THE HYDRODYNAMIC SOURCE TERM:

BOUNDARY LAYER CUTTING AND FLOW CONDITIONING

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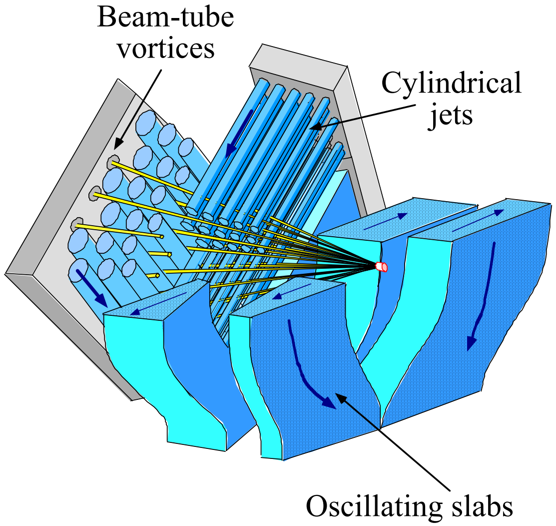
RPD-2002 Chamber

- **Use cylindrical jets and liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles**
  - **Oscillating slabs create protective pocket to shield chamber side walls**
  - **Lattice of stationary jets shield front/back walls while allowing beam propagation and target injection**



Picture courtesy P.F. Peterson, UCB

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

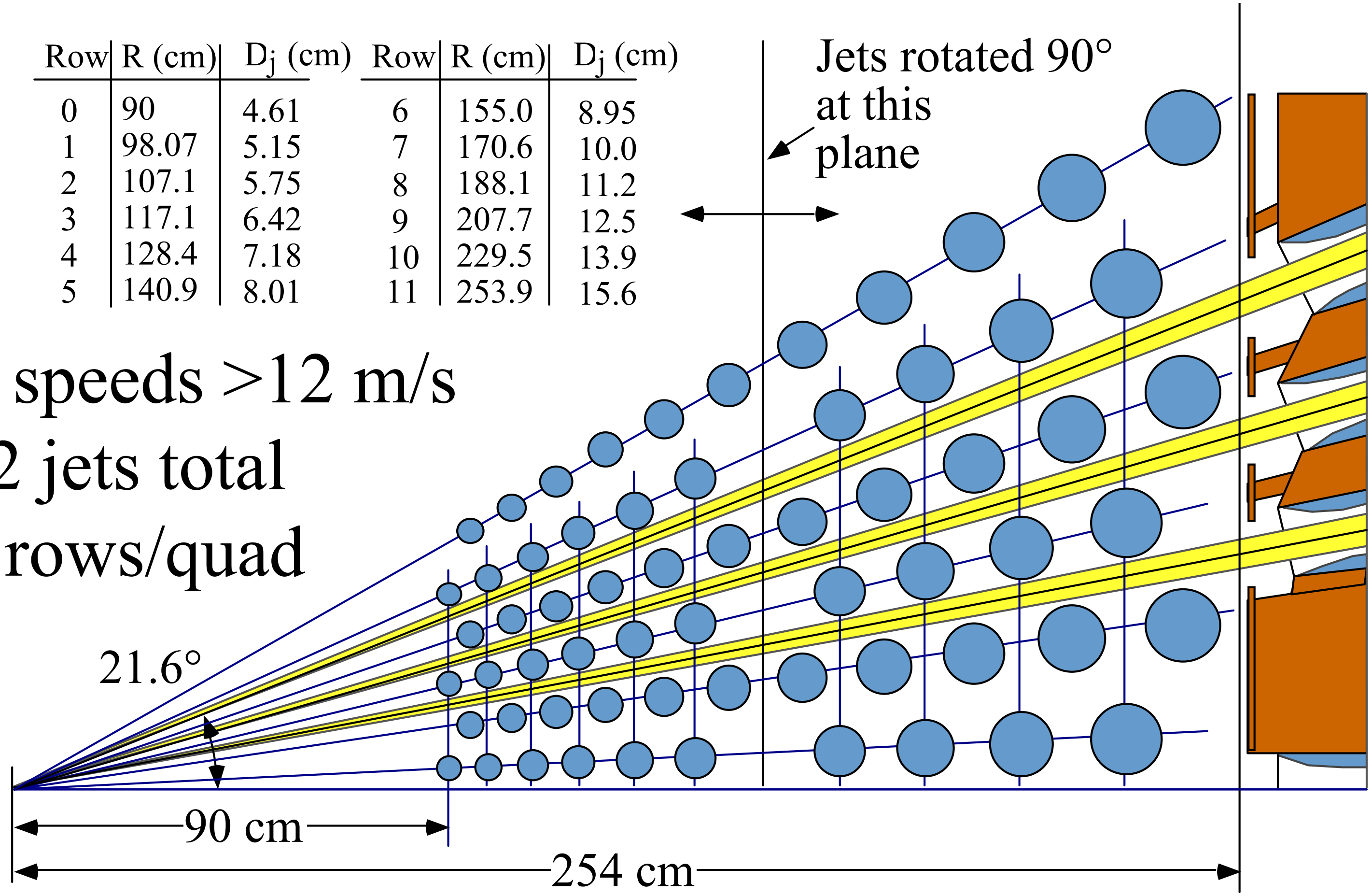
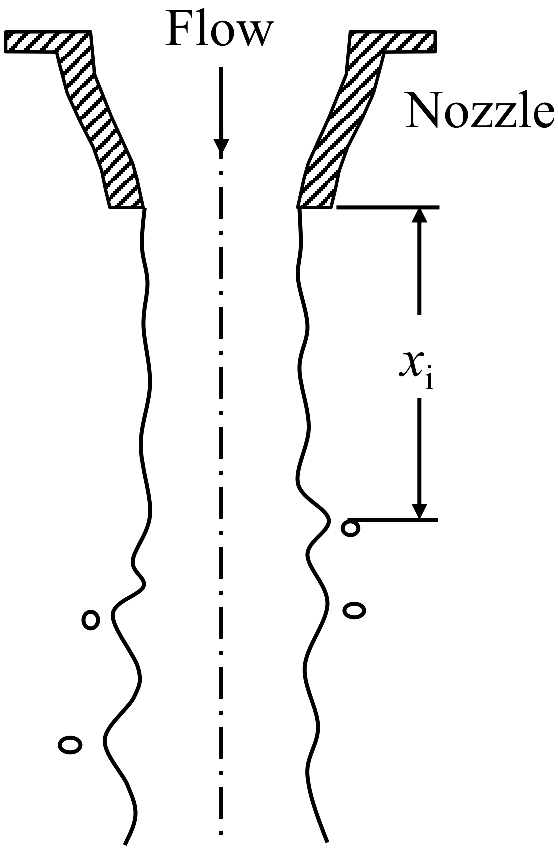


Diagram courtesy P.F. Peterson, UCB

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 $G(x = 1$ 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

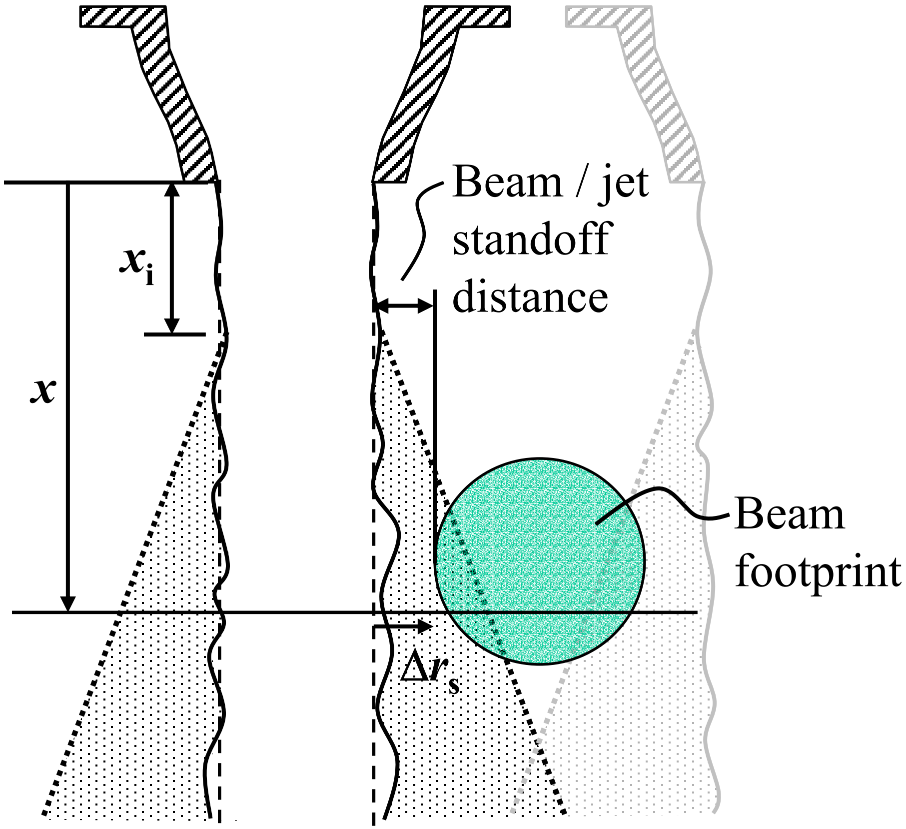
- **Evaporation rate due to target energy deposition assuming 6 Hz**

