FLOW CONDITIONING DESIGN IN TURBULENT LIQUID SHEETS

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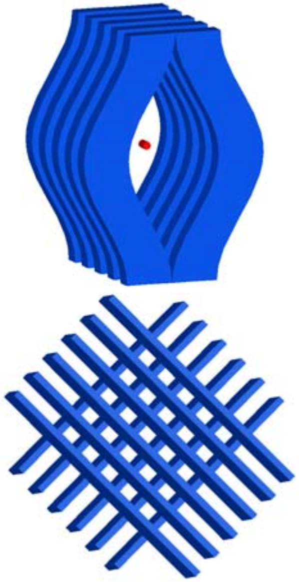
Thick Liquid Protection

- Protect IFE reactor chamber first walls with liquid "curtain" to absorb radiation from fusion events
- Increase chamber lifetime and decrease chamber radius

HYLIFE-II (High-Yield Lithium-Injection Fusion Energy)

- Oscillating slab jets, or liquid sheets, create protective pocket to shield chamber side walls
- Lattice of stationary sheets shield front/back walls while allowing beam propagation and target injection



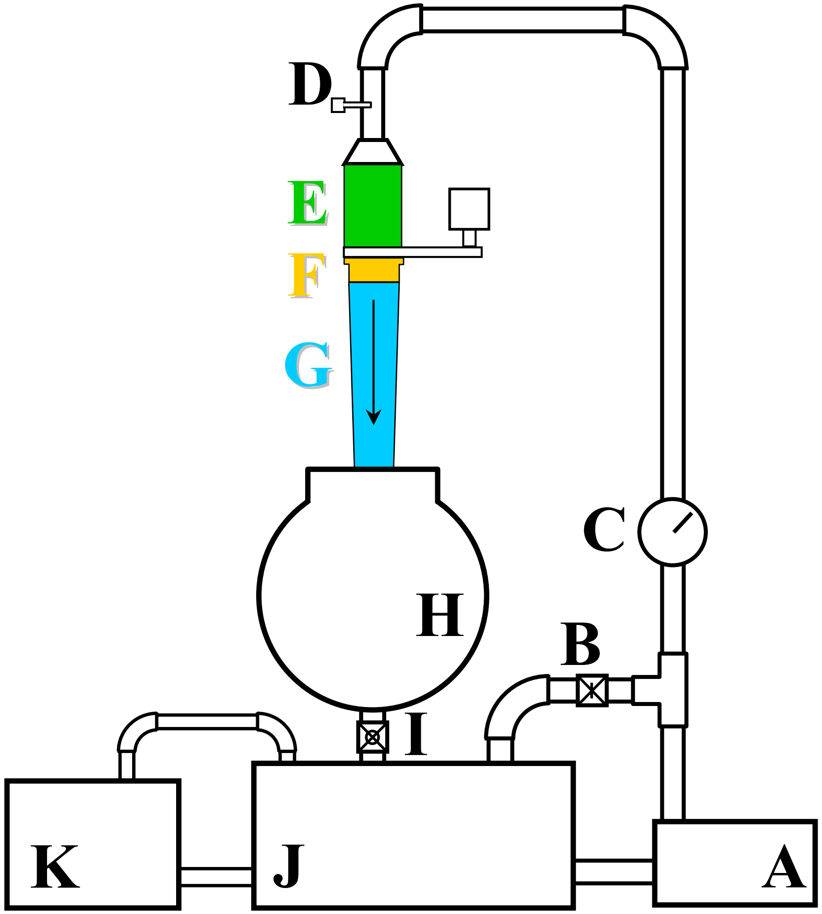
Motivation

- Effective protection ⇒ Minimize clearance between edge of liquid sheet and driver beams
  - Minimize interference with target injection, beam propagation
  - How are velocity fluctuations near the nozzle exit influenced by different flow conditioner (*vs*. nozzle) designs?
  - How are velocity fluctuations related to free-surface fluctuations downstream of the nozzle exit?
  - Are fine screens required in the flow conditioner?
  - Will more screens reduce free-surface fluctuations?

Objectives

- Quantify effect of flow conditioner designs in terms of mean velocity and turbulence intensity just upstream of nozzle exit
- Quantify surface ripple in terms of free-surface fluctuations within range of interest for HYLIFE-II
- Measure loss coefficient across the flow conditioner / nozzle assembly for different flow conditioner configurations

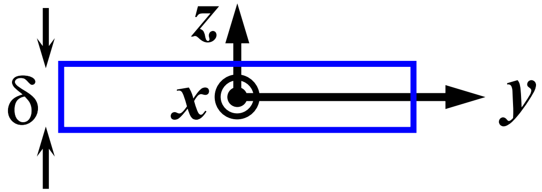
Flow Loop



- **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
H 400 gal tank
I Butterfly valve
J 700 gal tank
K 20 kW chiller
E Flow conditioner
F Nozzle
G Liquid sheet

