Measurements of Turbulence Convection Speeds in Multistream Jets Using Time-Resolved PIV

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Motivation

- **Goal**: Noise reduction concepts and prediction tools to engineer them on aircraft.

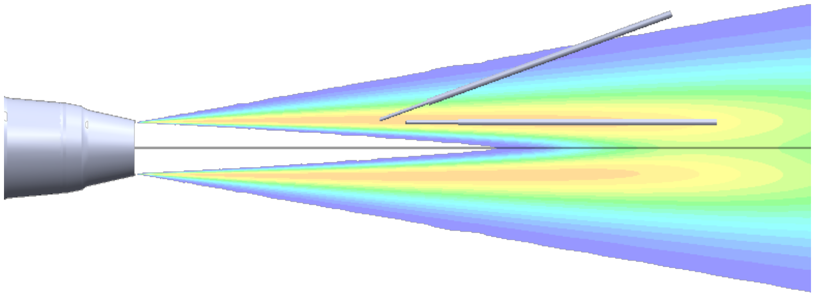
- Explore noise reduction concepts keyed to local convection speed, influenced by modifying flow profiles (*a la* Papamoschou)
  - Offset externally mixed nozzles

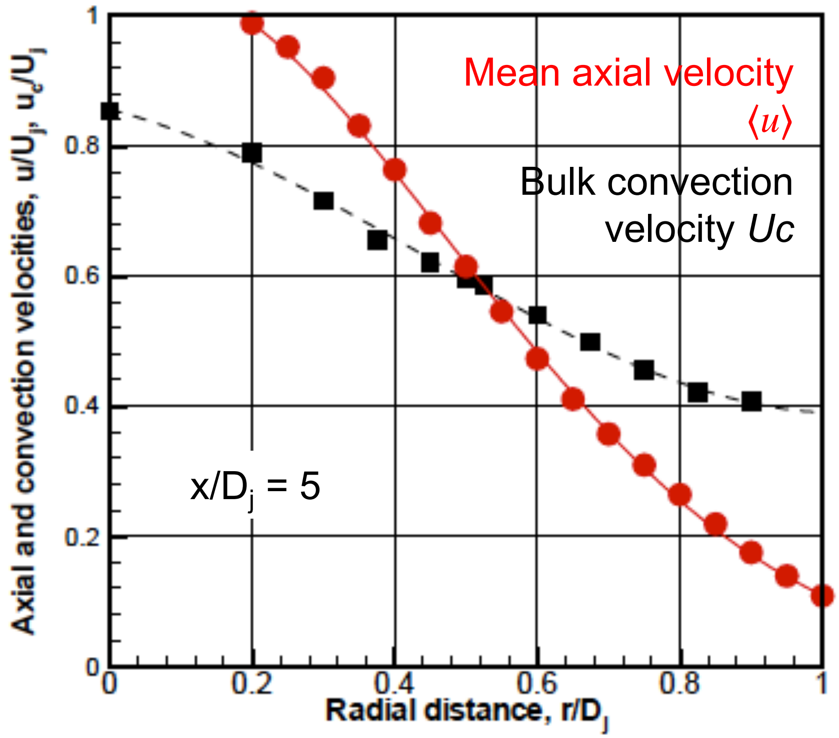
- Only a small part of turbulent energy couples to acoustic far-field, and convection speed one aspect of this 'filter'.
- Convection speed of turbulent eddies play key role in acoustic analogies.
  - To create a design tool, relate Uc to parameters from RANS solutions

- Important to note: convection speed of what?
  - Bulk turbulent velocity, pressure, vorticity, scalar
  - Spatial, frequency modes of these parameters?

Previous experimental work

- Older hot-wire work
  - Two probes, separate in space, measure time delay in correlation
  - Common result shown, radial profile of convection speed Uc, mean velocity $\langle u \rangle$
  - Usually measured in potential core region
  - Uc matches $\langle u \rangle$ at $\langle u \rangle / U_{jet} \cong 0.6$
  - $Uc = 0.6Uj$ often used as simple model for convection speed at jet cross-section, including hydrodynamic near-field

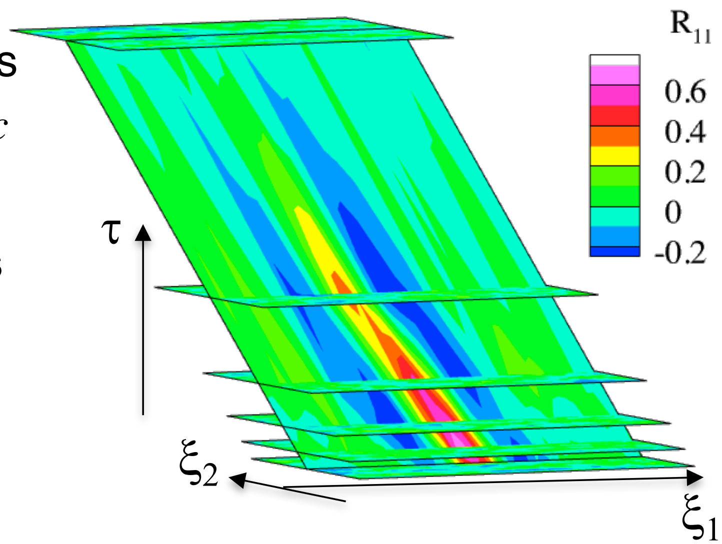




Morris, P.J. and Zaman, K.B.M.Q., “Velocity Measurements in Jets with Application to Noise Source Modeling,” *AIAA 2009-17* (2009).

Recent experimental efforts

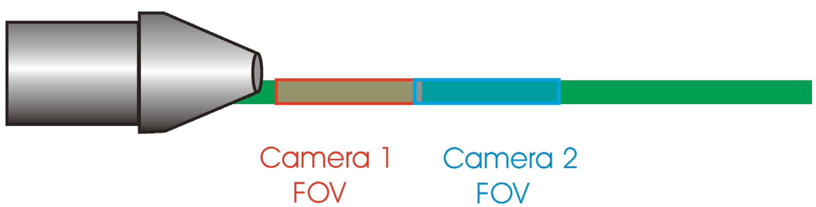
- Multiple-PIV tests
  - Dual conventional PIV setups
  - Two velocity fields acquired at discrete time delays
  - Correlations of velocity fields give $R(\xi_1, \xi_2. \tau) \rightarrow Uc$
- Time-resolved PIV tests
  - Acquire velocity fields over contiguous time series
  - Limited spatial fields, typically looking at large x
- PLIF/PDV image correlation
  - Correlation of scalar «==» velocity?
- Time-resolved DGV
  - Limited spatial extent
- Most work limited to single-stream jets
- Need to measure convection speed of turbulence in **multi-stream, non-axisymmetric** jets **efficiently**
  - Limited to bulk turbulence, possibly filtered by frequency

