LES-BASED NOISE PREDICTION FOR SHOCKED JETS IN STATIC AND FLIGHT CONDITIONS

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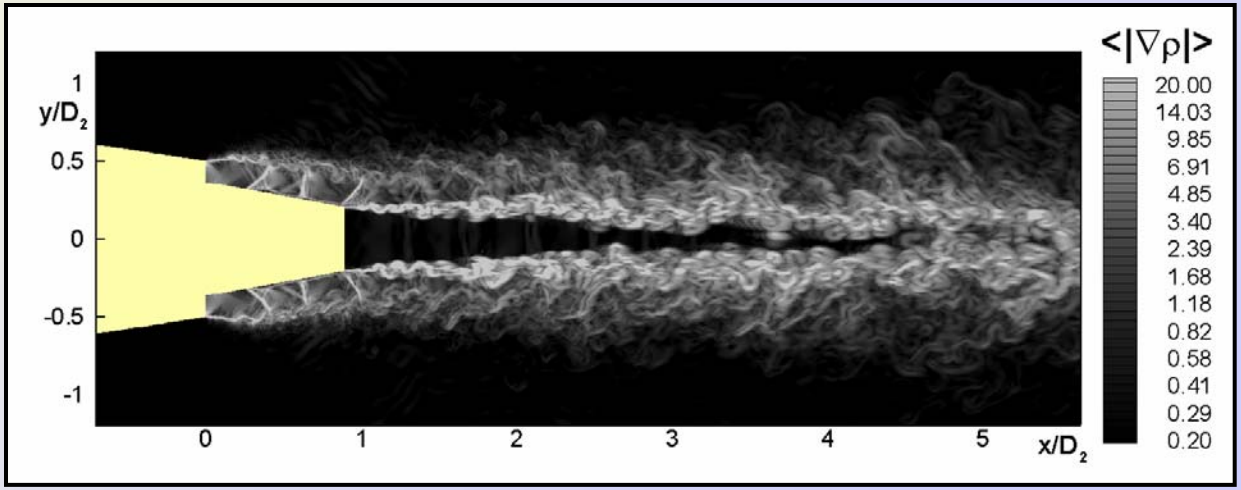
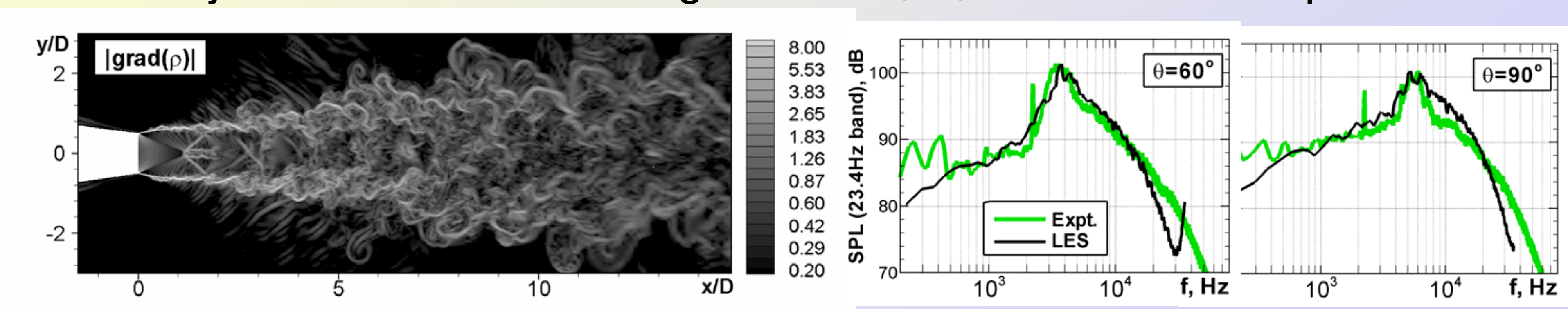


OUTLINE

- Motivation and objectives
- Outline of numerical system
- Results of broadband shock-cell noise computations
  - Single sonic under-expanded jets in flight
  - Dual shocked jets in static conditions
- Conclusions

Motivation & Objectives

- Prediction of broadband shock-cell (BBSC) noise of imperfectly expanded jets is of substantial practical interest:
  - **Shocks are typical of airplane exhaust jets in cruise**
  - **This noise-component is a significant part of cabin noise**
- In earlier works, it has been shown that the LES-based CFD-CAA numerical system developed in our group is capable of predicting BBSC jet-noise in a wide range of NPR, T, and nozzle shapes



Density gradient field and noise spectra from LES of hot under-expanded jet

- However, till now simulations were carried out only for single jets in static conditions, whereas in practice major interest is in:
  - **Jets in flight conditions**
  - **Dual jets**

Motivation & Objectives

- The goal of the present study is to fill in this gap by numerical analysis of:
  - **Effect of flight on noise of single under-expanded jets**
  - **Peculiarities of shock-associated noise generated by dual jets at operating conditions typical of current turbofan engines**
    - Hot subsonic primary stream
    - Cold sonic under-expanded secondary stream

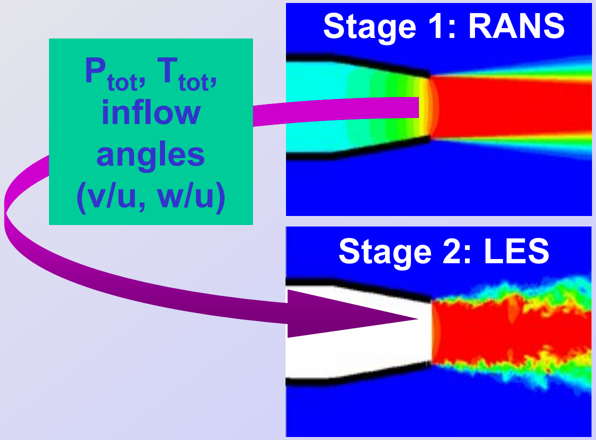
Motivation & Objectives

- Judging by experiments, the broadband component of shock-noise from both types of jets exhibits some non-trivial features
  - **Jets in flight: At fixed emission angle BBSC noise is almost insensitive to the presence of a co-flowing stream (alteration is explained almost solely by propagation effects)**
  - **Dual jets: As found by Tam et al. (2009), two distinct BBSC-noise components are present originating from interaction of shock cells with large turbulent structures of outer (1st type) and inner (2nd type) shear layers, respectively**
    - 1st type – is similar to BBSC noise of single jets, peaks upstream
    - 2nd type – is very different and peaks downstream at $\theta=110^o - 120^o$
    - The angle-dependencies of the peak-frequencies for 2 types of noise are also different (Tam's theory gives the formulas)
- Major objective is to check if the numerical system is capable of reproducing these subtle features

Outline of Numerical System

- Established since 2002; unchanged for the last 5 years

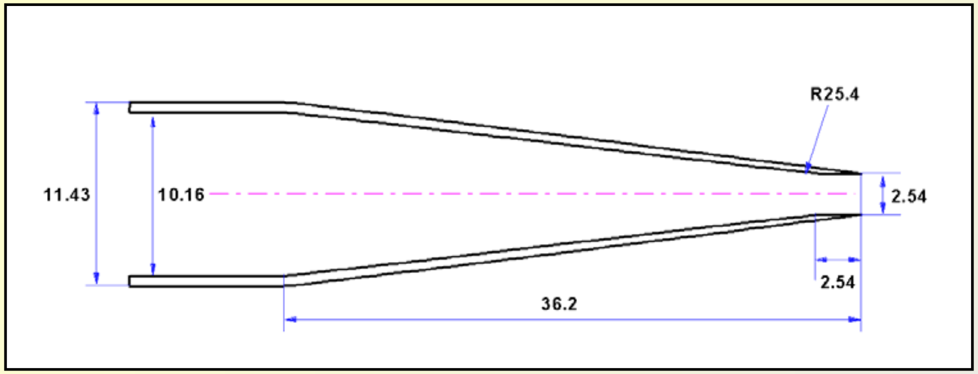
  - **Implicit, high-order low-dissipation numerical scheme (weighted, 4th-order centered / 5th-order upwind-biased)**
  - **Simple and robust algorithm of local automatic activation of flux-limiters – for treatment of jets with shocks**
  - **"Implicit" version of LES (ILES – the SGS model is not activated) – for representation of jet turbulence**
  - **Two-stage RANS-LES approach – for treatment of complex nozzles and imposing BC's at jet's inflow in the LES-stage of simulation**



  - **Permeable FWH surface–integral method (without external volume sources) – for the far-field noise computation**

