



Experimental investigations into shock boundary layer interactions

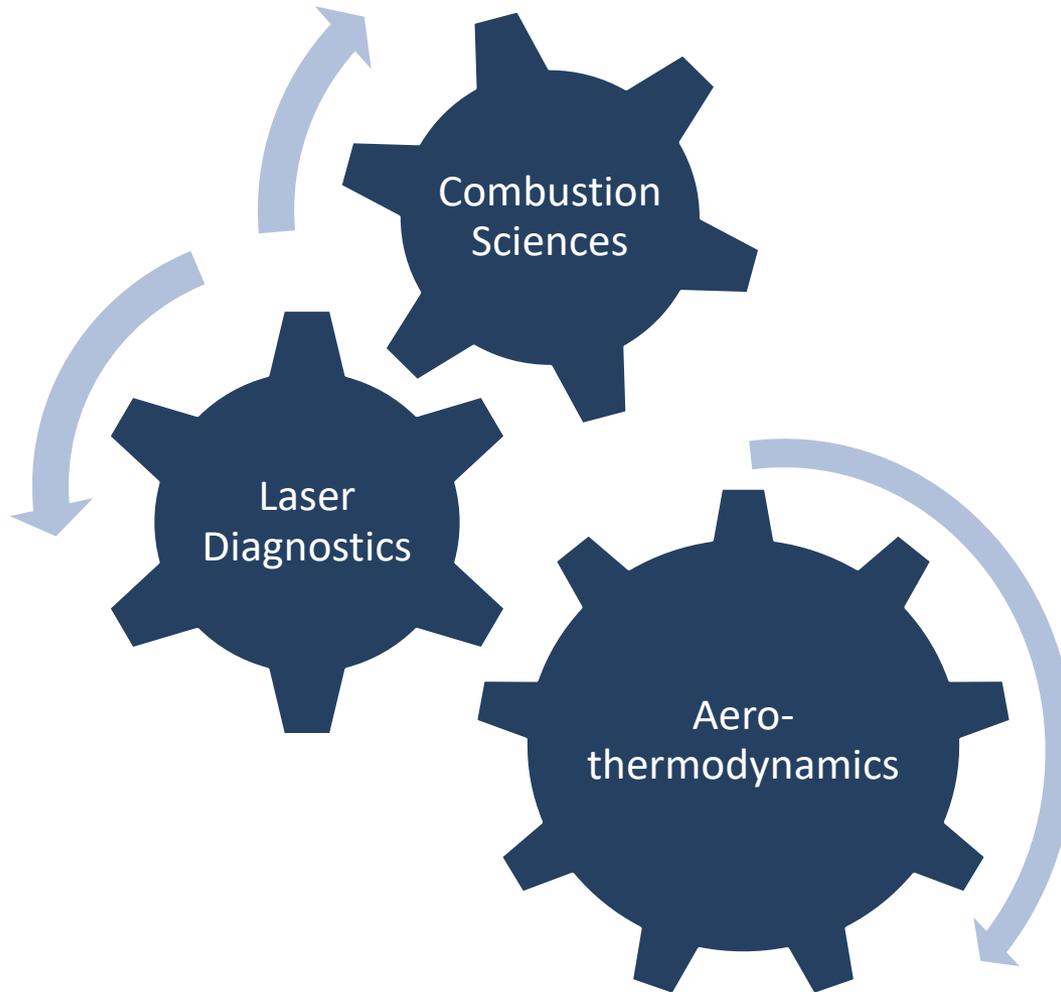
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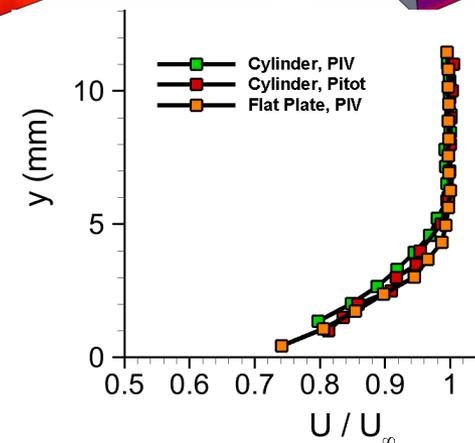
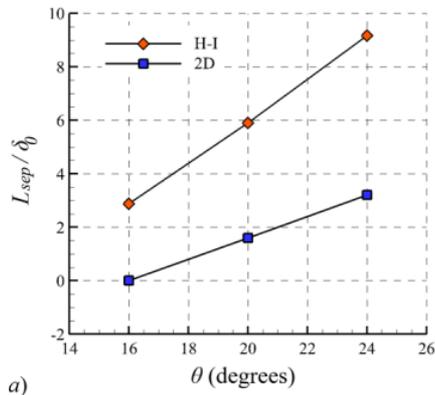
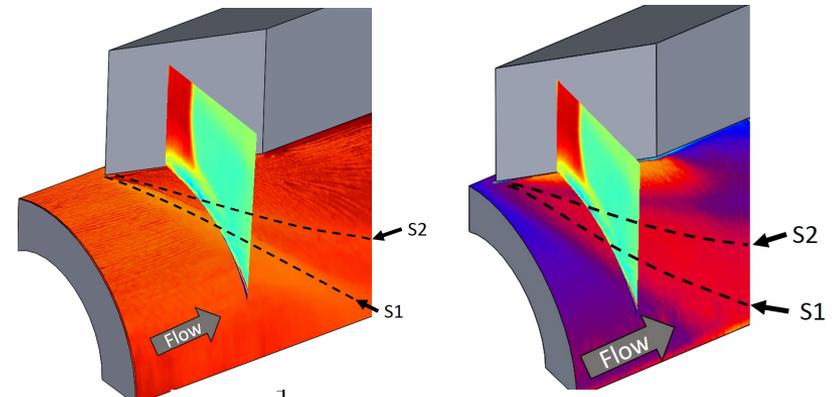
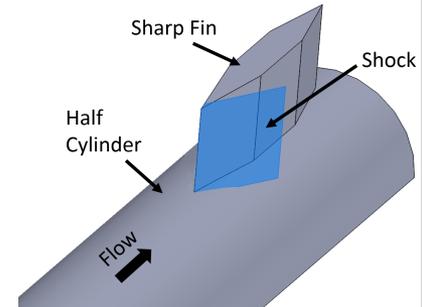
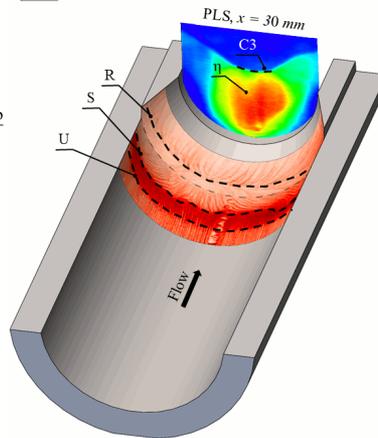
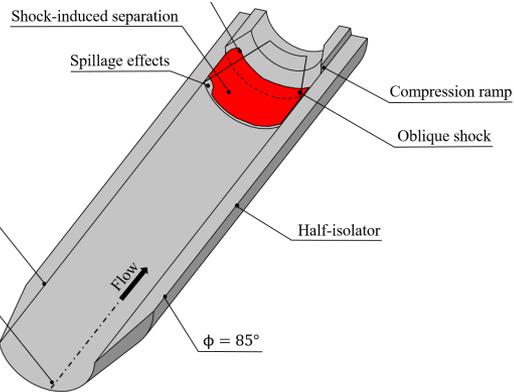
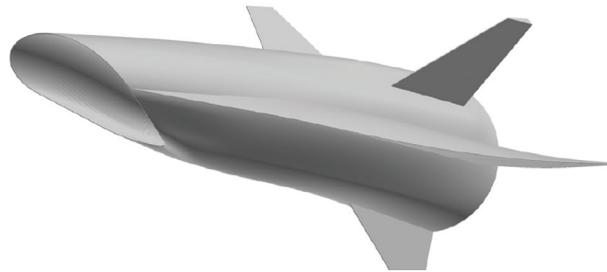
Overall research theme



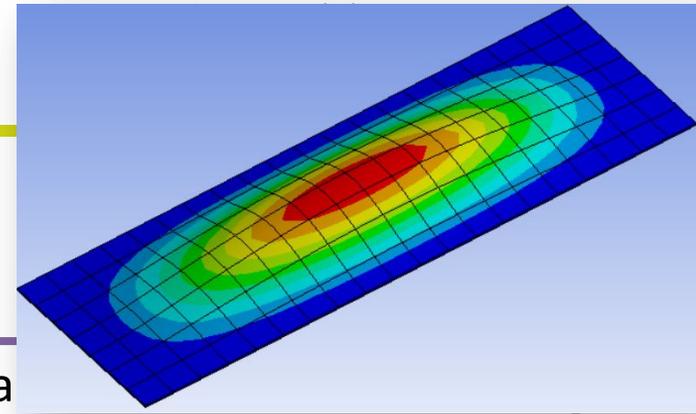
Layout of research areas



Highlights of Aerothermodynamics Research



Highlights of Aerothermodynamics



Shock strength

- Inherent shock osc.
- Permanent flow sep.

- Inherent shock osc.
- No permanent flow sep.

- Weak shock
- No inherent shock osc.
- No flow sep.

Increasing flowfield complexity

- What is the impact on the flowfield?
- What is the impact of the flowfield on the structure?
- When are such interactions *significant*?
- What parameter(s) quantify the extent of FSI coupling?

Increasing structural effects on flowfield

- flex. amp. $\ll \delta_0$
- flex. amp. $\sim \delta_0$
- flex. amp. $\gg \delta_0$

Panel flexure amplitude



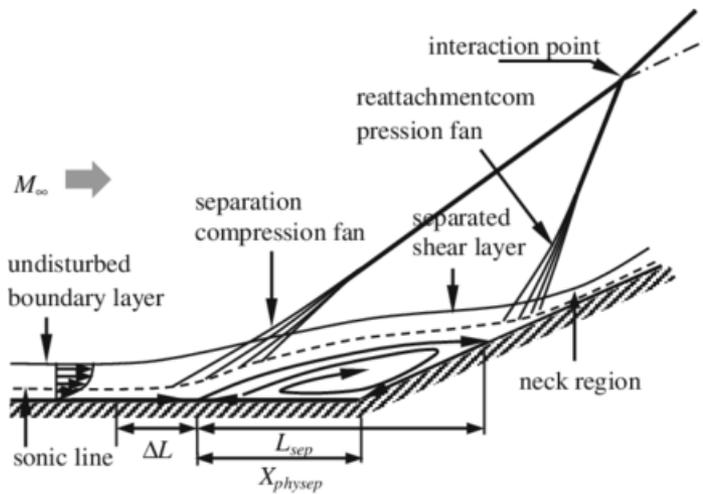


Sidewall and corner separation effects on shock boundary layer interactions

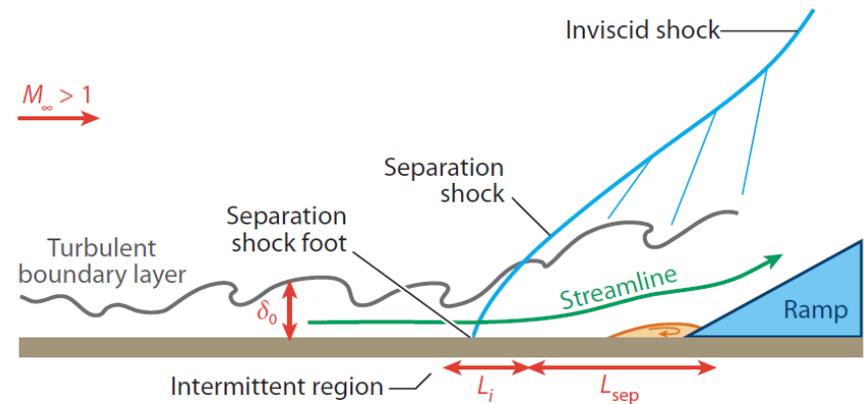


BACKGROUND

▶ Previous work in 2-D SBLIs



Verma *et al.* (2014)

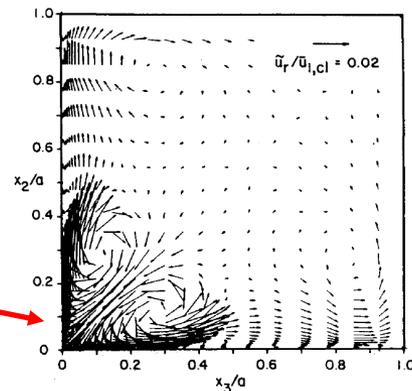
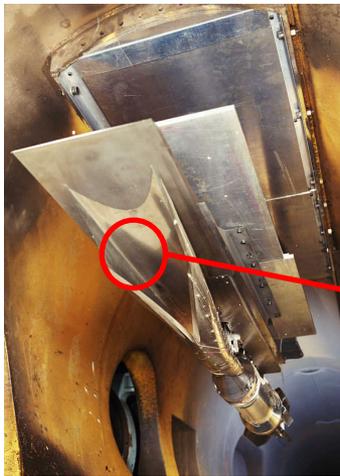


Clemens & Narayanaswamy (2014)

BACKGROUND

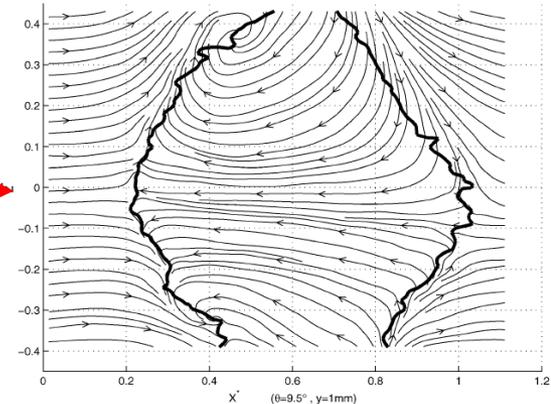
- ▶ Previous work in 2-D SBLIs
- ▶ Actual inlets are seldom two-dimensional
- ▶ Floor/sidewall junctions generate corner boundary layers 3-D SBLIs
 - ▶ Majority of experiments limited to mean, unstart is transient

How do the centerline (primary) and corner SBLIs behave dynamically?



