Application of Time-Resolved PIV to Supersonic Hot Jets

This presentation lays out the groundbreaking work at bringing high-speed (25kHz) particle image velocimetry (PIV) to bear on measurements of noise-producing turbulence in hot jets. The work is still in progress in that the tremendous amount of data obtained are still be analyzed, but the method has been validated and initial results of interest to jet noise modeling have been obtained. After a brief demonstration of the validation process used on the data, results are shown for hot jets at different temperatures and Mach numbers. Comparisons of first order statistics show the relative indifference of the turbulence to the presence of shocks and independence to jet temperature. What does come out is that when the shock-containing jets are in a screech mode the turbulence is highly elevated, showing the importance of removing screech phenomena from model-scale jets before applying findings to full-scale aircraft which typically do not contain shocks.

Application of Time-Resolved PIV to Supersonic Hot Jets

Mark Wernet and James Bridges

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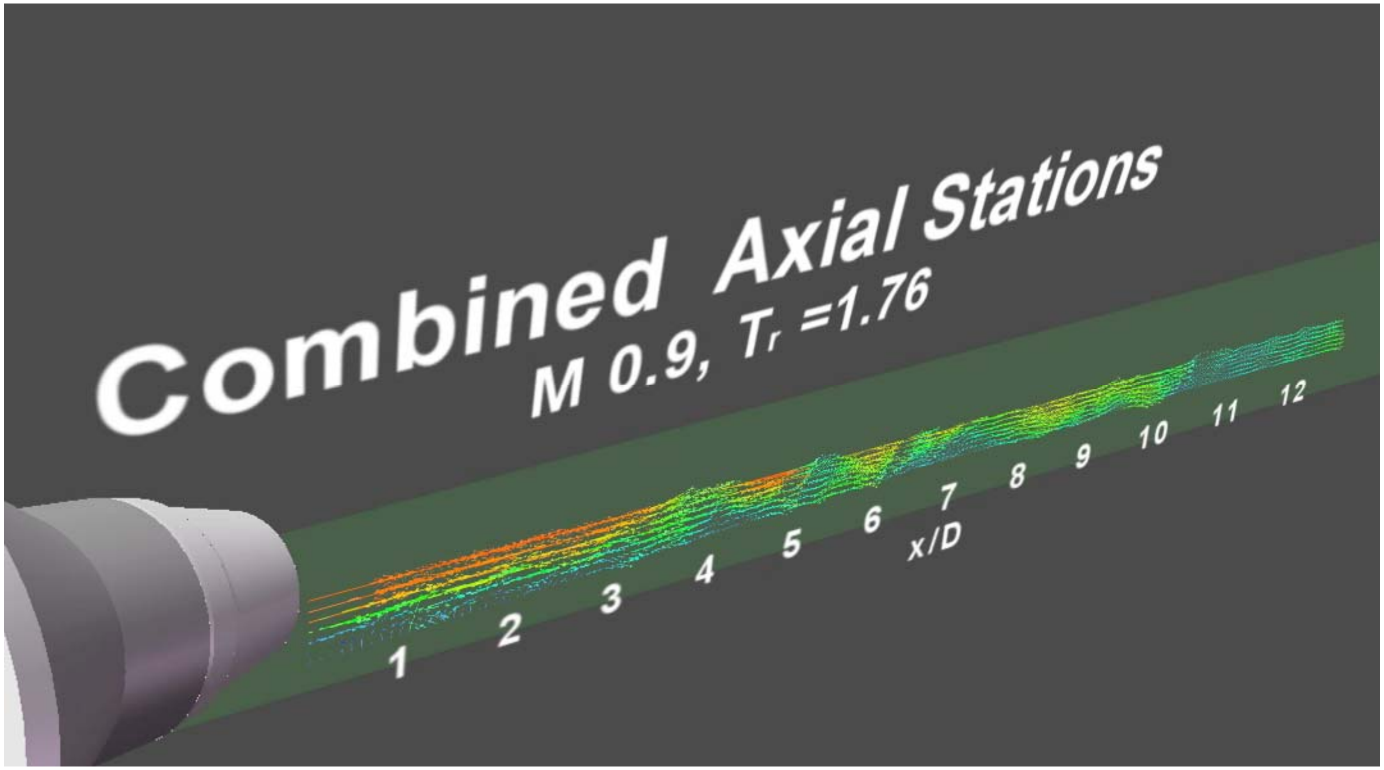
Oct 31, 2007



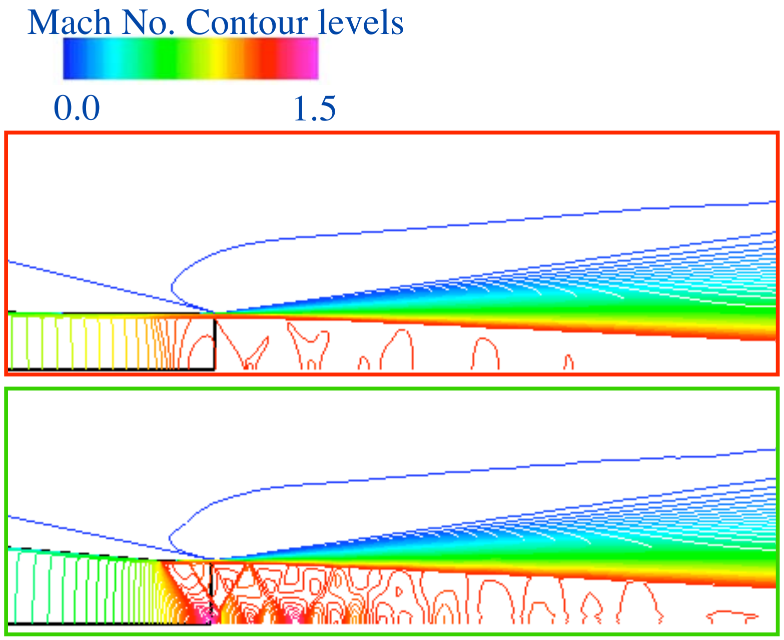
Outline

- Motivation
- Time-Resolved PIV
- Validation
- Test Plan
- Effect of Mach, Velocity, Expansion Ratio on
  - mean and mean-square turbulent velocity
- Summary of findings