Broadband Shock Cell Noise of Single Sonic Under-Expanded Jets in Flight

Geometry and Flow Regimes

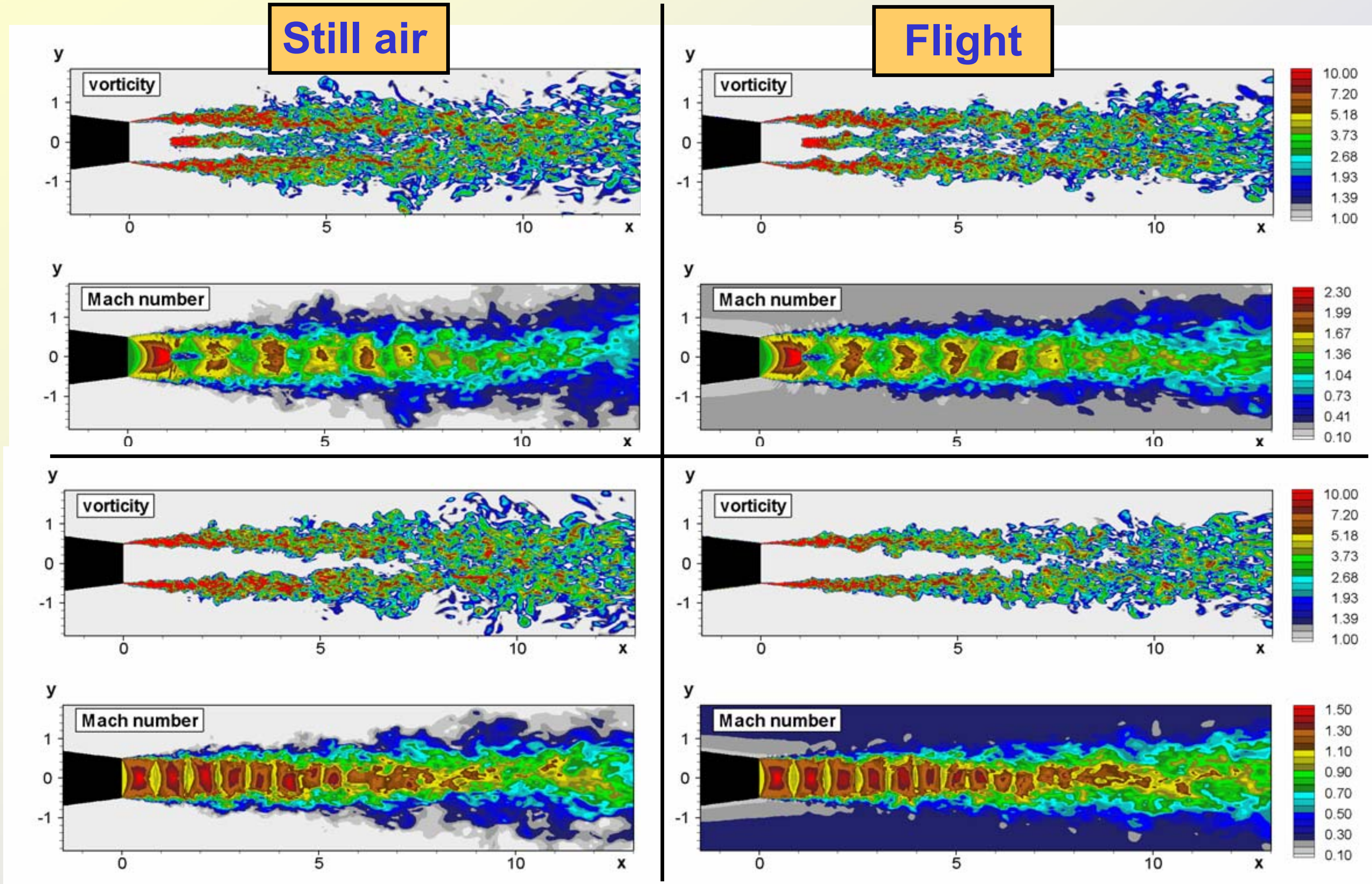


Experiments of Ahuja, Tanna and Tester, 1978

NPR up to 3.86 (P_{JET}/P_a up to 1.8), $1<T_s/T_a<3$, and M_{CF} up to 0.26

- Attractive feature of experiments: special measures were undertaken to suppress the screech which "contaminates" most other noise-data for shocked jets in flight
  - **This facilitates comparison of predictions with data (in CFD, screech is also excluded by using very thin nozzle edge)**
- Simulations were carried out for 2 "extreme" sets of operation conditions
  - **Hot jet with strong under-expansion: Ts/Ta=3, P_{JET}/P_a=1.8**
  - **Unheated slightly under-expanded jet: Ts/Ta=1, P_{JET}/P_a=1.16**
- For each of these sets, 2 cases were considered
  - **Jet in still air**
  - **Jet in flight (co-flow), at highest Mach number M_{CF} = 0.26**

Flow Visualizations: Vorticity and Mach Number



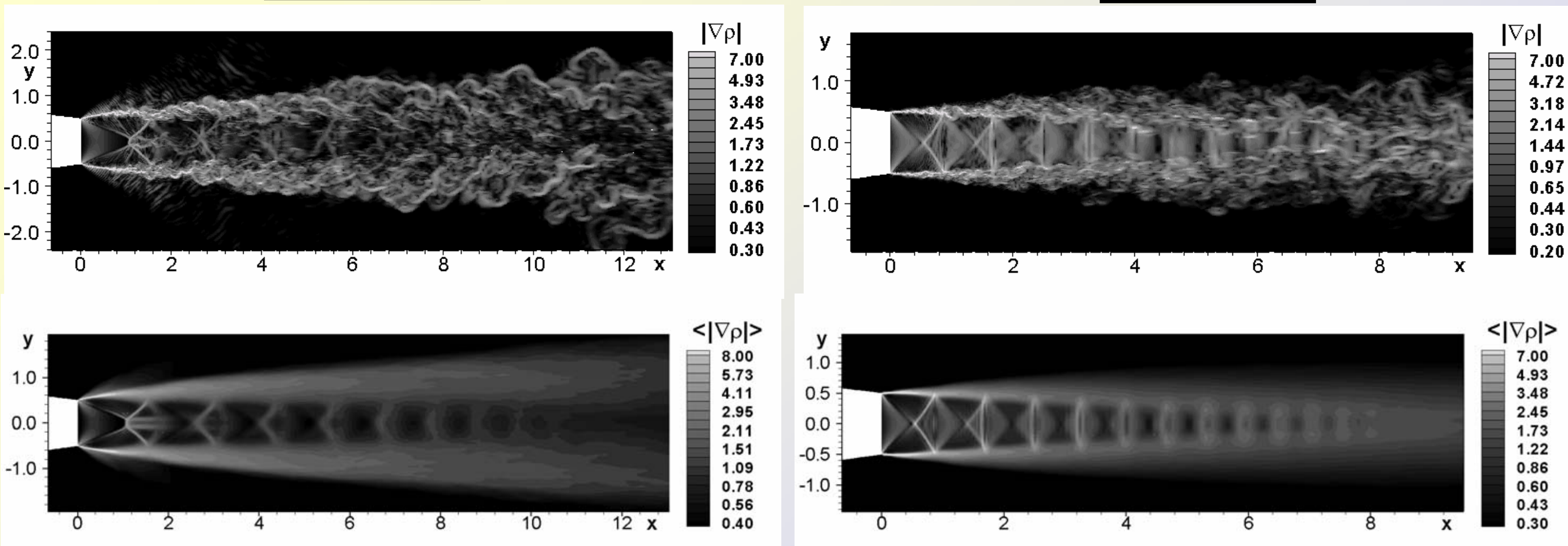
Hot jet, strongly under-expanded

Cold jet, slightly under-expanded

- Train of shock cells interacting with turbulence, more expressed for cold jet
- Strongly under-expanded jet: Mach-disk is formed in the end of 1st shock cell, with subsequent subsonic zone and internal shear-layer
- Co-flow leads to narrowing of plume and elongation of potential core but almost does not affect transition to turbulence (thick BL on outer nozzle wall)

Flow Visualizations: "Numerical Schlierens"

