Jet Noise Predictions with Wall-Modeled LES

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NASA's Commercial Supersonic Technology (CST)

During take-off and landing engine noise is the dominant noise source

Jet noise mainly comes from high speed exhaust turbulence at the end of the nozzle as well as from the mixing of turbulent structures

- NASA initiated research activities towards Commercial Supersonic Technologies (CST)
- Within this project Three main Technical Challenges (TC) have been defined
  - TC 1.1 Low Boom Design Tools
  - TC 1.2 Sonic Boom Community Response Metric & Methodology
  - **TC 2.2 Low Noise Propulsion for Low Boom Aircraft**
- Develop an understanding of the effects of shielding surfaces on the aerodynamic noise sources from jet flows.

Picture Credit: NASA / Lockheed Martin

Integrated Propulsion Noise

Predicting Jet Noise for Full-Scale Low-Boom Flight Demonstrator

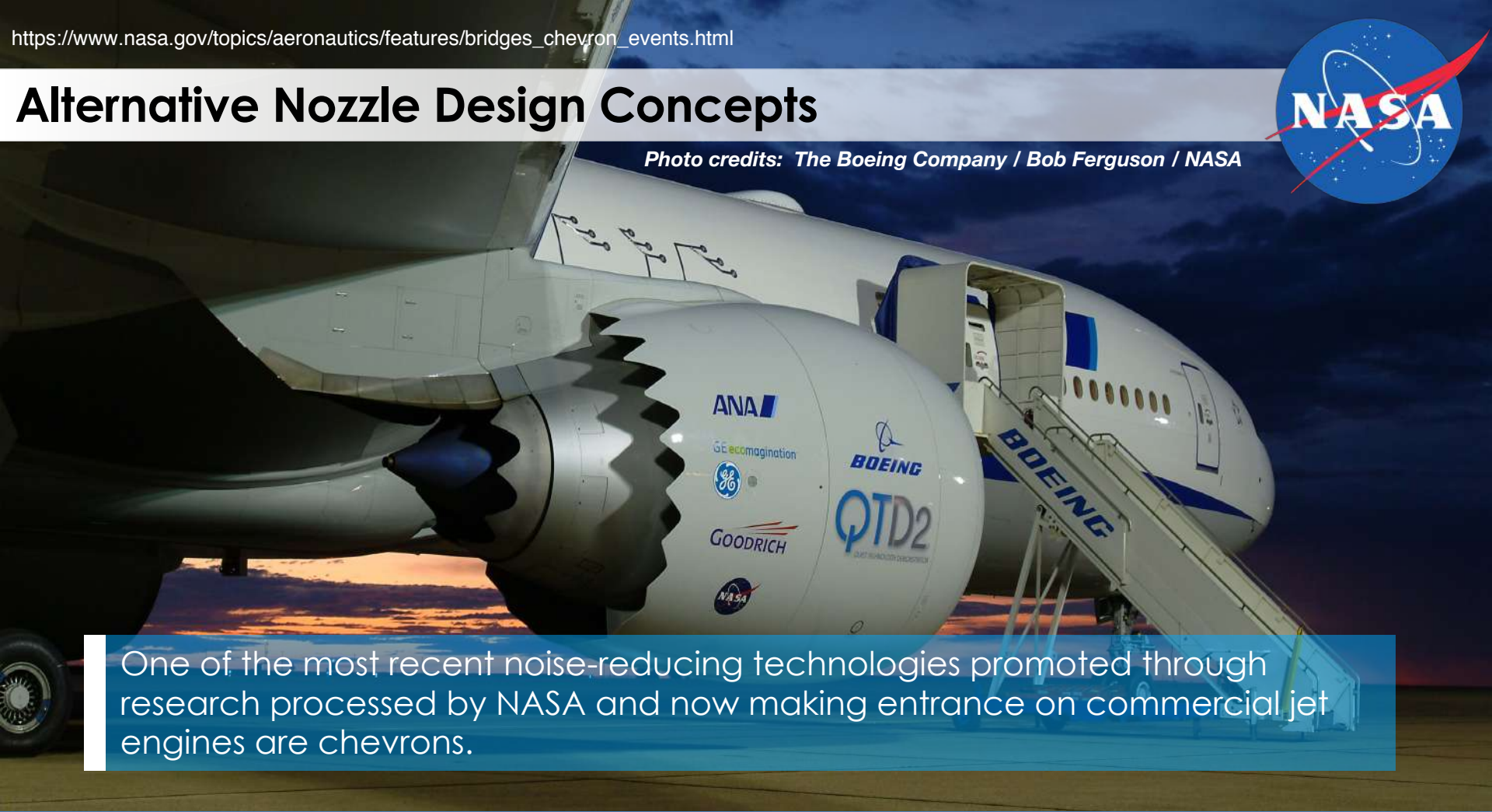


Integrated propulsion noise or jet surface Interaction noise (JSI) becomes increasingly more important with future aircraft designs

https://www.nasa.gov/topics/aeronautics/features/bridges_chevron_events.html

Alternative Nozzle Design Concepts

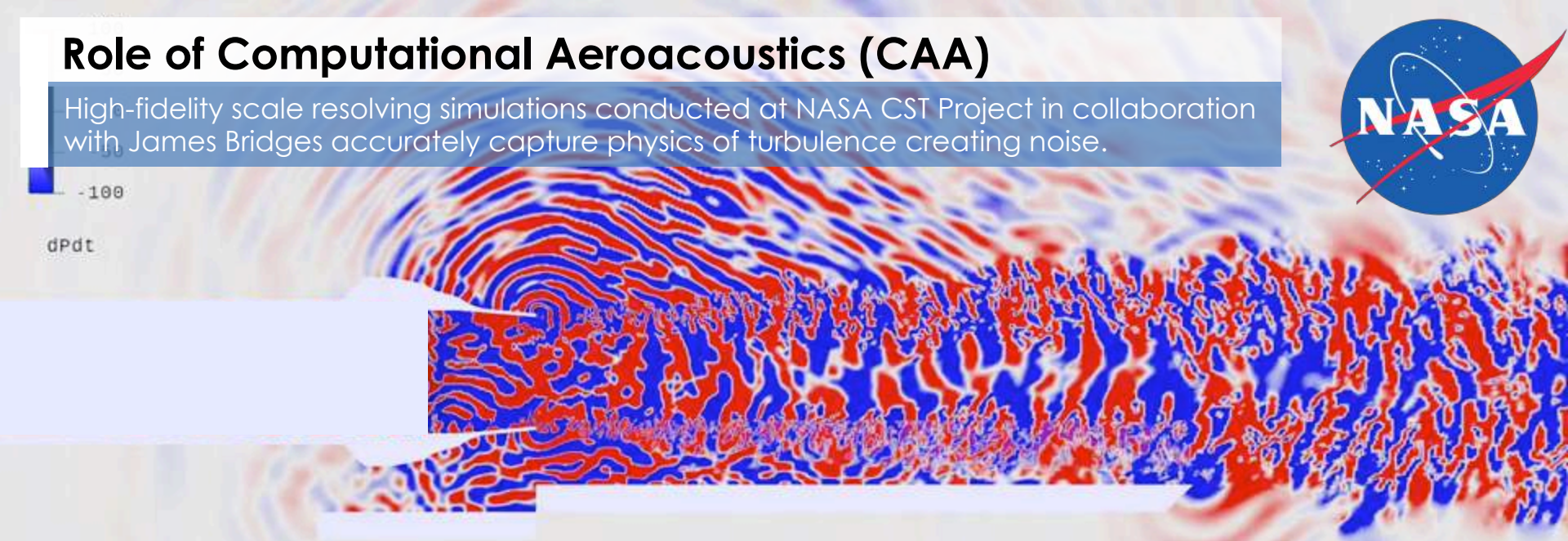
Photo credits: The Boeing Company / Bob Ferguson / NASA



One of the most recent noise-reducing technologies promoted through research processed by NASA and now making entrance on commercial jet engines are chevrons.