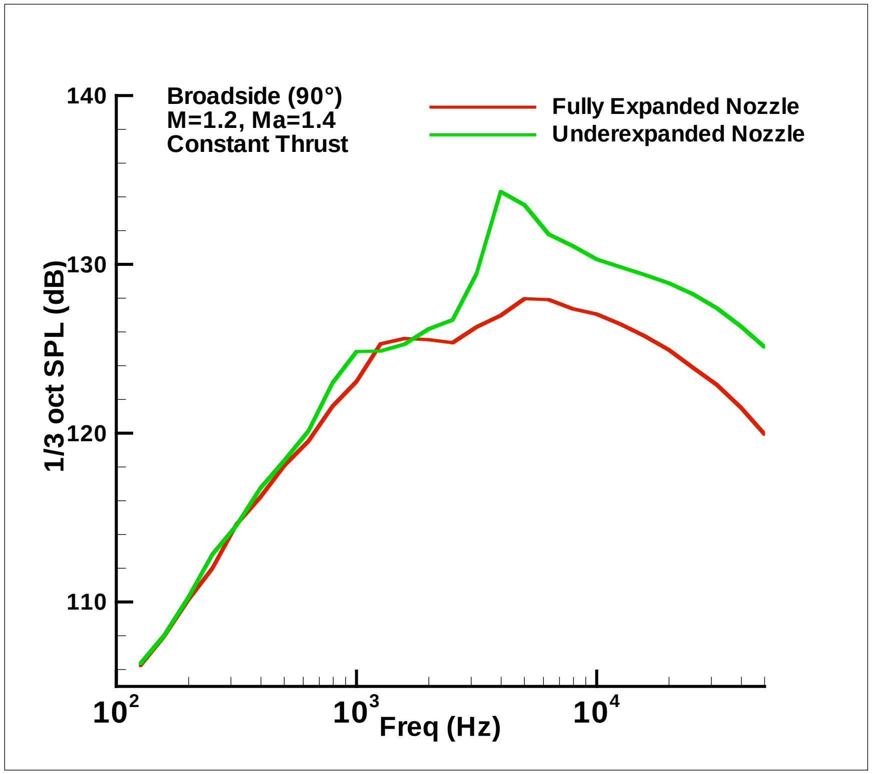
Motivation

Shock Noise in Jets

- Presence of shocks in jets produces efficient sound source
- Comparison of noise from convergent and properly expanded nozzles shows magnitude of problem



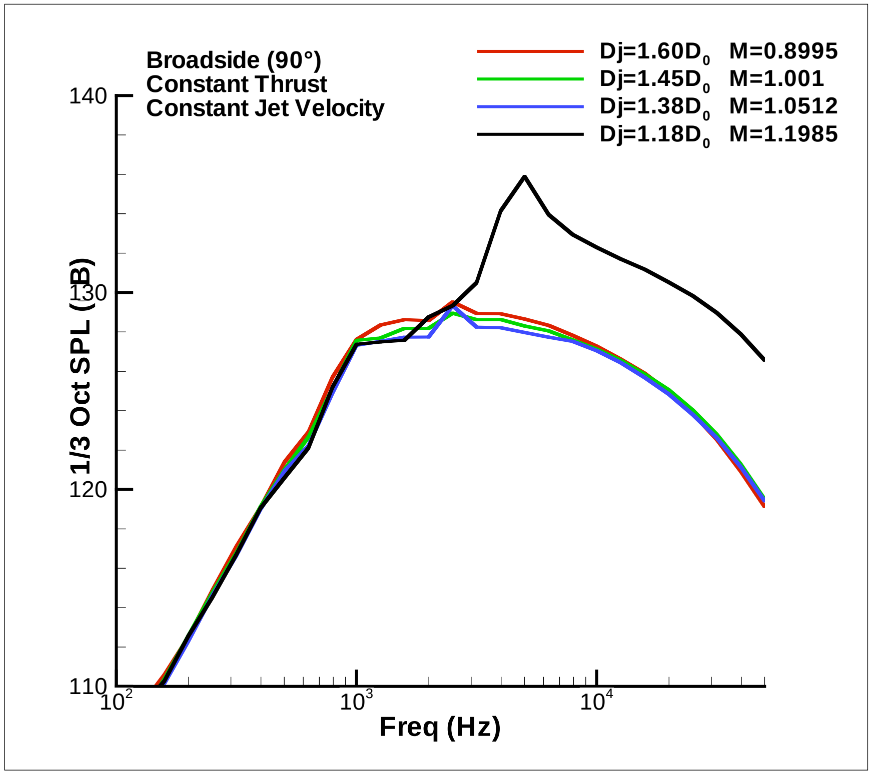
Mach 1.2 jets, equal thrust



Efficiency of Shock Noise in Jets

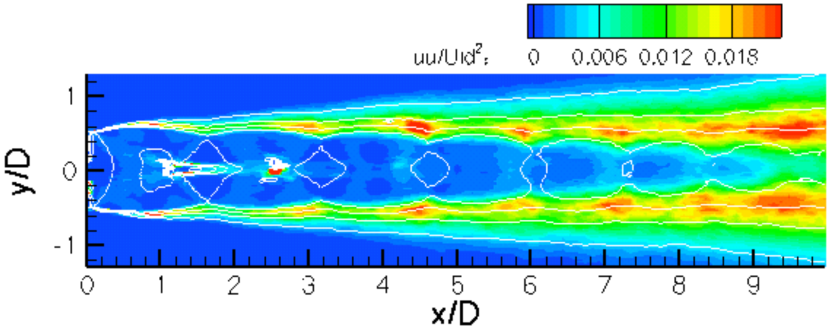
- In trading Engine Diameter for plume Mach number, jet mixing noise smoothly varies, easily traded.
- Shock noise has abrupt onset with improperly expanded flow.
- Broadband shock noise not easily eliminated.

Important to predict shock noise accurately since optimum designs may push into shocked exhaust plumes.



