Jet Aeroacoustics:
Some insights from Numerical Experiments

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Takao Suzuki, Ted Manning, Daniel Bodony, Joseph W Nichols, Simon A. Mendez, Yaser Khalighi, Parviz Moin

1 CASCADE TECHNOLOGIES 2 INSTITUT P' 3 CALIFORNIA INSTITUTE OF TECHNOLOGY 1891 4 ITA 5 LELAND STANFORD JUNIOR UNIVERSITY DIE LUFT DER FREIHEIT WEHT 1891

5th International Workshop on Computational Experiment in AeroAcoustics -- CEAA 2018, Svetlogorsk, Russia, Sept 19–22, 2018

Outline

- *Physical and Numerical Modeling Issues*

- *Some insights from data analysis*

  Jet Noise Sources --- Subsonic

  Jet Noise Sources --- Supersonic

- *Open Issues*

  Jet Noise Scaling

  Noise Source Modeling

  Imperfectly-expanded Jets

- *Summary and conclusions*

Physical and Numerical Modeling Issues

- *Nozzle*
- *Nozzle exit boundary layer state*
- *Entrainment and co-flow*
- *Installation effects*

- *Spatial and temporal resolution – Numerical Dispersion and dissipation*
- *Sub-filter scale modeling*
- *Boundary conditions*
- *Far-field Acoustic Predictions*
- *Managing the data*

Physical and Numerical Modeling Issues

- *Nozzle*
- *Nozzle exit boundary layer state*

international journal of aeroacoustics volume 4 · number 3&4 · 2005 – pages 213 – 246 213

Noise prediction for increasingly complex jets. Part I: Methods and tests

Michael L. Shur*, Philippe R. Spalart**, and Michael Kh. Strelets***

AIAA Aviation
22-26 June 2015, Dallas, TX
21st AIAA/CEAS Aeroacoustics Conference

AIAA 2015-2535

Large eddy simulation for jet noise: the importance of getting the boundary layer right

Guillaume A. Brès*
Cascade Technologies Inc., Palo Alto, CA 9

AIAA Journal
Vol. 46, No. 2, February 2008

Current Status of Jet Noise Predictions Using Large-Eddy Simulation

Daniel J. Bodony* and Sanjiva K. Lele†

Will discuss shortly

J. Fluid Mech. (2018), *vol.* 851, *pp.* 83–124. © Cambridge University Press 2018 83
doi:10.1017/jfm.2018.476

Importance of the nozzle-exit boundary-layer state in subsonic turbulent jets

Guillaume A. Brès[1,†], Peter Jordan[2], Vincent Jaunet[2], Maxime Le Rallic[2], André V. G. Cavalieri[3], Aaron Towne[4], Sanjiva K. Lele[5], Tim Colonius[6] and Oliver T. Schmidt[6]

Physical and **Numerical** Modeling Issues

- *Far-field Noise Predictions*

aeroacoustics volume 8 · number 5 · 2009 – pages 477–492 477

aeroacoustics volume 12 · number 1+2 · 2013 – pages 1 – 20 1

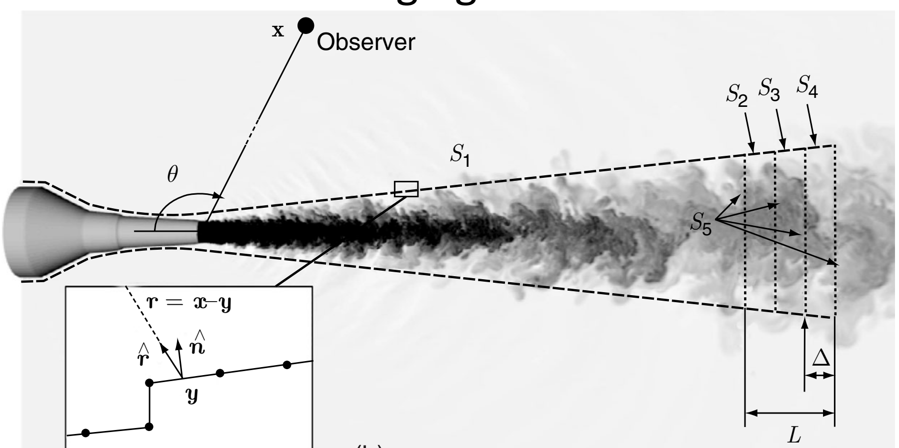
- Frequency domain FW-H equation
- Pressure-substituted surface source term
- Multiple-outflow disk averaging

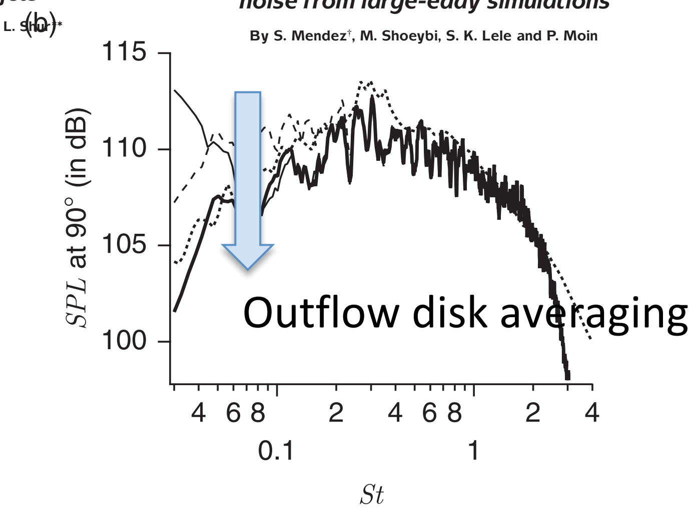
Variants of the Ffowcs Williams - Hawkings equation and their coupling with simulations of hot jets

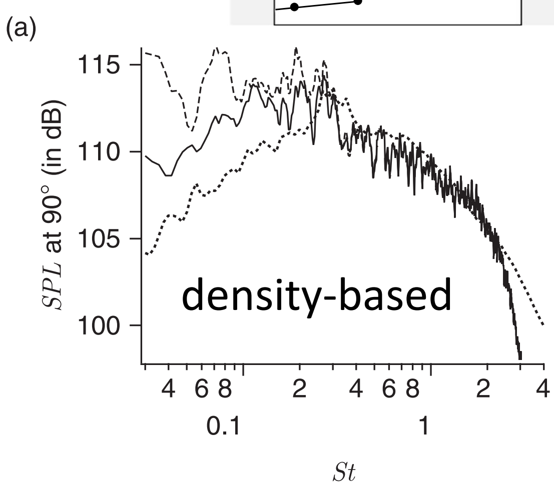
Philippe R. Spalart* and Michael L. Shur**

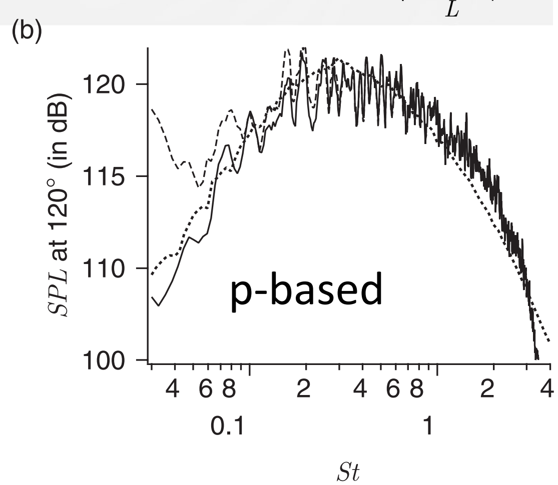
On the use of the Ffowcs Williams-Hawkings equation to predict far-field jet noise from large-eddy simulations

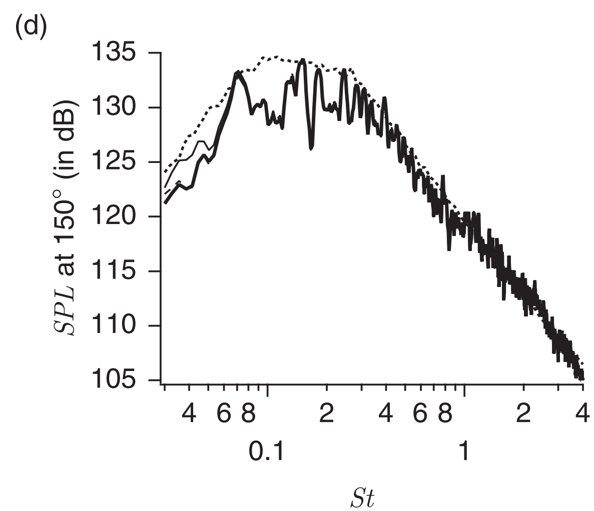
By S. Mendez†, M. Shoeybi, S. K. Lele and P. Moin











From Mendez et al (2013) Int. J. Aeroacoustics

Numerical setup

Importance of nozzle BL

Bres et al 2015, 2018

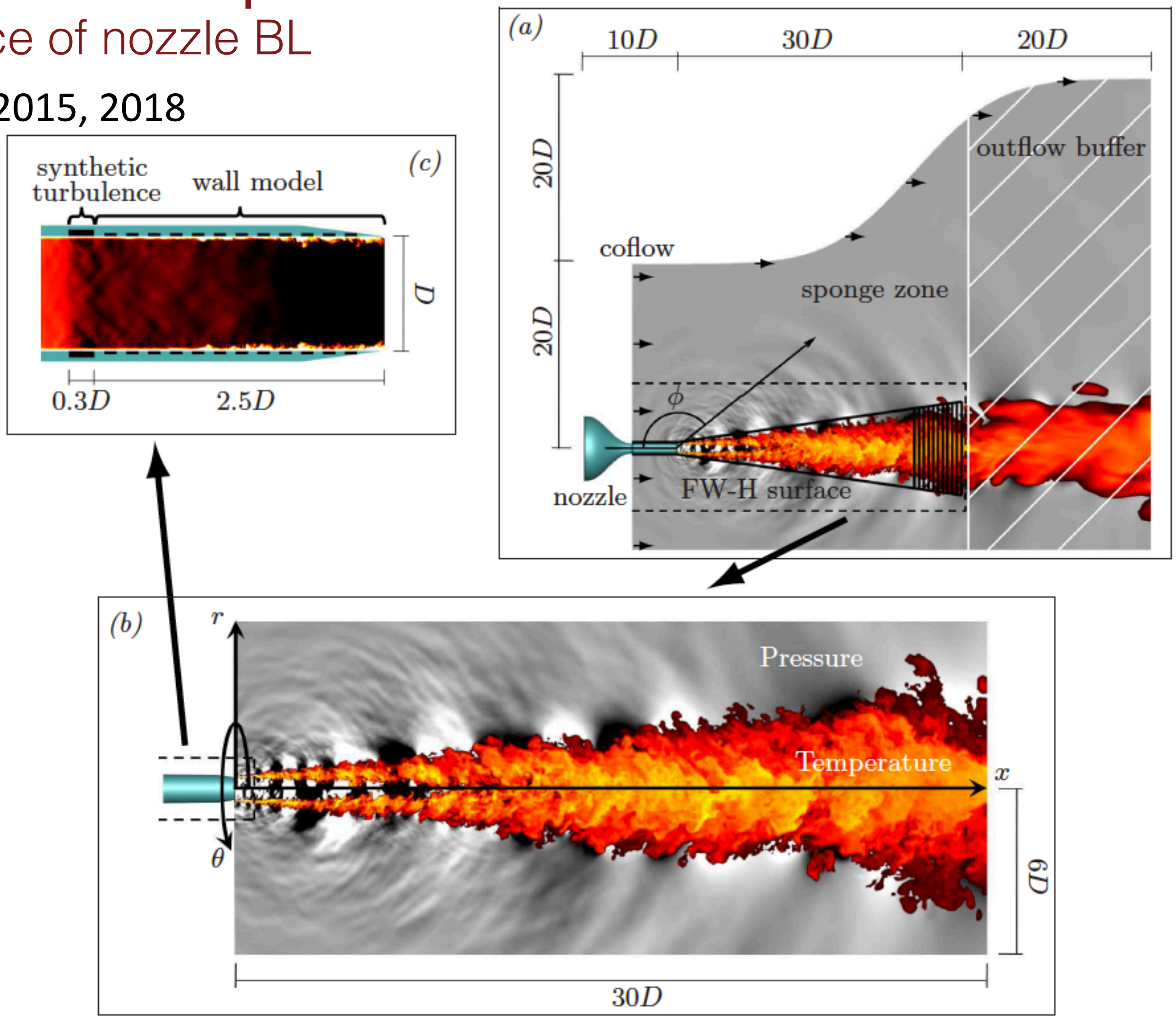
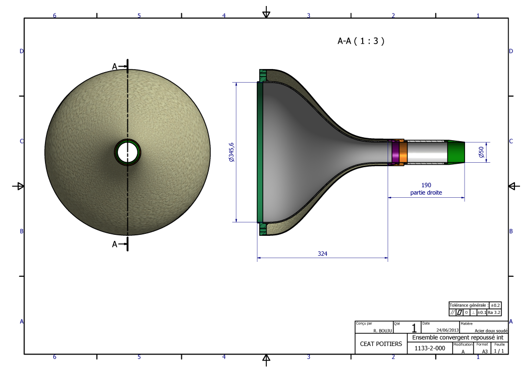
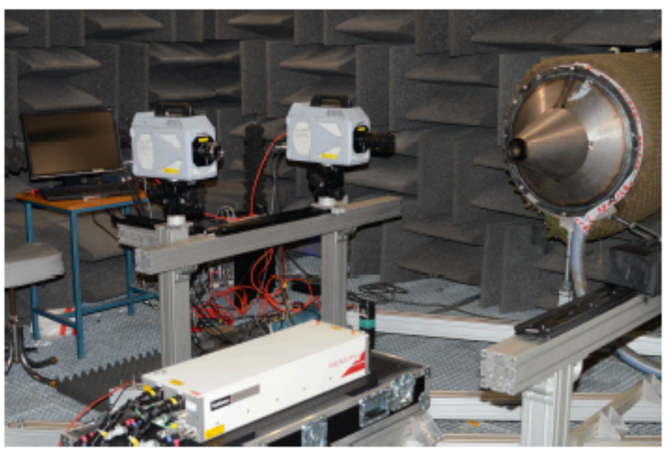


Figure 2. Schematics of the flow configuration and simulation setup: (*a*) overview of the computational domain; (*b*) spatial extent of the LES database; (*c*) modeling inside the nozzle.

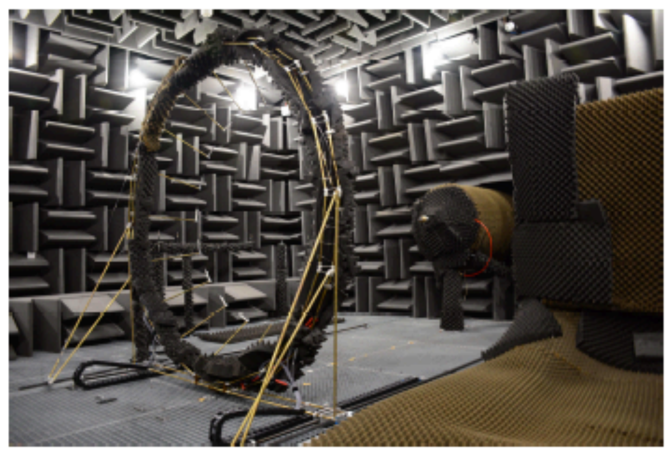
Experimental configuration

- *Isothermal Mach 0.9 jet*
  - geometry and operating conditions provided by Prof. Peter Jordan and coworkers, from Institute PPRIME, Poitiers, France.
  - hot-wire, LDA and PIV for velocity measurements
  - near-field and far-field microphone arrays for noise measurements
  - Reynolds number $Re_D = 10^6$ matched in LES



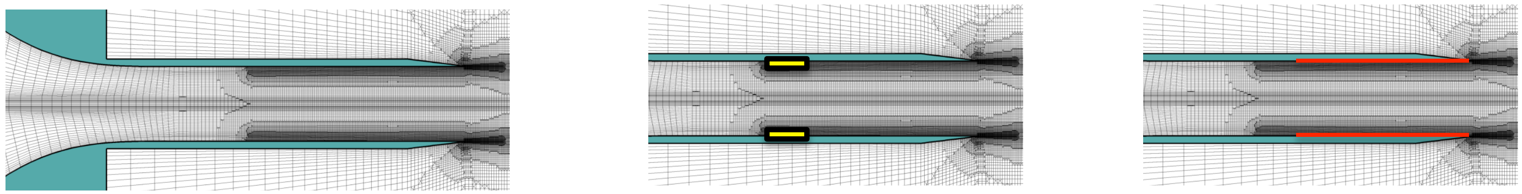


(*a*) PIV system



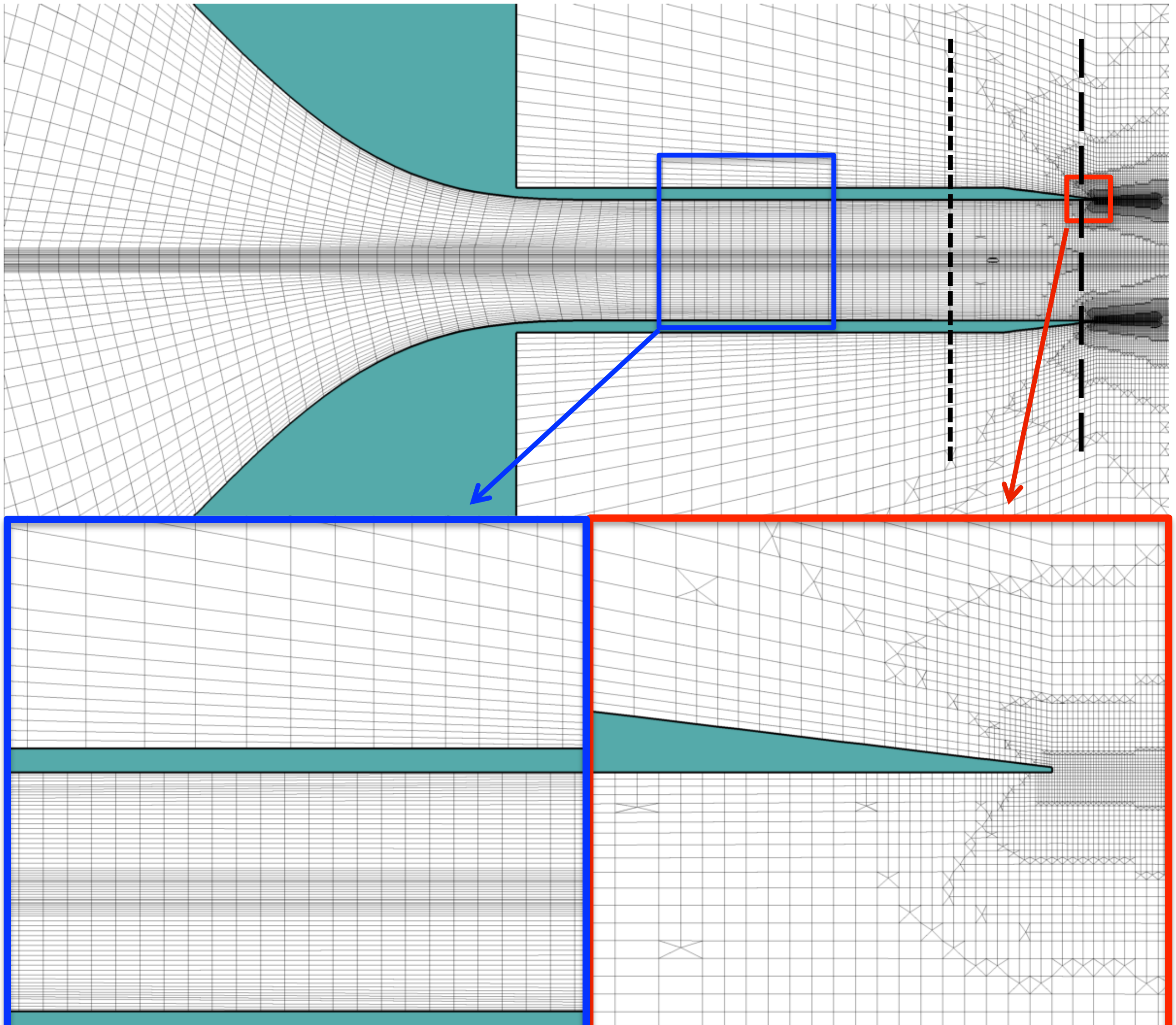
(*b*) 18-microphone azimuthal array

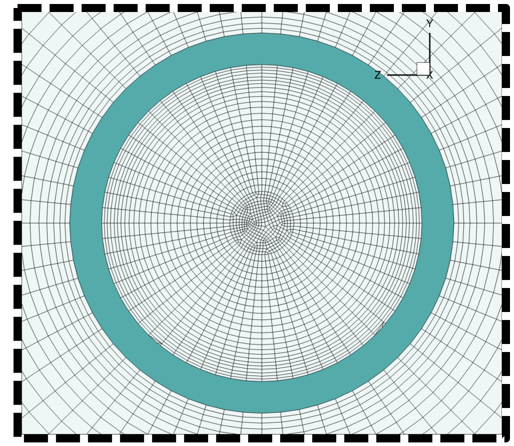
Numerical Model Summary



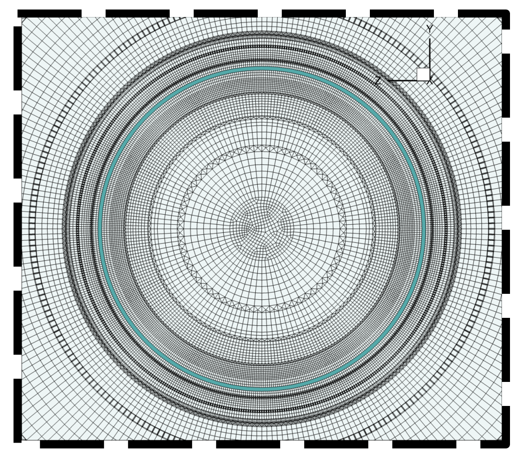
Case name	Mesh size (10^6 cells)	BL refinement	Synthetic turbulence u'_{trip}/u_τ	Wall model	dtc_∞/D	$t_{sim}c_\infty/D$	Database sampling $\Delta tc_\infty/D$
Baseline LES cases							
10M	10.8				0.001	2000	
64M	64.2				0.0005	300	
LES cases with nozzle interior flow modeling							
BL16M	15.9	×			0.001	300	
BL16M_Turb2	15.9	×	2		0.001	300	
BL16M_Turb	15.9	×	0.8		0.001	300	
BL16M_WM	15.9	×		×	0.001	300	
BL16M_WM_Turb2	15.9	×	2	×	0.001	300	
BL16M_WM_Turb	15.9	×	0.8	×	0.001	2000	0.2
BL69M_WM_Turb	69.0	×	0.8	×	0.0005	1150	0.2
						500	0.05

“Adapt” tool: Meshing strategy inside the nozzle
Baseline mesh (10 M cv)