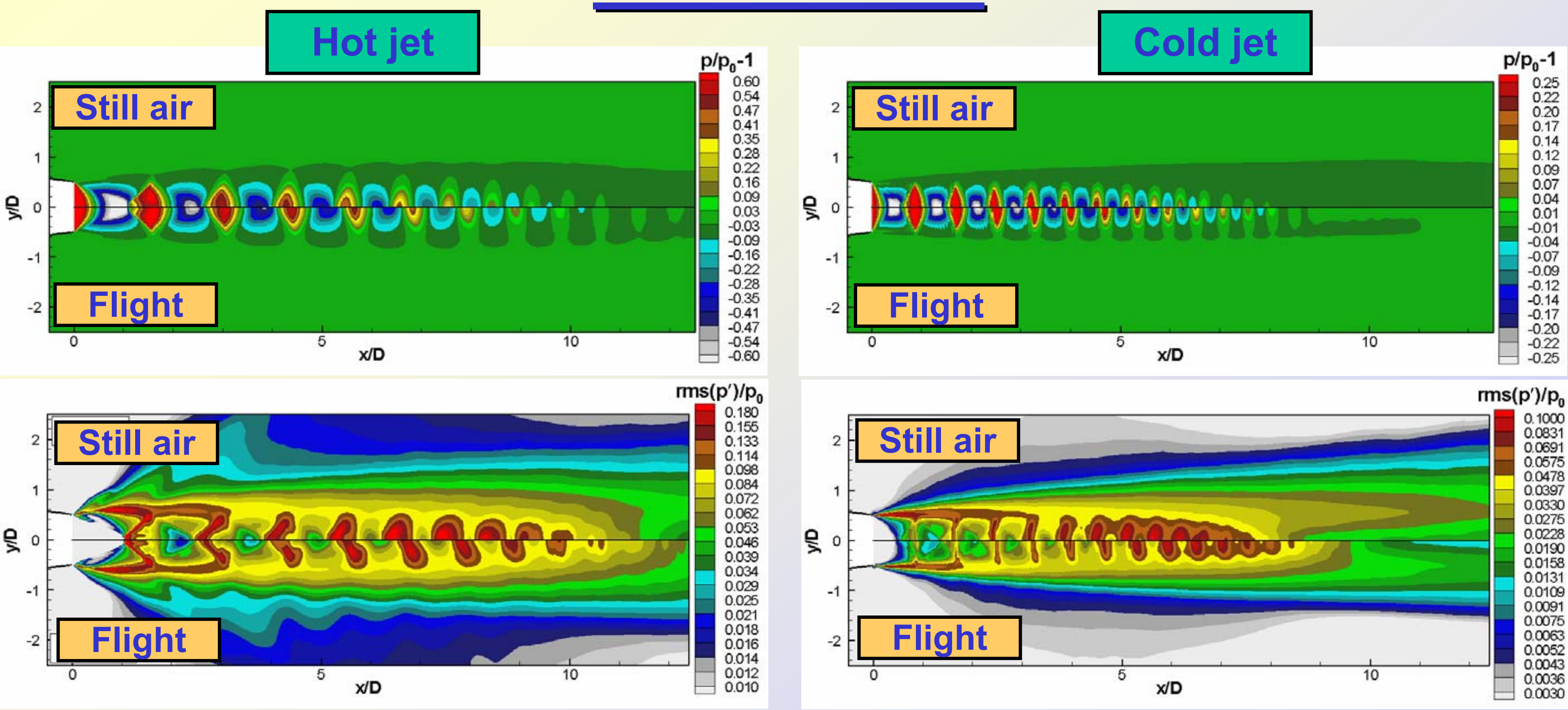
Hot jet **Cold jet**



Animations and time-averaged magnitude of density gradient (jets in co-flow)

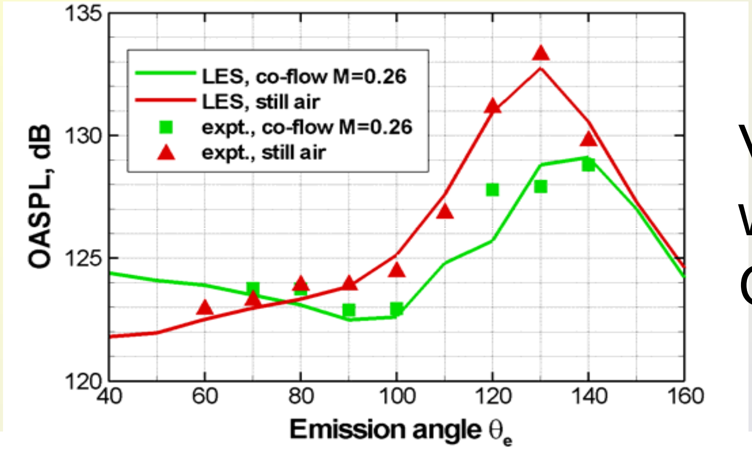
- Interaction of shock-cells with turbulence is more visual in "numerical Schlierens", here shown for jets in co-flow
- Mean fields reveal quite regular diamond-shaped shock-cell system (evidence of sufficient time-sample)

Effect of Co-flow on Mean Pressure and Pressure Fluctuations

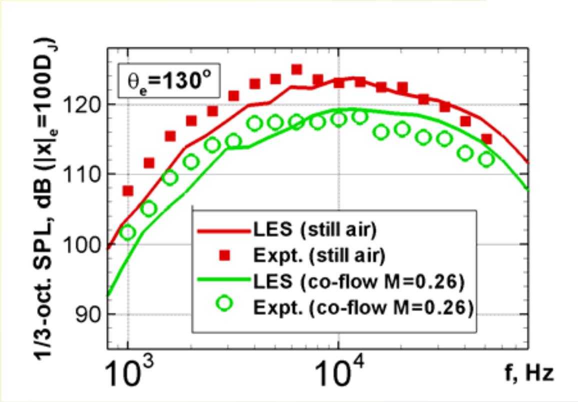


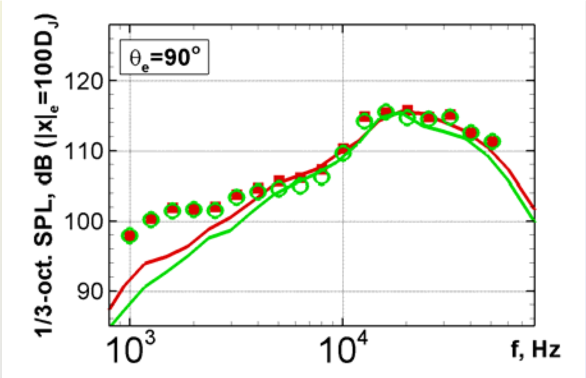
- Consistently with experiment, the shocks strength is virtually insensitive to the presence of co-flow
- Almost no alteration of length of first 2-3 shock cells by co-flow (thick BL)
- Further downstream, a minor elongation of shock cells is observed, again in agreement with experimental observations

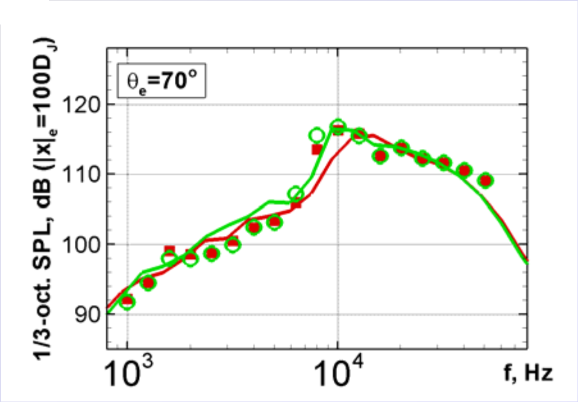
Far-Field Noise Directivity & Spectra: Hot Jets



Very good agreement with experiment for both OASPL and spectra

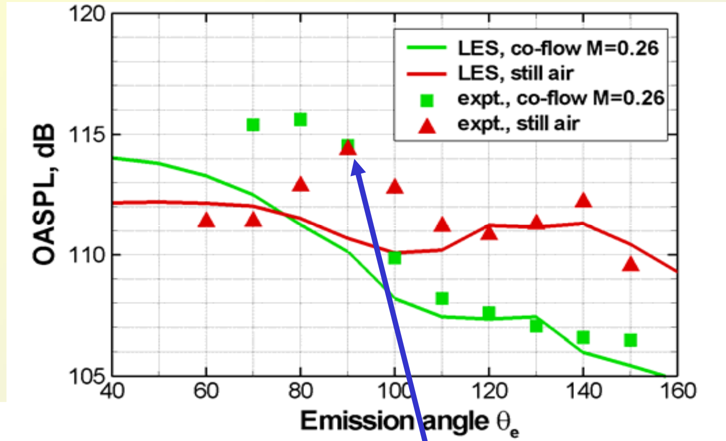




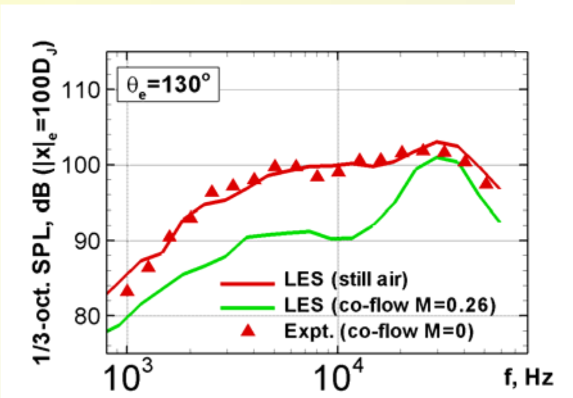


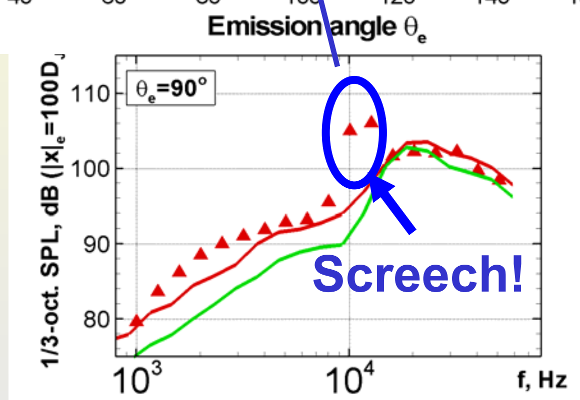
- Co-flow results in significant decrease of strongest low-frequency noise in the peak-radiation direction (similar to non-shocked jets)
- Simulations capture the weak sensitivity of BBSC noise to the presence of co-flow, at least at the present co-flowing stream velocities
- Slight shift of shock-noise peaks to lower frequencies also reproduced

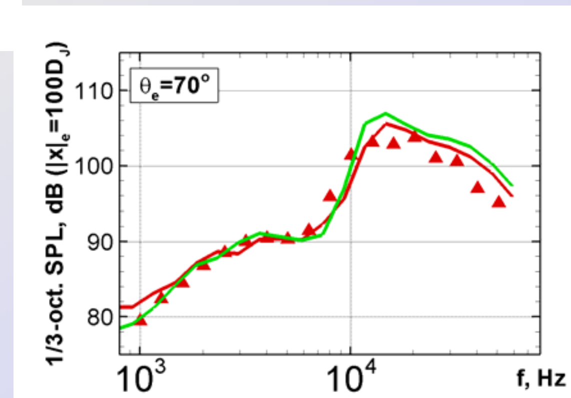
Far-Field Noise Directivity & Spectra: Cold Jets