	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

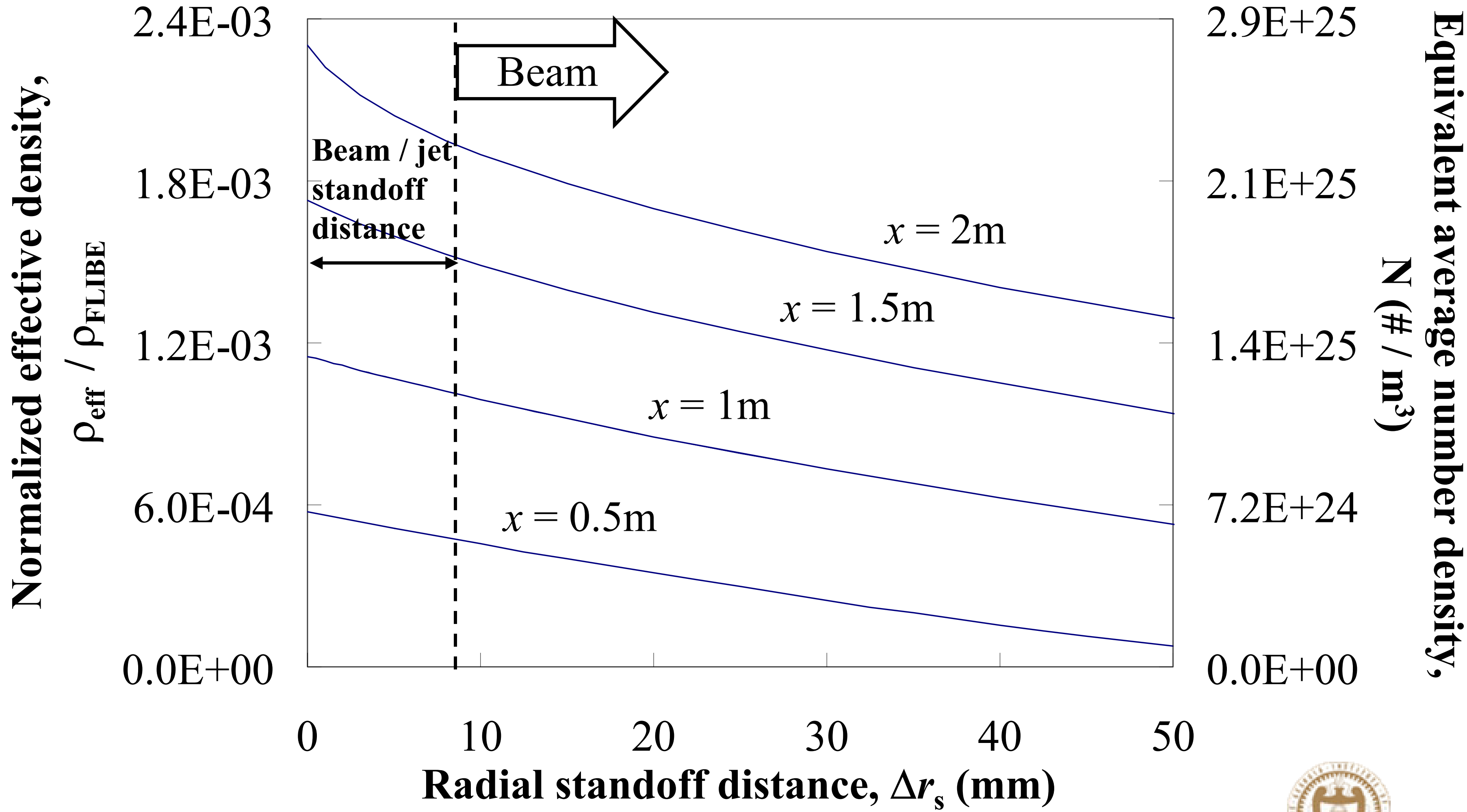
- **Hydrodynamic source term ~1300 kg/s !**
  - **Must be reduced (flow conditioning, nozzle, BL cutting, etc.)**

Implications for Beam Propagation

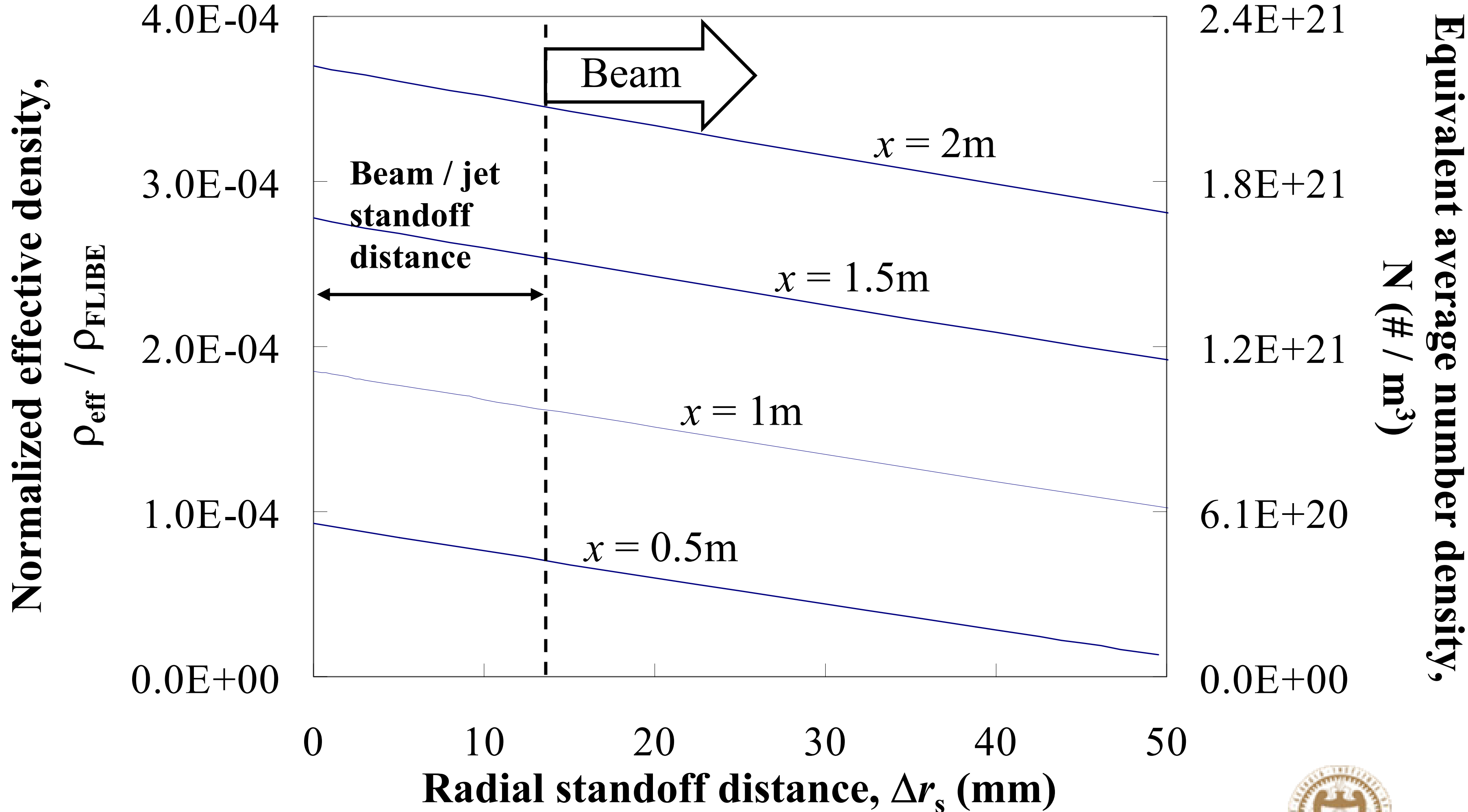


- **Droplets enter into beam footprint**
- **Radial standoff, Δr_s**
  - **Measured from nominal jet surface**
- **Equivalent number density dependent on x and Δr_s**
  - **Ignores jet-jet interactions**

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



Implications for Typical RPD-2002 Jet: *d* = 15.6 cm (Row 11)



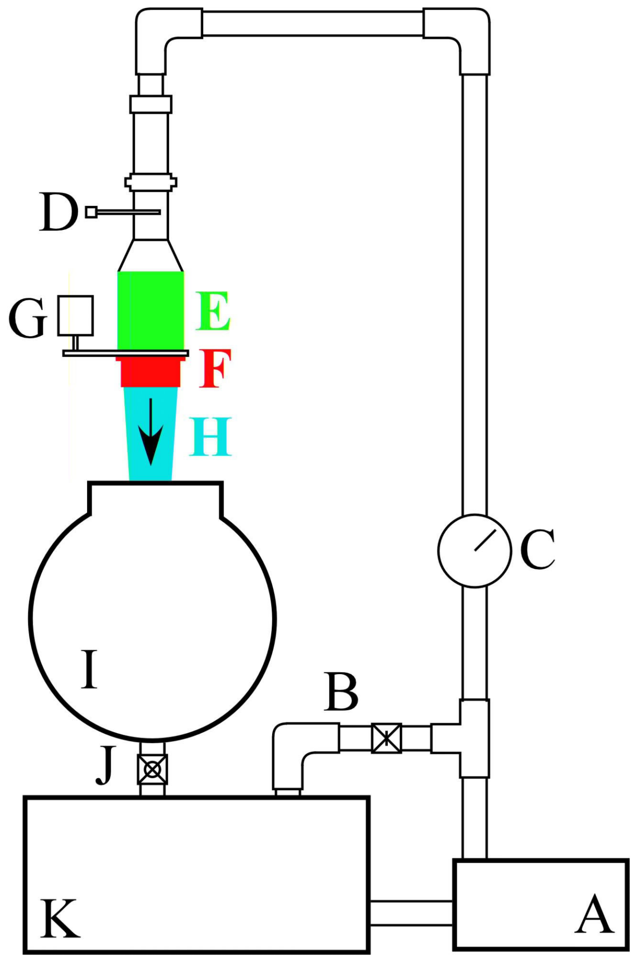
Beam Propagation Implications

- 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?