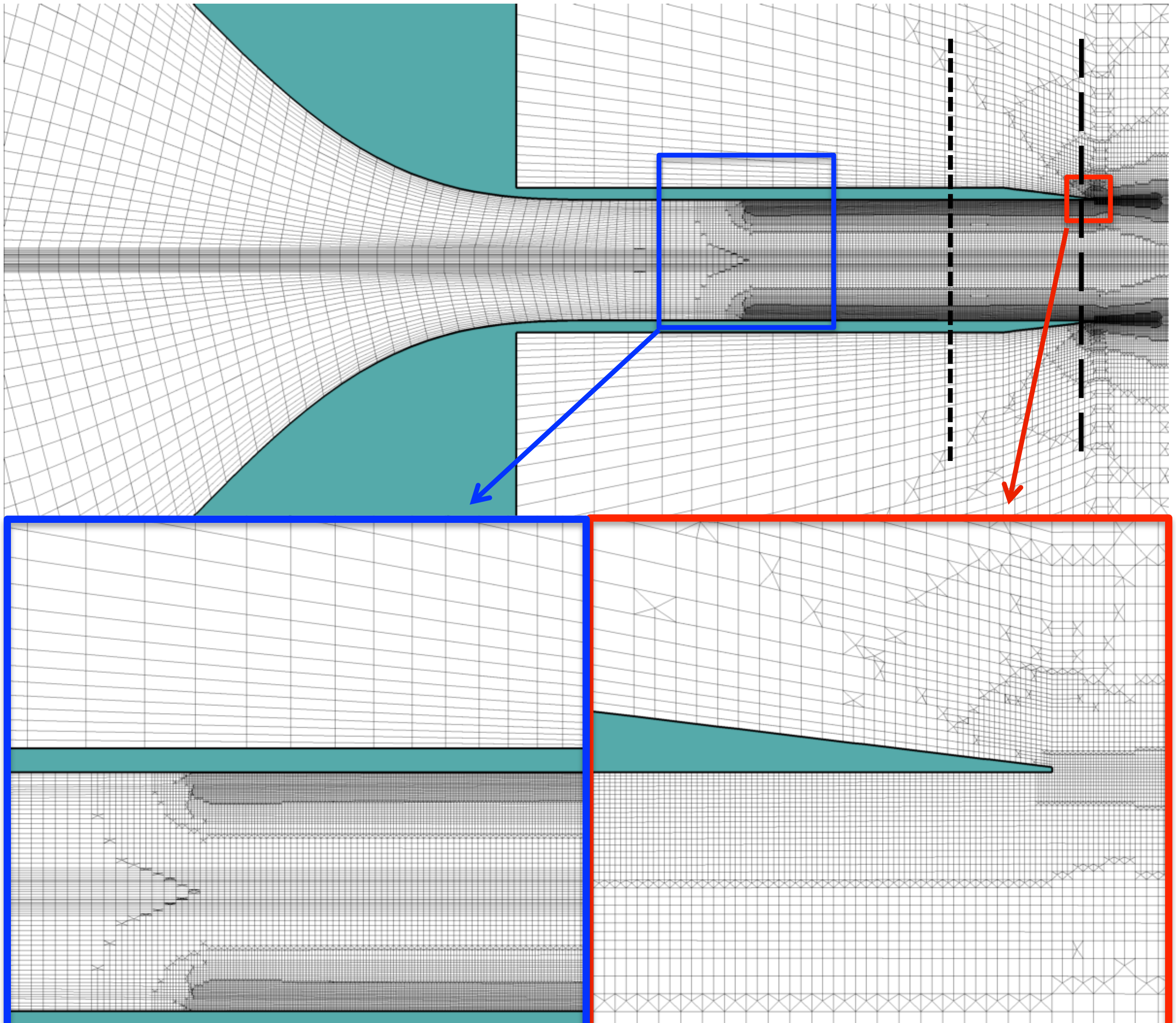


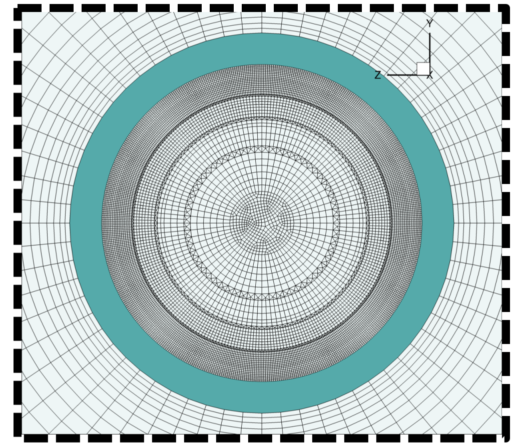
x/D = -1



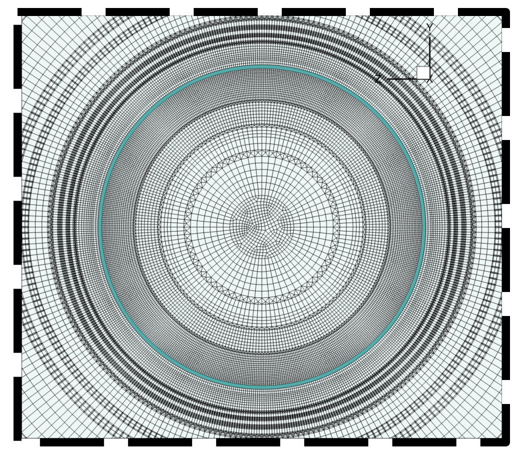
x/D = -0.05

“Adapt” tool: Meshing strategy inside the nozzle
BL-adapted mesh (16 M cv)





x/D = -1

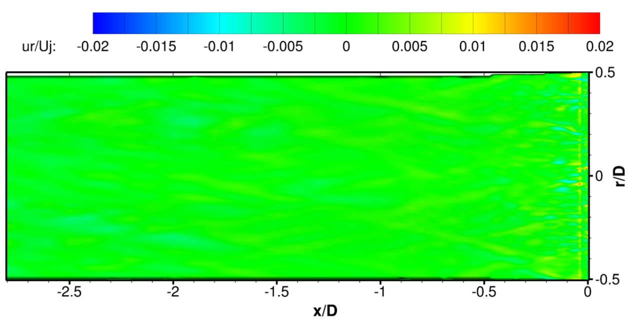


x/D = -0.05

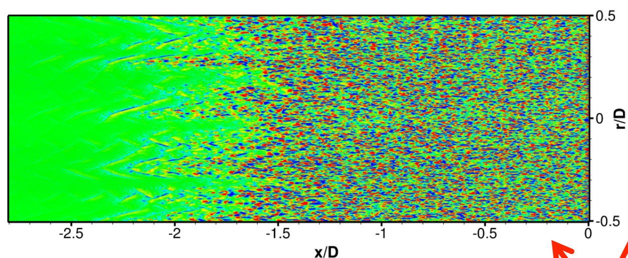
Effect of adaptive refinement inside the nozzle
Flow field

surface normal velocity

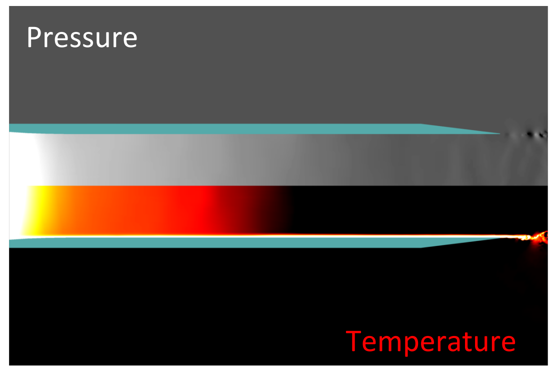
10M

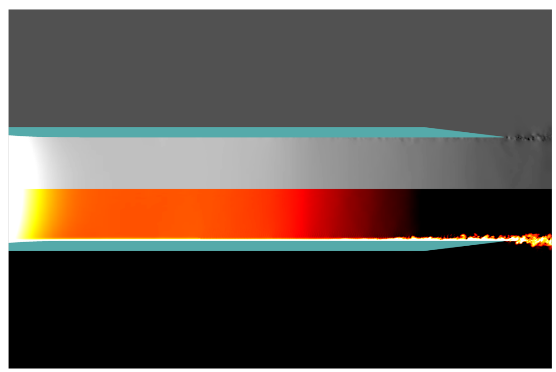


BL16M

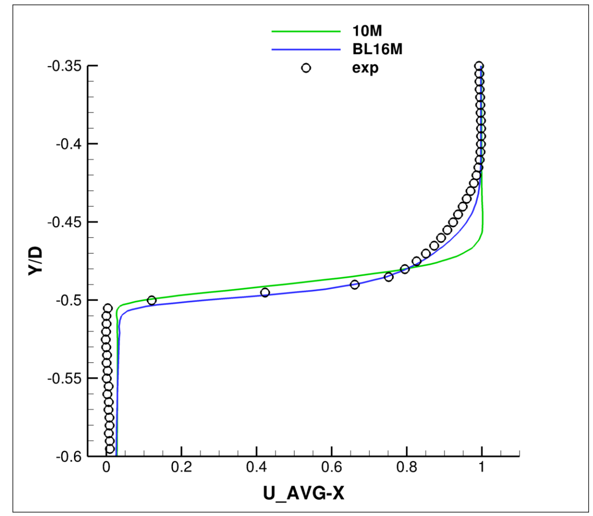


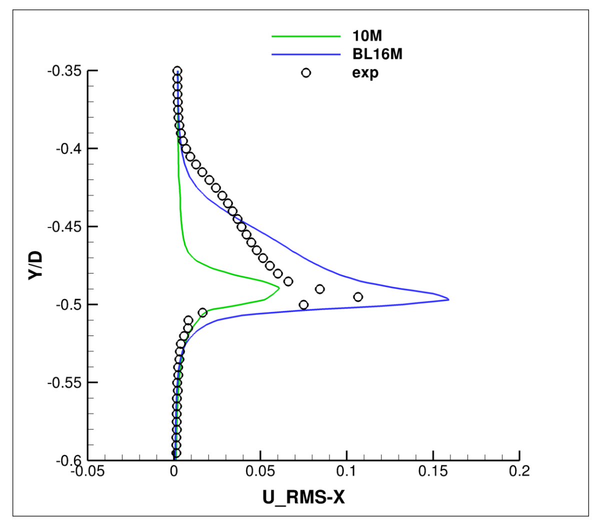
nozzle interior flow





nozzle exit profiles





Some near-wall turbulent structures now captured

Improvement of mean exit profile but near-wall fluctuation over-predicted

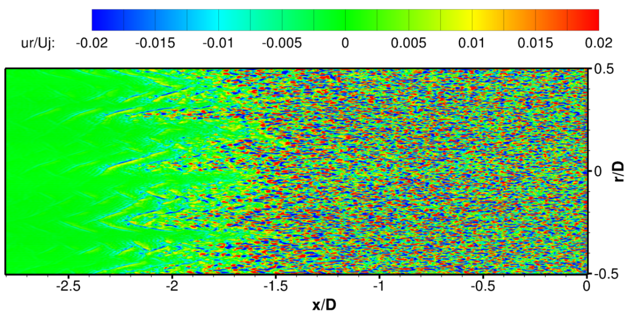
Effect of synthetic turbulence & wall modeling
Flow field

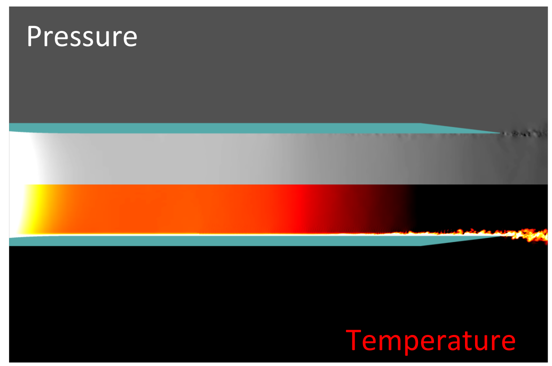
surface normal velocity

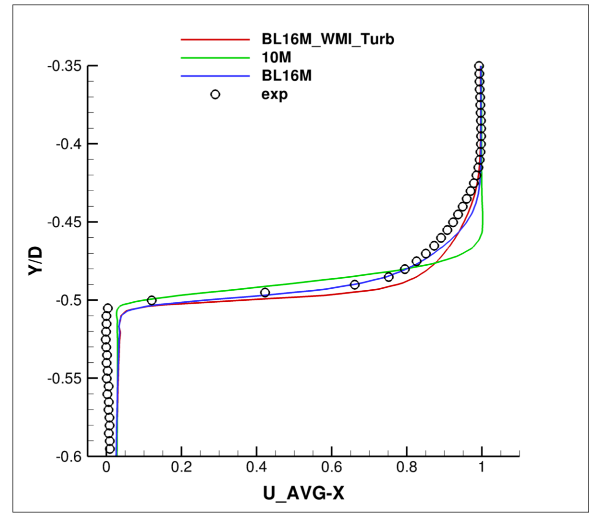
nozzle interior flow

nozzle exit profiles

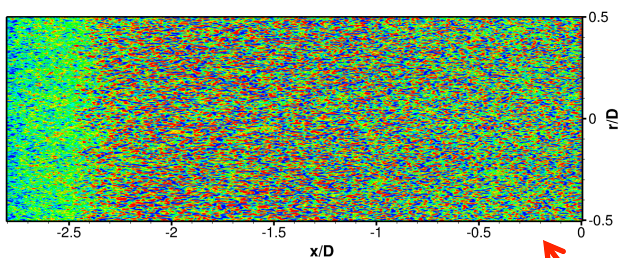
BL16M

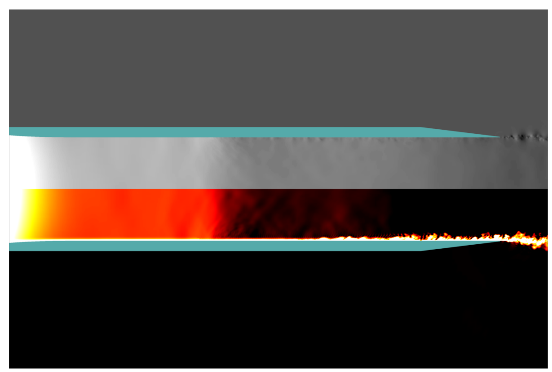


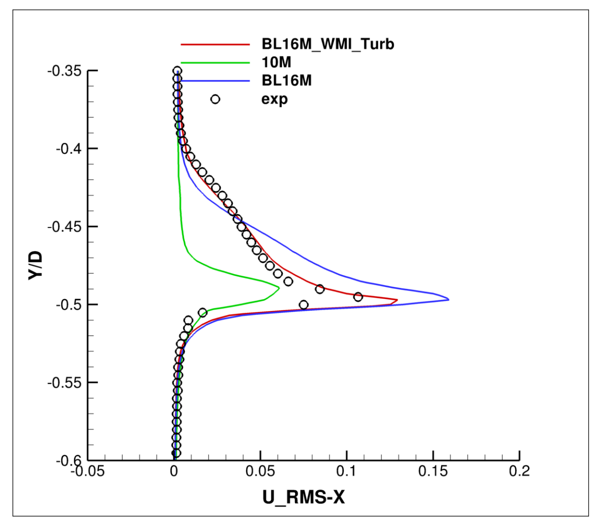




BL16M_WM_Turb



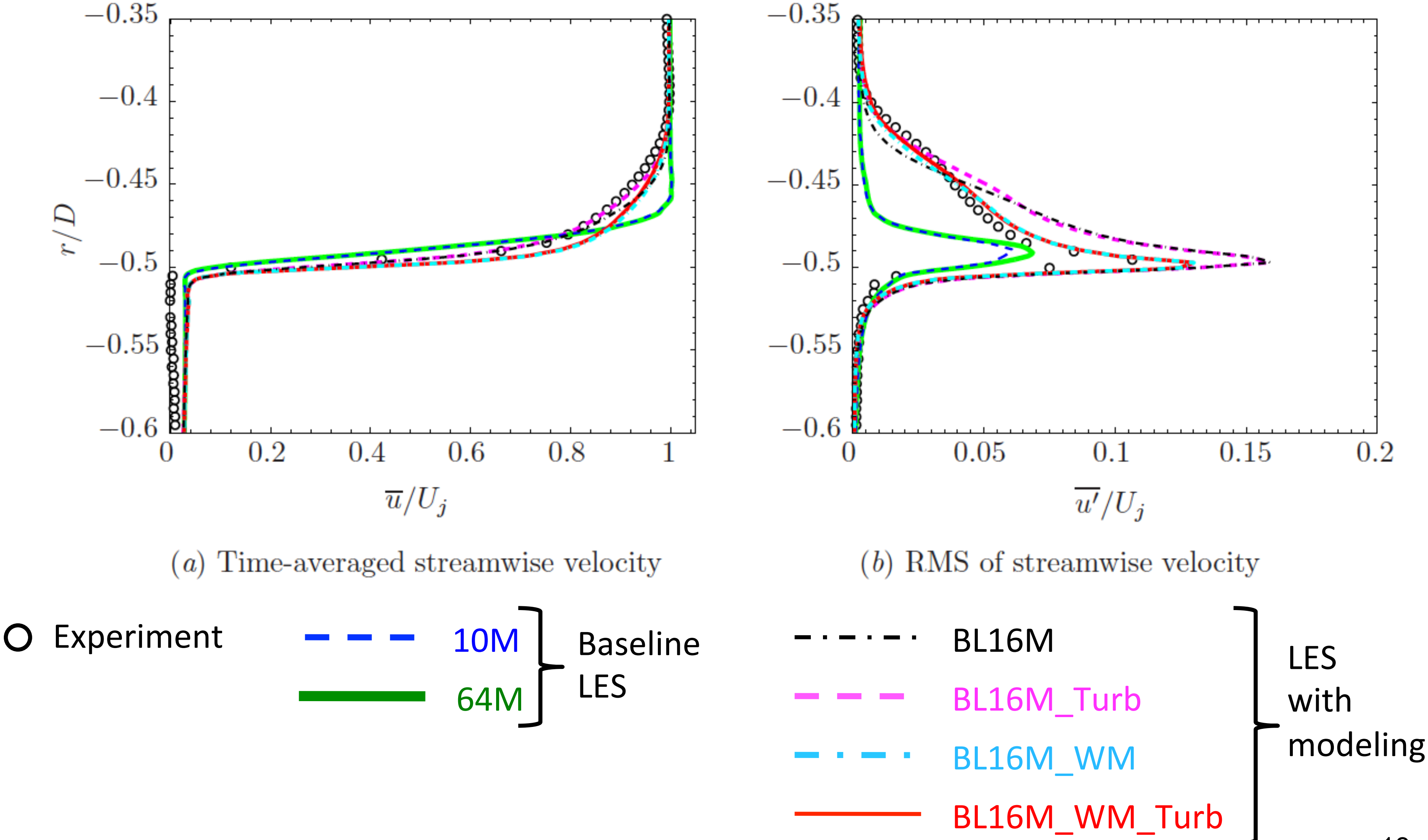




Development of realistic turbulence near the wall and in the core flow

Significant improvement of RMS exit profiles

Nozzle exit profiles

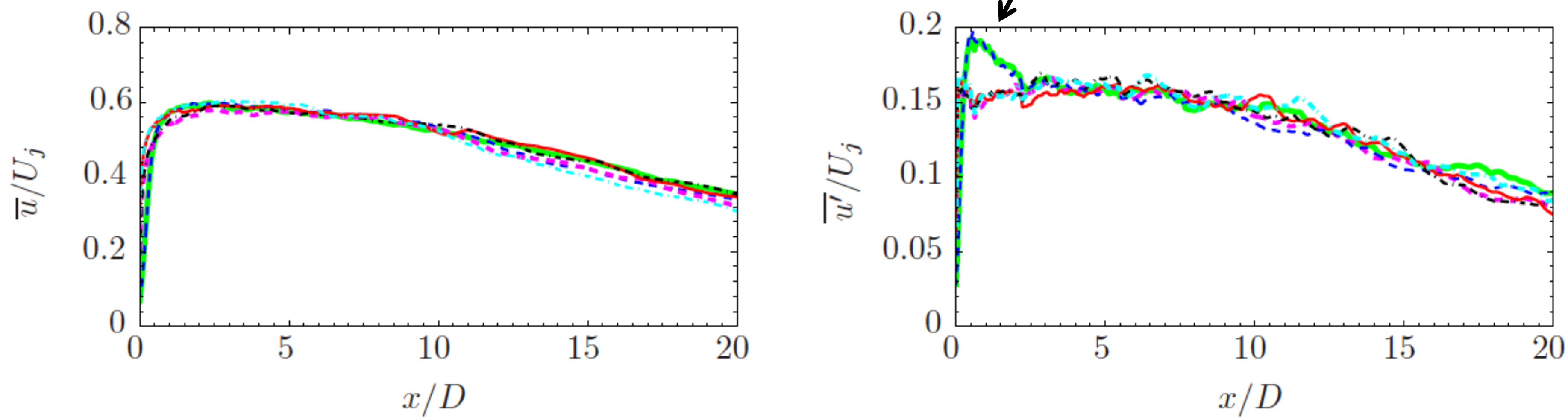


(a) Time-averaged streamwise velocity

(b) RMS of streamwise velocity

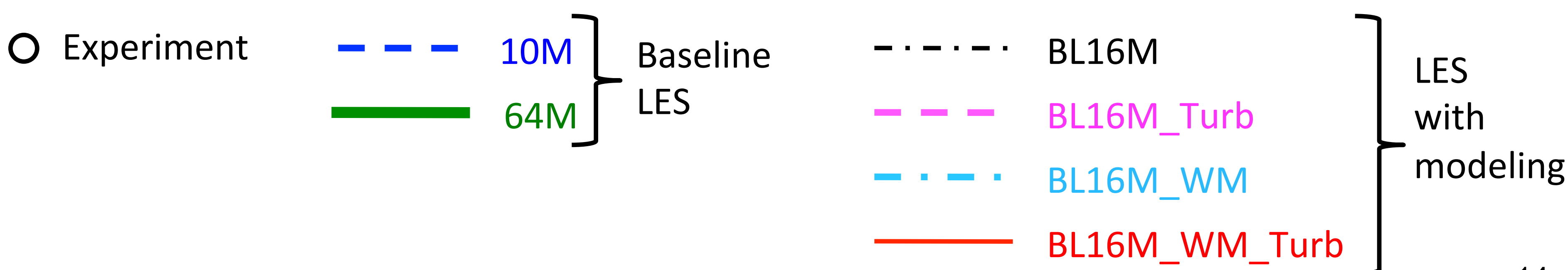
Lipline profiles

RMS overshoot caused by laminar to turbulent transition nearly completely removed with modeling

