Noise of Embedded High Aspect Ratio Nozzles

- A family of high aspect ratio nozzles were designed to provide a parametric database of canonical embedded propulsion concepts. Nozzle throat geometries with aspect ratios of 2:1, 4:1, and 8:1 were chosen, all with convergent nozzle areas. The transition from the typical round duct to the rectangular nozzle was designed very carefully to produce a flow at the nozzle exit that was uniform and free from swirl. Once the basic rectangular nozzles were designed, external features common to embedded propulsion systems were added: extended lower lip (a.k.a. bevel, aft deck), differing sidewalls, and chevrons. For the latter detailed Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) simulations were made to predict the thrust performance and to optimize parameters such as bevel length, and chevron penetration and azimuthal curvature. Seventeen of these nozzles were fabricated at a scale providing a 2.13 inch diameter equivalent area throat.
- The seventeen nozzles were tested for far-field noise and a few data were presented here on the effect of aspect ratio, bevel length, and chevron count and penetration. The sound field of the 2:1 aspect ratio rectangular jet was very nearly axisymmetric, but the 4:1 and 8:1 were not, the noise on their minor axes being louder than the major axes. Adding bevel length increased the noise of these nozzles, especially on their minor axes, both toward the long and short sides of the beveled nozzle. Chevrons were only added to the 2:1 rectangular jet. Adding 4 chevrons per wide side produced some decrease at aft angles, but increased the high frequency noise at right angles to the jet flow. This trend increased with increasing chevron penetration. Doubling the number of chevrons while maintaining their penetration decreased these effects. Empirical models of the parametric effect of these nozzles were constructed and quantify the trends stated above.
- Because it is the objective of the Supersonics Project that future design work be done more by physics-based computations and less by experiments, several codes under development were evaluated against these test cases. Preliminary results show that the RANS-based code JeNo predicts the spectral directivity of the low aspect ratio jets well, but has no capability to predict the non-axisymmetry. An effort to address this limitations, used in the RANS-based code of Leib and Goldstein, overpredicted the impact of aspect ratio. The broadband shock noise code RISN, also limited to axisymmetric assumptions, did a good job of predicting the spectral directivity of underexpanded 2:1 cold jet case but was not as successful on high aspect ratio jets, particularly when they are hot. All results are preliminary because the underlying CFD has not been validated yet. An effort using a Large Eddy Simulation code by Stanford University predicted noise that agreed with experiments to within a few dB.

National Aeronautics and Space Administration

Fundamental Aeronautics Program

Supersonics Project

Noise of Embedded High Aspect Ratio Nozzles

Presented by James Bridges
NASA Glenn / Acoustics Branch

2011 Technical Conference
March 15-17, 2011
Cleveland, Ohio

Acknowledgements

- In NASA Supersonics Project, exploration and development of low-noise concepts is highly connected to the development and validation of noise prediction tools.
- This presentation incorporates the efforts of many researchers at Glenn and Langley Research Centers:

  - James Bridges—Experiment design, acoustic measurements
  - Franco Frate—CFD, test hardware design
  - Steve Miller—RANS-based acoustic prediction (RISN code)
  - Stewart Leib—RANS-based acoustic prediction (3D Green's functions)
  - Abbas Khavaran—RANS-based acoustic prediction (JeNo code)
  - Khairul Zaman—Flow measurements
  - Gary Podboy—Phased array measurements

- There is also affiliated work under NASA NRA contract at Stanford University

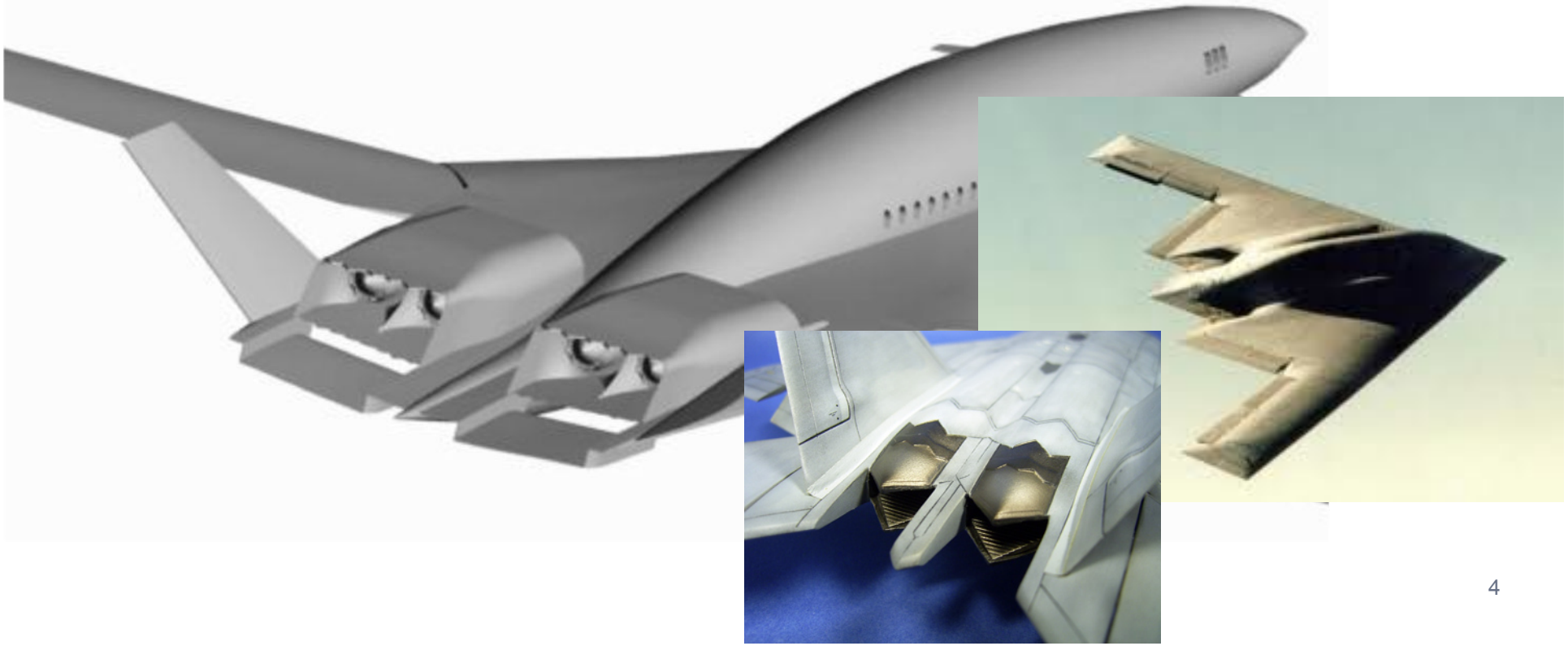
  - Sanjiva Lele, Joseph Nichols—LES predictions (CharLES code)
  - Jim DeBonis—NASA Tech monitor

Outline

- Motivation / Previous work
- Design of nozzle configurations
- Sample acoustic test results
- Empirical modeling for trends and systems studies
- RANS-based noise predictions
- LES noise predictions

Motivation

- Highly embedded propulsion systems, such as may be required for low sonic boom, often employ high aspect ratio nozzles and aft decks
- Highly variable cycle nozzles can be implemented with fewer moving parts in a 2D geometry
- Database and design tools for jet noise for such configurations nonexistent
- Jet noise prediction tools assume axisymmetry and no surfaces



Previous work

- GE CR&D (1970s)
  - 6:1 rectangular nozzle, cold and hot subsonic cases
  - Found suppression of OAPWL relative to round jet
  - Found up to 2dB azimuthal dependence, esp high frequencies
  - Peak jet noise reduced, some high frequency increase, esp minor axis
- GTRI (2002-2004)
  - 1.5:1, 4:1, 8:1 rectangular nozzles, subsonic cases
  - Showed variation of noise with aspect ratio
  - Peak jet noise reduced by 6dB, high frequencies reduced as well

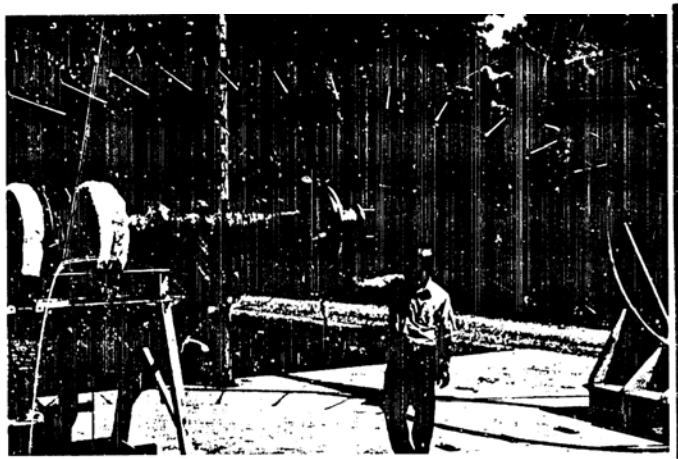


Figure 3-1. CR&D Hot Jet Noise Facility.

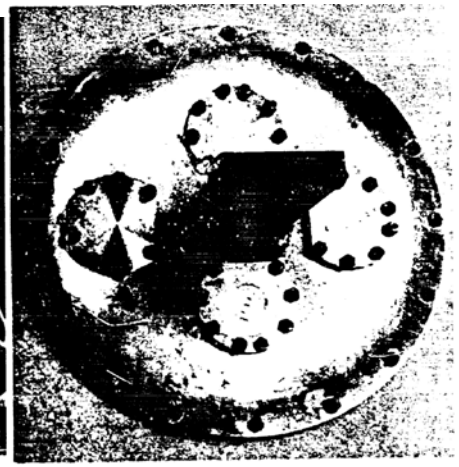
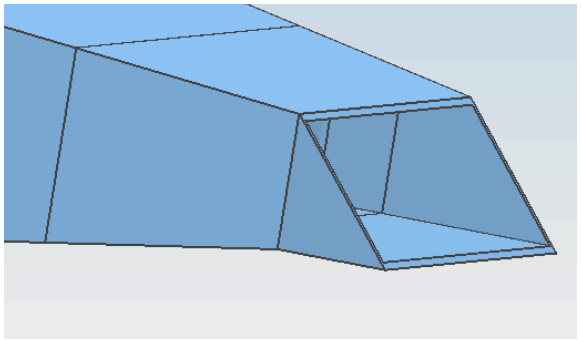
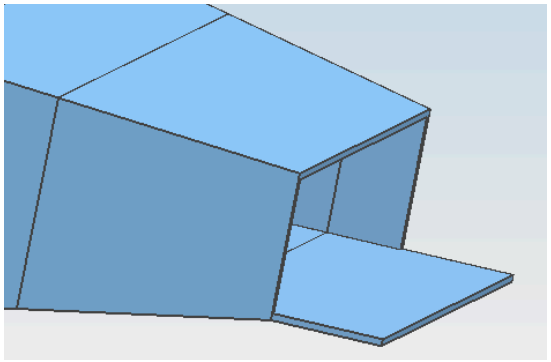


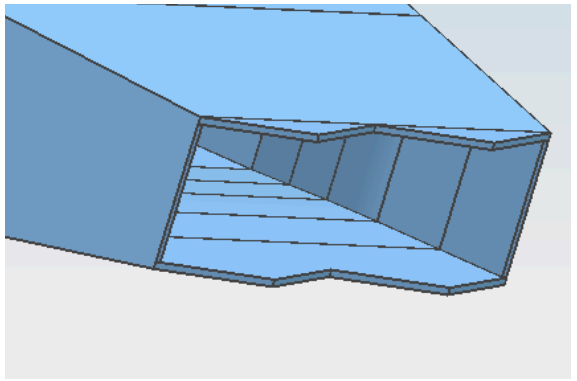
Figure 5-9. Rectangular Jet Nozzle.