Objectives

- **Estimate rate of droplet formation due to hydrodynamics (turbulent breakup) for the thick liquid protection concept**
- **Evaluate effectiveness of boundary layer cutting**
  - **Can the hydrodynamic source term be reduced / eliminated?**
  - **Can BL cutting be used to reduce the hydrodynamic source term?**
  - **Can BL cutting be used in lieu of “traditional” flow conditioning?**

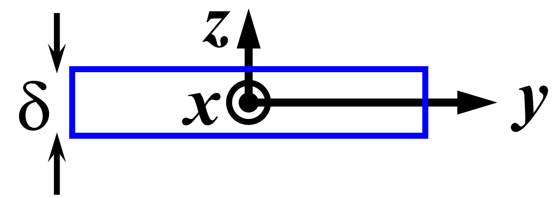
Flow Loop



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

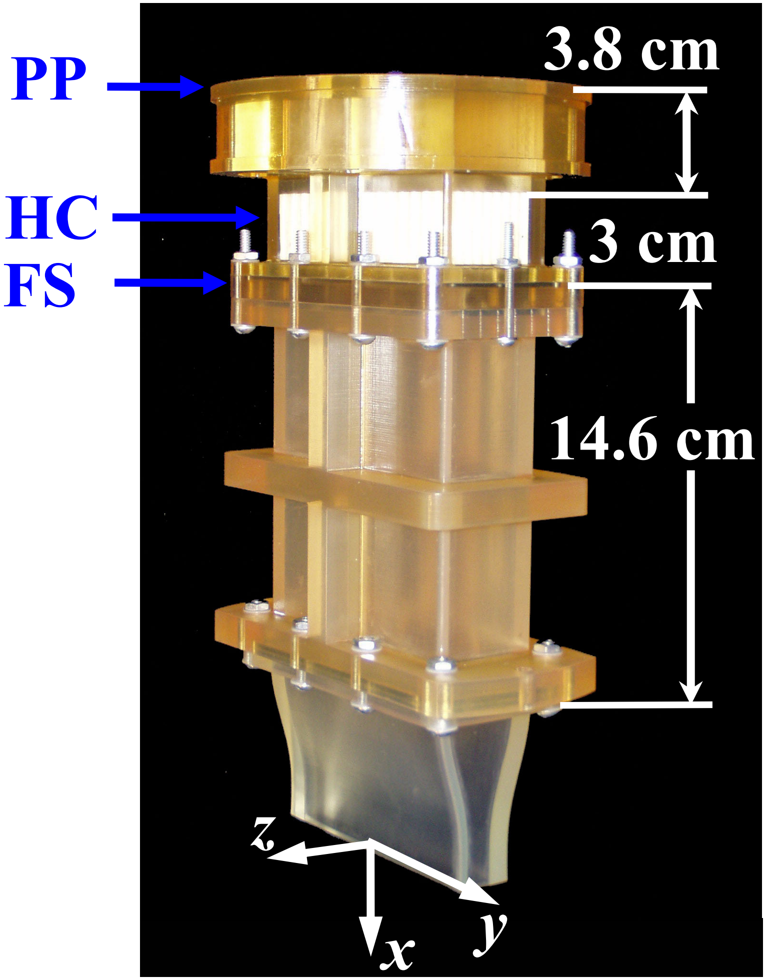
A	**Pump**	**B**	**Bypass line**
C	**Flow meter**	**D**	**Pressure gage**
E	**Flow conditioner**		
F	**Nozzle**	**G**	**Oscillator (Not used)**
H	**Sheet**	**I**	**400 gal tank**
J	**Butterfly valve**	**K**	**700 gal tank**

Experimental Parameters



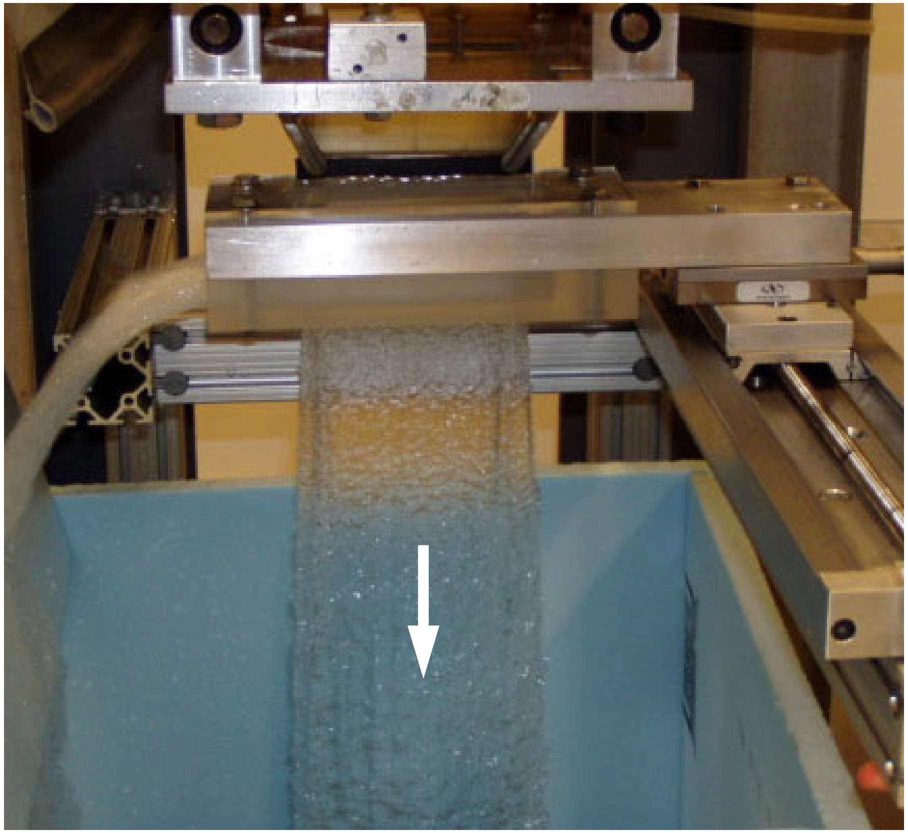
- **δ = 1 cm; aspect ratio AR = 10**
- **Near-field: $x / \delta \leq 25$**
- **Reynolds number Re = 130,000** [$Re = U_o\delta / \nu$; U_o average speed; ν liquid kinematic viscosity]
  - Re = 138,000 – 467,000 for RPD-2002
- **Weber number We = 19,000** [$We = \rho_L U_o^2 \delta / \sigma$; ρ_L liquid density; σ surface tension]
  - We = 68,000 – 230,000 for RPD-2002
- **Froude number Fr = 1,400** [$Fr = U_o^2 / (g\delta)$; g gravitational acceleration]
- **Fluid density ratio ρ_L / ρ_G = 850** [ρ_G gas density]

Flow Conditioning



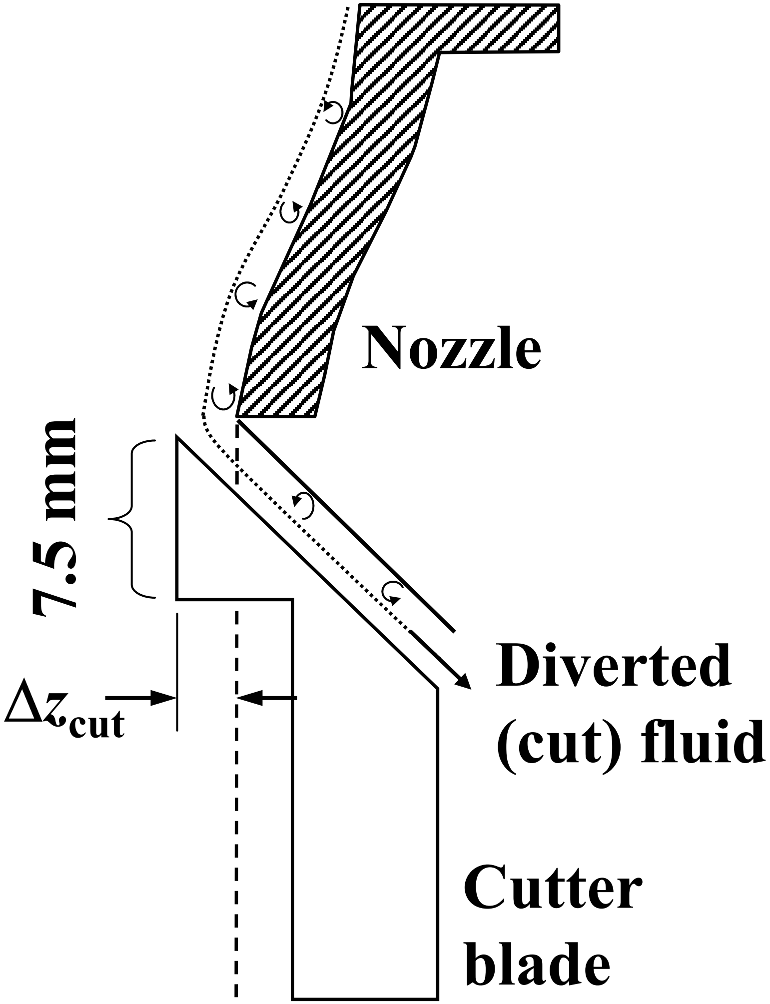
- **Round inlet (12.7 cm ID) to rectangular cross-section 10 cm × 3 cm ($y \times z$)**
- **Perforated plate (PP)**
  - Open area ratio 50% with staggered 4.8 mm dia. holes
- **Honeycomb (HC)**
  - 3.2 mm dia. × 25.4 mm staggered circular cells
- **Fine mesh screen (FS)**
  - Open area ratio 37.1%
  - 0.33 mm dia. wires woven w/ open cell width of 0.51 mm (mesh size 30 × 30)
- **5th order contracting nozzle**
  - Contraction ratio = 3