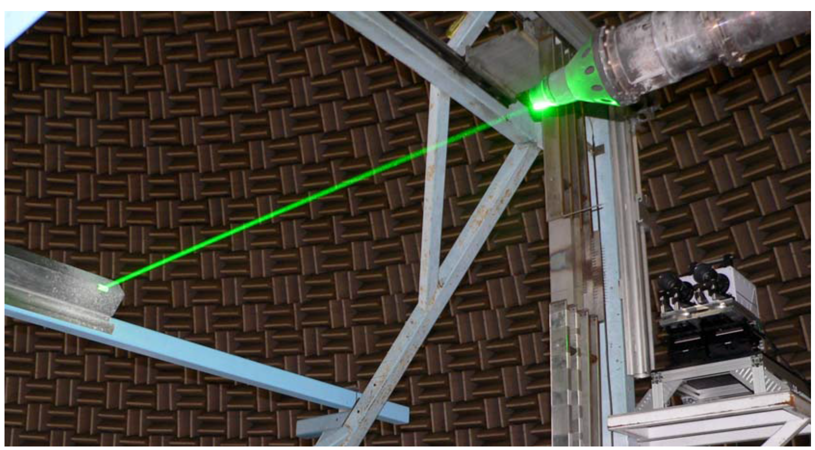


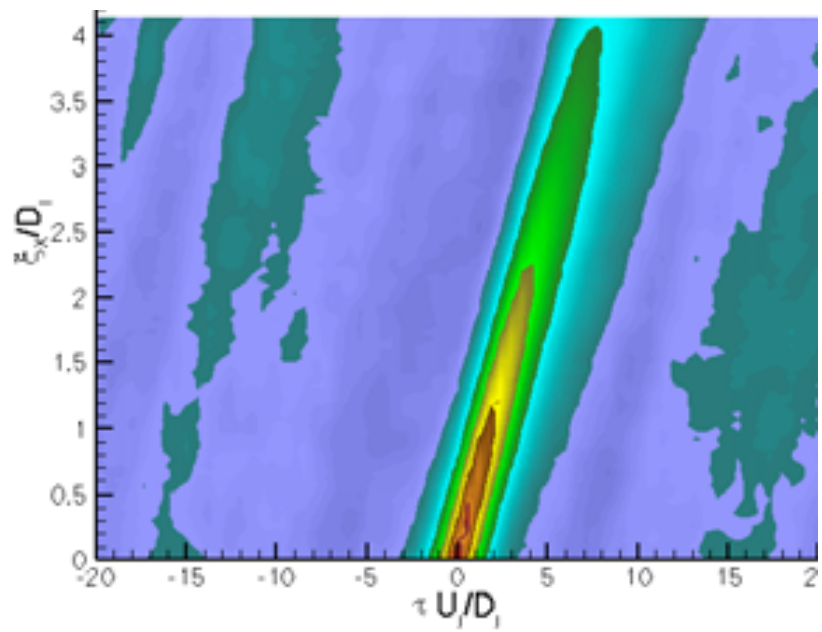
Bridges & Wernet, "Measurements of the Aeroacoustic Sound Source in Hot Jets " AIAA 2003-3130

Previous TRPIV Methodology

- Previous time-resolved PIV
  - CCD arrays combined in 20x300mm FoV to compliment narrow axial laser sheet
  - 25kHz dual laser rate
  - Acquire axial strips of velocity map movies along lipline and along centerline
  - Process to space-time correlations of velocities, Reynold stresses
  - **Required many moves of optics to capture entire jet**



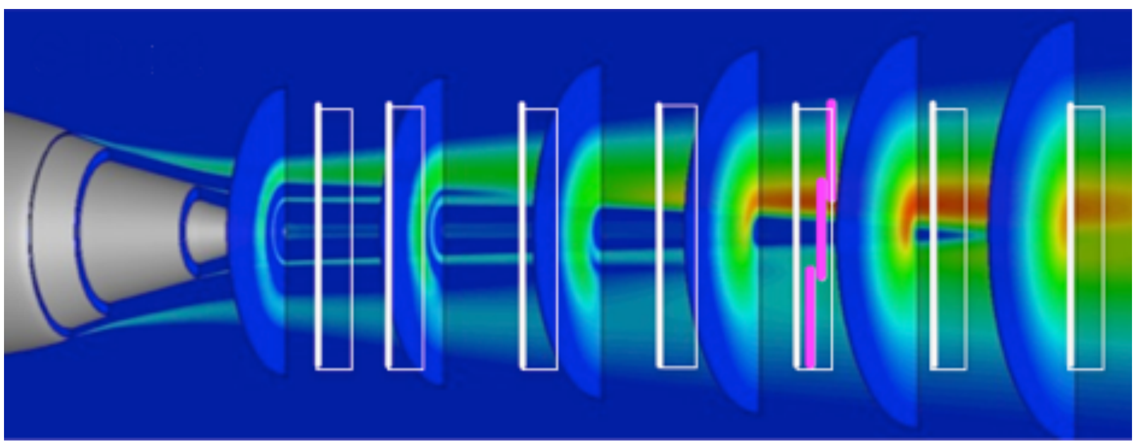


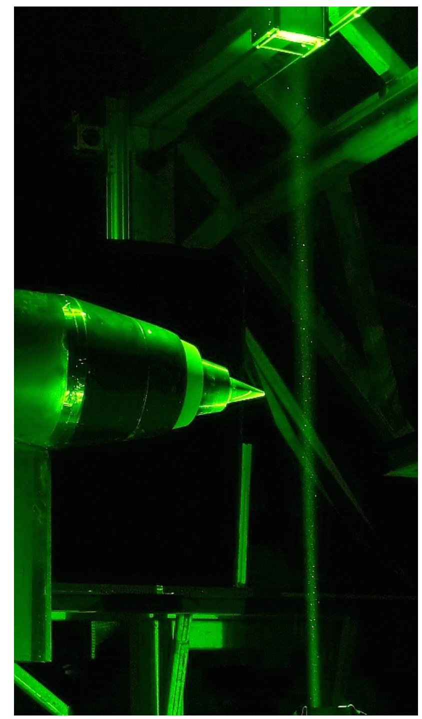


Bridges & Wernet, “Effect of Temperature on Jet Velocity Spectra “ AIAA 2007-3628

New TRPIV methodology

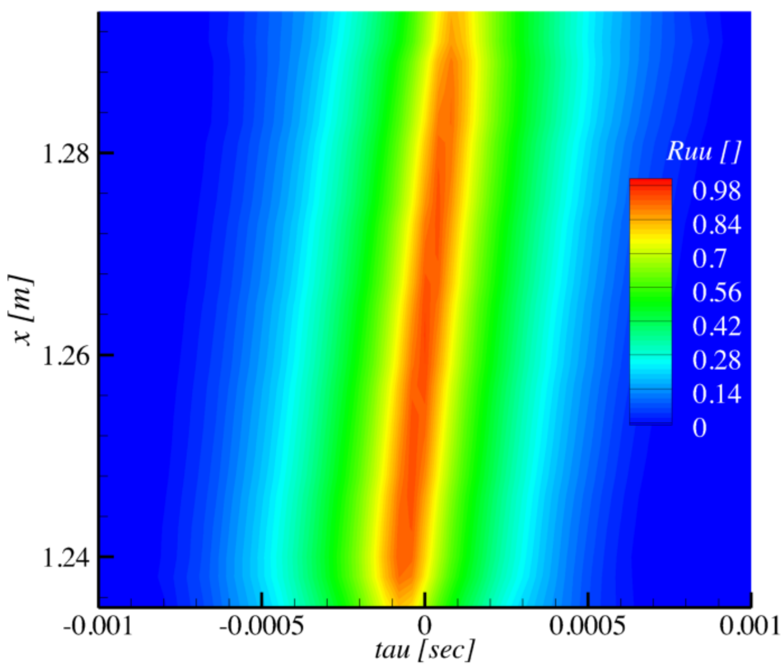
- Lightsheet in streamwise plane, at 90° to jet axis
- Narrow (axial) sheet width
- Camera vertical FoV: 55x140mm, translated three times to acquire full 360mm cross-section of jet
- Acquire velocity maps at 25kHz.
- Process velocity map movie to get axial profile of convection velocity