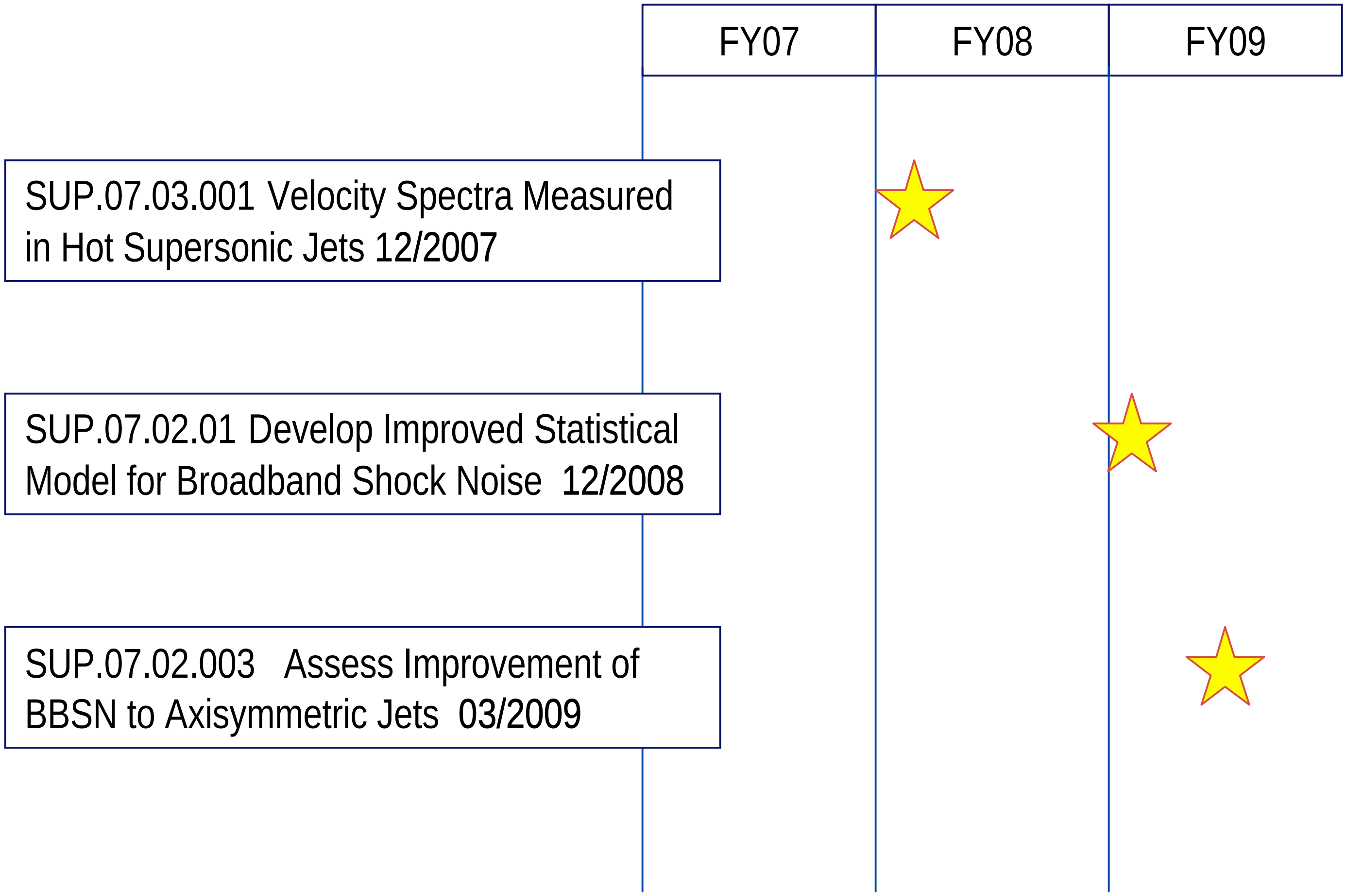
Modeling of Broadband Shock Noise

- See Previous Speaker!
- Requires validation of assumptions used in model development
- Requires validation of RANS CFD used for input
- Requires modeling spectra and lengthscales of turbulence near shocks



- Obtaining spectral information in hot supersonic jets requires Time-Resolved Particle Image Velocimetry

Applicable Supersonics Airport Noise Milestones

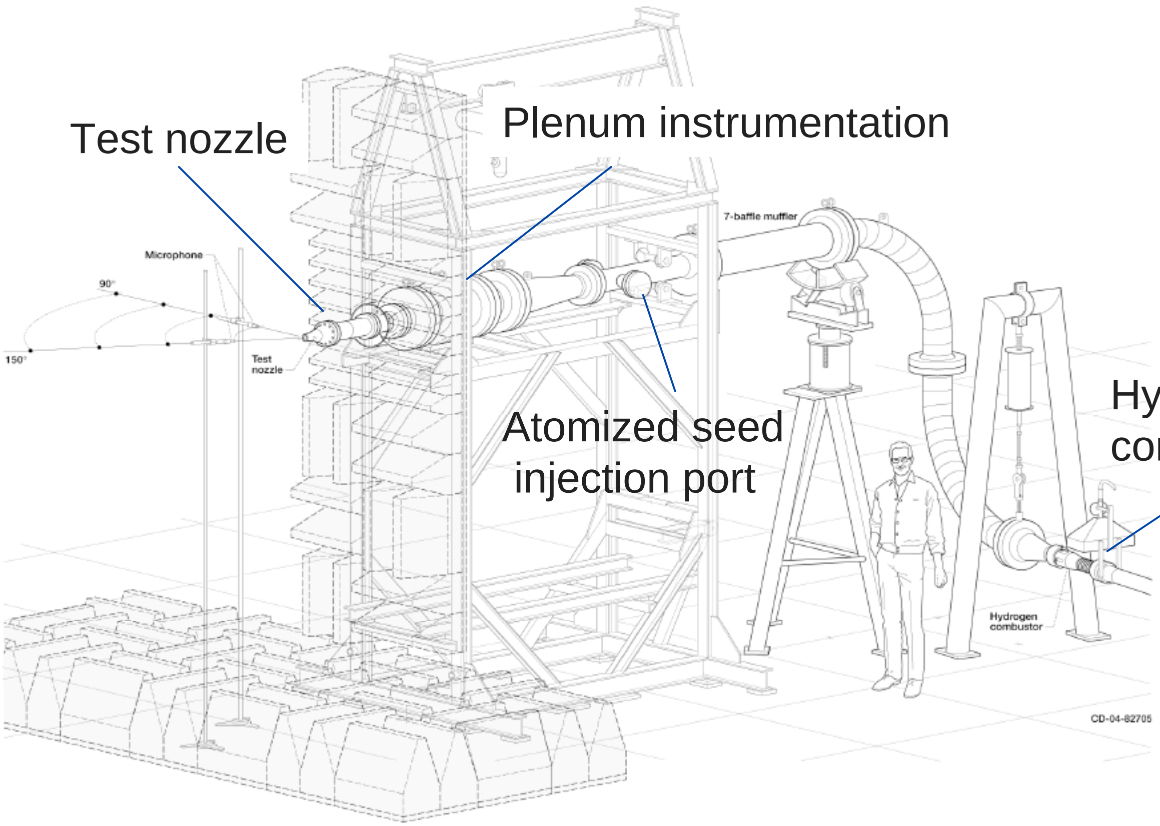


SUP.07.03.001 Velocity Spectra Measured in Hot Supersonic Jets 12/2007

SUP.07.02.01 Develop Improved Statistical Model for Broadband Shock Noise 12/2008