Boundary Layer Cutter



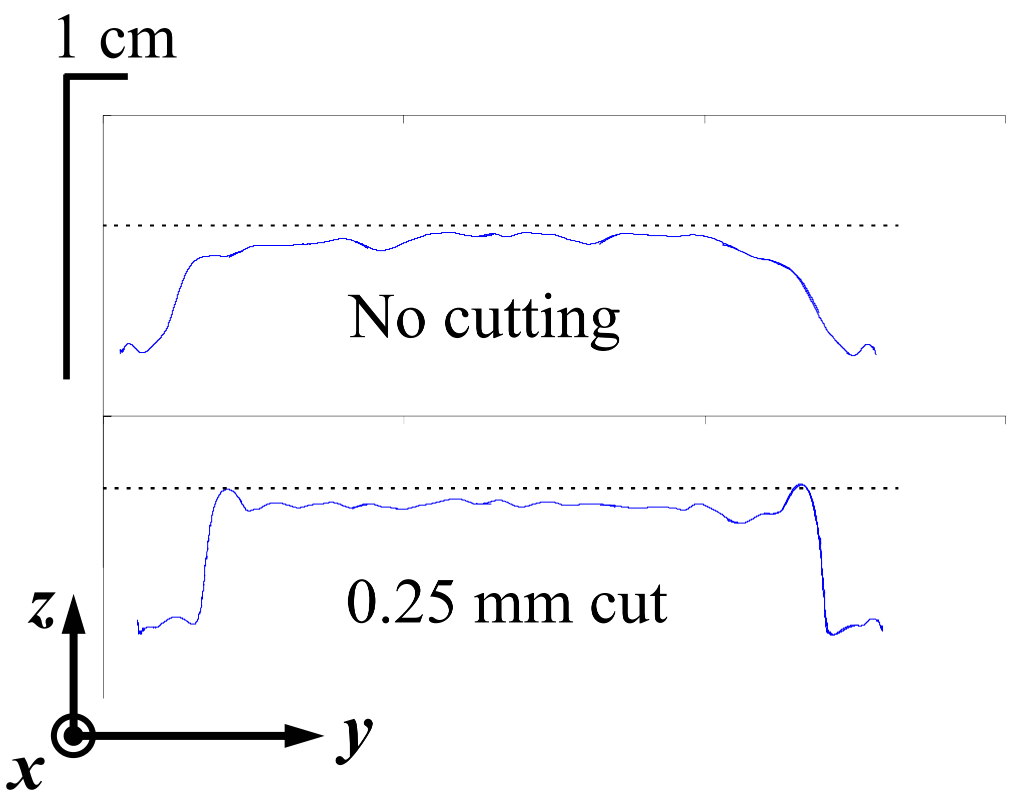
- "Cut" (remove BL fluid) on one side of liquid sheet
- Independently control:
  - Cut depth, Δz_{cut}
  - Downstream location of cut, x
- Removed liquid (~0.18 kg/s) diverted to side

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

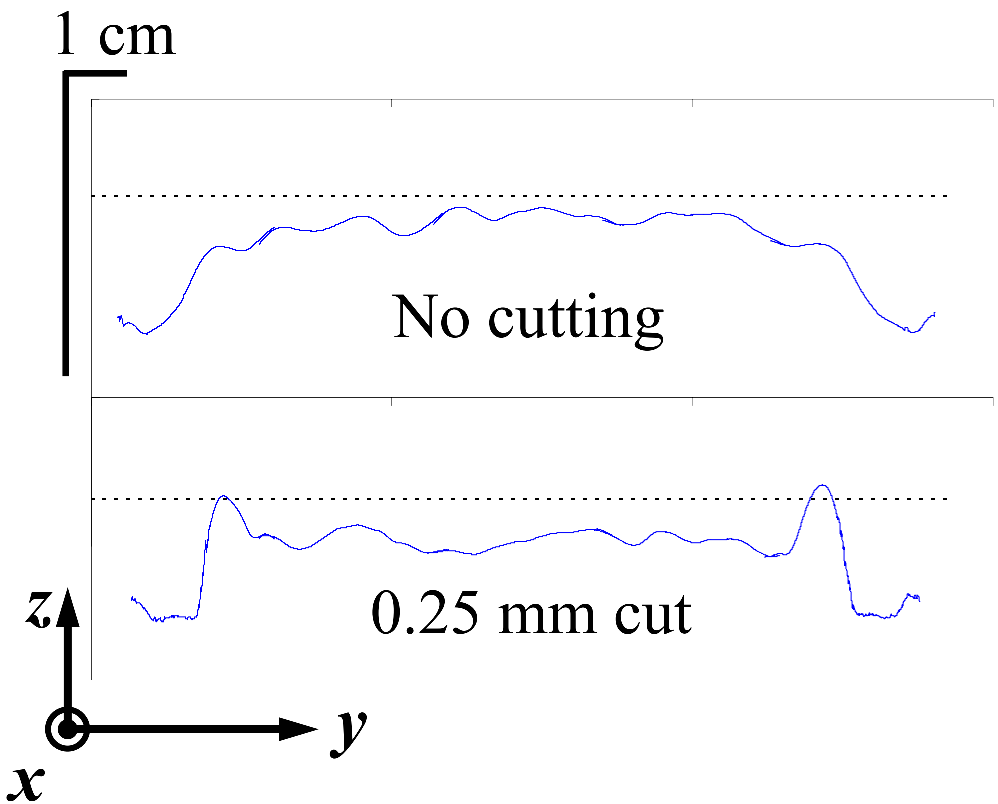
Jet Profiles
(x / δ = 15)



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**

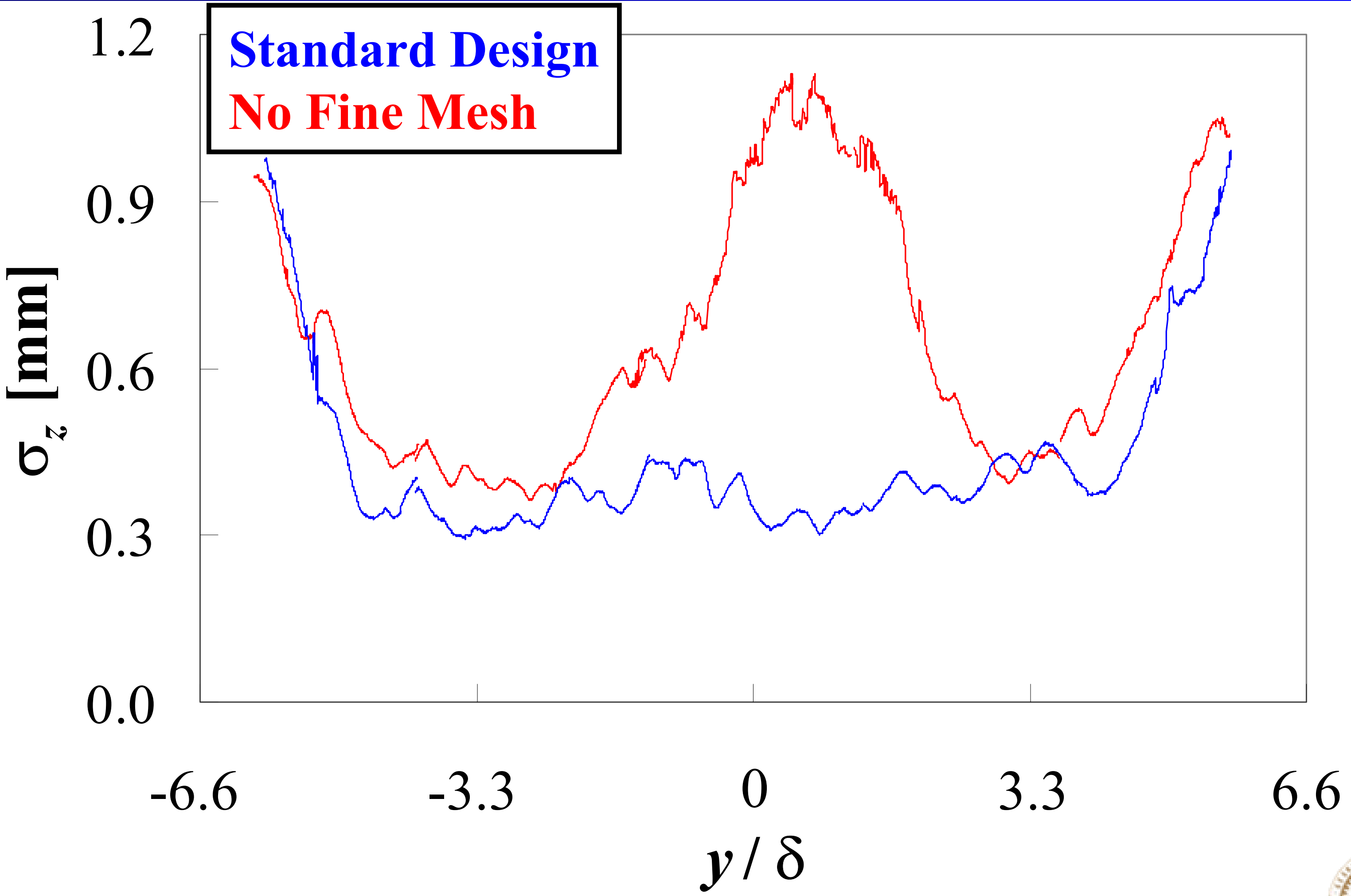
Jet Profiles
($x / \delta = 25$)