Role of Computational Aeroacoustics (CAA)

High-fidelity scale resolving simulations conducted at NASA CST Project in collaboration with James Bridges accurately capture physics of turbulence creating noise.



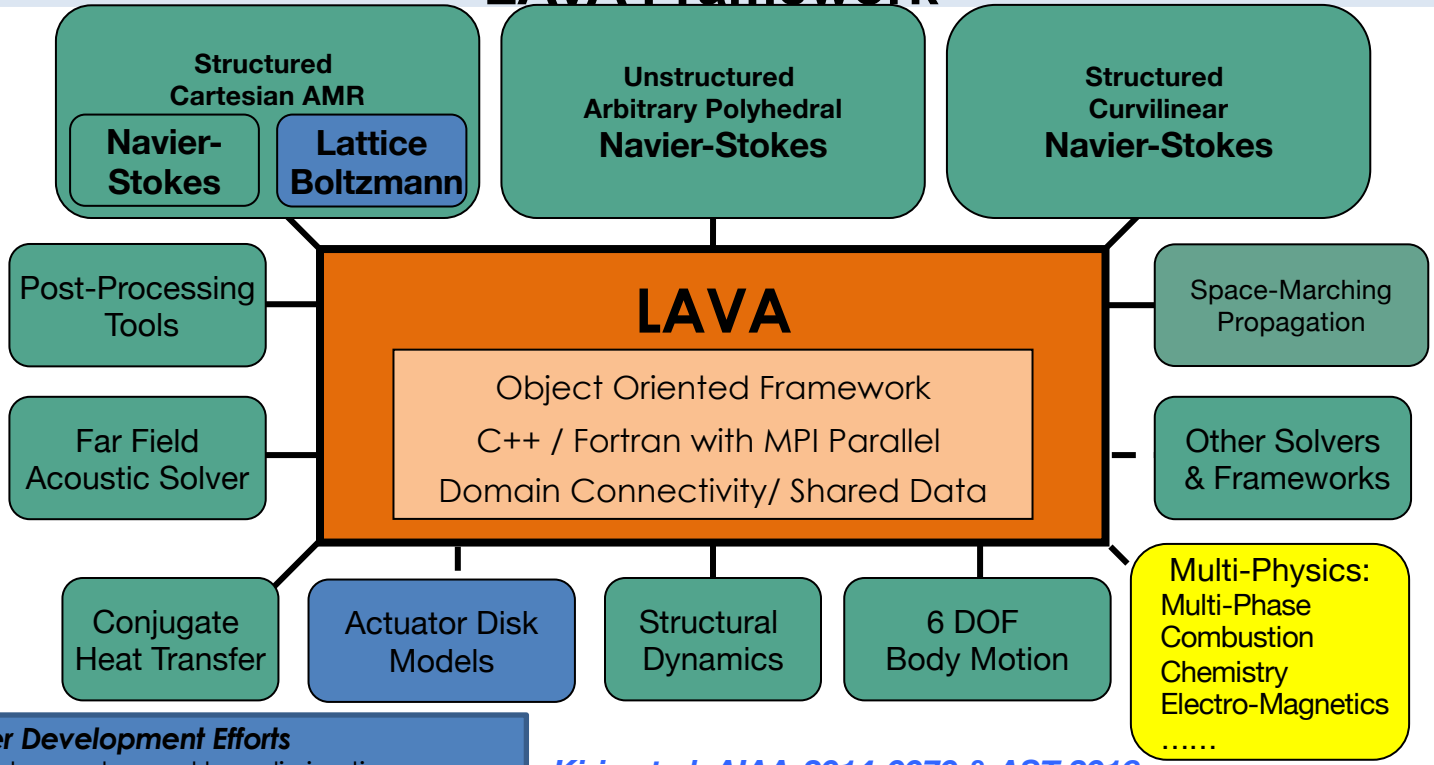
Determining where and how noise is created and how noise can be "shielded" from the observer could help reduce overall jet engine noise.