Agreement of OASPL near 90º is much worse than for the hot jet







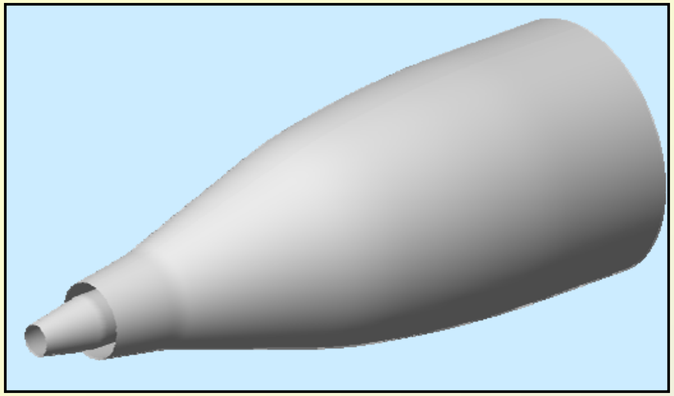
- Examination of experimental spectrum at 90º suggests that this is explained by contamination of the data by screech
  - ➢ **Computed spectra at 130º and 70º (no screech in expt.) and at 90º outside the frequency-range of screech agree with data fairly well**
- In terms of supporting the capability of numerical system to predict noise of shocked jets in flight, outcome of the study is quite positive

BBSC Noise of Dual Jets with Subsonic Primary and Sonic Under-Expanded Secondary Streams

Recent paper of Tam et al.:

BBSC noise generated by such jets has 2 different components originating from interaction of shock cells with large turbulent structures of outer and inner shear layers

Geometry, Flow Regime, and Grid

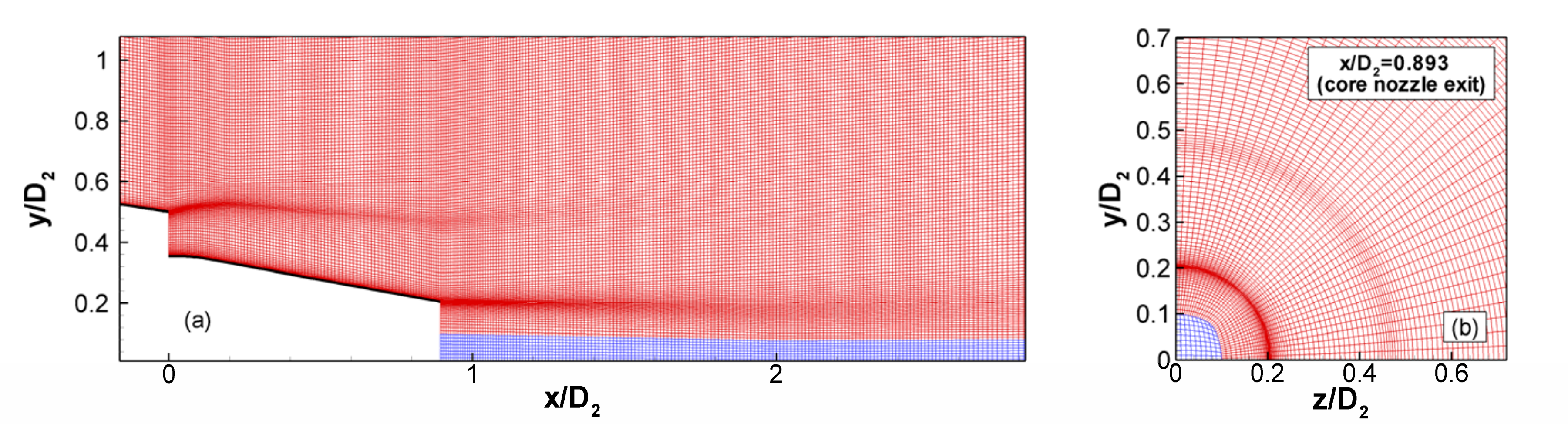


Dual staggered nozzle system, AR = 3 (experiment of K. Viswanathan)

Conditions with clearly expressed two BBSC noise components:

Core jet: $M_1=0.85$ (NPR=1.6), $T_{1s}/T_a=2.26$

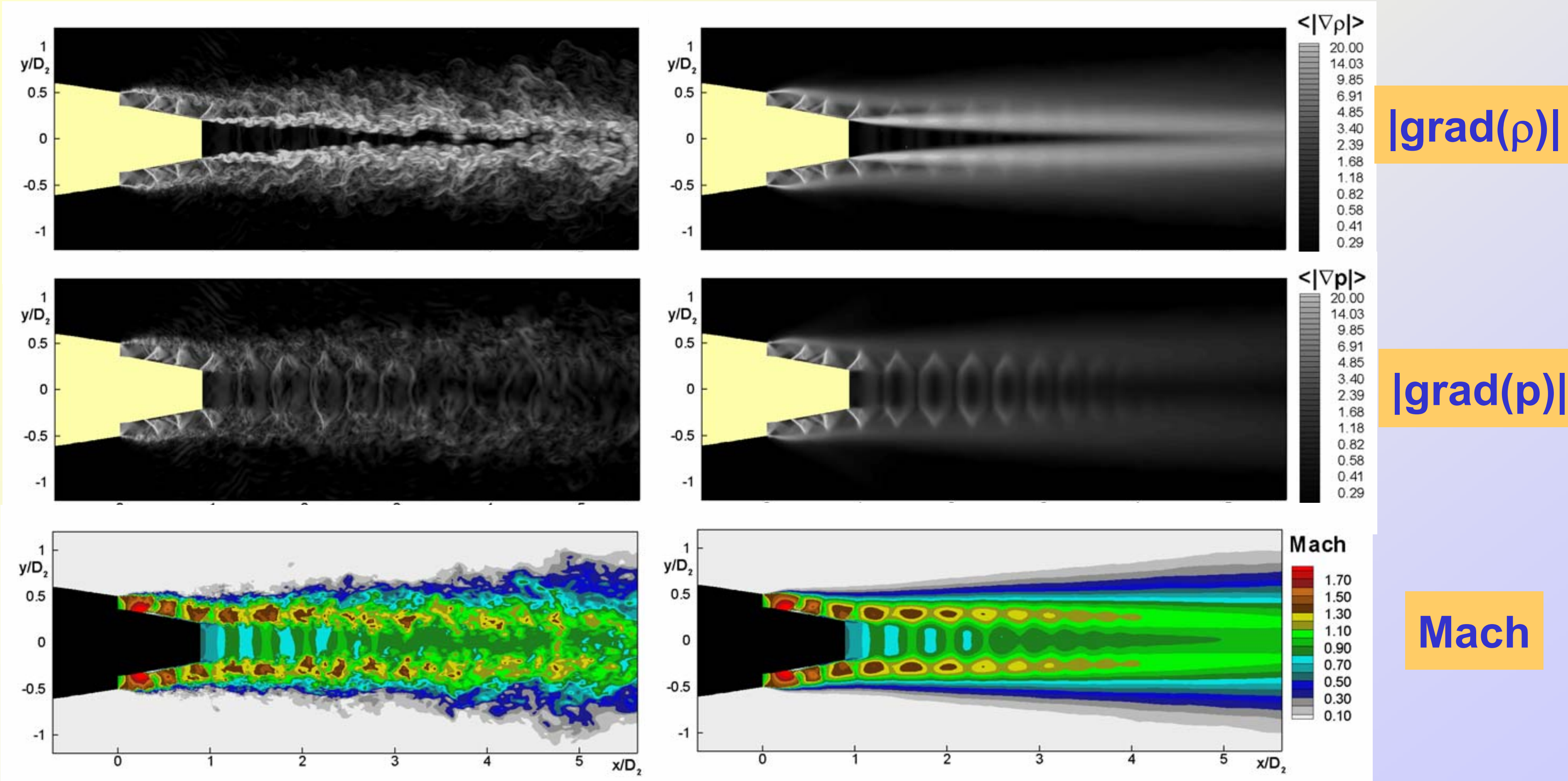
Fan jet: $M_{2FE}=1.36$ (NPR=3), $T_{2s}/T_a=1$