SUP.07.02.003 Assess Improvement of BBSN to Axisymmetric Jets 03/2009

Small Hot Jet Acoustic Rig (SHJAR)
NASA Glenn AeroAcoustic Propulsion Lab



Test nozzle

Plenum instrumentation

Atomized seed injection port

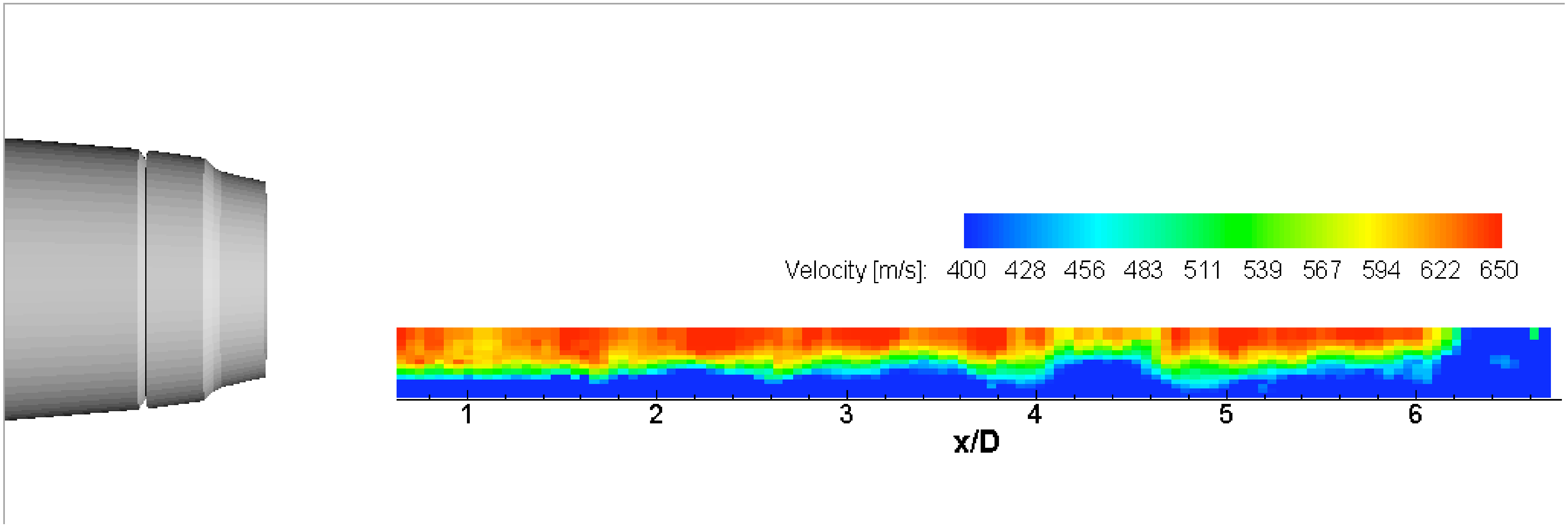
Hydrogen combustor

Time-Resolved Particle Image Velocimetry

- Applied to Jet Flows in NASA Glenn AeroAcoustic Propulsion Lab

Time-Resolved Particle Image Velocimetry

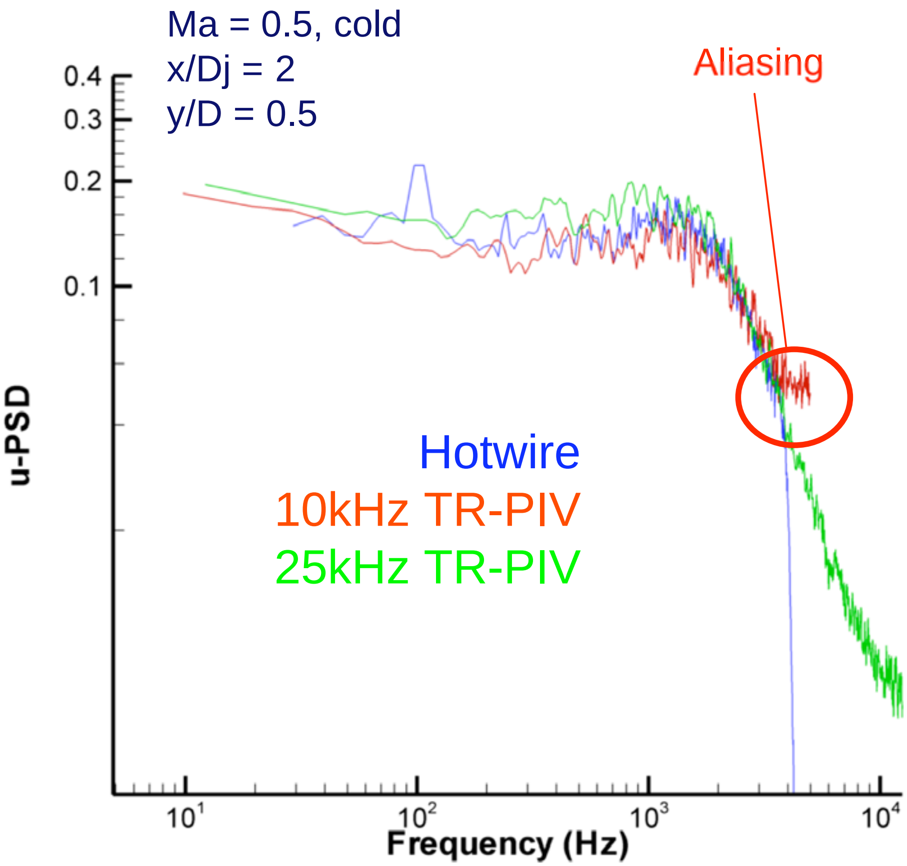
- Applied to shear layer of supersonic jet
- Raw data, u(x,y,t) at 10kHz
- M=1.4, $T_t/T_{amb} = 3$

