Experimental Investigations of Active Control of a Turbulent Boundary Layer for Skin Friction Drag Reduction

Airbus/SIG Workshop

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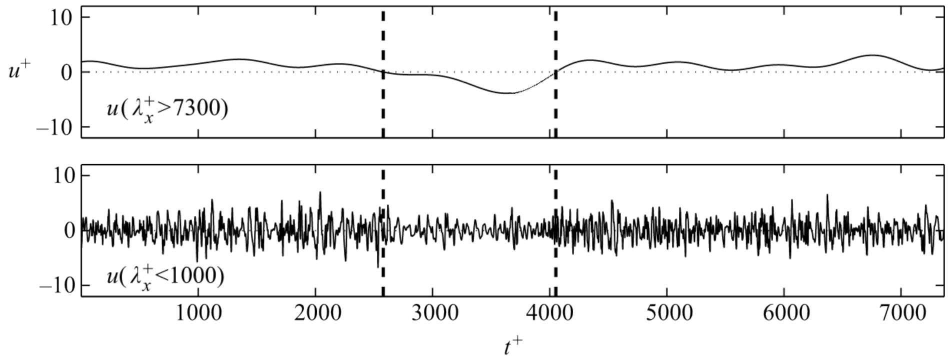
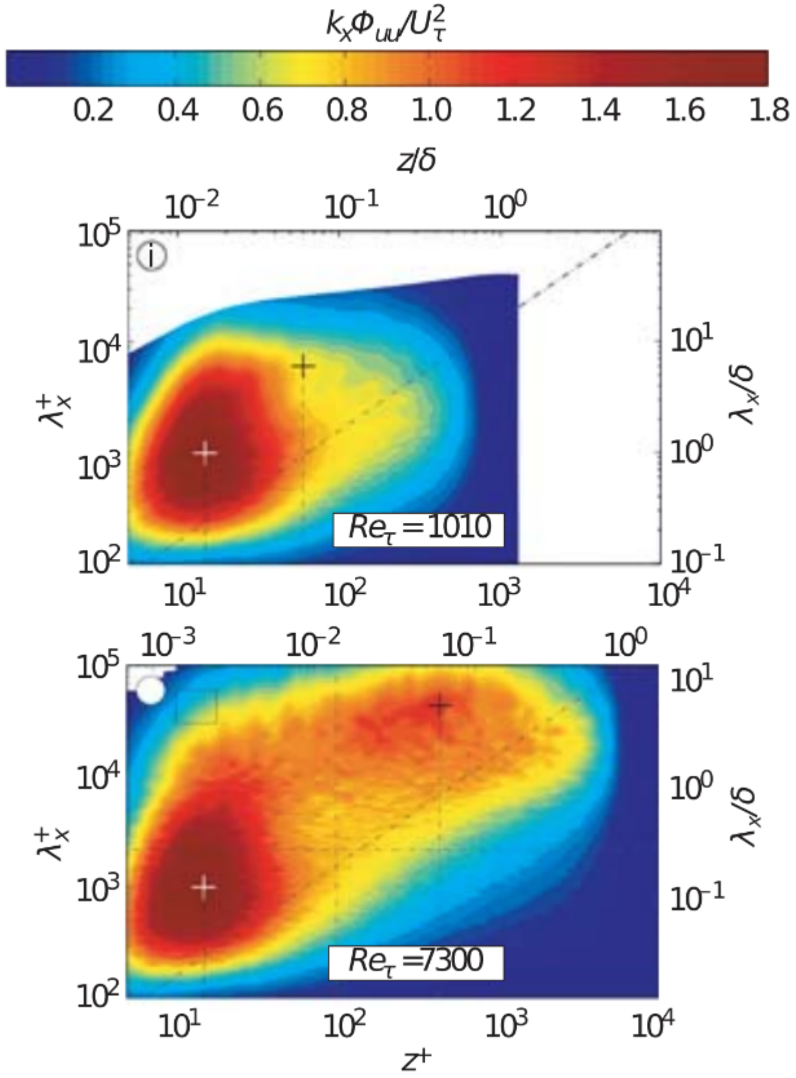
Introduction

- Control skin-friction drag in a TBL:
  - Target turbulence production in near wall cycle
    - Small length and time scales
    - Riblets (e.g. Walsh 1983), oscillating wall (e.g. Choi 1998), etc.
  - Target large scale coherent structures in the log region
    - Shown to have a modulation effect on near wall cycle (Hutchins & Marusic 2007b)
    - Contain increasingly larger fraction of TKE as Re increased
    - Continuous jets (Abbasi 2017), wall deformation (e.g. Bai 2014), etc.
- We use synthetic jets to attempt to affect large scale structures in a TBL with a goal of reducing skin-friction



Hutchins & Marusic 2007b



Hutchins & Marusic 2007a

Wind Tunnel and Flow Characteristics

Flow characteristics:

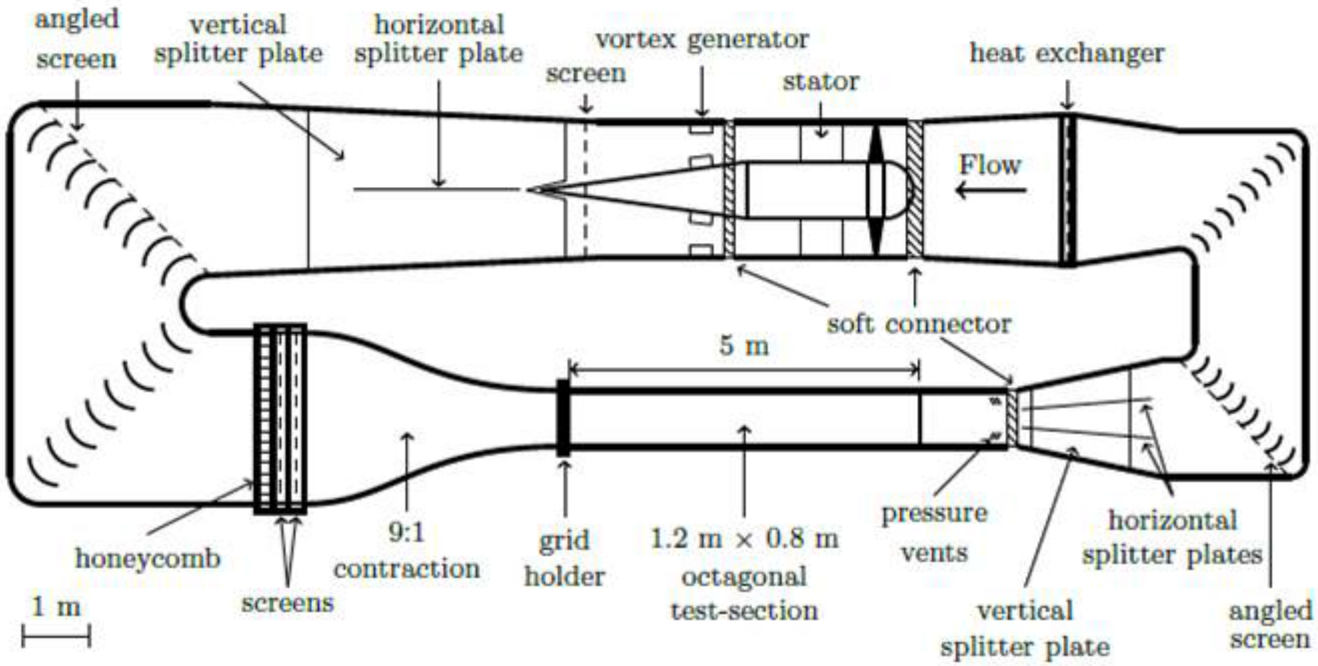
U_∞	δ	δ^*	θ	H	U_τ	c_f	Re_θ	Re_τ
10.01 m/s	42.5 mm	7.19 mm	5.16 mm	1.395	0.401 m/s	0.0032	3200	1070

$$Re_\theta = \frac{\theta U_\infty}{\nu}$$

$$Re_\tau = \frac{\delta U_\tau}{\nu}$$

$$U_\tau = \sqrt{\nu \frac{\partial u}{\partial x}\bigg|_w}$$

$$c_f = 2\left(\frac{U_\tau}{U_\infty}\right)^2$$



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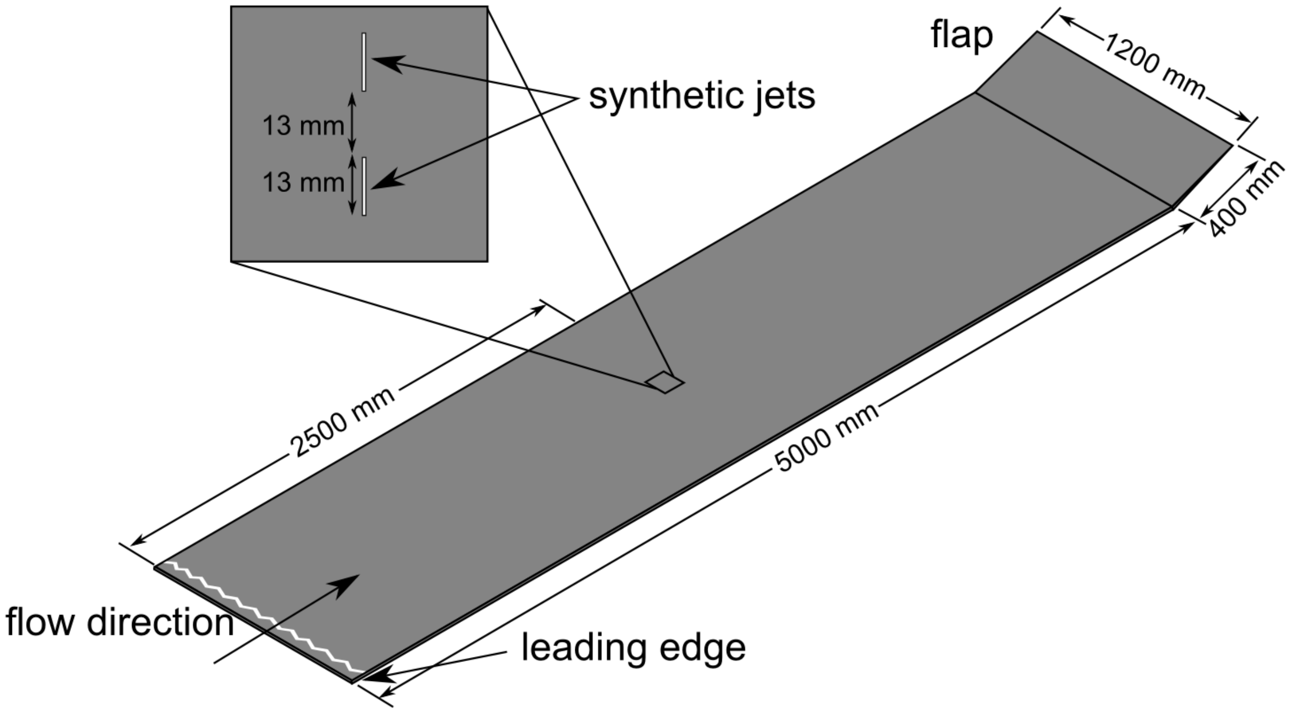