Fragments of LES-grid

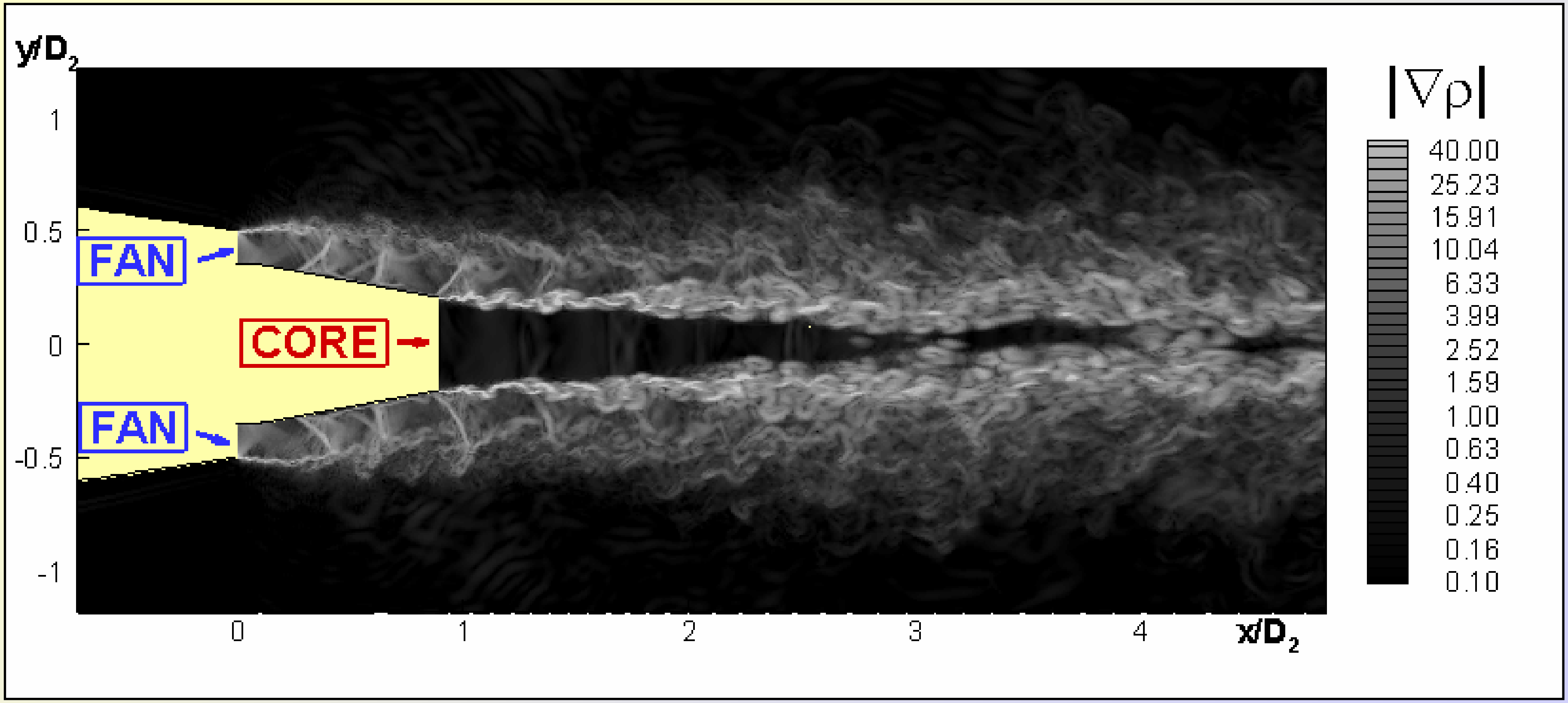
- Grid is adjusted to two shear layers, based on coupled RANS carried out in the 1st stage of two-stage RANS-LES procedure
- Strongly clustered in the expected "shock-area"
- $N_x \times N_r \times N_\phi = 700 \times 190 \times 144$, ~19 million cells total

Flow Visualization and Mean Shock-Cell Pattern



- Figures reveal a number of shock cells interacting with outer wall of the inner nozzle and turbulence of both shear layers
- Observed symmetry of mean shock-wave pattern supports sufficiency of time sample

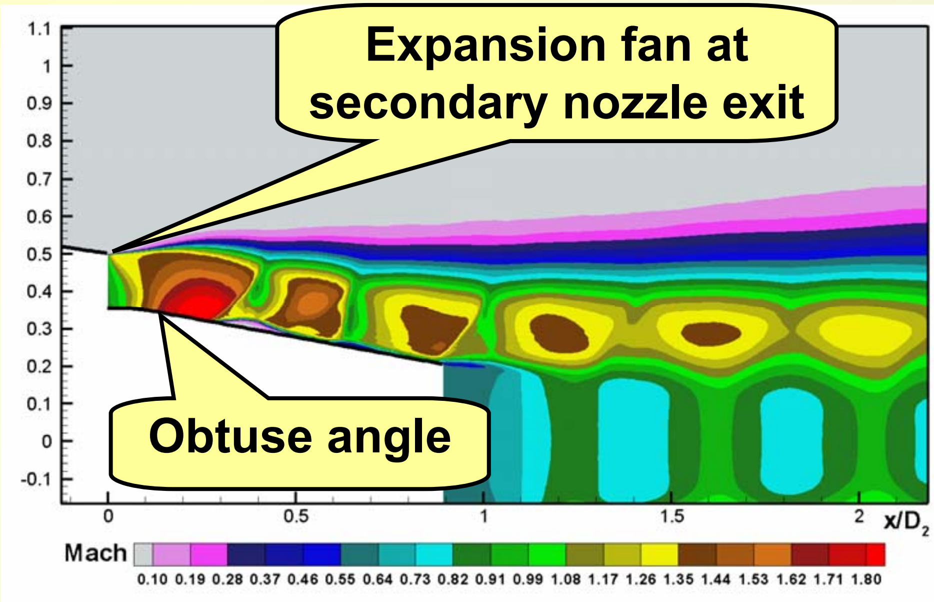
Interaction of Shocks with Turbulence



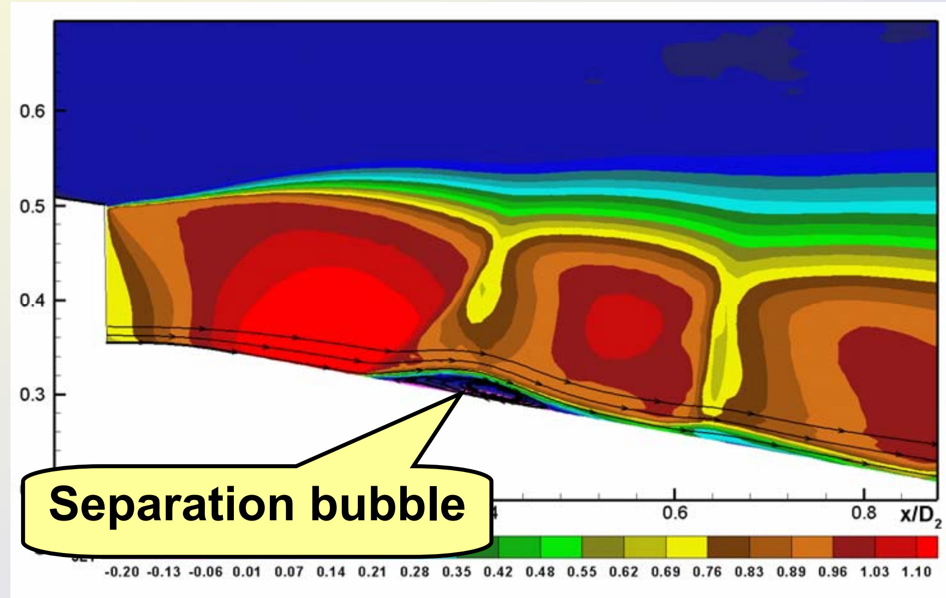
Animation of magnitude of density gradient ("numerical Schlieren")

- Rapid transition and clearly expressed turbulent vortical structures in the inner shear layer, in spite of small mean velocity gradients
  - **Caused by high density gradients**