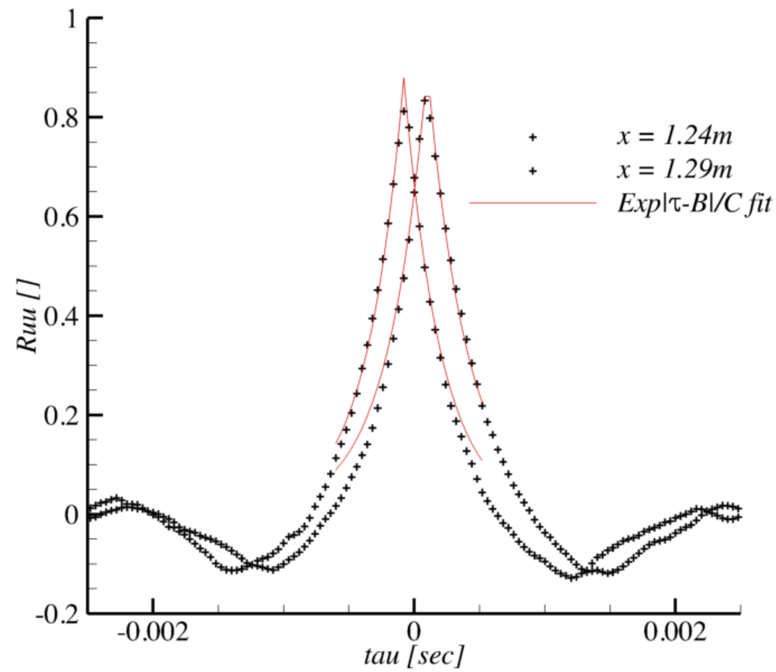




Correlation processing

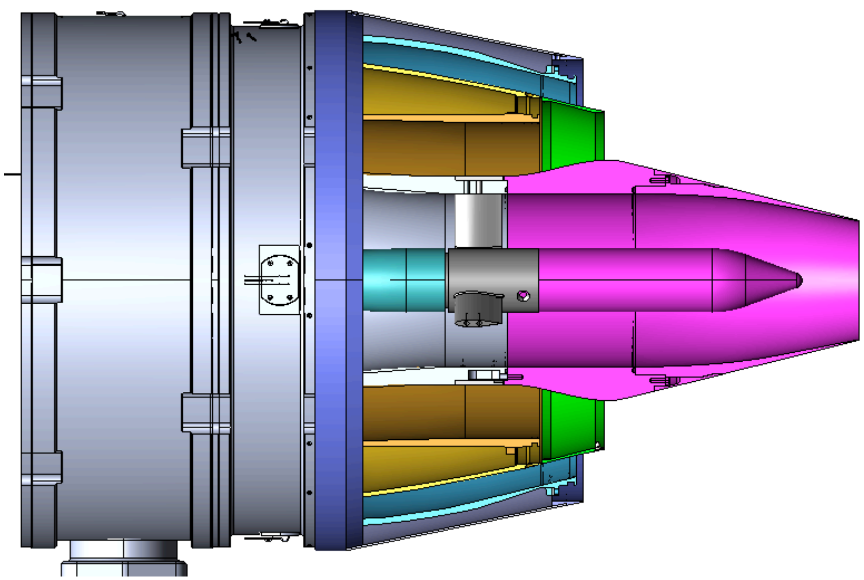
- Basic concept of computing convection velocity is simple:
  - Calculate space-time correlation, track peak x(t), take derivative
- Wide range of convection velocities in same measurement
  - FoV limits maximum time delay τ
  - Acquisition rate limits temporal accuracy
  - Use fitting of single-power exponent to get subsample resolution





Axisymmetric single-stream jets

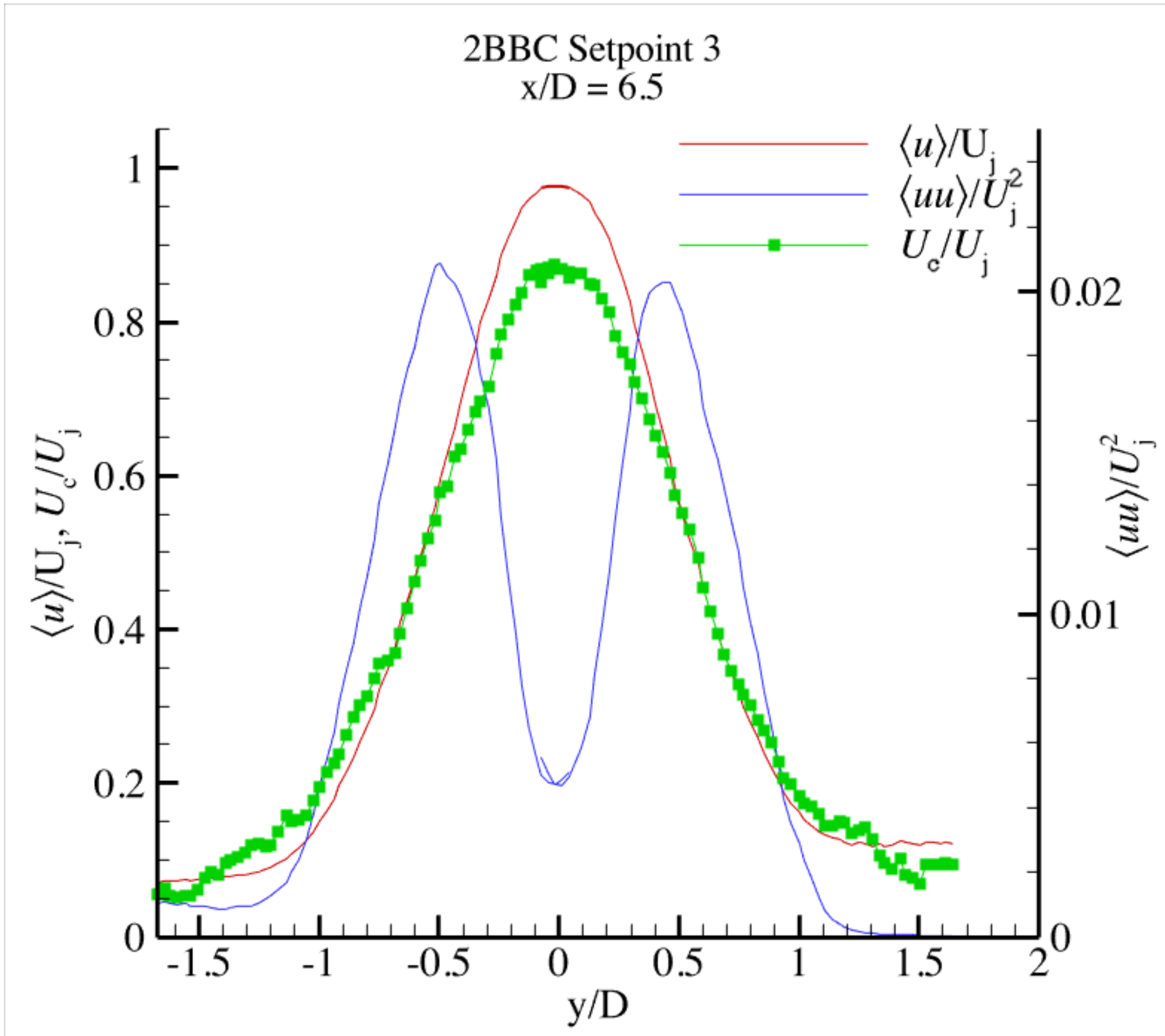
- Single-stream (internal plug), 95mm ø
- Replicate literature for cold subsonic jets
- Replicate NASA Consensus data
  - Confirm basic velocity statistics, mean $\langle u \rangle$ and variance $\langle uu \rangle$
  - Tanna matrix of velocity, temperature



Setpoint	V_j [m/s]	V_j/c_∞	$T_{s,j}/T_\infty$
3	172	0.5	0.96
7	310	0.9	0.84
23	172	0.5	1.76
27	310	0.9	1.76
29	460	1.33	1.76
49	500	1.48	2.70

