IMPACT OF BOUNDARY-LAYER CUTTING ON FREE-SURFACE BEHAVIOR IN TURBULENT LIQUID SHEETS

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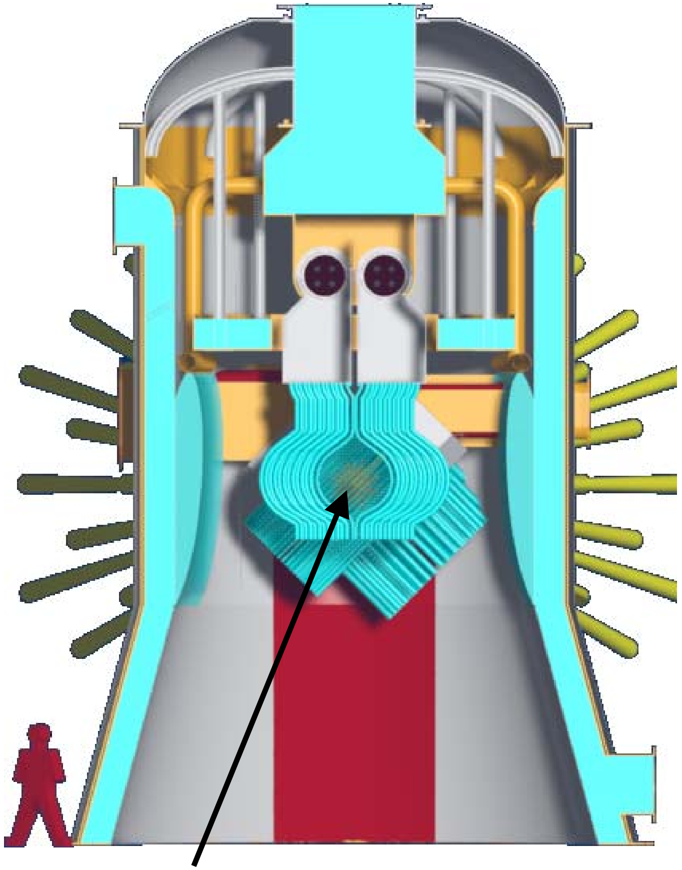
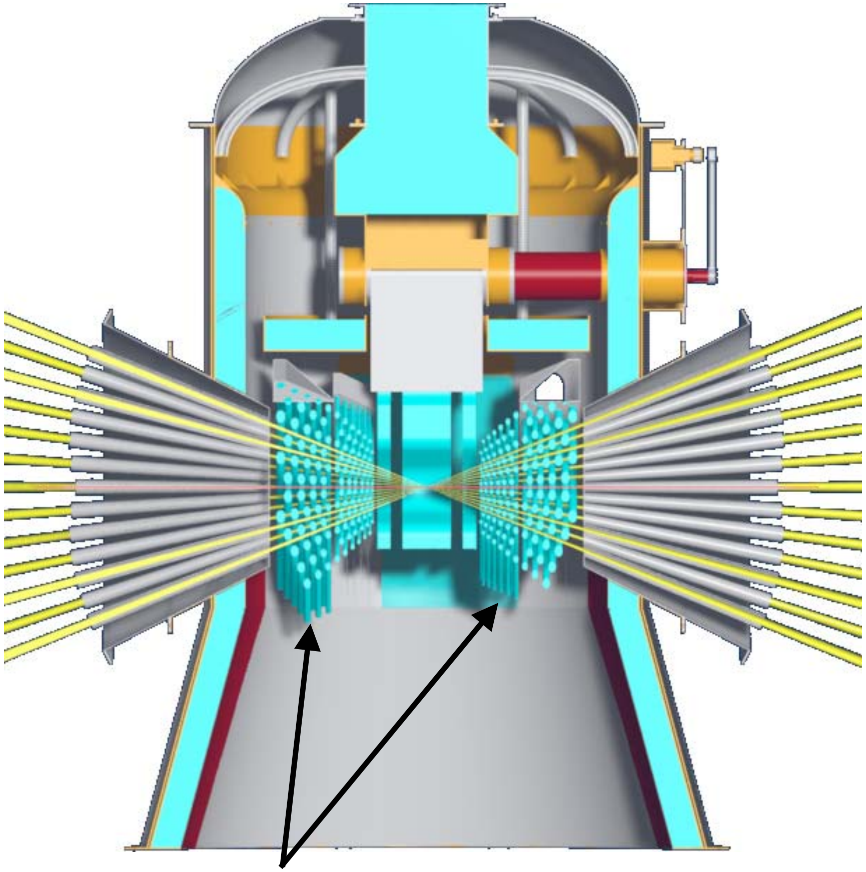
Thick Liquid Protection
(HYLIFE-II)



Oscillating pocket



Protective lattices

Picture courtesy of Ryan Abbott (LLNL)

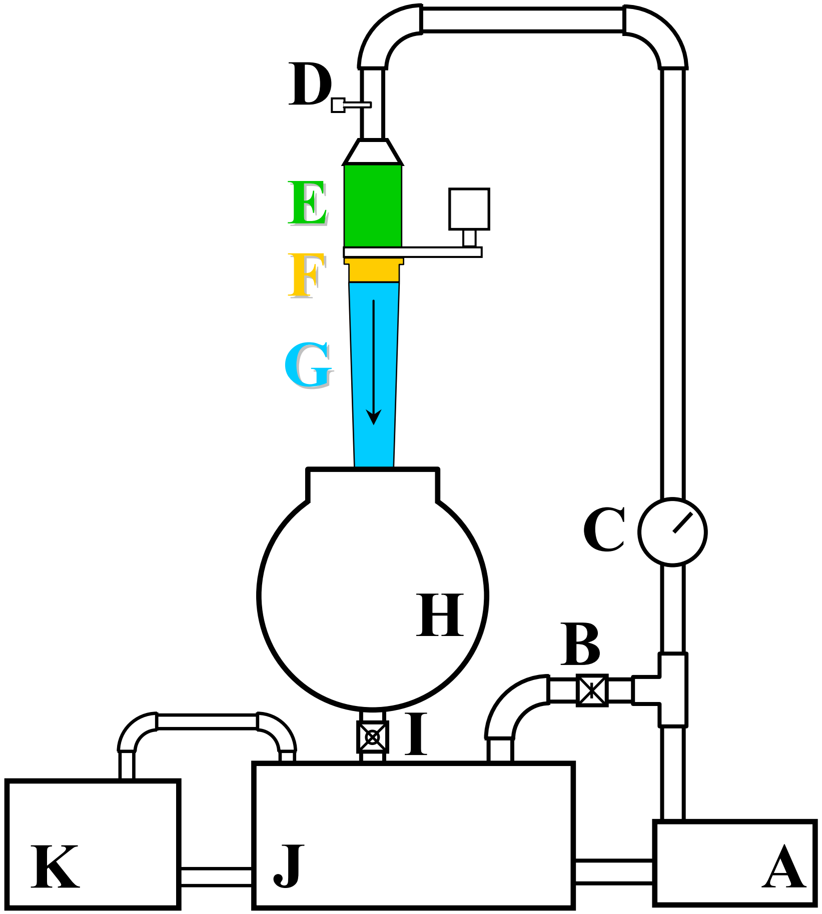
Motivation

- Provide effective thick liquid protection
  - Minimize interference with beam and target propagation ⇒ smooth jets
- What type(s) of flow conditioning are necessary to produce jets that meet HYLIFE-II requirements?
  - Is boundary-layer cutting required?
  - If so, can boundary-layer cutting be optimized?