Experimental Parameters



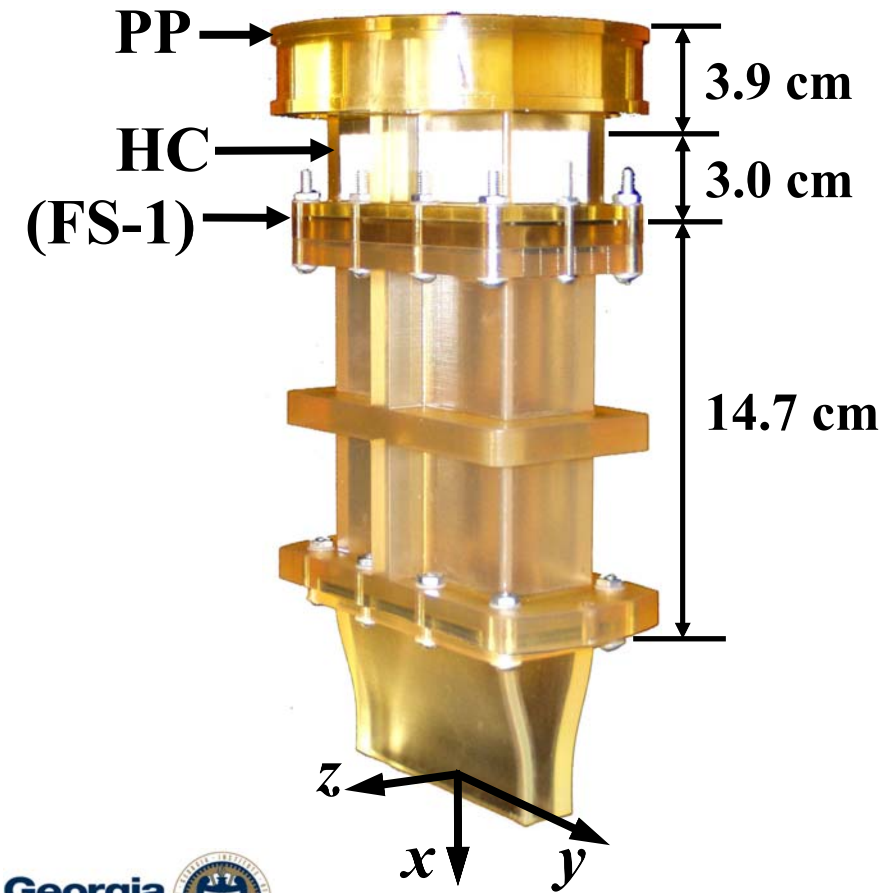
- **δ = 1 cm; aspect ratio AR = 10**
- **Near-field: $x / \delta \leq 25$**
- **Reynolds number $Re = 0.5 – 1.2 \times 10^5$**
  - [$Re = U_o\delta / \nu$; U_o average speed; ν liquid kinematic viscosity]
- **Fluid density ratio $\rho_L / \rho_G = 850$** [ρ_G gas density]
- **Velocity and rms fluctuations**
  - **u and u': Streamwise (x-component)**
  - **w and w': Transverse (z-component)**
- **σ_z standard deviation of free surface z-location**

Flow Conditioning Elements

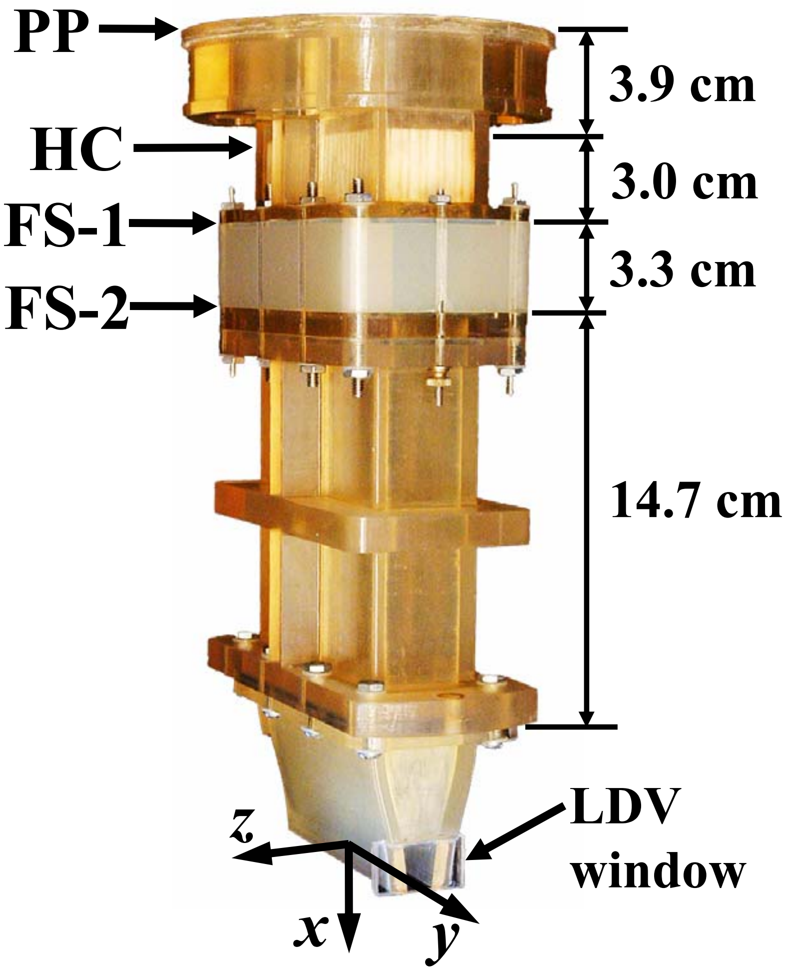
- Rectangular flow cross-section 10 cm × 3 cm ($y \times z$)
- Perforated plate (PP)
    - Open area ratio 50% with staggered 4.8 mm dia. holes
- Honeycomb (HC)
    - 3.2 mm dia. × 25.4 mm staggered circular cells
- Fine screen (FS-1)
    - Open area ratio 37.1%
    - 0.33 mm dia. wires woven w/ open cell width of 0.51 mm (mesh size 30 × 30)
- Fine screen (FS-2)
    - Open area ratio 36.0%
    - 0.25 mm dia. wires woven w/ open cell width of 0.38 mm (mesh size 40 × 40)
- Nozzle
    - 5th order polynomial contour with contraction ratio = 3

Flow Conditioning Configurations

No Screen / (One Screen*)