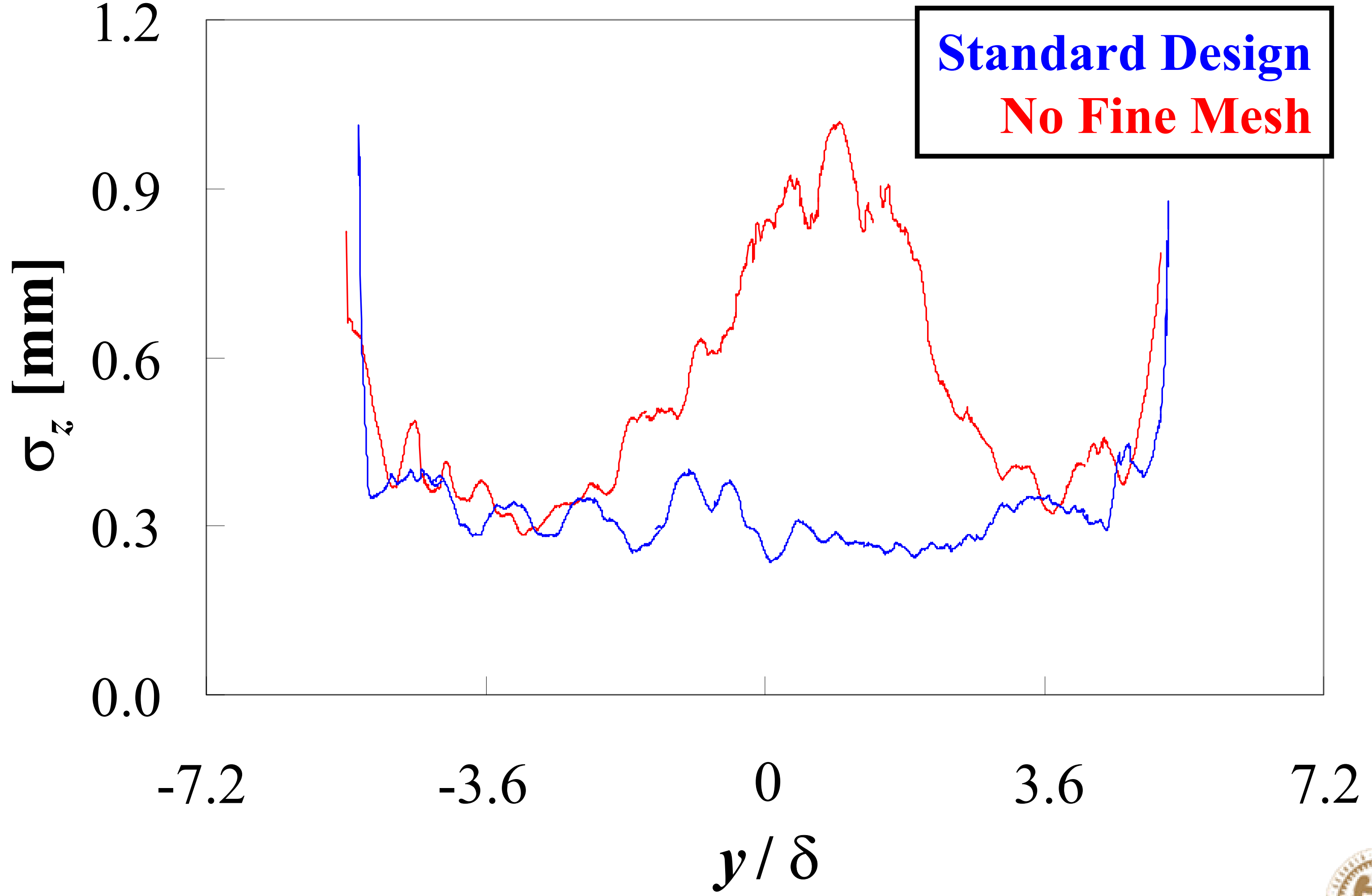
Note: Vertical axis at 5× magnification

- **Uncut jet inside nominal free surface**
- **"Dog-bone" structures more pronounced**
  - **Sharp transition to edges of jet**
- **Jet width (*y*-extent) decreases with cutting**

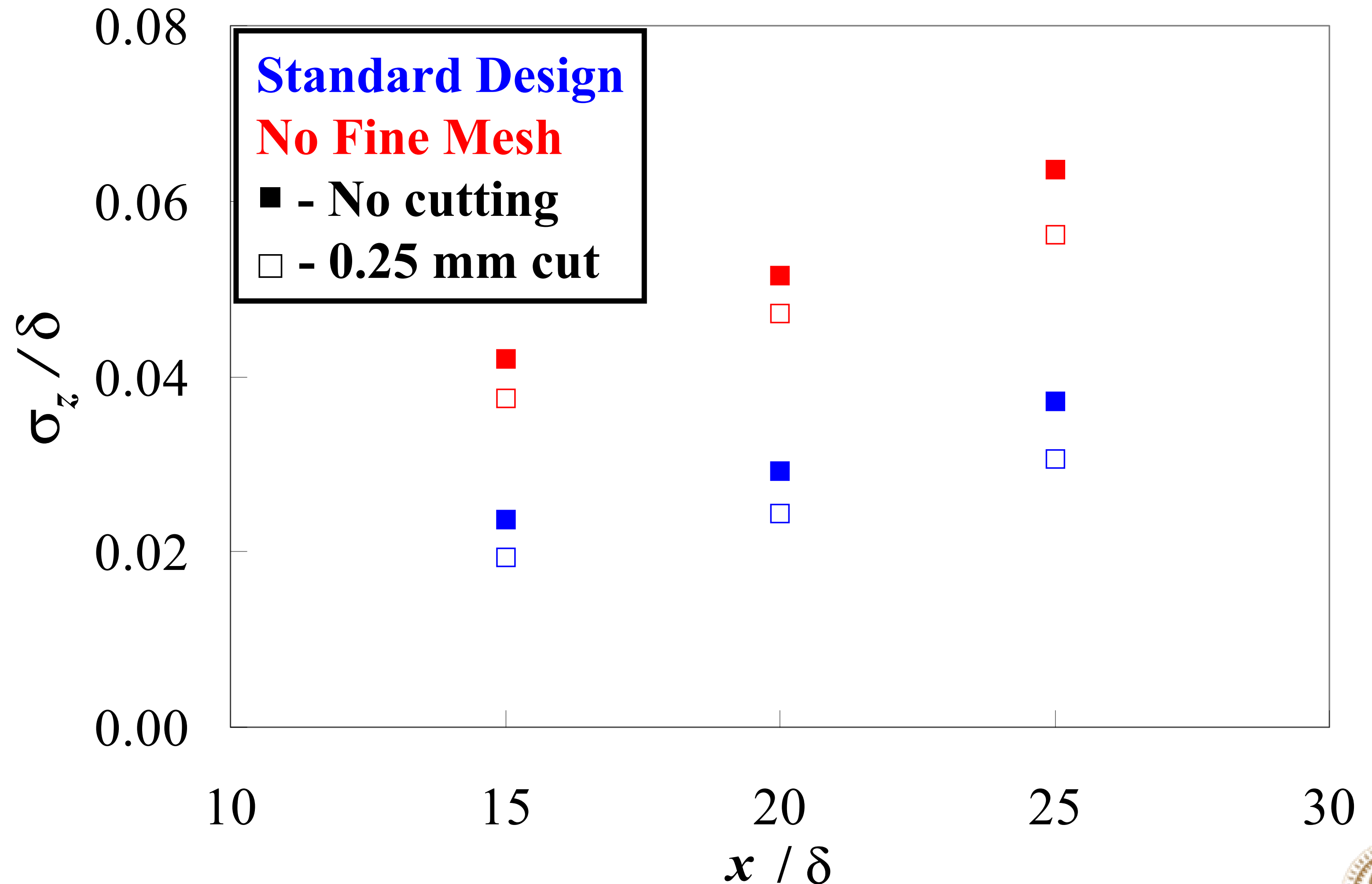
Flow Conditioning Effects
(x / δ = 25)



BL Cutting Effects ($x / \delta = 25$; $\Delta z_{cut} = 0.25$ mm)



Average* Surface Ripple for *Re* = 130k

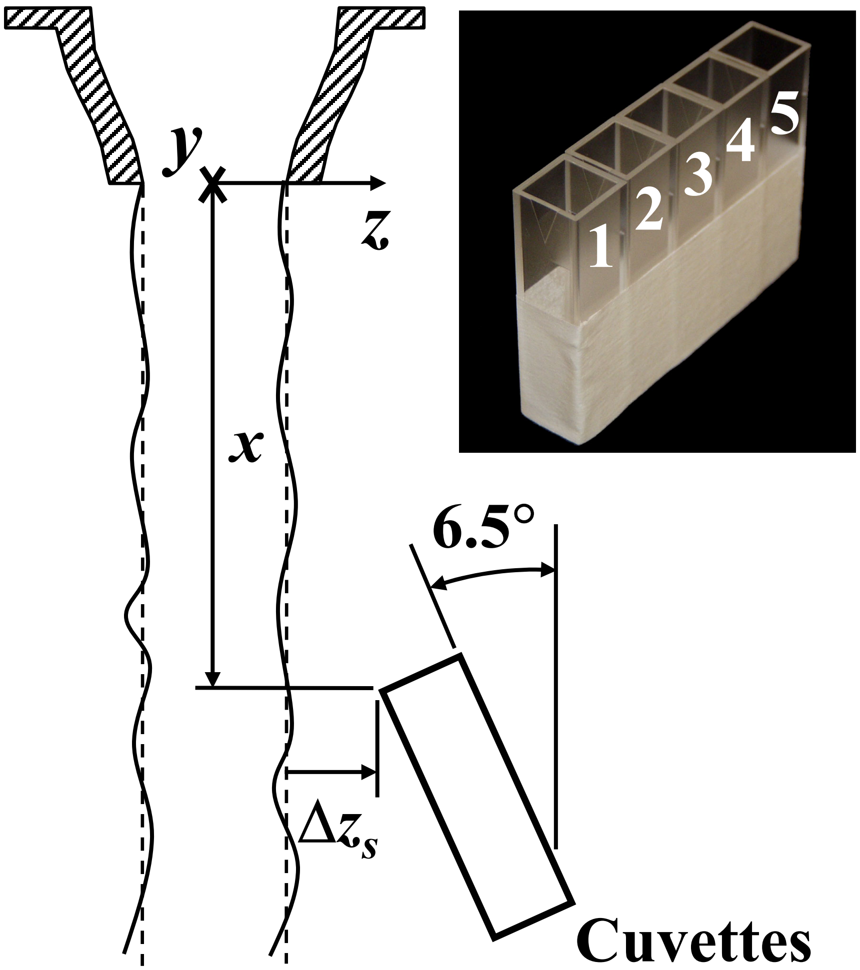


*Averaged over central 75% of flow, excludes "dog-bone" regions

Summary: BL Cutting

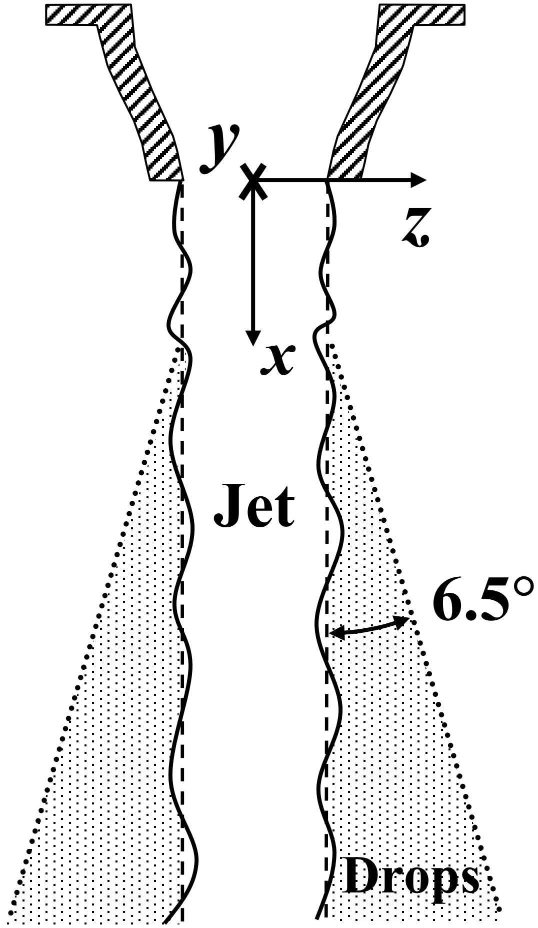
- Reduces surface ripple by 17% for Δz_{cut} = 0.25 mm and standard flow conditioner
  - Preliminary data suggest 48% reduction in surface ripple for Δz_{cut} = 0.38 mm (Re = 97,000; $x / \delta = 16$)
- Re-emergence of "dog-bone" structures as seen at lower *Re*
- Jet width (y-extent) decreased by ~6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