Synthetic Jets

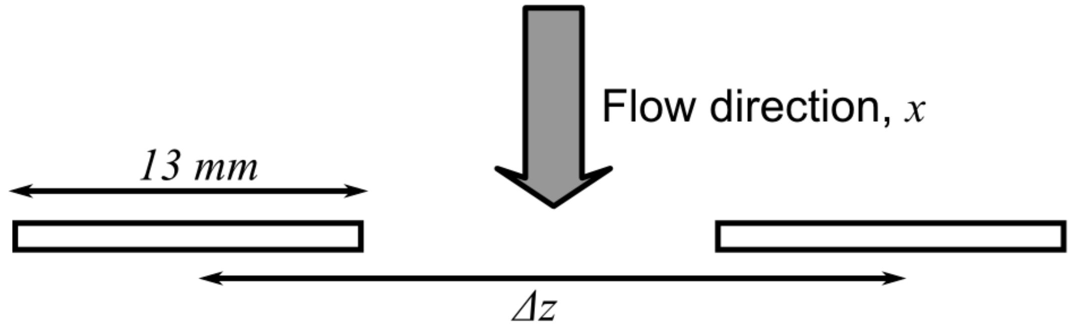
Parameters:

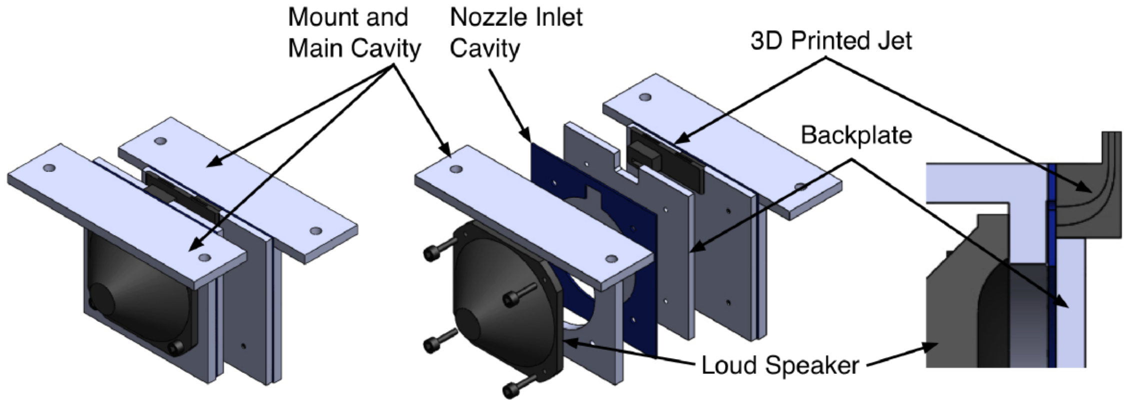
Strouhal number, $St = \frac{f\delta}{U_\infty}$

Blowing ratio, $r = \frac{U_j}{U_\infty}$

where $U_j = \frac{1}{T}\int_0^{T/2} u_j(t)\mathrm{d}t$

Jet Spacing, $\Delta z/\delta$





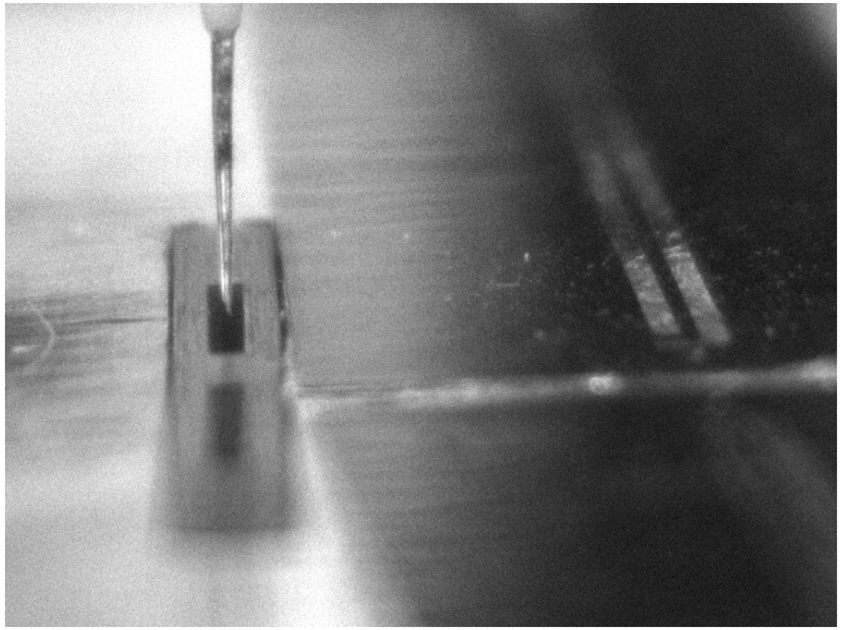
- Size of jet orifice slots chosen to match large scale structures in the log region
- Spanwise extent of structures is approx. $0.2\delta - 0.3\delta$ (Ganapathisubramani (2005))
- At our experimental conditions, this results in a slot width of 13 mm.

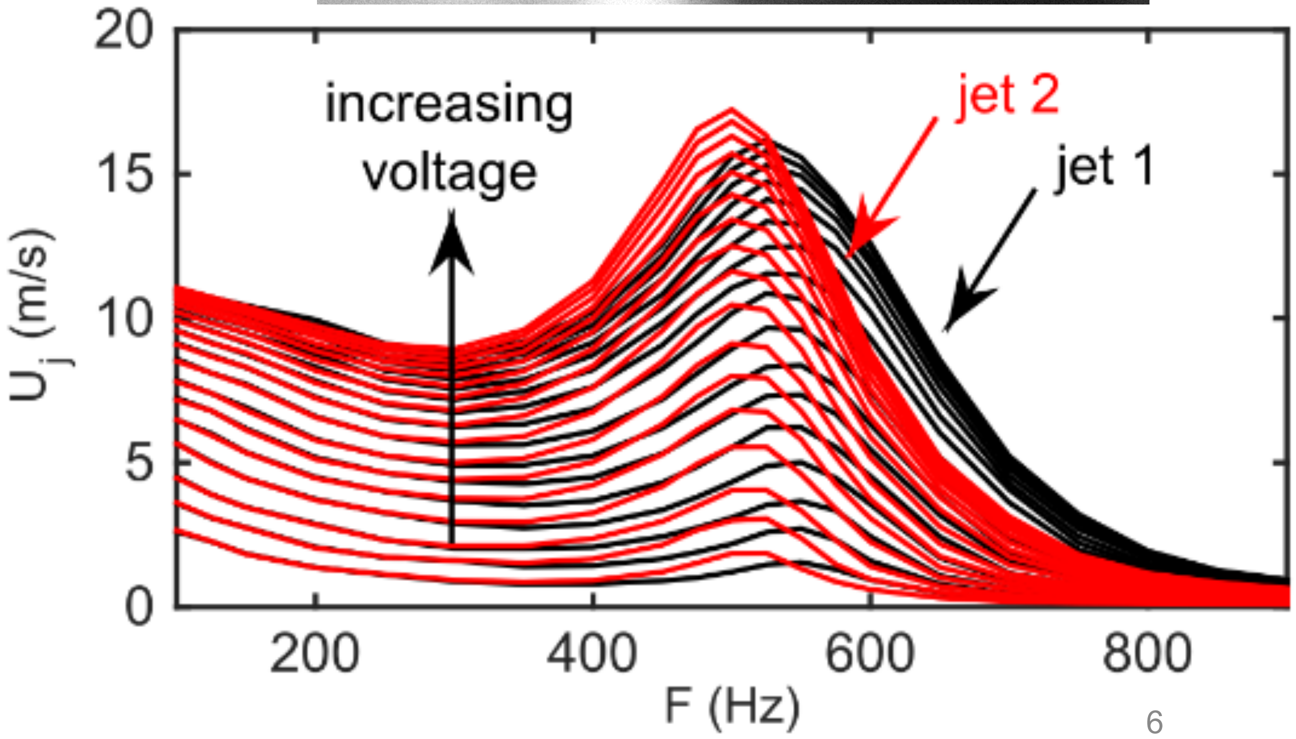
Synthetic Jet Calibration

- Vary the frequency and voltage output by function generator to SJ speakers

- Hot wire at jet exit to measure jet velocity U_j

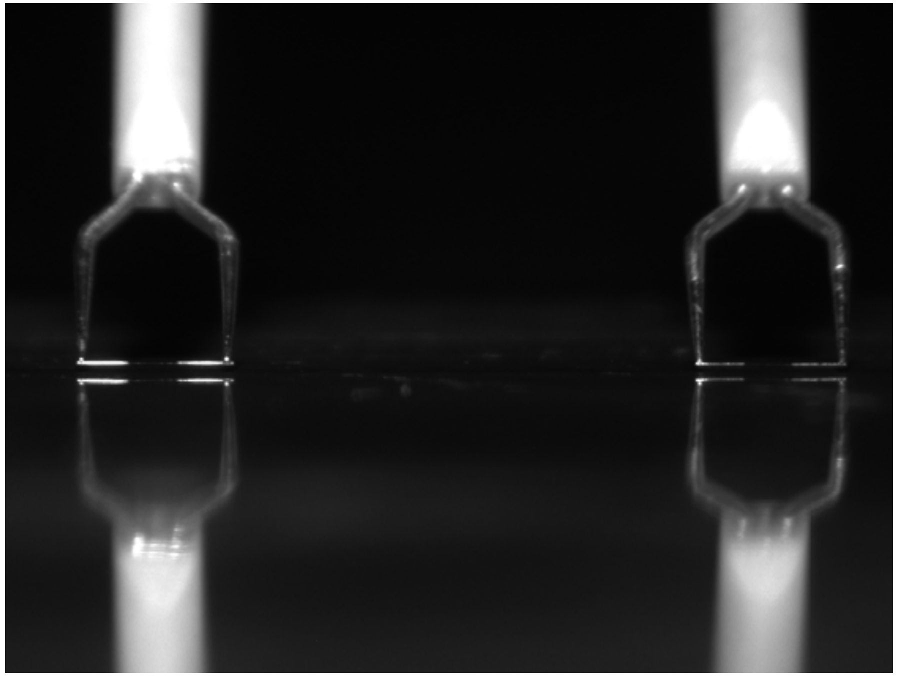
- Do independently for each jet





Hot Wire Measurements

- Two hot-wires spaced 13 mm apart in spanwise direction
- 5 cases investigated
  - Effect of Strouhal number
  - Effect of blowing ratio