Objectives

- Estimate amount of turbulent breakup at free surface ("hydrodynamic source term")
- Quantify free-surface fluctuations
- Optimize effectiveness of boundary-layer (BL) cutting
  - Determine minimum "cut" mass flux to meet propagation requirements
  - Minimize surface ripple

Flow Loop

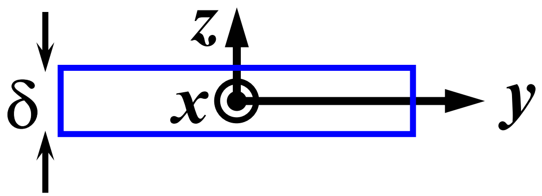


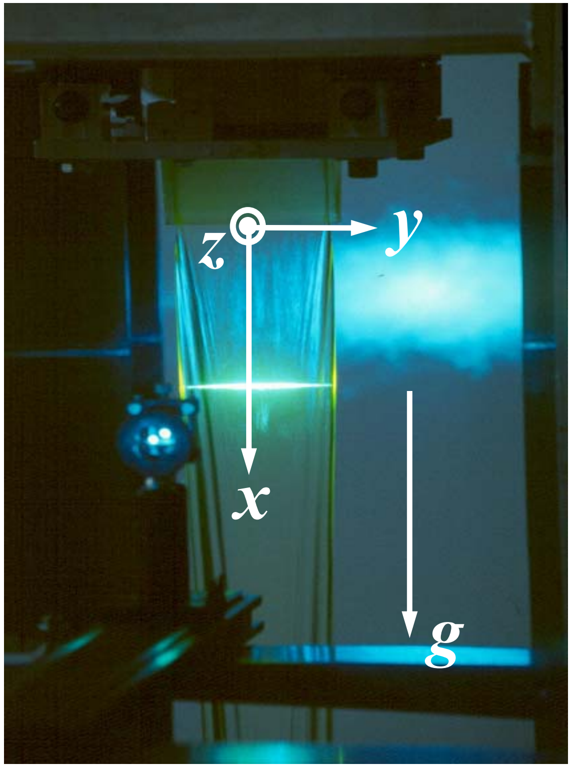
- **Pump-driven recirculating flow loop**
- **Test section height ~ 1 m**
- **Overall height ~ 5.5 m**

A	**Pump**	**H**	**400 gal tank**
B	**Bypass line**	**I**	**Butterfly valve**
C	**Flow meter**	**J**	**700 gal tank**
D	**Pressure gage**	**K**	**20 kW chiller**