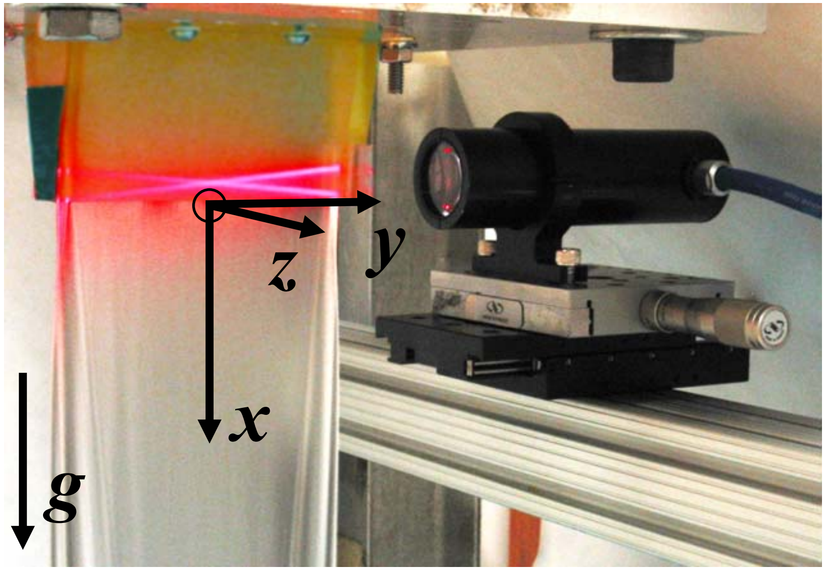


Two Screens

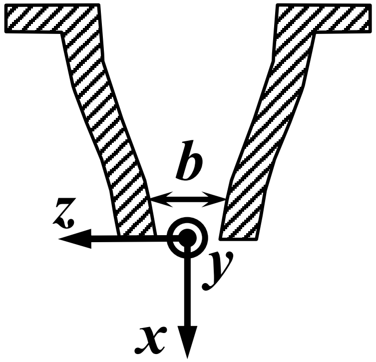


* Standard design

Laser-Doppler Velocimetry (LDV)

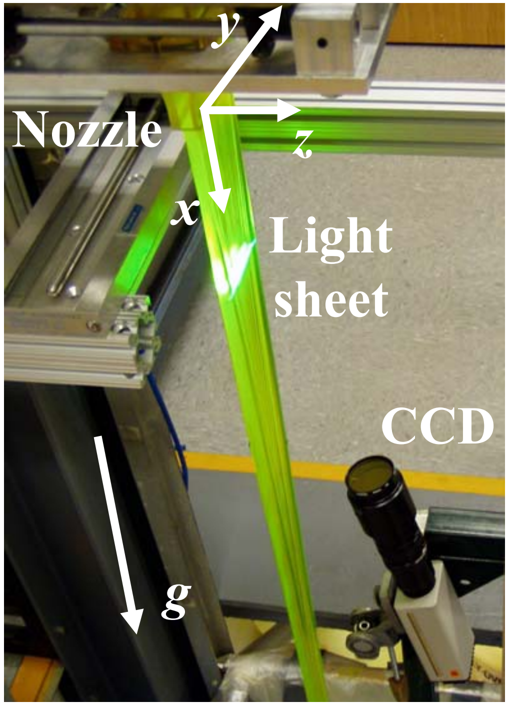


Probe shown in streamwise configuration



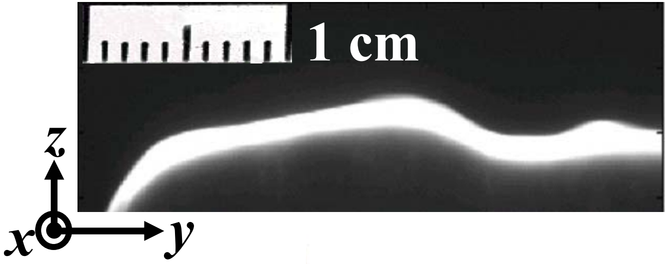
- Single component backscatter operation
- Frequency shift of 1.3 MHz for *w* measurements
- Probe volume 230 × 50 × 1250 μm (*x*, *y*, *z*) at FWHM
- Positioning controlled by two linear stages
- Water seeded with TiO_2 particles (typical dia. 0.3 μm)
- Velocity profiles at $x = -6$ mm
  - $b = 10.95$ mm

Planar-Laser Induced Fluorescence (PLIF)

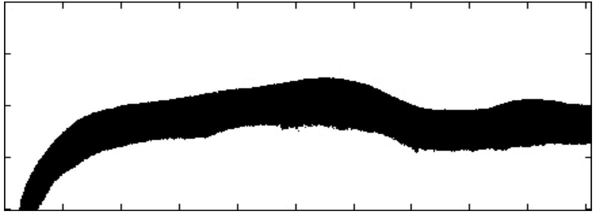


- **Water dyed w/disodium fluorescein (26 mg/L)**
- **Free surface = interface between fluorescing (bright) water and (dark) air**
- **Image obliquely with B/W CCD camera**
  - **Exposure one convective time scale $\tau = \delta / U_o$ = 0.9 – 2.2 msec**
- **Surface ripple measurements span > 2000 τ**
- **Threshold individual images**
  - **Threshold value from image grayscale histogram**
  - **Grayscale > threshold ⇒ water**
    ≤ threshold ⇒ air