Davis *et al.* (1986)

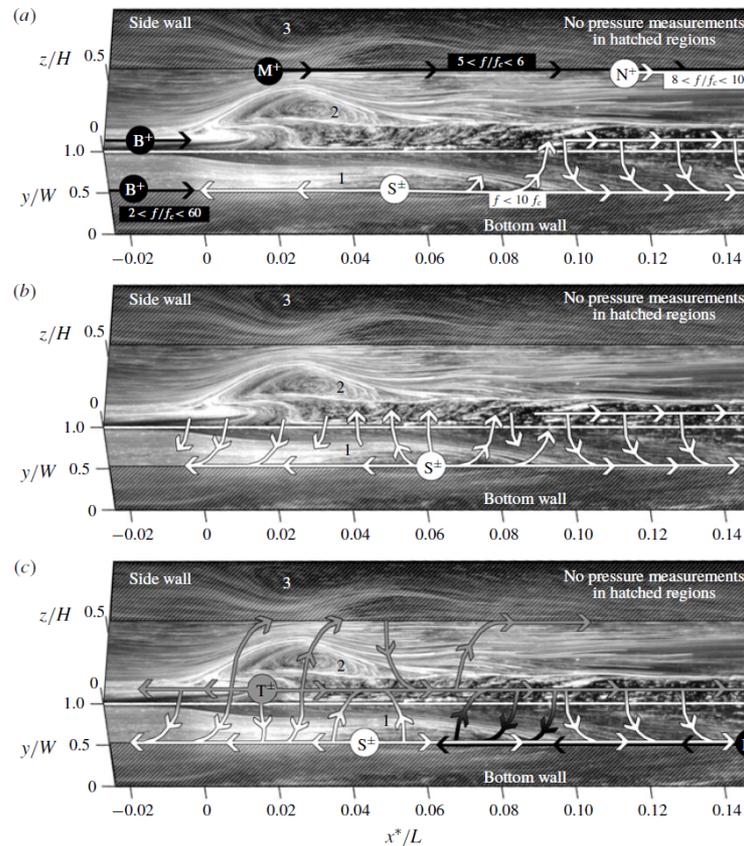
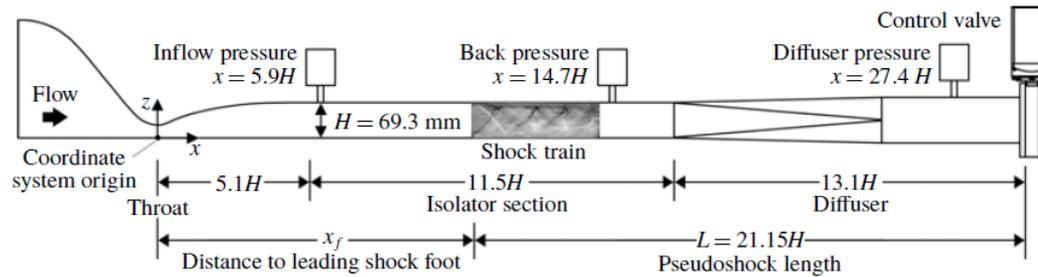
2D BL →



Dupont *et al.* (2005)



Evidences of dynamic sidewall/primary sep coupling

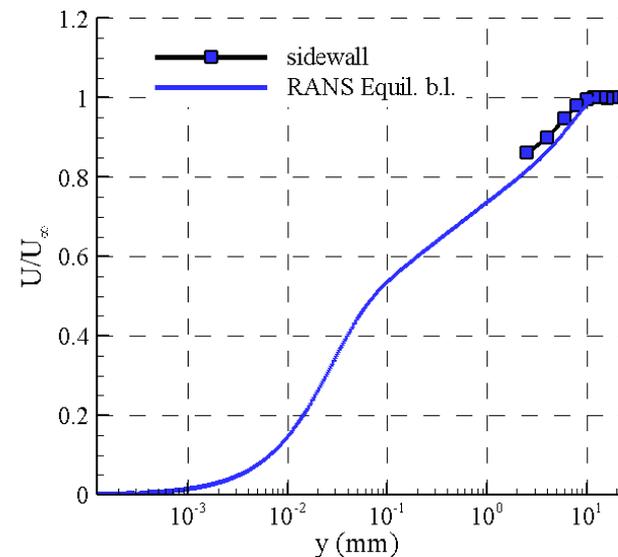
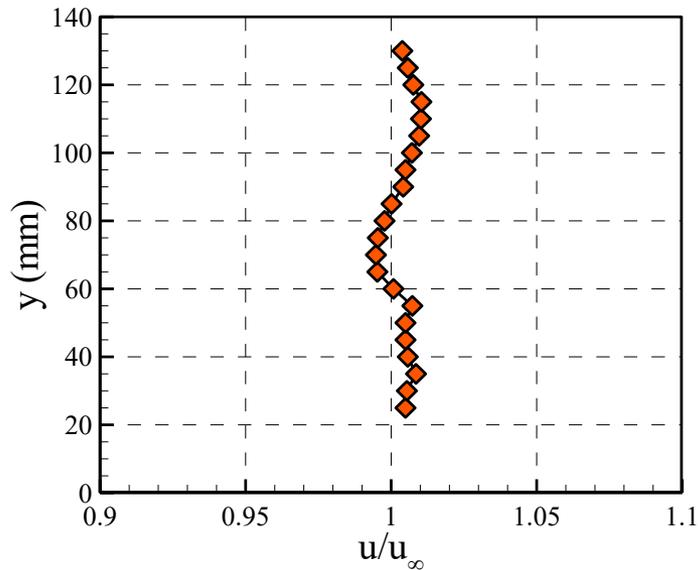


Hunt & Gamba, 2019

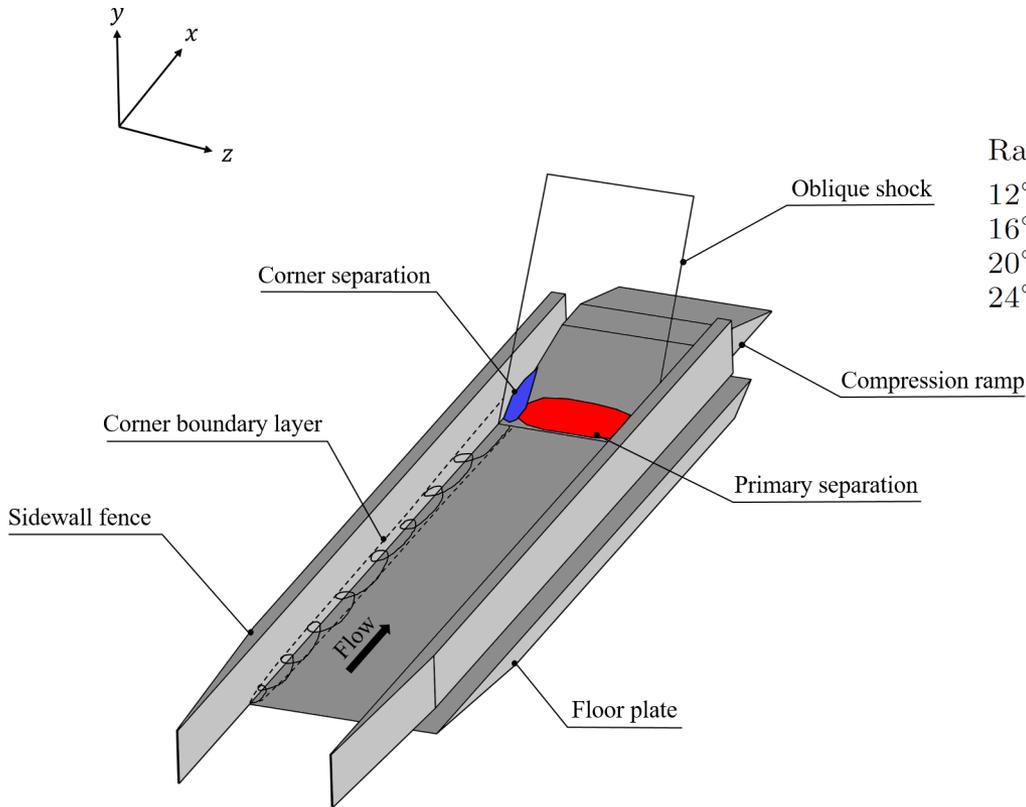
WIND TUNNEL AND FREESTREAM CONDITIONS



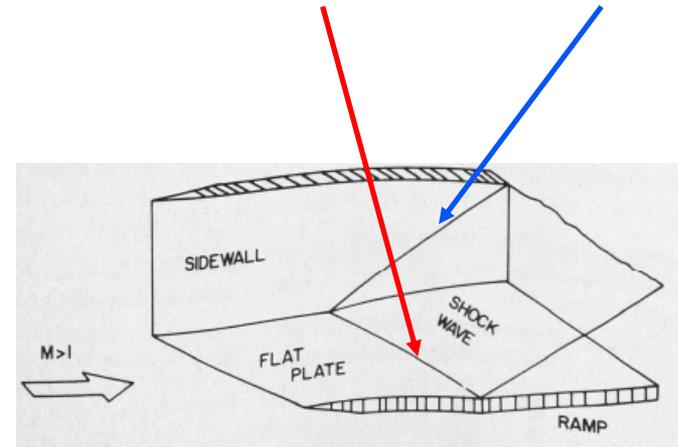
Parameter	Value	
M_∞	2.5	
p_∞	32.5	kPa
T_∞	140	K
u_∞	583	m/s
Re/m	5.3×10^7	m^{-1}



WALL-BOUNDED (W-B) COMPRESSION RAMP MODEL



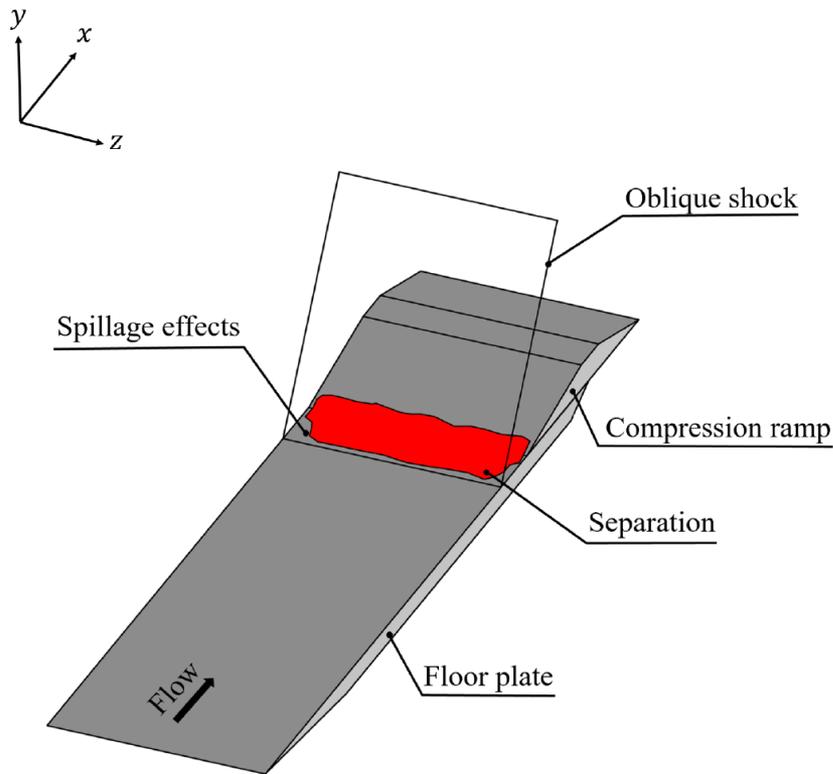
Ramp angle	p_b/p_∞	% of 2D K.L.	% of skewed-shock K.L.
12°	2.09	73	135
16°	2.60	90	168
20°	3.21	112	207
24°	3.94	137	255



Korkegi (1975)

"2-D" COMPRESSION RAMP MODEL

- ▶ For comparisons between wall-bounded/half-cylinder interactions and planar SBLI