E Flow conditioner
F Nozzle
G Liquid sheet

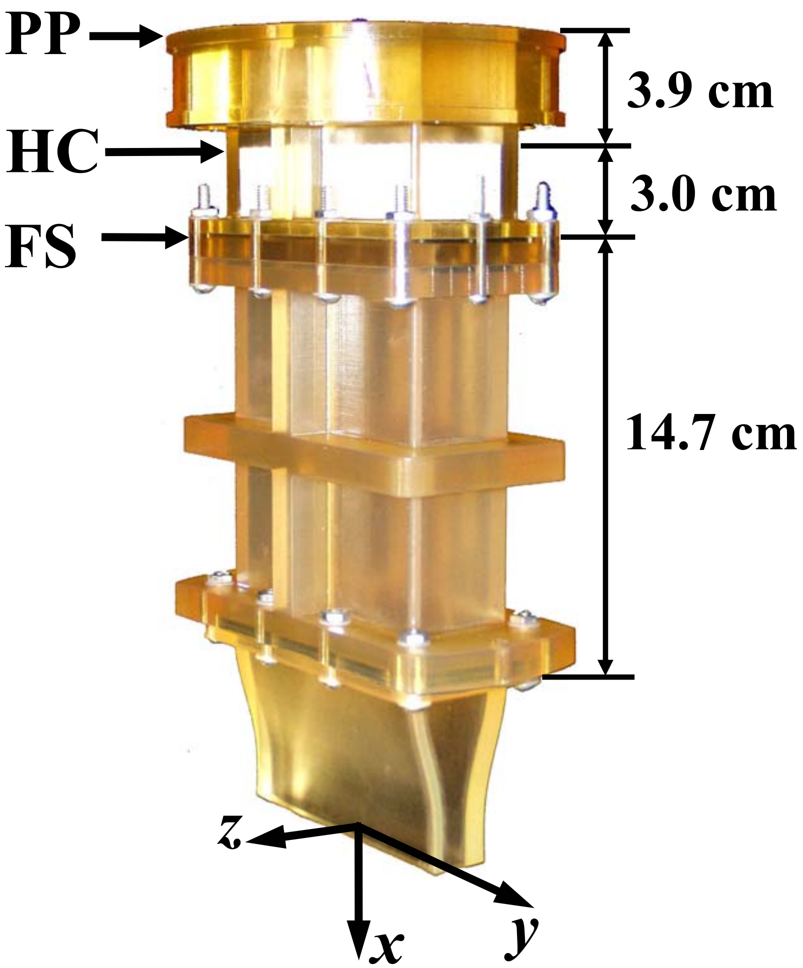
Experimental Parameters





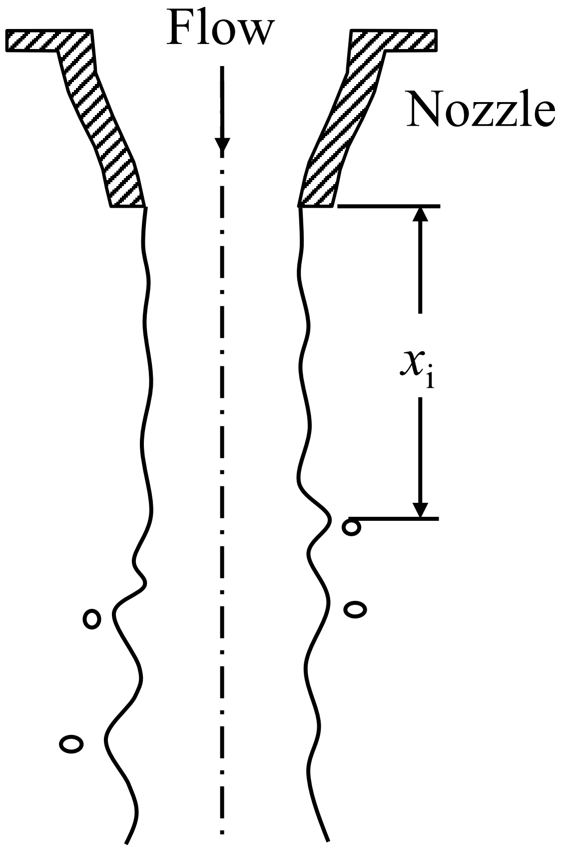
- Char. length scale $\delta = 1$ cm
- $Re = U_o \delta / \nu = 120{,}000$
- $We = \rho_L U_o^2 \delta / \sigma = 19{,}000$
- *Re* 50% and *We* 20% of HYLIFE-II values
- $\rho_L / \rho_g = 850$
- Near field: $x / \delta \leq 25$ matching extent of HYLIFE-II protective pocket
- BL cutter removal rate: $\dot{m}_{\text{cut}} / \dot{m}_{\text{fl}} = 0\text{–}\ 1.9\%$
- σ_z standard deviation in *z*-position of free surface

Flow Conditioning Elements



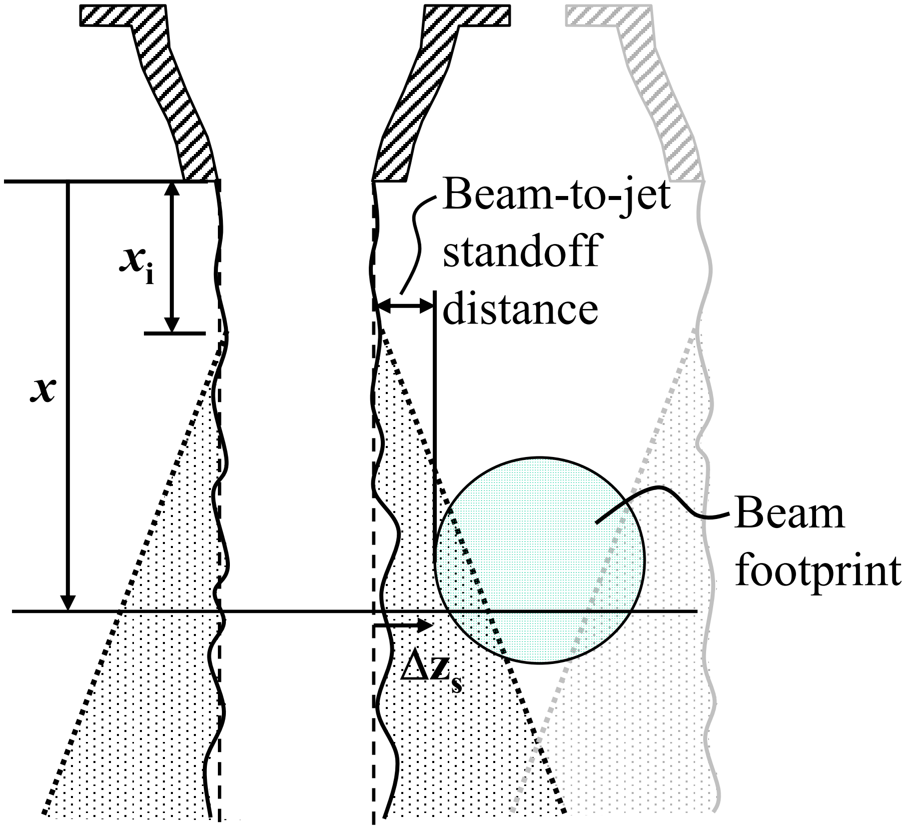
- **Round inlet (12.7 cm ID) to rectangular cross-section 10 cm × 3 cm (*y* × *z*)**
- **Perforated plate (PP)**
  - Open area ratio 50% with staggered 4.8 mm dia. holes
- **Honeycomb (HC)**
  - 3.2 mm dia. × 25.4 mm staggered circular cells
- **Fine screen (FS)**
  - Open area ratio 37.1%
  - 0.33 mm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

Turbulent Breakup



- **Turbulent primary breakup mechanism**
  - **Formation of instabilities followed by ligaments and finally droplets**
  - **Possible sources of instabilities**
    - **Vorticity imparted at nozzle exit**
    - **Instability in boundary layer**
    - **Sudden velocity profile relaxation**
- **Onset of breakup, x_i**
  - **Location of first observable droplets**
  - **$x_i \downarrow$ as $We \uparrow$**

Beam Propagation



- **Droplets travel into beam footprint**
- **Jet standoff distance, Δz_s**
  - **Measured from nominal jet surface**
- **Equivalent number density dependent on x and Δz_s**
  - **Ignores jet-jet interactions**

Atomization Work

- Considerable database from combustion and spray research group at UM (Faeth et al.)
    - Most recently: Sallam, Dai, & Faeth, Int. J. of Multiphase Flow, 28 : 427 – 449 (2002)
- Correlations developed for
    - Round and annular jets
    - Fully-developed turbulent flow at exit
    - No flow conditioning, contraction/nozzle or BL cutting
    - Jets issue into air at atmospheric pressure
    - Working fluids: water and ethanol

Surface Breakup Efficiency Factor

- **Radial droplet velocity relative to jet surface**

  $$\tilde{v}_r \cong 0.045\,U_o$$

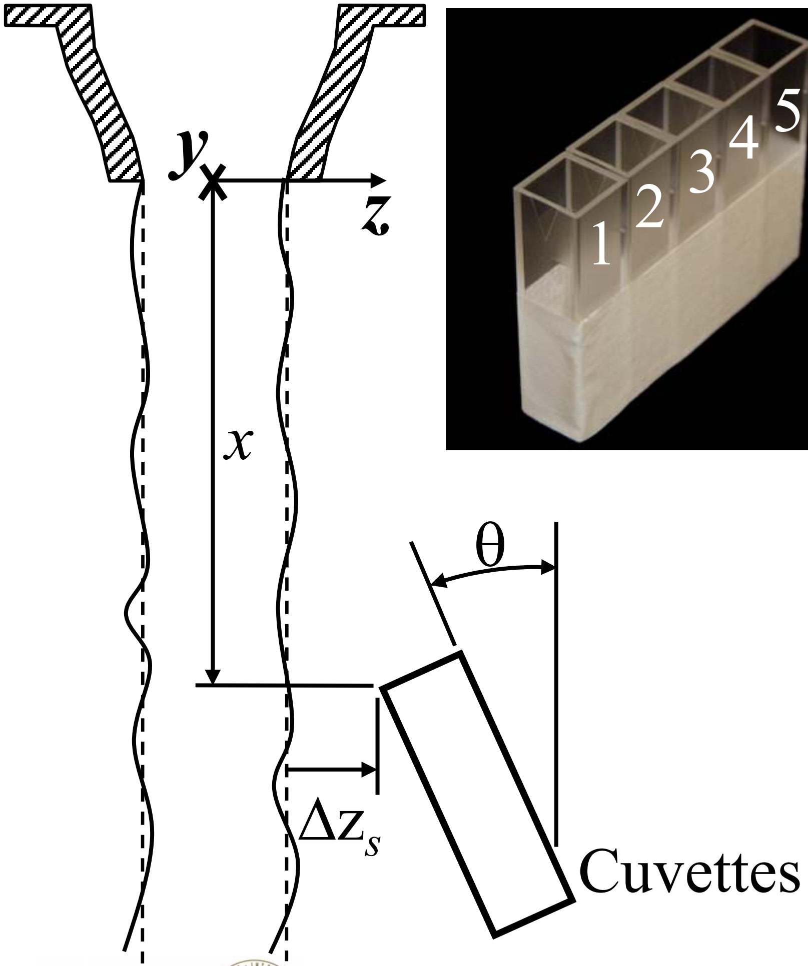
- **Surface breakup efficiency factor**
  - **Gives a measure of the flux of droplets from free surface**
  - **ε = 1 indicates droplets are forming over entire surface area of liquid surface**