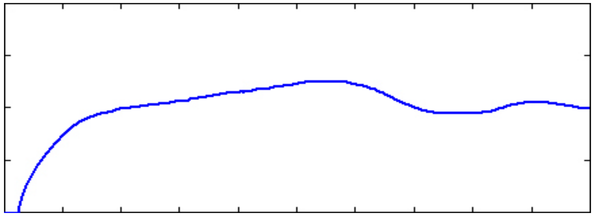
Original image



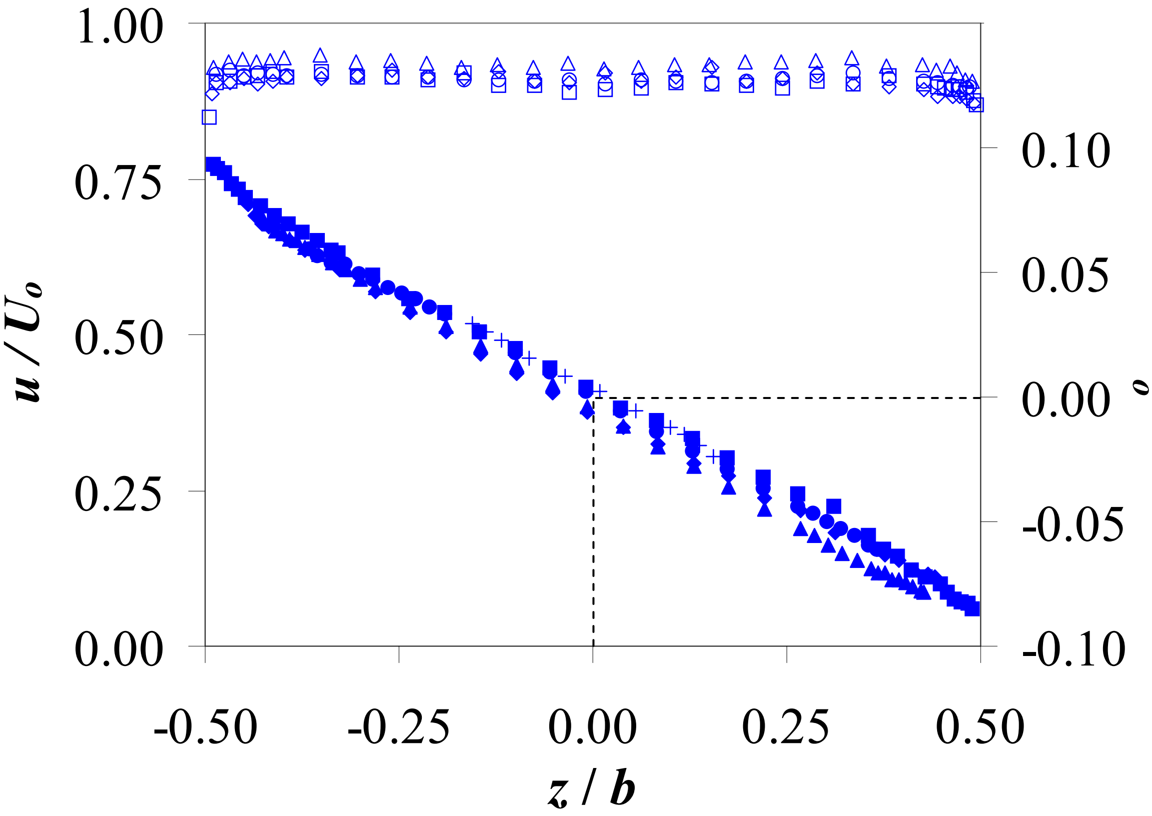
Thresholded image



Free surface

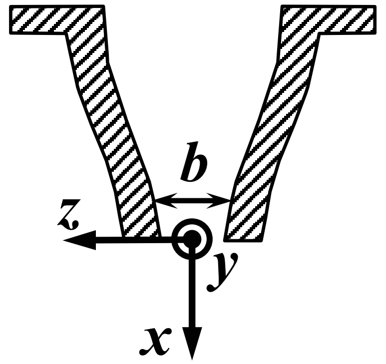


Velocity Profiles: *Re* = 120,000
(One Screen)