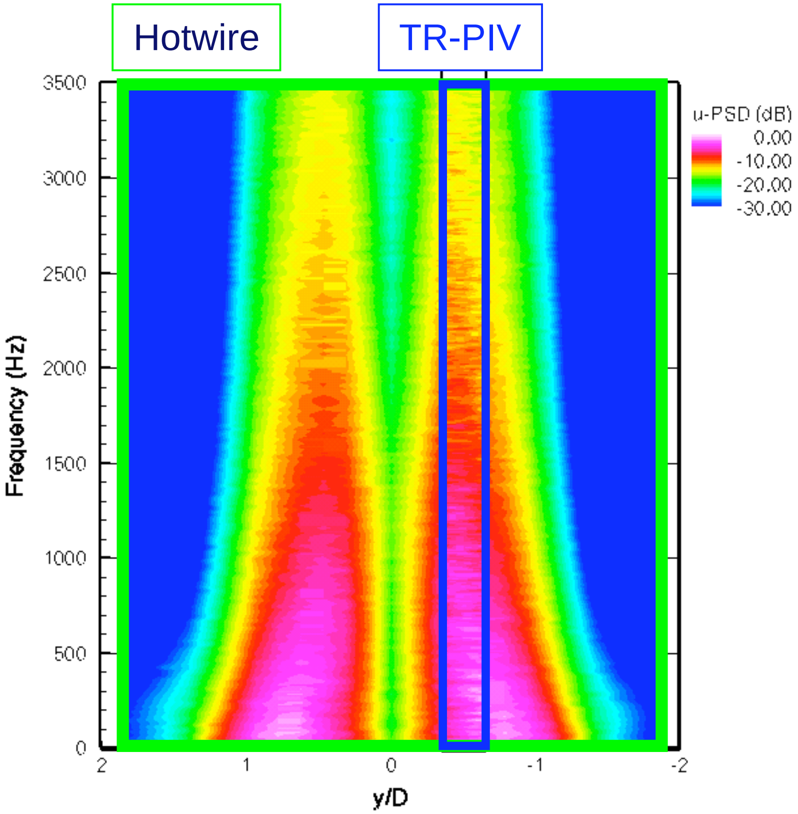


Validation of TR-PIV

Power Spectral Density w/Subregion Distortion

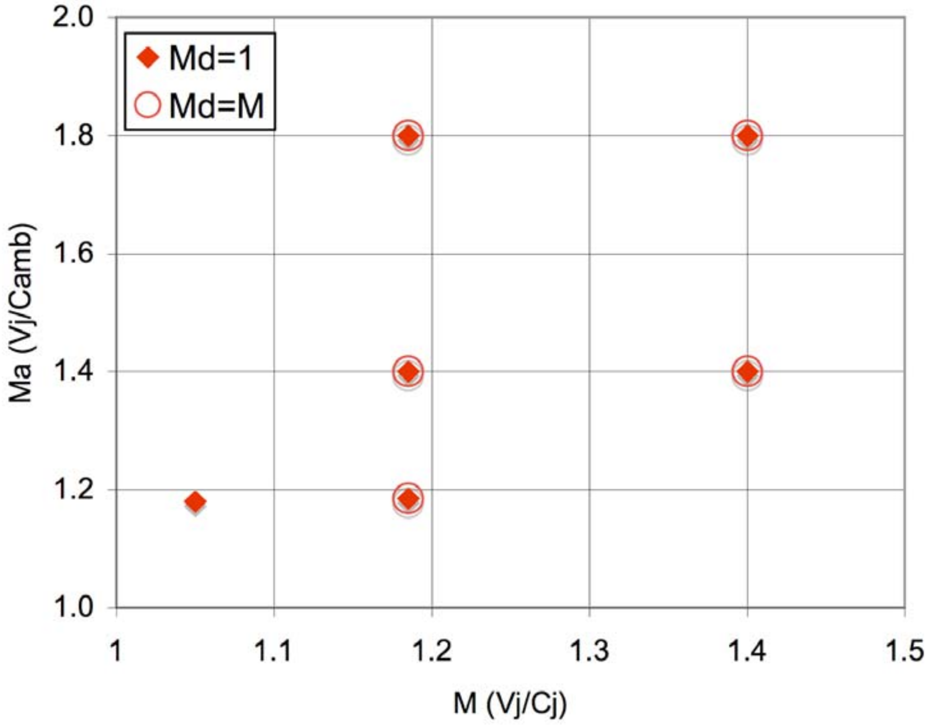
- 10 kHz & 25 kHz TR-PIV closely agree with hotwire results
- High frequency lift in 10kHz data shown to be due to aliasing





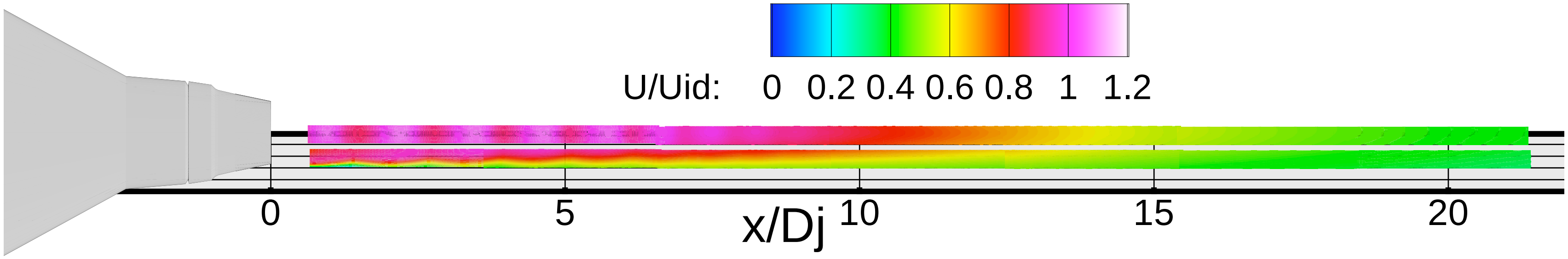
Test Plan

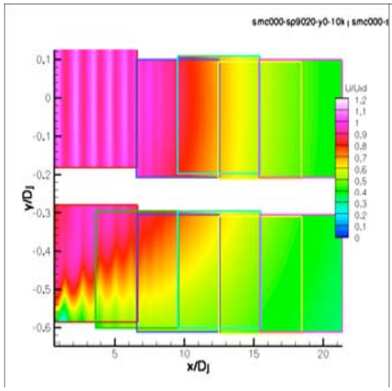
- Nozzles (51mm Dj exit)
  - Conic (Md = 1)
  - Convergent-Divergent, Md = 1.185, 1.4
- Flow conditions
  - Constant $M = V_j/C_j$, $Ma = V_j/C_{amb}$



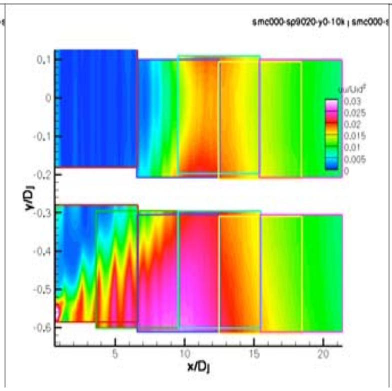
Results

- Current status of analysis: Simple time-average statistics
- Orientation to data presentation
- Use compressed axial scale for clarity