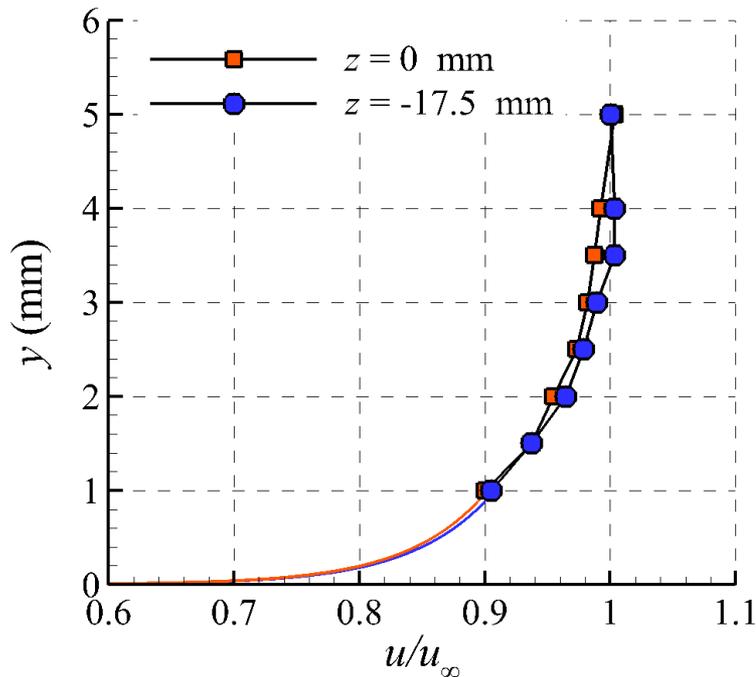


Ramp angle	p_b/p_∞	% of 2D K.L.
12°	2.09	73
16°	2.60	90
20°	3.21	112
24°	3.94	137

WALL-BOUNDED (W-B) COMPRESSION RAMP MODEL

► Inflow characterization

- Wall normal pitot sweeps at centerline ($z = 0 \text{ mm}$), quarter-span ($z = 17.5 \text{ mm}$) at $x = -50 \text{ mm}$

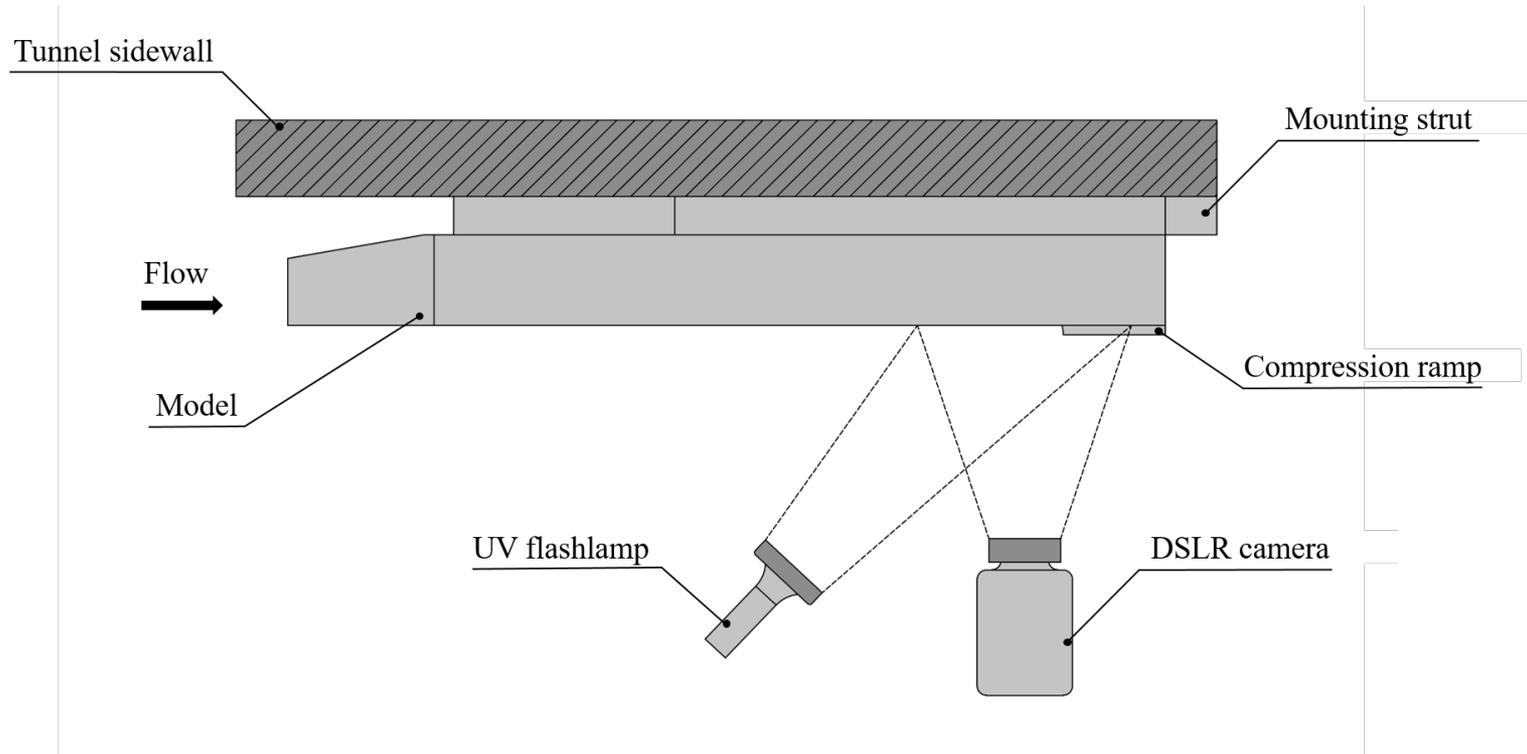
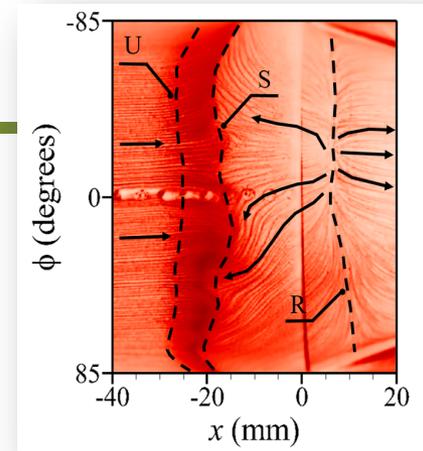


Parameter	W-B (centerline)	W-B (quarter-span)
$\delta_{99\%}$	5 mm	3.5 mm
δ^*	0.25 mm	0.22 mm
θ	0.22 mm	0.19 mm
Re_θ	11700	10000
H	1.14	1.15



Experimental Methods

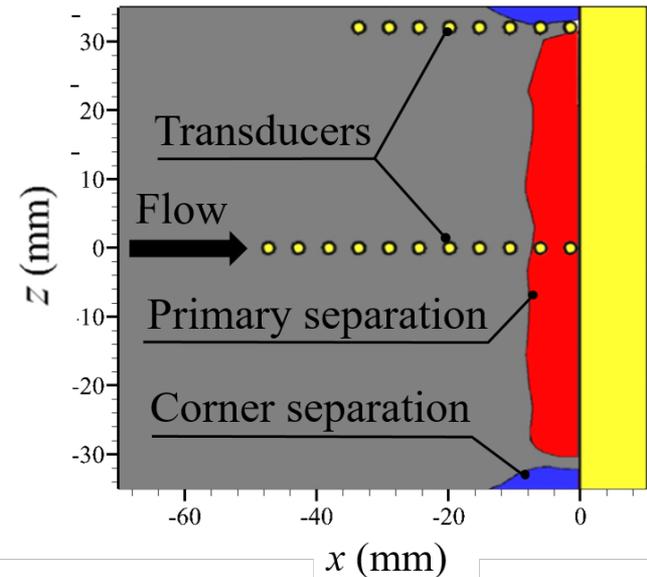
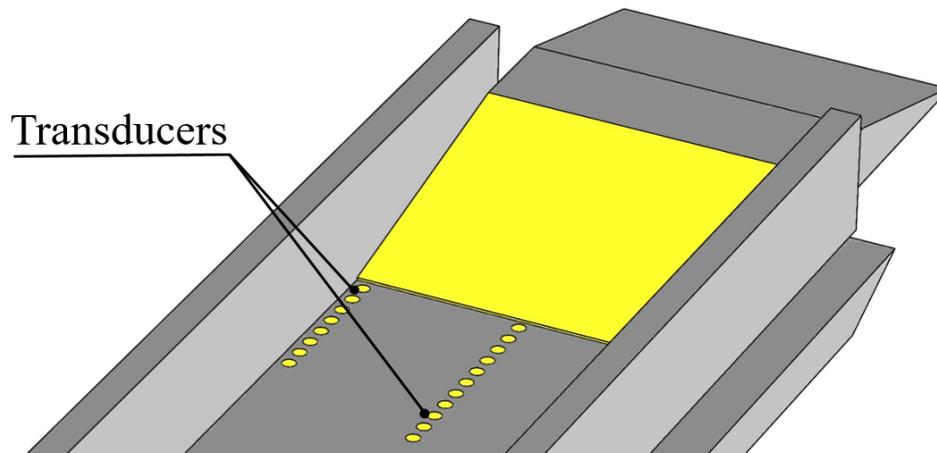
- ▶ Surface streakline visualization
 - ▶ Qualitative identification of flow features
 - ▶ DayGlo Rocket Red/mineral oil
 - ▶ Deduction of SBLI dynamics (highly low-passed)



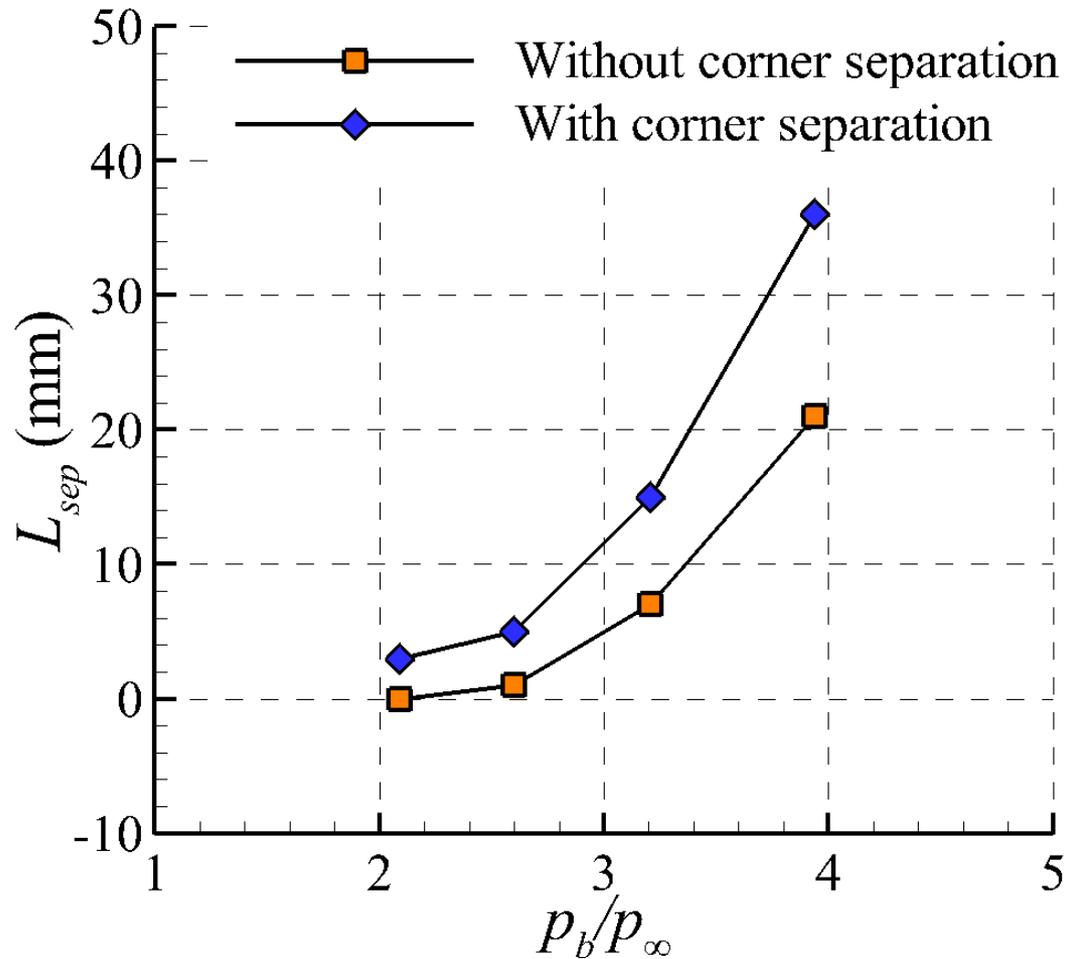
Experimental Methods

- ▶ High-frequency wall static pressure measurements
 - ▶ Kulite XCQ-062-15A (50 kHz frequency response)
 - ▶ Quantitative understanding of characteristic motions
 - ▶ Point measurements spanning incoming boundary layer through ramp leading edge