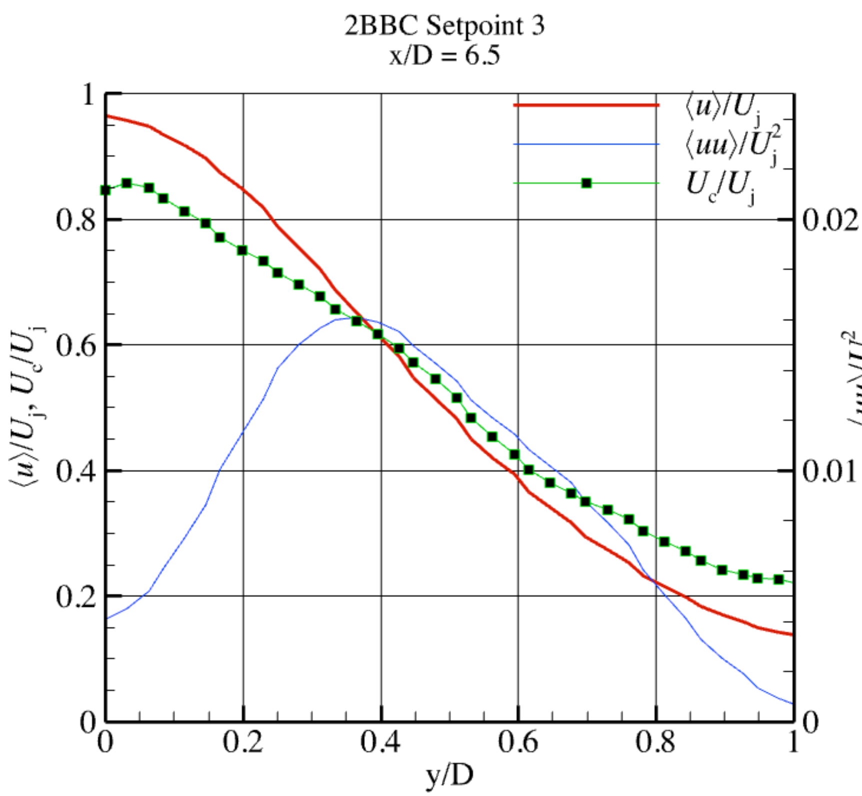
Typical result

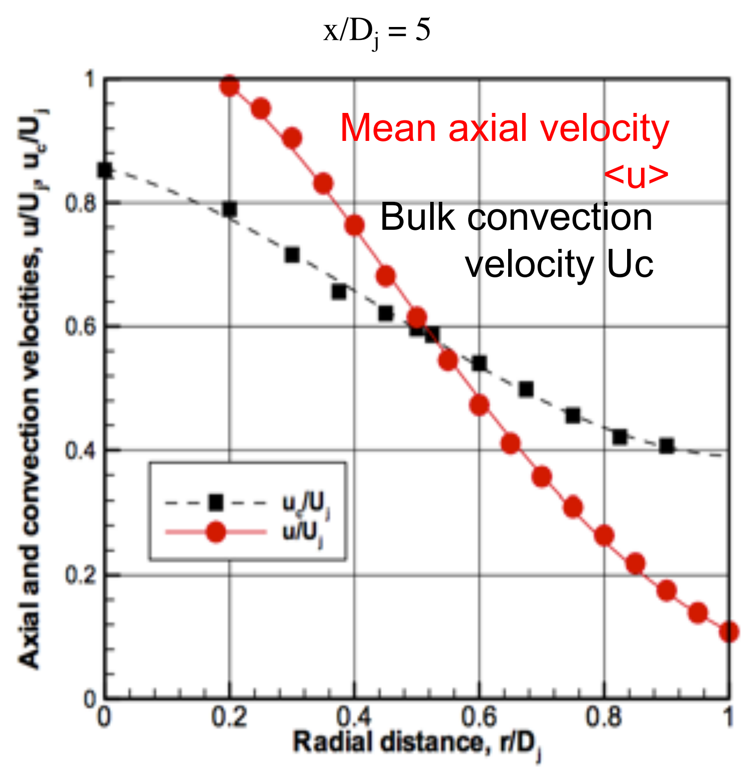
- Single-stream jet (unheated, Ma = 0.5)



Comparison with historical data

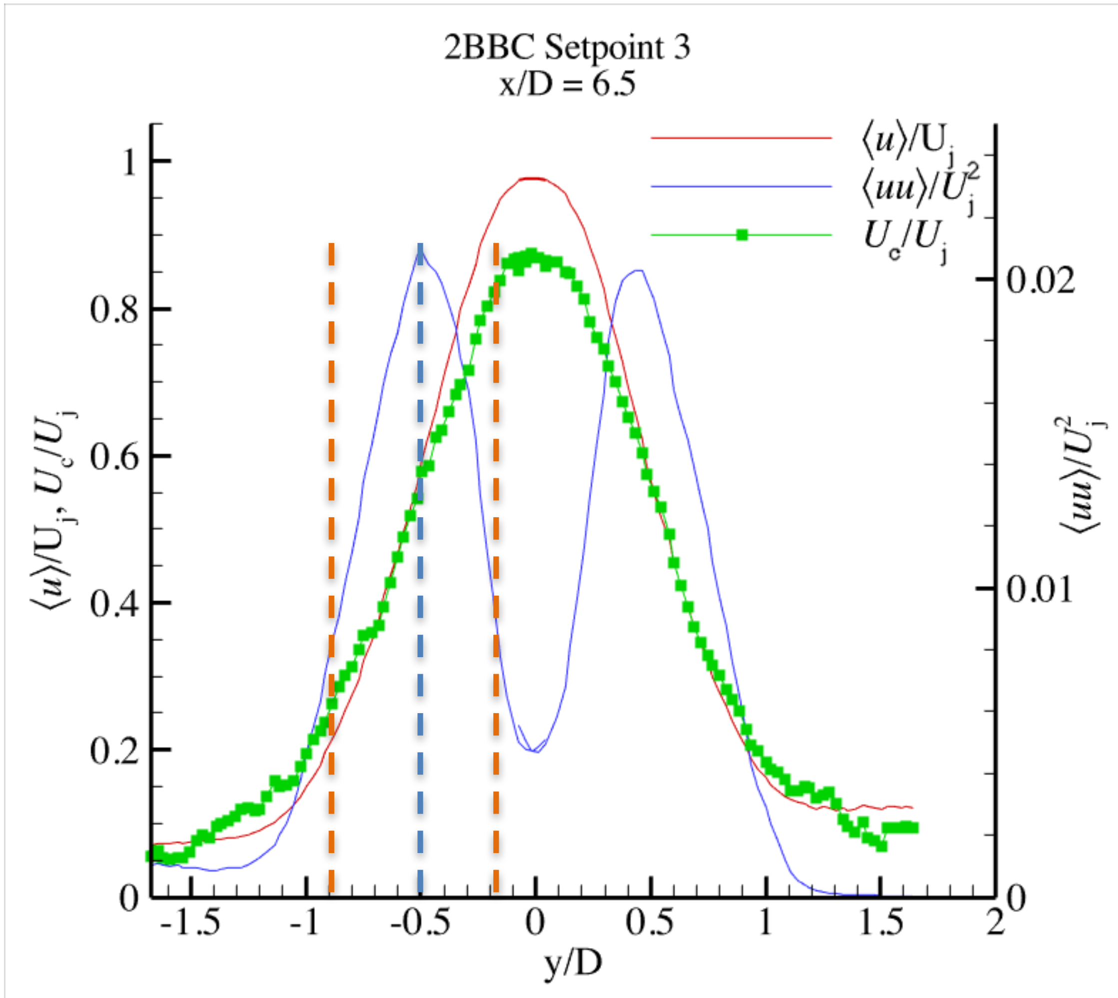
- Single-stream jet (unheated, Ma = 0.5)
- x/Dj = 6.5 (TRPIV) vs x/Dj = 5 (hotwire)
- $Uc = \langle u \rangle$ at $\langle u \rangle = 0.6$
- TRPIV measures lower Uc at outer jet edge than hotwire