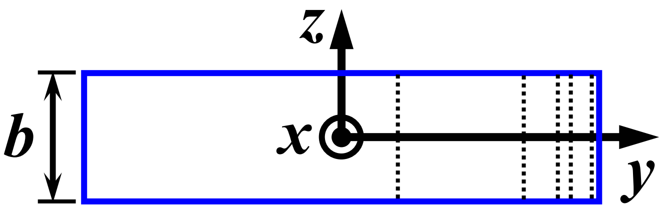


■ w / U_o
☐ u / U_o

y / δ
■ 4.838 ◆ 4.438 ▲ 4.163 ● 3.688 + 1.188

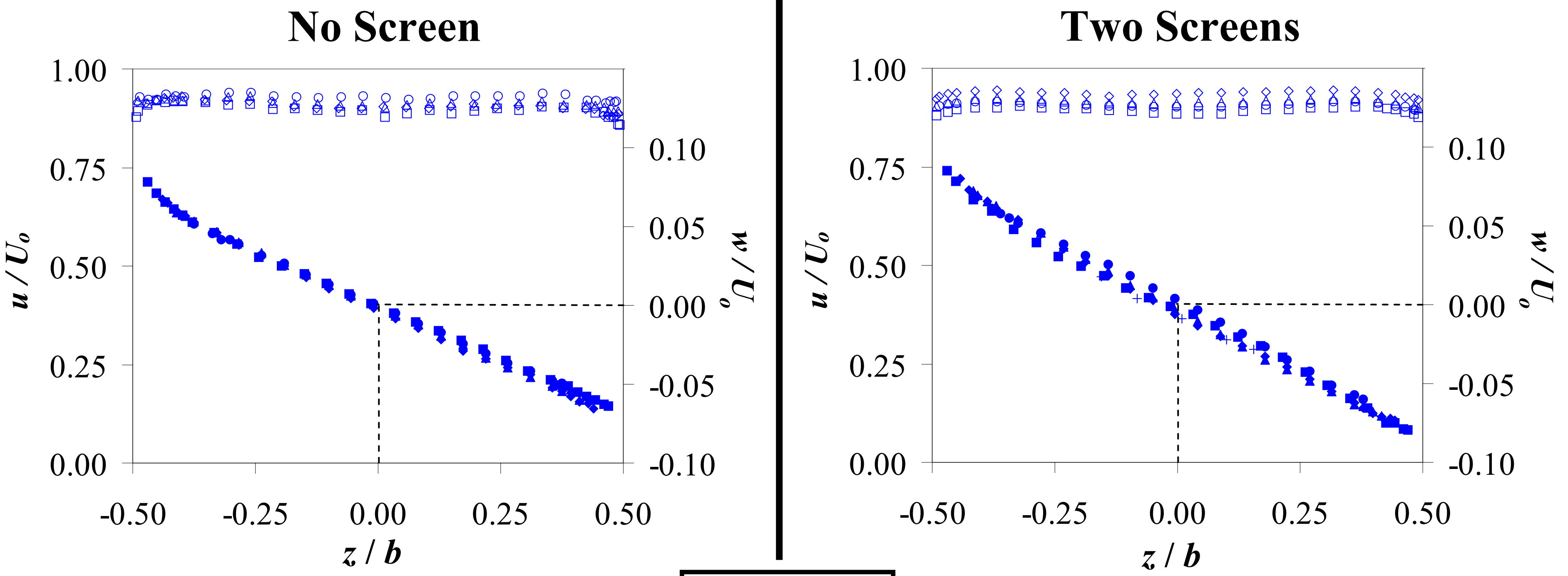


***b* = 10.95 mm**



Profiles along dotted lines

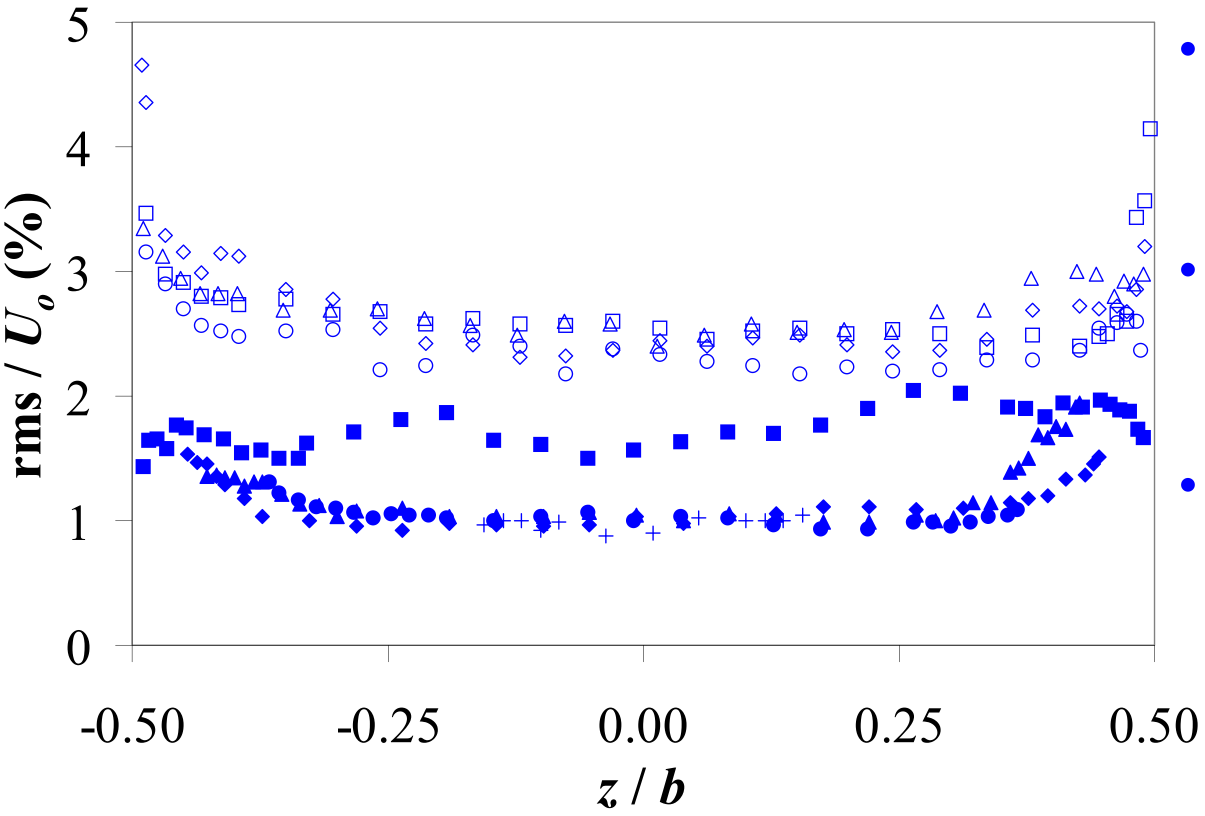
Velocity Profiles: *Re* = 120,000
(No Screen and Two Screens)