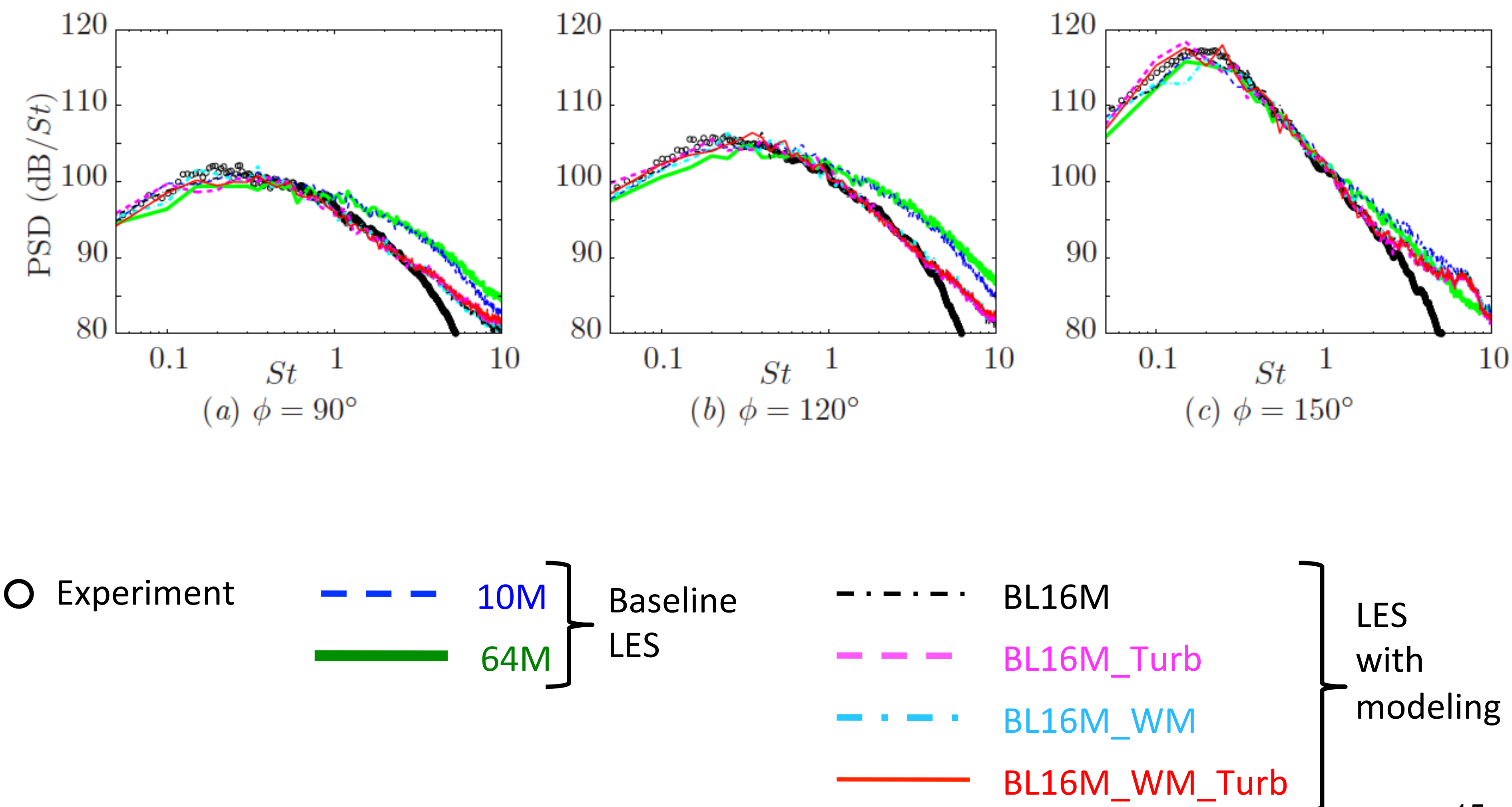


(a) Time-averaged streamwise velocity

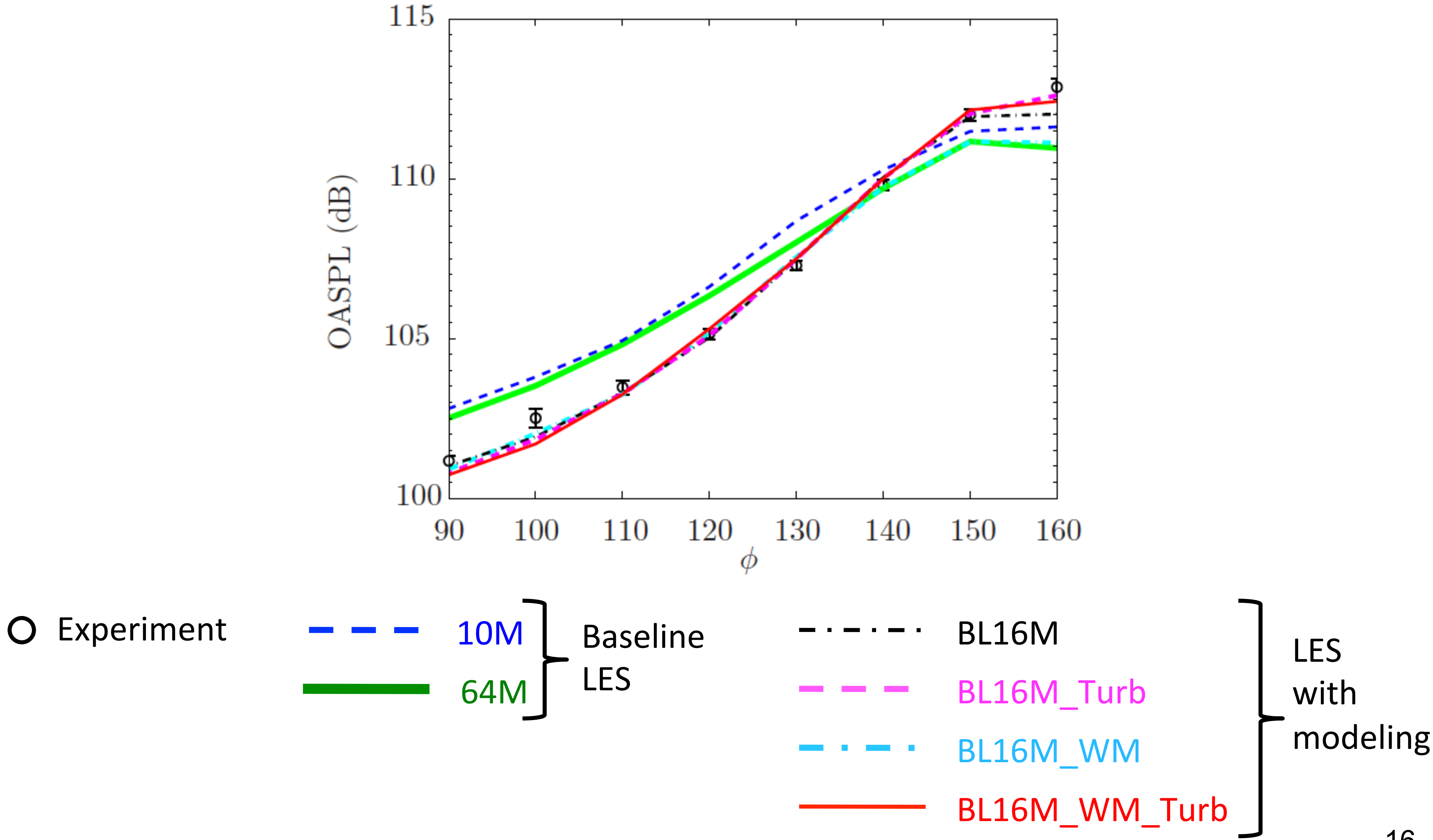
(b) RMS of streamwise velocity



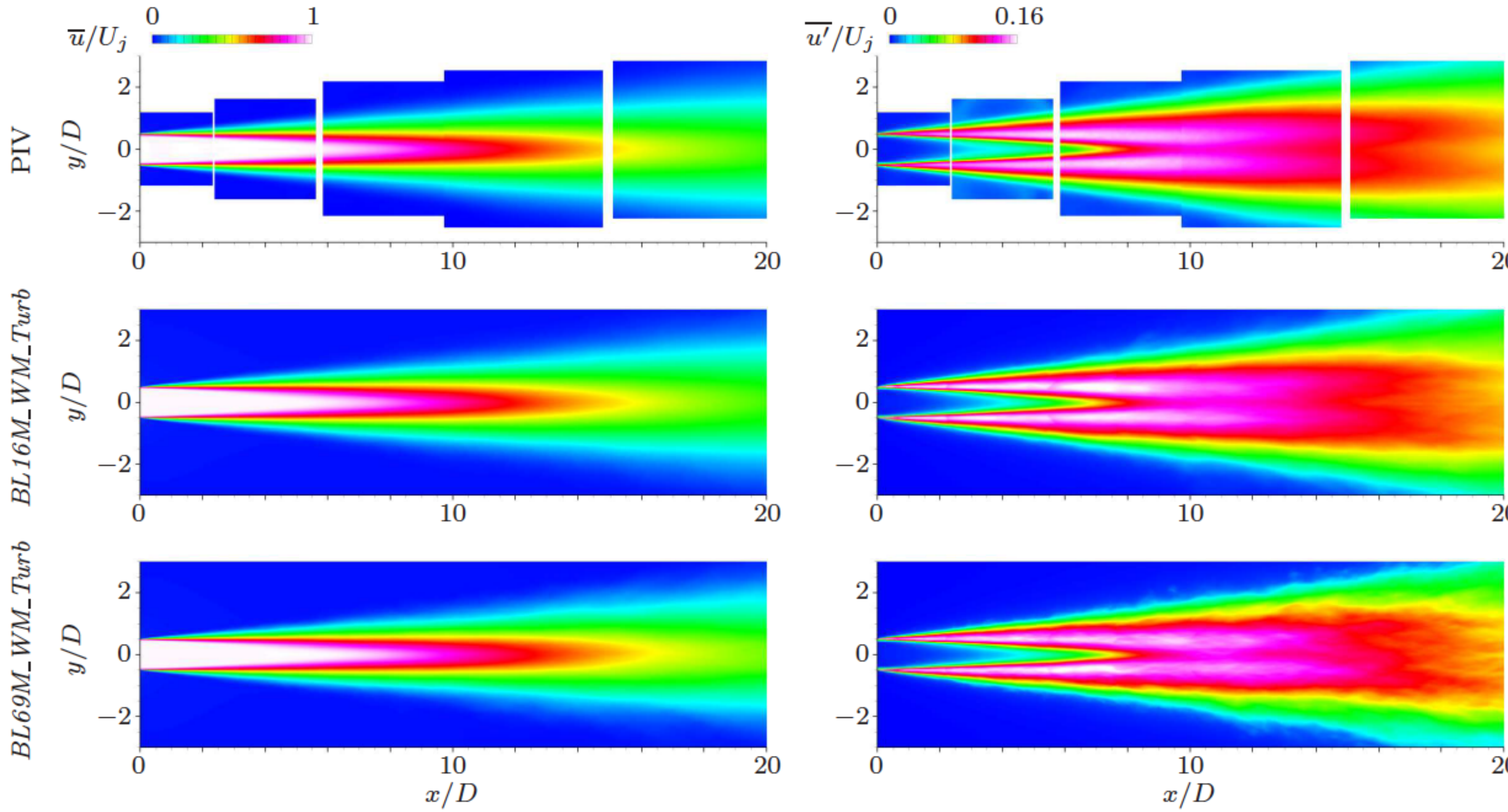
Effects of modeling
Far field spectra



Effects of modeling
Noise directivity



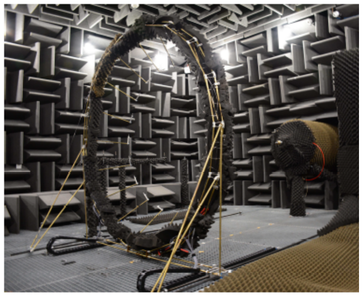
Flow field statistics



(*a*) Time-averaged streamwise velocity

(*b*) RMS of streamwise velocity

Far-field noise

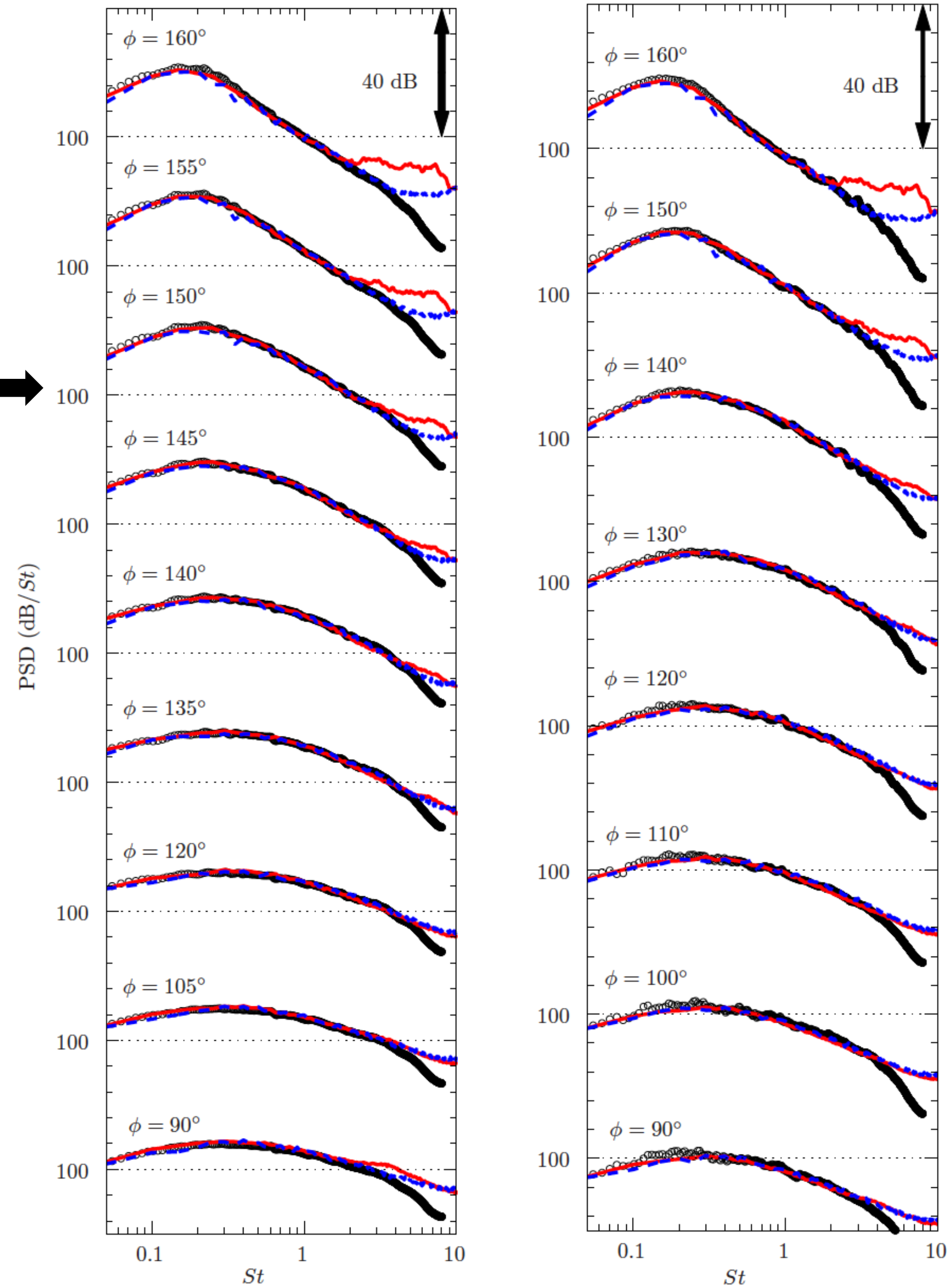


cylindrical array

Experiment

BL16M_WM_Turb

BL69M_WM_Turb



(a) Cylindrical array of radius $r = 14.3D$

(b) Far-field array at constant distance $50D$

single far-field microphones at 50 D

Outline

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- *Some insights from data analysis*

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    Jet Noise Sources --- Supersonic

- *Open Issues*

    Jet Noise Scaling

    Noise Source Modeling

    Imperfectly-expanded Jets

- *Summary and conclusions*

Wave packets in jet turbulence

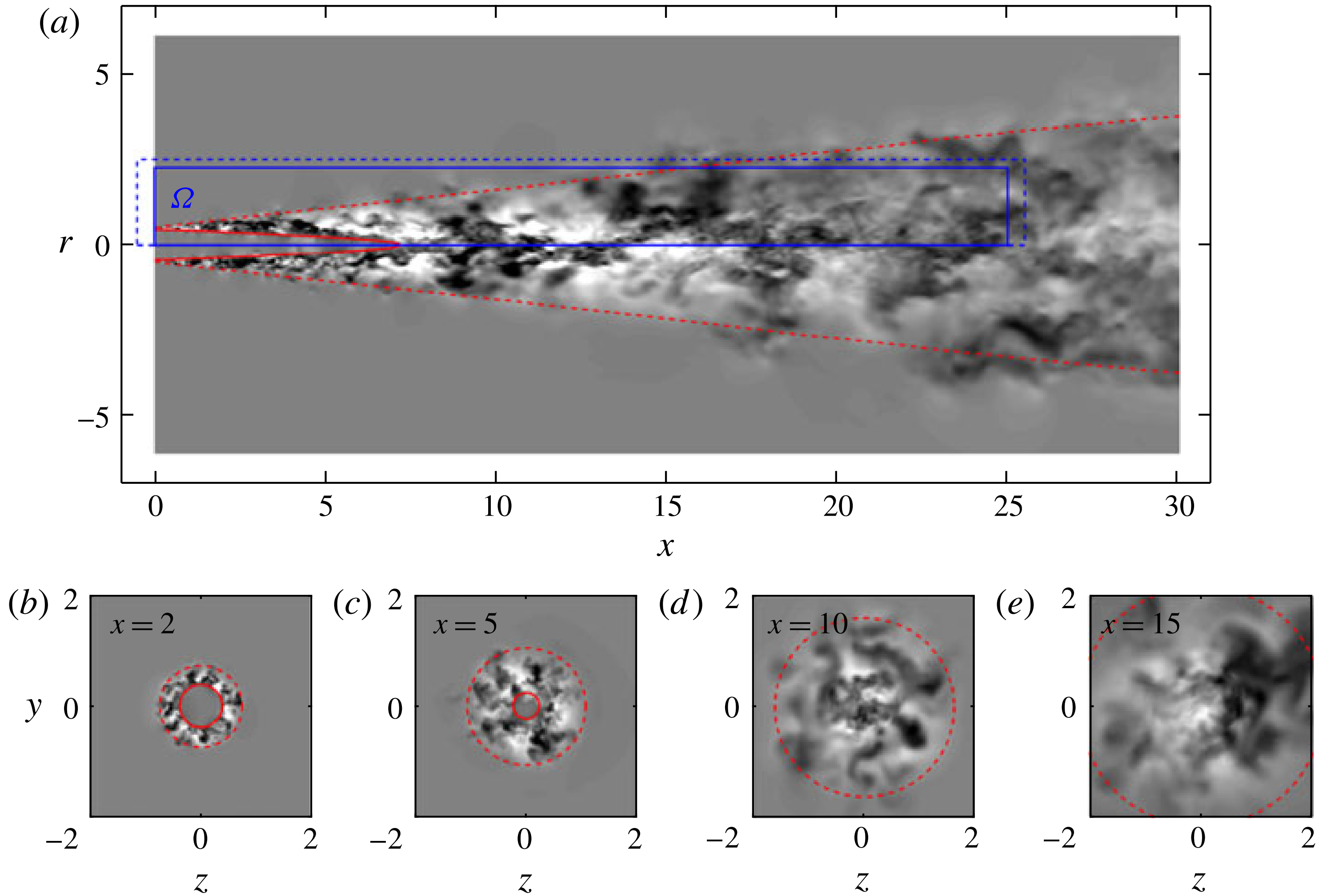

FIGURE 1. (Colour online) Instantaneous streamwise perturbation velocity (□■■, $-0.5 \leqslant u'_x/\|u'_x\|_\infty \leqslant 0.5$) and streamwise mean velocity (—— (red), $\bar{u}_x = 0.95$; - - - (red), $\bar{u}_x = 0.05$) of the LES: (*a*) streamwise plane and computational domain Ω used for the linear stability analysis (—— (blue), solution domain; - - - (blue), sponge region) and (*b–e*) transverse planes at $x = 2$, 5, 10 and 15, respectively.

Schmidt et al 2017 J. Fluid Mech., Vol. 825

Wave packets in jet turbulence

m = 0
St = 0.5

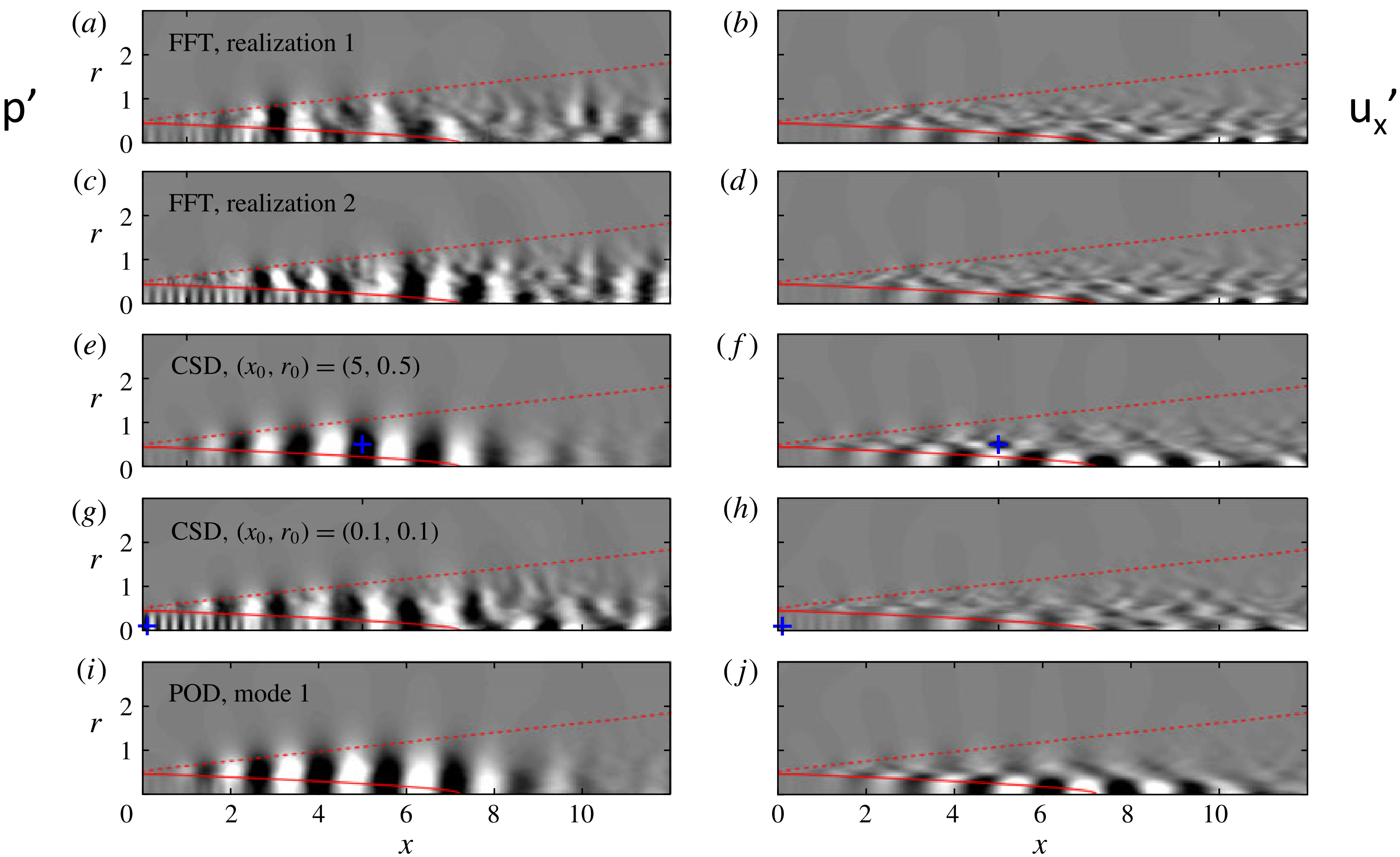

FIGURE 2. (Colour online) Spectral decomposition and coherent feature extraction for $m = 0$, $St \approx 0.5$ (, ± 0.5 of the maximum value): (*a–d*) the first two realizations of the 256 snapshot based Fourier decomposition; (*e–h*) CSD using different correlation points (x_0, r_0); (*i,j*) leading POD mode estimates. The pressure and streamwise velocity component are shown in the left and right column, respectively. The CSD correlates each point of the flow field with a location (x_0, r_0) marked by '+', and the POD is based on the volume weighted 2-norm.