Flow Visualization by Timothy Sandstrom NASA Ames Research Center

Outline

- Motivation
- Computational Methodology & different Wall-Modeling Approaches
  - Zonal Hybrid RANS/LES (ZDES)
  - Wall stress based Equilibrium Wall-Model (WSM)
- Experimental Setup
- Results of Validation Study
  - Hybrid RANS/LES (Round Jet, Jet surface Interaction, chevron nozzle)
  - Difference in mesh quality and resolution
  - Effects of dissipation on boundary layer turbulence
- Summary and Future Work

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Other Development Efforts
- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

Kiris at al. AIAA-2014-0070 & AST-2016

Connected	Existing	Developing
Not Yet Connected	Future	Framework

Wall-Modeled Large Eddy Simulation (WMLES)

inner layer ($y/\delta_0 \lesssim 0.2$) modeled while outer layer resolved

LES domain extends all the way to the wall

Wall-stress Model (WSM)

$\vec{u}$, ∇P

τ_w ; qw

LES

exchange of information at interface

RANS in near wall region X% of BL
LES in outside region

Hybrid RANS/LES (ZDES)

1D: Analytical wall law

- Utilizes wall-functions like Musker's Law, Spalding , ….
- Takes $\vec{u}$ from LES to compute wall shear stress
- simple and negligible numerical effort

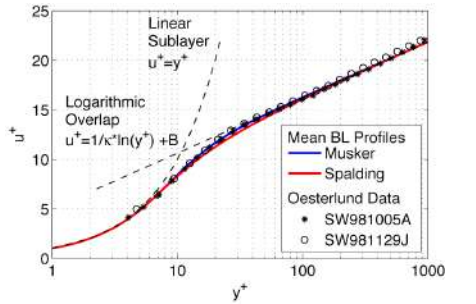
2D: TBL equations ODE WM

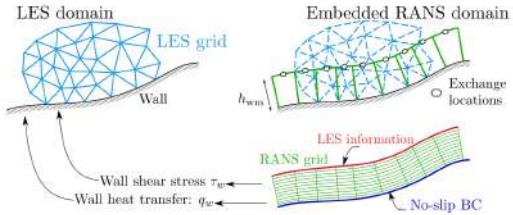
- Solves TBL equations in the BL
- Needs separate embedded grid
- Computationally more expensive
- Potential to include additional physics

1.5D: Integral WM

- Integrate TBL equations vertically using given velocity profiles

$$Y_\tau^+ = U_1^+ + exp(-\kappa C)\left[exp(\kappa U_1^+) - 1 - \kappa U_1^+ - \frac{1}{2}(\kappa U_1^+)^2 - \frac{1}{6}(\kappa U_1^+)^3\right]$$





- Grids require viscous wall-spacings $y^+ < 1$
- Require implicit time-stepping methods
  - Additional numeric complexity
  - Larger time-steps possible

Seamless Methods (DES, DDES,…)

- Transition location between RANS and LES not specifically set.
- Interface height and location defined by grid and solution

Zonal Methods (ZDES)

- User manually describes regions in which RANS and LES is used (requires experience and knowledge of problem)
- Interface height and location explicitly described

Experimental Setup

NASA Aero-Acoustics Propulsion Lab (AAPL)