Design—Internal Flow and External Features

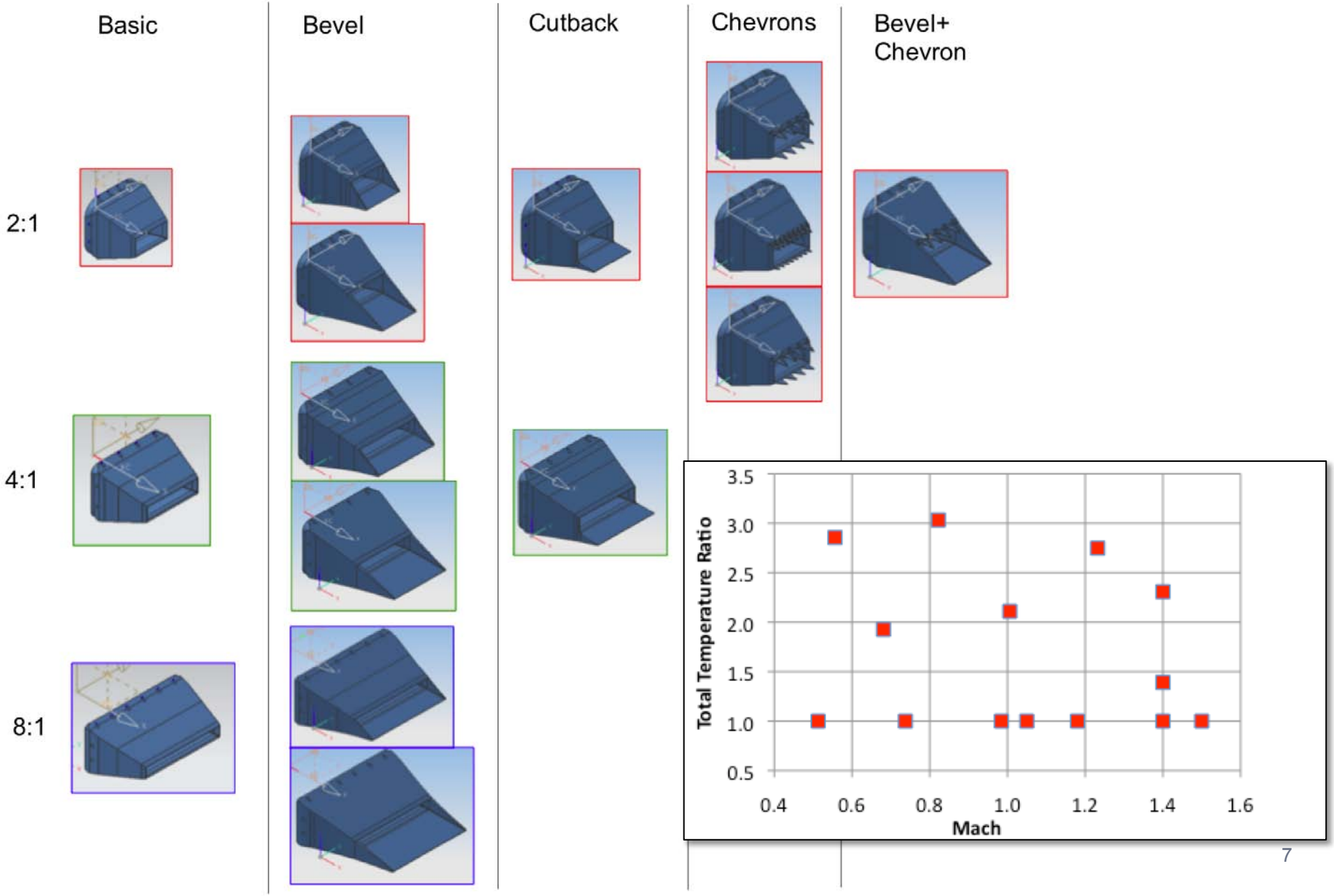
- Challenge:
  - Create multiple high-aspect-ratio nozzles with common parts.
  - Flow at exit uniform.
  - Short length to minimize weight.
  - Handle hot flow.
  - Aspect ratios 2:1, 4:1, 8:1
- Mount to small hot jet rig (SHJAR) and to twin jet rig —> 2.13” De
- Once clean transitions designed, shift focus to external flow and external features
  - Bevels, with and without sidewalls
  - Chevrons





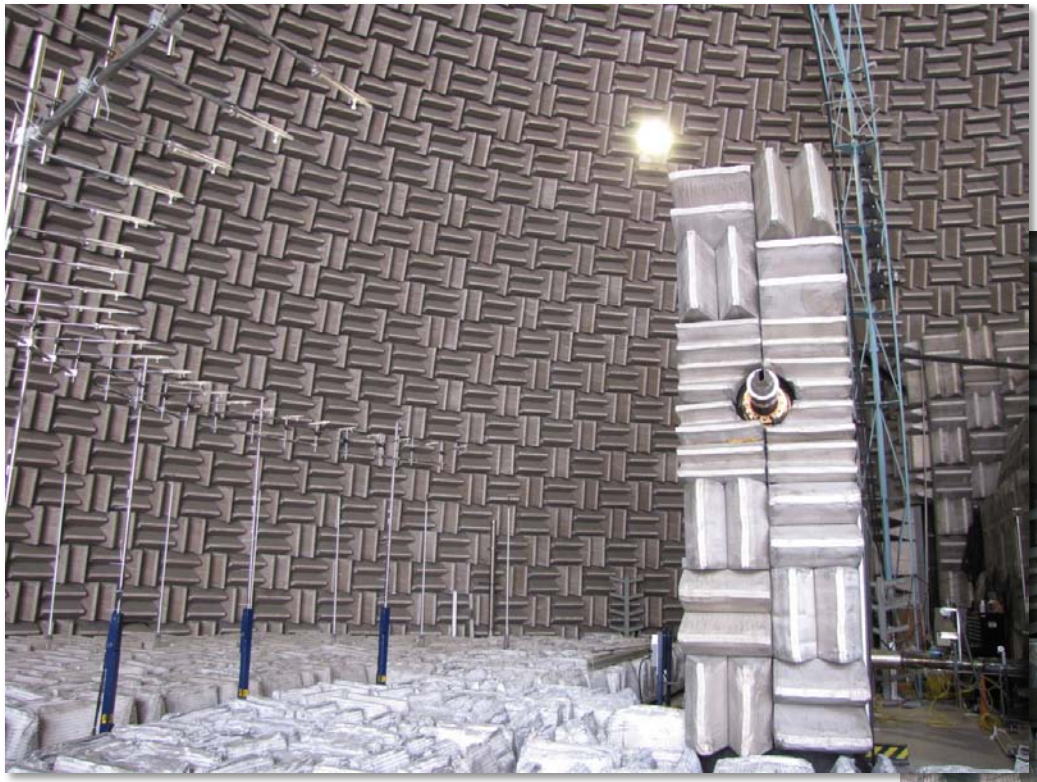


Design—Test plans



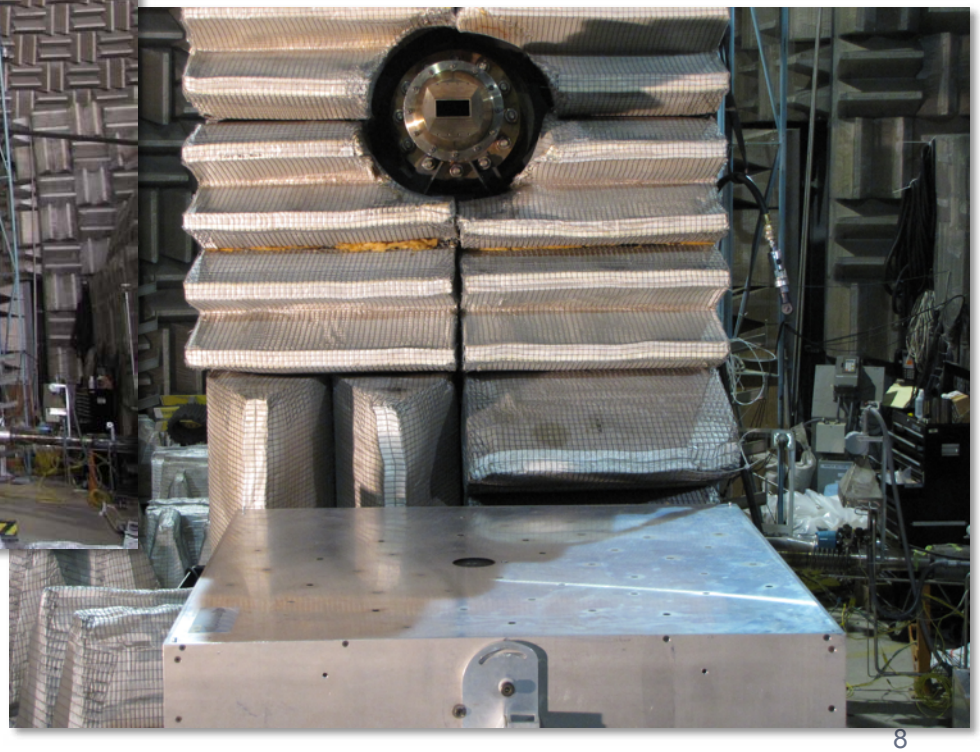
Facilities

- NASA Glenn Research Center
- Small Hot Jet Acoustic Rig (SHJAR)



