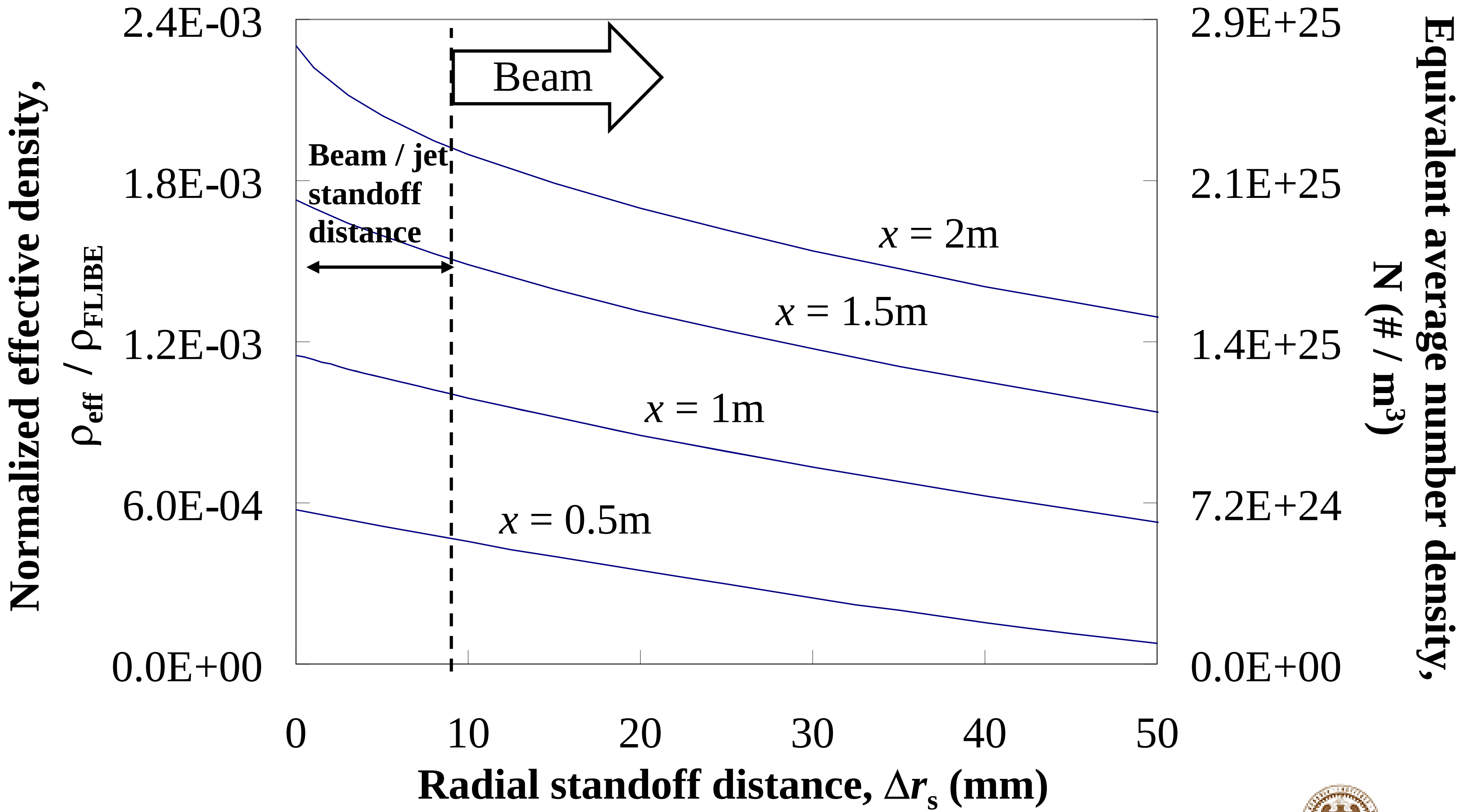
- **Sauter mean dia. ≈ 5.7 mm for all jets at x = 1 m**
  - SMD at $x_i \approx 0.82 - 1.0$ mm for $d = 4.61 -$ 15.6 cm, respectively