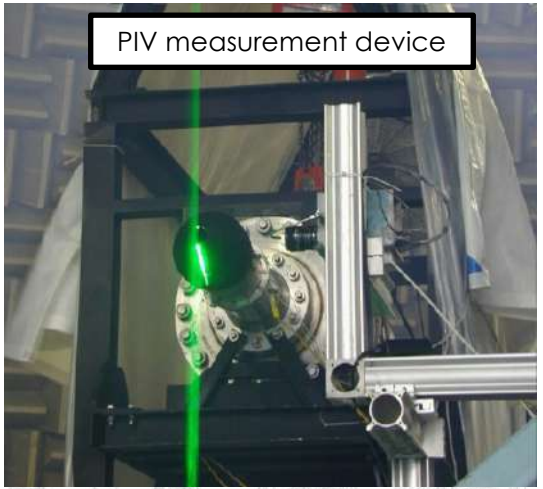
boundary layer thickness is 5.5 larger





- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) with 12" extension

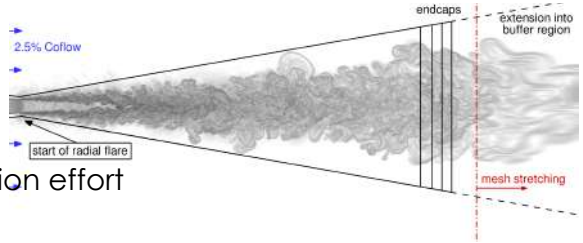
Bridges et. al. (NASA-TM-2011-216807)	SP7
Acoustic Mach number U_{jet}/c_∞	0.9
Jet temperature ratio T_e/T_∞	0.835
Nozzle pressure ratio p_t/p_∞	1.861
Nozzle Diameter D	0.0508 [m] 2.0 [inch]
Reynold number Re_D	1 Million