$$\varepsilon = G \big/ \rho_L \tilde{v}_r \qquad G \equiv \text{mass flux of droplets}$$

- **Efficiency factor correlation (valid for We_d = 235–270,000)**

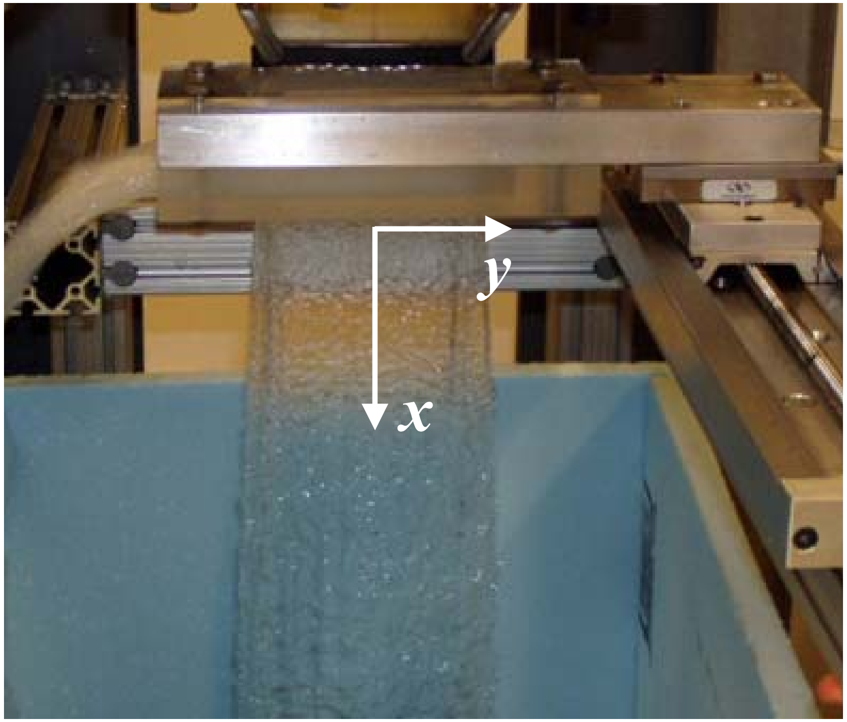
$$\varepsilon = 0.272\left[x \big/ \left(d_h\, We_d^{\,1/2}\right)\right] \qquad d_h = \text{hydraulic diameter}$$

Mass Collection



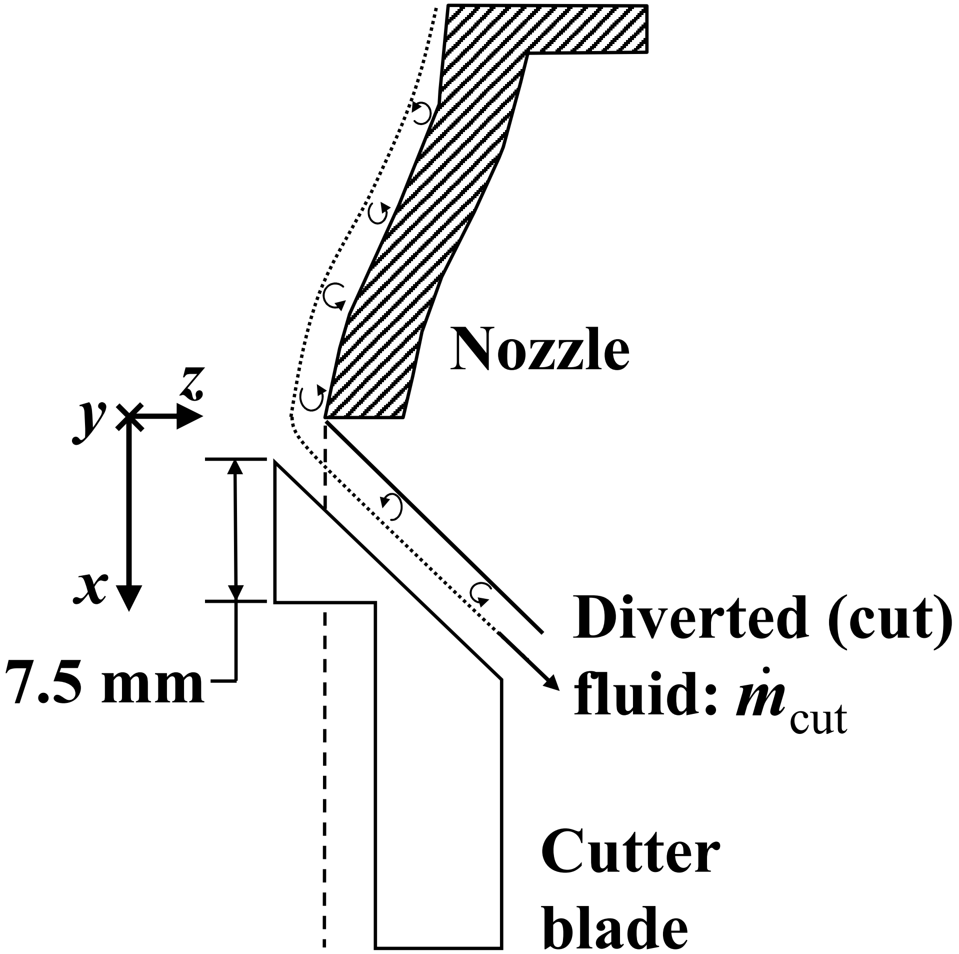
- **Cuvette opening = 1 cm × 1 cm w/ 1 mm walls**
- **5 cuvettes placed side by side**
  - **Cuvette #3 centered at $y = 0$**
- **Located at x, Δz_s away from nominal jet position**
  - **Δz_s varied from ~ 2.5 – 15 mm**
- **Shallow angle of inclination, $\theta = 6.5°$**
- **Samples acquired over 0.5 – 1 hr**
- **Collected mass used to calculate:**
  - **Mass flux, G [kg / (m^2·s)]**
  - **Equivalent number density, N [m^{-3}]**