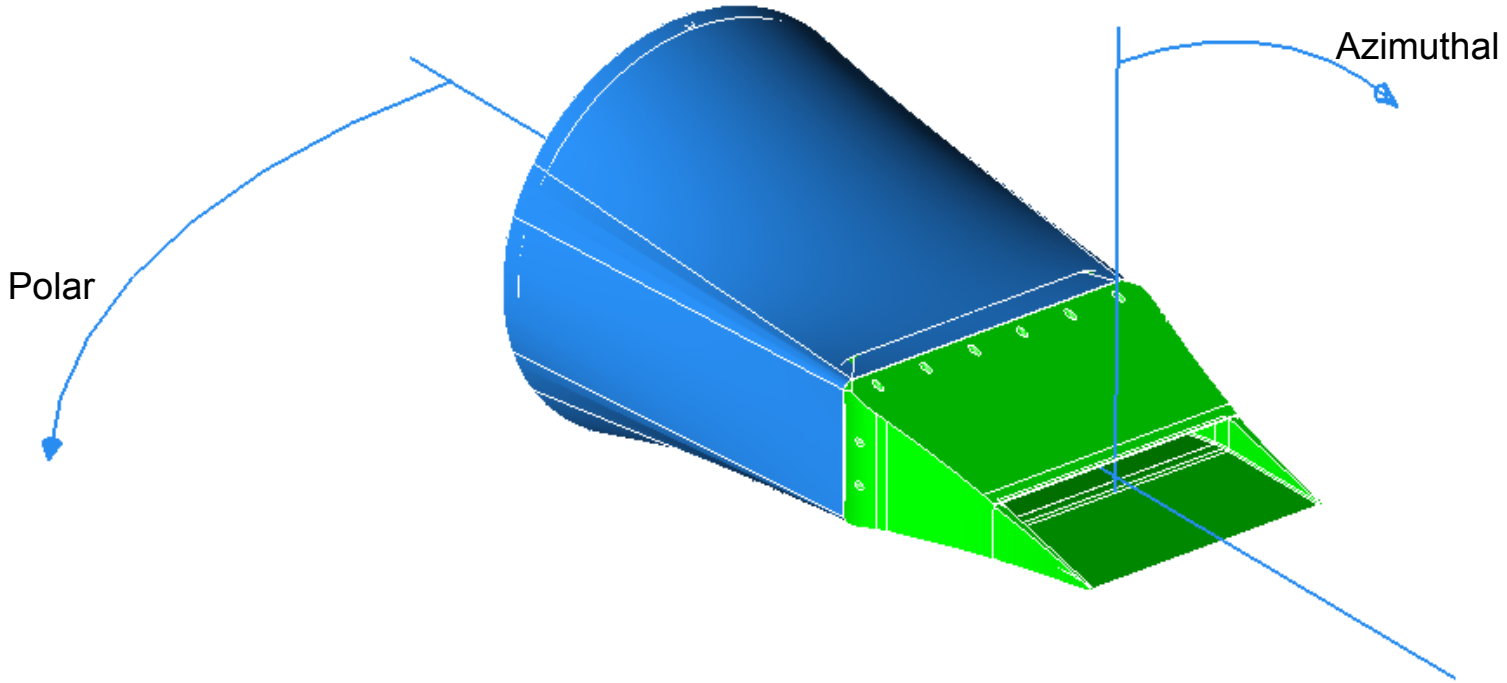
Far-field array r/D=70

Array 48



Sample far-field acoustic test results

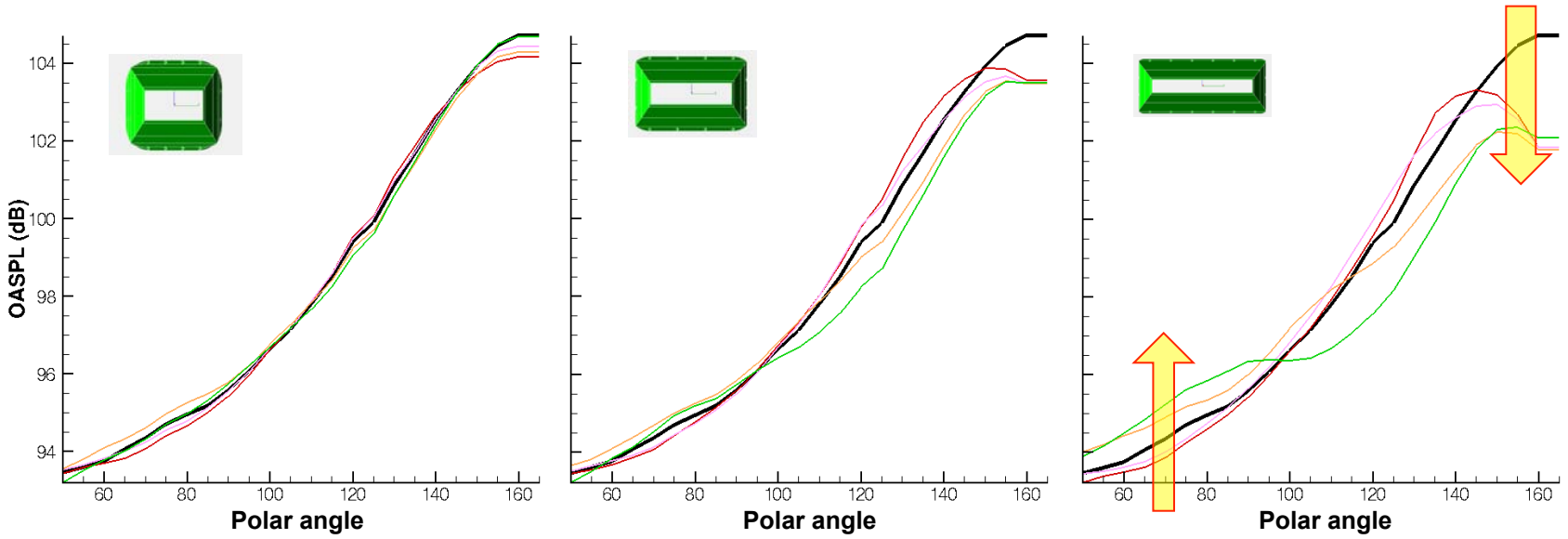
- Nomenclature

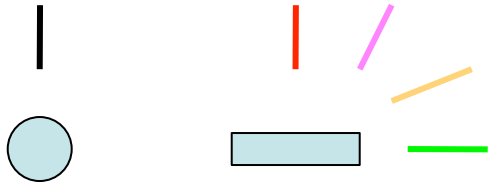


Aspect Ratio—OASPL

- Colored lines for different azimuthal planes
- Black line for round jet

Aspect Ratio 2:1 4:1 8:1

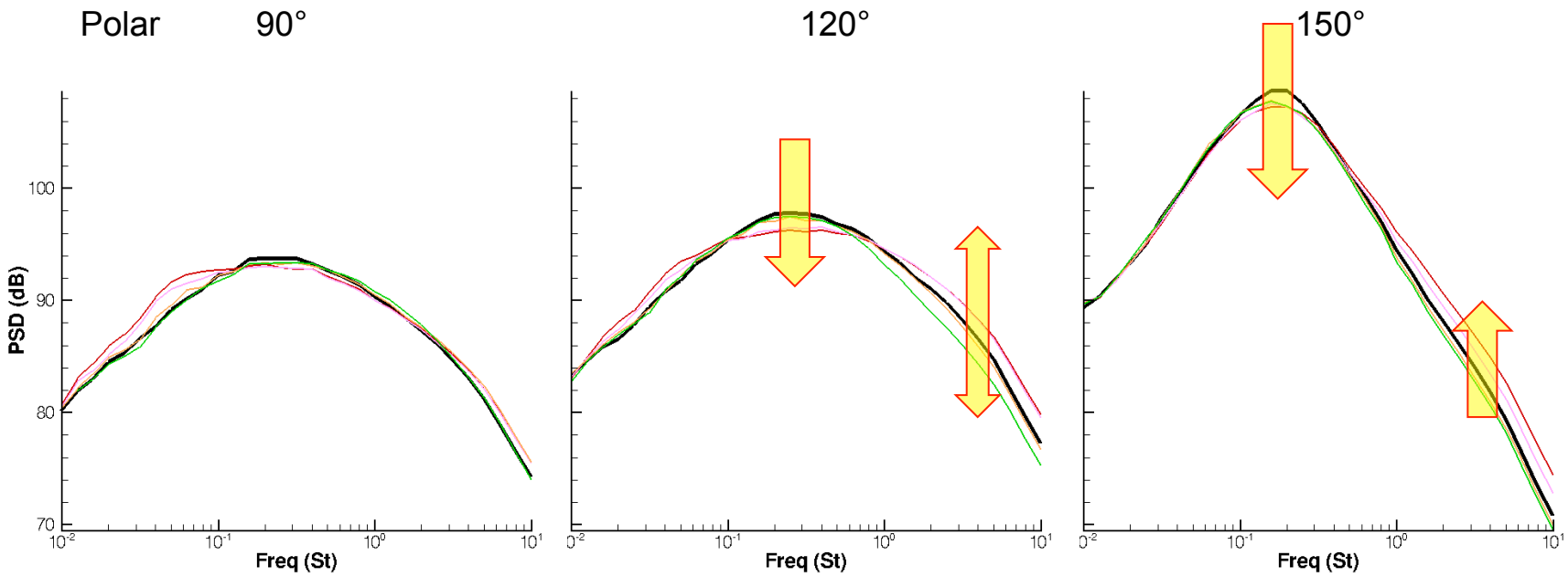


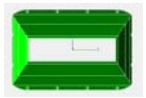


M=0.96, cold

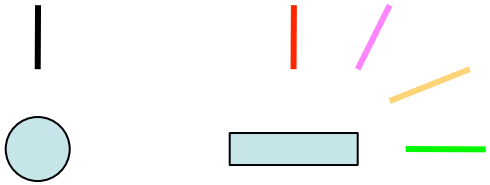
Aspect Ratio—SPL

- Colored lines for different azimuthal planes
- Black line for round jet





4:1

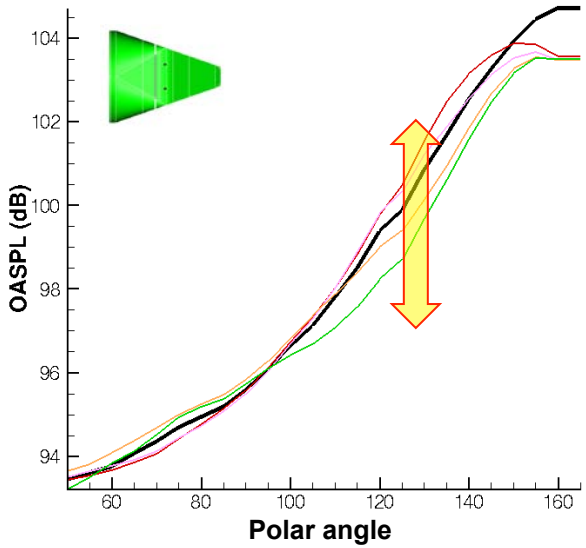


M=0.96, cold

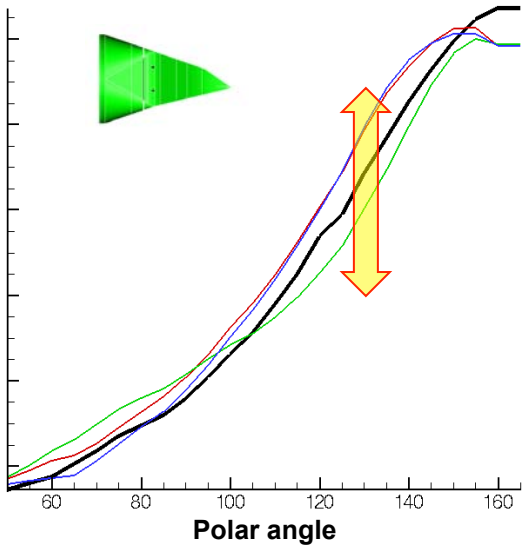
Bevel Length—OASPL

- Colored lines for different azimuthal planes