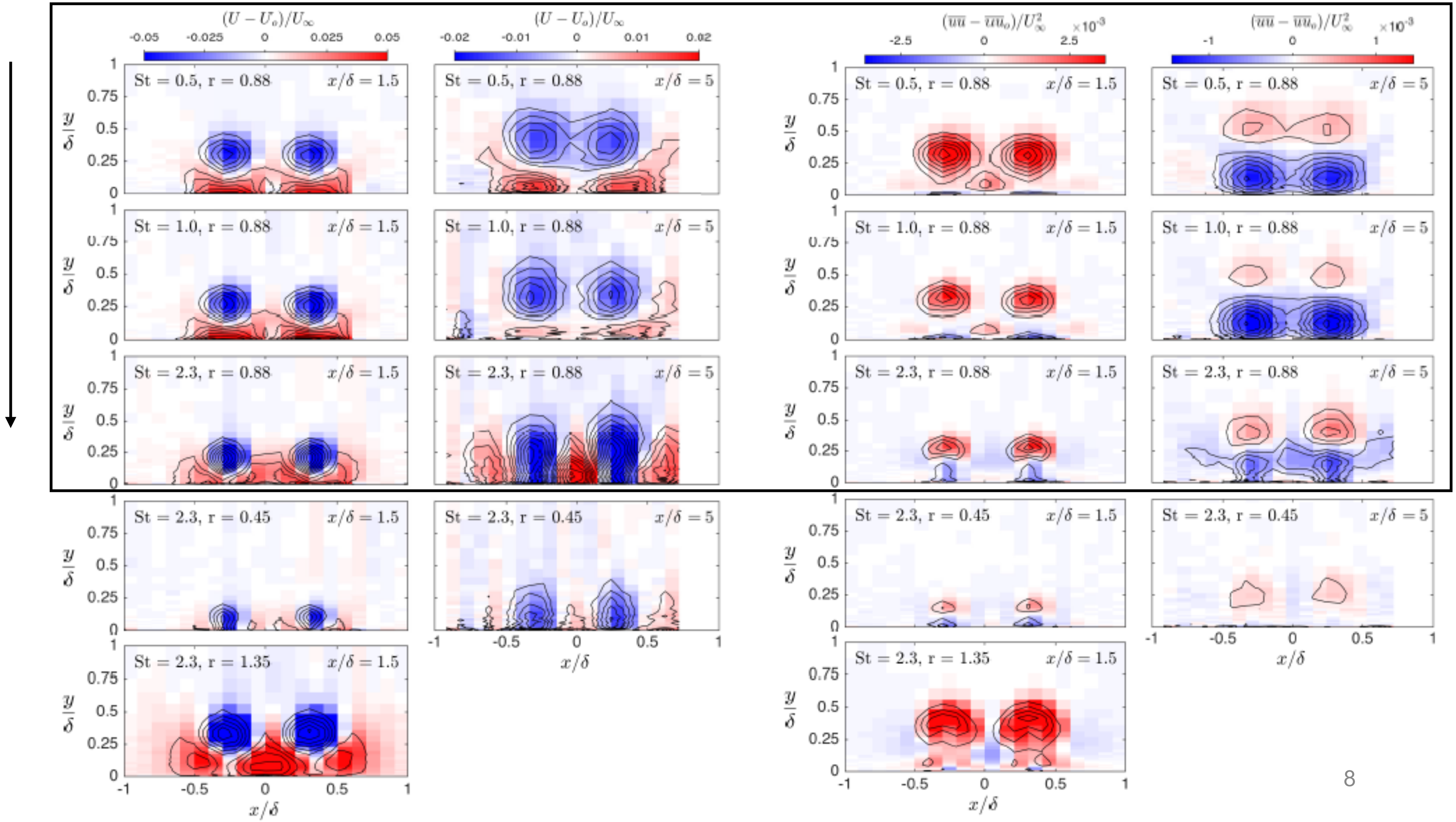
Case	(Hz)	U_j (m/s)	St	r
1	119	8.8	0.5	0.88
2	238	8.8	1.0	0.88
3	548	8.8	2.3	0.88
4	548	4.5	2.3	0.45
5	548	13.5	2.3	1.35

Effect of Jets on Mean Flow

Mean

Fluctuating

Constant *r*
Increasing *St*



Effect of Jets on Mean Flow

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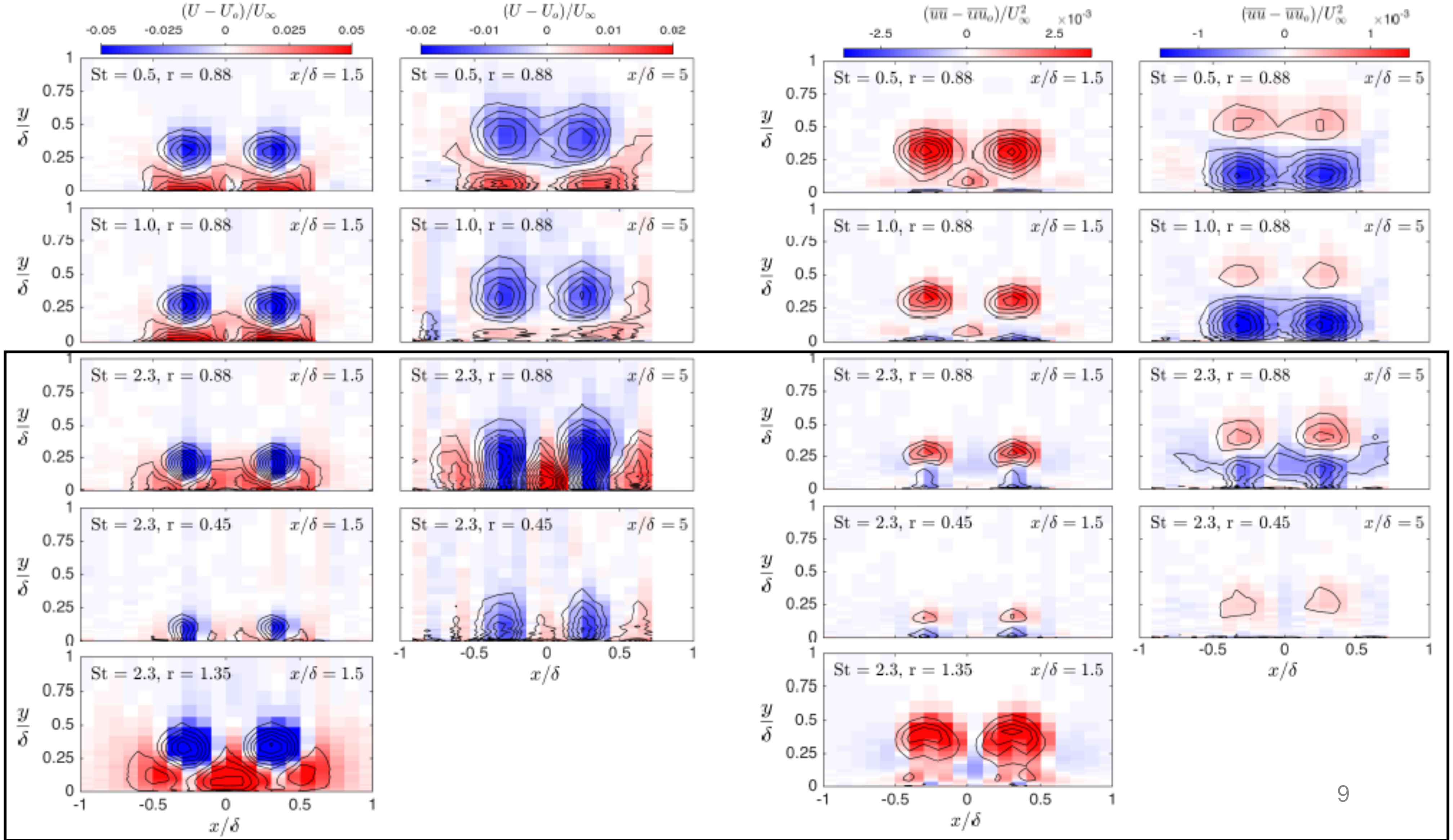
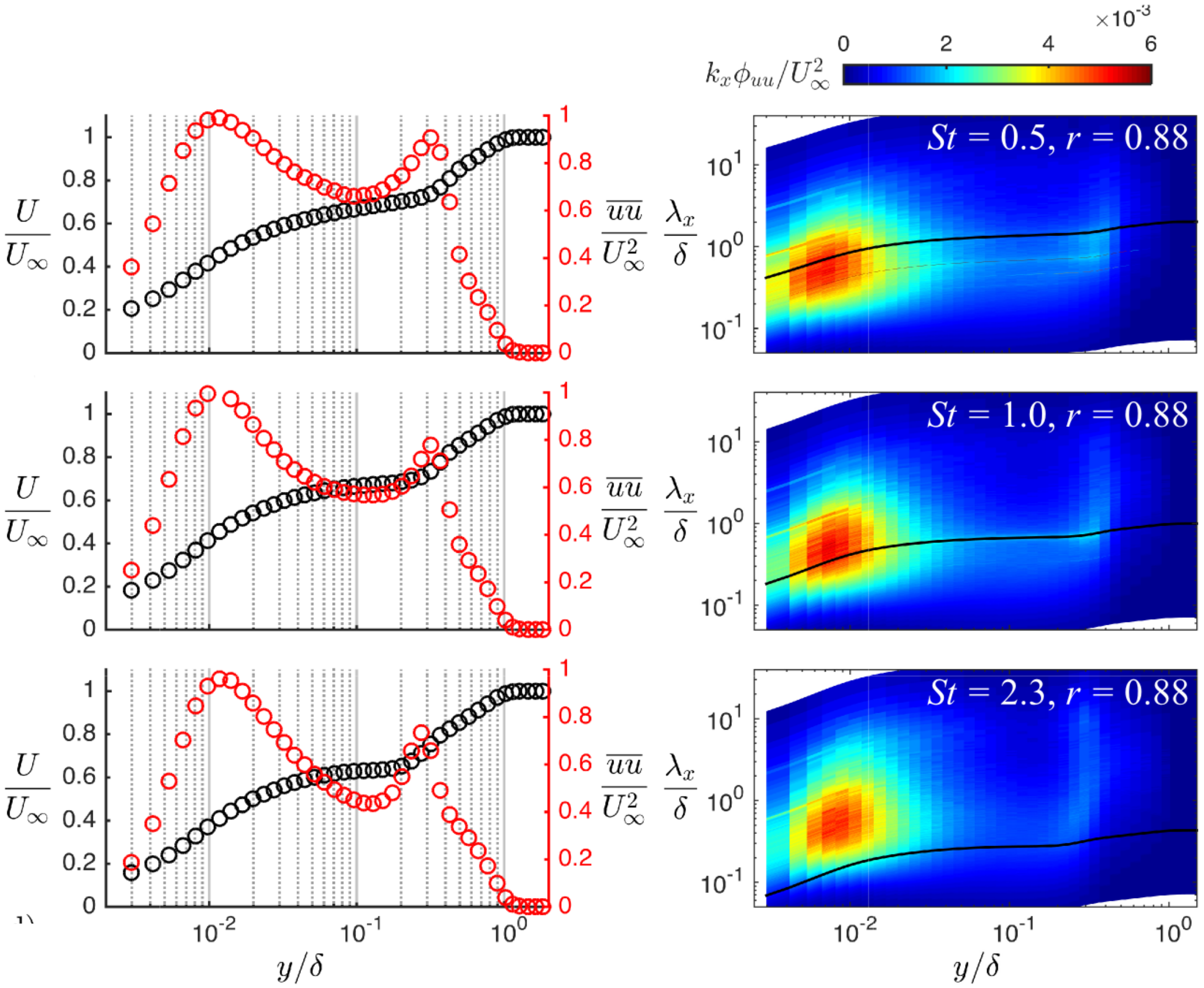