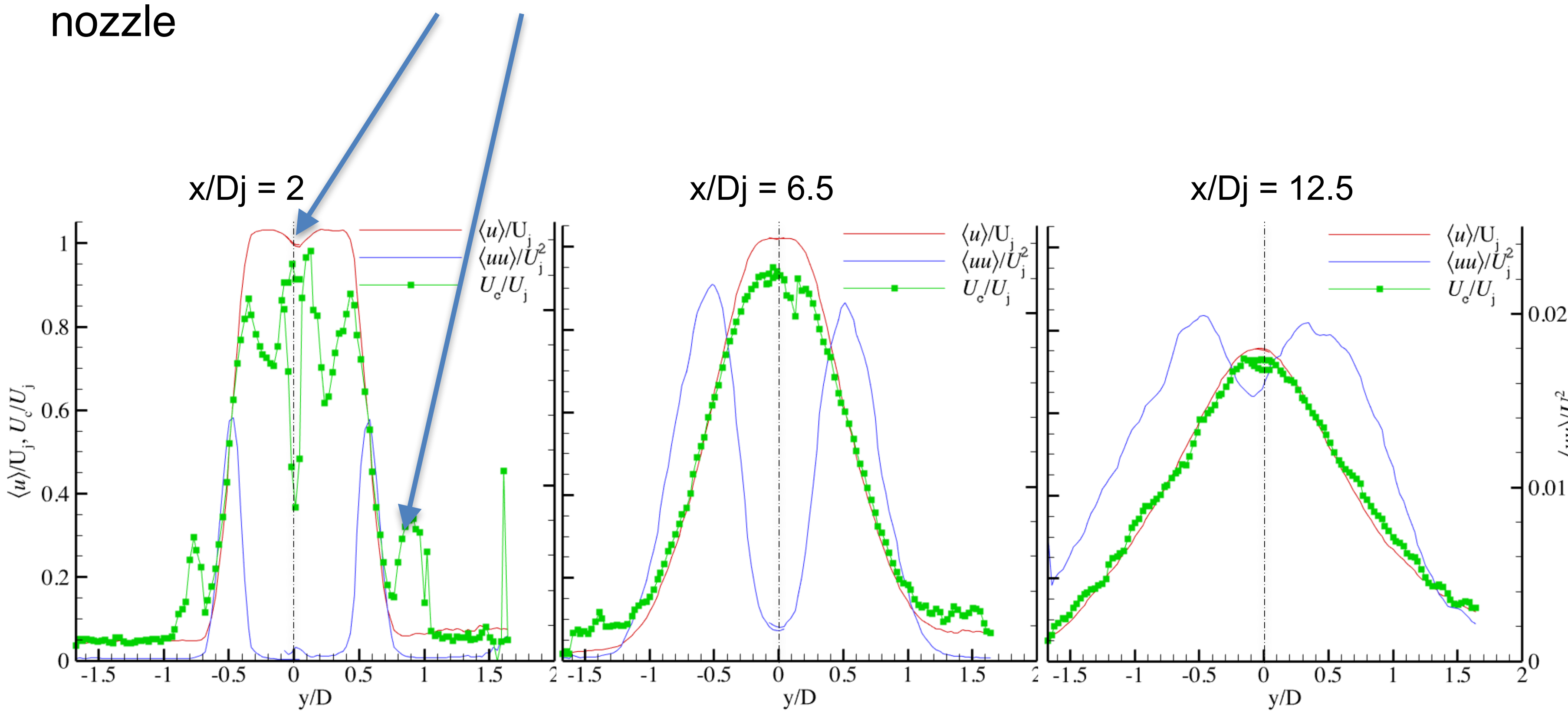
Features

- Single-stream jet (unheated, $Ma = 0.5$)
- $Uc = \langle u \rangle$ where $\langle uu \rangle$ is high. Uc not matching $\langle u \rangle$ where $\langle uu \rangle$ weak.



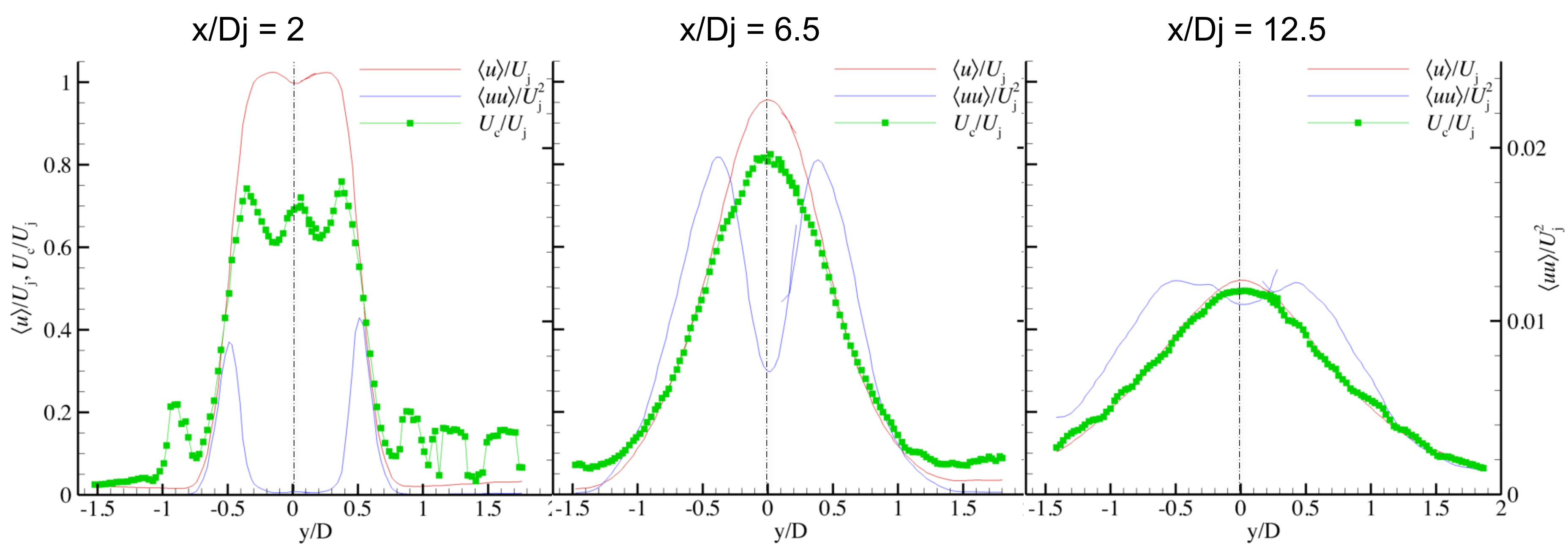
Trends with axial location

- Single-stream jet (unheated Ma = 0.5)
- $Uc \sim \langle u \rangle$ where $\langle uu \rangle >> 0$
- Interesting details around wake of plug on centerline and outside jet near nozzle



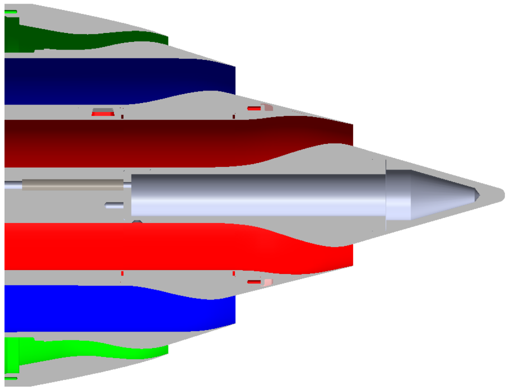
Impact of heat

- Single-stream jet (Ts/T_∞=2.7, Uj/c_∞ = 1.48)
- Convection speed roughly same as mean velocity where $<uu> \neq 0$



Axisymmetric multi-stream jets

- Nozzle hardware from three-stream externally mixed experiments of Henderson
  - Axisymmetric (C1T1) with A1:A2:A3 = 1:2.5:1
- Flow conditions
  - Representative of engines
  - Chosen for variations in shear layers
  - Hope to see variations in convection speed