- Black line for round jet

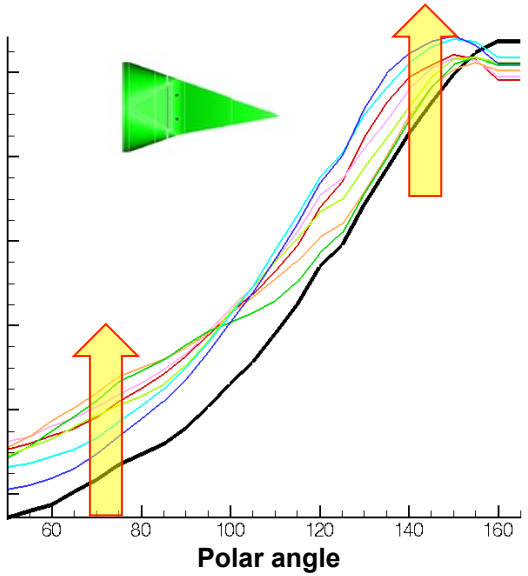
L/h = 0

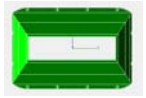


L/h = 1.4

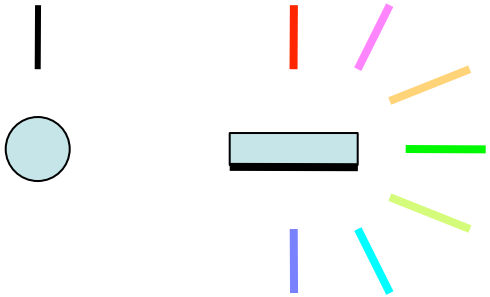


L/h = 2.8





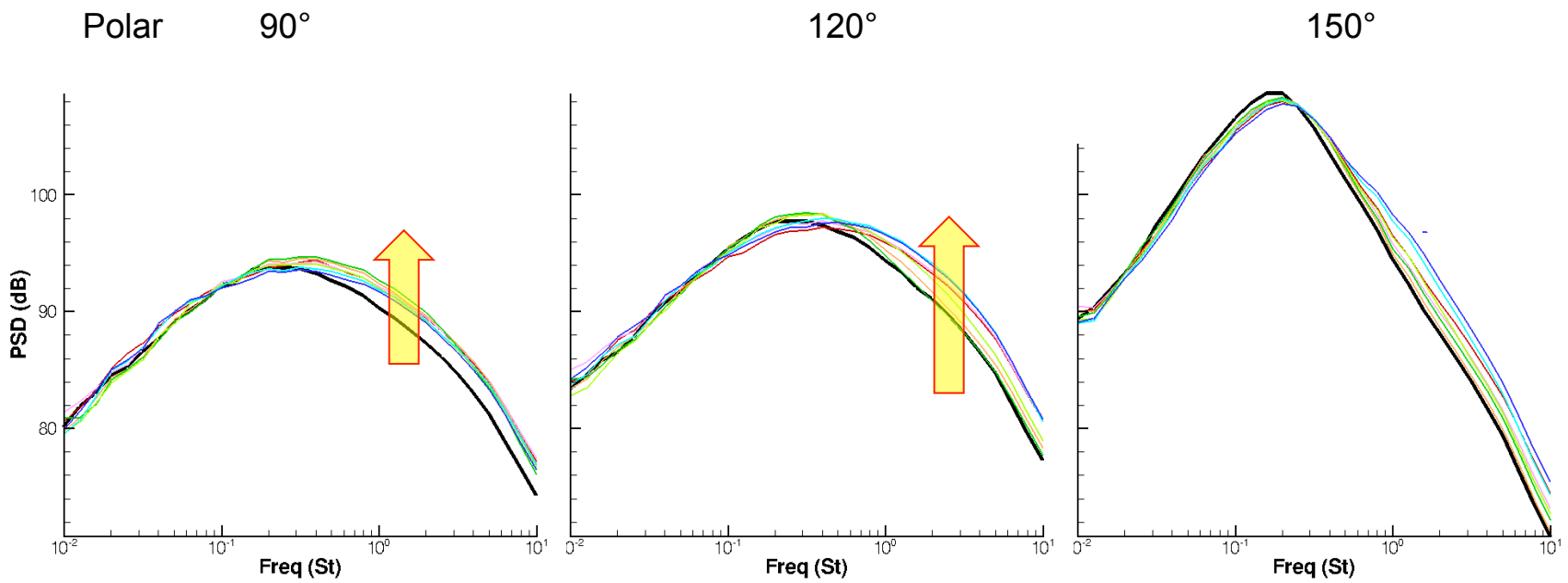
4:1

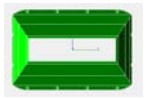


M=0.96, cold

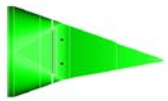
Bevel Length—SPL

- Colored lines for different azimuthal planes
- Black line for round jet

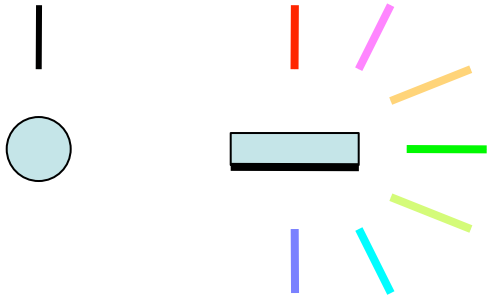




4:1



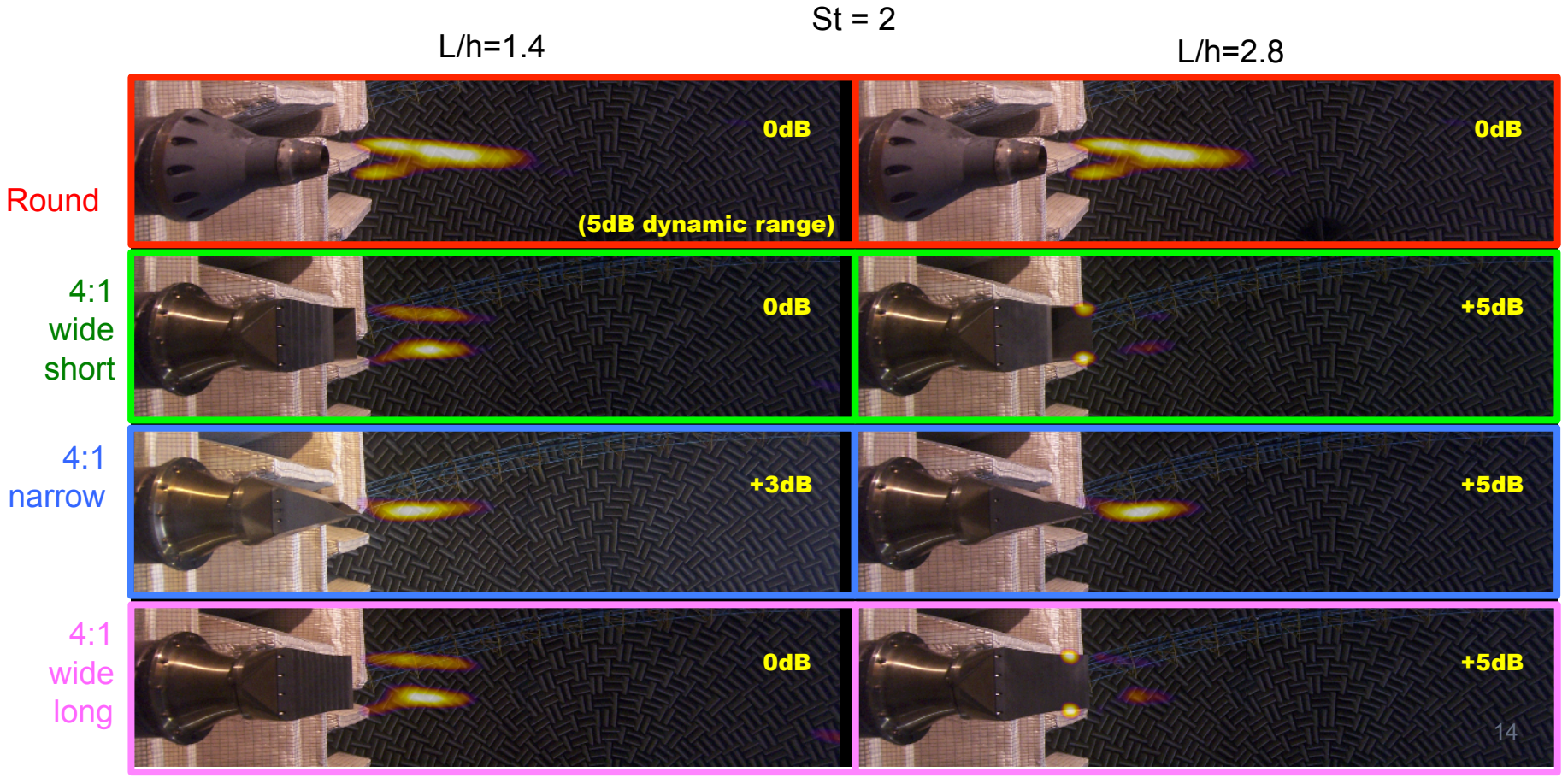
L/h=2.8



M=0.96, cold

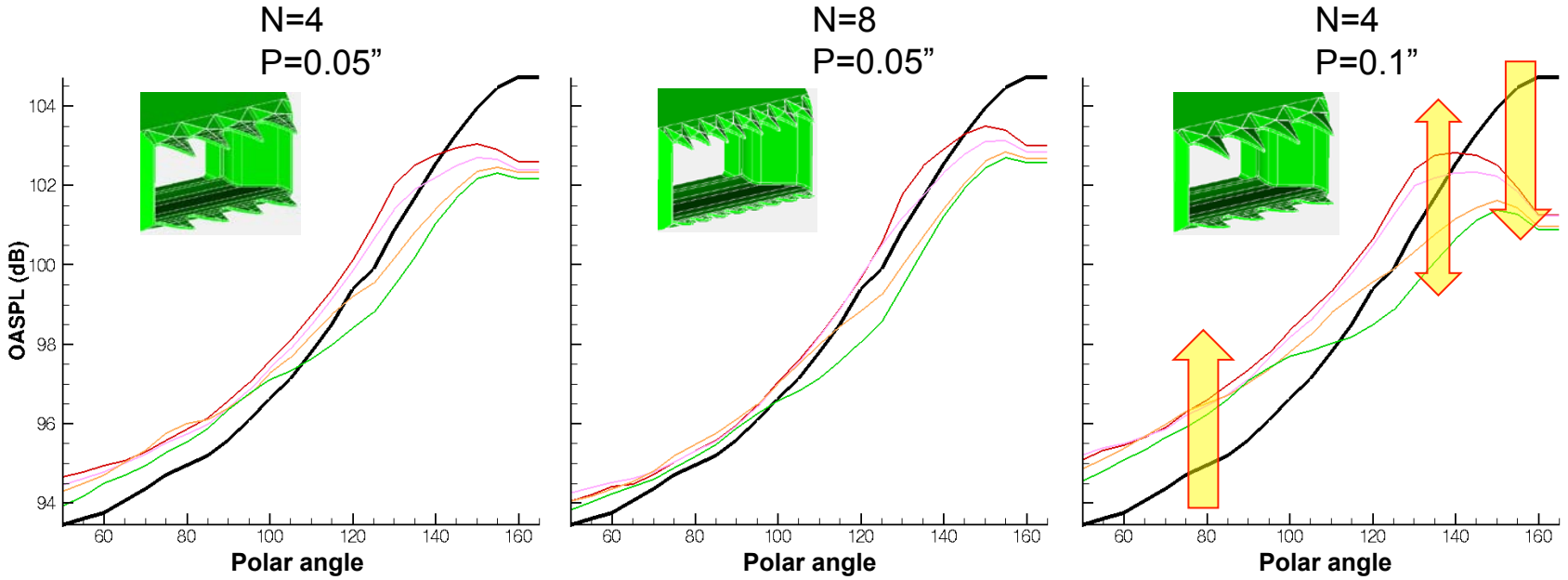
Bevel Length—phased array

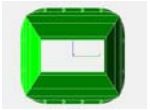
- Insight:
  - Increasing bevel length introduces new source at sidewall
  - Visible from both upper and lower sides