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Wave packets in jet turbulence

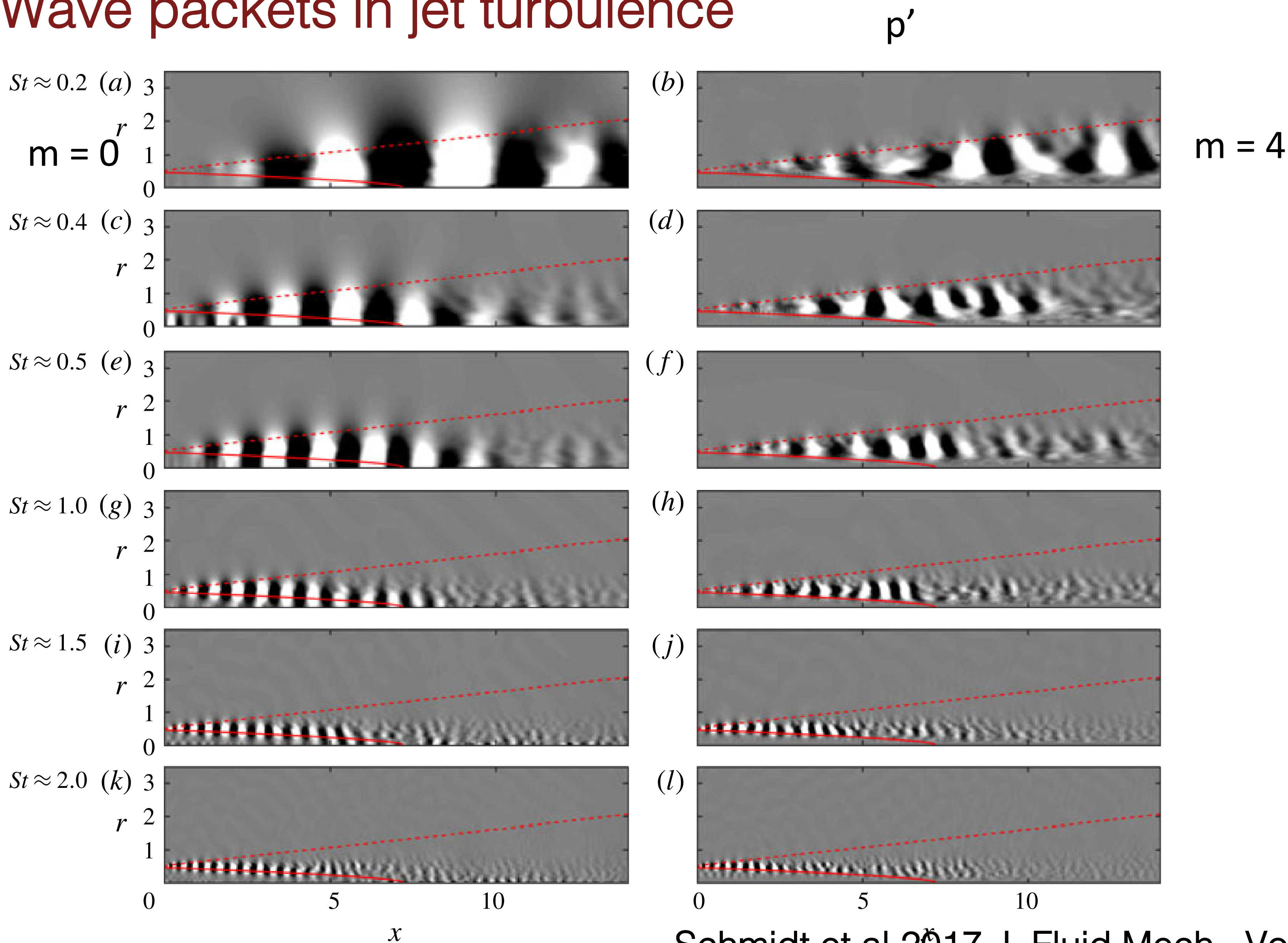

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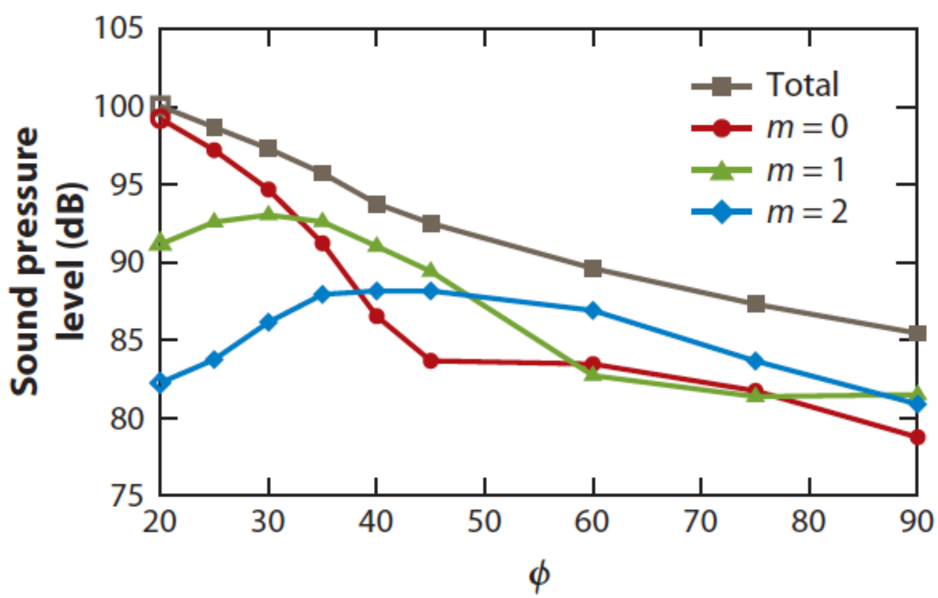
FIGURE 3. (Colour online) Spectral estimation of pressure POD modes (□■■, $-0.25 \leqslant \Psi_p/\|\Psi_p\|_\infty \leqslant 0.25$) for different Strouhal numbers: (*a*,*c*,*e*,*g*,*i*,*k*) $m = 0$; (*b*,*d*,*f*,*h*,*j*,*l*) $m = 4$.

Azimuthal mode analysis

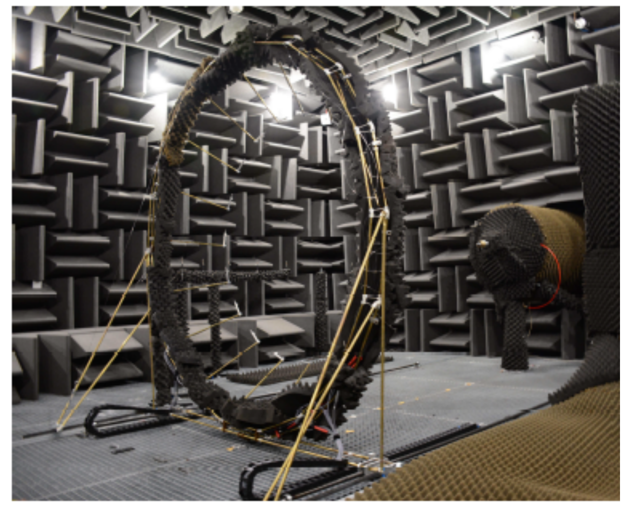
- *Previous studies have suggested that low-frequency (St <1) noise may be decomposed (almost entirely) into just 3 Fourier azimuthal mode: m=0, 1 & 2*
    - Juvé et. al. (AIAA J. 1979), Kopiev et. al. (AIAA 2010-4018), Cavalieri et. al, (JSV 2011, JFM 2012), Lorteau et. al. (PoF 2015)
    - Important implications towards noise reduction strategies



From Cavalieri et. al., JFM 2012
(exp. data on subsonic jet at St=0.2)

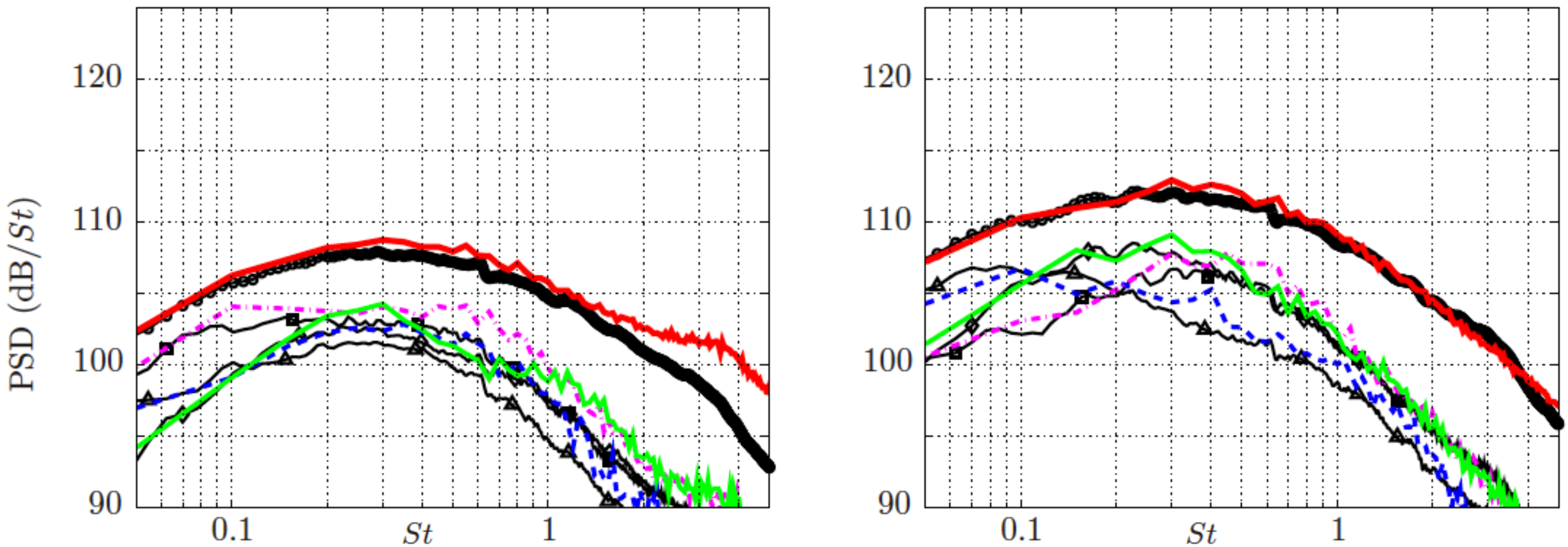
Analysis on cylindrical array

- *Experiment:*
  - 18 microphones evenly-spaced in the azimuthal direction, on cylindrical array of radius 14.3D
  - Available data, provided by PPRIME
    - *individual PSD*
    - *azimuthal-averaged PSD*
    - *PSD for mode m=0, m=1 and m=2*



- *LES:*
  - Same number of microphone & locations
  - Noise computed with FW-H solver
  - Analysis of azimuthal mode done independently of exp analysis

Azimuthal decomposition of Exp & LES radiated noise: At inlet angles 90 deg & 120 deg



(a) $\phi = 90°$ (b) $\phi = 120°$

<u>Symbols</u>: Exp

(○ ,) total

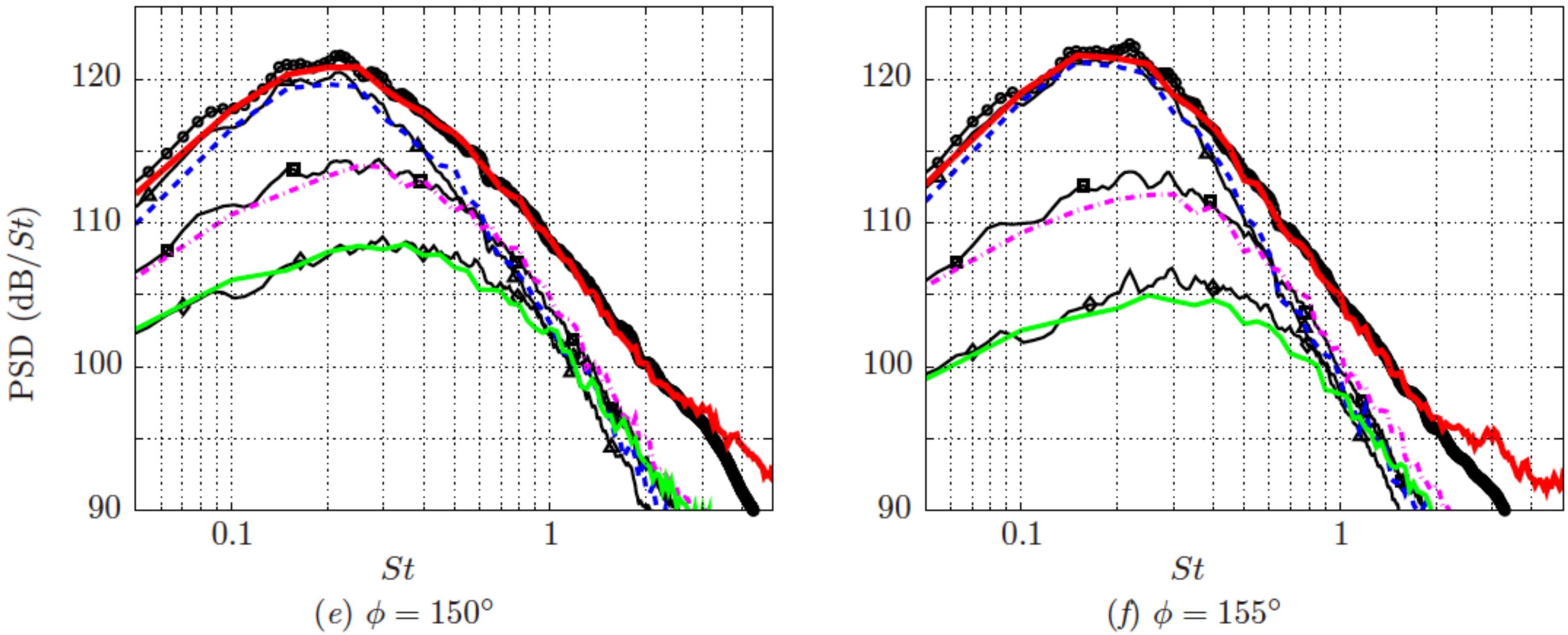
<u>Lines</u>: LES

(△ ,) mode $m = 0$

(□,) mode $m = 1$

(◇ ,) mode $m = 2$

Azimuthal decomposition of Exp & LES radiated noise: At inlet angles 150 deg & 155 deg



Symbols: Exp

(○ , ▬▬) **total**

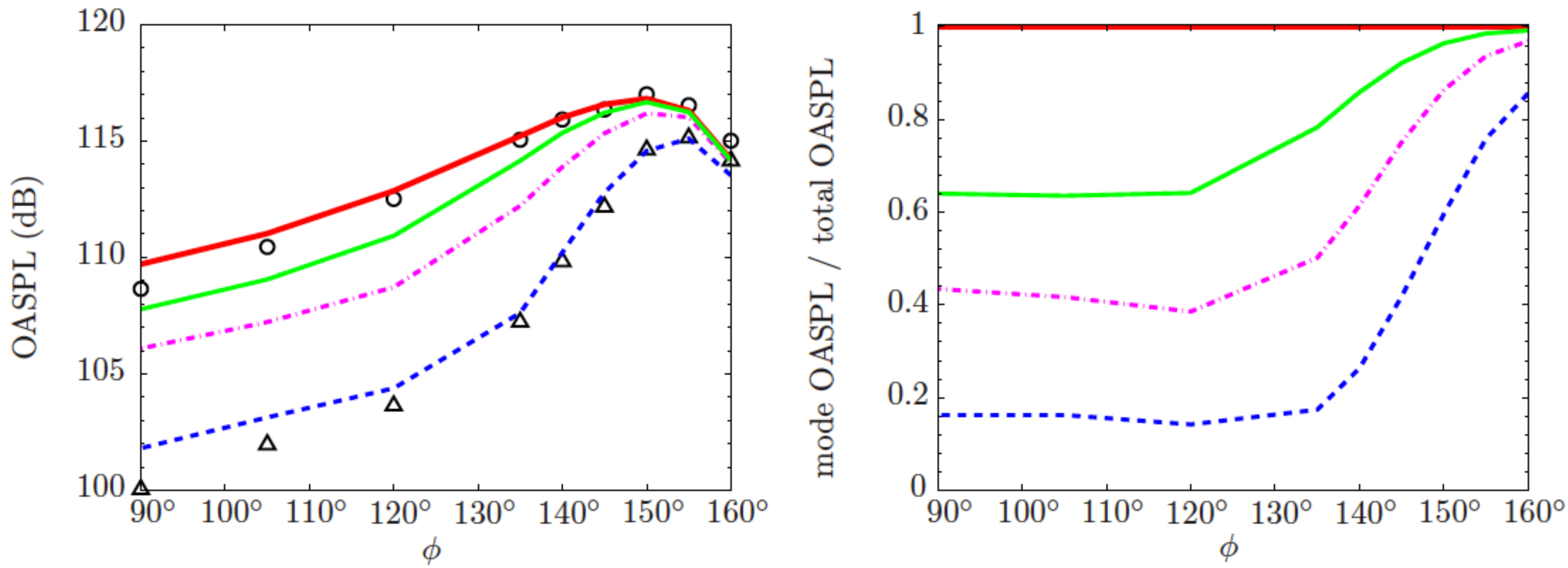
Lines: LES

(△ , - - - -) **mode** $m = 0$

(□, ─ · ─) **mode** $m = 1$

(◇ , ────) **mode** $m = 2$

Azimuthal decomposition of Exp & LES radiated noise: Overall Sound Pressure Levels



(a) Overall Sound Pressure Level

(b) Mode contributions

Symbols: Exp

(○ , ━━) **total**

Lines: LES

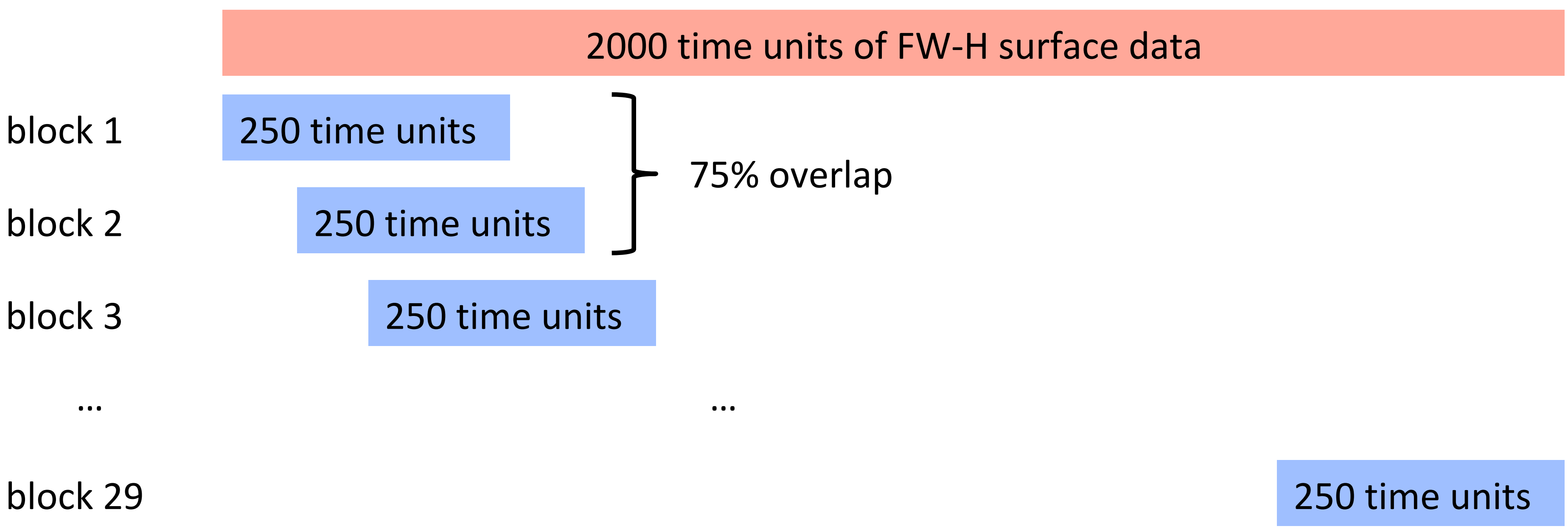
(△ , - - -) **mode** $m = 0$

(-·-) **modes** $m = 0$ & 1

(──) **mode** $m = 0$, 1 & 2

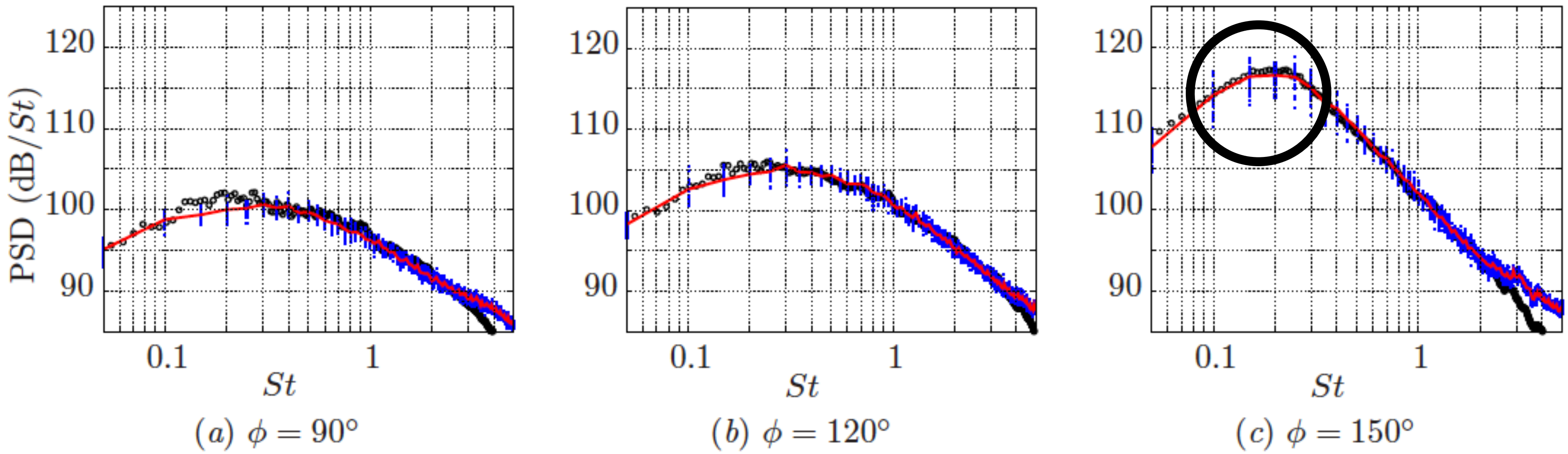
Noise temporal intermittency

- *Previous studies have suggested that the peak radiated noise around St ≈ 0.2 is observed to recur in temporally localized bursts*
    - Understanding the “louder” or “quieter” events in the flow could have interesting applications towards noise reduction strategies
- *Leverage long LES database generated during this project to investigate far-field noise temporal intermittency.*



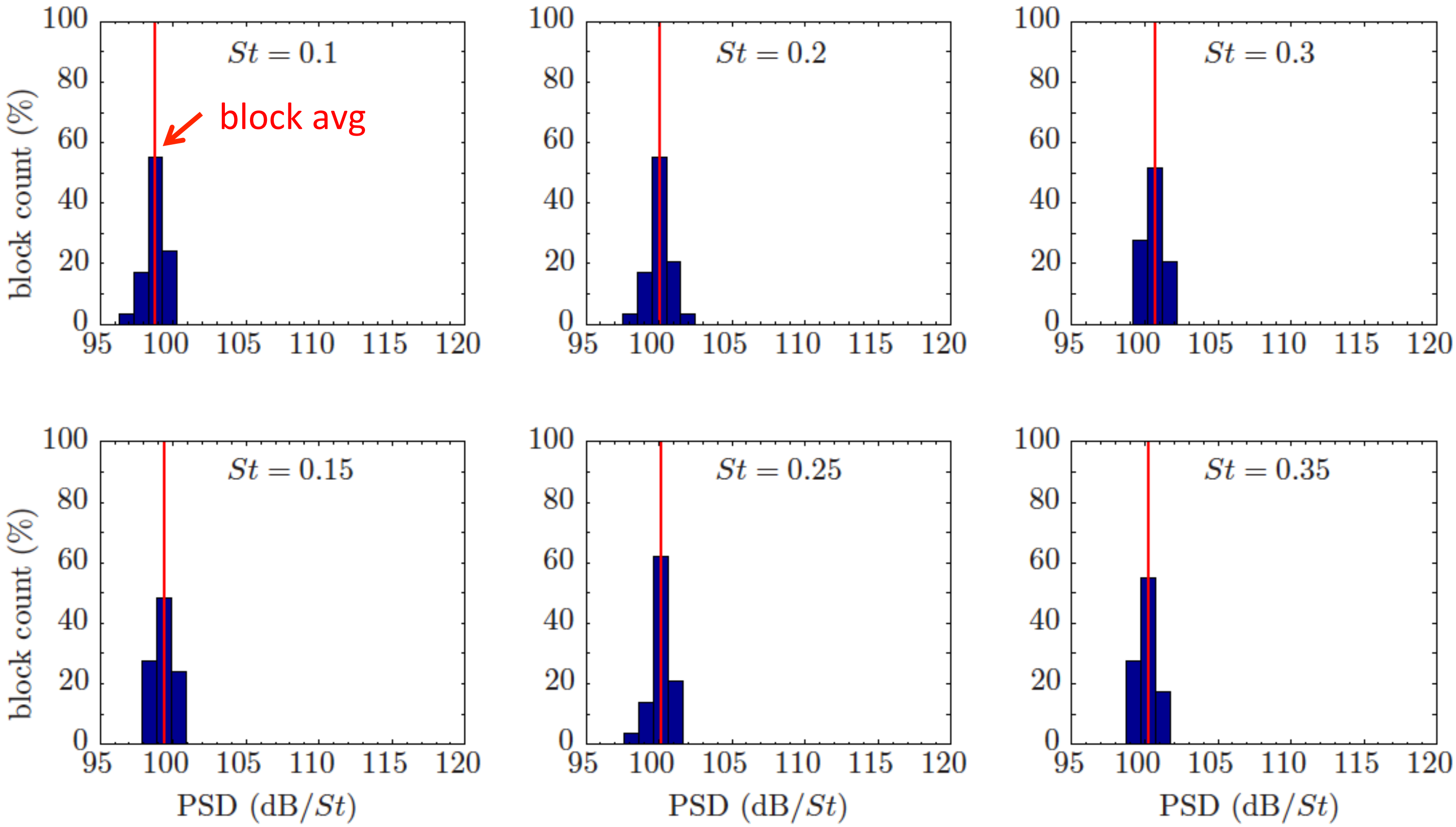
Block decomposition of **input FW-H data**:
29 blocks of 250 time units, 75% overlap
At inlet angles 90 deg & 150 deg