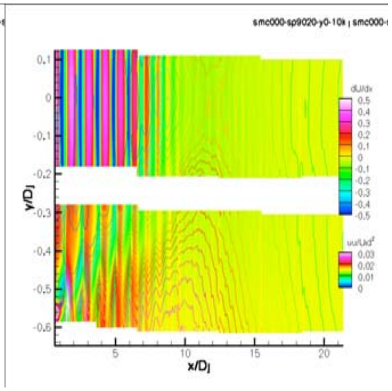




U/Uid



$\overline{uu}/Uid^2$



(dU/dx)/Uid

Effect of Ma, M on Mean Velocity—Underexpanded Jets

M= 1.05

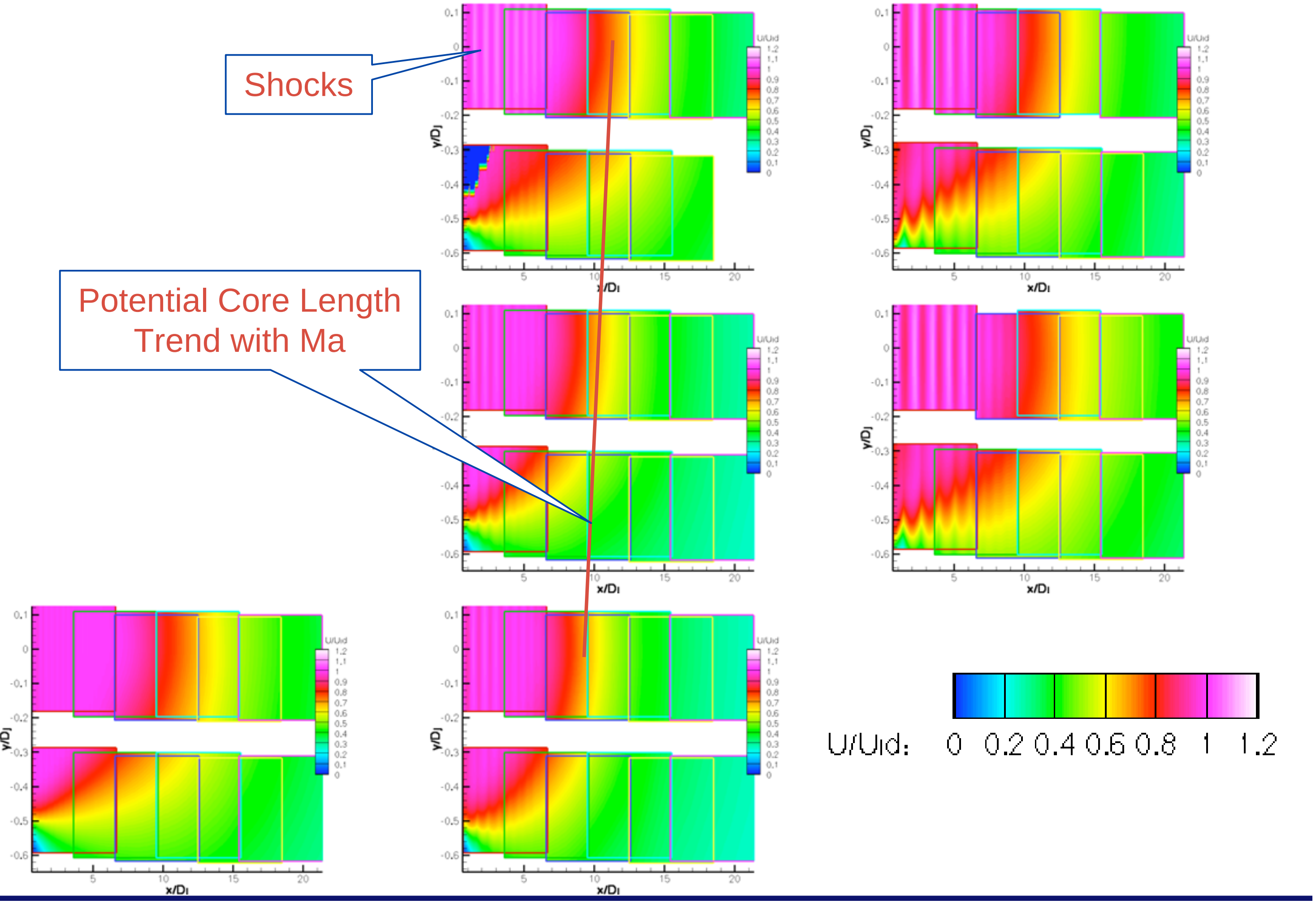
M= 1.185

M= 1.4

Ma = 1.8

Ma = 1.4

Ma = 1.185



Shocks

Potential Core Length Trend with Ma

U/Uid: 0 0.2 0.4 0.6 0.8 1 1.2

Effect of Ma, M on Mean Velocity—Fully Expanded Jets

M= 1.05

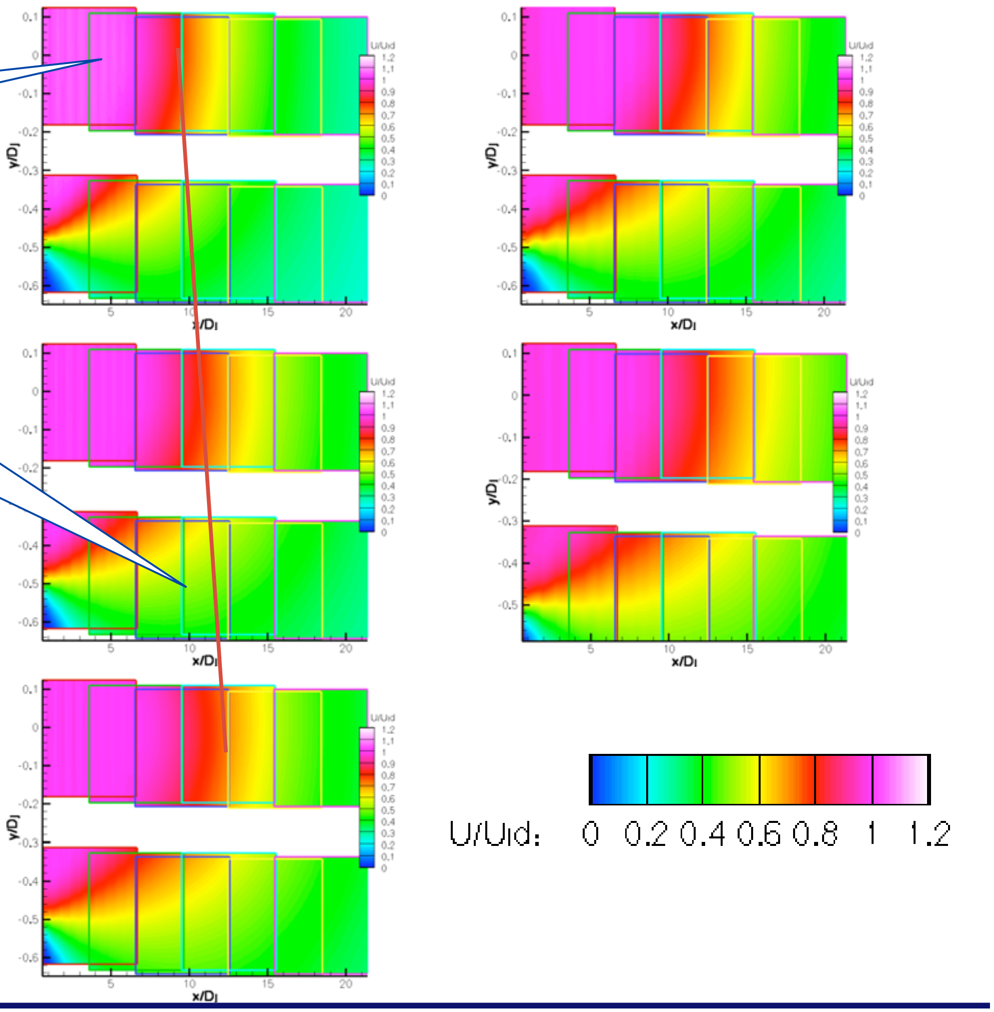
M= 1.185

M= 1.4

Ma = 1.8

Ma = 1.4

Ma = 1.185



Shocks?!

Potential Core Length Trend with Ma?!

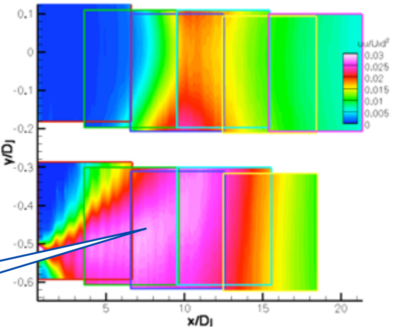
Effect of Ma, M on Turbulent Velocity—Underexpanded Jets