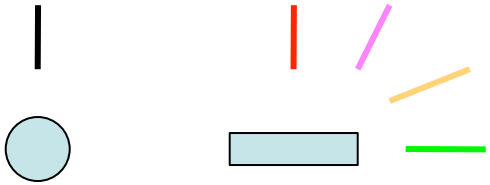
Chevrons—OASPL

- Colored lines for different azimuthal planes
- Black line for round jet





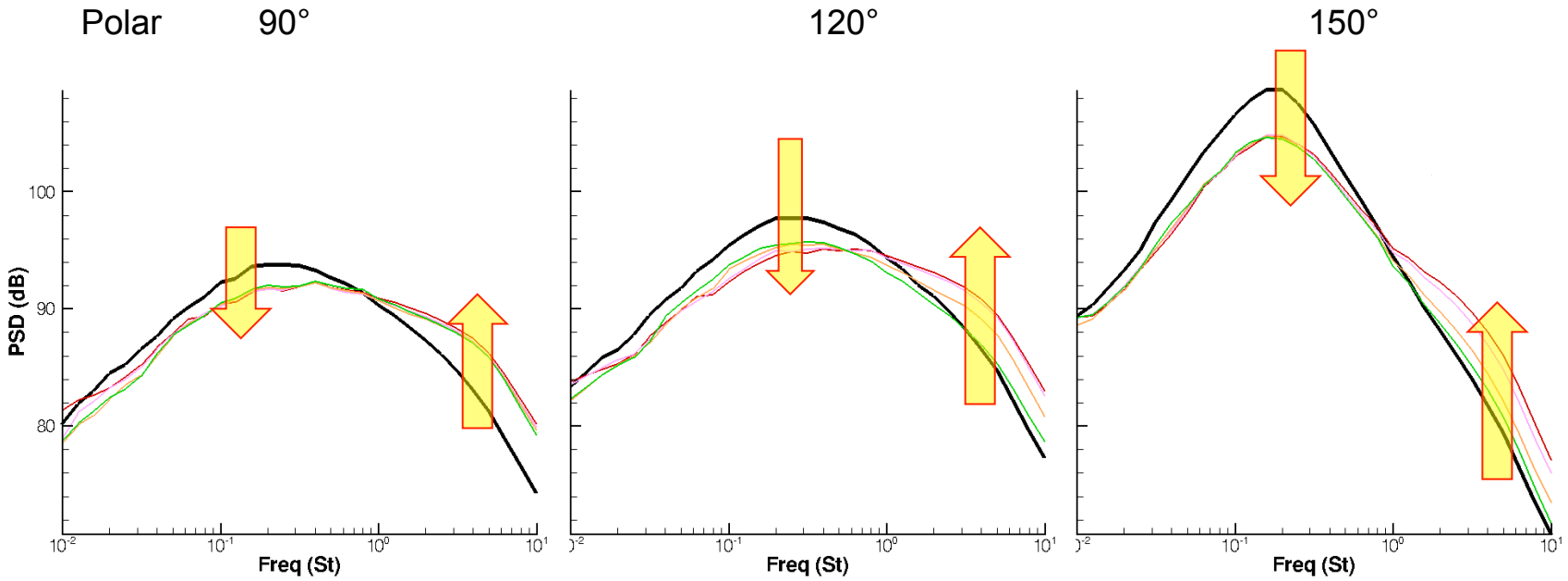
2:1

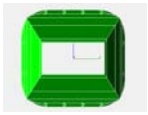


M=0.96, cold

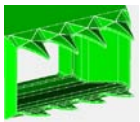
Chevrons—SPL

- Colored lines for different azimuthal planes
- Black line for round jet

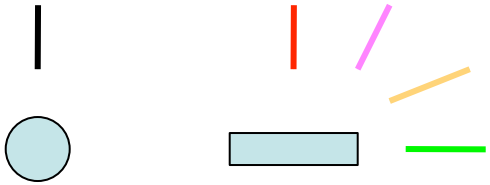




2:1



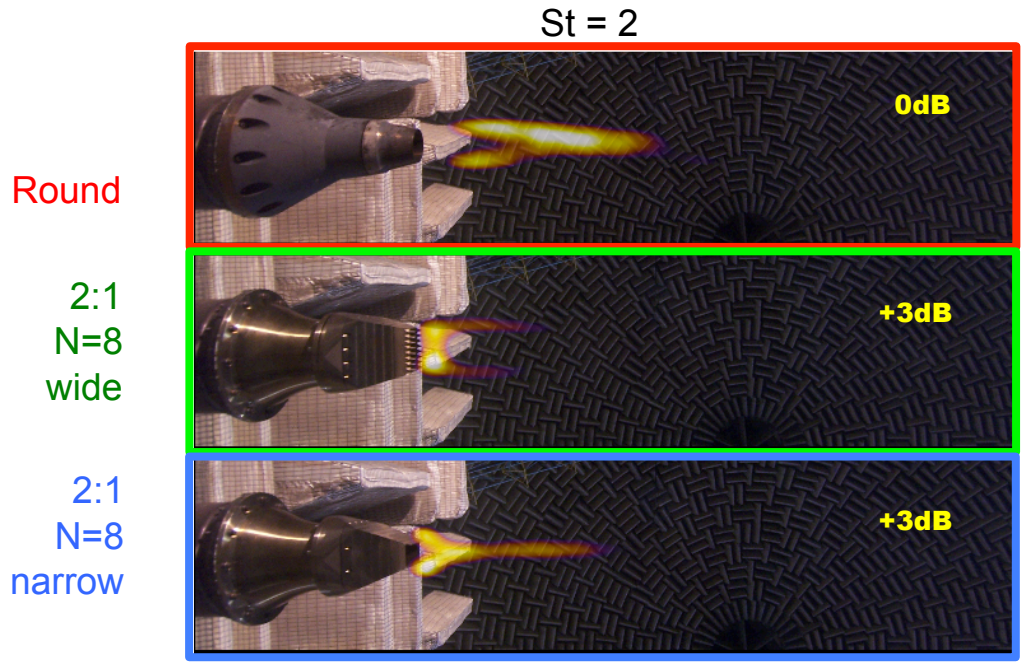
N=4
P=0.1”



M=0.96, cold

Chevrons—phased array

- Insight:
  - Sources brought close to nozzle exit
  - For 2:1, view factor not important—no azimuthal dependence



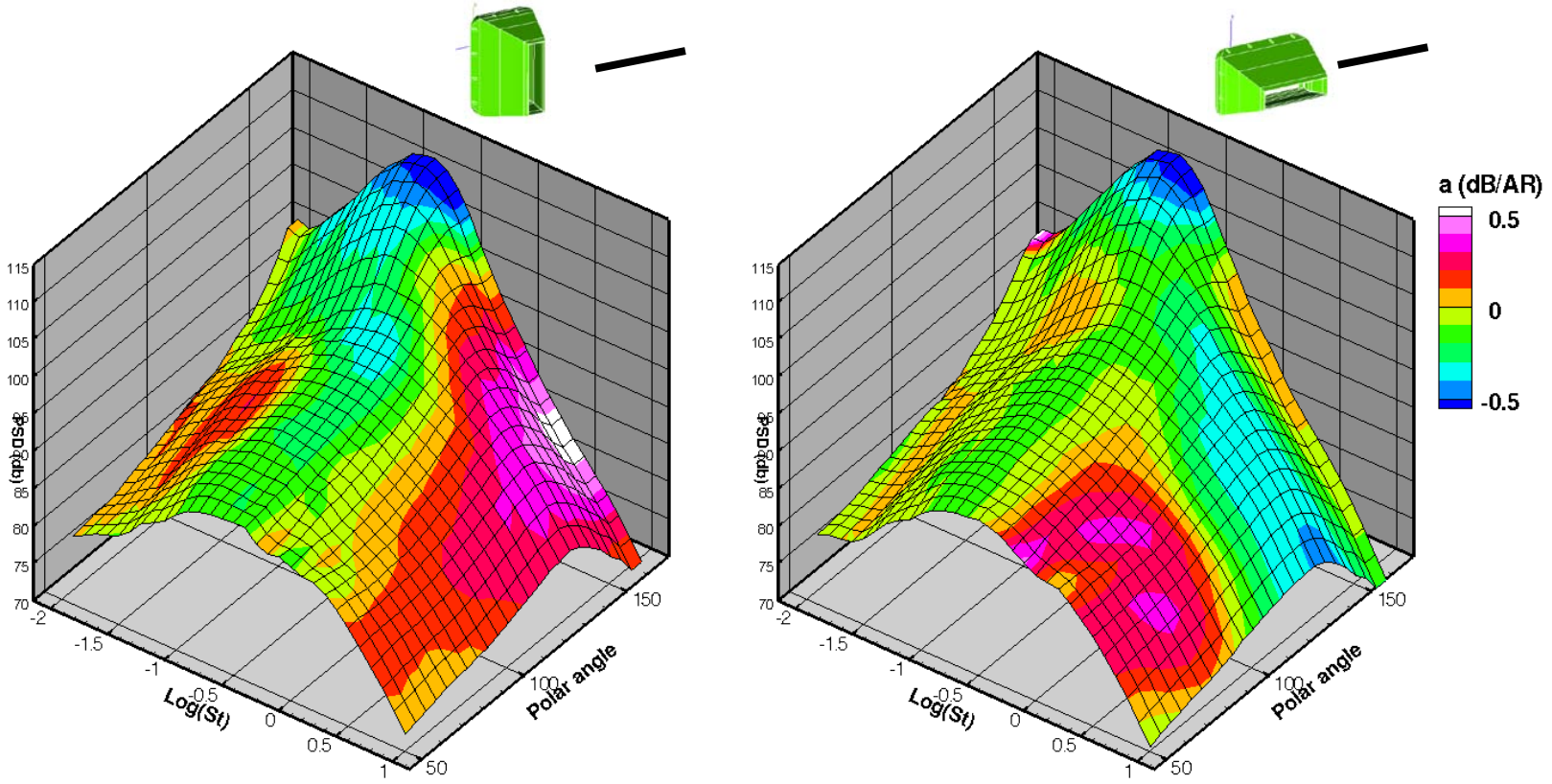
Parametric Modeling—Description

- Simple parametric models of the impact of various geometric features created
- Aspect Ratio and Bevel Length:
  - PSD = power spectral density in dB
  - PSD0 = power spectral density of round jet
  - AR = Aspect ratio
  - L/h = bevel length relative to nozzle height

$$PSD(AR, L/h; f, \theta, \phi) = PSD0(f, \theta) + AR * a(f, \theta, \phi) + L/h * b(f, \theta, \phi) + AR * L/h * c(f, \theta, \phi)$$

Parametric Modeling—Aspect Ratio

- Bilinear model fitted to 3 aspect ratios x 3 bevel lengths each
- Linear coefficient for aspect ratio depicts basic sensitivities
- Surface shape is spectral directivity, color is aspect ratio coefficient