Boundary-Layer Cutter



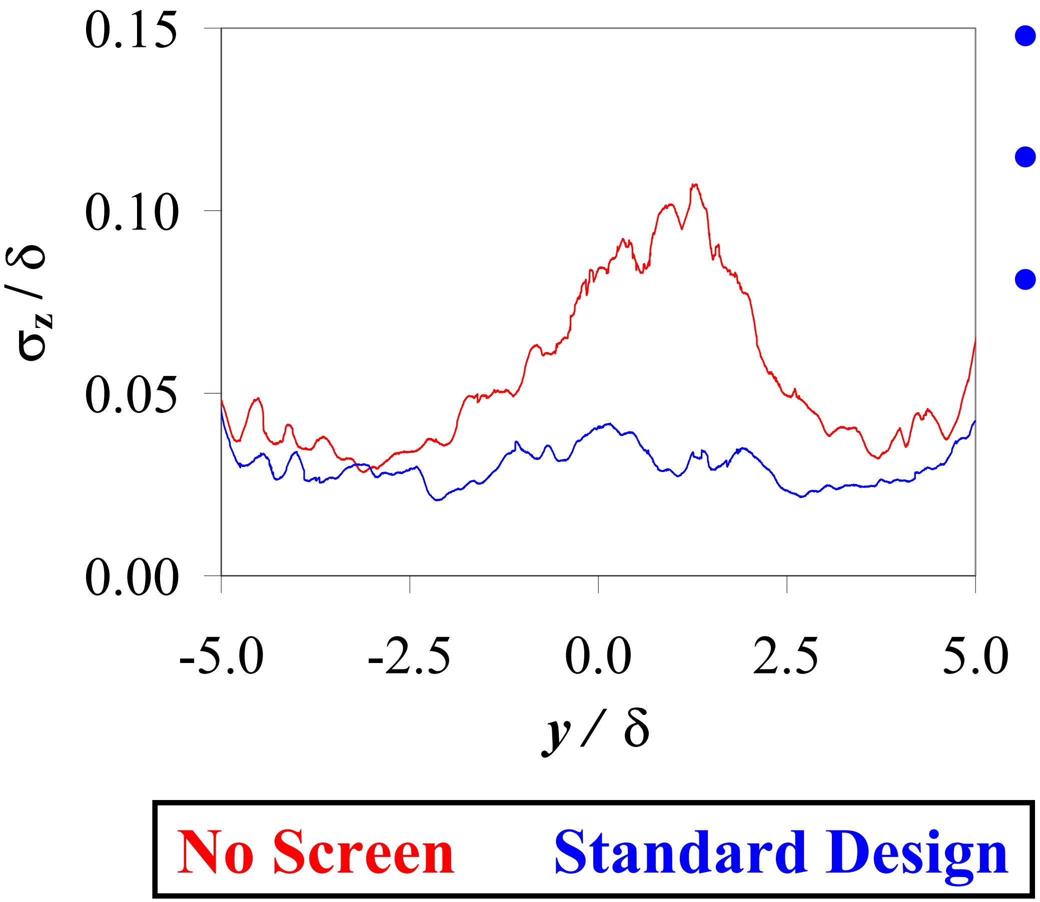
- "Cut" (remove BL fluid) on one side of liquid sheet
- Independently control removal rate: $\dot{m}_{\mathrm{cut}}$
- Removed liquid diverted to side

Cutter Details

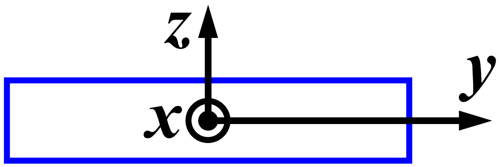


- **Aluminum blade inserted into flow**
  - **Remove high vorticity / low momentum fluid near nozzle wall**
  - **Blade width (*y*-extent) 12 cm *vs.* W_o = 10 cm**
  - **Blade edge 0.76 mm downstream of nozzle exit**
- **Relatively short reattachment length**
  - **Nozzle contraction length 63 mm**

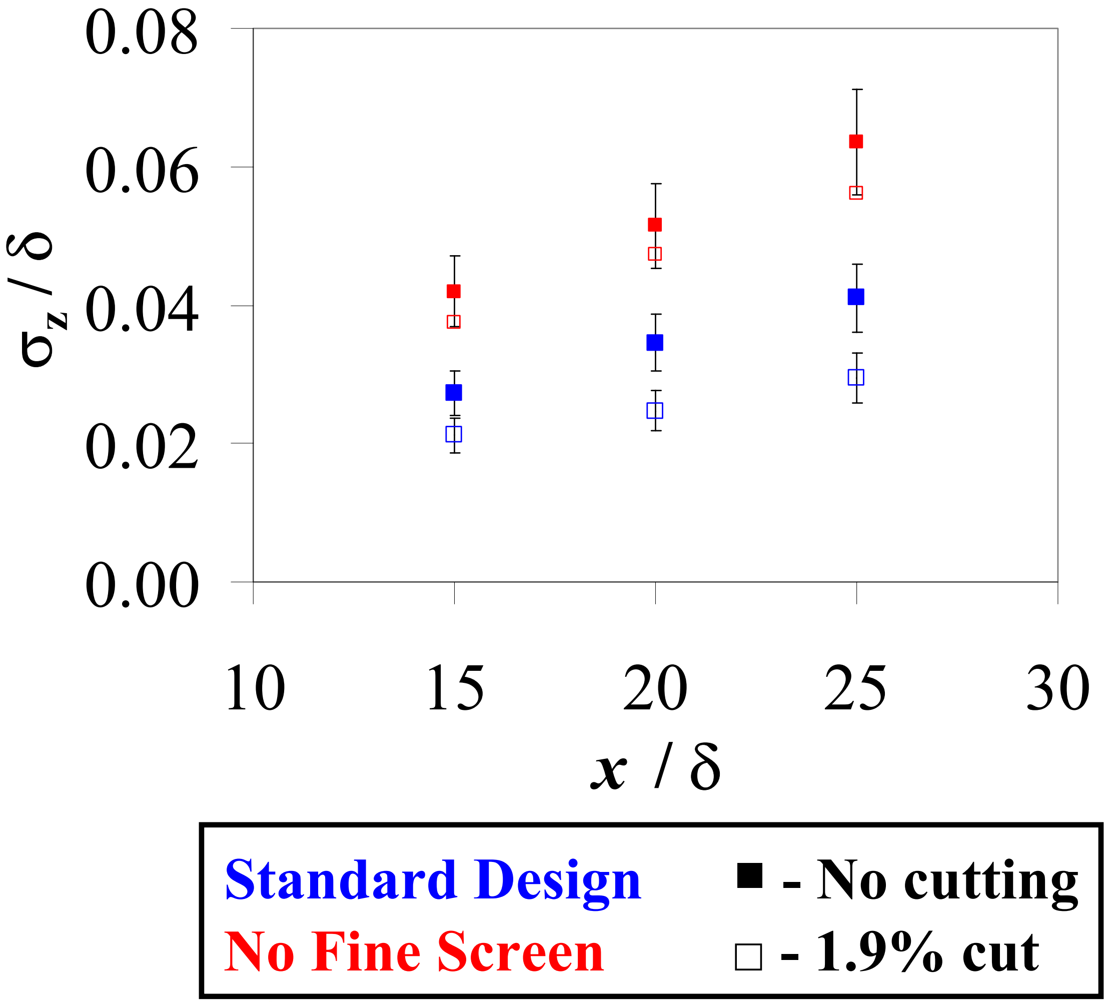
PLIF Results
(Initial Conditions)