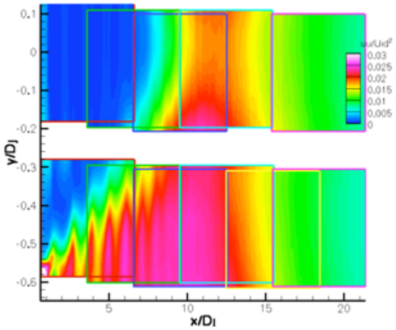
M= 1.05

M= 1.185

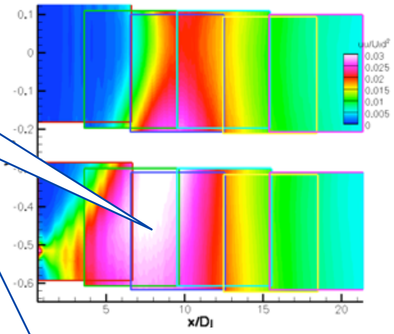
M= 1.4

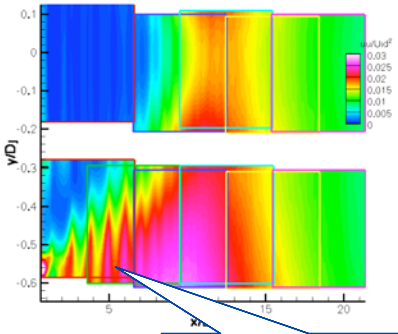
Ma = 1.8



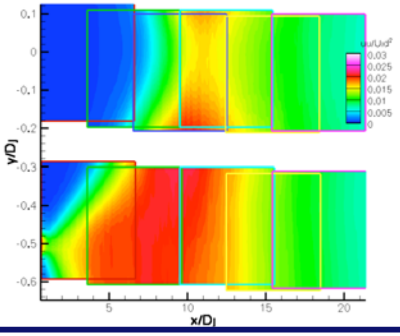


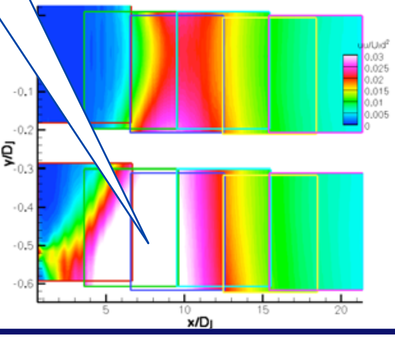
Ma = 1.4





Ma = 1.185





Peak turbulence decreases with Ma

Strong modulation of turbulence by shocks

uu/U_{jd}^2: 0 0.01 0.02 0.03

Effect of Ma, M on Mean Velocity—Fully Expanded Jets

M= 1.05

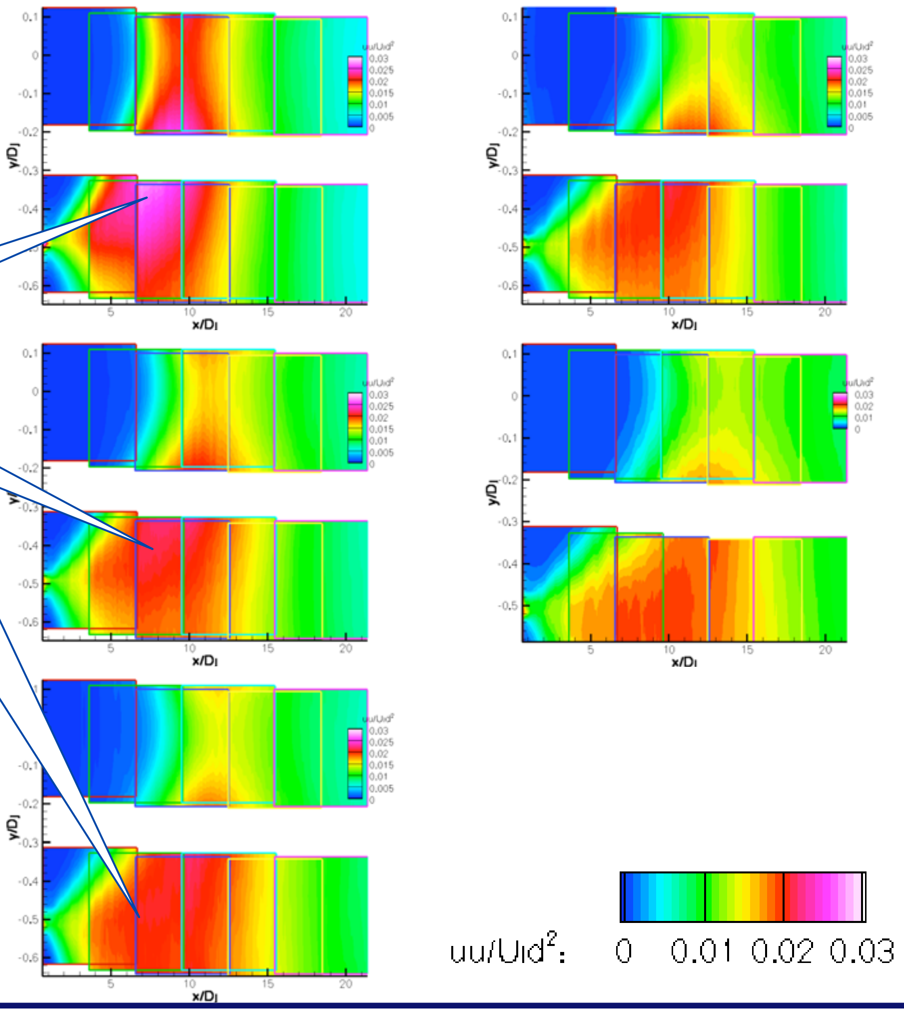
M= 1.185

M= 1.4

Ma = 1.8

Ma = 1.4

Ma = 1.185



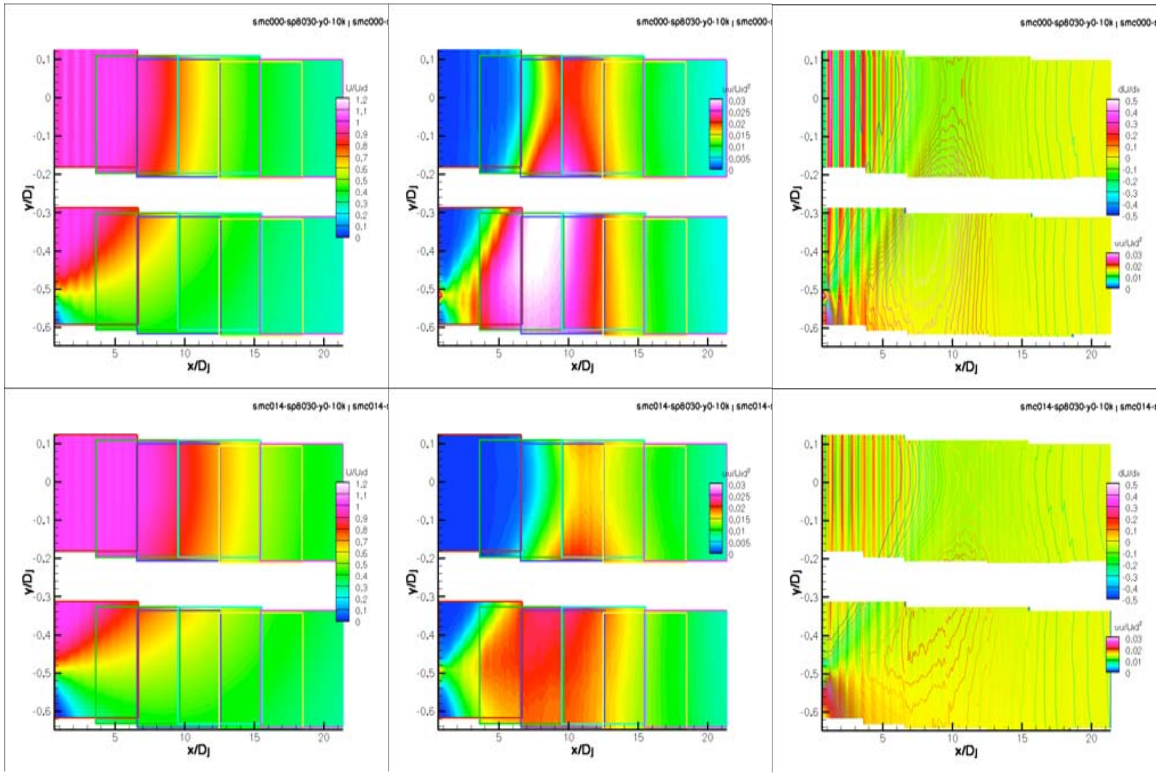
Peak turbulence increases with Ma

Shocks in Supersonic Jets

- Underexpanded/Properly Expanded Nozzle
- M=1.185, Ma=1.4, Ts/Tamb = 1.4

Convergent

Convergent-Divergent



C-D nozzle extends potential core, reduces TKE, ‘reduces’ shocks.

Analysis Yet To Be Done…

- Velocity spectra, especially at and between shock-shear layer interaction
- Space-time correlations
  - Lengthscales near shocks
  - Extended correlations —> noncompact models for high speed mixing noise sources
- …

Summary