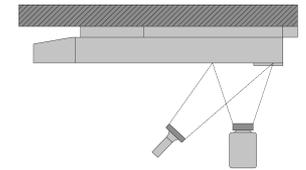
Spatial resolution: $\delta/2$



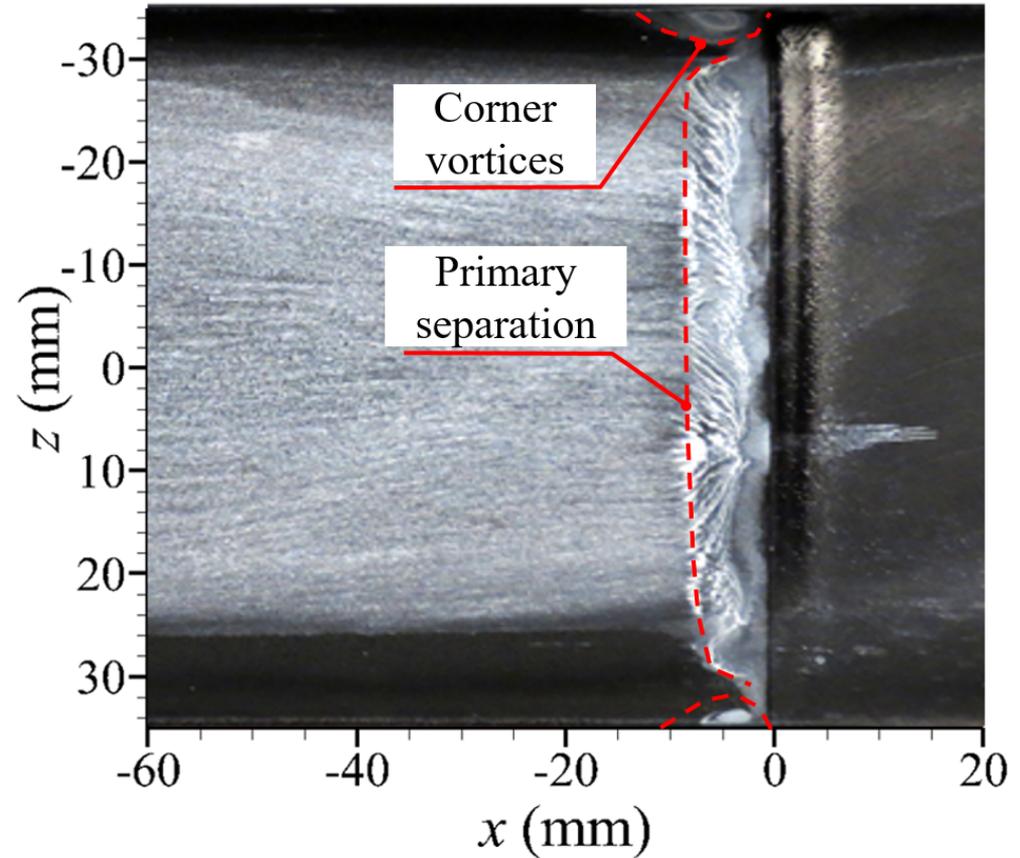
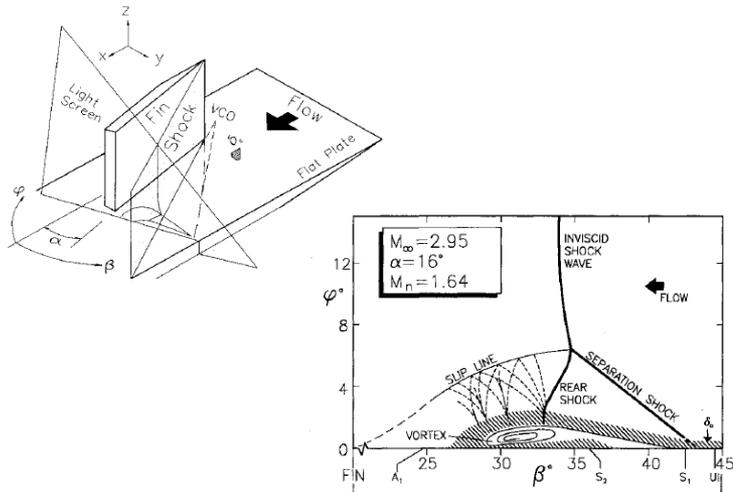
Sidewall effects on Mean Separation Scales



Unsteady Streakline Visualization

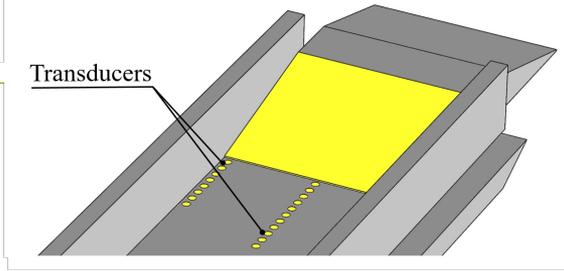


- ▶ Wall-bounded SBLI, $\theta = 12^\circ$
 - ▶ Small-scale primary separation
 - ▶ Interaction relatively straight along bulk of span
 - ▶ Corner vortices, direction rotation agrees with skewed fin SBLI

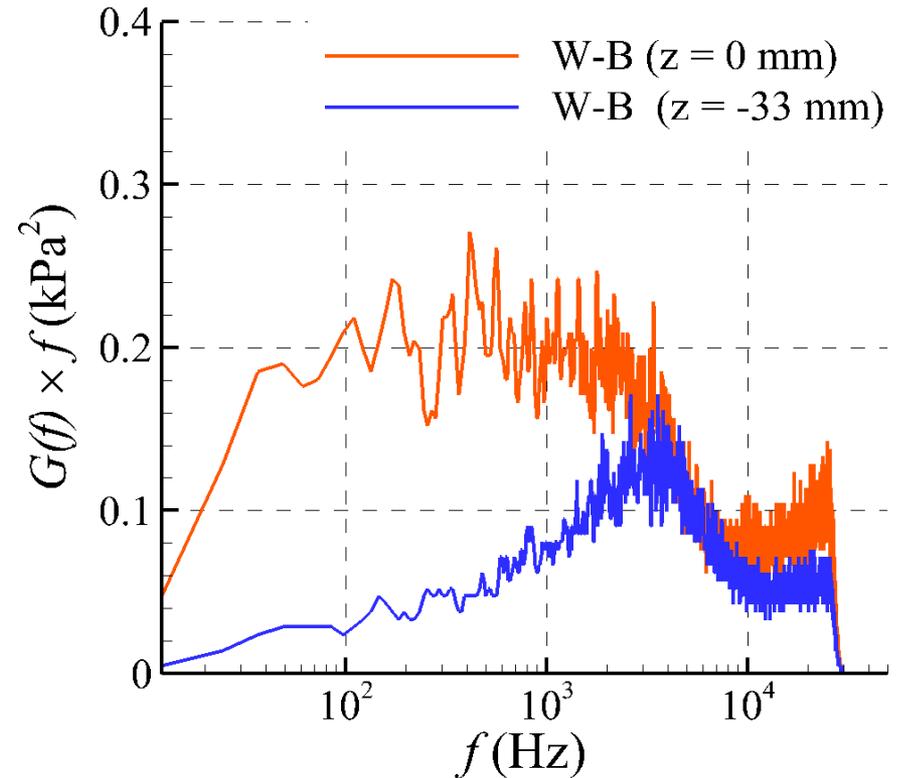
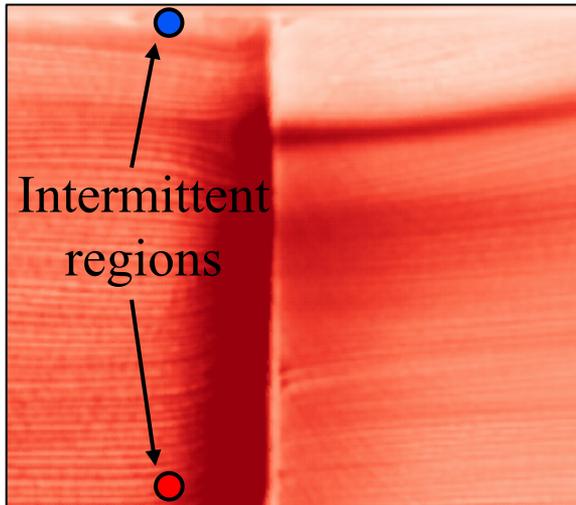


Alvi & Settles (1992) [37]

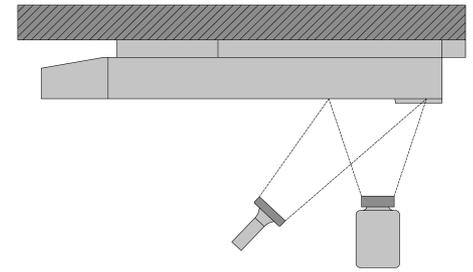
Unsteady Power Spectra



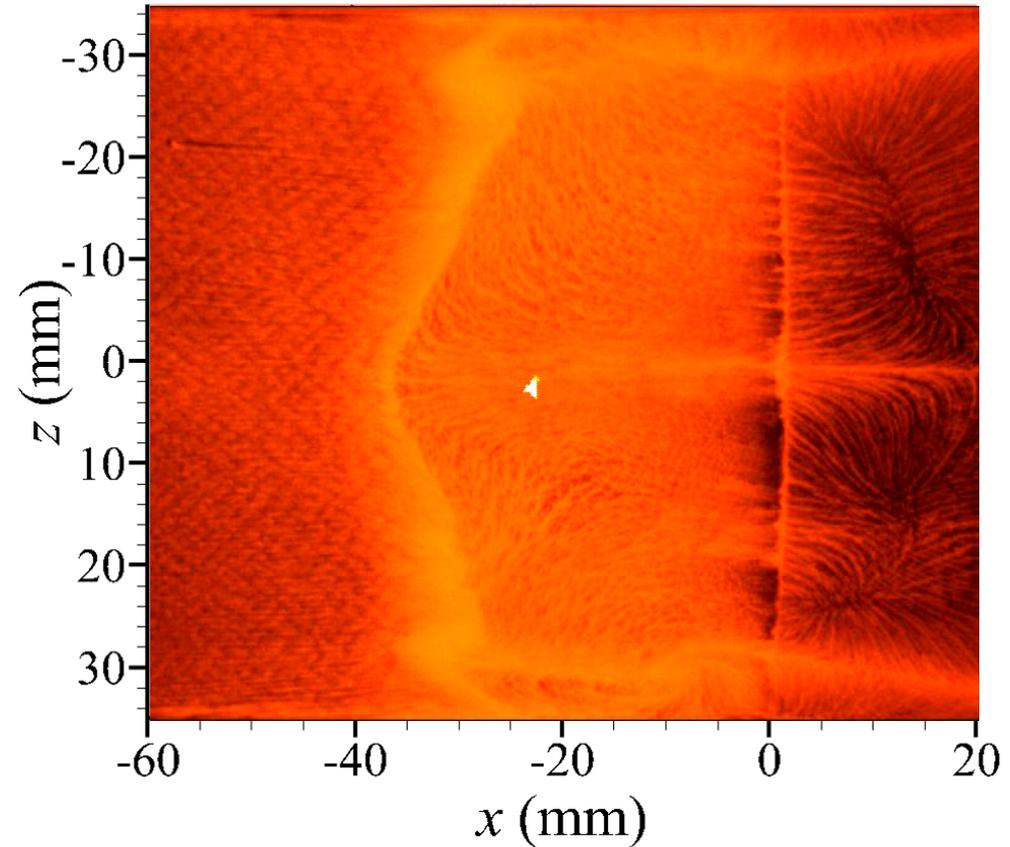
- ▶ Wall-bounded SBLI, $\theta = 12^\circ$
 - ▶ Intermittent region power spectra
 - ▶ Primary fluctuations are broadband
 - ▶ Corner spectrum is more focused



Unsteady Streakline Visualization

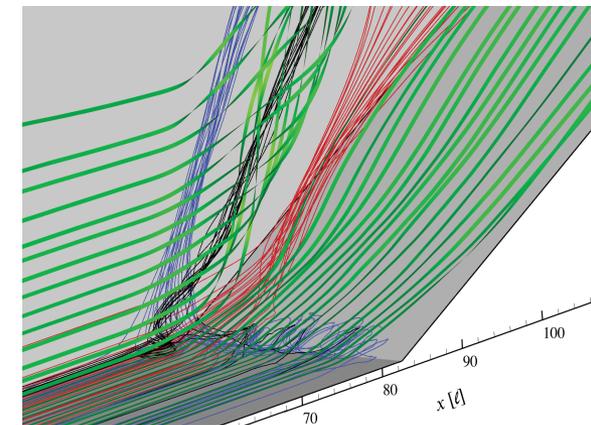
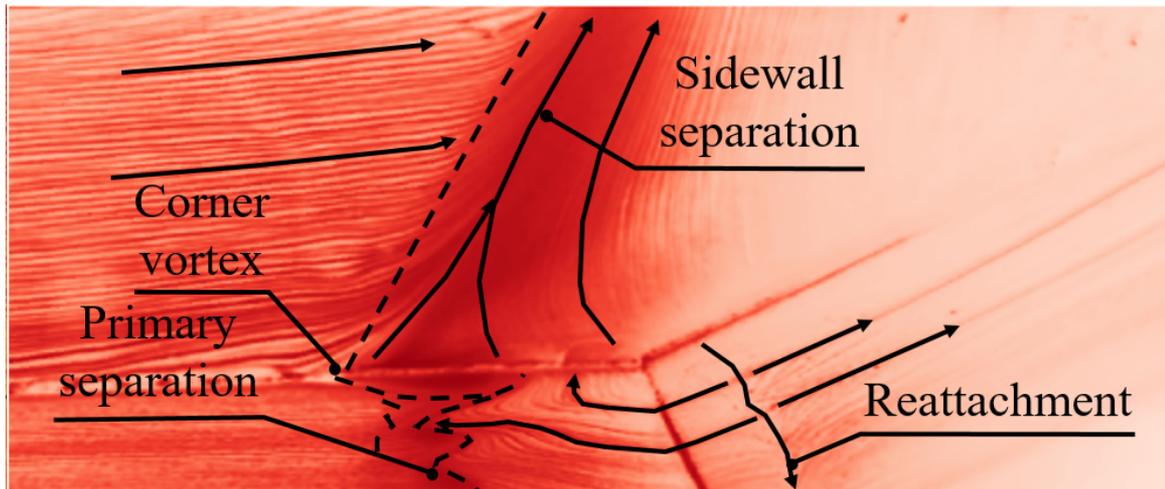