Larger scatter of data at St = 0.1 – 0.3



Experiment
LES – block average
LES – individual blocks

Block decomposition of **input FW-H data**:
29 blocks of 250 time units, 75% overlap
At inlet angle 90 deg & St=0.1 to 0.35



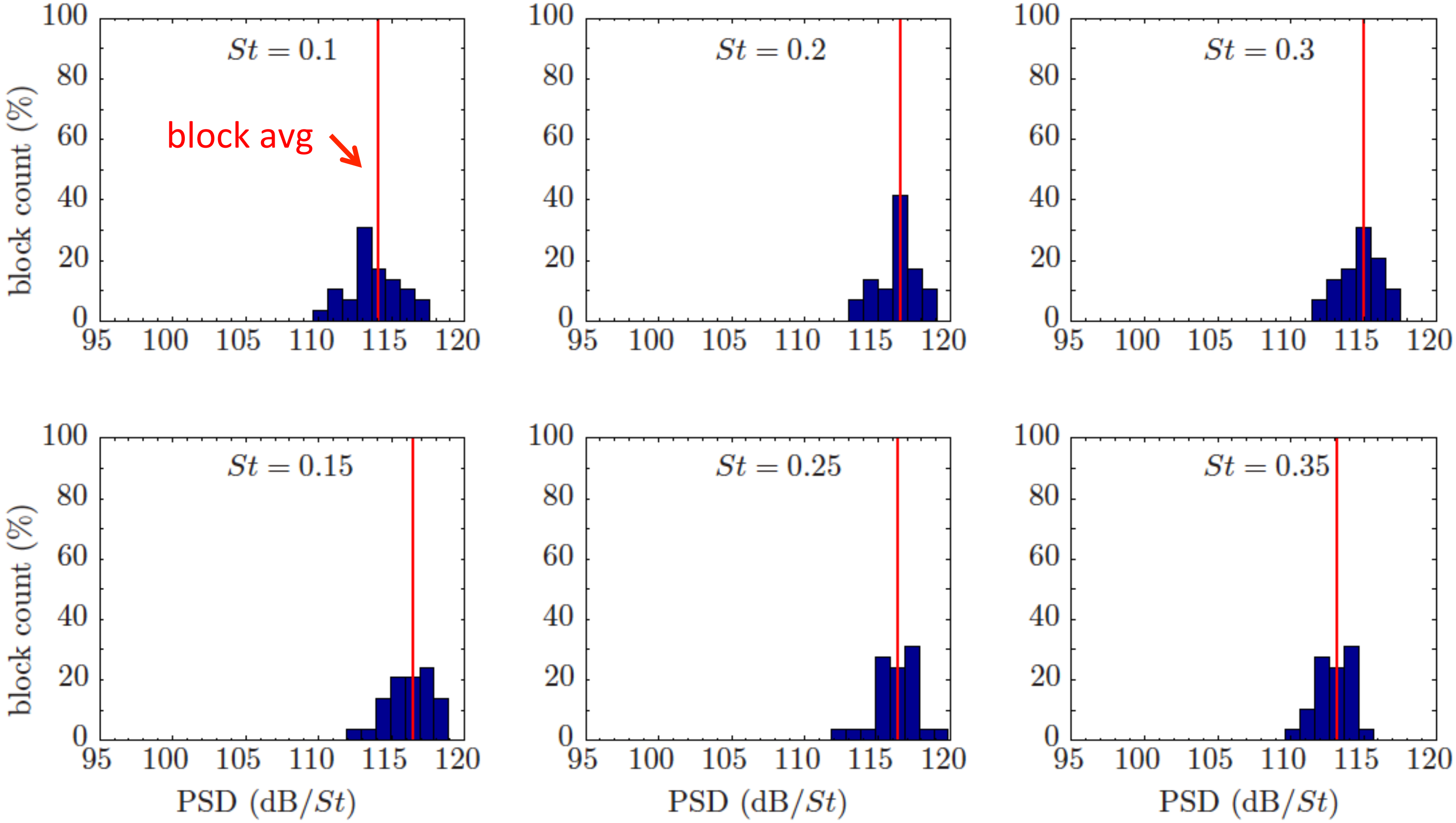
(a) $\phi = 90°$

probability distribution: narrow head, small support (Gaussian-like distribution)

up to 85% chance for block data to be with +/- 1dB of mean

no significant intermittency

Block decomposition of **input FW-H data**:
29 blocks of 250 time units, 75% overlap
At inlet angle 150 deg & St=0.1 to 0.35



$(b)\ \phi = 150°$

probability distribution: wider head, larger support

up to 50% chance for block data to be with +/- 1dB of mean

Evidence of intermittency in wavepacket noise radiation

Supersonic Jets

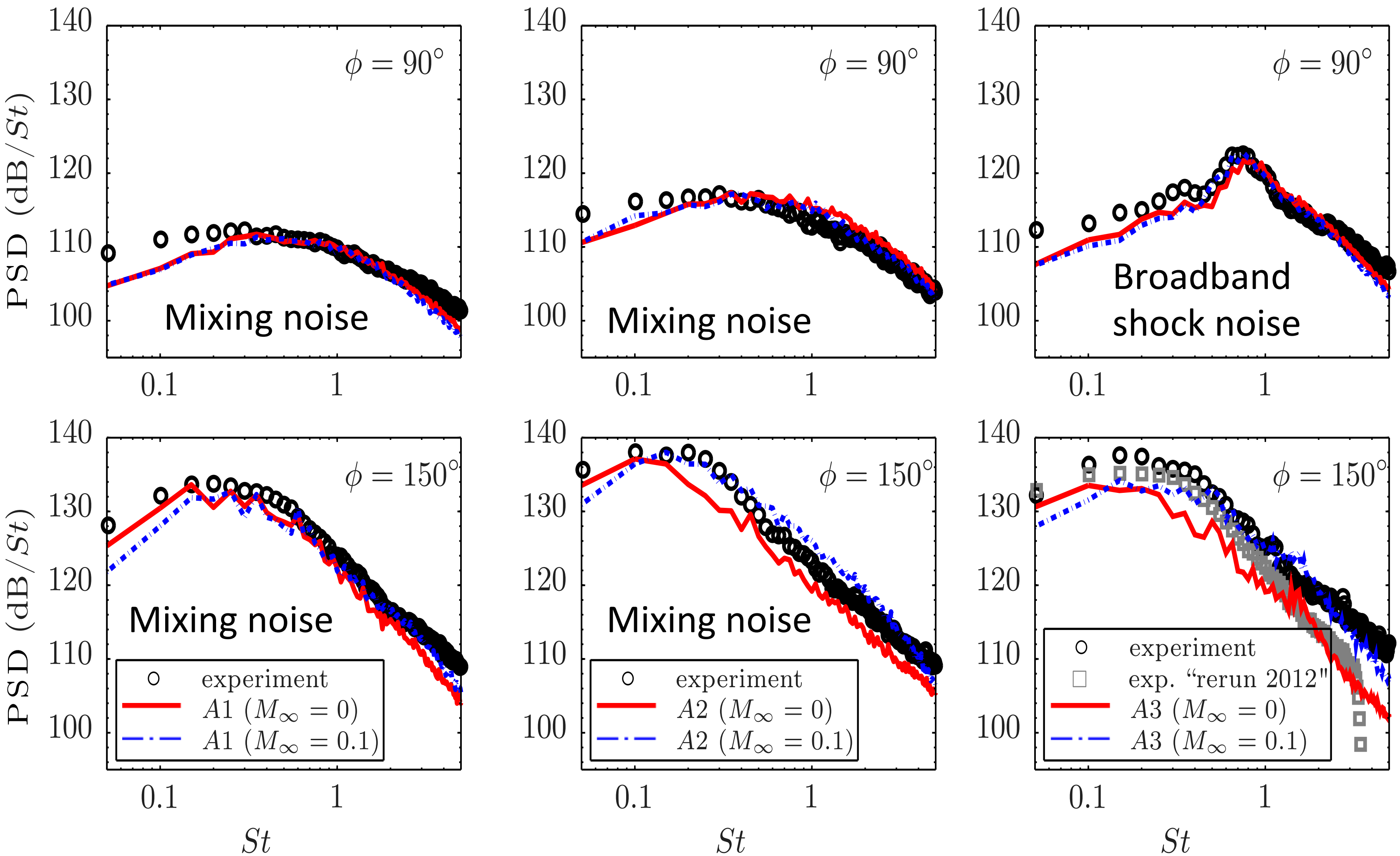
- *Mixing noise and broadband shock associated noise*
- *Crackle*
- *Screech*

Supersonic Jets

Bres et al. AIAA J (2017)

Blind comparisons (UTRC Expts.)

M_j = 1.5; T_j/T_∞ = 1; M_j = 1.5; T_j/T_∞ = 1.74; M_j = 1.35; T_j/T_∞ = 1.85;

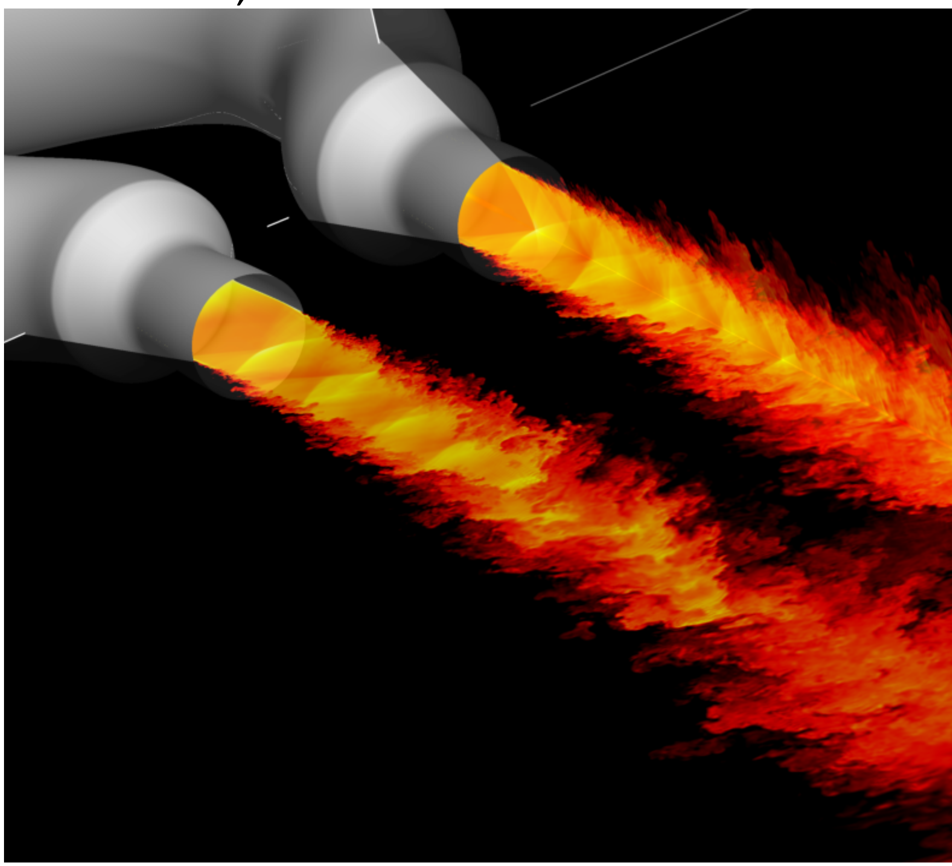


a) Isothermal ideally expanded jet **b) Hot ideally expanded jet** **c) Hot overexpanded jet**

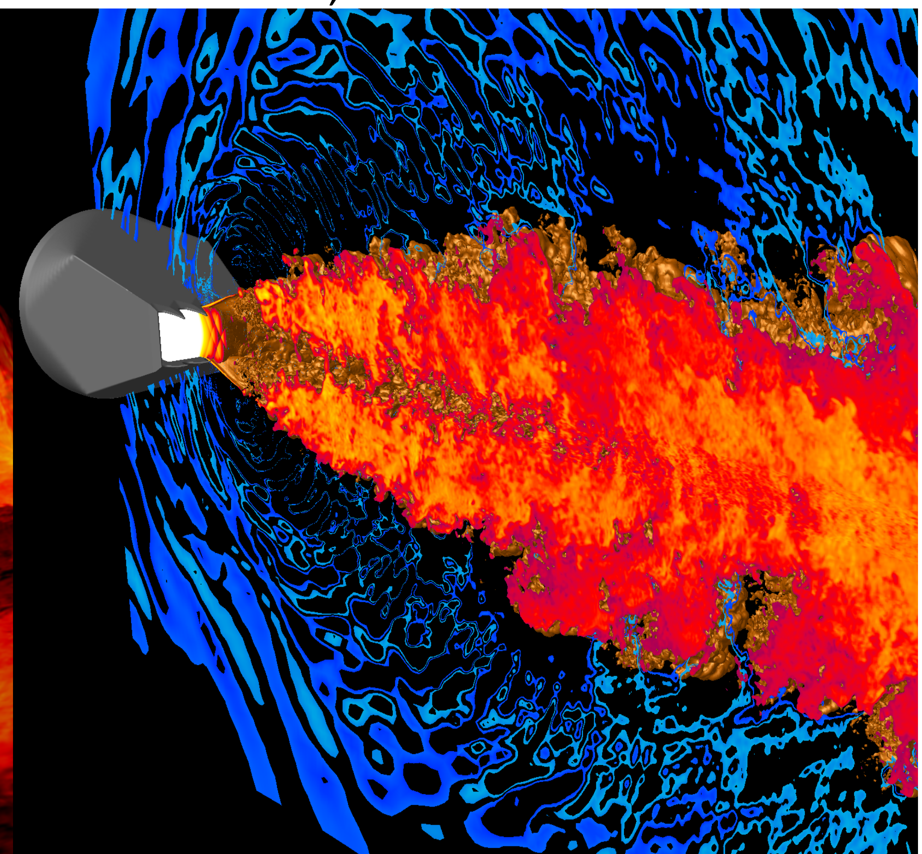
Some other hot supersonic jets

Cascade Technologies

Bres et al, 2014



Nichols et al, 2012

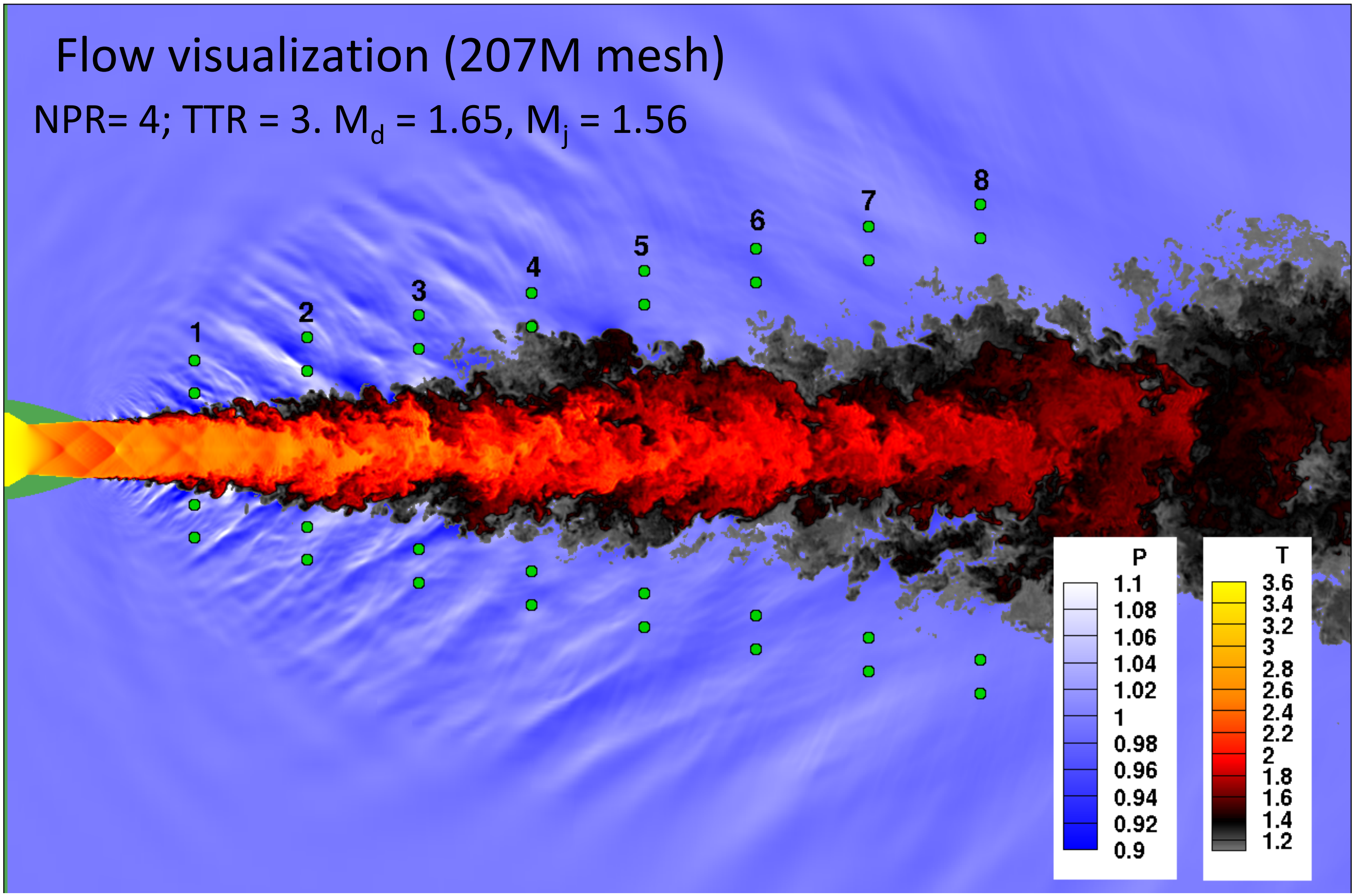


Crackle: Most Annoying Component of Supersonic Jet Noise (Ffowcs Williams, 1975)

Intermittent, Steep N-wave signature, Skewness

What causes crackle ? Mechanism unknown –source nonlinearity vs non-lin. Propgn.

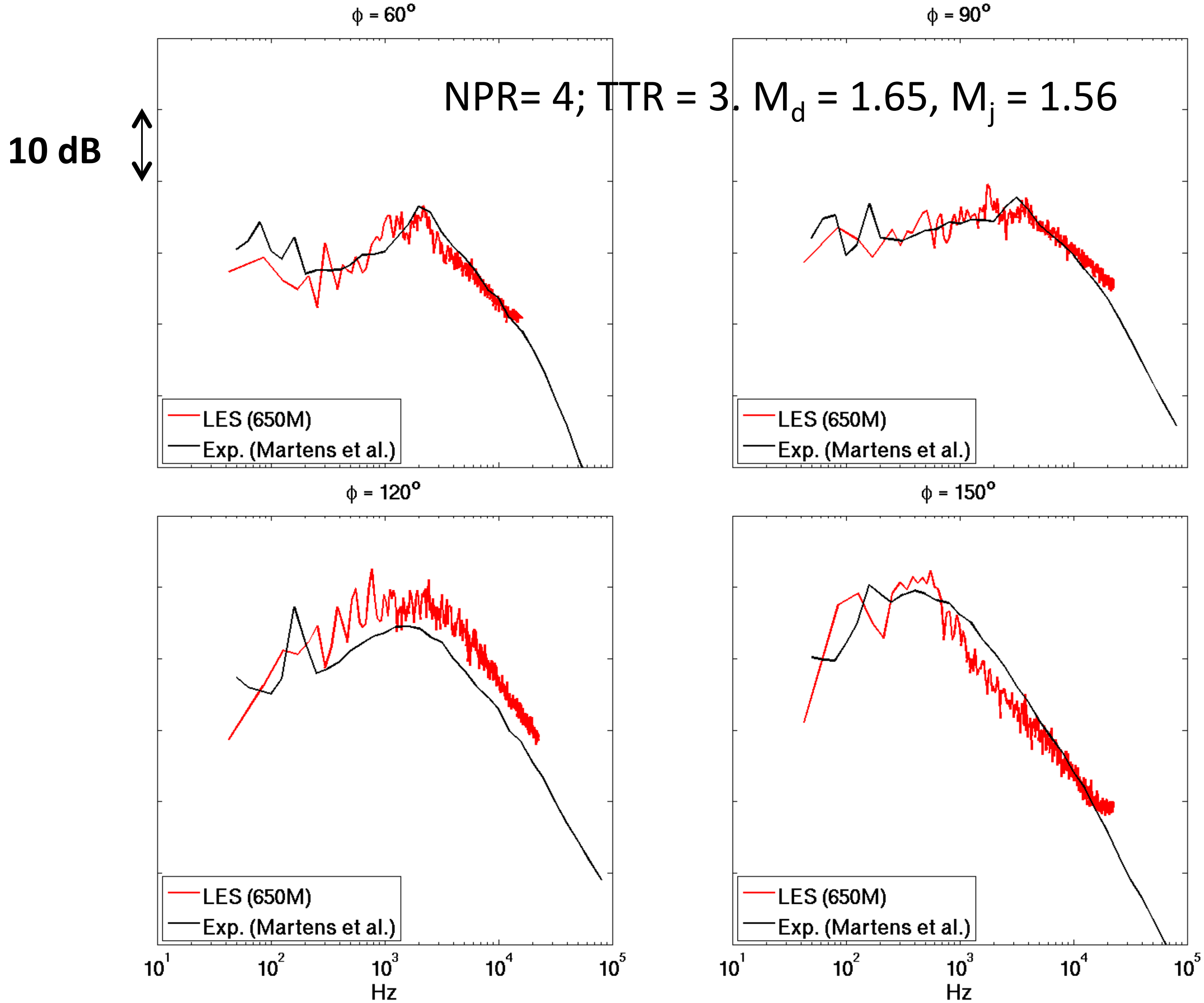
Nichols et. al. 2013, ASME J. Eng. Gas Turbines and Power 213, Vol. 135.