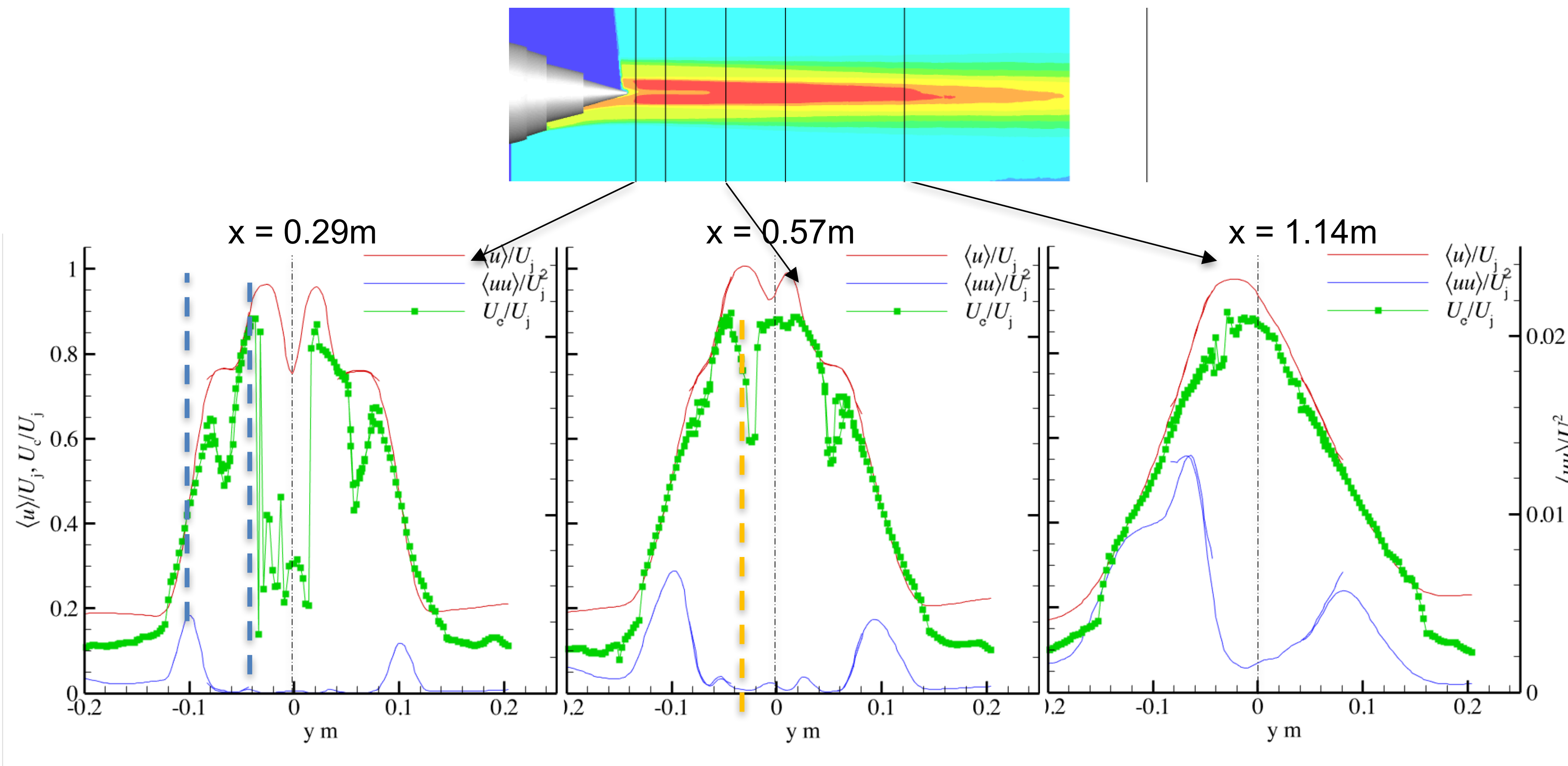


Setpoint	NPR_1	NTR_1	NPR_2	NTR_2	NPR_3	Mf	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]	V_∞ [m/s]
58833	1.5	3	1.8	1.25	1.8	0.3	430	330	330	102
58533	1.5	3	1.8	1.25	1.5	0.3	430	330	275	102
58233	1.5	3	1.8	1.25	1.2	0.3	430	330	190	102
58033	1.5	3	1.8	1.25	1.06	0.3	430	330	102	102
58030	1.5	3	1.8	1.25	1	0	430	330	0	0
55833	1.5	3	1.5	1.25	1.8	0.3	430	275	330	102
85210	1.8	1.25	1.5	1.25	1.2	0	330	275	190	0
88533	1.8	3	1.8	1.25	1.5	0.3	510	330	275	102

Henderson, B.S., and Wernet, M.P. "Characterization of Three-Stream Jet Flow Fields." *54th AIAA Aerospace Sciences Meeting*. 2016.

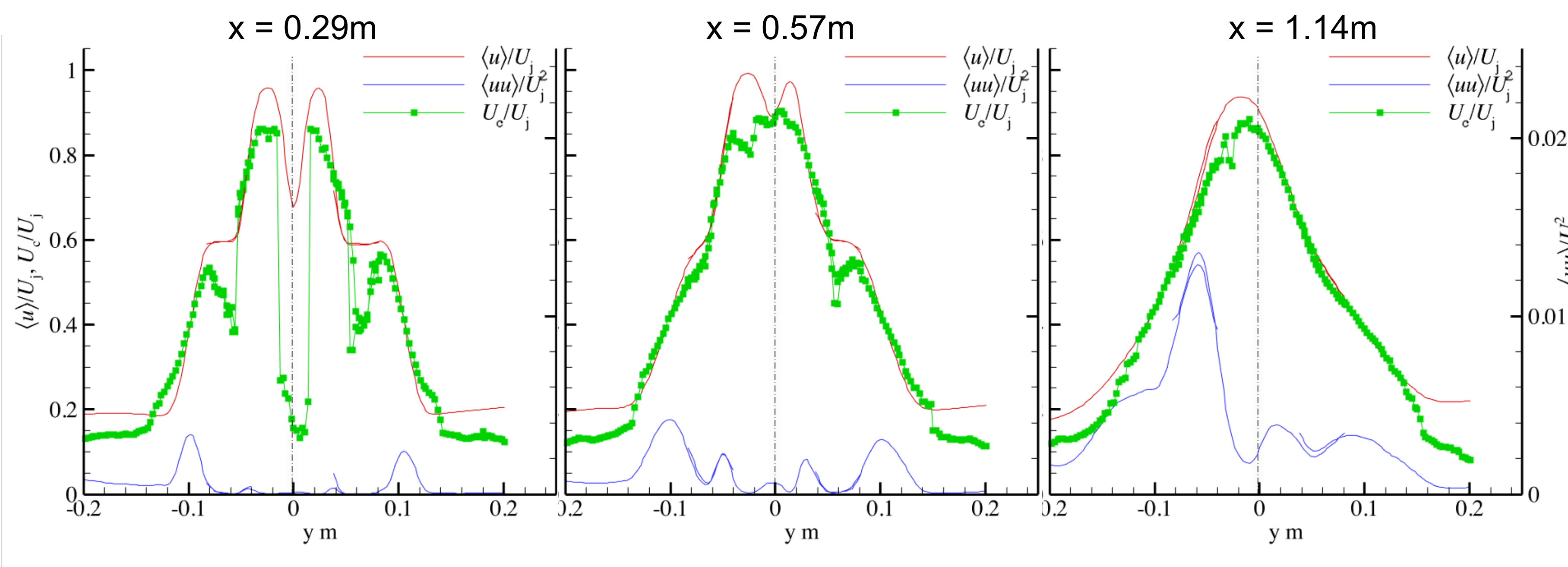
Two-stream jet

- ‘Dual stream’ jet (Velocity ratios 430:330:330:102)
- ‘Axisymmetric’ jet not so symmetric in reality.
- Where $\langle uu \rangle$ is relatively small, Uc closer to nearest $\langle u \rangle$ where $\langle uu \rangle$ is large.



Three-stream jet

- Three-stream jet (Velocity ratios 430:275:330:102)
- Tertiary stream mixes out by first measurement station
  - Only two shear layers present
- Strong asymmetry grows
  - Asymmetry in $\langle uu \rangle$ much stronger than in $\langle u \rangle$
- Uc still tracks $\langle u \rangle$