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

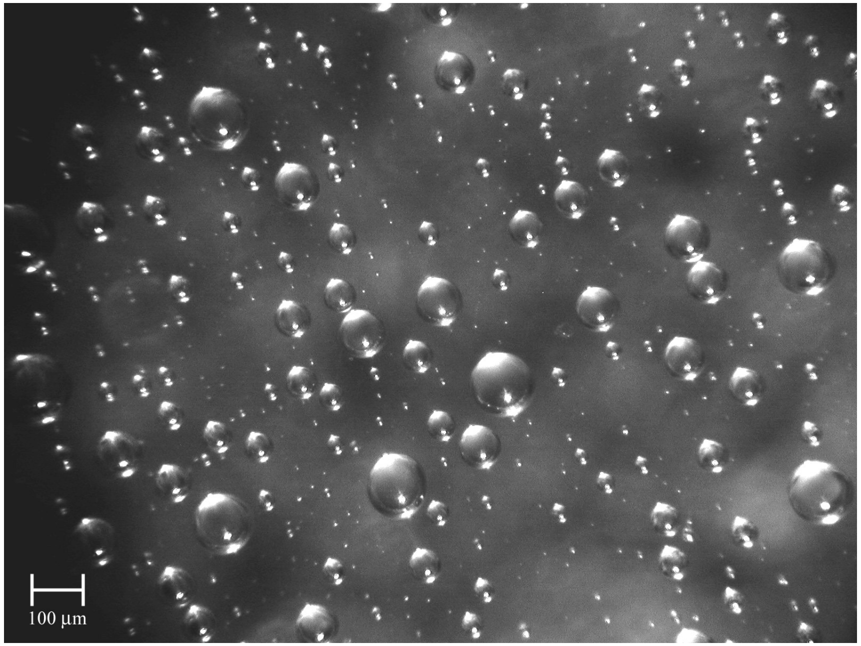
Droplet Trajectories



- **Droplets follow ballistic path based on $\tilde{u}$ and $\tilde{v}$**
  - **Absolute streamwise and radial velocities**

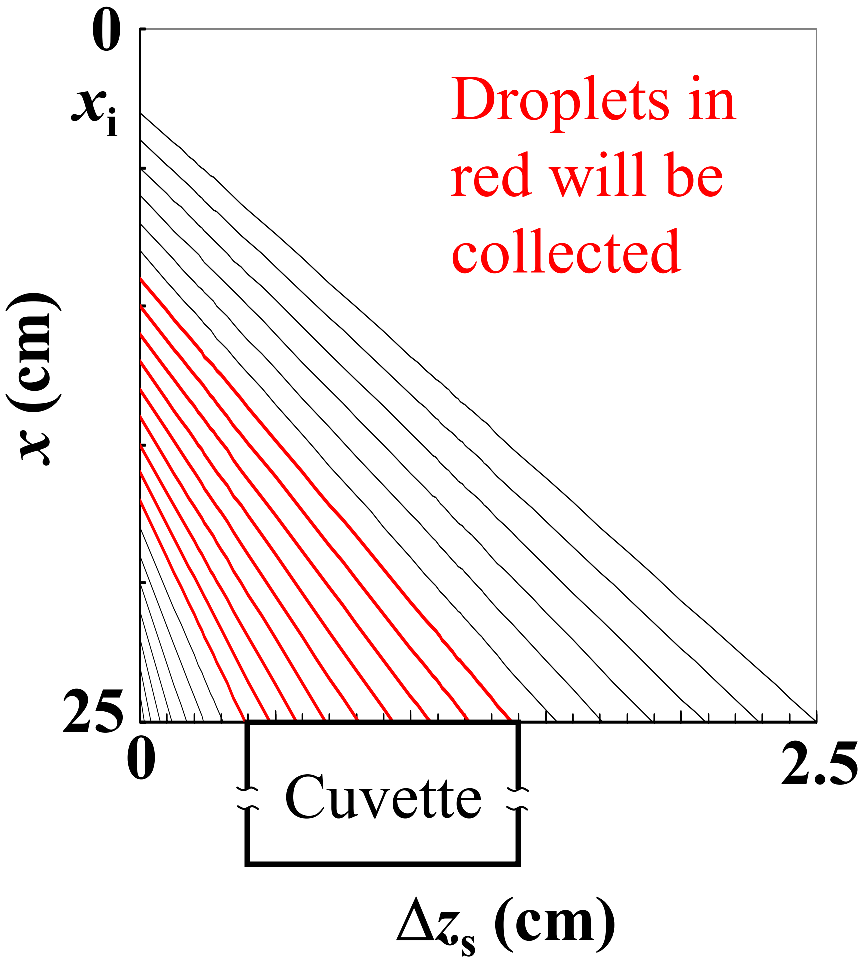
    $\tilde{u} = 0.78 \cdot U_o, \quad \tilde{v} \leq 0.088 \cdot U_o$
  - **Neglects gravitational and aerodynamic effects**
- **Droplet "halo" forms starting at x_i**
  - **Droplets only inside halo**

Droplet Visualizations



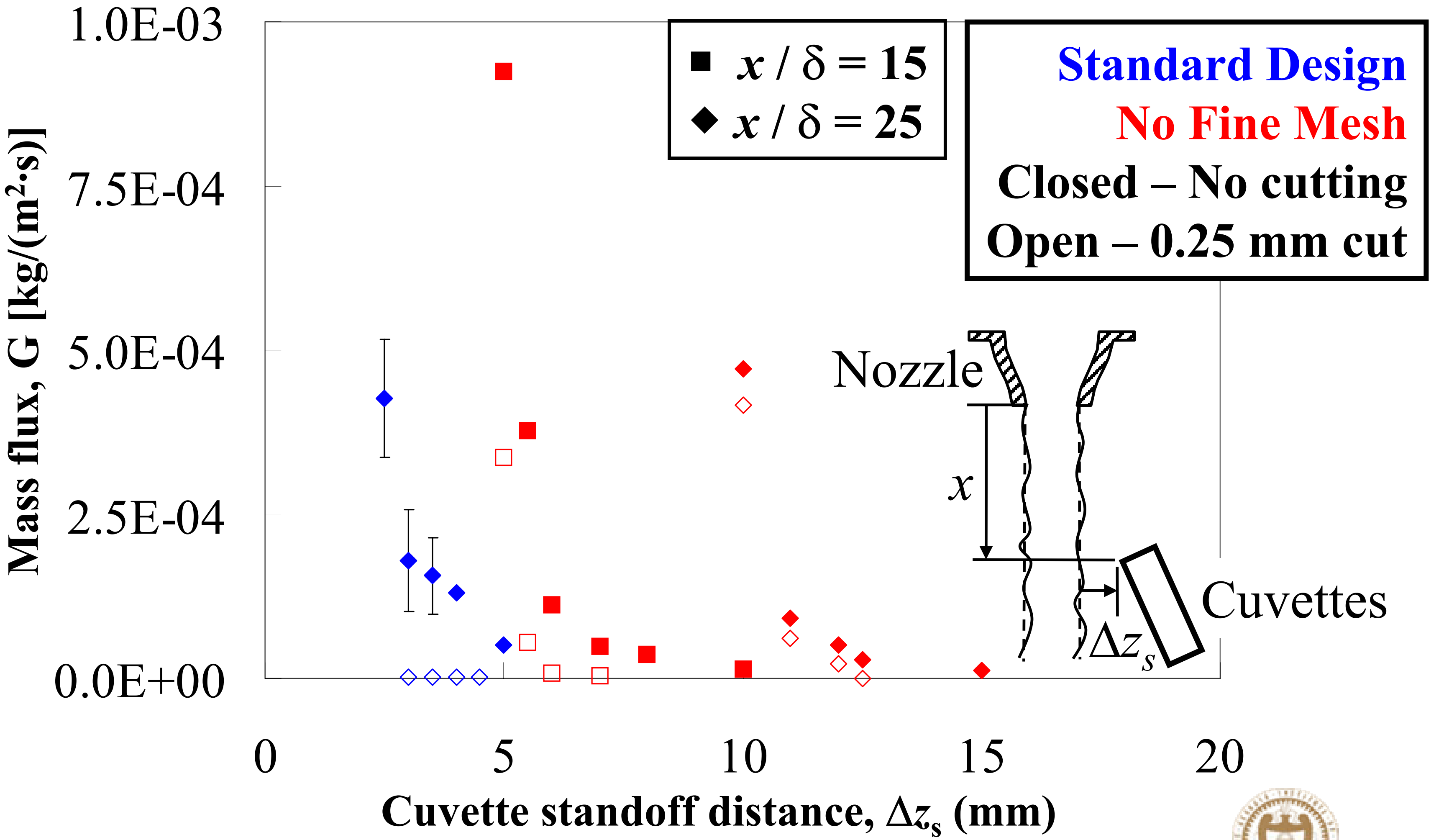
- Model predicts SMD = 0.6 – 1.3 mm
  - No flow conditioning
- Droplets collected on coated microscope slide
  - Standard flow conditioning
  - Re = 130,000; x / δ = 25
  - Diameters O(1–100 µm)
- Initial visualizations for no fine mesh suggest intermittent ejection of large (~1 mm dia.) drops