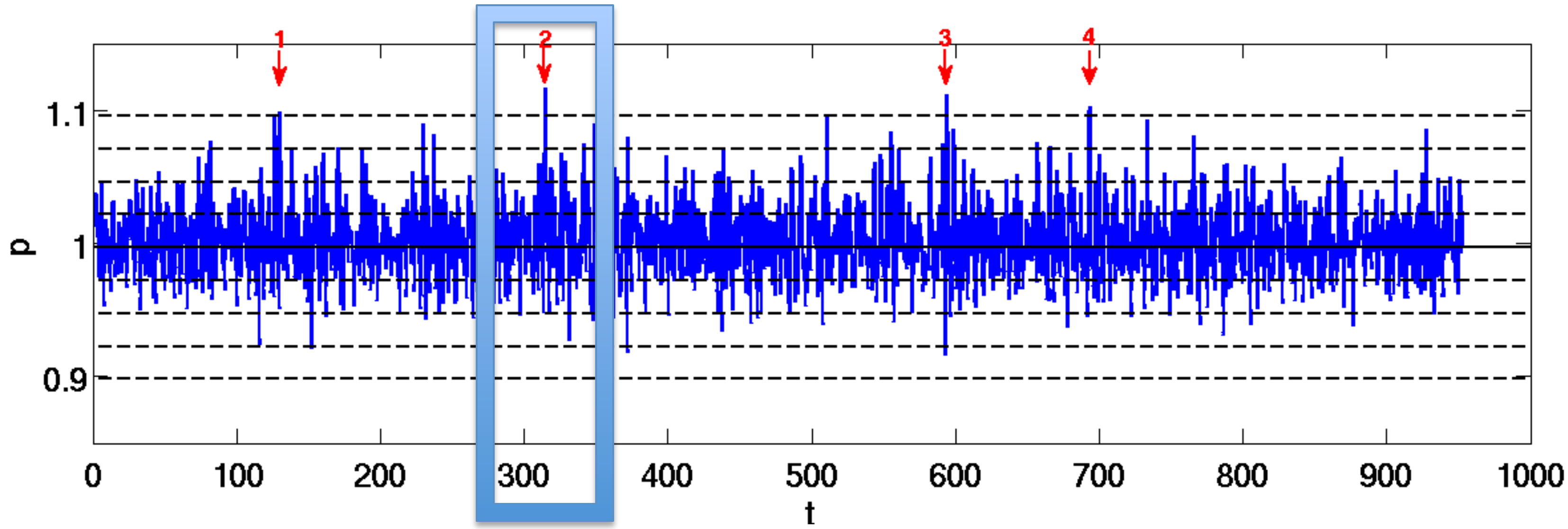
Validation: Far-field spectra

(measurements by S. Martens, GE)

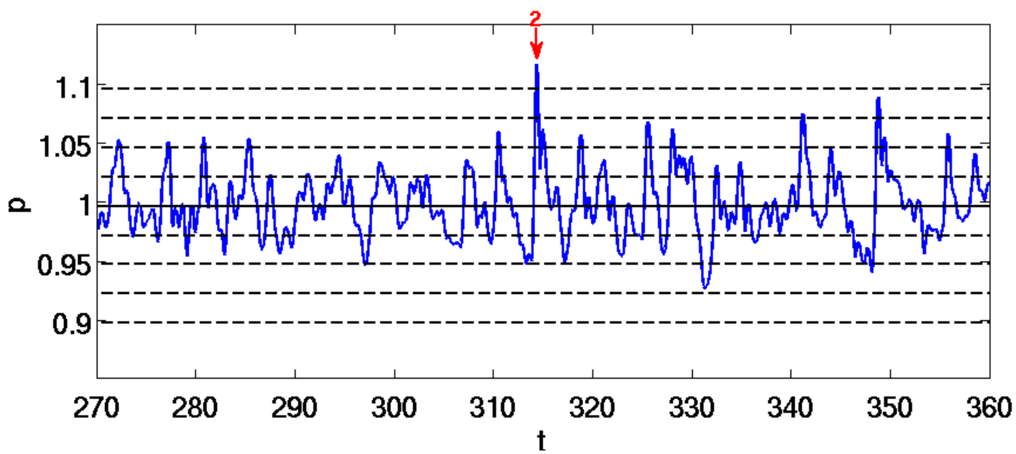
NPR= 4; TTR = 3. M_d = 1.65, M_j = 1.56

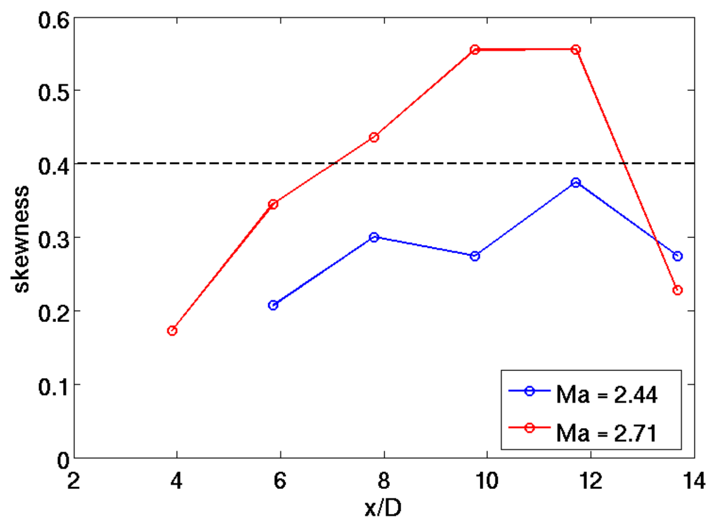


Pressure signal (skewness 0.425)

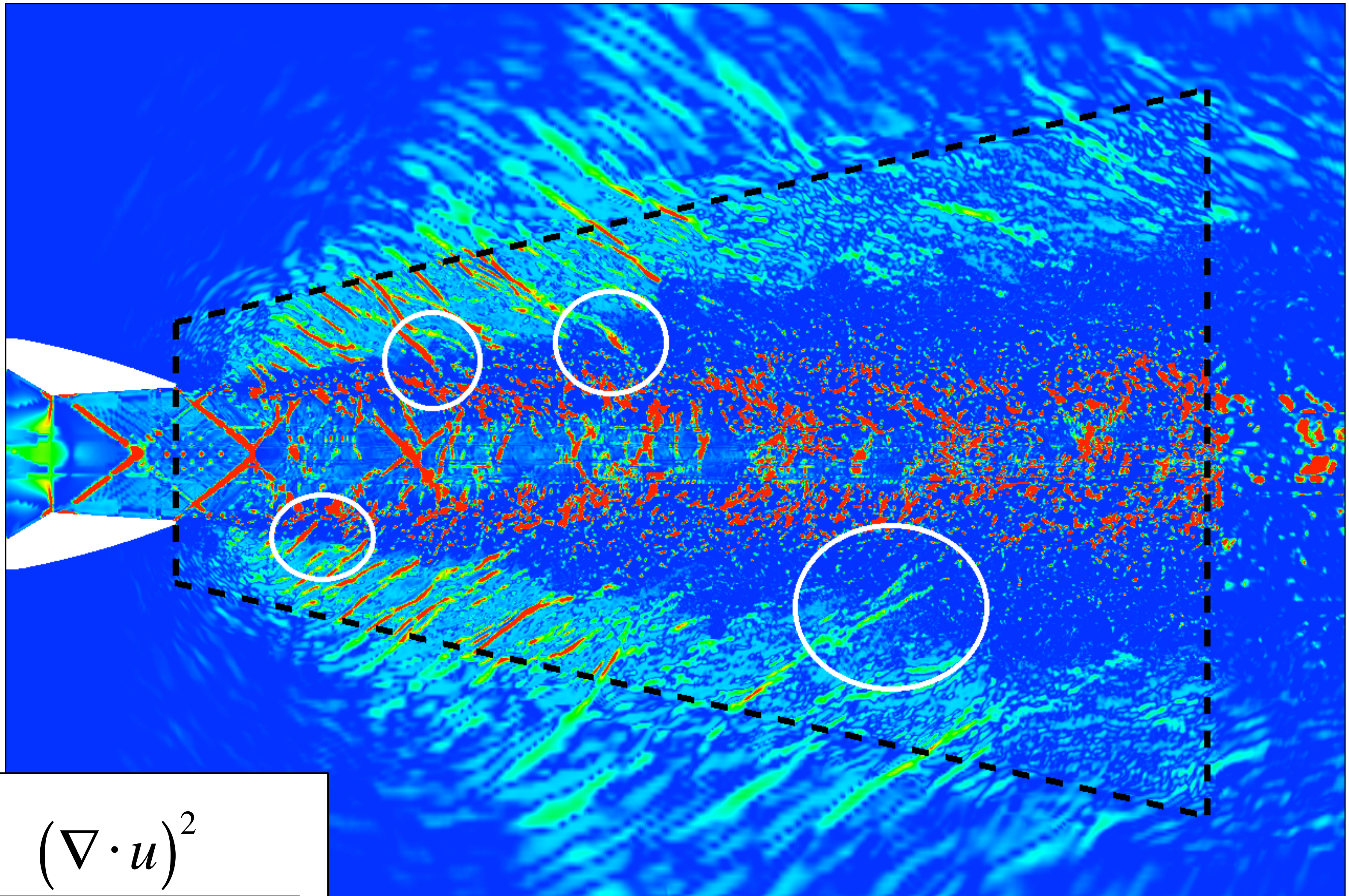


(Zoom)





Crackle is emitted as weak shocklets



$$\frac{(\nabla \cdot u)^2}{(\nabla \cdot u)^2 + \Omega^2 + \varepsilon}$$

(Ducros et al., 1999; Bhagatwala & Lele, 2009)

Modeling Jet Screech

→ Acoustically significant part of jet noise (when present)

→ significant fatigue loads on nozzle, empenage, control surfaces

→ Twin jet screech coupling specially damaging

Advanced airframe configurations

- Close coupling of Propulsion & Airframe
- Distributed propulsion/multiple nozzles

122 *M. B. Alkislar, A. Krothapalli and L. M. Lourenco*

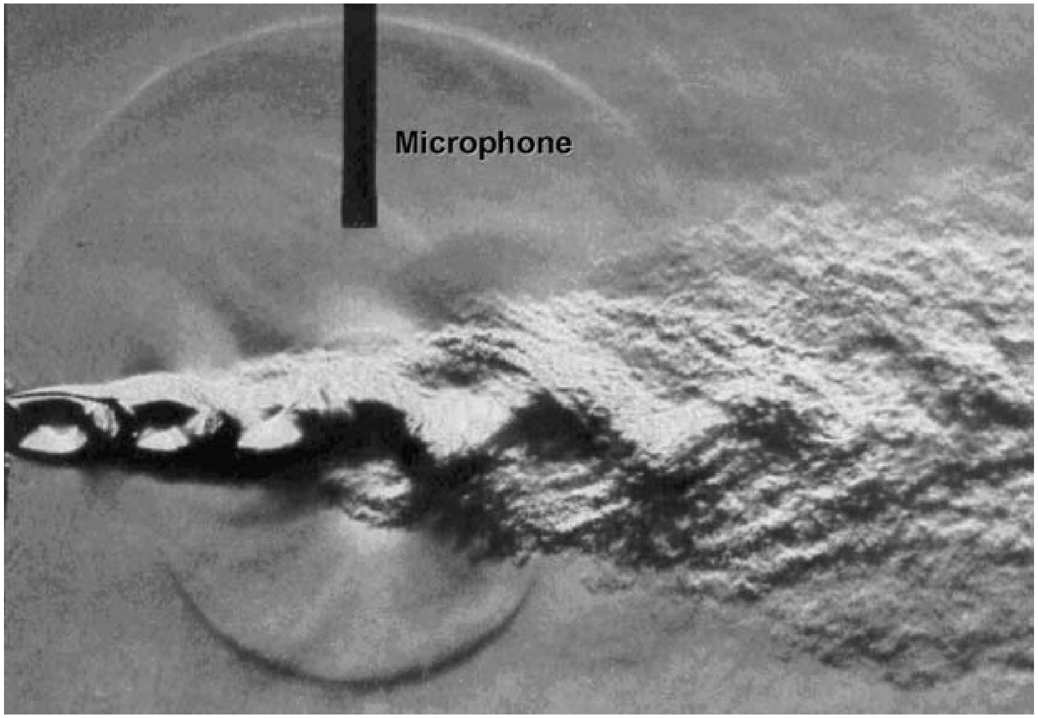


FIGURE 1. Schlieren picture of a screeching rectangular jet issuing from a converging nozzle. Nozzle aspect ratio of 10, nozzle pressure ratio of 3.5.

Current Status of Screech Prediction

Well established theory for screech frequency

Powell 1953, Tam 1980s, Raman 1990s

Screech as a Feedback loop

involving instability waves, shock-cell structure,

upstream traveling sound, receptivity at nozzle lip

Recently role of upstream traveling instability waves in feedback loop has been identified

Bogey & Gojon (2016) Impingment tones

Jordan et al. (2018) Screech (Caltech- Wavepackets)

Edgington-Mitchell (2018) AIAA Aviation

Current Status of Screech Prediction - II

No established theory for screech amplitude or mode staging

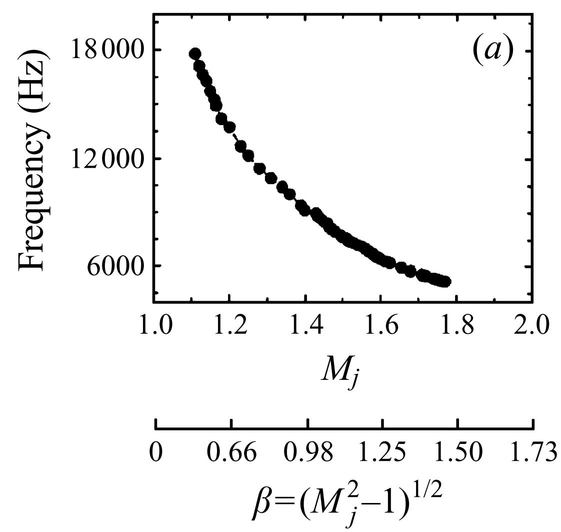
- *Observed since Powell 1953, Tam 1980s, Raman 1990s*
  - *Gain and loss in screech feedback loop*
    - *Powell 1964, Cain & Kerschen 1990s*

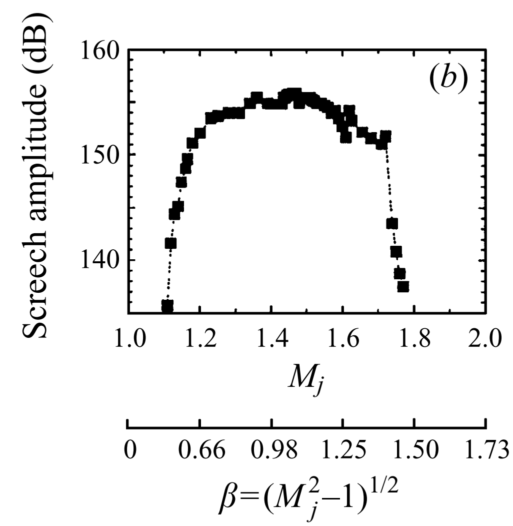
Shock leakage mechanism

- *Manning & Lele (1998,2000), Suzuki & Lele (2003)*
- *Shariff & Manning (2013)*

Observed Berland et al (2007)
de Cacqueray et al (2011, 2014)
Edgington-Mitchell (2017-18)

Raman 1997 JFM

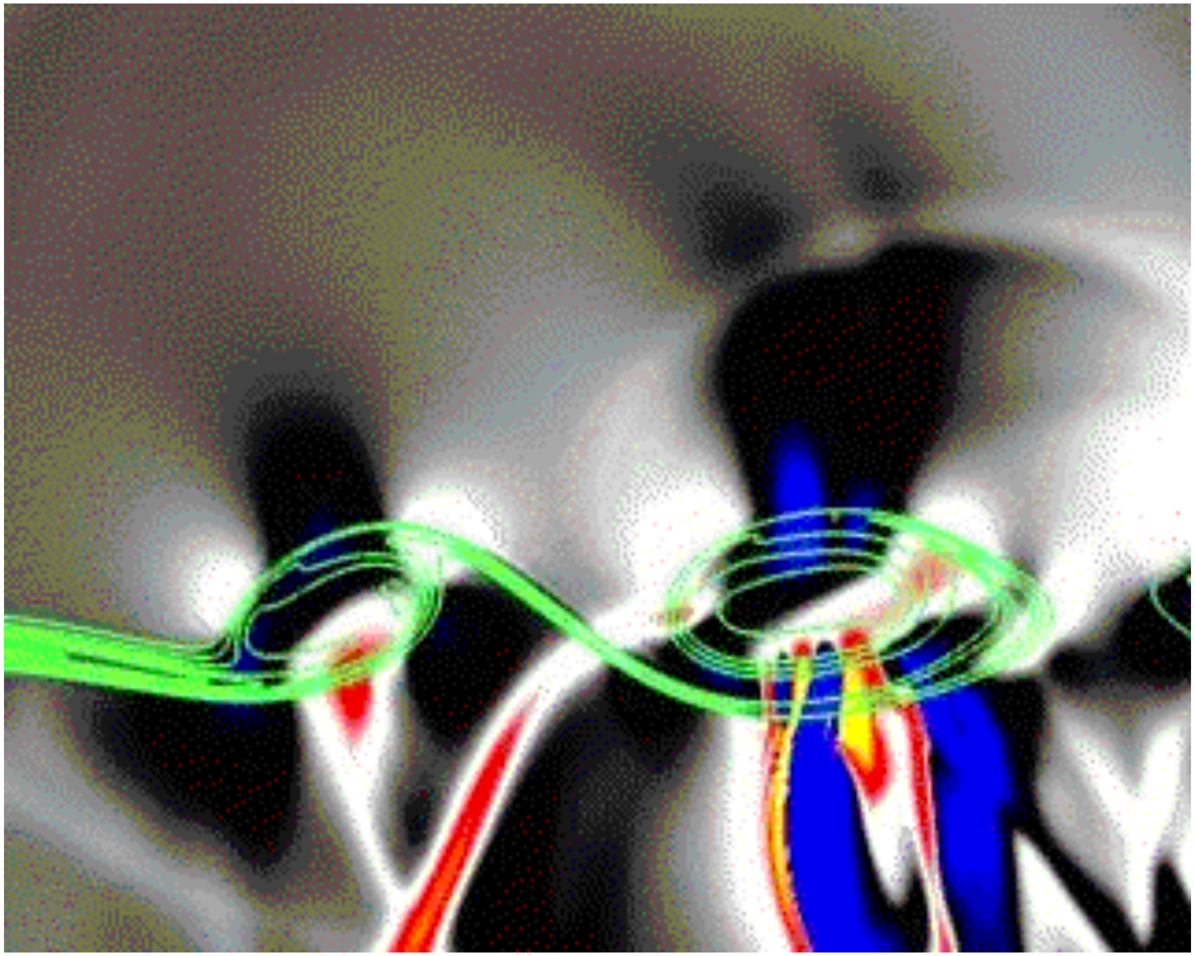




Current Status of Screech Prediction - II

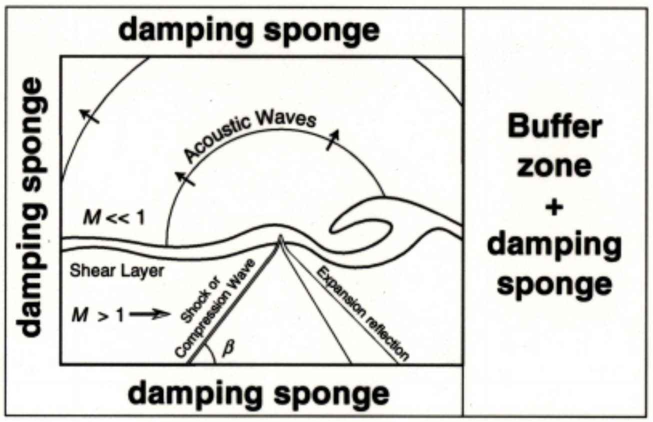
Shock leakage mechanism – Numerical Model Problem

Manning & Lele (1998,2000), Suzuki & Lele (2003)

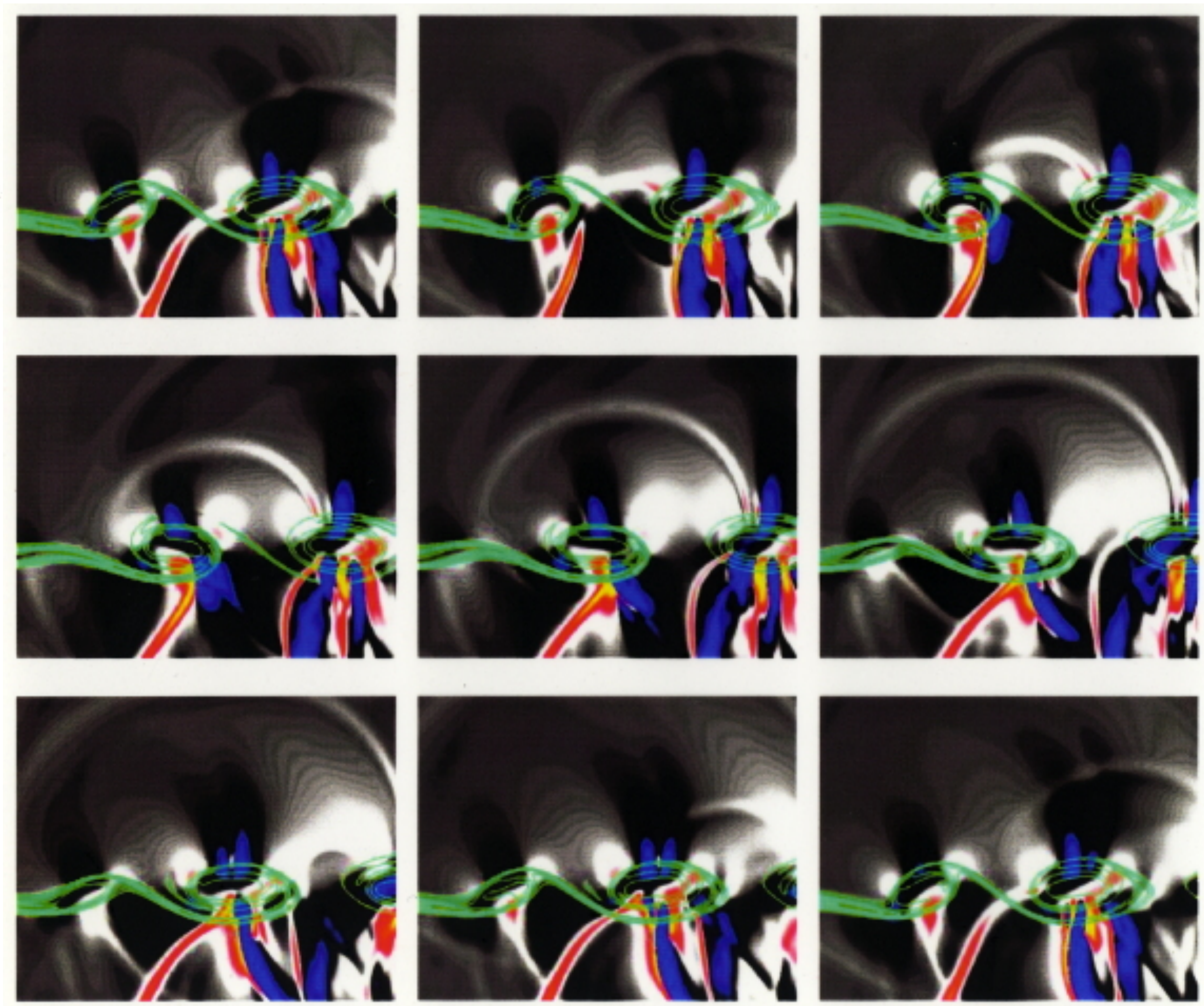


Supersonic Jet Noise – Numerical Experiments

Manning T. & L (2000), Suzuki T. & L (2003) Shock Leakage



Model problem for screech emission



T. A. Manning

Is this mechanism operative in a turbulent jet with screech ?