Constant *St*
Varying *r*

Turbulent Spectra

- Larger effect on log region with lower Strouhal numbers

Constant *r*
Increasing *St*

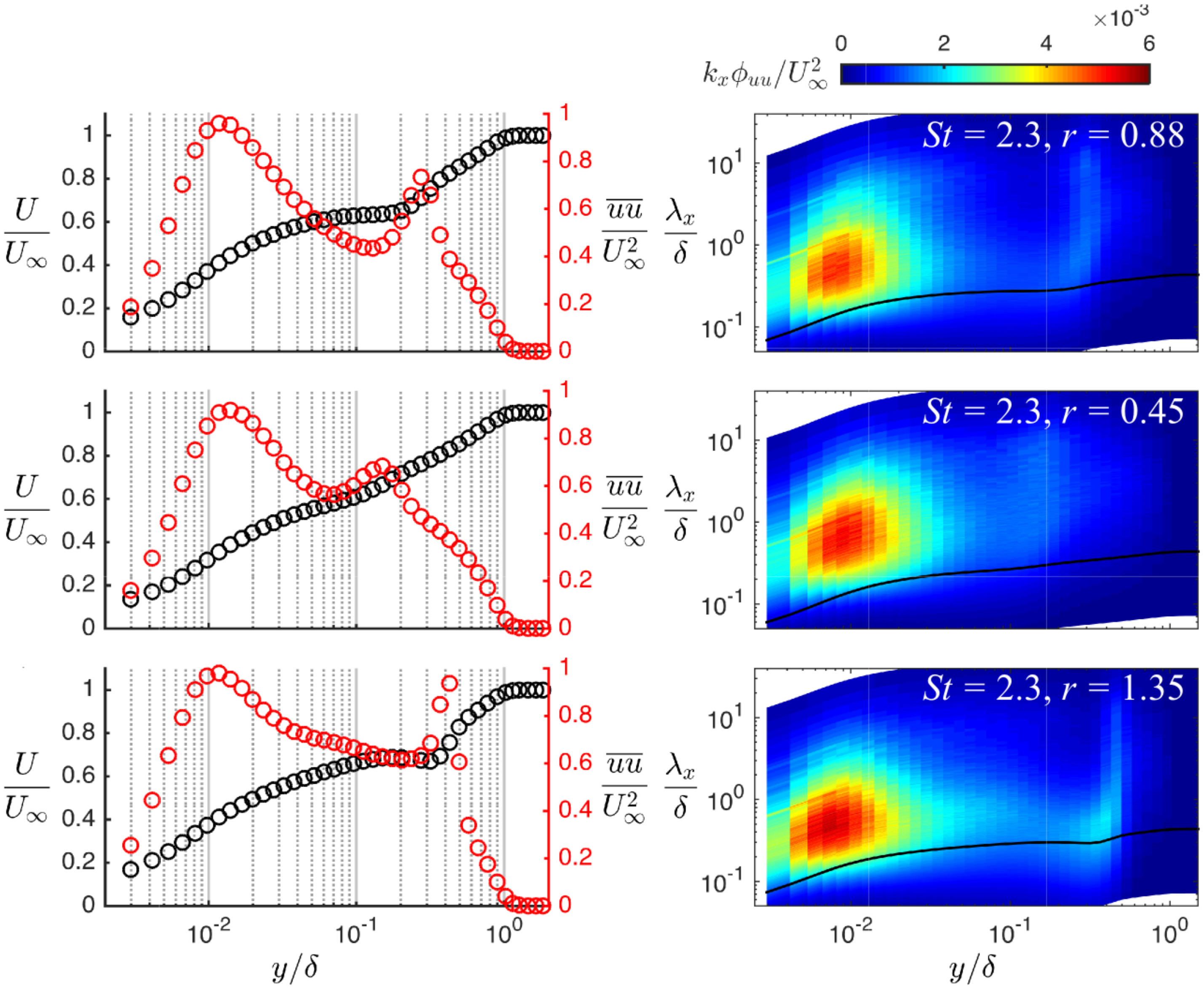


Turbulent Spectra

- Increased blowing ratio increases the y of max input of streamwise turbulence intensity
  - Increased jet penetration

Constant *St*
Varying *r*

- Larger effect on log region with larger blowing ratios



Skin Friction Measurements

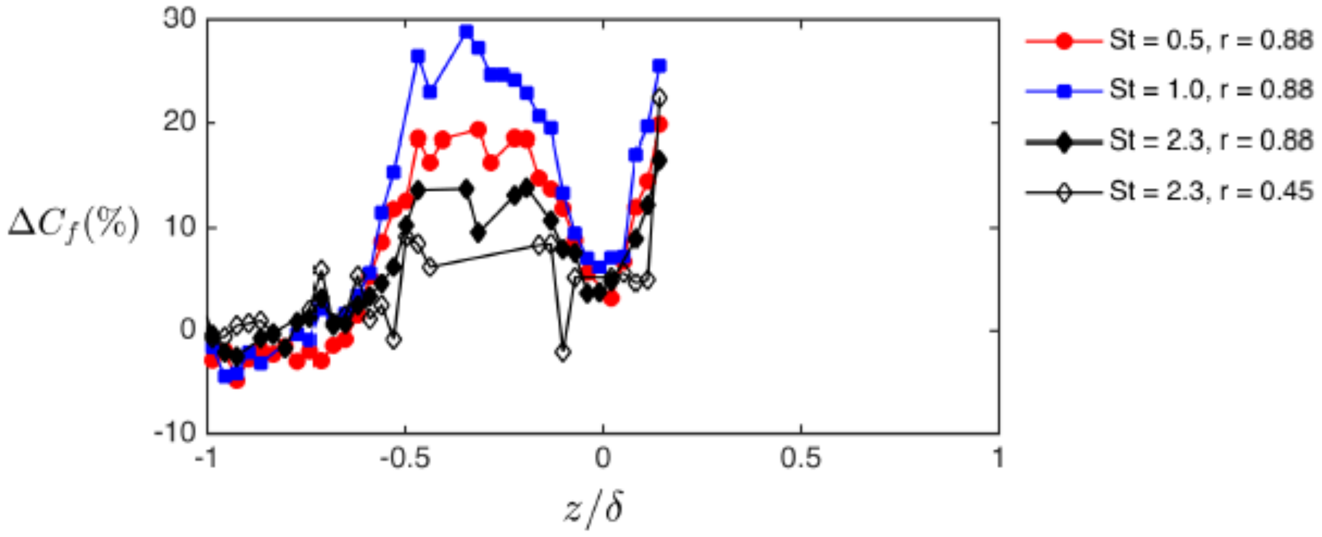
- Net skin friction reduction at $x/\delta = 5$ downstream of jets for $St = 2.3,\ r = 0.45$