- $x / \delta = 25$
- $\dot{m}_{\text{cut}} / \dot{m}_{\text{fl}} = 1.9\%$
- **Large central fluctuation without fine screen**
    - Fine screen has greater impact on σ_z



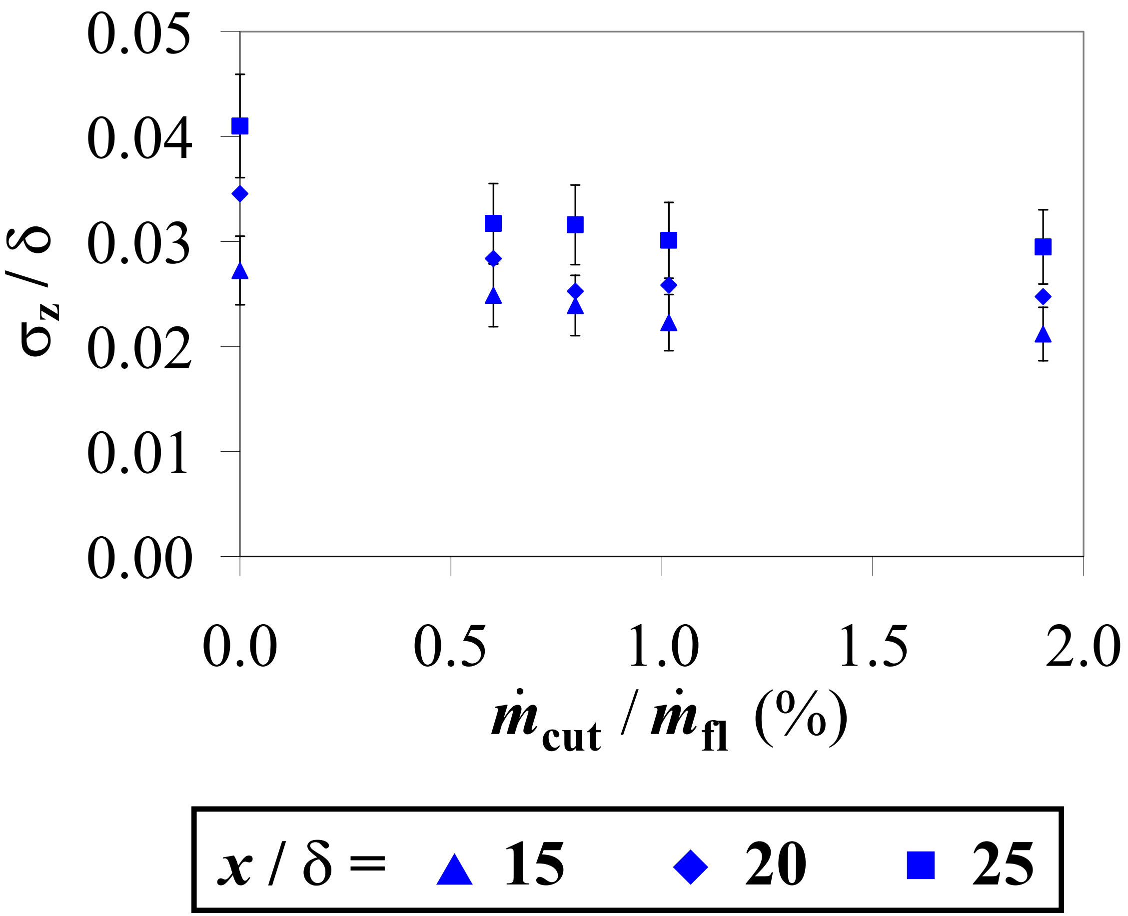
Average PLIF Results



- **Averaged over central 75% of jet**
- **Fluctuations 1.5× for no fine screen**
- **BL cutting reduces σ_z by 33% for standard flow conditioner design**

PLIF Results

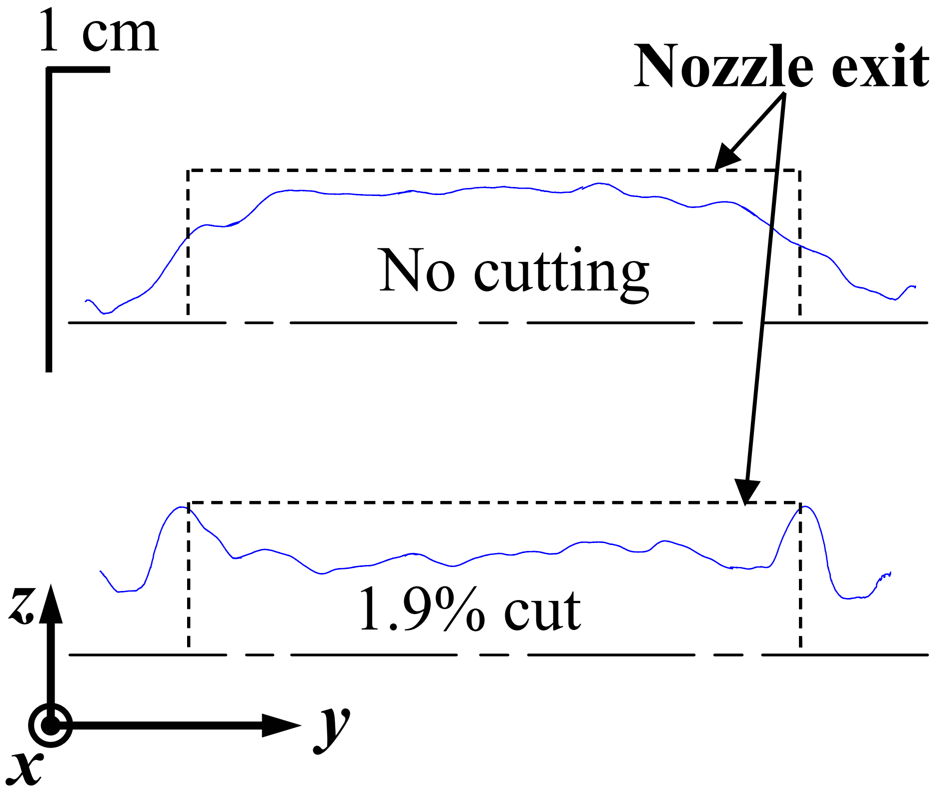
(BL Cutting)