Some open Issues:

- *Reduced models of jet noise – what complexity is required to capture effects of noise reduction concepts ?*
  chevrons, tabs, micro-jets, etc.
  Optimal mixing enhancement for noise reduction

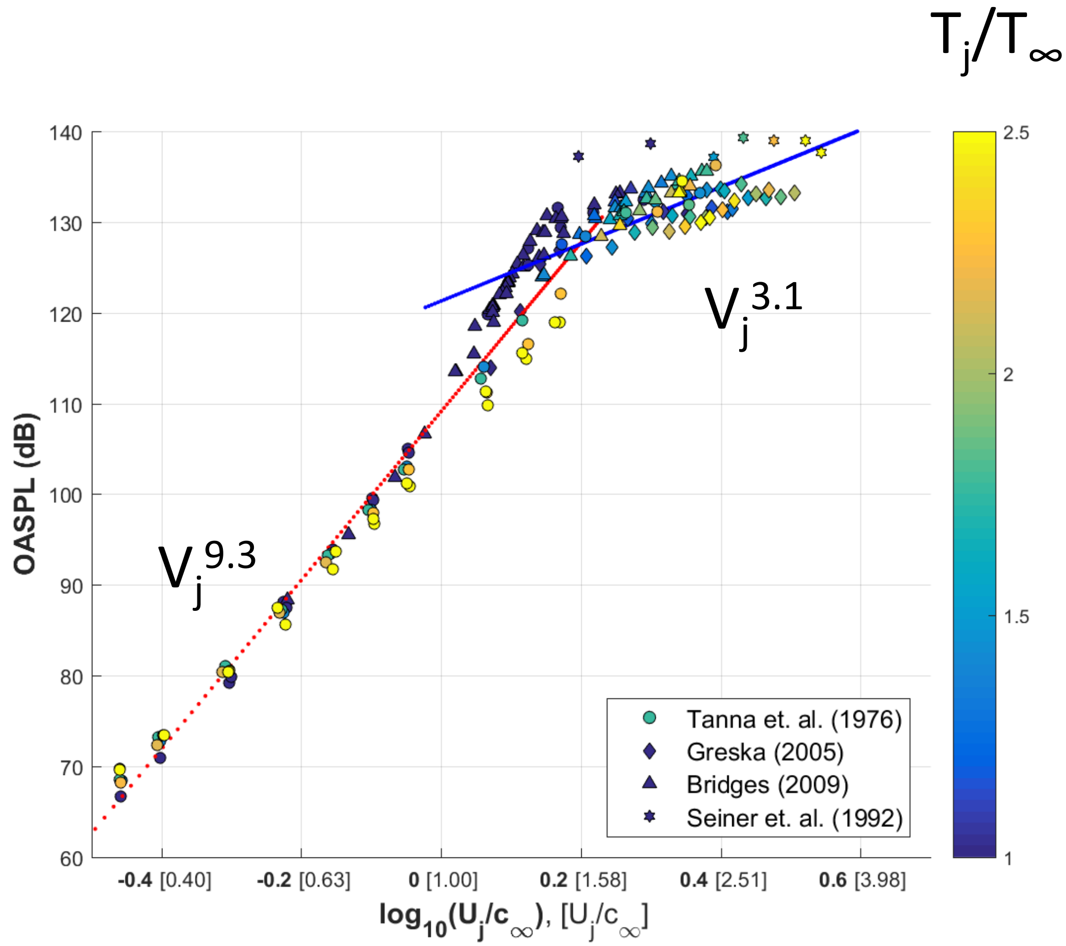
- *Scaling of supersonic hot jet noise*

- *Two-components of jet noise*

- *Amplitude prediction of self-excited tonal emission*
  (edge tones, screech)

Scaling of Hot Supersonic Jet Noise

OASPL in peak direction

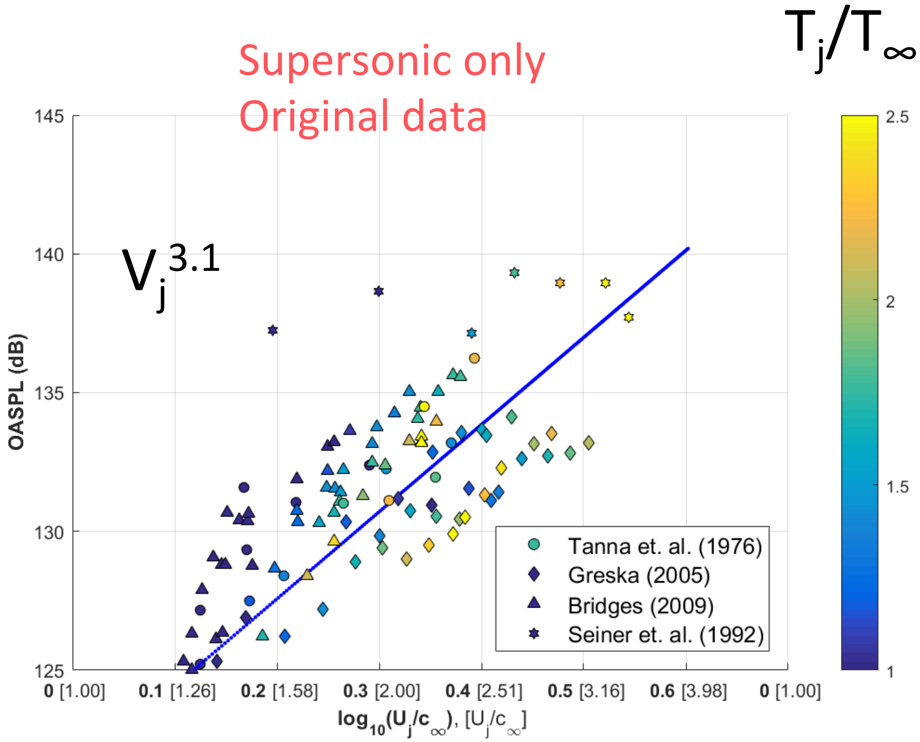


From: Sinha & Lele AIAA-2017-3027

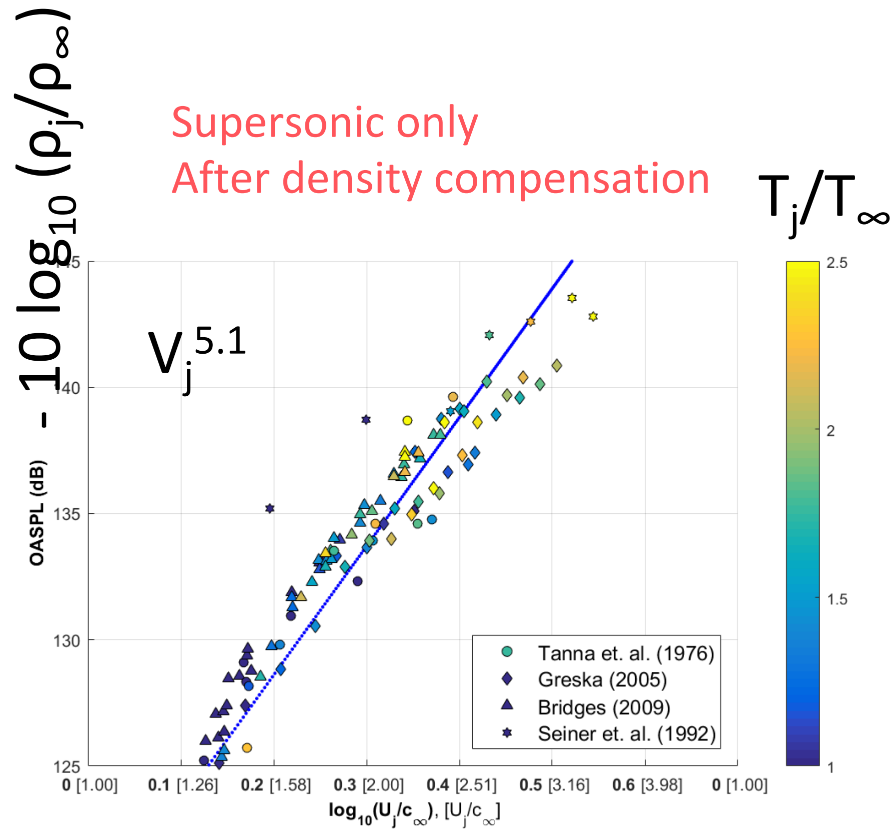
Scaling of Hot Supersonic Jet Noise

Peak Noise Radiation

Supersonic only
Original data



Supersonic only
After density compensation



Limited range of U_j/C_∞ , T_j/T_∞

Ultimate scaling over a wider range ?

From: Sinha & Lele AIAA-2017-3027

Some open Issues :

- *Reduced models of jet noise – what complexity is required to capture effects of noise reduction concepts ?*
  chevrons, tabs, micro-jets, etc.
  Optimal mixing enhancement for noise reduction

- *Scaling of supersonic hot jet noise*

- *Two-components of jet noise*

  Different mechanisms of radiation ?
  Different components − coherent scales and turbulence ?

- *Amplitude prediction of self-excited tonal emission (edge tones, screech)*

- *More complete Theory ?*

Conclusions

- *An isothermal Mach 0.9 jet at Reynolds number Re = 10^6 was simulated with unstructured LES*
- *Modeling is applied inside the nozzle to ensure a fully turbulent jet*
  - Localized near-wall adaptive mesh refinement
    - *significant improvements at minimal computation cost*
  - 1D RANS Wall modeling
    - *improved RMS profiles and predictions of fluctuations*
  - Synthetic turbulence
    - *weak sensitivity to forcing parameters*
    - *best results when combined with wall model*
- *An extensive LES database was generated for analysis and modeling of jet-noise source mechanisms*
  - Azimuthal decomposition showed that the first 3 modes m=0,1 & 2 are dominant
  - Analysis confirmed temporal intermittency of the peak radiated noise
  - LES uncovered a novel class of resonant acoustic modes that are trapped within the potential core of the jet (AIAA-2016-2808, AIAA-2016-2809)
  - Additional analysis, PSE and experiments: AIAA-2016-2865, AIAA-2016-3056, AIAA-2016-3016

Conclusions -II

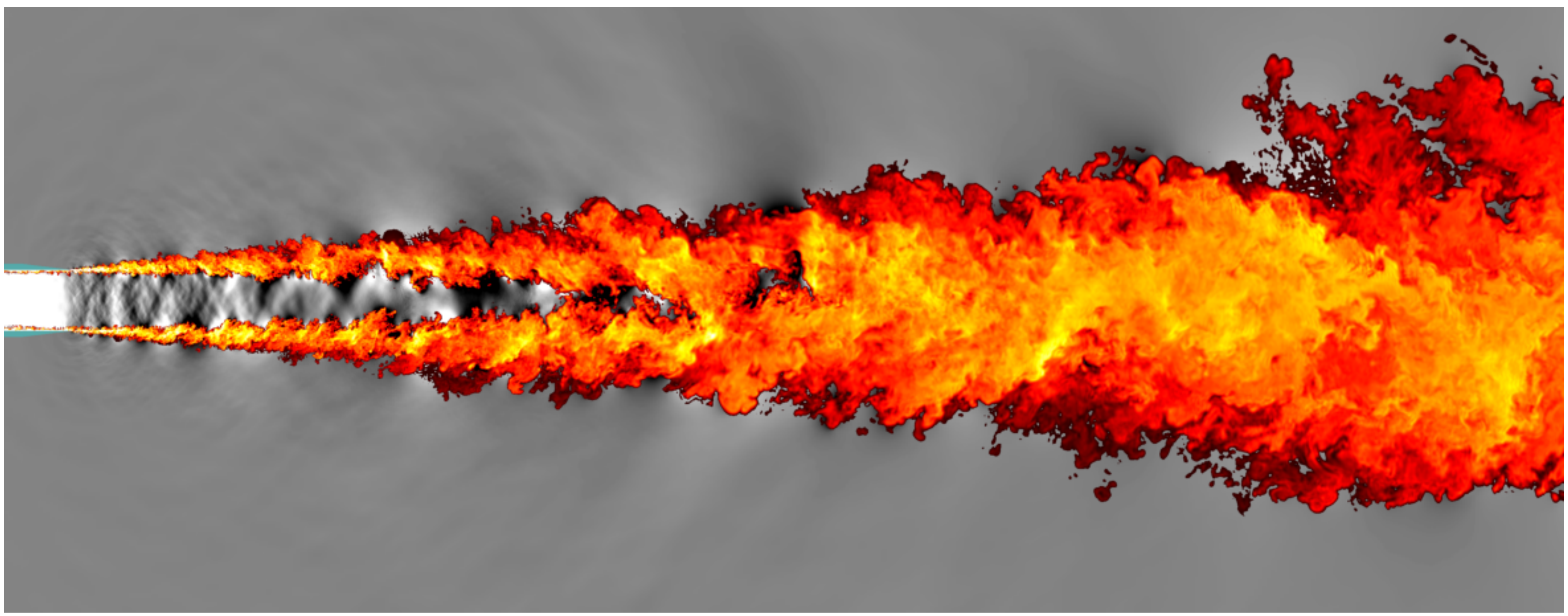
- *Many questions on jet noise remain open … scaling,.. theory*
  Combined numerical simulations and experiments may help settle them

- *Numerical simulations have many potential uses*

  - Low order modeling of jet noise
  - Analysis/Design/Optimization/Control
  - Numerical experiments -- *What If ?*
    Aha! Physical Understanding

Acknowledgements

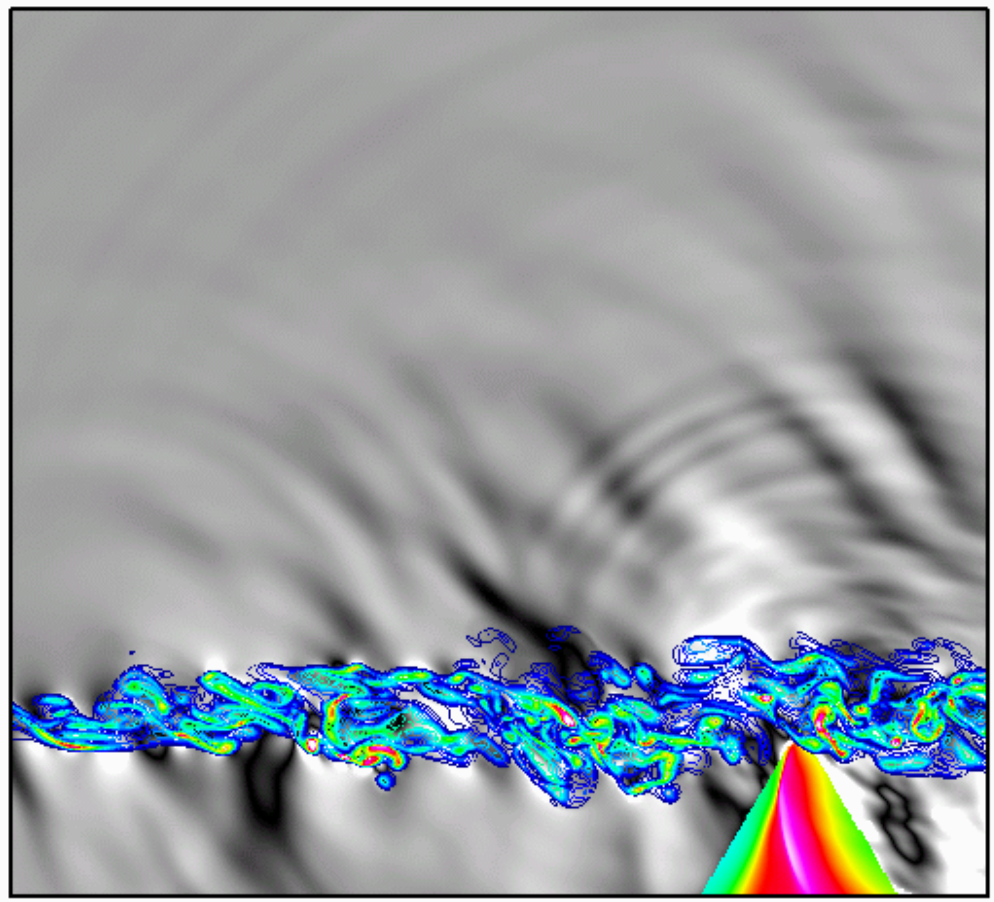
- *LES work supported in part by NAVAIR SBIR project, under the supervision of Dr. John Spyropoulos*
- *Computer time provided by HPCMP on DoD facilities in ERDC and AFRL.*
- *Experimental work supported by the French National Research Agency (ANR) through the project COOLJAZZ*



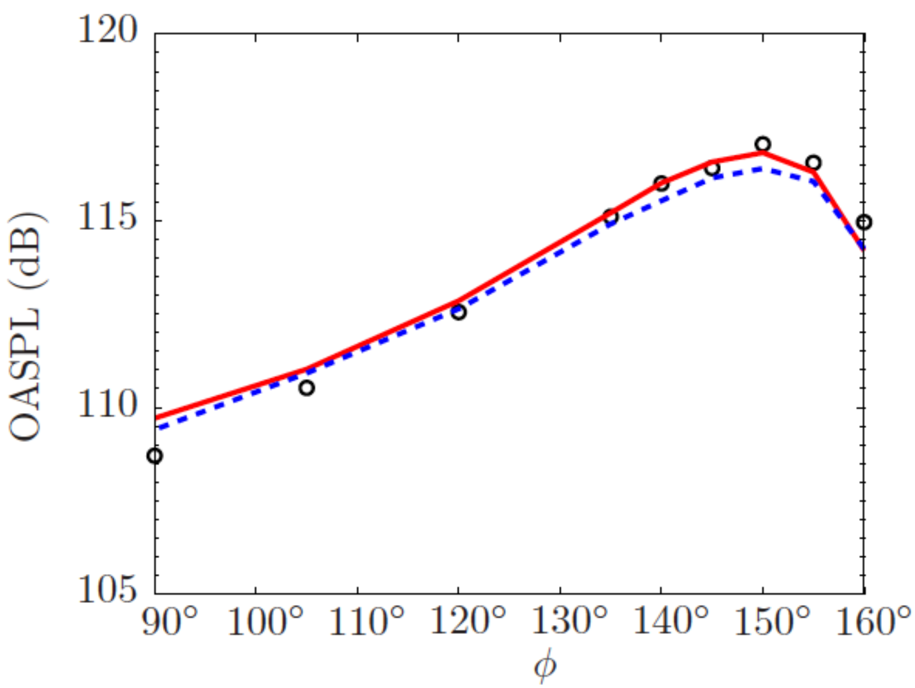
Supersonic Jet Noise – Numerical Experiments

Lui, C. & L (2003)

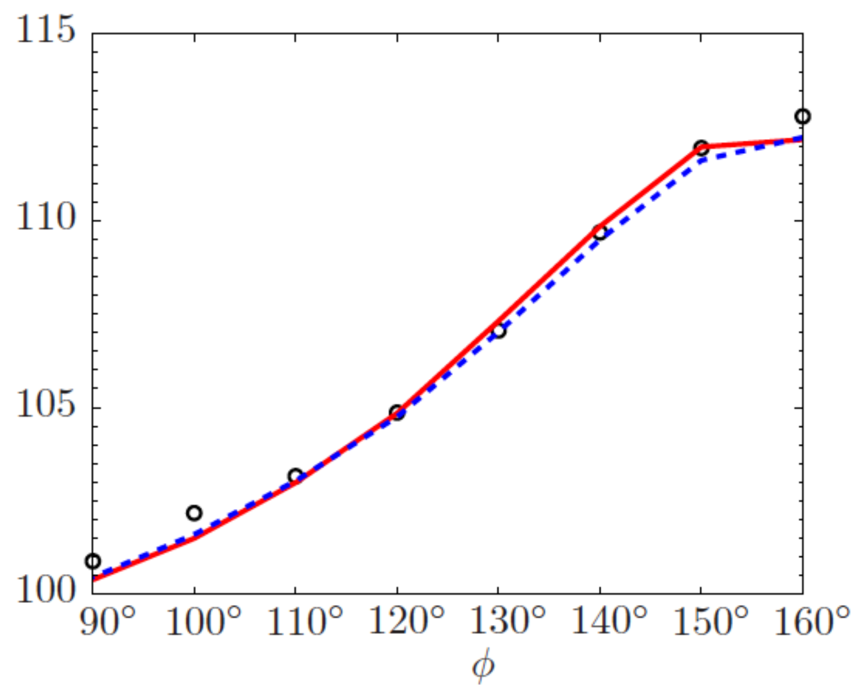
Model problem for screech/broadband noise emission



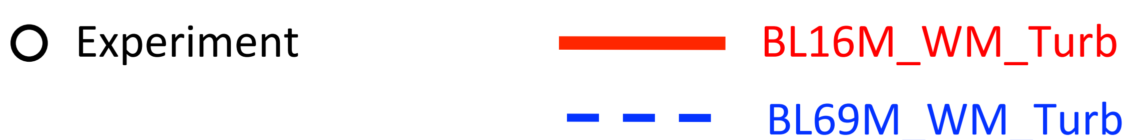
Radiated noise directivity



(a) Cylindrical array of radius $r = 14.3D$



(b) Far-field array at constant distance $50D$



LES Database for modeling and analysis

- *Case “BL16M_WM_Turb”*
  - down-selected to generate the LES database for Stanford CTR summer program 2014
  - runtime extended from 300 to 2000 time units
  - full LES flow field collected every 0.2 time units (sampling frequency St=5)

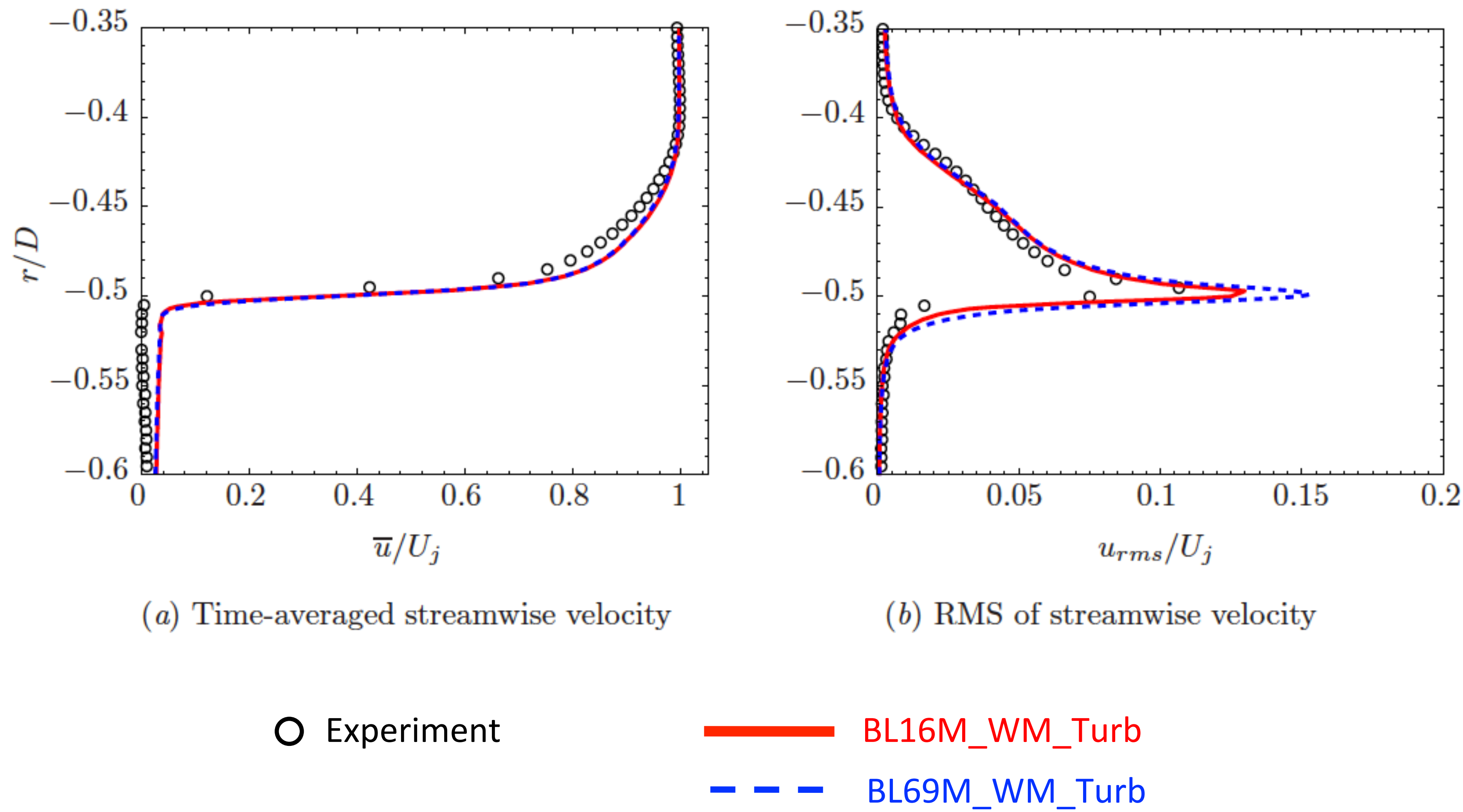
- *Simulation on refined mesh: case “BL69M_WM_Turb”*
  - LES data collected for 1150 time units
  - full LES flow field collected every 0.2 time units (sampling frequency St=5) & subset collected every 0.05 time units (sampling frequency St=20)