- Lower blowing ratio preferred

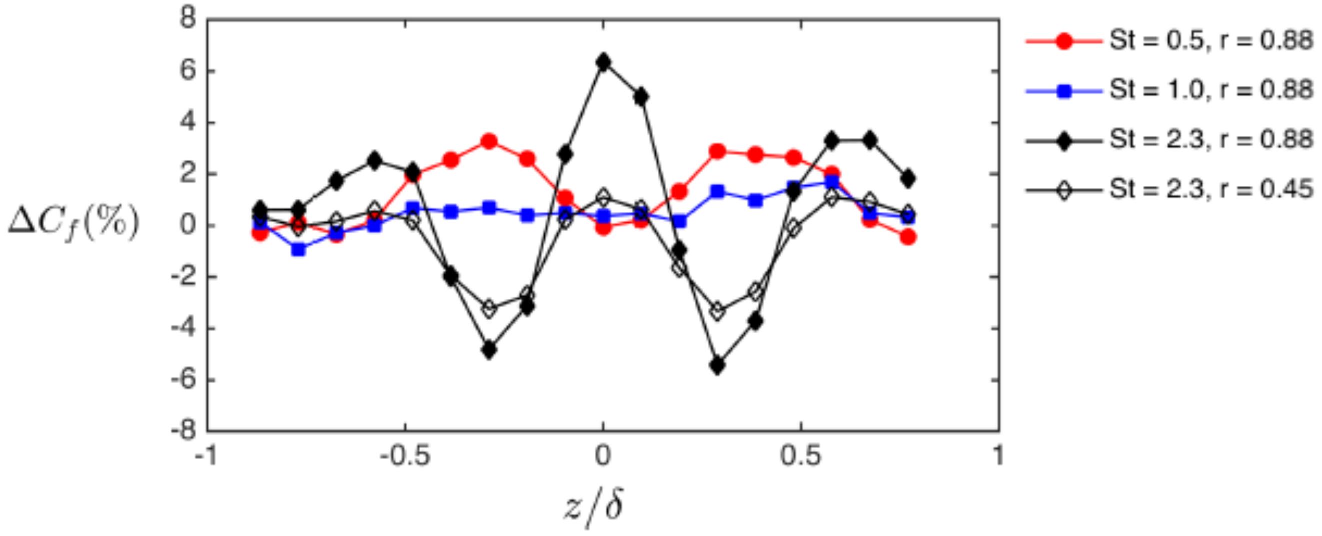
- Clauser chart fit:

$$\frac{U}{U_\tau} = \frac{1}{\kappa}\log\left(\frac{yU_\tau}{\nu}\right) + A$$

Constants: $\kappa = 0.41,\ A = 5.0$



(a) $x/\delta = 1.5$ oil film interferometry data.



(b) $x/\delta = 5$ Clauser chart measurements of the skin friction.

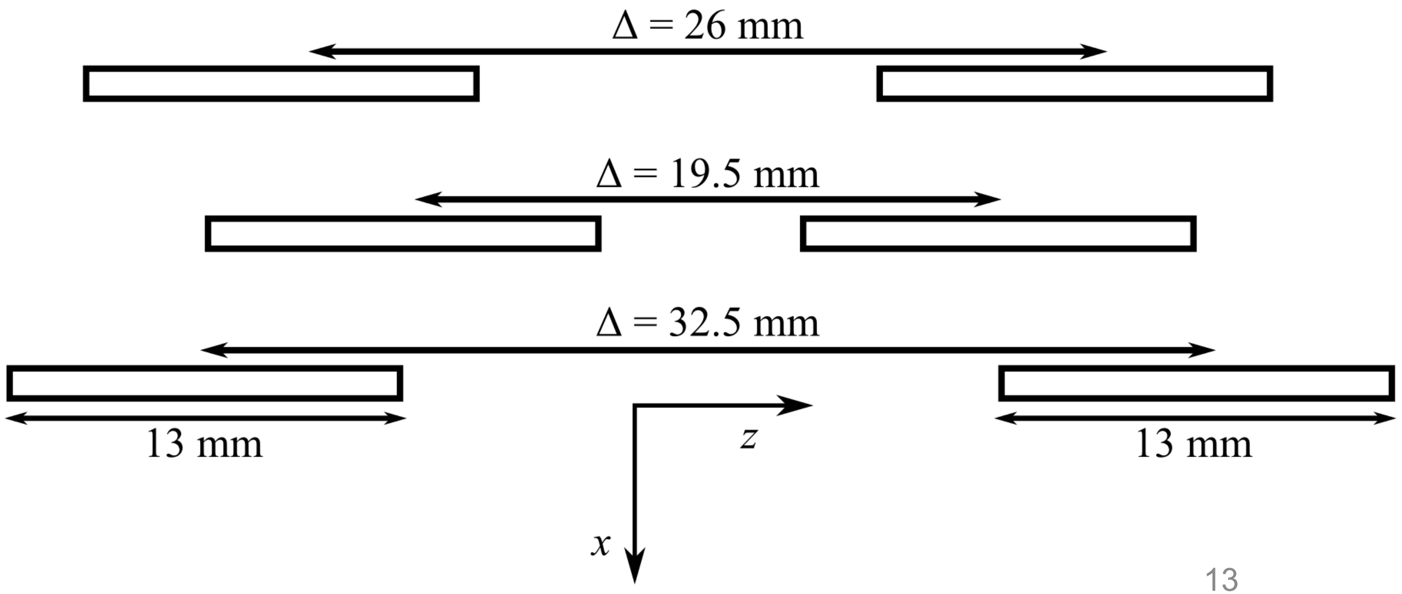
Skin Friction Parameter Mapping

- 3 parameters investigated:
  - Strouhal number, St
  - blowing ratio, r
  - jet spacing, Δ

- Additional measurements at low St and r as necessary

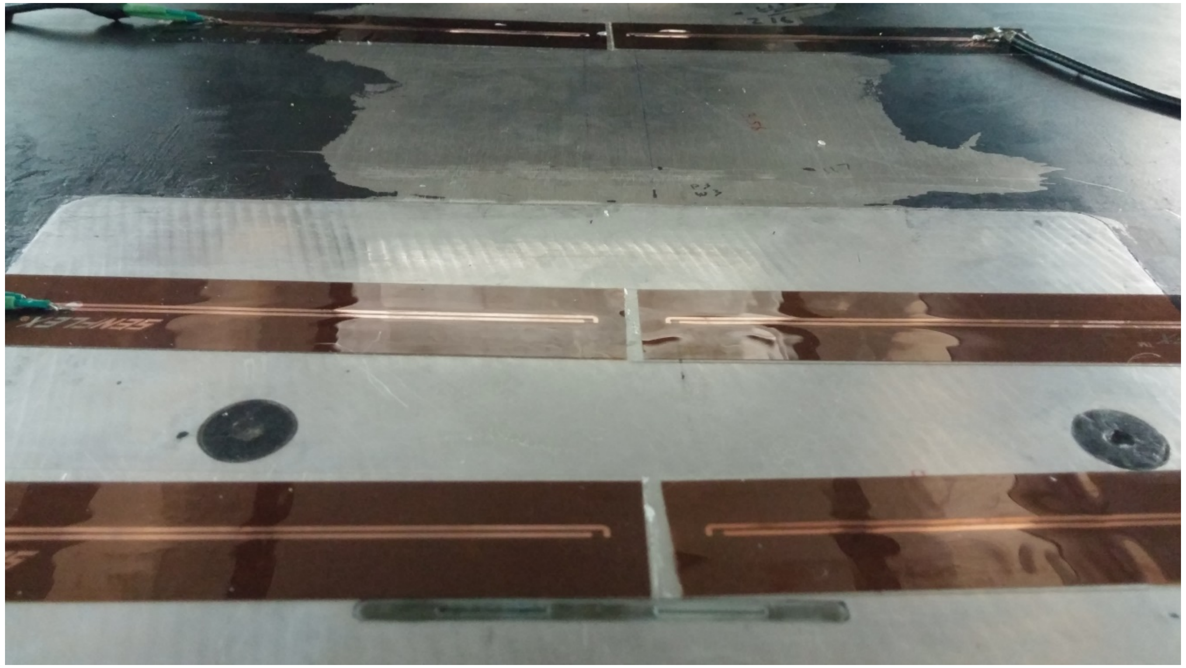
- C_f measured at 6 locations behind jets

Parameter	Min	Max	# Points
St	0.042	2.7	14
r	0.1	1.4	14
Δ/δ	0.46	0.76	3



Hot Films

- Nickel sensing element
- Copper leads
- Polyimide substrate
- 120 x 20 x 0.127 mm



- 6 total: 3 streamwise locations (0.33δ, 1.5δ, 5δ) x 2 spanwise locations (behind jet, between jets)

- Controlled with a CTA at overheat ratio of 1.4 – 1.6
- Calibrated before and after measurements to account for drift