Reynolds number Re_τ	800
Boundary layer thickness	0.0128 D

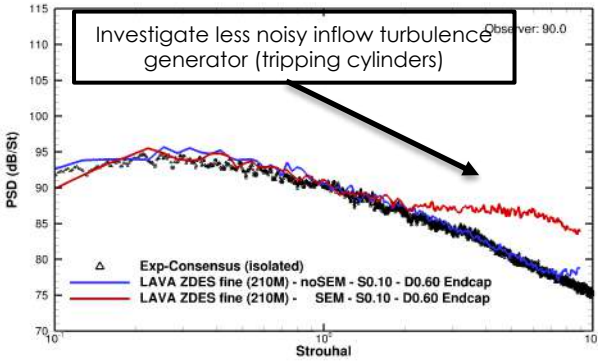


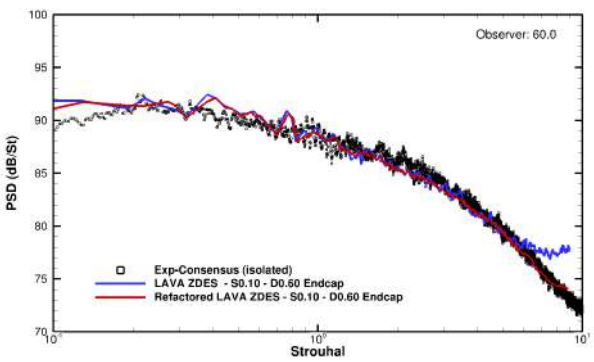
- 65" radius anechoic dome
- Located at Glenn Research Center (GRC)
- Small Hot Jet Acoustic Rig (SHJAR)
- Far-field acoustics, phased arrays, flow rakes, hotwire, schlieren, PIV, IR, Rayleigh, Raman, PSP

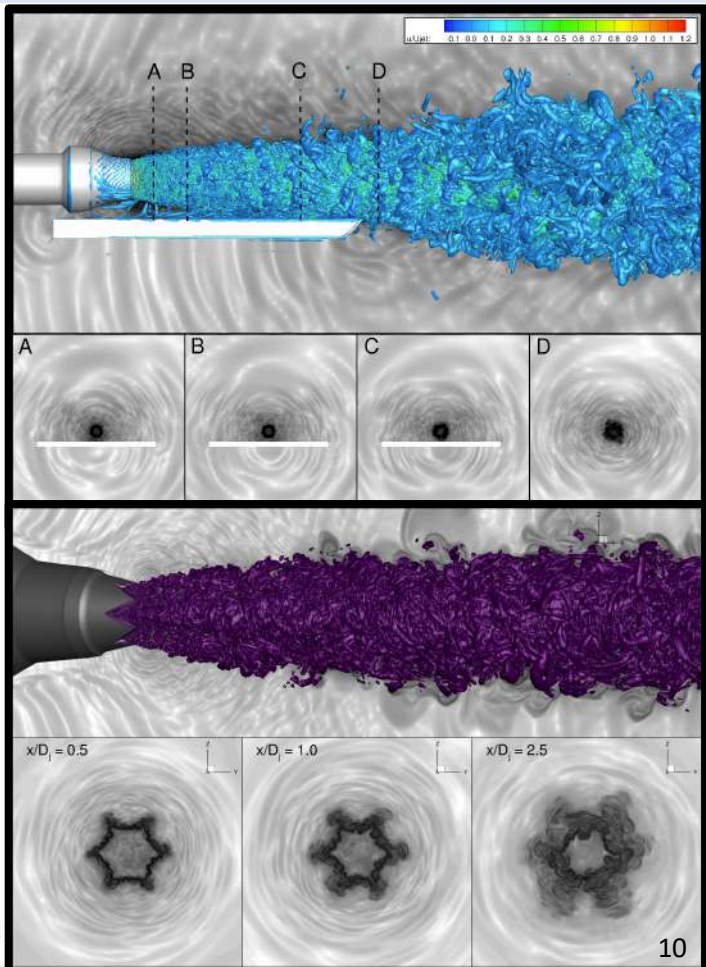
Jet Noise Predictions with Hybrid RANS/LES