Details of Mean Flow Near Fan Nozzle Exit



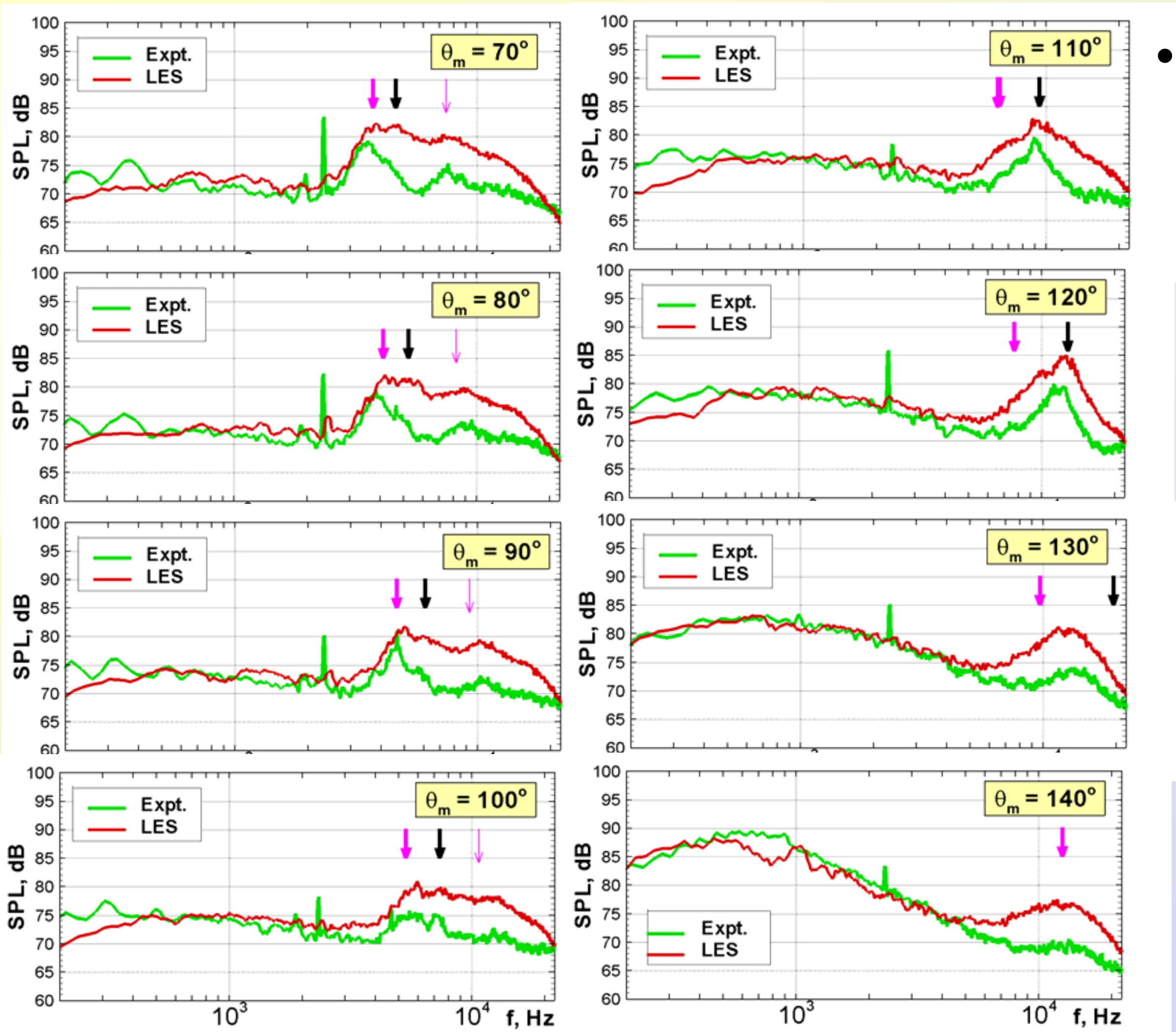
Mach number



Streamwise velocity

- <u>A peculiar feature:</u> additional expansion wave is formed by obtuse angle on the outer wall of the inner nozzle
- In conjunction with expansion fan of the under-expanded secondary jet, this raises the Mach number near the wall to about 2
  - ➢ **Leads to formation of strong “closing” shock and a shock-induced separation bubble**

Narrowband Far-Field Noise Spectra



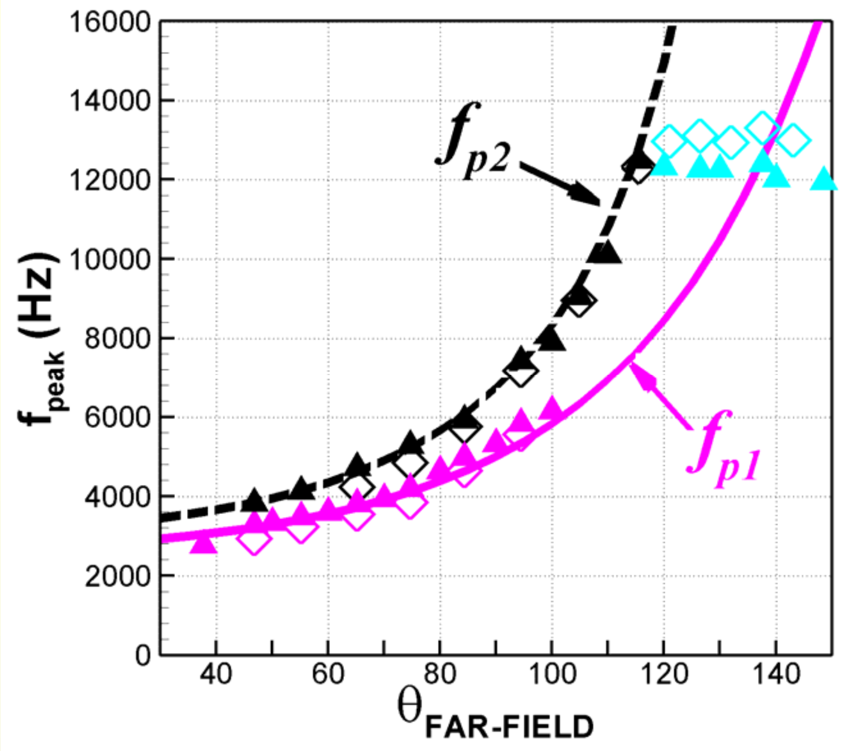
- Simulation captures major qualitative effects observed in experiments and explained by the theory of Tam *et al*.:
  - ➢ Presence of 2 BBSC-peaks at $\theta<100^o$ (BBSC noise of 1st type, from outer layer, dominates)
  - ➢ Rapid growth of 2nd type BBSC noise peak between 100^o and 110^o (1st BBSC peak becomes almost indiscernible)
  - ➢ Sharp roll-off of BBSC noise of 2nd type at large observer angles

Thick purple arrow: peak of 1st- type BBSCN

Thick black arrow: peak of 2nd- type BBSCN

Thin purple arrow: harmonic of 1st-type BBSCN

Peak Frequencies of Two Types of BBSC Noise



$$f_{p1} = \frac{(V_c)_{outer}}{L_{SH}[1+(M_c)_{outer}\cos\theta_{FF}]}$$

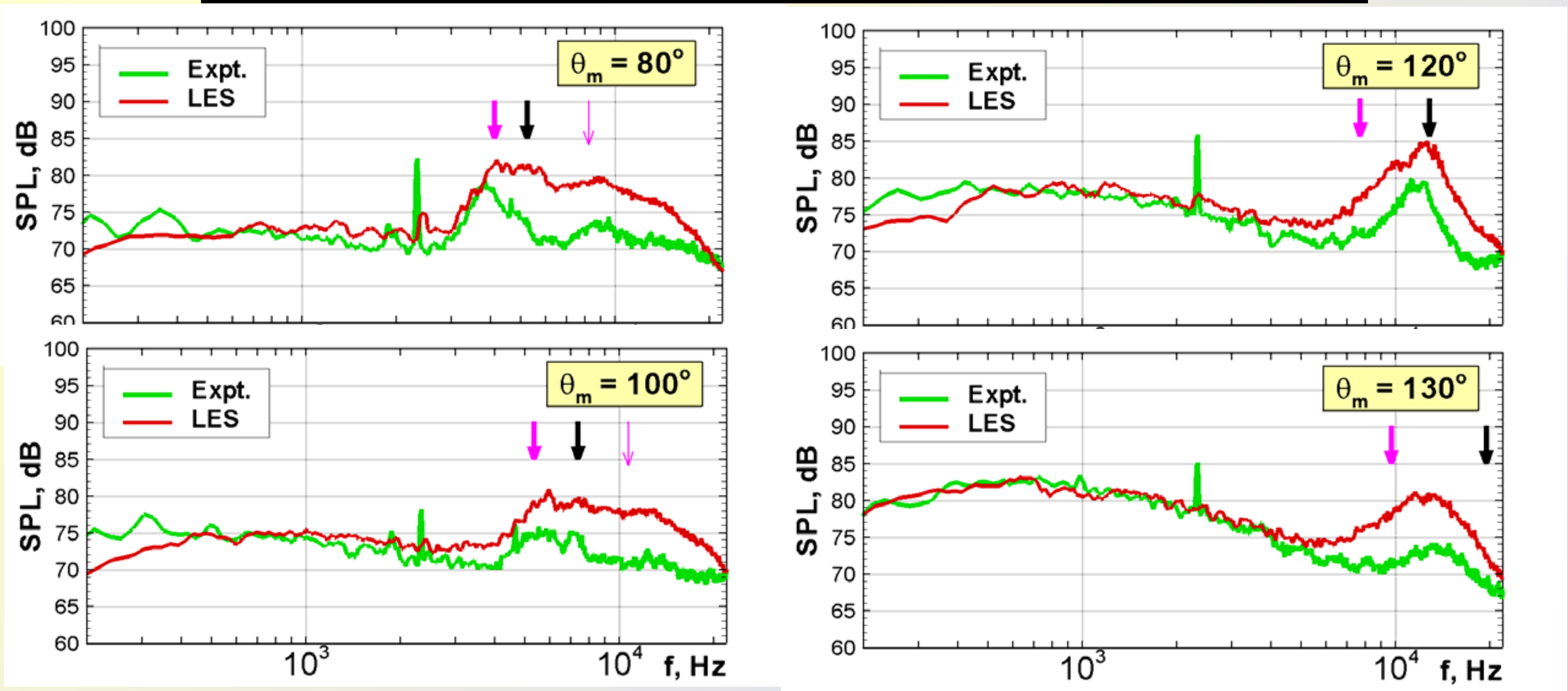
$$f_{p2} = \frac{(V_c)_{inner}}{L_{SH}[1+(M_c)_{inner}\cos\theta_{FF}]}$$

Lines: Theory
Open symbols: Experiment
Closed symbols: LES

Purple: BBSCN of 1^{st} type
Black: BBSCN of 2^{nd} type
Cyan: High-frequency maximums at $\theta > 120^o$ (non-BBSC nature)

- Uncanny agreement of predicted frequencies of both peaks with experiment and theory
- Also in agreement with the theory, the roll-off of BBSC noise of 2^{nd} type (from inner shear layer) happens at $\theta=120^o$, where the peak frequencies of both experimental and predicted spectra start to deviate from the f_{p2} curve
- All these peculiar features of the BBSC noise of dual jets are reproduced

Comparison of Noise Levels



- Although predicted spectral shapes are correct, quantitative agreement is poor
  - ➢ **At high frequencies ($f > f_{BBSCN}$), SPL is overestimated by up to 7 dB which is much worse than in all our earlier studies, even with coarse grids**
- A reason for this large disagreement remains unclear. The only conjecture is that this is caused by the separation bubble on outer wall of inner nozzle
  - ➢ **In this situation, the 2-stage RANS-LES approach may become inaccurate and fail to reproduce the strong flow unsteadiness in vicinity of the bubble, which seems to be very likely in experiment**

CONCLUSIONS

- Two new applications of the LES-based numerical system to the prediction of the BBSC noise of jets are presented
- The first, single shocked jets in flight, is quite successful
- The second, dual shocked jet, is semi-successful
  - On one hand, simulations capture all subtle features of the noise generated by such jets and reproduce the experimental spectral shapes fairly well
  - On the other hand, the quantitative agreement on the noise levels is worse than in all our previous studies
  - The causes of this are not clear so far, and additional numerical and experimental investigations are needed for their identification

Thank you!