- ▶ Wall-bounded SBLI, $\theta = 24^\circ$
 - ▶ Large primary separation
 - ▶ Spanwise flow toward corner junctions
 - ▶ Corner SBLI and primary SBLI integrated



Unsteady Streakline Visualization

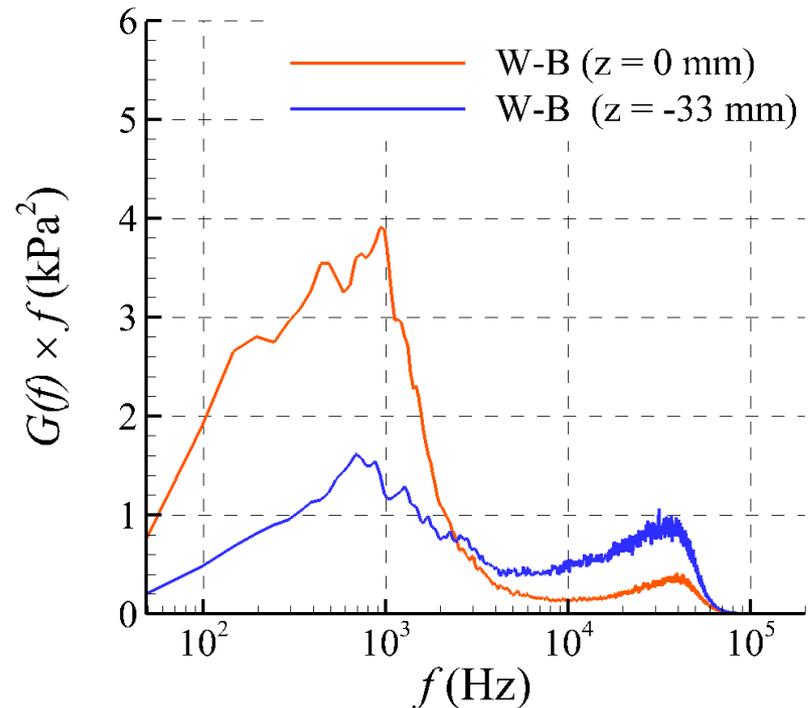
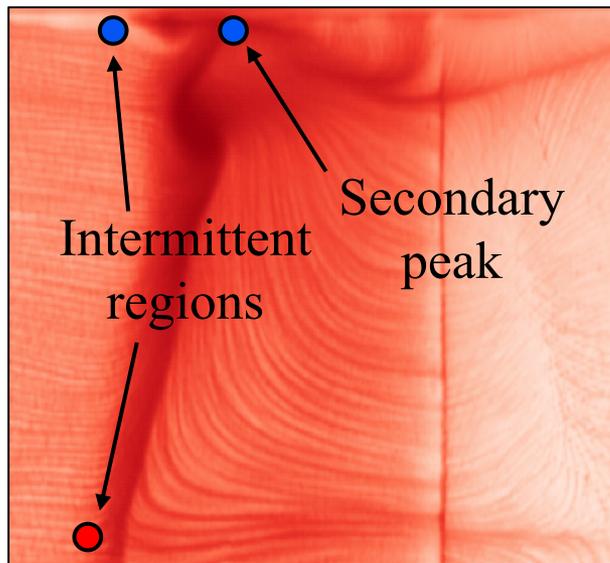
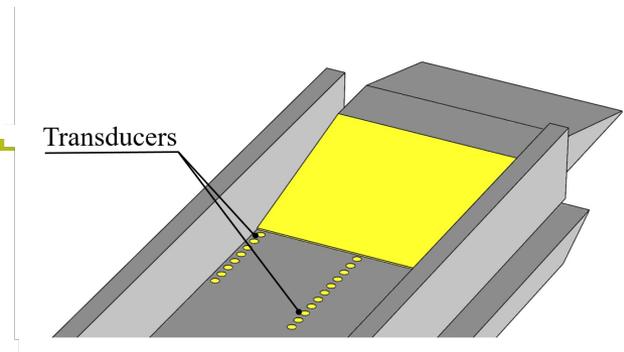
- ▶ Wall-bounded SBLI, $\theta = 24^\circ$
- ▶ Sidewall interaction visualization
 - ▶ Corner vortex is footprint of sidewall “fin” SBLI vortex, mass removal from primary separation



Bisek (2015)

Unsteady Spectral Analysis

- ▶ Wall-bounded SBLI, $\theta = 24^\circ$
 - ▶ Shift toward lower frequencies, higher amplitudes
 - ▶ Primary and corner SBLI have similar dominant frequencies

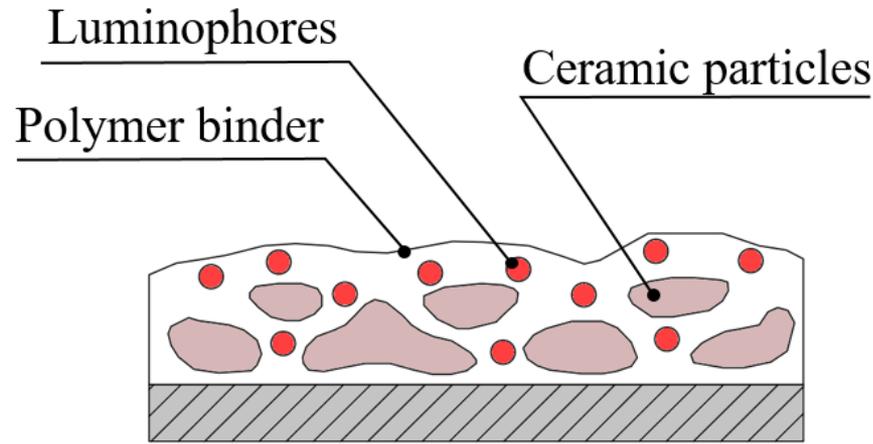


Quick summary

- ▶ Presence of sidewall hastens the separation onset and inflates the separation size
- ▶ The corner and sidewall separation appear to function like a spillage mechanism to the primary separation
- ▶ The corner separation and primary separation pulsation spectra look a lot similar to one another at elevated shock strengths
- ▶ *Does the corner separation dynamics actually couple with the primary separation?*
- ▶ *Need a holistic imaging of the separated flow at a very high bandwidth*
- ▶ *Start with high frequency surface pressure imaging*



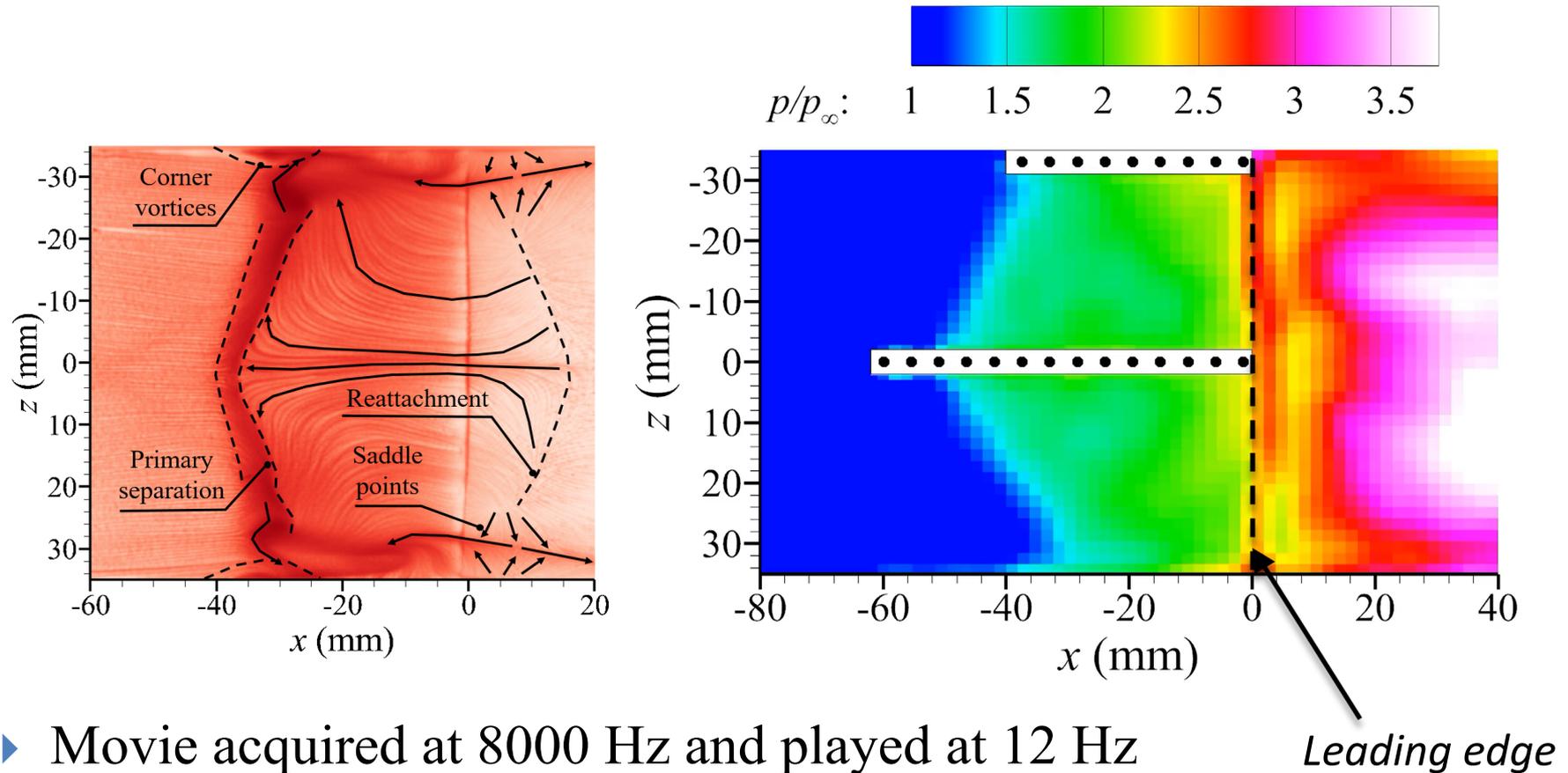
Fast pressure sensitive paint



- ▶ Polymer ceramic pressure sensitive paints sensitive to local oxygen conc., hence pressure dependence
- ▶ We adapted a low cost version of pc-PSP that has response time better than $50\mu\text{s}$

High frequency pressure imaging

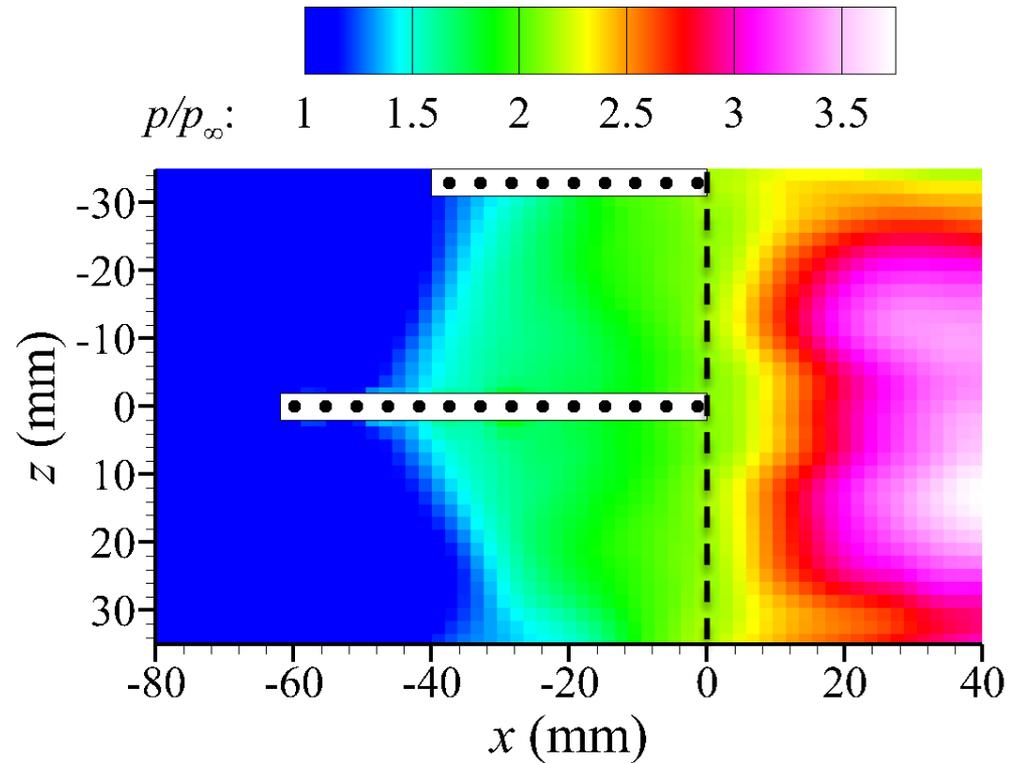
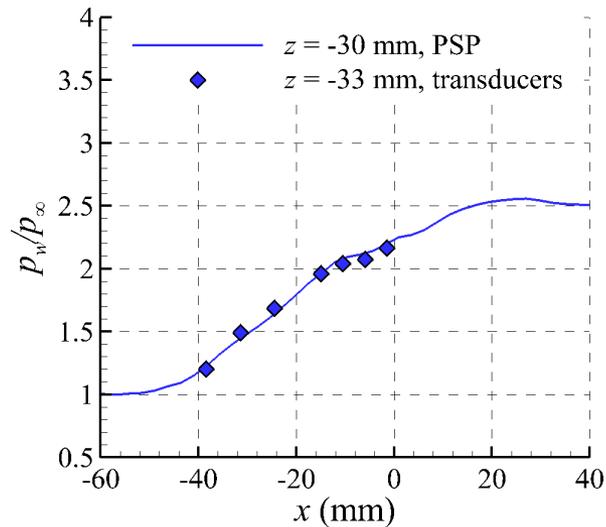
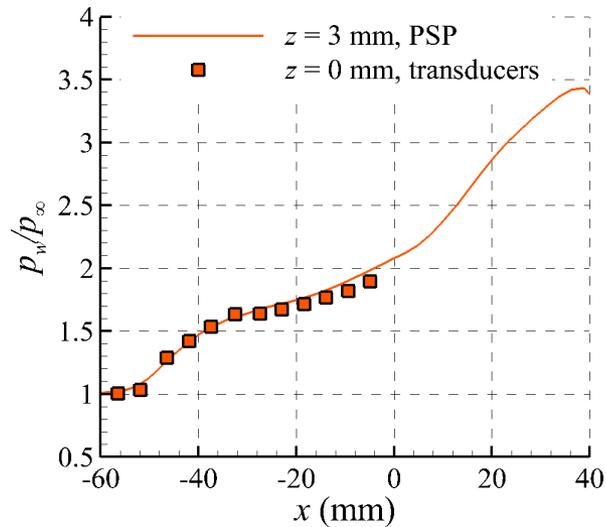
24° compression ramp