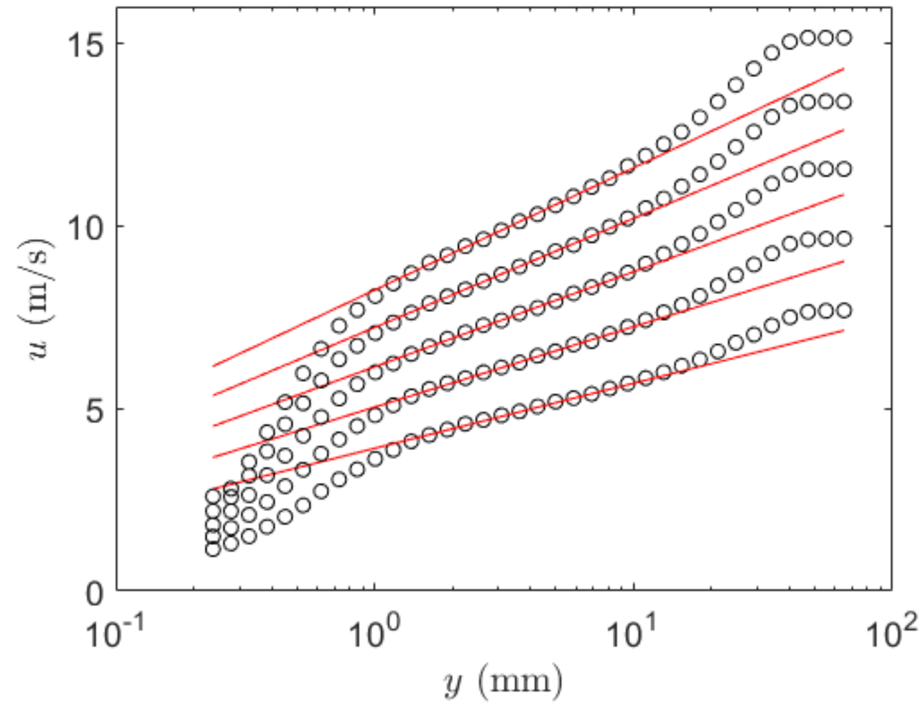
Shear Stress Calibration

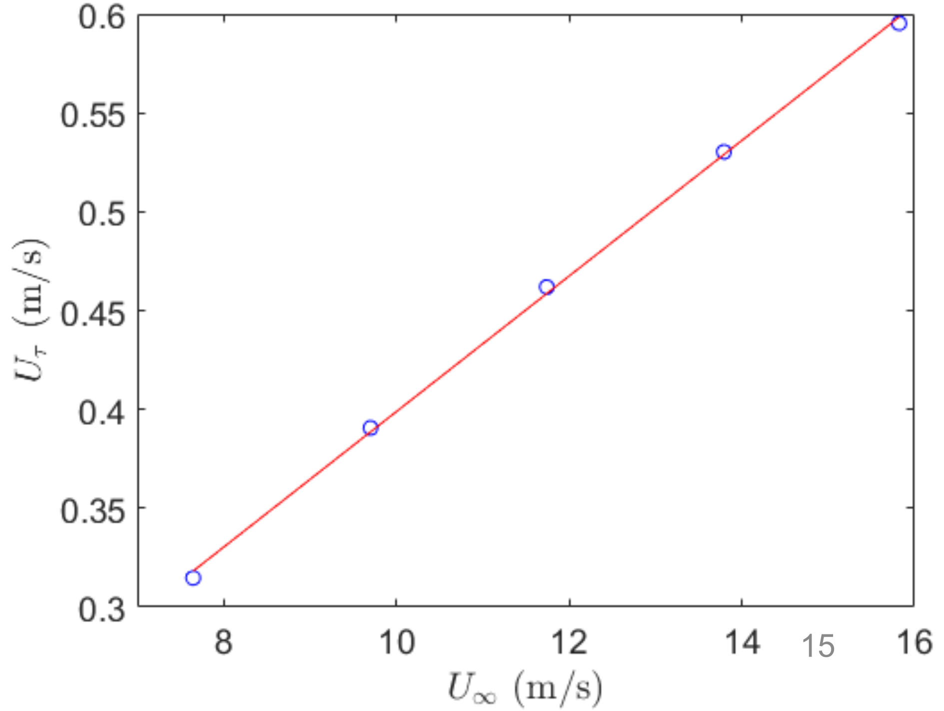
- Measure BL profiles at range of
- Extract U_τ using a Clauser chart fit to log region of each profile:

$$\frac{U}{U_\tau} = \frac{1}{\kappa}\log\left(\frac{yU_\tau}{\nu}\right) + A$$

Constants: $\kappa = 0.41,\ A = 5.0$

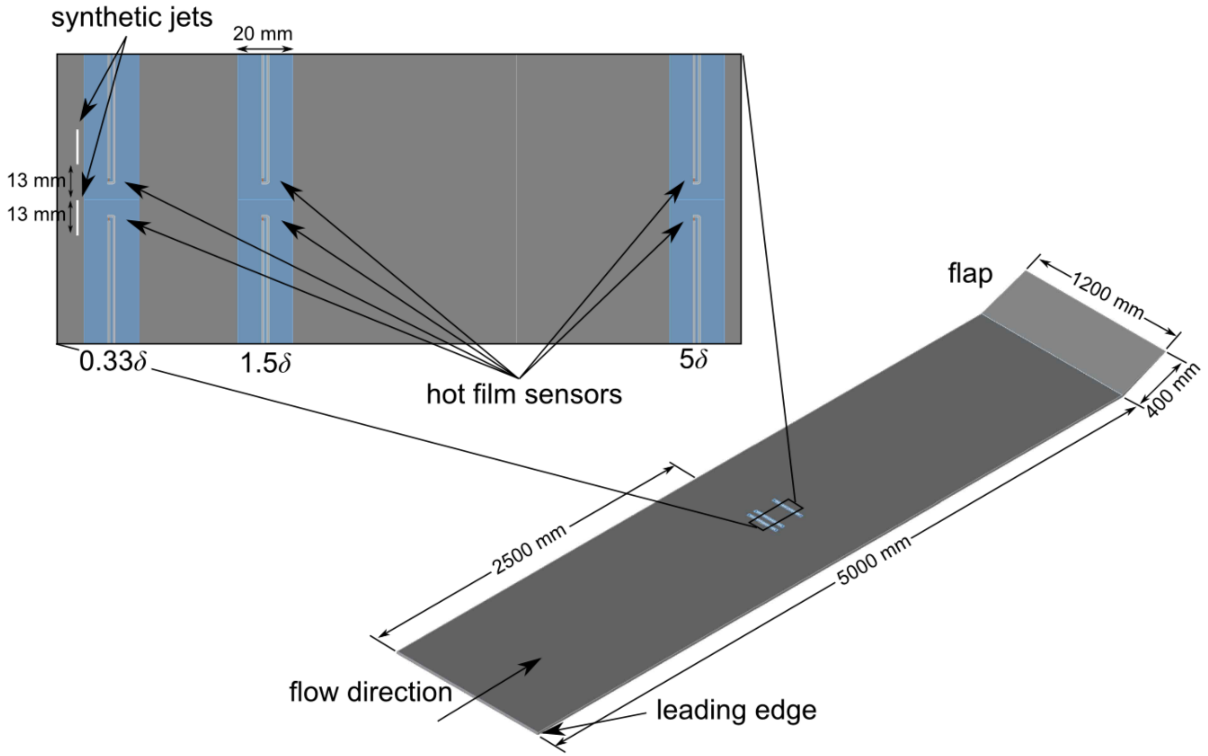
- Extract parameters of fit to U_τ vs. U_∞
- Independently done at location of each hot film