- Validation of Jet noise prediction with Hybrid RANS/LES
  (Round Jet SMC000, Jet Surface Interaction, Chevron nozzle SMC001)
- Hybrid RANS/LES does excellent job in predicting near- and far-field results.
- Addition of multi-block capability in solver improved far-field results additionally.
- For increased complexity of geometry hybrid RANS/LES approach has introduced additional difficulties:
  - cell aspect ratios
  - number of mesh points
  - increased manual mesh generation effort

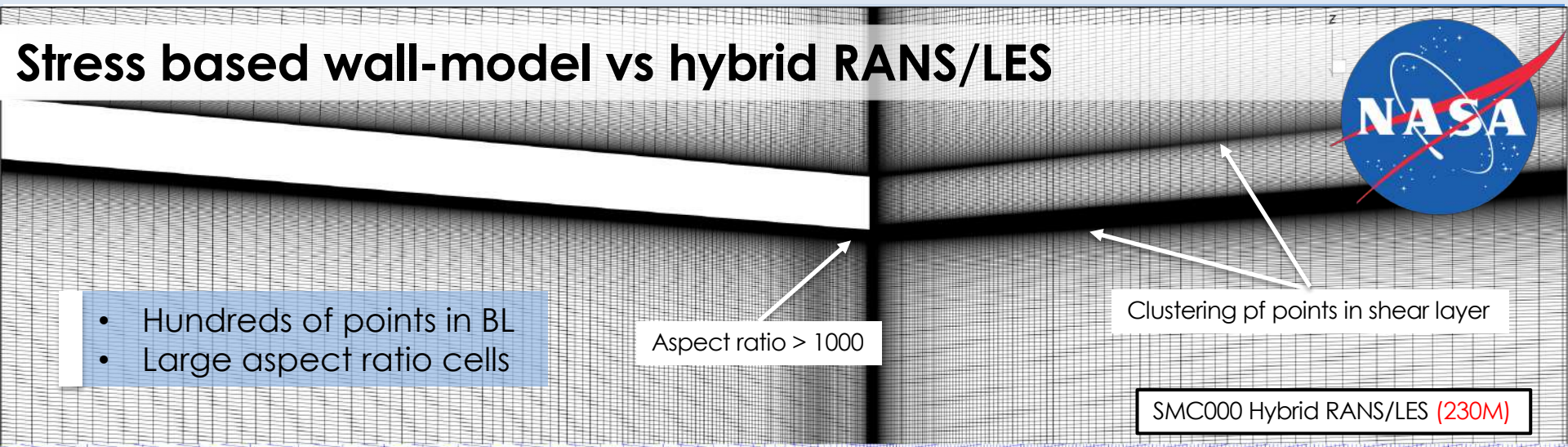








Stress based wall-model vs hybrid RANS/LES

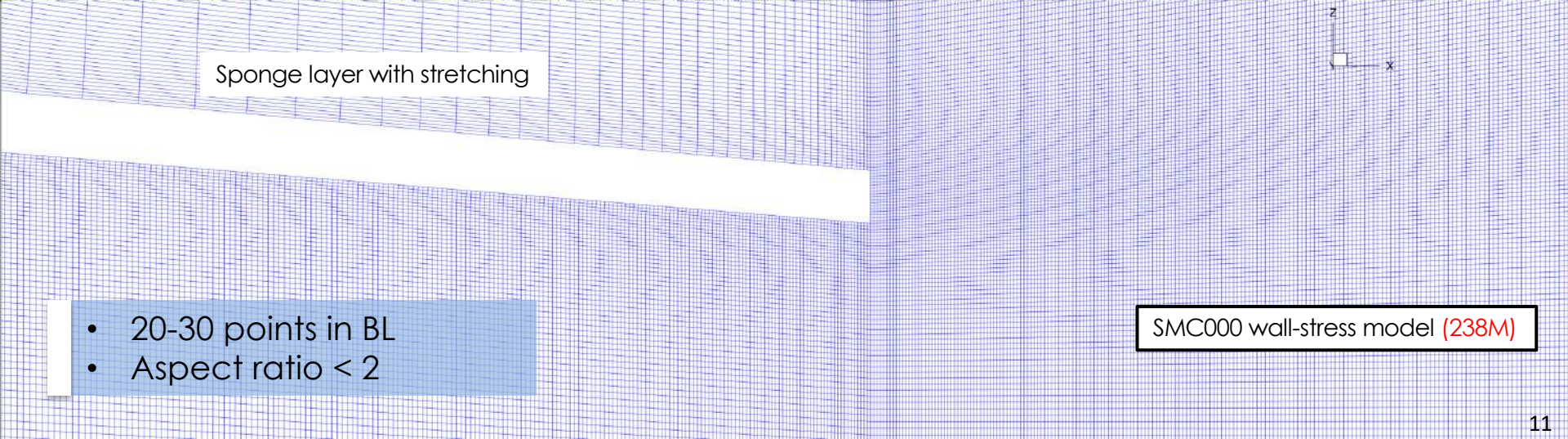


- Hundreds of points in BL
- Large aspect ratio cells

Aspect ratio > 1000

Clustering pf points in shear layer

SMC000 Hybrid RANS/LES (230M)