- ▶ Movie acquired at 8000 Hz and played at 12 Hz

Leading edge

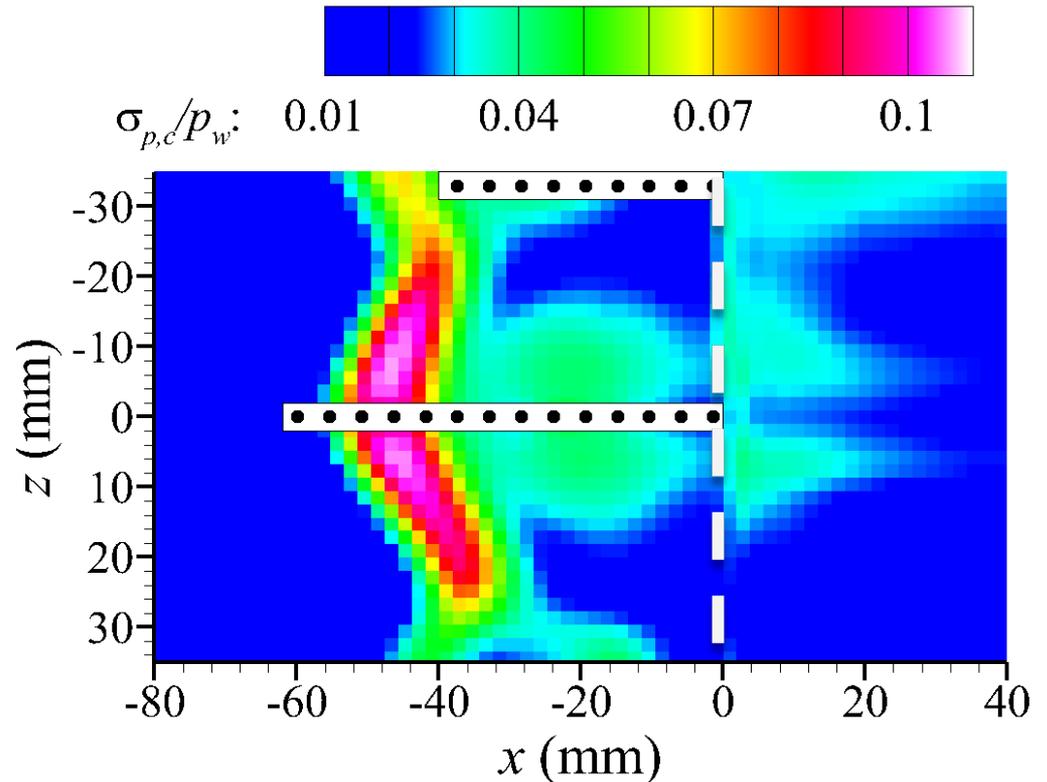
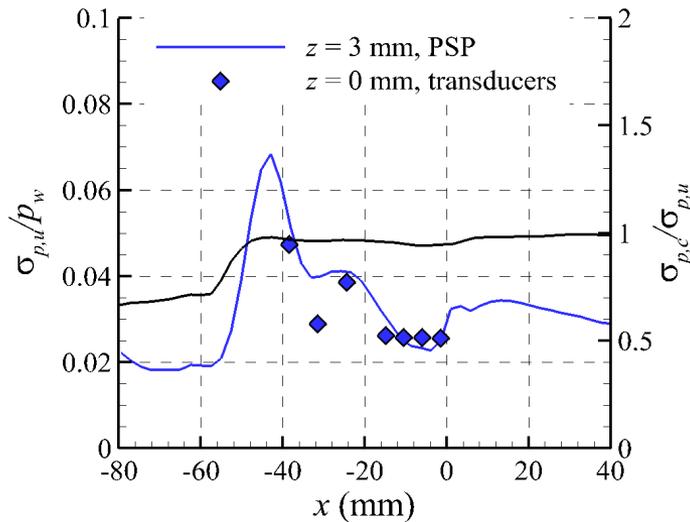
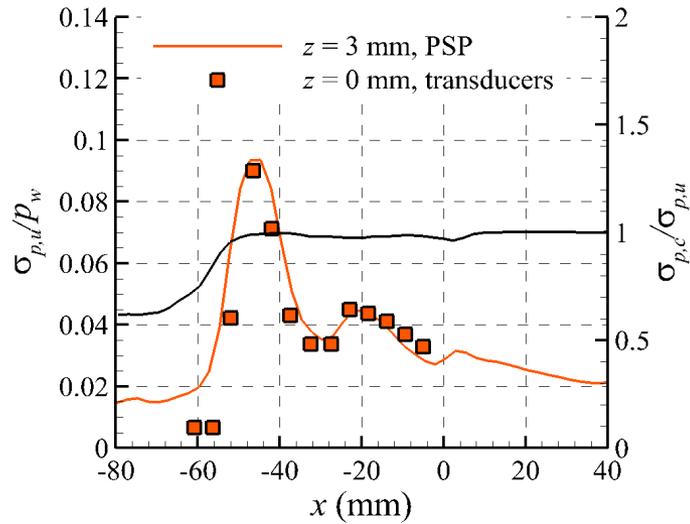
High frequency pressure imaging – validation



Ensemble averaged pressure field



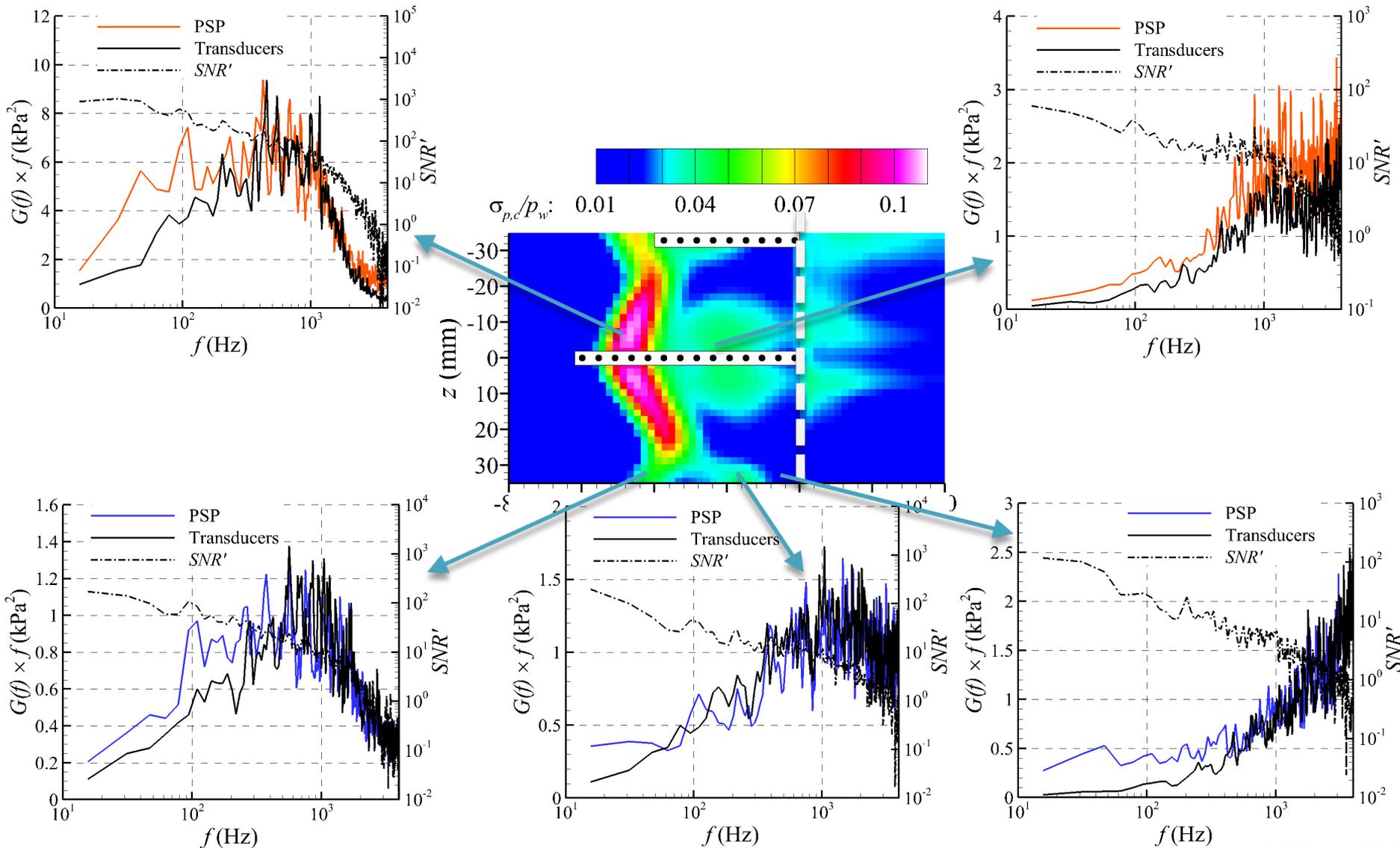
High frequency pressure imaging – validation



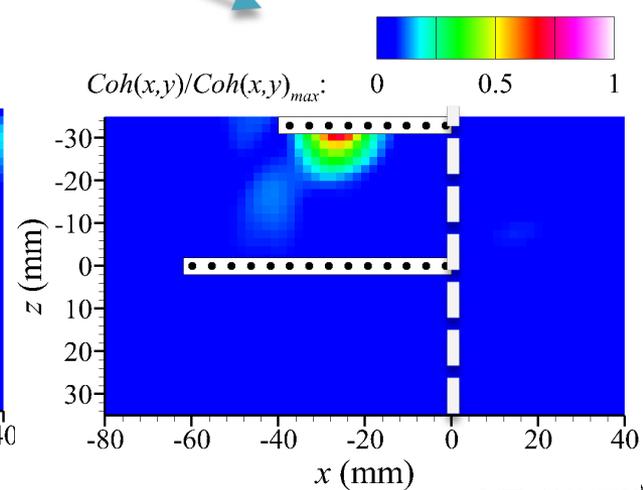
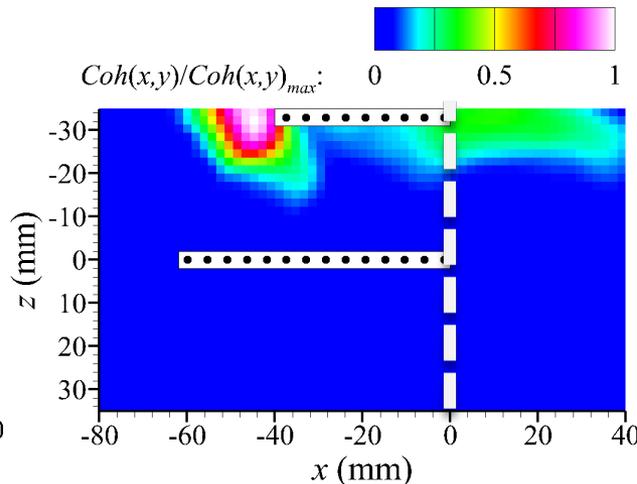
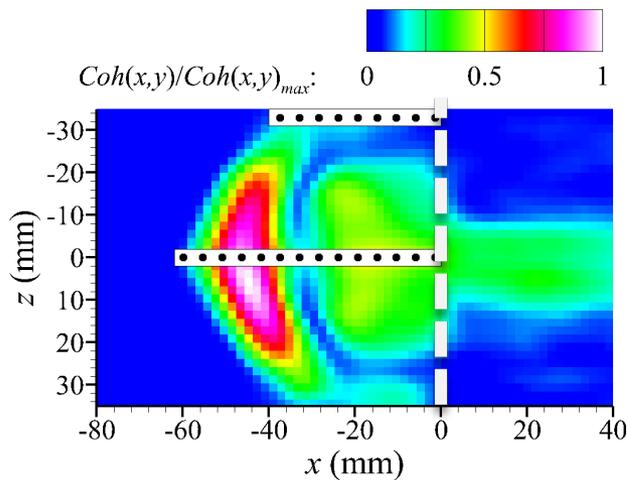
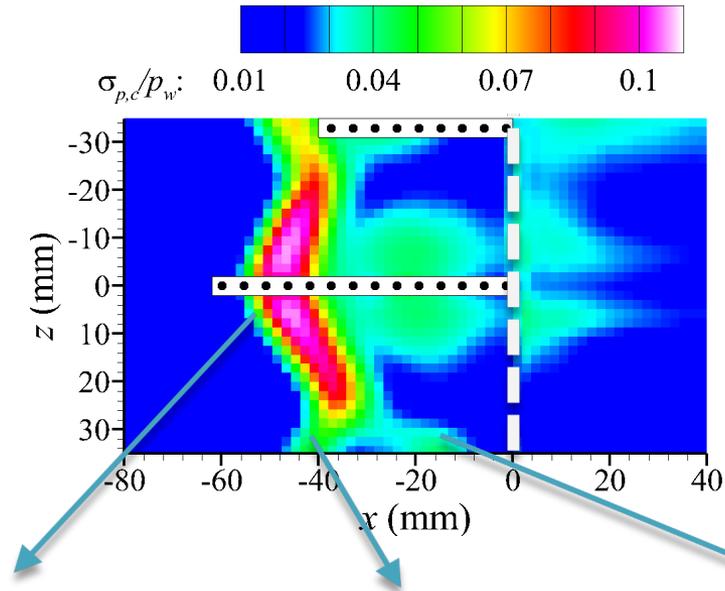
r.m.s. pressure field