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

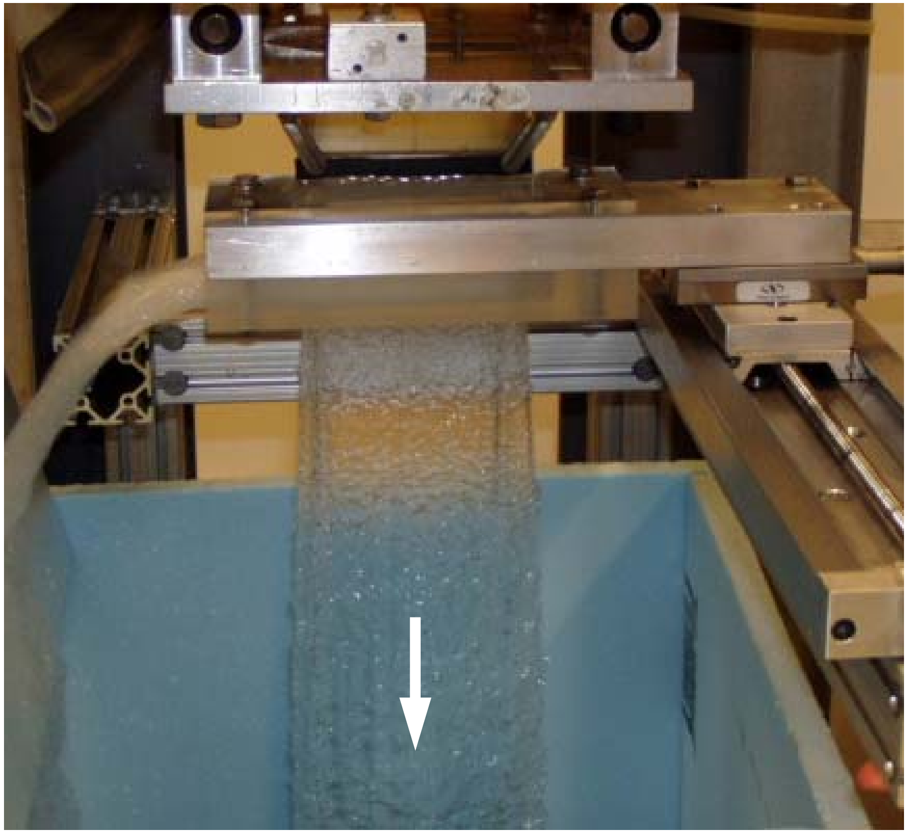
Implications for Typical RPD-2002 Jet: *d* = 4.61 cm (Row 0)



Beam Propagation Implications

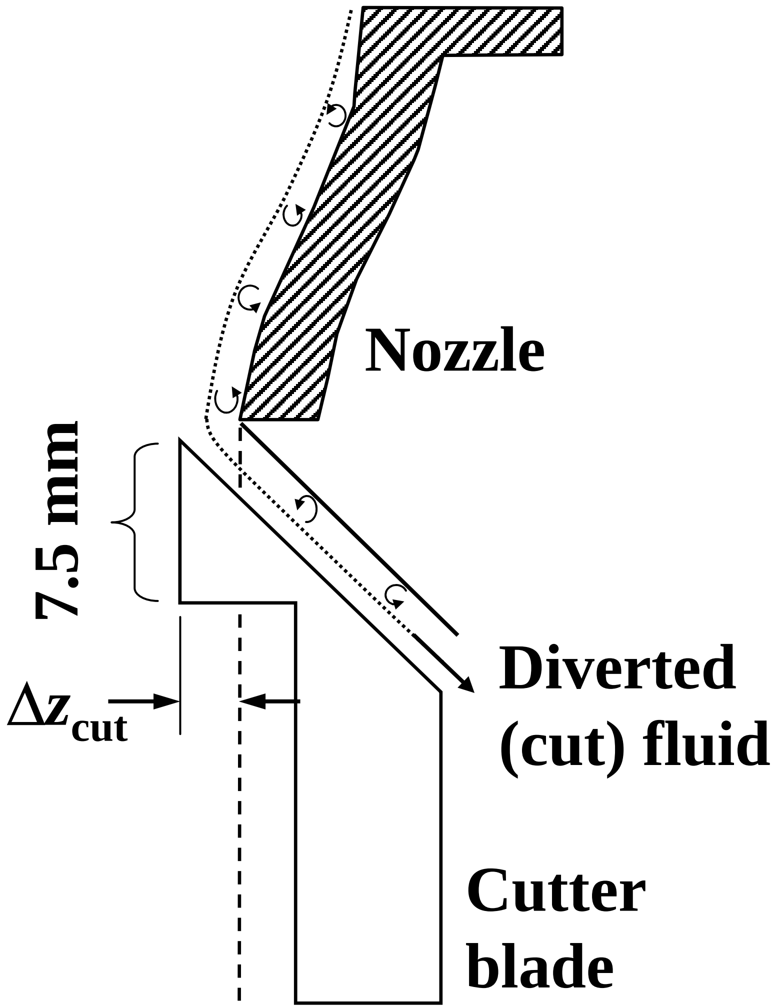
- **Model predictions imply protection concept is incompatible with beam propagation requirements**
- **However, model is based on :**
  - Fully developed turbulent pipe flow at exit
  - No flow conditioning, nozzle or BL cutting
- **Can nozzles / jets be designed to reduce these number densities to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