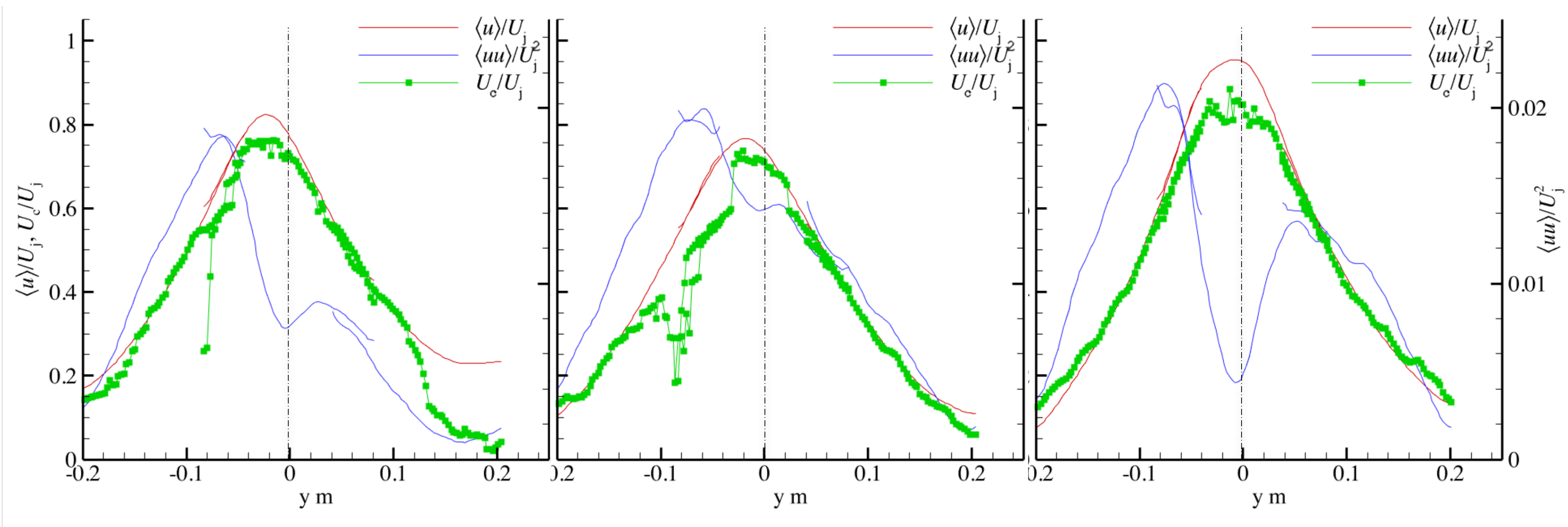


Source of Asymmetry?

- Due to geometric defect? Nonuniform ambient? Unstable hot core?
- Compare with and without flight stream, with and without hot core.
- Asymmetry in all, especially $\langle uu \rangle$.
- Constant in plots is geometry.
- Never assume symmetry!

All unheated

430:330:0:102 x = 1.52m | 430:330:0:0 x = 1.52m | 330:275:190:0 x = 1.52m

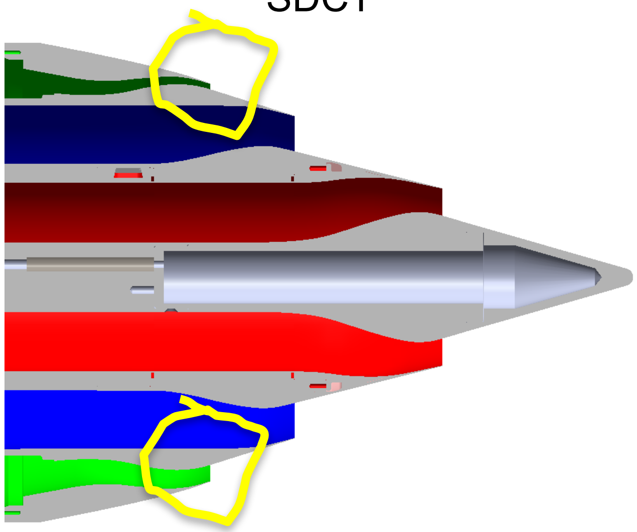


Non-axisymmetric multi-stream jets

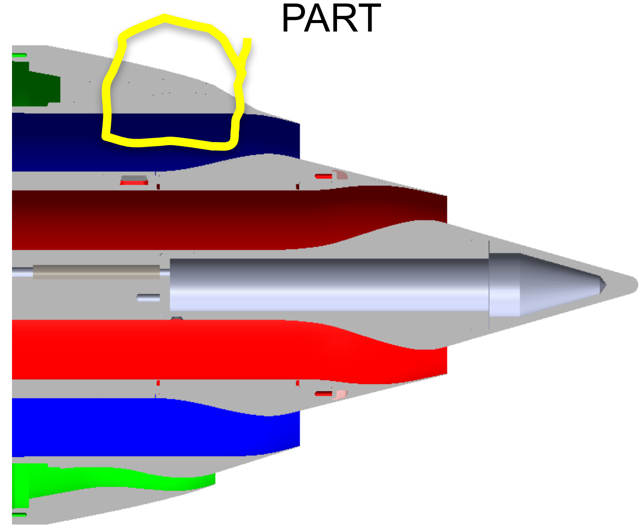
- Asymmetric velocity profiles
  - Offset (SDCT) with Δz = 4mm (D_3 = 294mm ø)
  - Partial duct (PART) with 180° tertiary stream
- Demonstrated non-axisymmetric sound fields

B.S. Henderson & D.L. Huff. "The Aeroacoustics of Offset Three-Stream Jets for Future Commercial Supersonic Aircraft", AIAA 2016-2992

SDCT



PART



Setpoint	NPR_1	NTR_1	NPR_2	NTR_2	NPR_3	Mf	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]	V_∞ [m/s]
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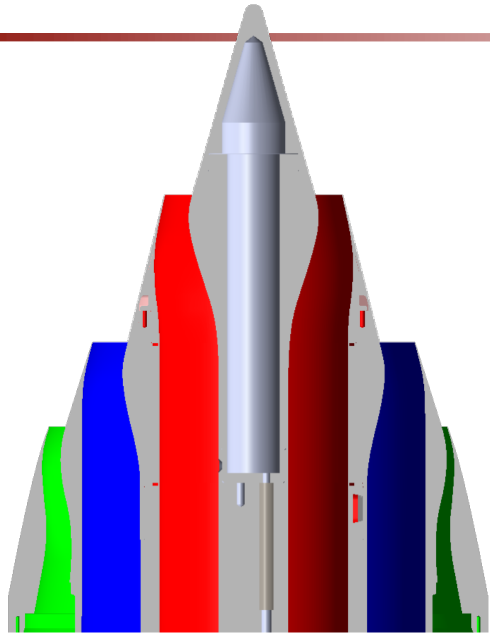
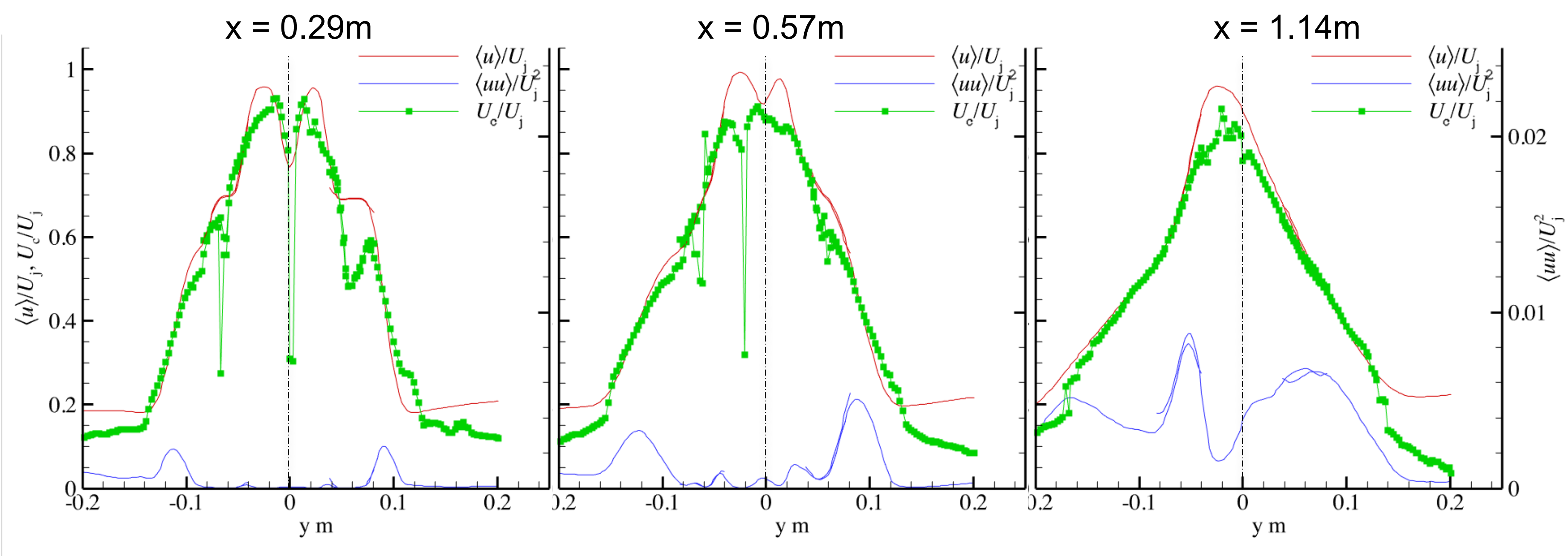
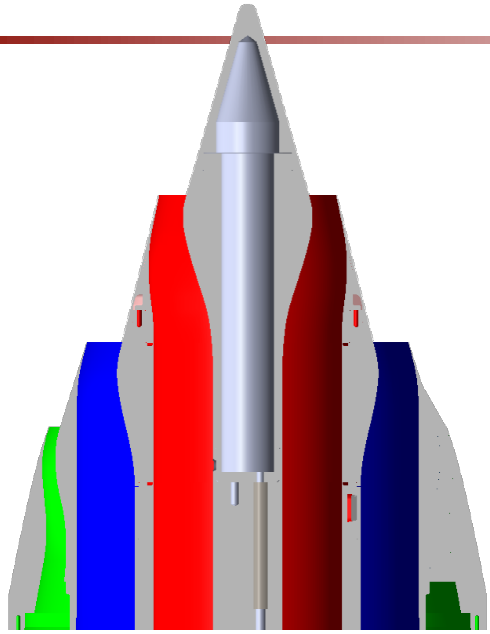
Three-stream offset jets--SDCT