- Comprehensive parametric dataset of time-resolved velocity fields acquired for convergent and properly expanded nozzles over a range of supersonic jet conditions with heat.
- Analysis underway--simple single-point stats current available
- Potential core length dependent upon shock strength.
- Turbulent kinetic energy intensified by shocks, especially with screech.

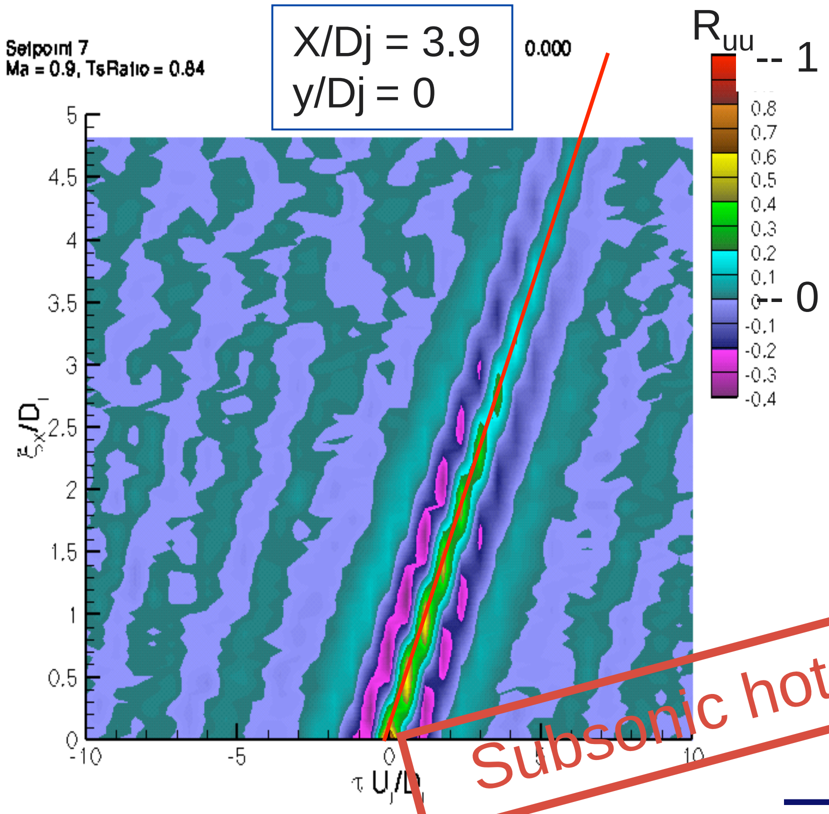
Acknowledgements

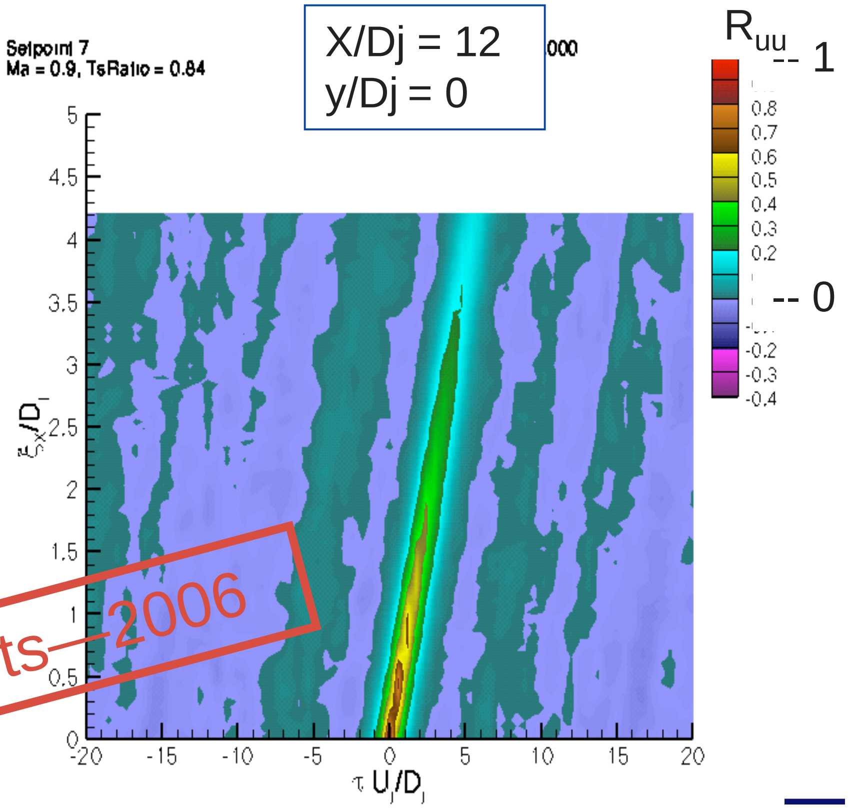
- Adam Wroblewski and Gary Clayo provided valuable assistance in fabrication, setup and operation of the TR-PIV.
- The staff of the AeroAcoustic Propulsion Lab at NASA Glenn operated the jet rig and overcame installation challenges.
- The Wernet and Bridges families provided significant release time.

Two-point space-time velocity correlation

- Defined with fixed reference point x:

$$R_{u_1u_1'} = \overline{u_1u_1'}(\xi_1,\tau;\vec{x}) = \frac{1}{T}\int_{t=0}^{t=T}(u_1-U_1)(\vec{x}+\xi_1/2,t)\;\;(u_1-U_1)(\vec{x}-\xi_1/2,t-\tau)\,dt$$





Subsonic hot jets—2006

TR-PIV installation in Small Hot Jet Acoustic Rig (SHJAR) at NASA Glenn