Overview of Numerical System: Local Flux Limiters for Shock Capturing

Treatment of jets with shocks – simple algorithm of *local automatic* activation of flux-limiters (to a considerable extent, permits to reconcile contradictory demands of shock capturing and turbulence resolution in LES with acceptable numerical dissipation)

- **For inviscid fluxes at cell-face $(i+1/2)$, low-dissipative (4/5th order) hybrid numerics are replaced by more dissipative 3rd order upwind scheme with activated flux limiters (Van Albada) if:**

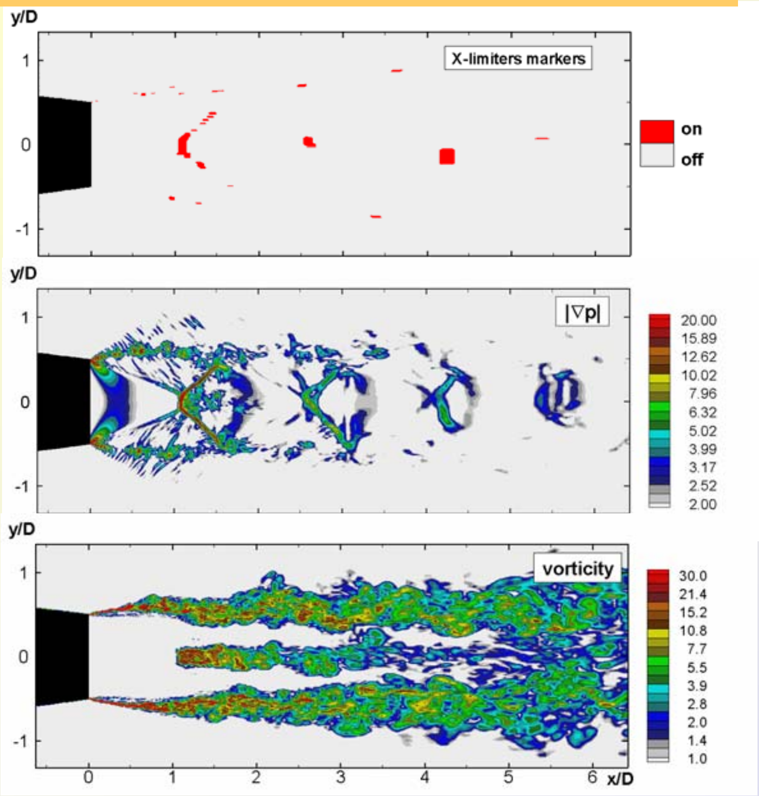
$$\frac{|p_{i+1} - p_i|}{\min\{p_i, p_{i+1}\}} > \varepsilon, \quad \varepsilon = O(1)$$

the pressure change between 2 adjacent control volumes is "too large"

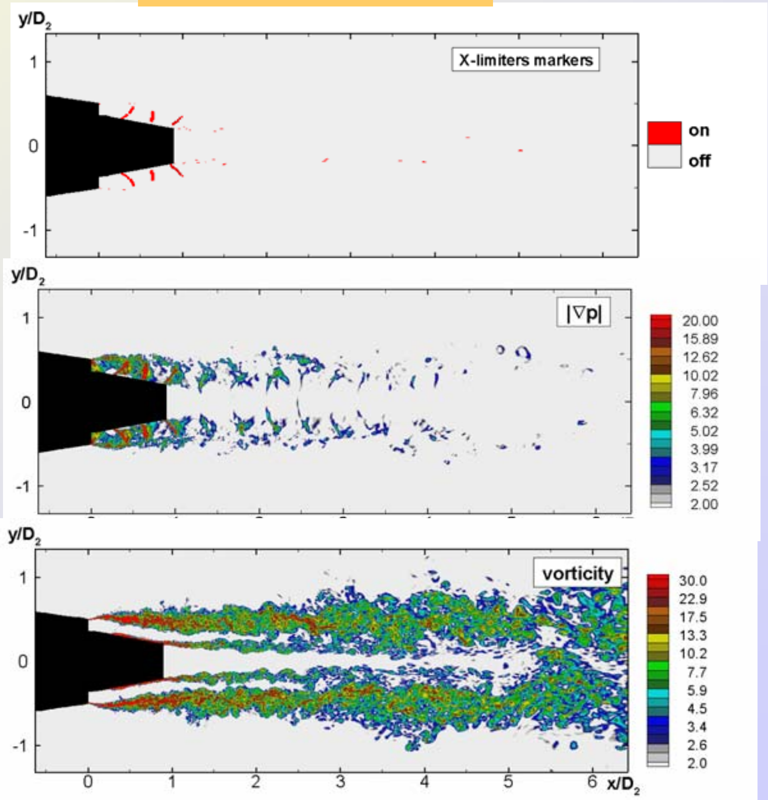
- **Provided that the grid ensures an adequate resolution of "smooth" flow regions, the switch occurs only at strong enough shocks**
- **To account for shocks oscillations, the switch is performed also at two neighboring cell faces $(i-1/2)$ and $(i+3/2)$**
- **The switch and limiters are "frozen" after 2 sub-iterations**

Overview of Numerical System: Flux Limiters “Markers” for 2 Shocked Jets

Single hot under-expanded jet in co-flow



Dual shocked jet

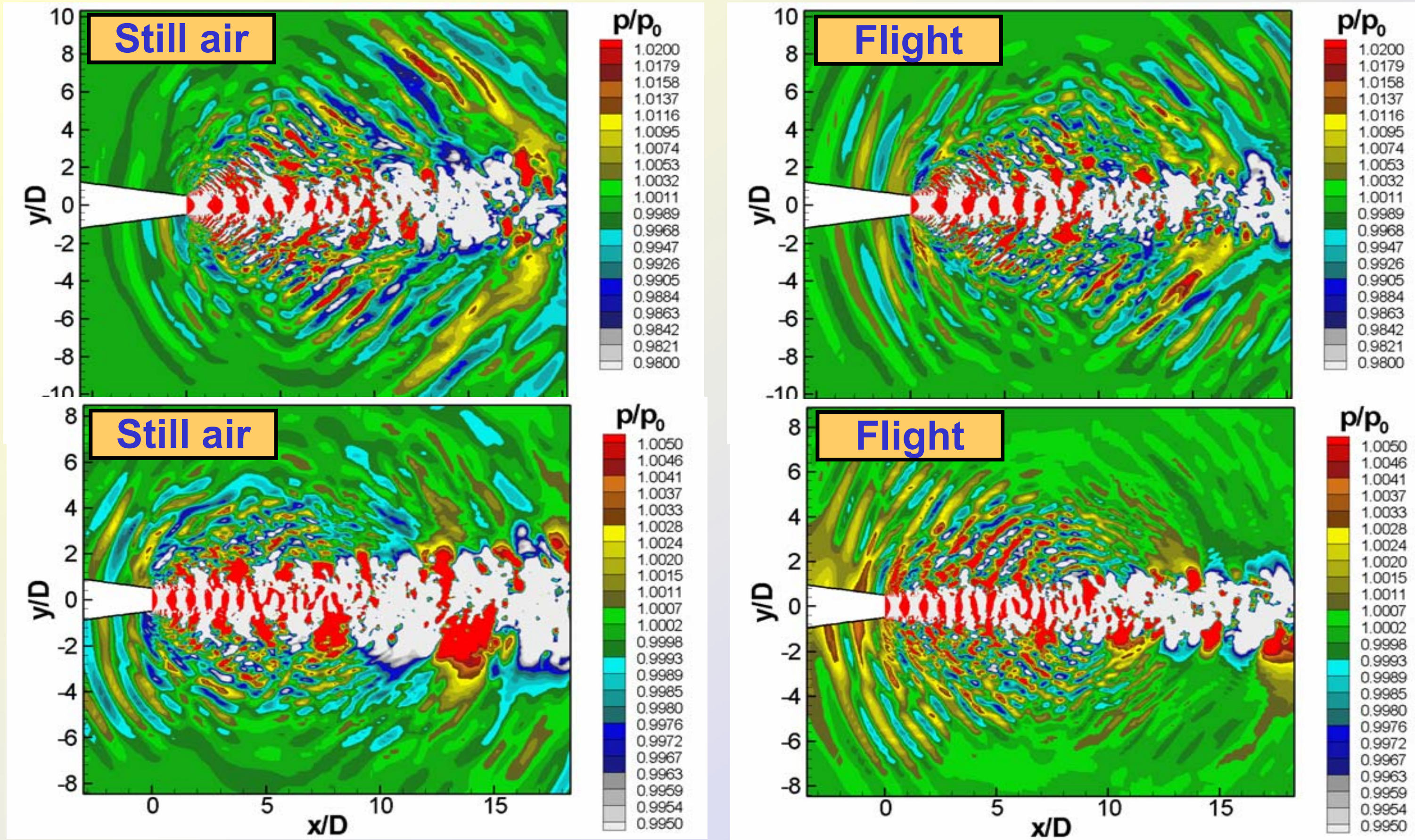


- Limiters (red) are activated only in restricted regions of high pressure gradients and virtually do not result in a damage of resolution of turbulence in jet shear layers or suppression of their instability
- Computations remain stable and sub-iterations converge fast