Parametric Modeling—Bevel Length

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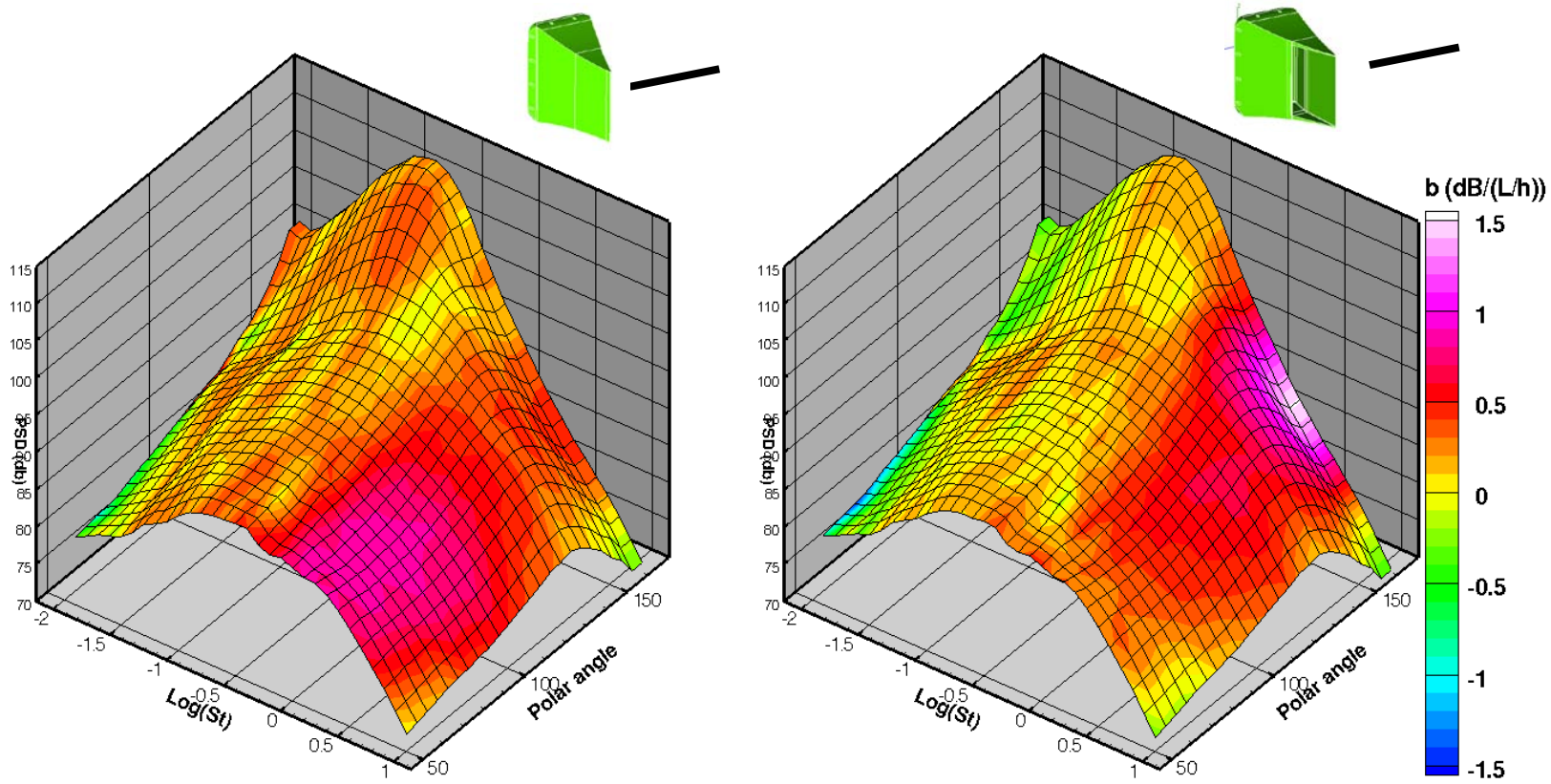
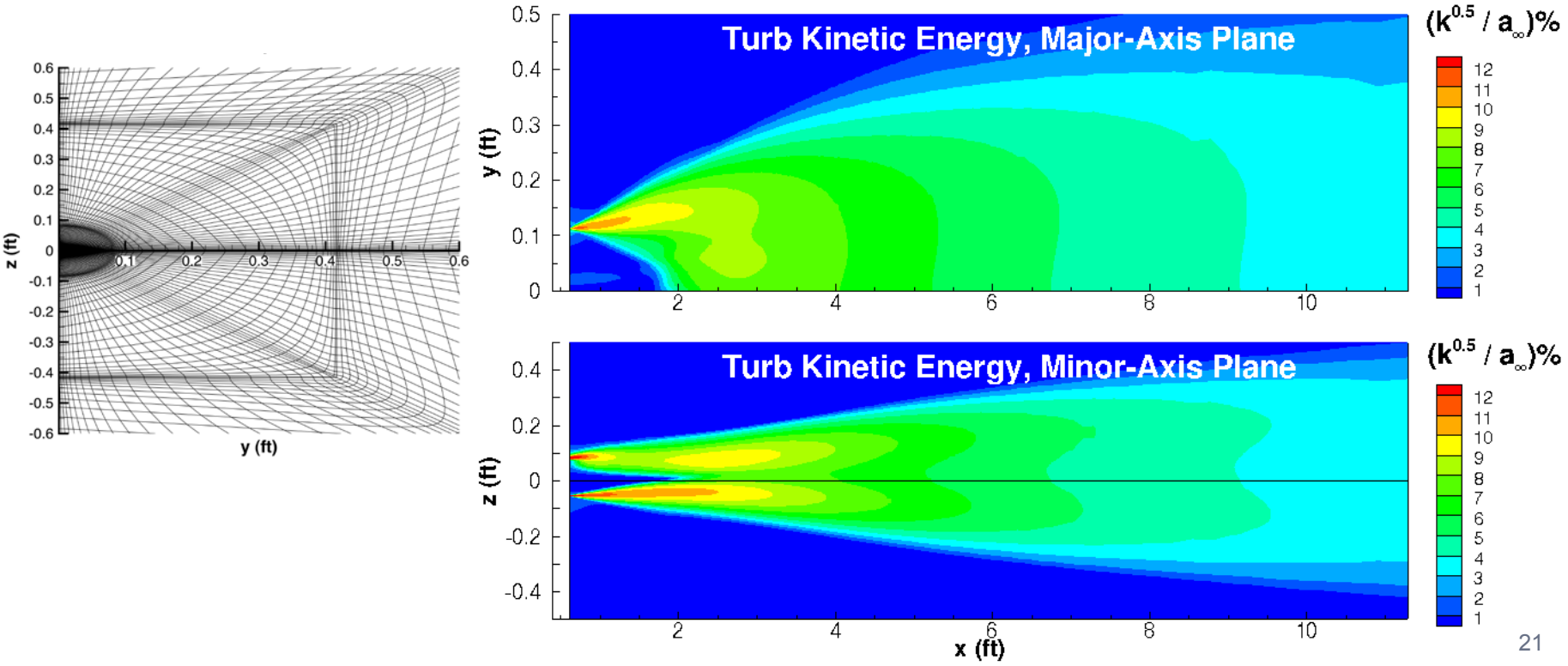


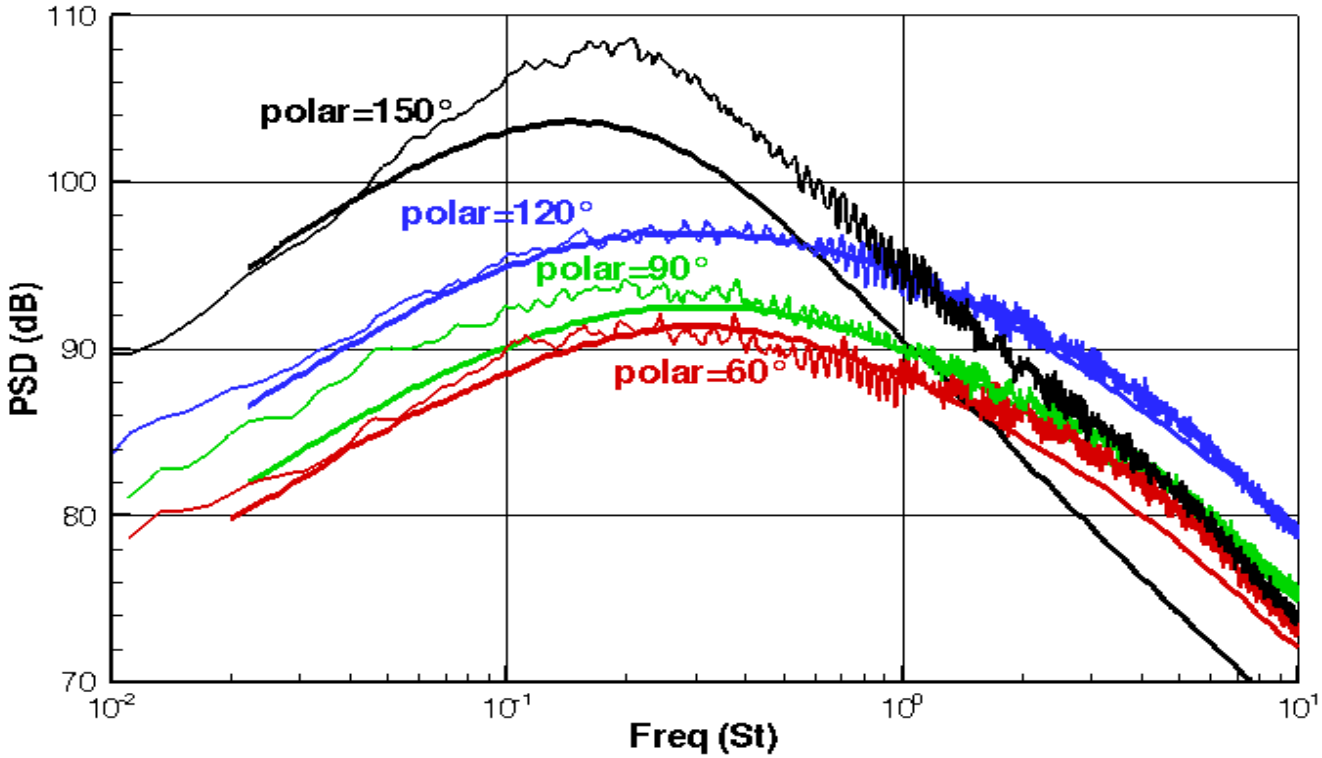
RANS-based noise prediction—CFD

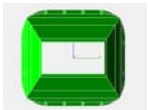
- All RANS-based noise predictions made with WindUS solutions
- Typical runs required 30M grid points on bi-symmetric fine grid
- Used SST turbulence model
- Stringent grid refinement and convergence criteria placed on TKE
- Thrust and flow angularity evaluated



RANS-based noise prediction—JeNo

- Uses axisymmetric approximation of jet mixing noise
- Until turbulent enthalpy code validated in Wind, JeNo limited to cold flows
- Predicted spectral levels within 2 dB for subsonic cold jets, most polar angles