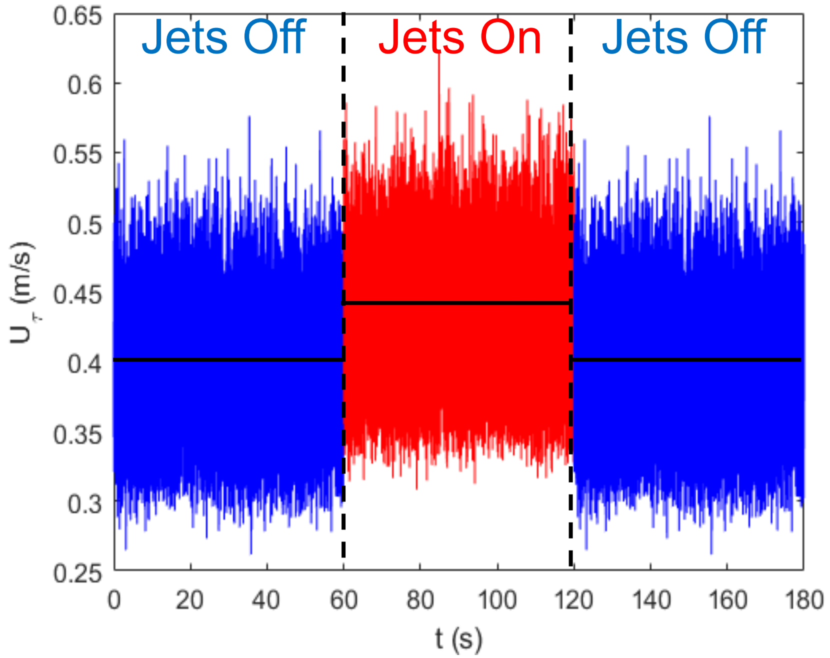


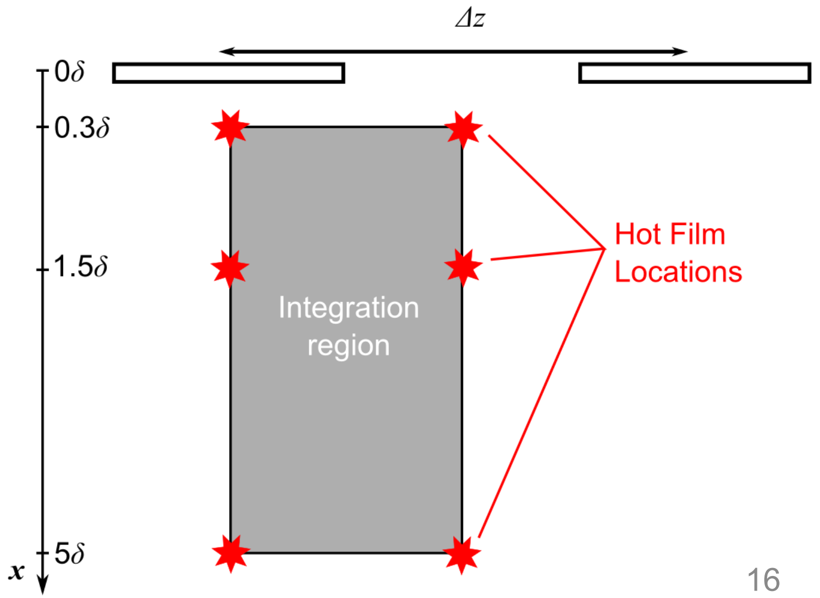


Skin Friction Measurements

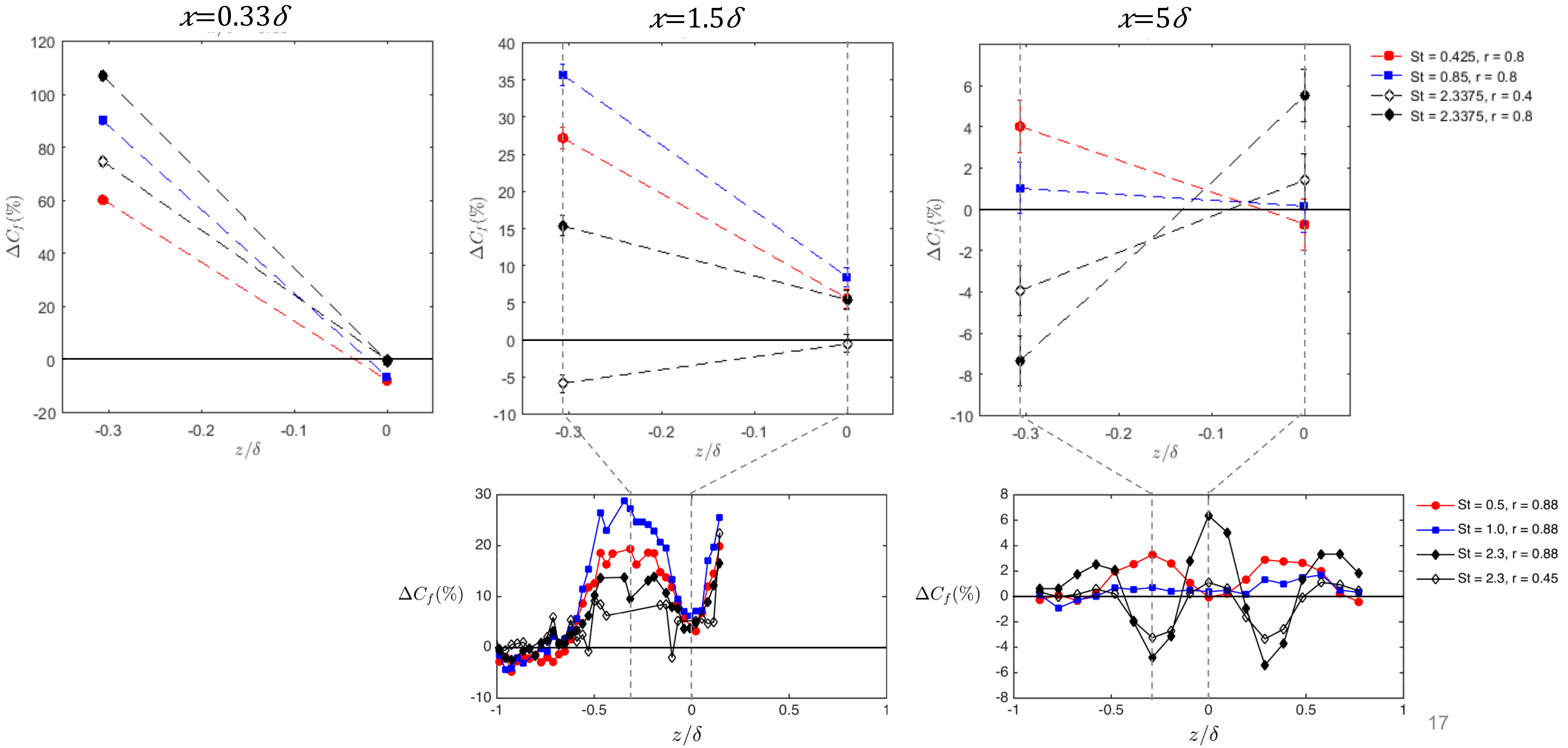
- Measure mean shear stress before, during, and after actuation at the 6 measurement locations
- Calculate $\Delta c_f = \frac{\tau_w - \tau_{w0}}{\tau_{w0}} \times 100\%$
- Integrate over the 6 points with a simple trapezoidal integration



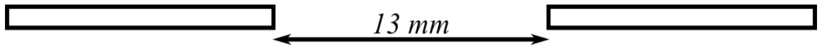




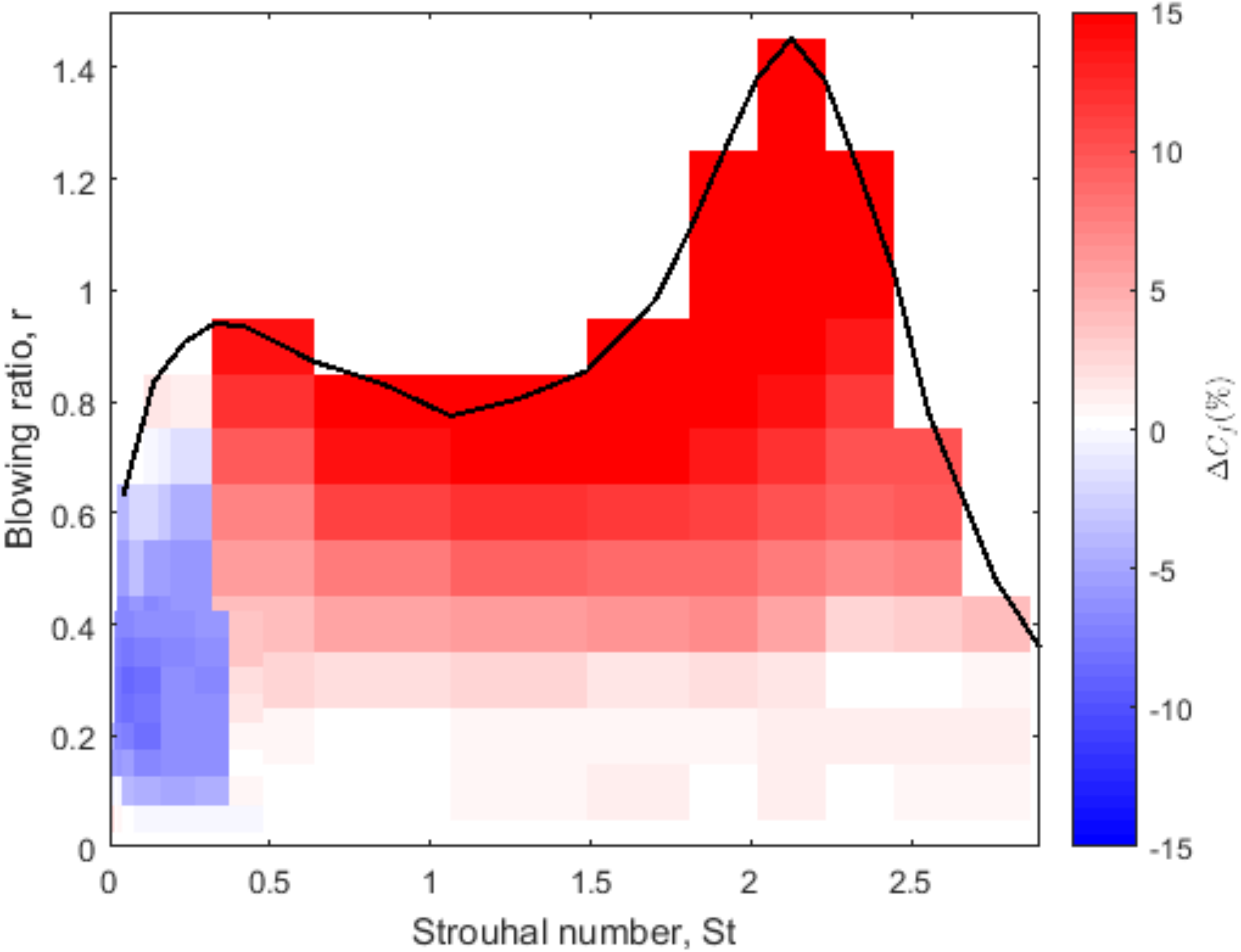
Comparison with OFI and Clauser chart



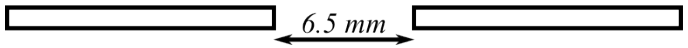
13 mm spacing – Parameter map



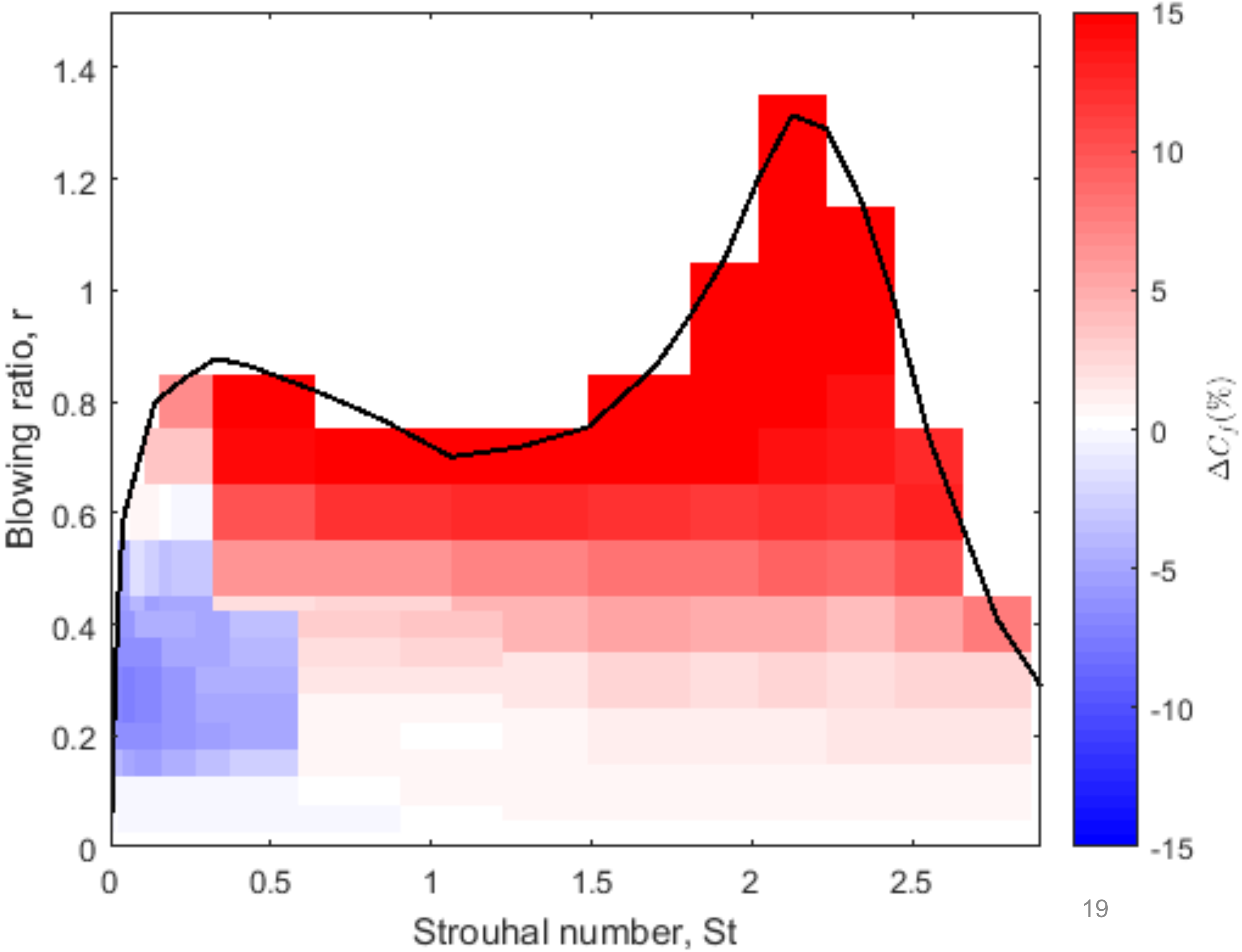
- Region of reduced skin friction centred at (St, r) = (0.043, 0.25)
- High blowing ratio results in skin friction increase
- Skin friction increase also at Strouhal number above 0.5