Effect of Flight on Near-Field Sound Wave Pattern

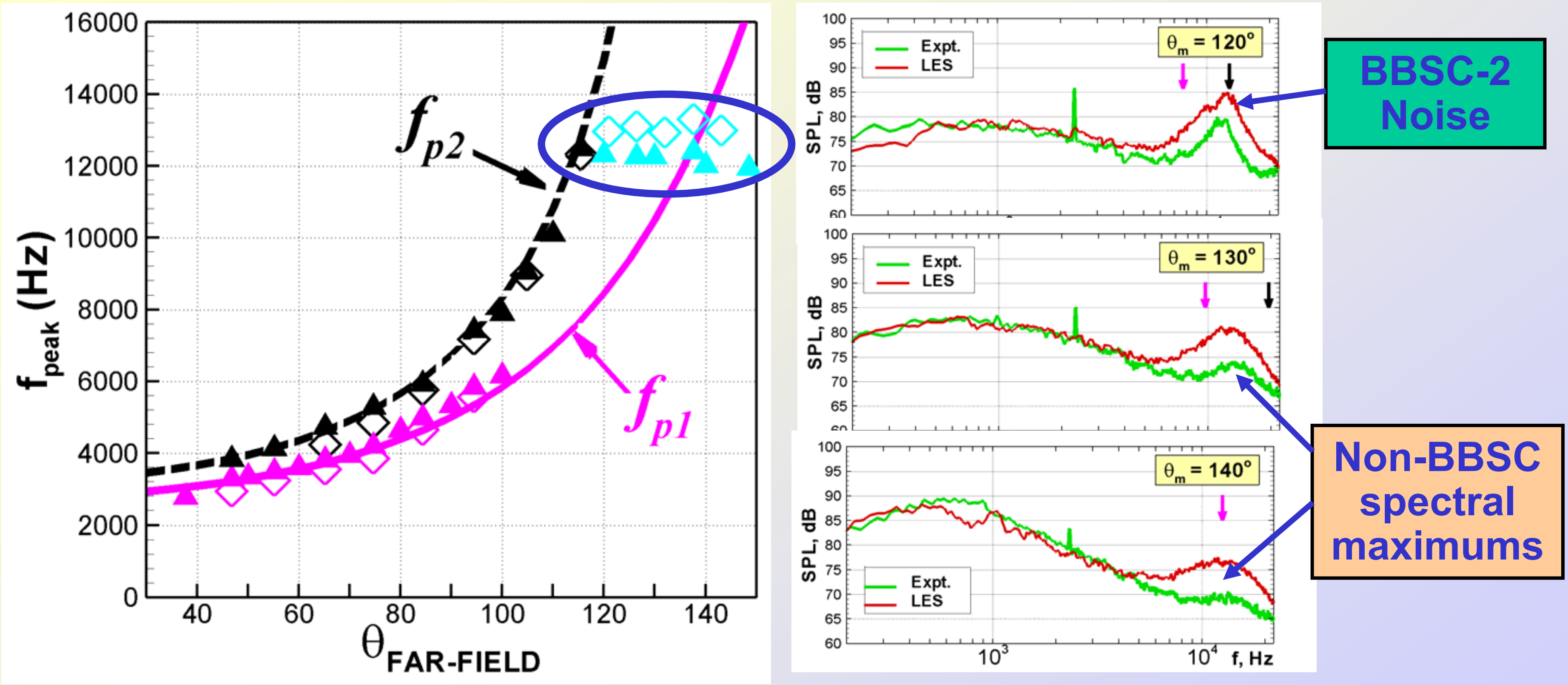
Hot jets

Cold jets



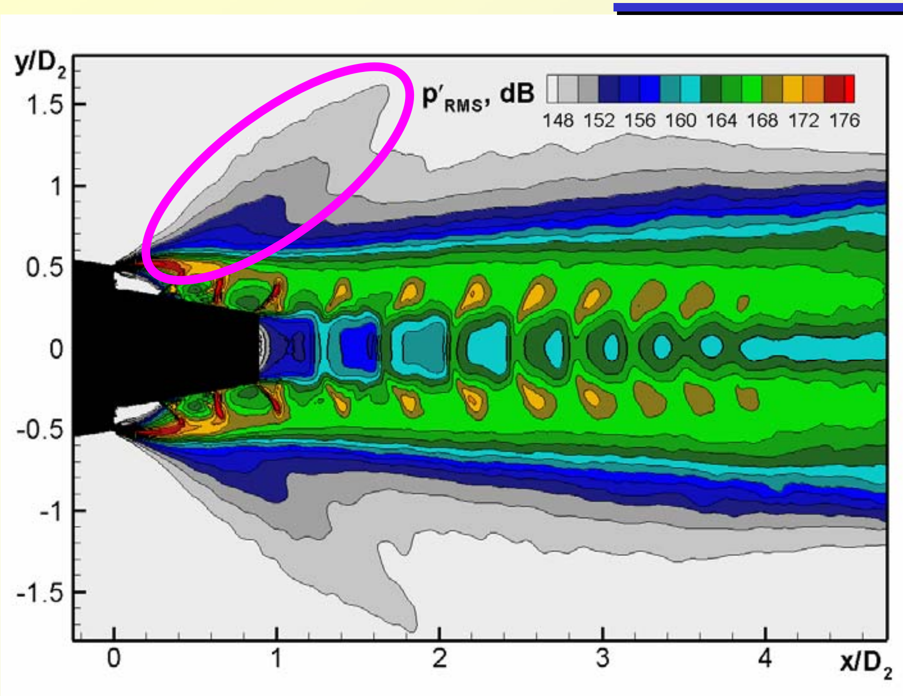
- Near-field acoustic pressure is rather sensitive to co-flow, the effect being stronger for the cold jet (twice higher U_{CF}/U_{JET} ratio than for the hot jet)
    - ➢ **Visual decrease of strongest low-frequency sound originating from the end of potential core and propagating mostly downstream**
- Strengthening of sound waves, representing BBSC noise in the upstream direction

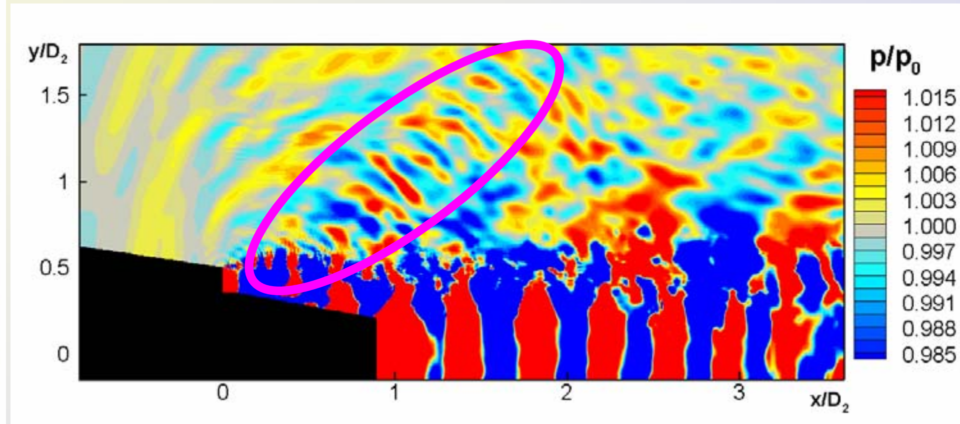
Nature of High-Frequency Maximums at θ>120°



- Maximums are observed at virtually constant frequency, both in experimental and predicted spectra (more pronounced in simulation)
  - **indicates that the nature of noise-source responsible for the maximums is different from that of the BBSC noise**
- Analysis of LES-flowfields suggests that this source is localized in a very restricted area of the initial part of the outer shear layer and is probably associated with short Mach waves originating from that region

High-Frequency Maximums at θ>120°: Source Location





RMS of pressure fluctuations and instantaneous pressure (in acoustic range)

- The origin of the noise responsible for the maximums is a small area in the outer shear layer near $x = 0.5D_2$
  - ➢ **Confirms that this noise-source has nothing common with the BBSC noise-source whose essential features are spatial coherence and quasi-periodicity over an extended area**