- **Standard flow conditioning**
- $\sigma_z \downarrow$ **as** $\dot{m}_{\text{cut}} \uparrow$
- **Cutting as little as** $\dot{m}_{\text{cut}} = 0.6\%$ **significantly improves surface smoothness**

Jet Profiles

($x / \delta = 25$)

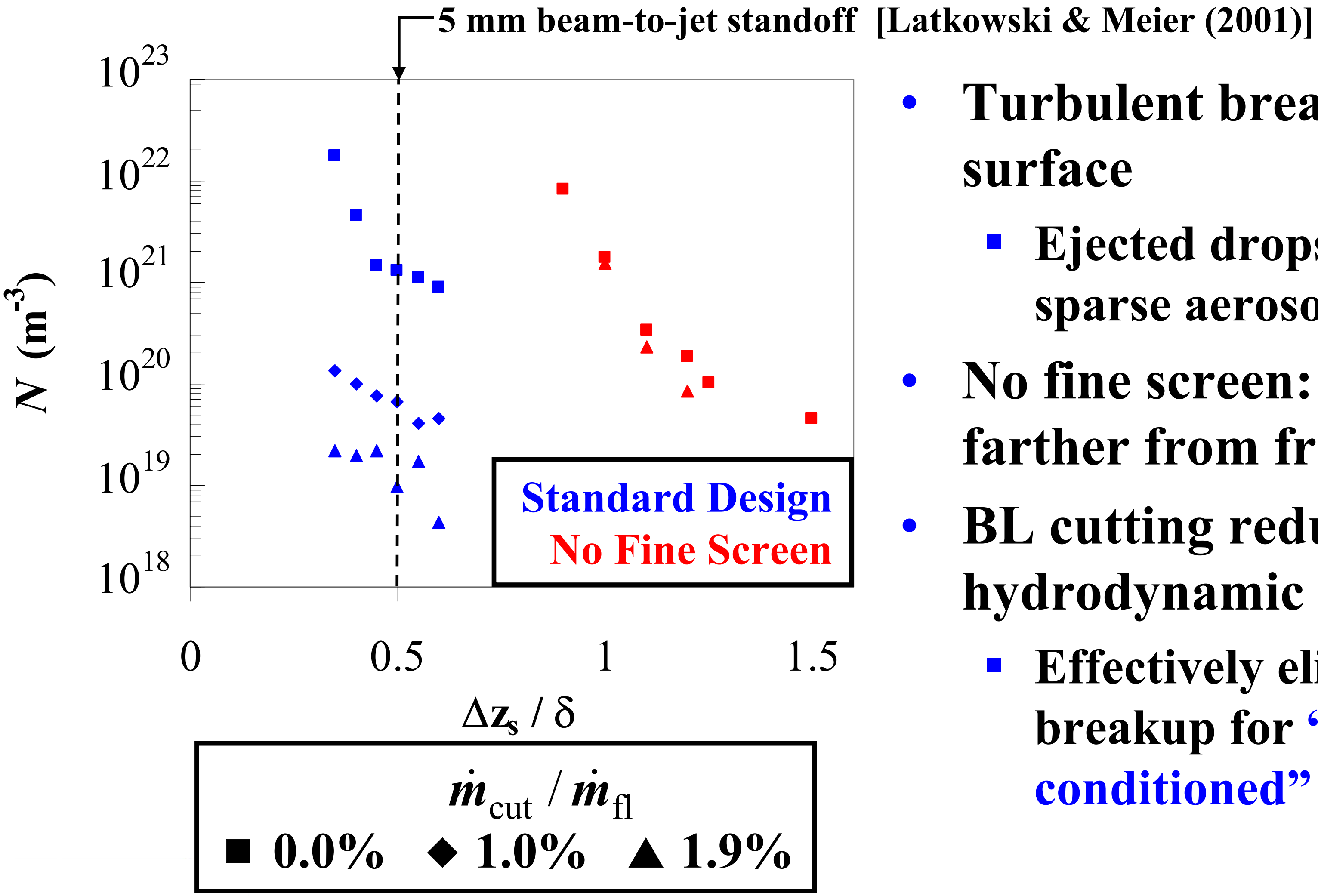


Notes: Vertical axis at 5× magnification
Average of 135 images over 4.5 s

- Std. flow conditioning
- Uncut jet inside nominal free surface
- BL cutting results in large protrusions near edges of jet
  - Sharp transition to edges of jet
- Jet width (y-extent) decreases with cutting
  - ~6 mm at $x/\delta = 25$