■ w / U_o
□ u / U_o

y / δ
■ 4.838 ◆ 4.438 ▲ 4.163 ● 3.688 + 1.188

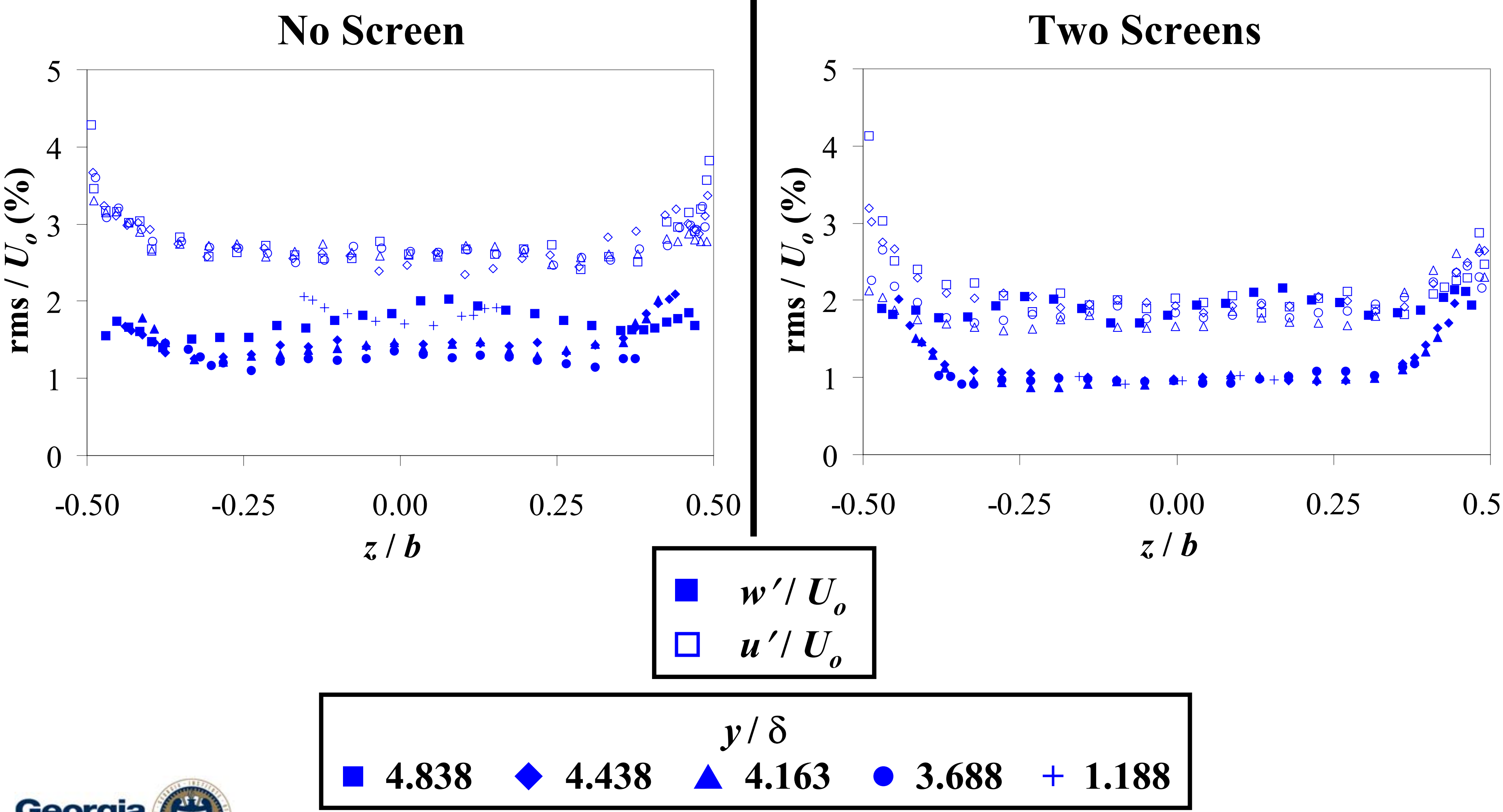
RMS Profiles: *Re* = 120,000
(One Screen)



- **Non-homogeneous turbulence**
  - **$u'/w' \approx 2$**
- **Nearly constant fluctuations for central 75% of *b***
- **Turbulent boundary layer indicated by marked increase in *u′*, *w′* near nozzle walls**

RMS Profiles: *Re* = 120,000

(No Screen and Two Screens)


No Screen

Two Screens

Average Streamwise RMS

(Re = 120,000)

y / δ	u' / U_o (%)		
	No Screens	One Screen	Two Screens
4.838	2.6	2.6	2.0
4.638	2.6	2.4	2.0
4.438	2.6	2.5	2.0
4.163	2.6	2.6	1.7
3.688	2.6	2.3	1.8
2.438	2.5	2.4	
Average	**2.6**	**2.5**	**1.9**

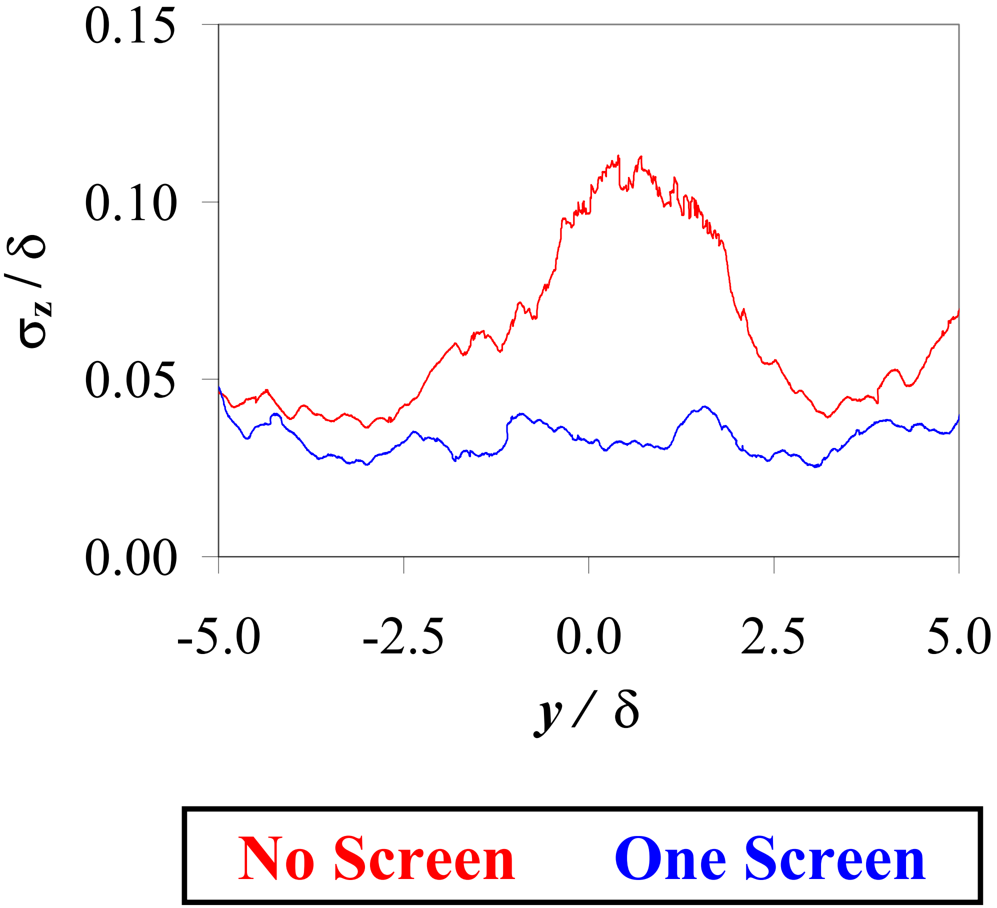
- Averaged over $|z| / b \leq 0.375$
- 95% confidence interval for all data ~0.1 %
- Two screens has less streamwise fluctuation