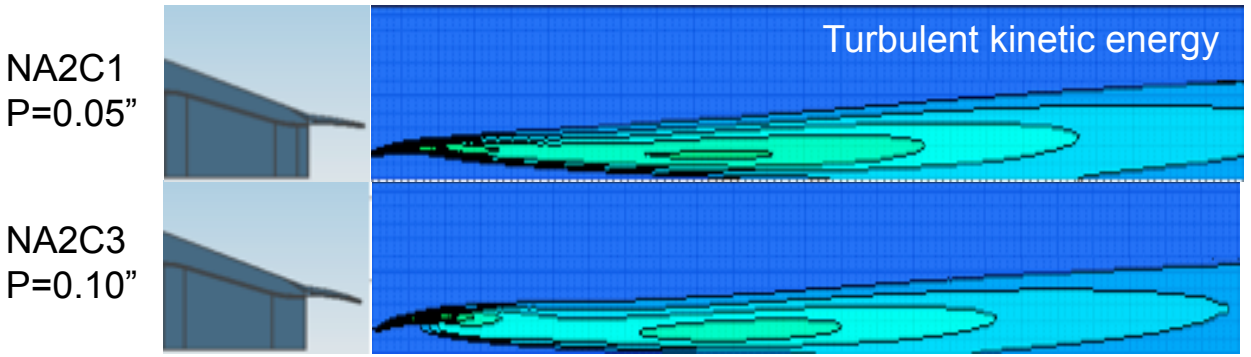


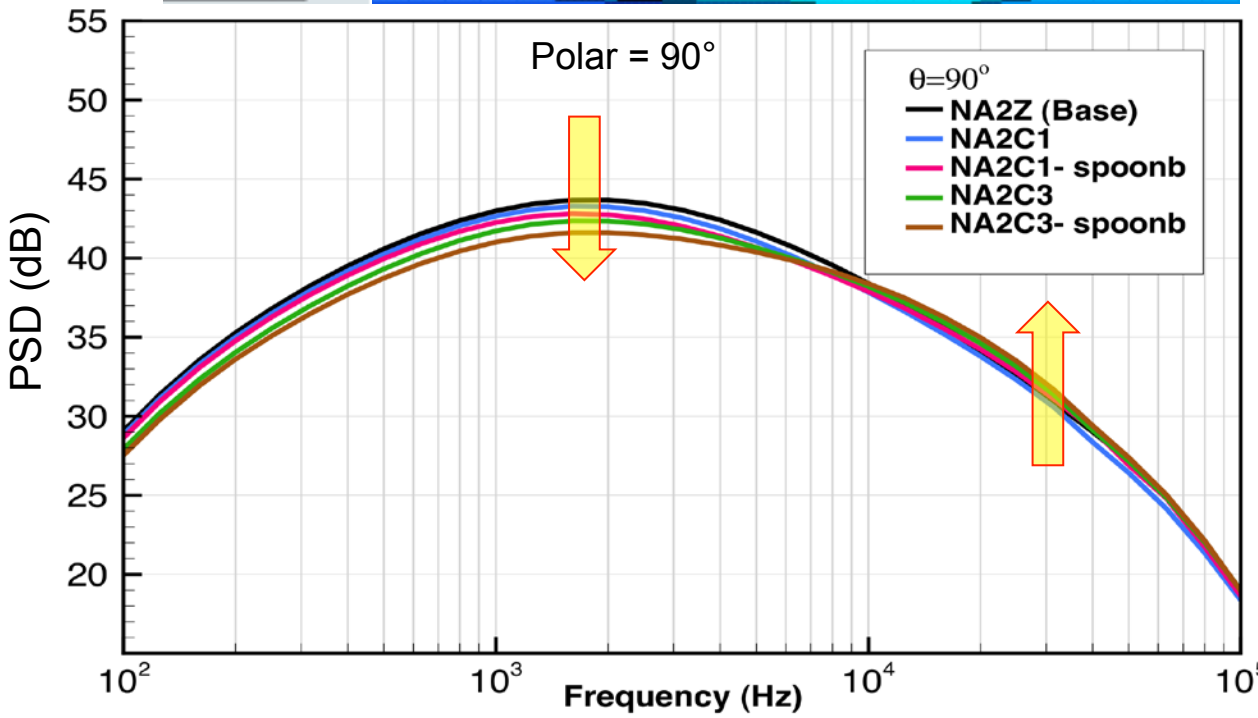
2:1

M=0.96, cold

RANS-based noise prediction—JeNo

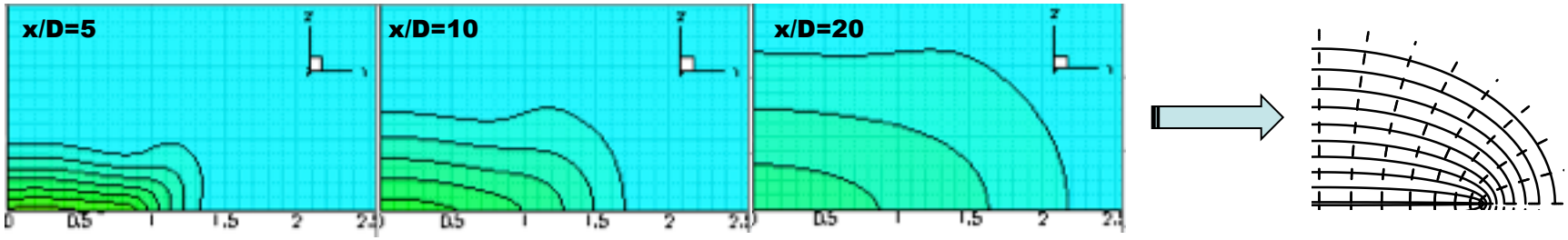
- JeNo used in evaluation of chevron designs for noise



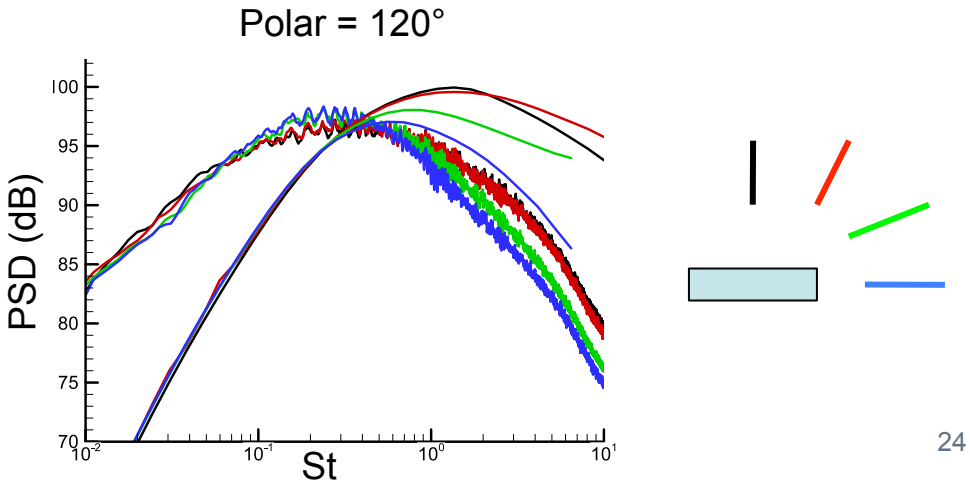


RANS-based noise prediction—Leib

- In acoustic analogy theory, refraction computed by Green's function
- Elliptic approximation to Green's function for prediction of nonaxisymmetric mixing noise
- Uses Goldstein-Leib formulation for mixing noise source terms
- Limited to cold flows at this time

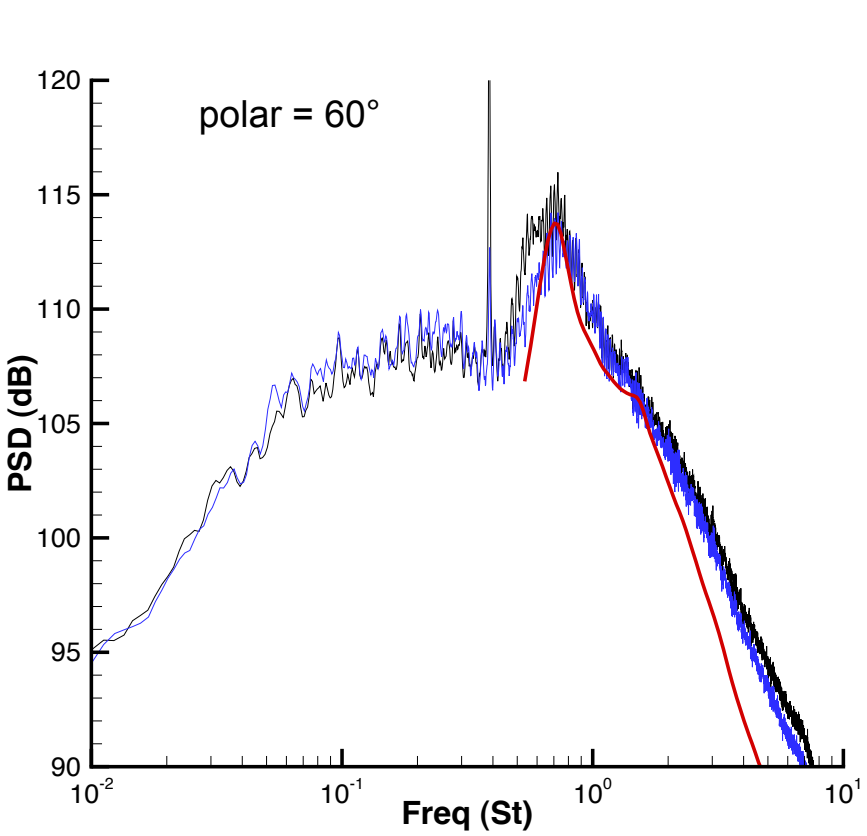


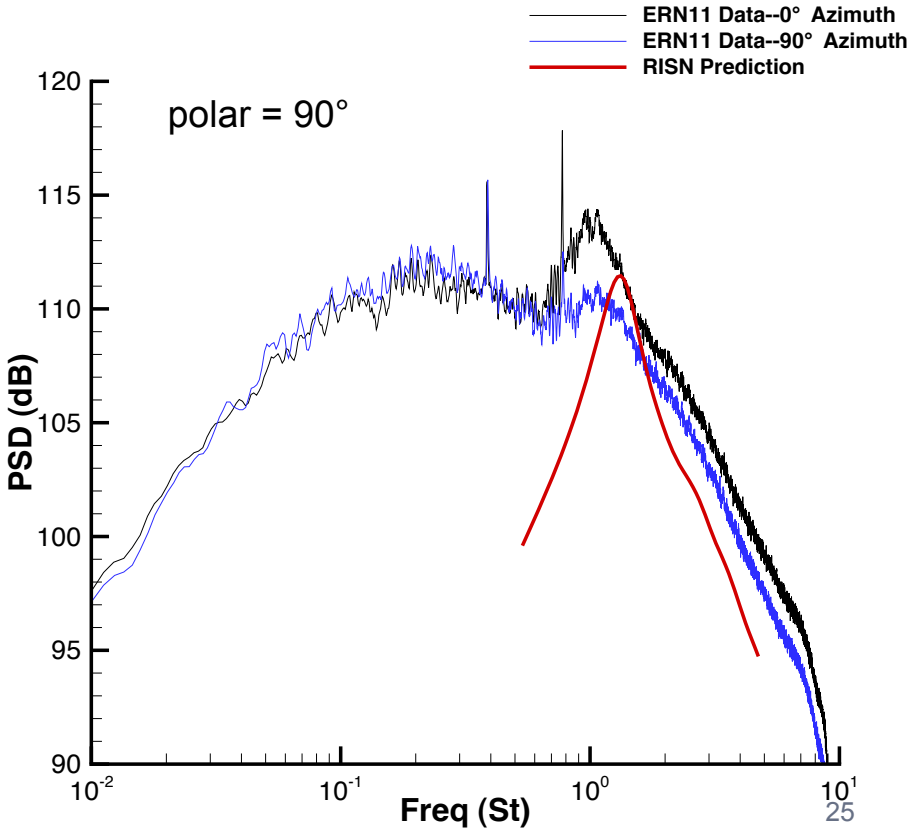
Prediction of azimuthal dependence of noise spectra for 4:1 rectangular jet at polar angle 120°—Data vs Leib