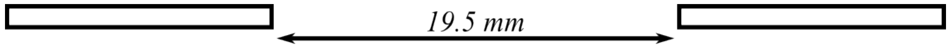
6.5 mm spacing – Parameter map



- Region of expected reduced skin friction centred at (St, r) = (0.032, 0.3)
- Nearly identical to the results with the 13mm spacing
- Slightly larger region of reduced skin friction



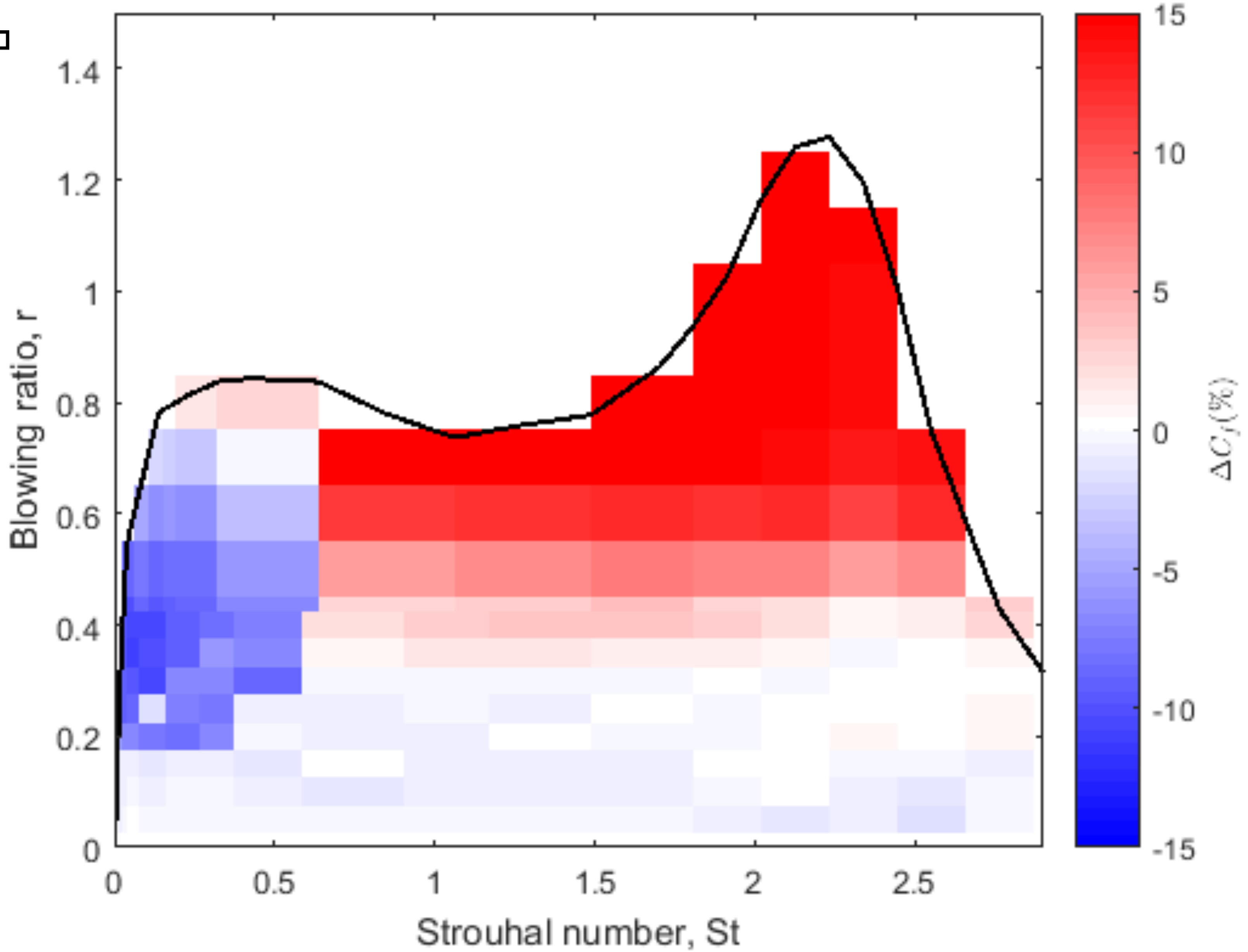
19.5 mm spacing – Parameter map



- Region of expected reduced skin friction centred at (St, r) = (0.0425, 0.35)

- Similar to the results with the 13mm and 6.5mm spacing

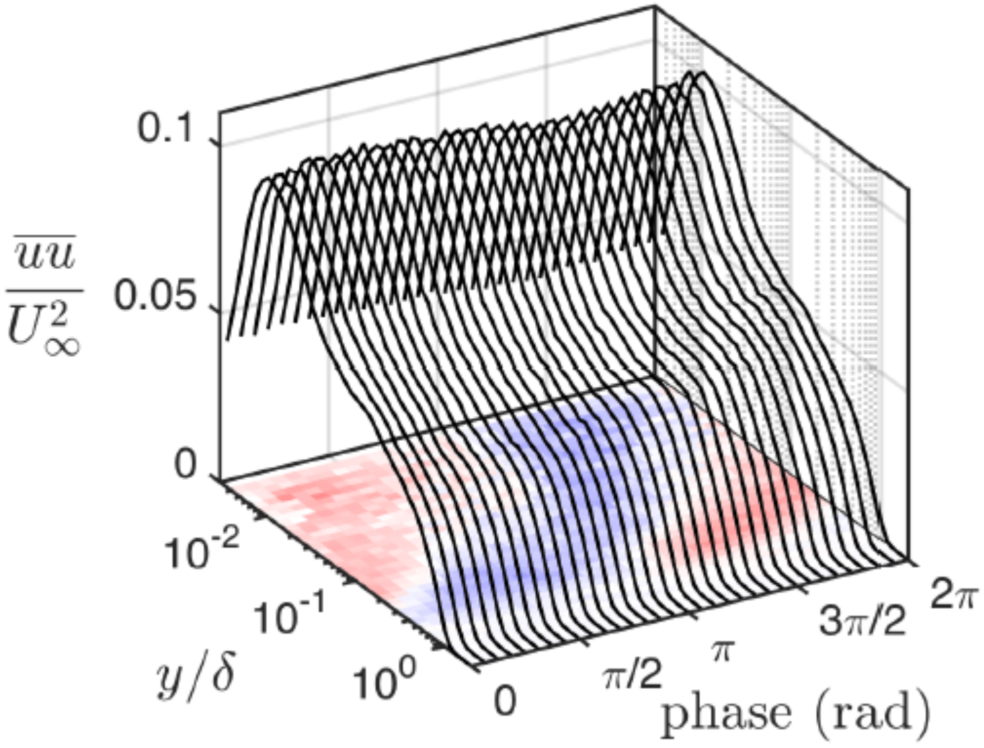
- Region of expected skin friction reduction is larger
  - Seemingly Strouhal number independent at low blowing ratio



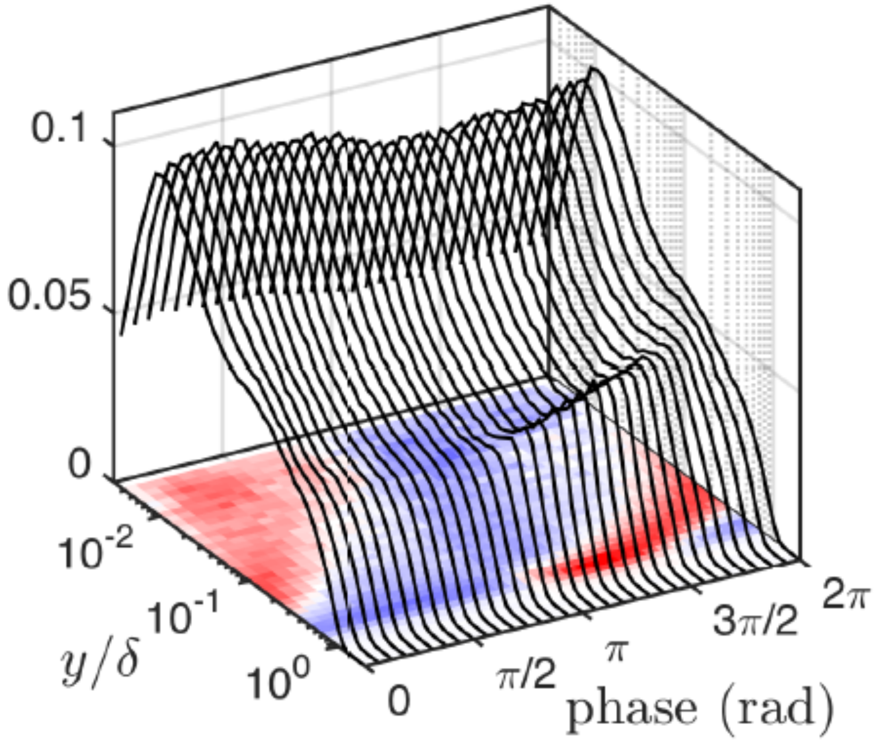
Low Frequency Forcing

- Amplitude modulation of near wall peak due to structures imparted by the synthetic jets
- Effect increases with increasing blowing ratio

St = 0.077, *r* = 0.3



St = 0.077, *r* = 0.675



Conclusions

- Skin friction increases with increasing Strouhal number and blowing ratio
- Largest "decrease" in skin friction centred around St = 0.04 and r = 0.3

- Amplitude modulation of synthetic jet structures on near wall peak

- Low Strouhal number and high blowing ratio causes largest input of streamwise turbulence intensity

- **Low frequency forcing most effective at manipulating boundary layer**

Questions?