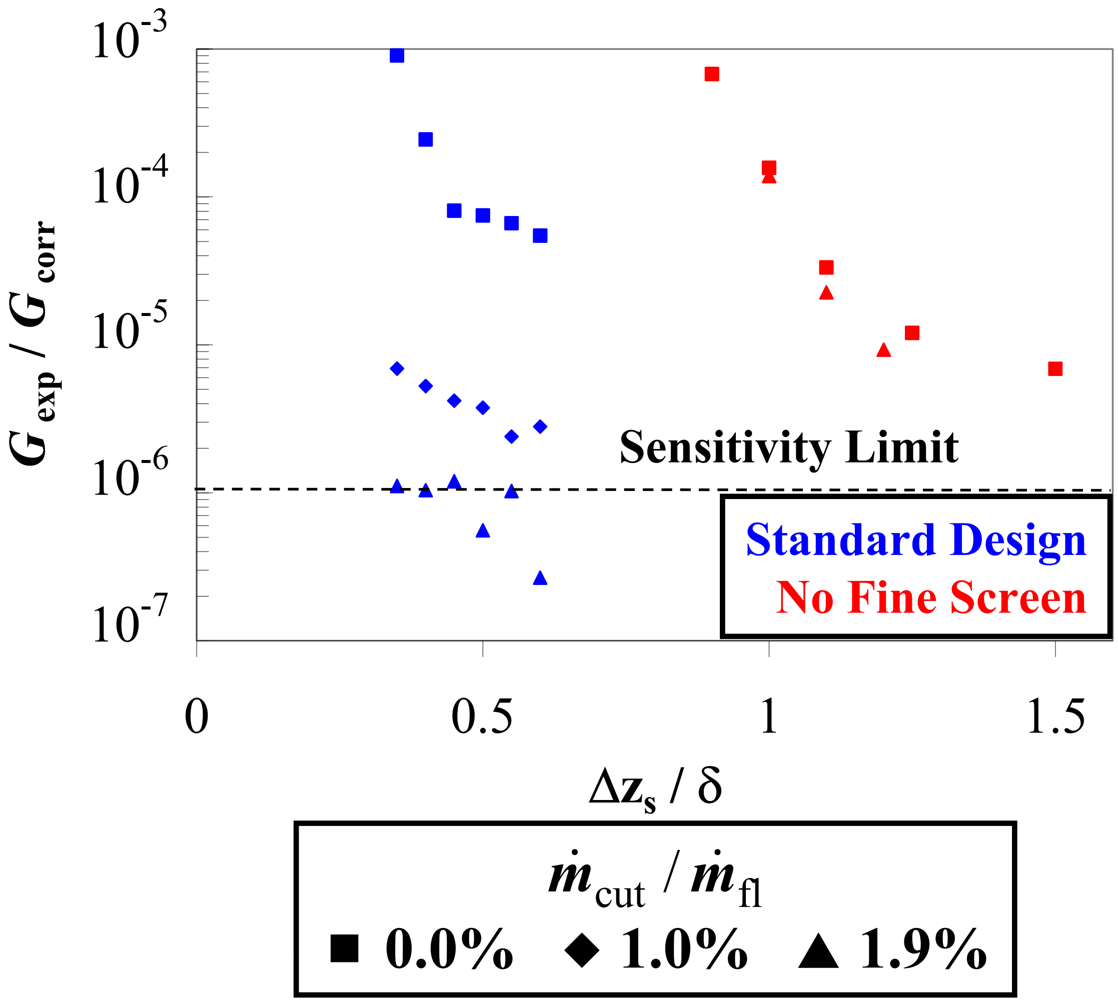
Equivalent Number Density

(x / δ = 25)



- **Turbulent breakup at free surface**
    - **Ejected drops form sparse aerosol around jet**
- **No fine screen: droplets farther from free surface**
- **BL cutting reduces hydrodynamic source term**
    - **Effectively eliminates breakup for "well conditioned" jet**

Model Comparison



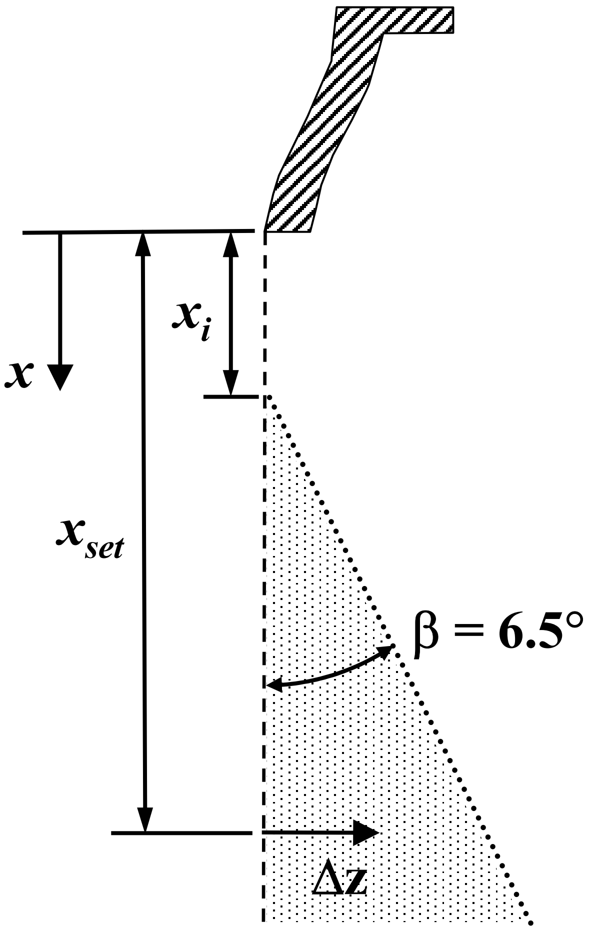
- **Correlation over-predicts breakup**
  - **Correlation based on fully-developed turbulent flow**
  - **Flow conditioning / contracting nozzle may reduce breakup by 10^3 - 10^5**
- **Zero collected mass within experimental error for $G_{exp} / G_{corr} < 10^{-6}$**

Conclusions

Characterized boundary layer cutting in turbulent liquid sheets in the near field at *Re* = 120,000

- **Optimum configuration: Standard flow conditioning with 1.0% of total mass flux cut from each face**
  - **Meets proposed upper limit of $N = 6 \times 10^{21}$ m^3**
  - **Surface ripple reduced by 31%**
- **Boundary layer cutting changes free-surface geometry**
  - **Large protrusions near edges of sheet**
- **Breakup correlation overestimates droplet mass flux (and number density) by 3 – 5 orders of magnitude**
  - **Reduction may be due to flow conditioning and nozzle**
  - **Demonstrates sensitivity of breakup to initial conditions**

Correlation Mass Flux - I



- **Droplets follow ballistic path based on:**
    - **Absolute streamwise and radial velocities**
      $$\tilde{u} = 0.78 \cdot U_o, \quad \tilde{v} \le 0.089 \cdot U_o$$
    - **Neglects gravitational and aerodynamic effects**
- **Droplet trajectory given by**
  $$\beta = \arctan\left(\frac{\tilde{v}}{\tilde{u}}\right) \le 6.5^{o}$$
- **Coordinate transformation**
  $$\tan(\beta) = \frac{\Delta z}{(x_{set} - x)} \quad \Rightarrow \quad x = \frac{-\Delta z}{\tan(\beta)} + x_{set}$$

Correlation Mass Flux - II

- **Solving for *G* and substituting for ε**

$$G = 0.272\left[\frac{x}{\left(d_h We_d^{1/2}\right)}\right]\cdot\left(\rho_\mathrm{L}\tilde{v}_r\right)$$

- **Substituting for *x***

$$G\left(\Delta z, x_{set}\right) = -0.272\left[\frac{\left(\Delta \mathrm{z}/\tan\left(\beta\right)\right)}{\left(d_h We_d^{1/2}\right)}\right]\cdot\left(\rho_\mathrm{L}\,\tilde{v}_r\right) + G\left(x_{set}\right)$$

Valid for $x_{set} > x_i$ and $0 < \Delta z < (x_{set} - x_i) \cdot \tan(\beta)$

- **For average correlation mass flux at $x/\delta = 25$ and $\Delta z_s = 5$ mm**
  - **$x_{set} = 25$ cm**
  - **Use $\Delta z = \Delta z_s + 6$ mm, for mass flux in center of cuvette**