RANS-based noise prediction—RISN

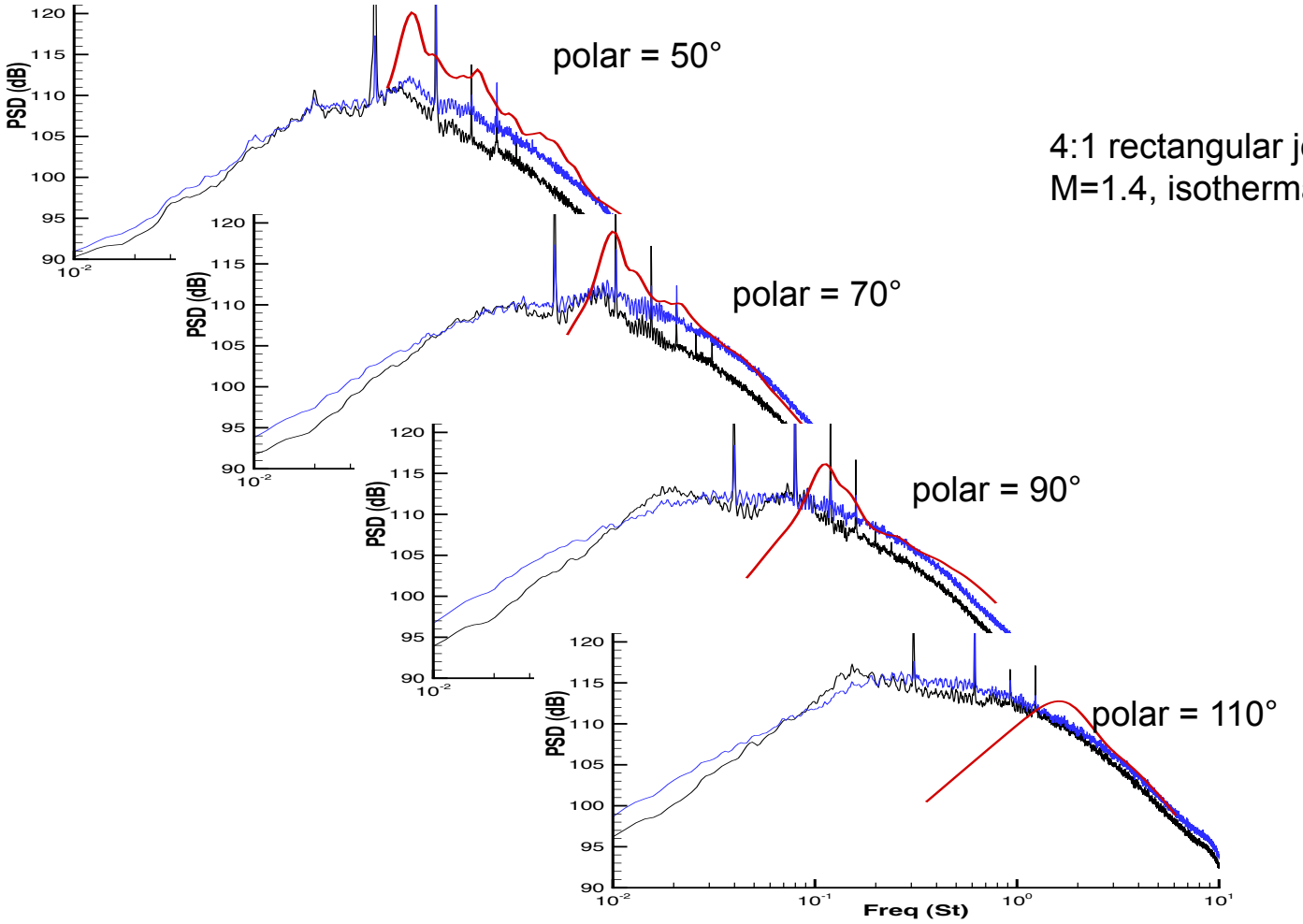
- Axisymmetric approximation of broadband shock noise computed from RANS CFD input
- No prediction of screech or amplification of BBSN by screech
- Blind comparison with M=1.23 hot 2:1 rectangular jet





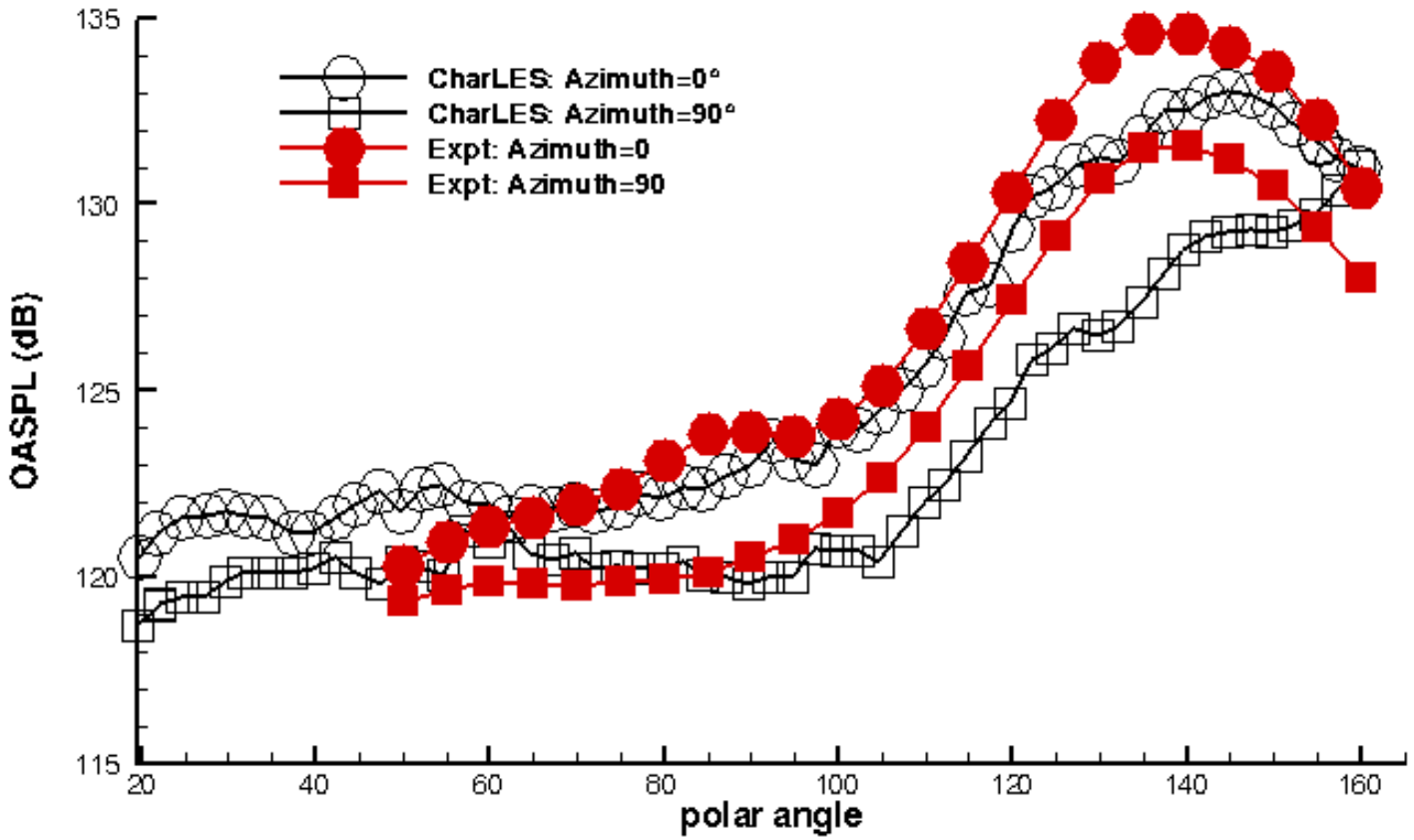
RANS-based noise prediction—RISN

- Prediction of three-dimensional directivity of BBSN still a challenge



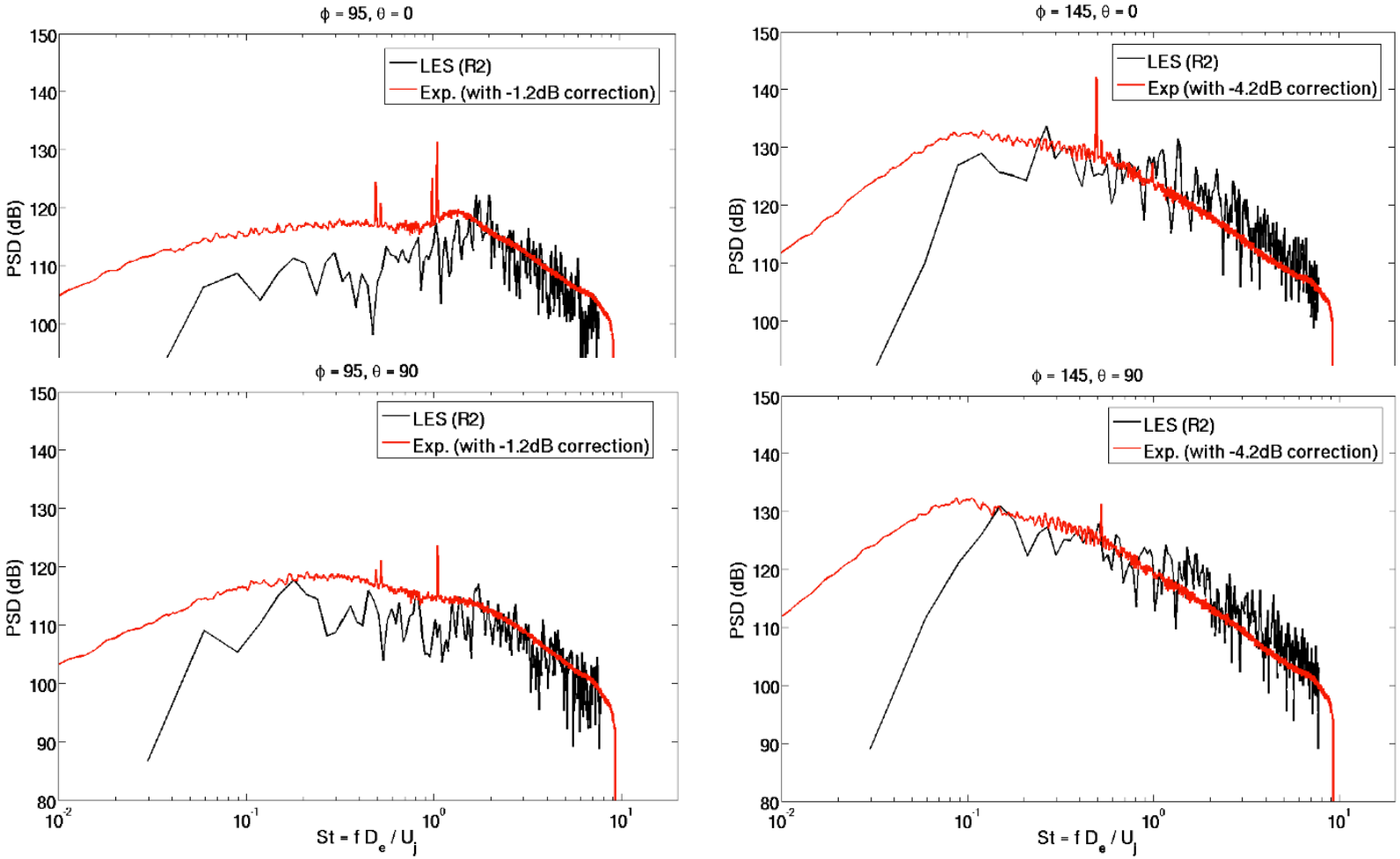
LES noise prediction—OASPL

- Stanford University has make LES-based predictions of far-field noise from 4:1 rectangular nozzle at hot supersonic flow condition.
- Very preliminary comparisons show remarkable agreement with data.
- More detailed comparisons underway



LES noise prediction—far-field spectra

- Blind comparisons of LES and ERN11 data



Summary/Status

- An initial set of high aspect ratio nozzles incorporating features common to embedded propulsion concepts has been designed and tested for far-field noise over a broad range of flow conditions.
- Simple parametric models have been constructed which capture trends over range of parameters tested.
- Shifts in distribution of noise sources
  - lower peak jet noise in the aft arc with increased aspect ratio, increased bevel length, and introduction of chevrons
  - Increase high frequency noise at broadside angles with same parametric variations.
  - result in increased EPNL by a few EPNdB for most subsonic configurations
- Phased array results show sources related to key nozzle features
- Empirical models of all possible parametric variations not feasible
- RANS-based prediction methods
  - Lack non-axisymmetric propagation ability
  - Lack hot flow CFD input for accurate source strength prediction
  - These aspects will be worked in coming years
- LES prediction accurate within few dB, at substantial cost.

NASA