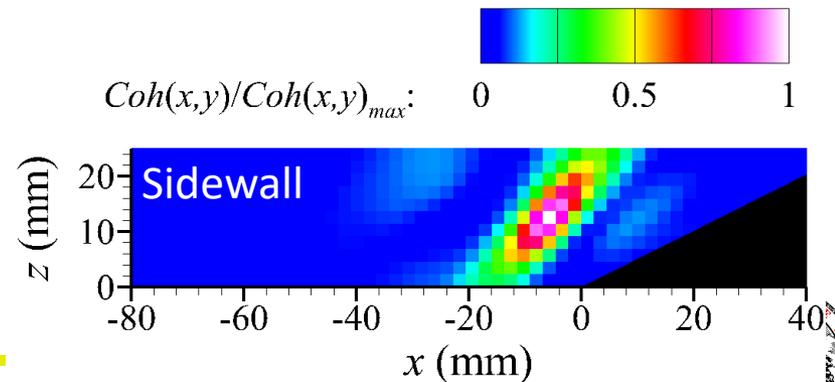
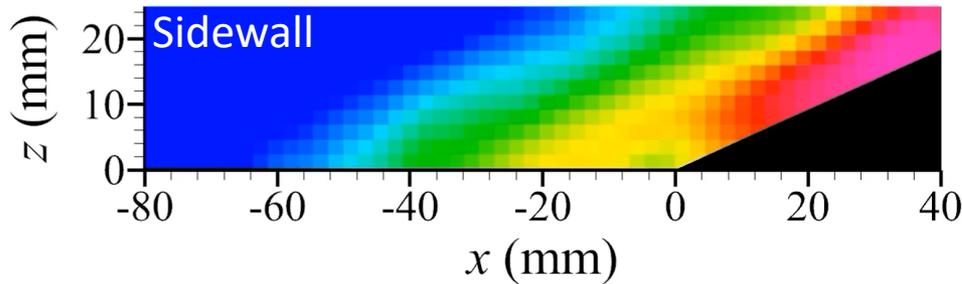
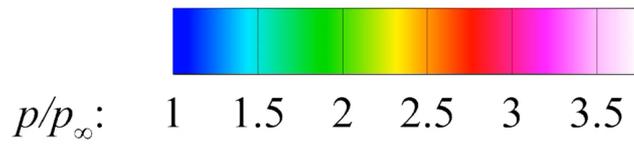
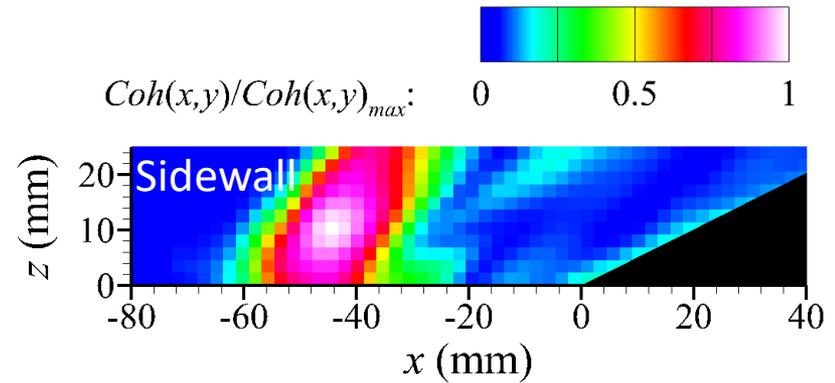
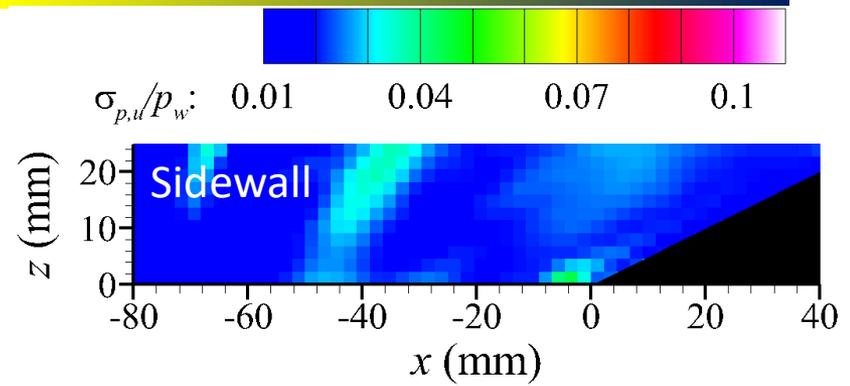
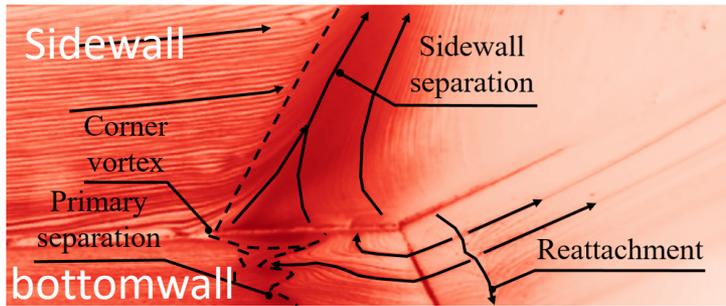
Power spectra validation and analysis



Cross-coherence maps

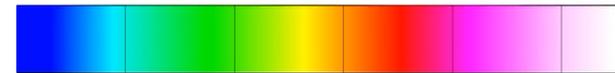


Sidewall pressure maps

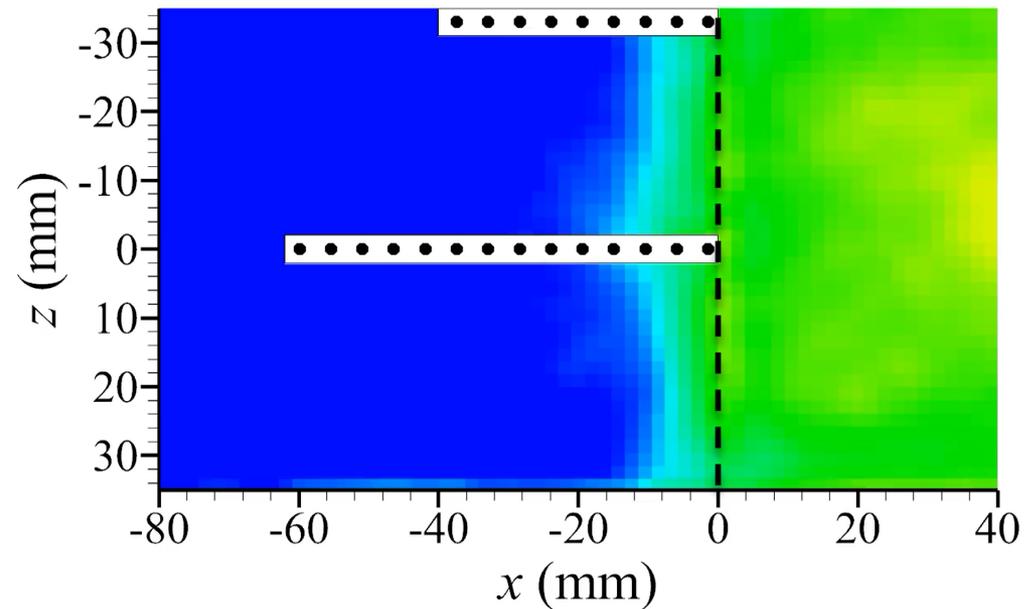
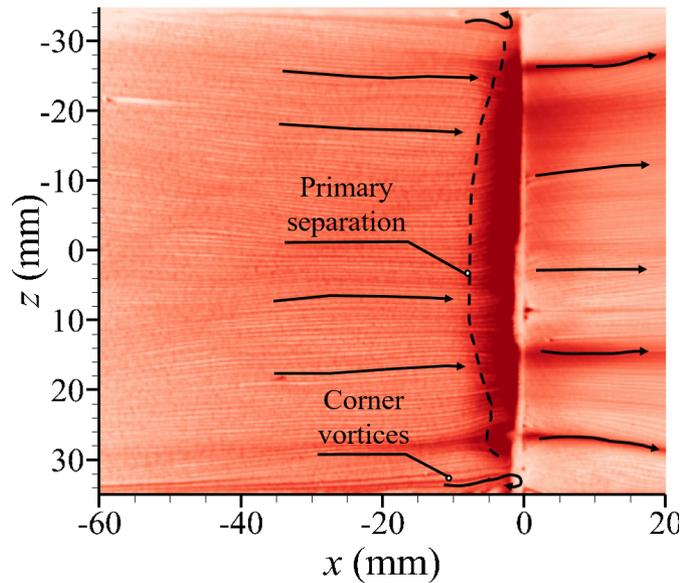


High Frequency Pressure Imaging

12° compression ramp

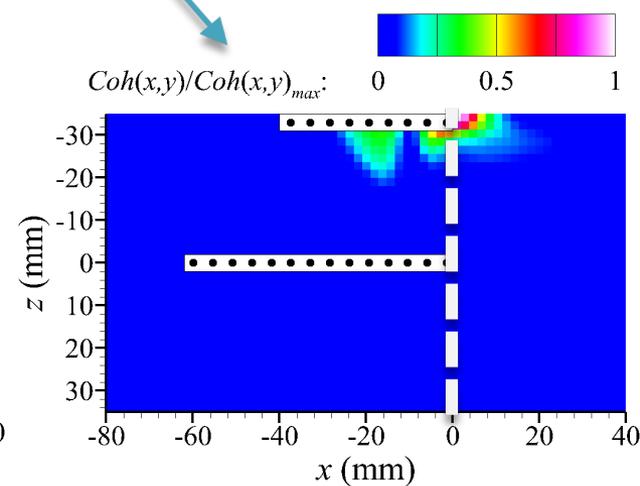
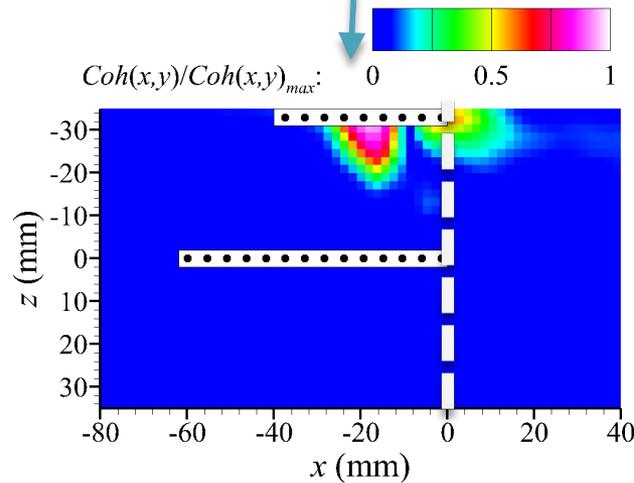
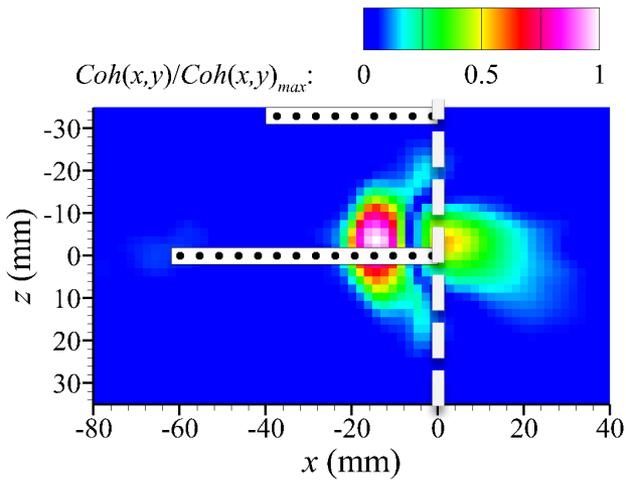
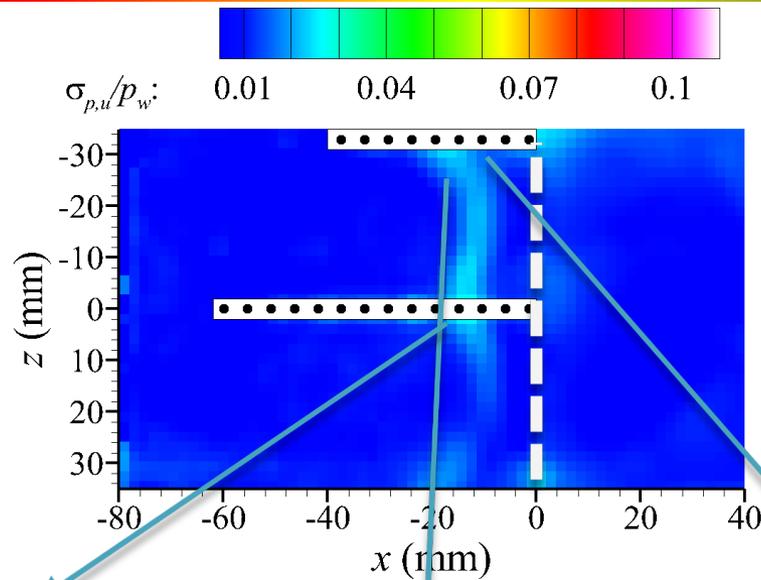