Average Transverse RMS
(Re = 120,000)

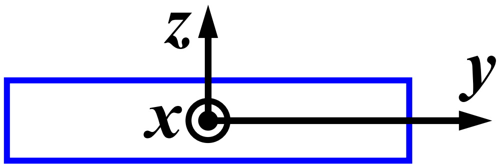
y / δ	w' / U_o (%)		
	No Screens	One Screen	Two Screens
4.838	1.7	1.7	1.9
4.638	1.5	1.3	1.2
4.438	1.4	1.0	1.0
4.163	1.4	1.1	1.0
3.688	1.3	1.1	1.0
2.438	1.1	1.0	1.0
1.188	1.9	1.0	1.0
Average	1.5	1.2	1.2

- Small decrease in w' with one screen
- No change in w' between one and two screens
- Significant central disturbance without screen
  - w' / U_o = 1.6 – 2.3 % at y / δ = 1.638 – 0.338, respectively

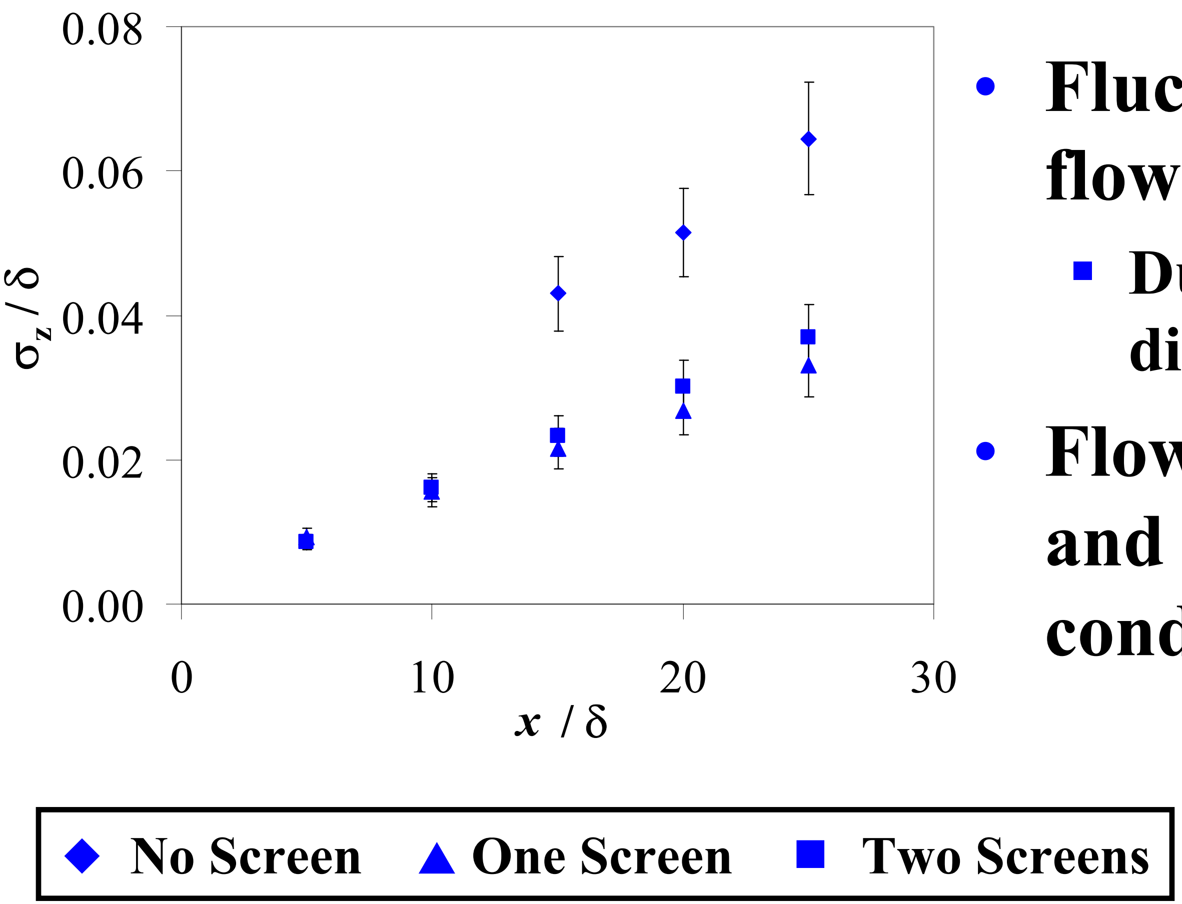
PLIF Results
(Effect of Initial Conditions)



- **$x / \delta = 25$**
- **$Re = 120{,}000$**
- **Large central fluctuation without fine screen**
  - **Also observed in transverse velocity fluctuations**