Collected Droplets

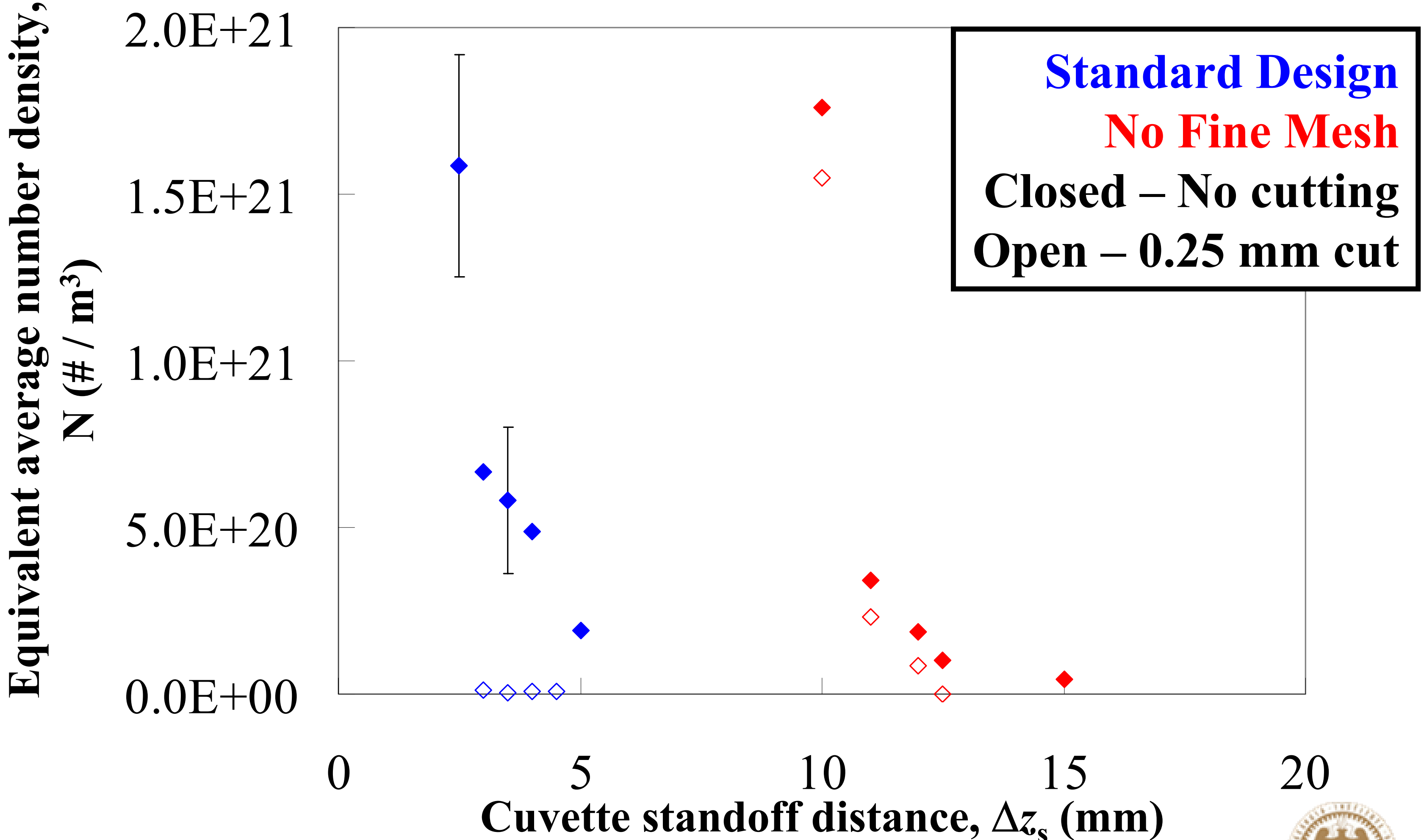


- Droplets with red trajectories collected by cuvettes
  - Cuvette shown at $x = 25$ cm, $\Delta z_s = 4$ mm, $\theta = 0°$
- Note that $z = 0$ corresponds to nominal free surface of jet

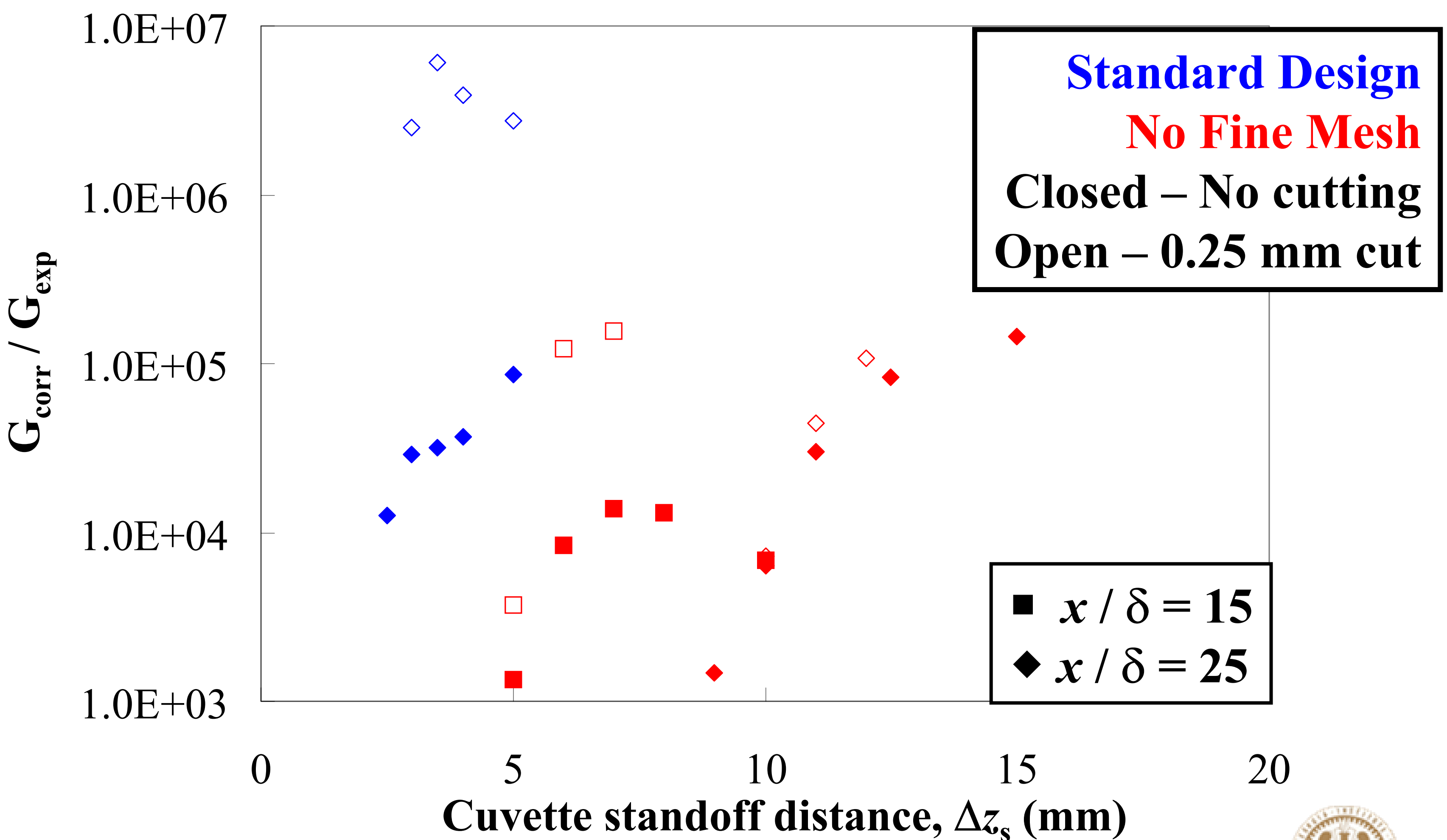
Experimental Mass Flux



Experimental Number Density
(x / δ = 25)



Model Comparison



Summary: Mass Collection

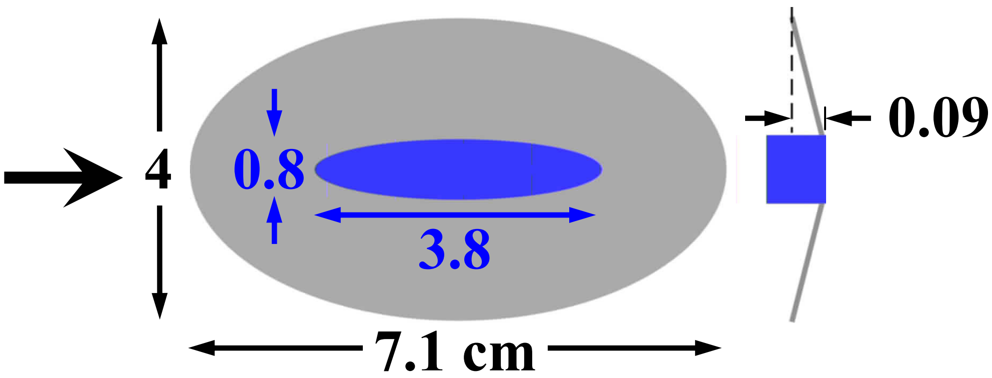
- **Flow straightening and contracting nozzle significantly reduce ejected droplet mass (by 3–5 orders of magnitude) compared w/model**
- **BL cutting has considerable impact on collected droplet mass**
- **BUT: proper flow conditioning more important**
- **Flow conditioning and BL cutting reduce collected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