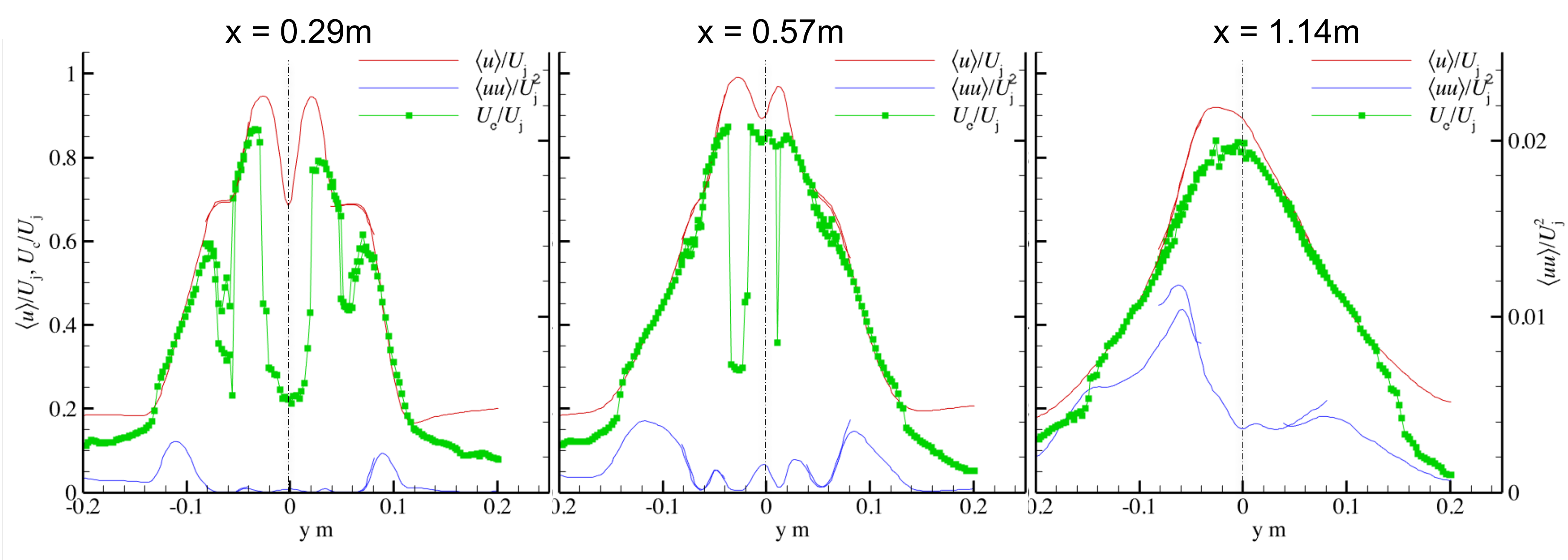
- Three-stream jet (Velocity ratios 430:330:275:102) with offset tertiary
- Tertiary stream evident on thick side (negative y) at x=0.29m
- Offset peak $\langle u \rangle$ by x=1.14m
- *Uc* still tracks $\langle u \rangle$.



Three-stream offset jets--PART

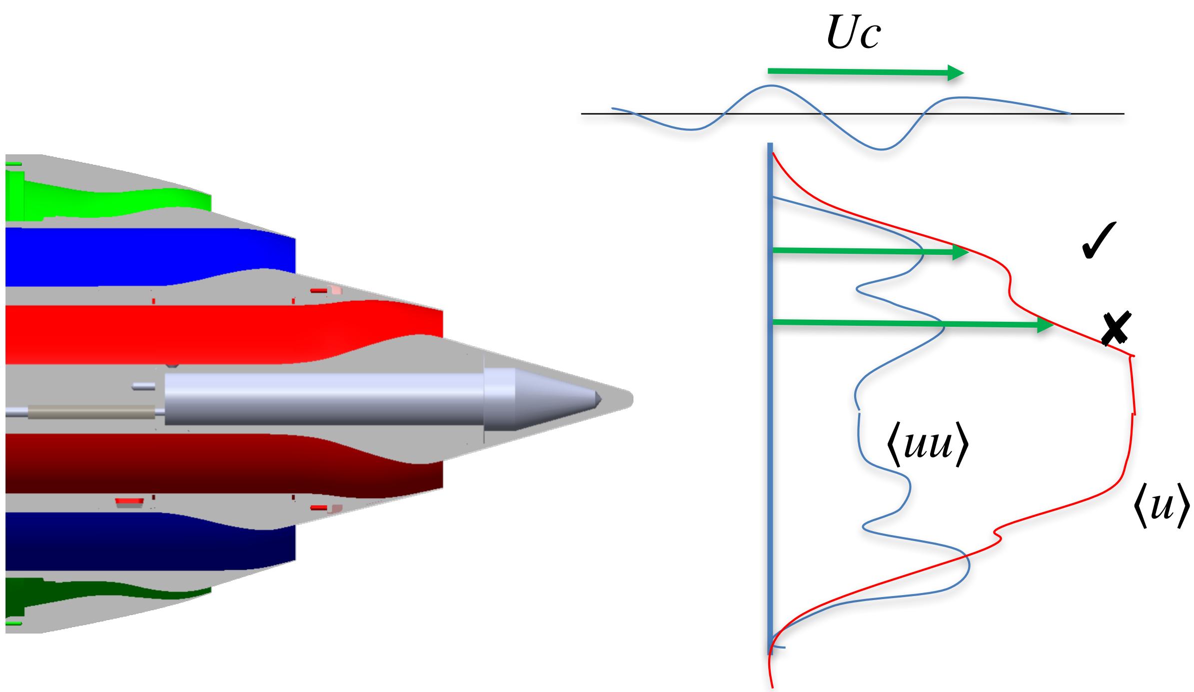


- Three-stream jet (Velocity ratios 430:330:275:102) with 180° tertiary (negative y)
- Tertiary stream reduced shear initially.
- Offset peak ⟨u⟩ by x=1.14m
- Uc still tracks ⟨u⟩



Conclusion

- **Rule:** Uc follows $\langle u \rangle$, where $\langle uu \rangle$ is strong. Where $\langle uu \rangle$ is not strong, Uc is biased toward Uc where $\langle uu \rangle$ is strong.
- Seems to be true for Uc of near-field hydrodynamic pressure as well.



Summary

- For single jets, $\langle uu \rangle$ peaks around $\langle u \rangle / Uj$ = 0.6, hence this value is dominant in most measurements, including local hydrodynamic pressure at jet edge.
- Applying the Rule to multi-stream jets: Uc of near-field hydrodynamic wave packets will be most influenced by closest (outermost) shear layer.
- If convection speed of near-field hydrodynamic wave packet determines source strength, then sound source is controlled by outermost shear layer.
- For engineering use, $Uc = \langle u \rangle$ is a good assumption for bulk turbulence.
  - Where $Uc \neq \langle u \rangle$, then $\langle uu \rangle$ too small to matter anyway.