Boundary Layer Cutter



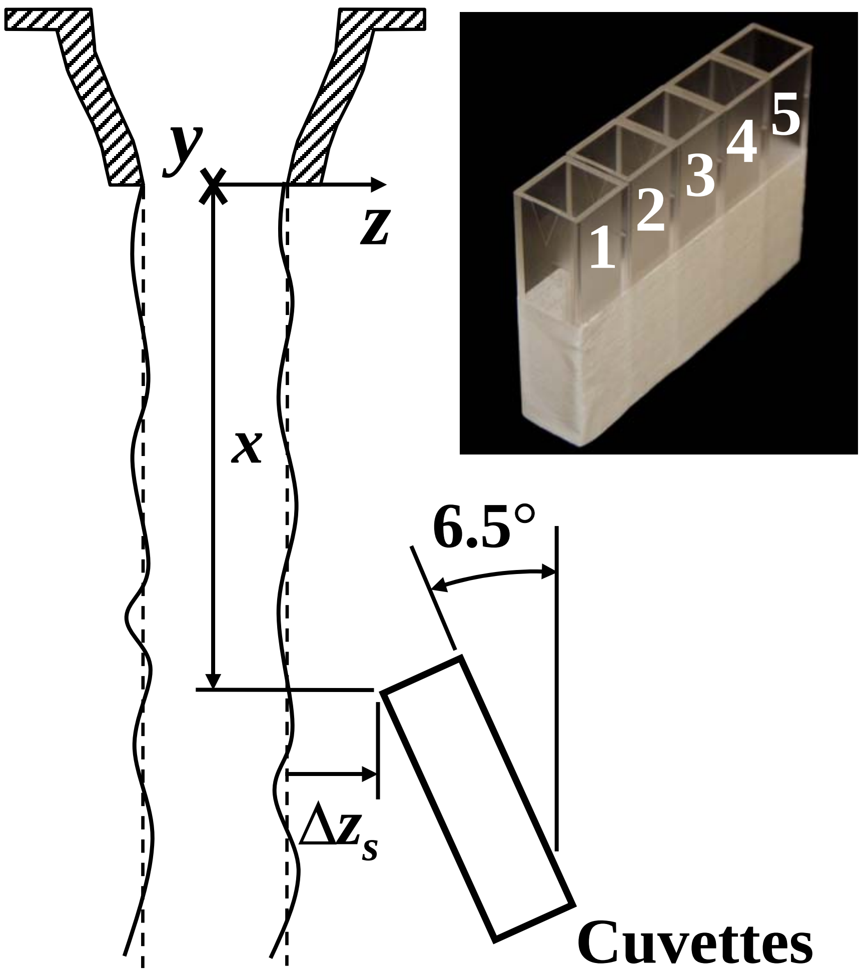
- **"Cut" (remove BL fluid) on one side of liquid sheet**
- **Independently control:**
  - Cut depth, Δz_{cut}
  - Downstream location of cut, *x*
- **Removed liquid (~0.18 kg/s) diverted to side**