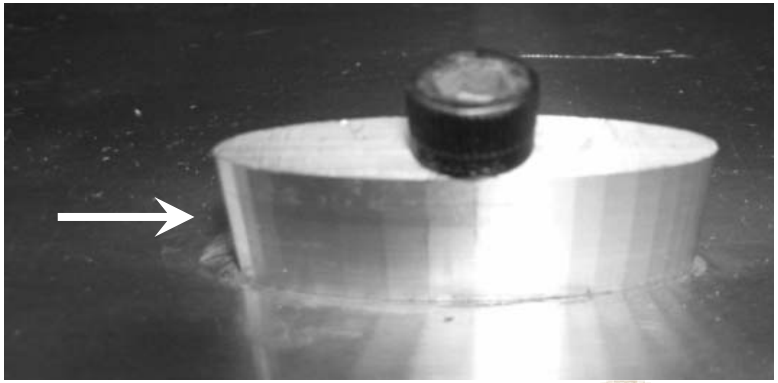
Conclusions

- 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

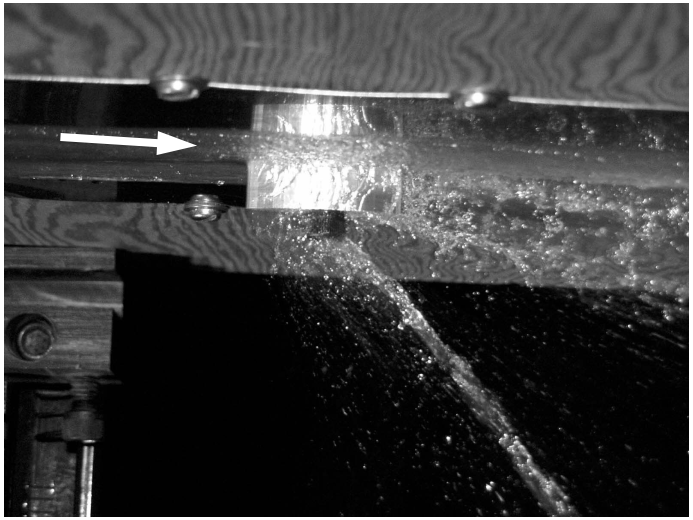
Hydrodynamically Shaped Penetration With Backwall Modification

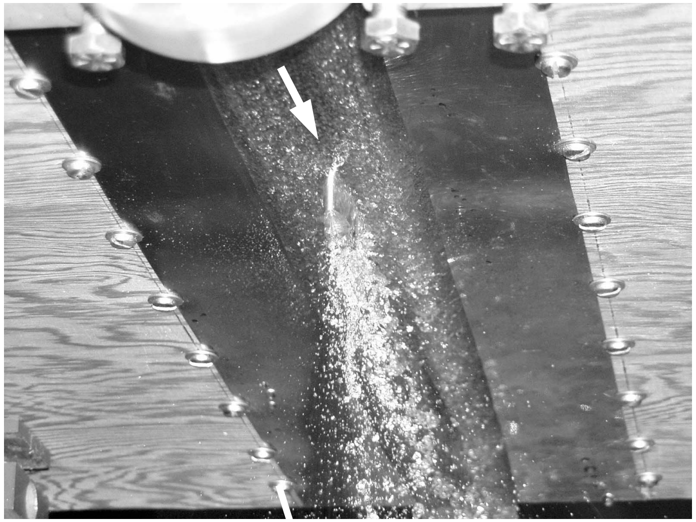
- Scaled penetration/backwall geometry shown in APEX study to ensure fluid closure downstream of penetration
  - Simulations for perfectly wetting fluid (0° contact angle)
  - Leading edge x = 16.4 cm from nozzle exit
- Downward and upward-facing flat surfaces
  - No centrifugal acceleration





Initial Results

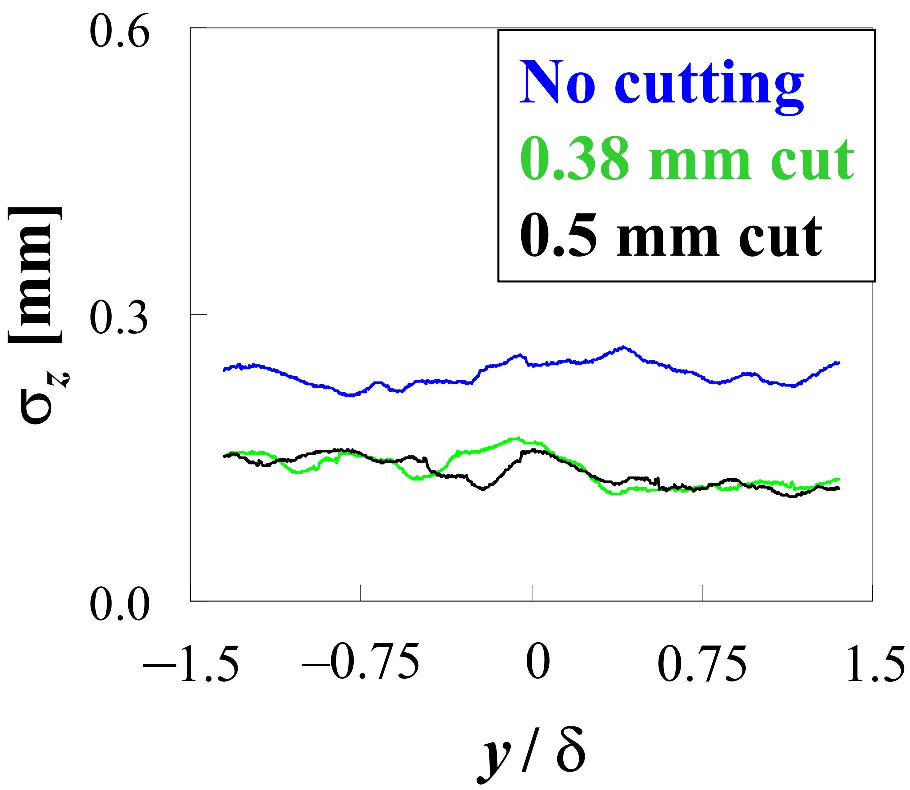




- **Water on stainless steel (contact angle ~50°)**
- ***Re* = 10,000; *We* = 1,000 (APEX: *Re* = 860,000; *We* = 305,000)**
- **Similar results for horizontal upward-facing surface**

Extra Slides

Effect of Cut Depth Δz_{cut}
$(x / \delta = 16)$



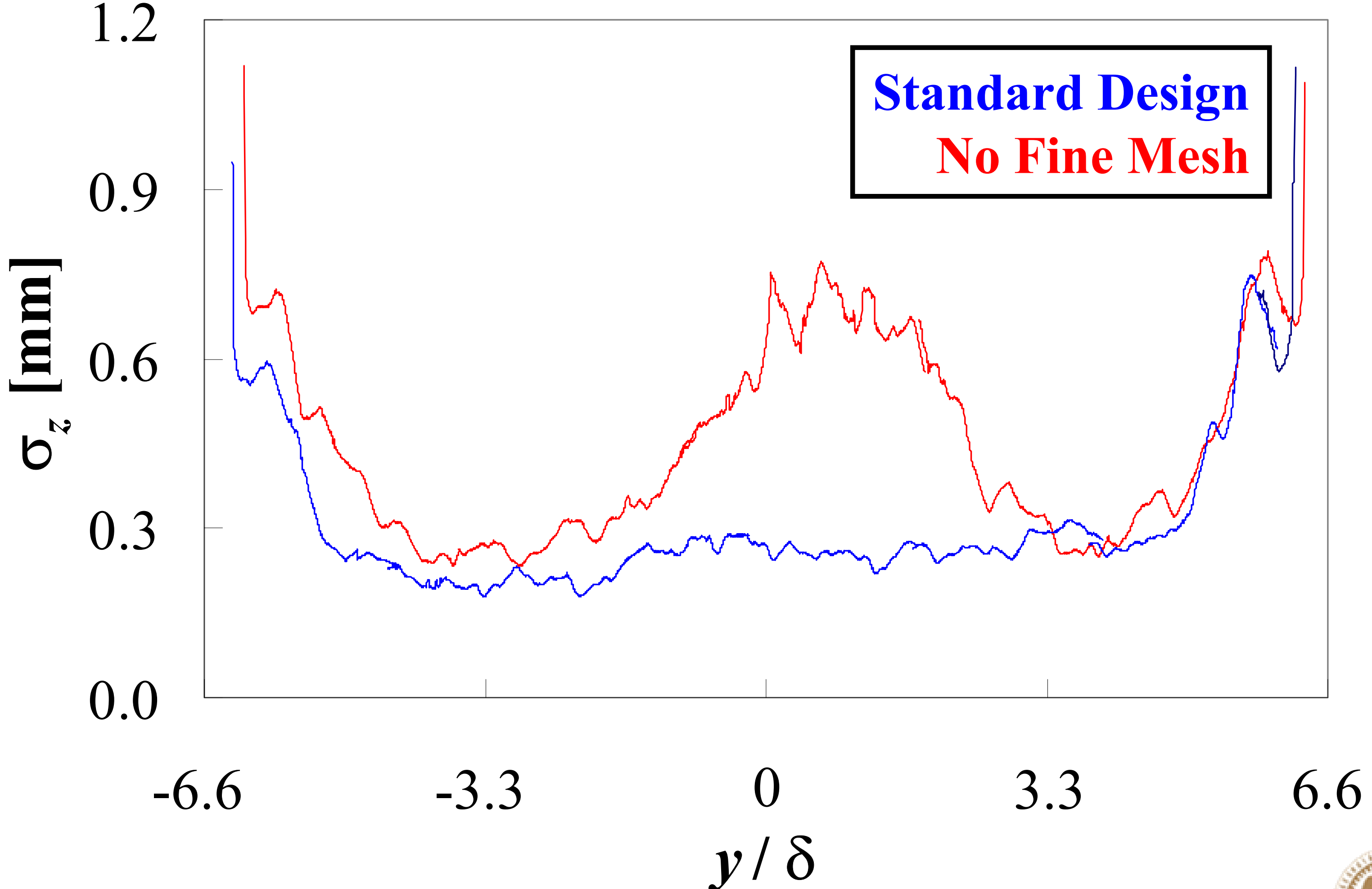
- **Surface ripple at jet center**
- **Cut jets appear "smoother"**
  - **σ_z independent of cut depth for $\Delta z_{cut} \geq 0.38$ mm**
  - **Average values:**

    σ_z = 0.238 mm for Δz_{cut} = 0

    σ_z = 0.137 mm for Δz_{cut} = 0.38 mm

    σ_z = 0.135 mm for Δz_{cut} = 0.5 mm
- **Surface ripple reduced by ~40%**

Flow Conditioning Effects ($x / \delta = 15$)



BL Cutting Effects ($x / \delta = 15$; $\Delta z_{cut} = 0.25$ mm)