p/p_∞ : 1 1.5 2 2.5 3 3.5

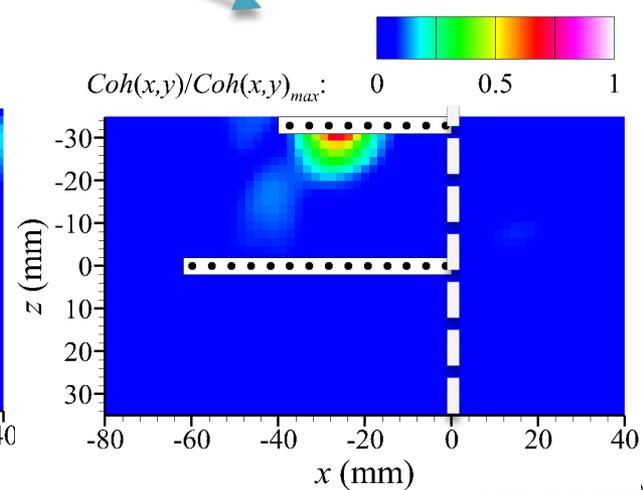
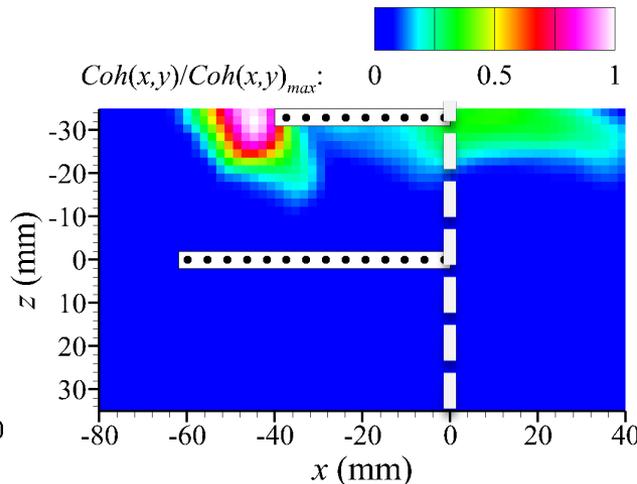
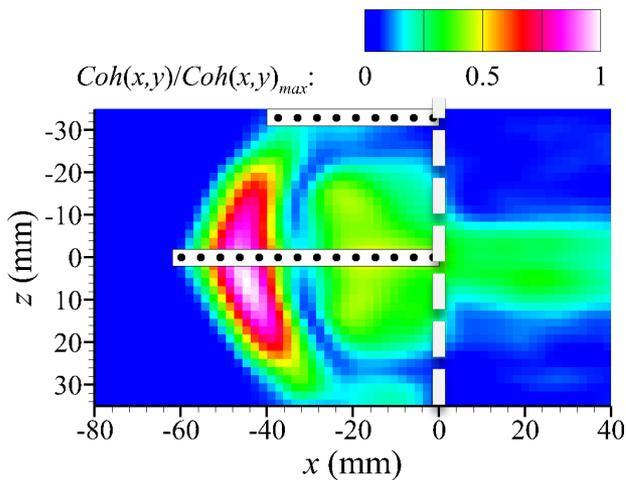
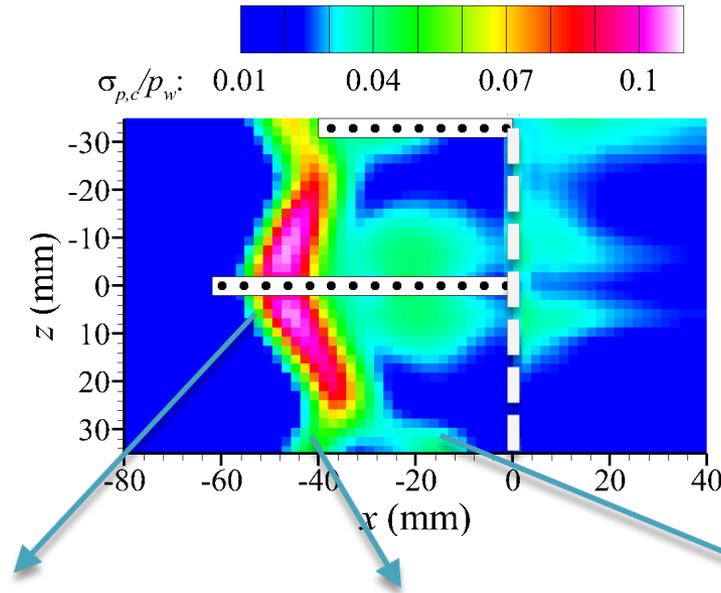


- ▶ Movie acquired at 8000 Hz and played at 12 Hz

Cross-coherence maps - 12° ramp



Cross-coherence maps - 24° ramp SBLI



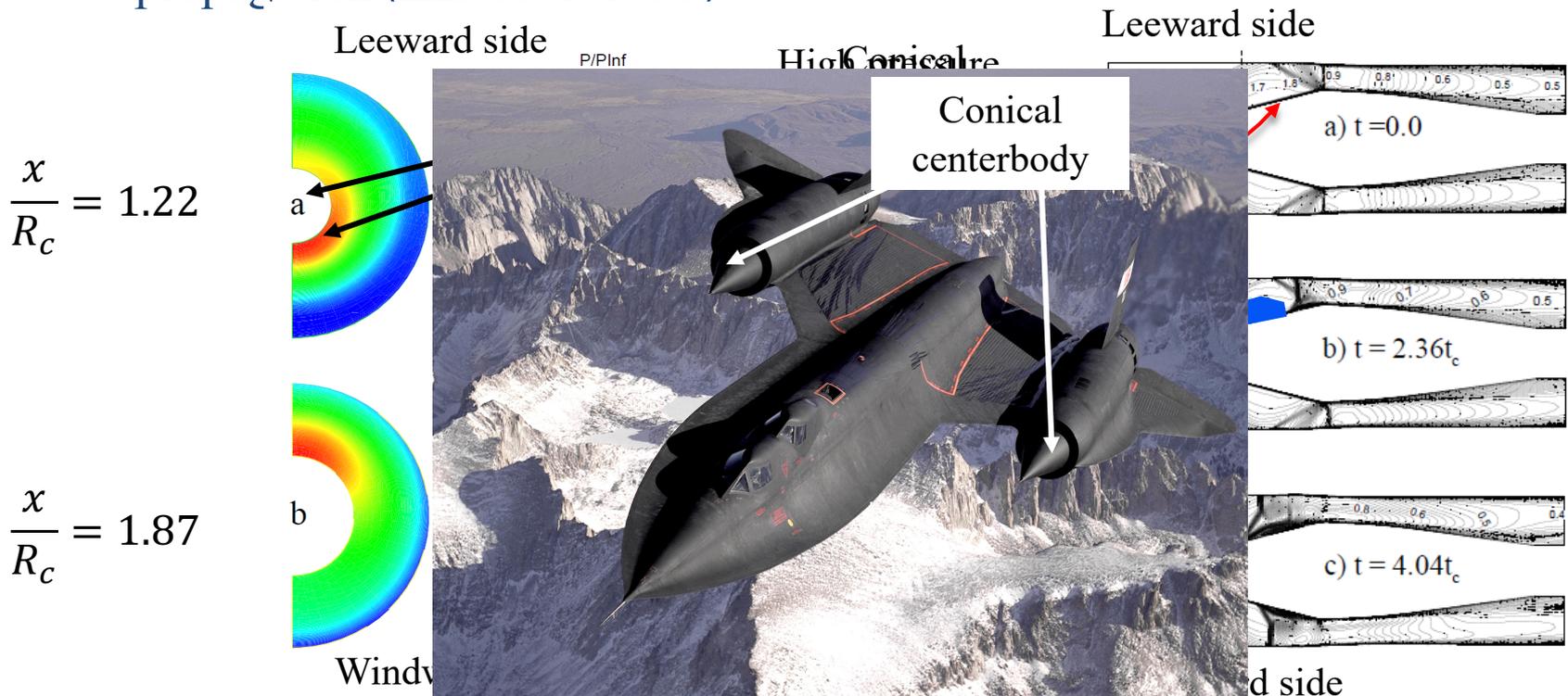
Conclusions

- ▶ Sidewall interference results in several interesting and non-intuitive outcomes on the primary separation
- ▶ Our new pressure imaging tool provide unprecedented information about how the corner and sidewall separation couples with primary separation
- ▶ We also developed new approaches to obtain velocity information very close to the wall
- ▶ Together these diagnostics open new windows to probe more challenging flowfields and generate data that could be used by the modeling community



UNSTART & SBLI IN AXISYMMETRIC CONFIGS

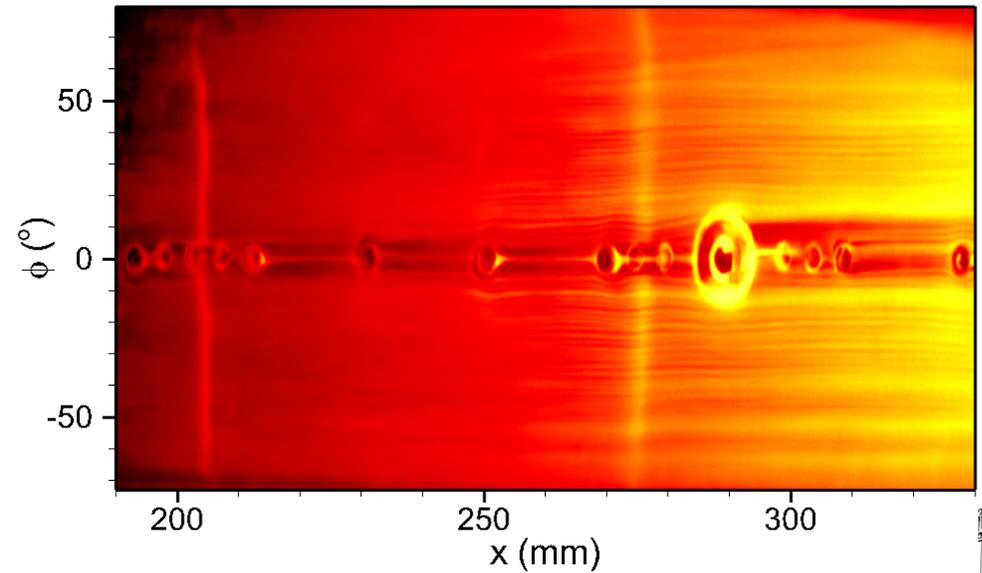
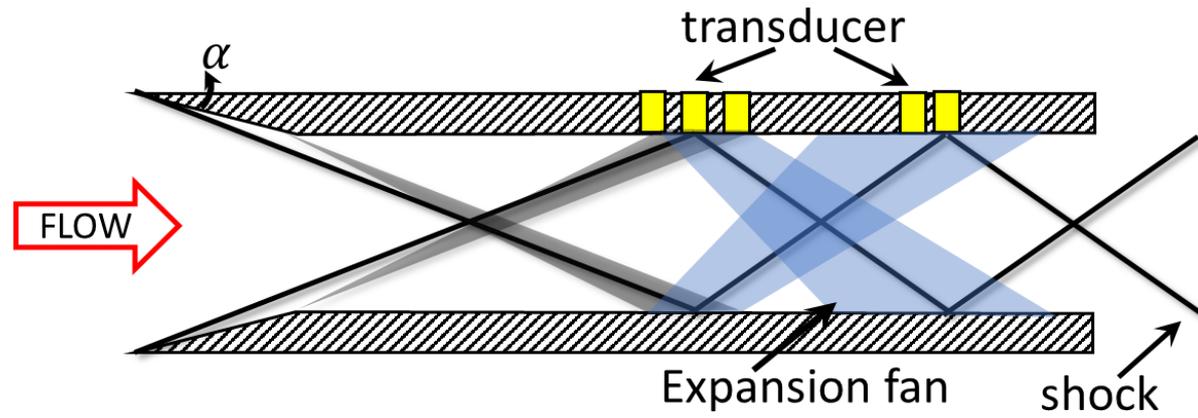
- ▶ Axisymmetric isolators are extremely sensitive to inflow distortion
 - ▶ Unstart at less than 3° angle of attack (Choby, 1972)
 - ▶ Boundary layer thickening on leeward side causes terminal shock propagation (Zha et al. 1998)



Zha et al. (1998)



Set



Mach number effects on SBLI two dimensionality