Cutter Details



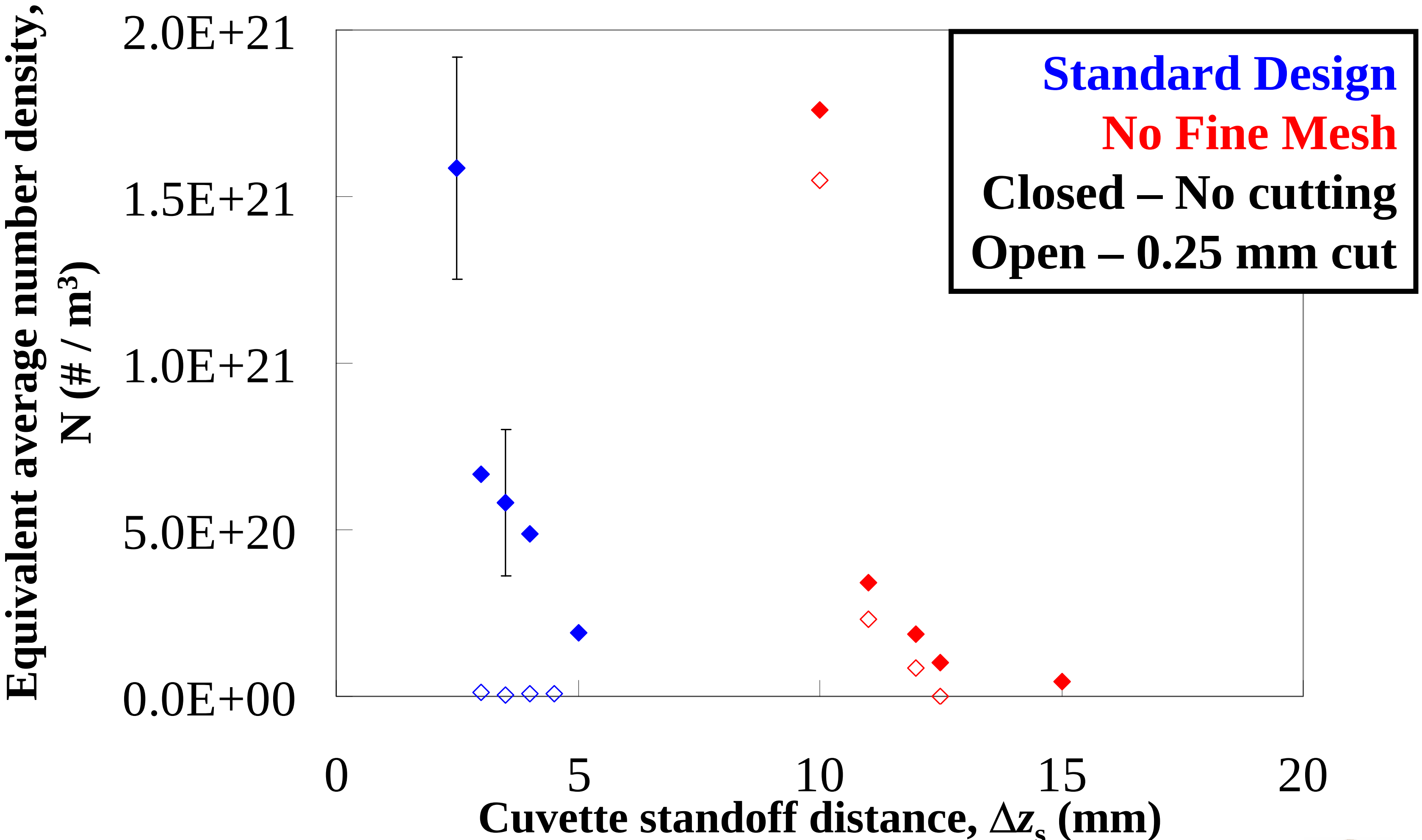
- **Aluminum blade inserted into flow**
  - Remove high vorticity / low momentum fluid near nozzle wall
  - Blade face tilted 0.4° from vertical
  - Blade width (*y*-extent) 12 cm
- **Relatively short reattachment length**
  - Nozzle contraction length 63 mm

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**

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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