Case name	Mesh size	Refinement BL	Refinement jet	M_j	T_j/T_∞	Re	dtc_∞/D	$\Delta tc_\infty/D$	$t_{sim}c_\infty/D$
BL16M_WM_Turb	15.9×10^6	$\times$		0.9	1.0	10^6	0.001	0.2	2000
BL69M_WM_Turb	69.0×10^6	$\times$	$\times$	0.9	1.0	10^6	0.0005	0.2 0.05	1150 500

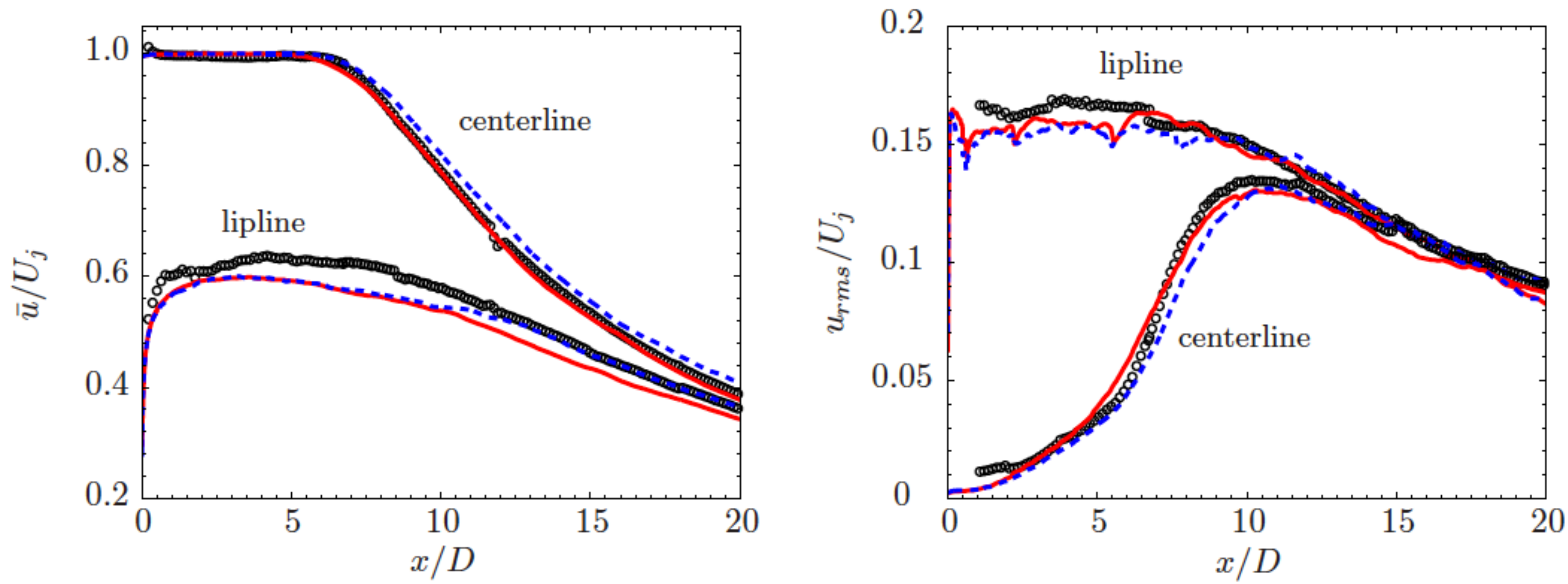
300 Kcore-h (12 days on 1024 cores)

2000 Kcore-h (16 days on 5152 cores)

Nozzle exit profiles



Centerline and lipline profiles



(a) Time-averaged streamwise velocity

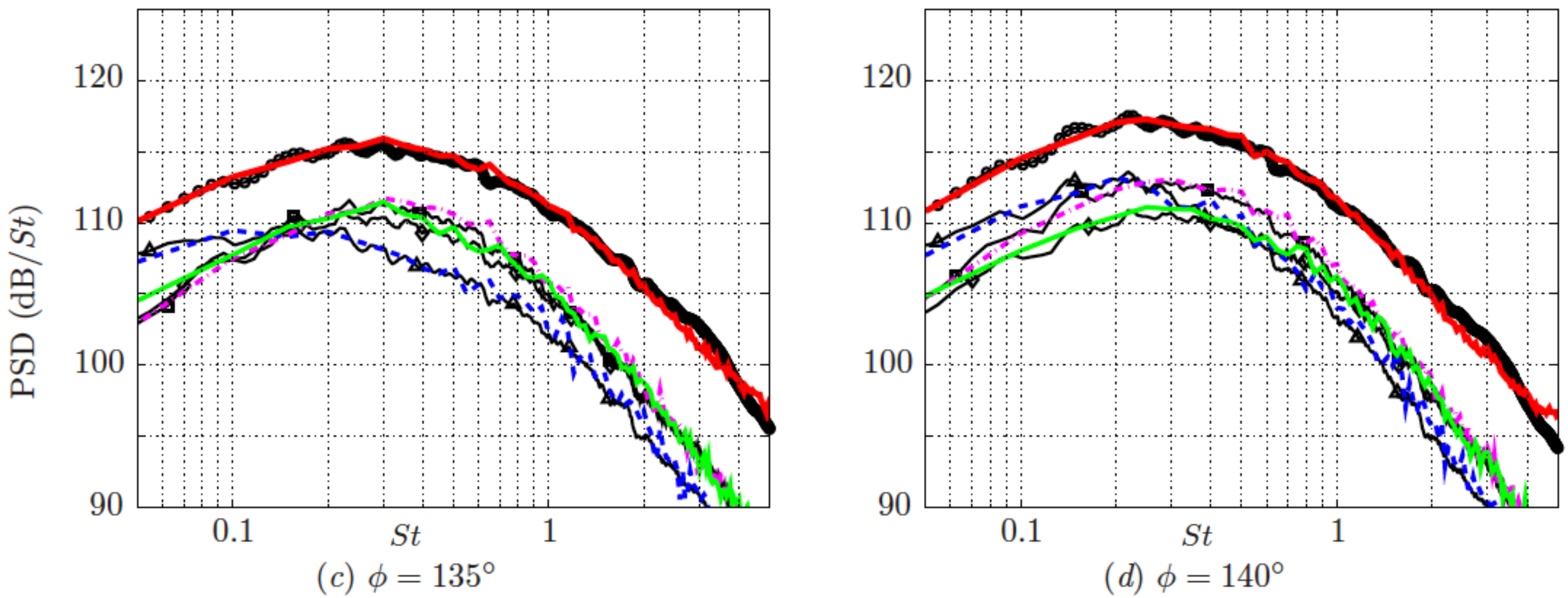
(b) RMS of streamwise velocity

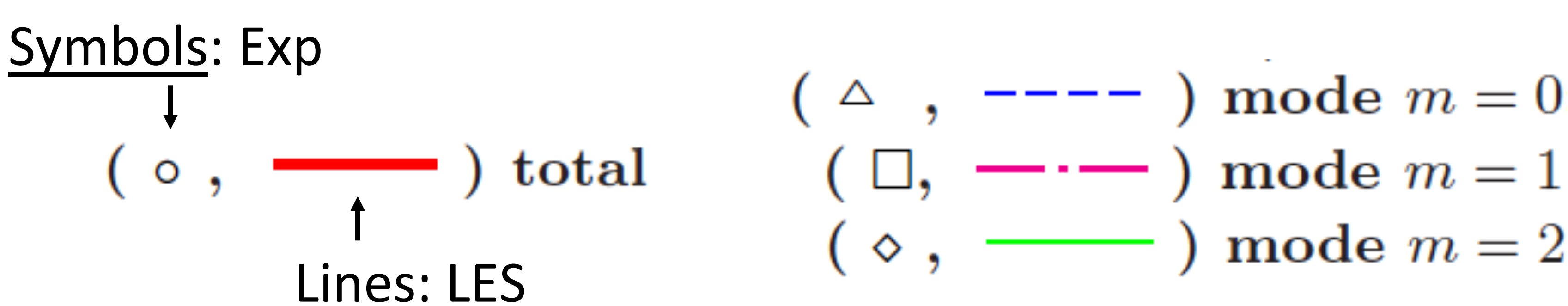
O Experiment

BL16M_WM_Turb

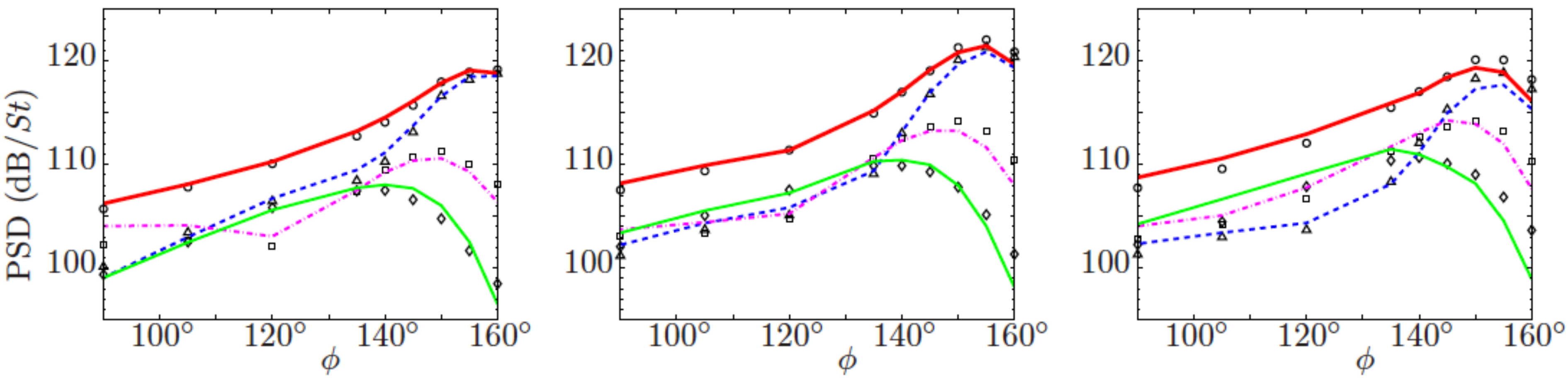
BL69M_WM_Turb

Azimuthal decomposition of Exp & LES radiated noise:
At inlet angles 135 deg & 140 deg

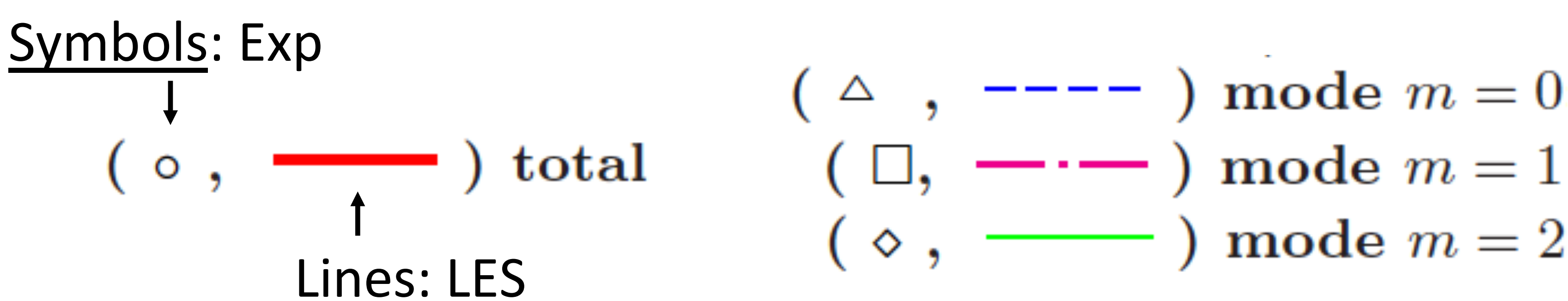




Azimuthal decomposition of Exp & LES radiated noise: At frequencies St=0.1, 0.2 & 0.3

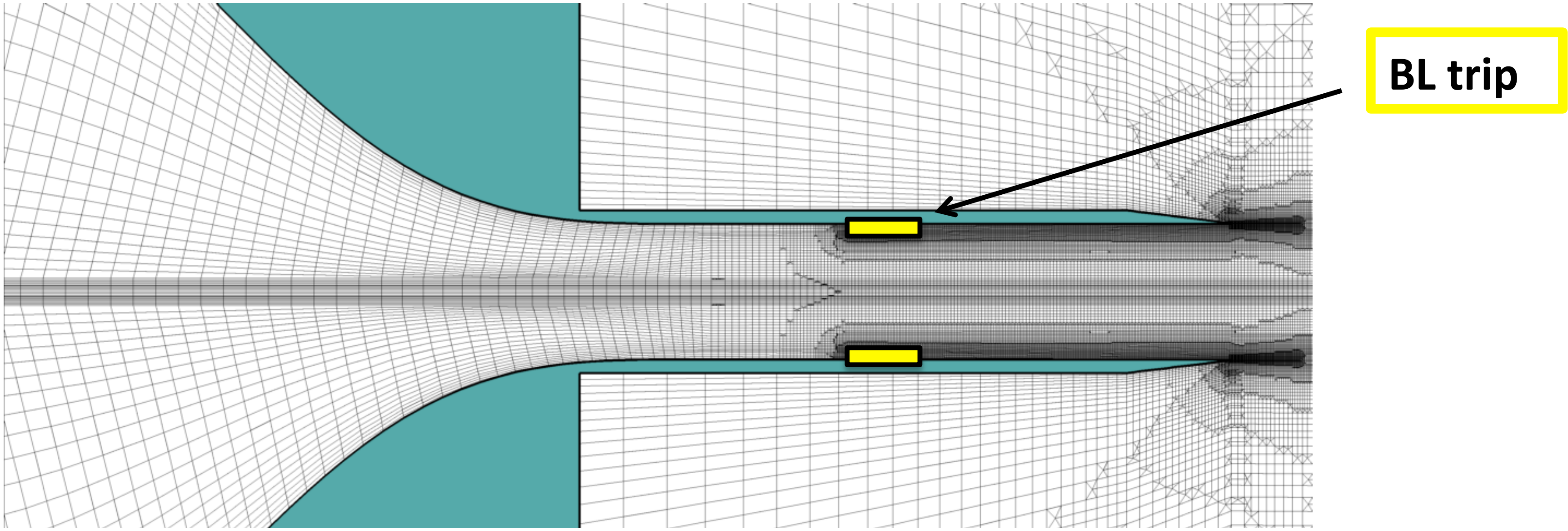


(a) $St = 0.1$ (b) $St = 0.2$ (c) $St = 0.3$



Synthetic Turbulence for Nozzle Interior Flow Modeling

- *Objective: develop robust and efficient method for generation of "realistic" turbulence inside the nozzle*
- *Cascade's approach:*
  - synthetic inflow turbulence based on unstructured filtering of velocity fluctuations
  - applied at the location of BL trip in experiment



Wall Model for Nozzle Interior Flow: Wall Stress Modeling

- *Traditional wall model:*
    - 1D RANS/LES coupling[1]
    - Applied inside nozzle, after BL trip

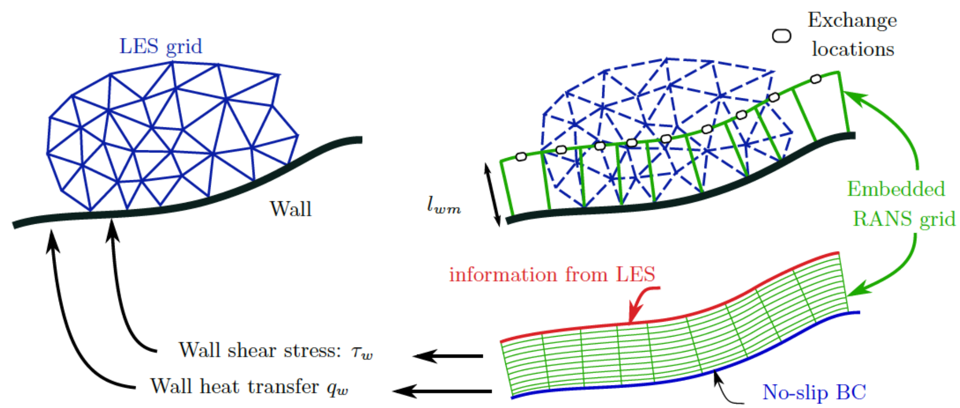
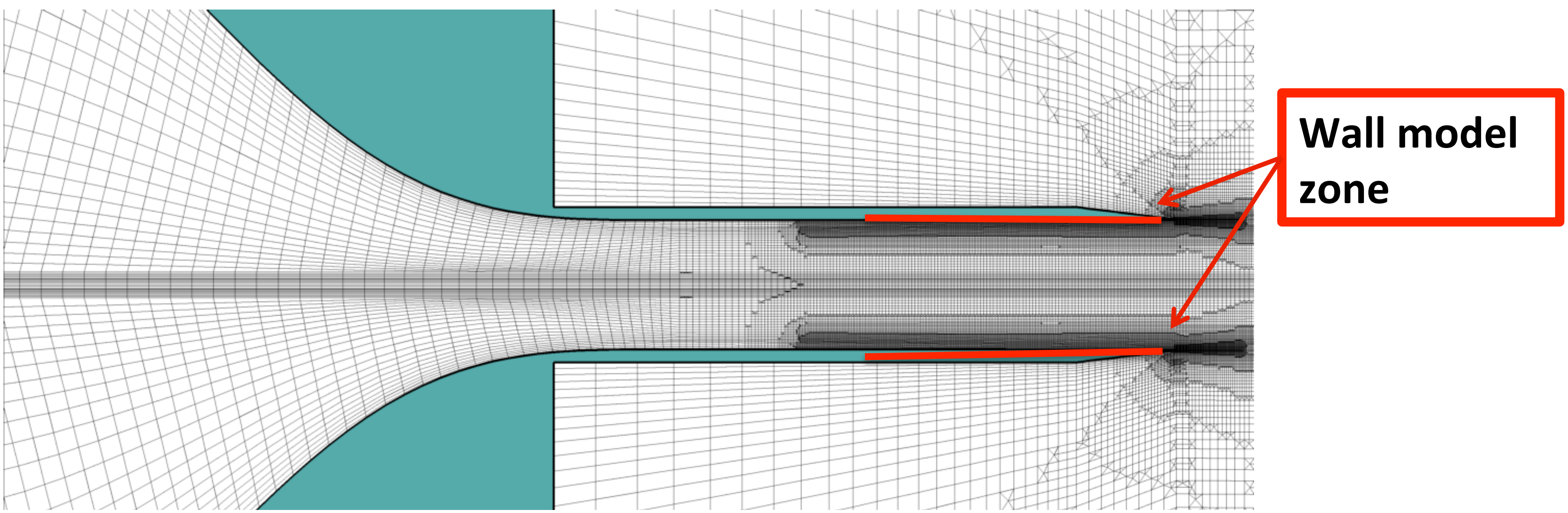


Figure 1. Wall-modeling procedure using unstructured grids.

[1]Bodart & Larsson, "Wall-modeled large eddy simulation in complex geometries with application to high-lift device", *CTR Brief 2011*

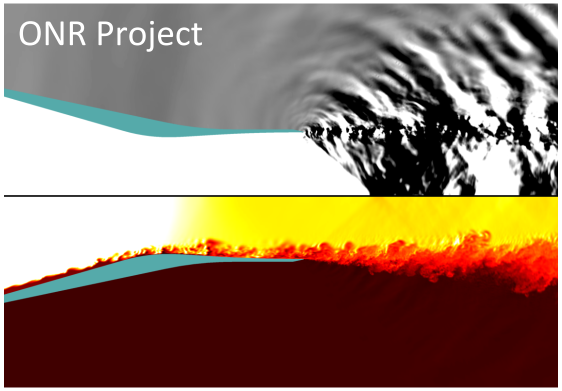


Objectives of the present collaborative effort

- *Generate extensive experimental & numerical databases to improve understanding and modeling of turbulent sources of sound in subsonic jets*

- *Resolve and/or model important features in the nozzle interior flow, seamlessly coupled with high-fidelity predictions of the jet plume and radiated noise*
  - improve meshing strategy for complex nozzle interior elements
  - improve wall-modeling for cost-effective simulations
  - improve boundary layers modeling inside nozzles, away from laminar flow assumption (which can potentially lead to spurious noise and unphysical separation)

Summary of research effort on interior flow modeling for jet predictions with the compressible flow solver “Charles”



Heated internally-mixed
dual-stream jet (Mj = 1.5)

CD nozzle

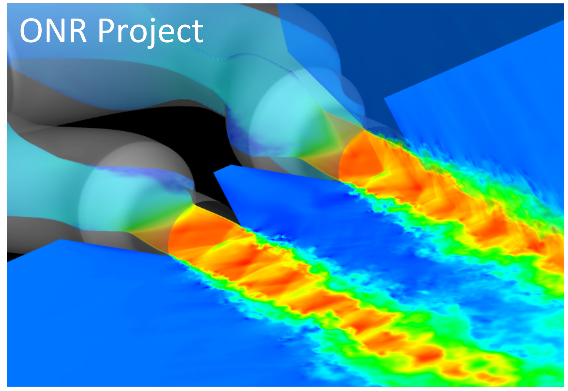
AIAA-2013-2142
19th Aeroacoustic Conf.
Berlin 2013

Adaptive mesh refinement
inside the nozzle: **IMPORTANT**

1D RANS wall model:
SUBTLE EFFECTS (?)

synthetic turbulence:
BENEFICIAL & LITTLE SENSITIVITY

limited increase
in computational cost



Heated over-expanded twin jets
(Mj = 1.35)

Y-duct, S-ducts & CD nozzles

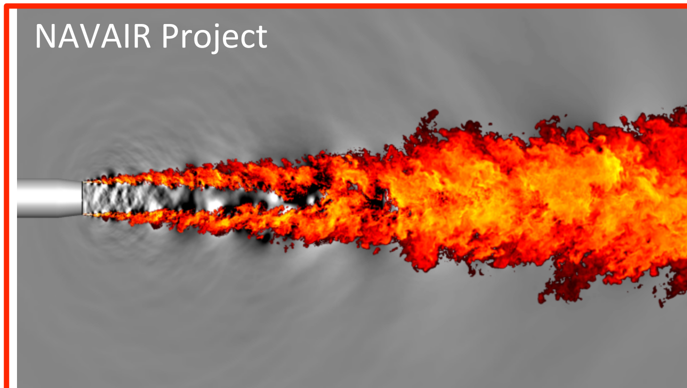
AIAA-2014-2601
20th Aeroacoustic Conf.
Atlanta 2014

Adaptive mesh refinement
inside the nozzle: **IMPORTANT**

1D RANS wall model:
SUBTLE EFFECTS (?)

synthetic turbulence:
BENEFICIAL & LITTLE SENSITIVITY

limited increase
in computational cost



Isothermal subsonic jet
(Mj = 0.9)

converging-straight pipe nozzle

CTR Summer Program 2014 &
21th Aeroacoustic Conf.
Dallas 2015

Adaptive mesh refinement
inside the nozzle: **IMPORTANT**

1D RANS wall model:
IMPORTANT

synthetic turbulence:
BENEFICIAL & LITTLE SENSITIVITY

limited increase
in computational cost

Analysis of Jet Noise Sources and Modeling

Coherent Structures – Wave packets ..

Azimuth Mode decomposition

Intermittancy

Mach wave radiation (Supersonic)

Statistical Modeling of sources (Generalized Acoustic analogy)

- *backup*