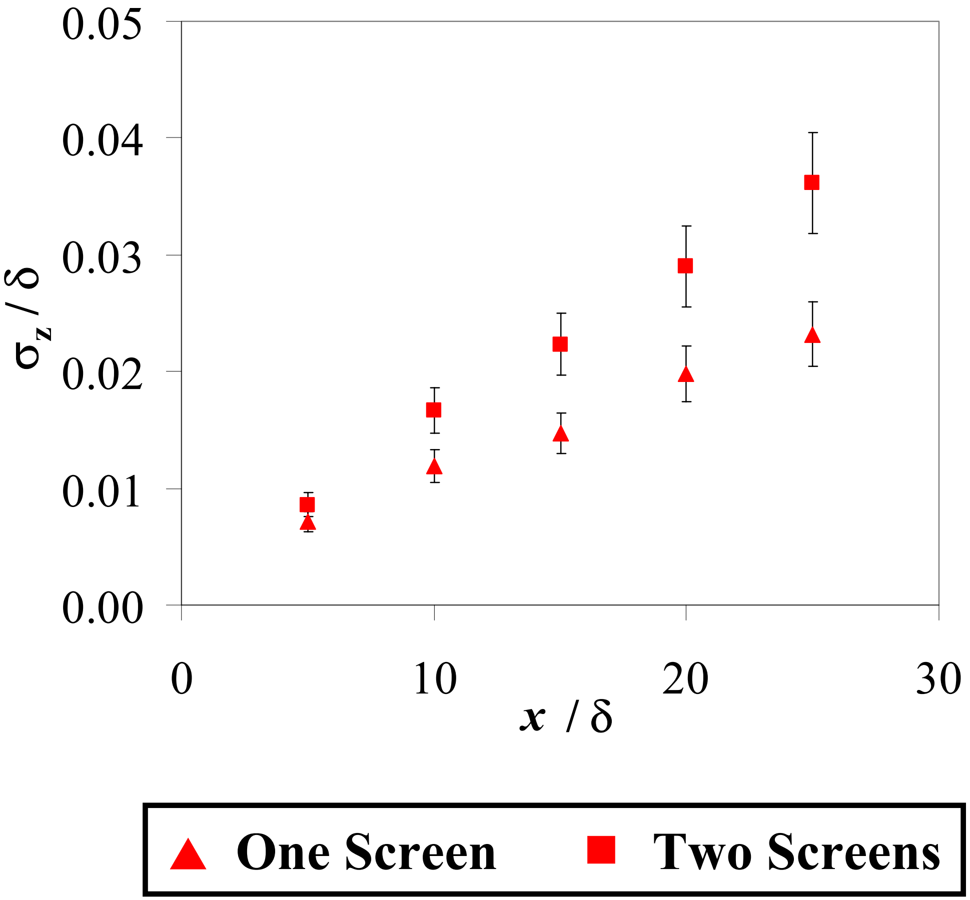
Average PLIF Results
(*Re* = 120,000)



- **Fluctuations ~ 1.5× for flows without fine screen**
  - **Due to central disturbance**
- **Flows similar for one and two screen flow conditioning**

Average PLIF Results

($Re = 50{,}000$)



- **One screen configuration produces smoother jet**
- **Streamwise and transverse rms identical within experimental error**

Loss Coefficient
(Re = 120,000)

	ΔP (kPa)	U_{in} (m/s)	U_o (m/s)	K_L
No Screens	69	2.35	10.72	1.25
One Screen	103	2.36	10.75	1.84
Two Screens	121	2.38	10.84	2.11

- $$K_L = \frac{\Delta \mathrm{P} + {}^{1}\!/_{2}\, \rho_{\mathrm{L}}\, U_{in}^2}{{}^{1}\!/_{2}\, \rho_{\mathrm{L}}\, U_o^2}$$

  where ΔP = Press. drop across flow conditioner assembly, ρ_L = fluid density, U_{in} = inlet velocity, and U_o = exit velocity
- Addition of screens increases loss coefficient
  - Pumping power ↑ as K_L ↑ for given flowrate

Conclusions
(Initial Conditions)

Characterized turbulent liquid sheets from three flow conditioning configurations for *Re* = 50,000 and 120,000

- **Quantified velocities / turbulence intensities near nozzle exit**
  - **Streamwise velocity measurements indicate uniform flow for all flow conditioner configurations**
  - **Second screen decreases streamwise velocity fluctuations**
  - **Elevated levels of transverse velocity fluctuations in center of jet for conditioning without a fine screen**
- **Quantified loss coefficient across flow conditioner**
  - **Addition of fine screens increases K_L**
    - **Requires higher pumping power**
    - **Increases likelihood of flow blockage due to trapped debris**

Conclusions
(Surface Ripple)

- **Quantified surface ripple for flows of interest in HYLIFE-II**
  - **One screen configuration produced smoothest flows for *Re* = 50,000 and 120,000**
    - **$\sigma_z / \delta < 0.04$ in near-field**
    - **Second screen increases surface ripple at *Re* = 50,000**
  - **Central disturbance observed in transverse velocity fluctuations and free-surface fluctuations for conditioning with no screen**

Implications for IFE

- **Turbulent liquid sheets at 50% of prototypical Reynolds number show:**
  - **One and two screen configurations meet HYLIFE-II surface ripple requirement of $\sigma_z < 0.07\delta$**
  - **One screen best practical configuration**
    - **Lower pumping power**
    - **Less likely to trap debris**
- **Flow conditioning design**
  - **Fine screen necessary to produce smooth free surface**
    - **Transverse fluctuations appear to be more correlated to free-surface fluctuations**
  - **Free-surface behavior highly sensitive to initial conditions**
    - **Must prevent blockages to avoid flow disruptions**

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