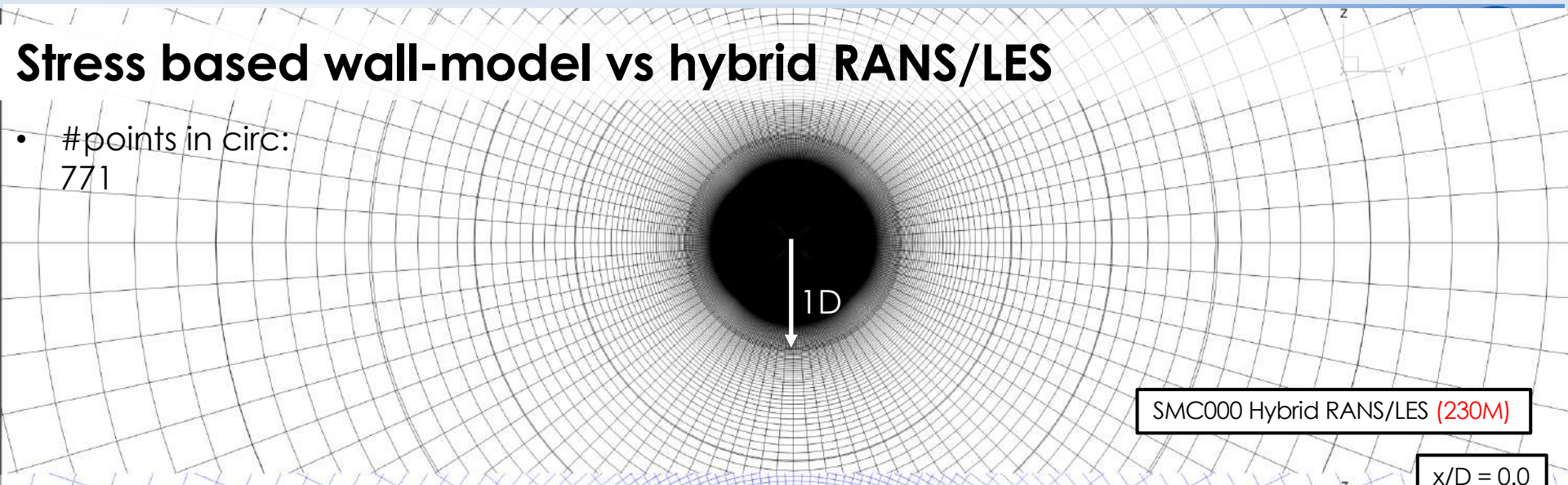
Sponge layer with stretching

- 20-30 points in BL
- Aspect ratio < 2

SMC000 wall-stress model (238M)

Stress based wall-model vs hybrid RANS/LES

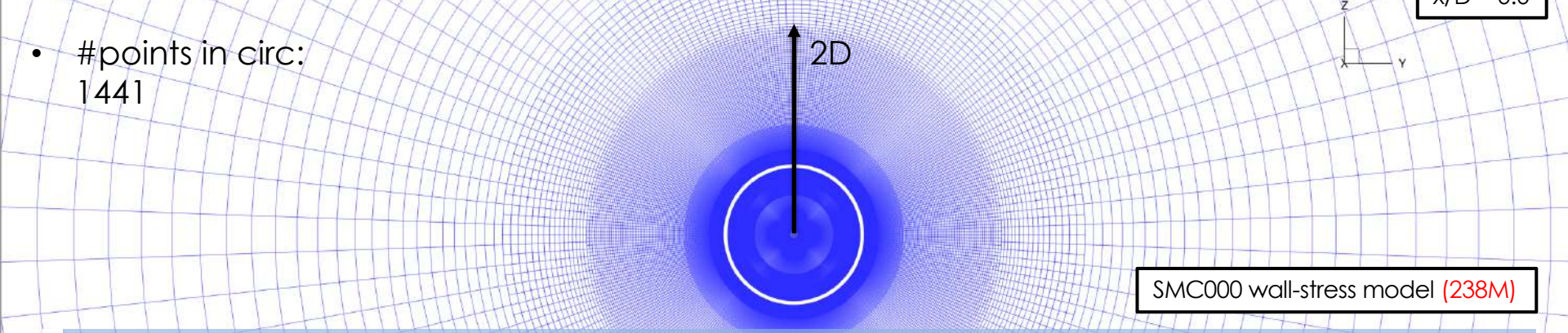
- #points in circ: 771



SMC000 Hybrid RANS/LES (230M)

x/D = 0.0

- #points in circ: 1441



SMC000 wall-stress model (238M)

- Significantly increased overall mesh resolution with same amount of total mesh points

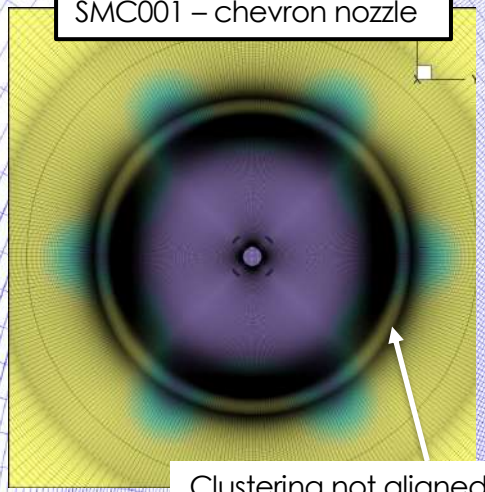
Stress based wall-model vs hybrid RANS/LES

clustering of mesh points due to viscous wall spacing does not necessarily align with physics

SMC000 Hybrid RANS/LES (230M)

x/D = 2.0

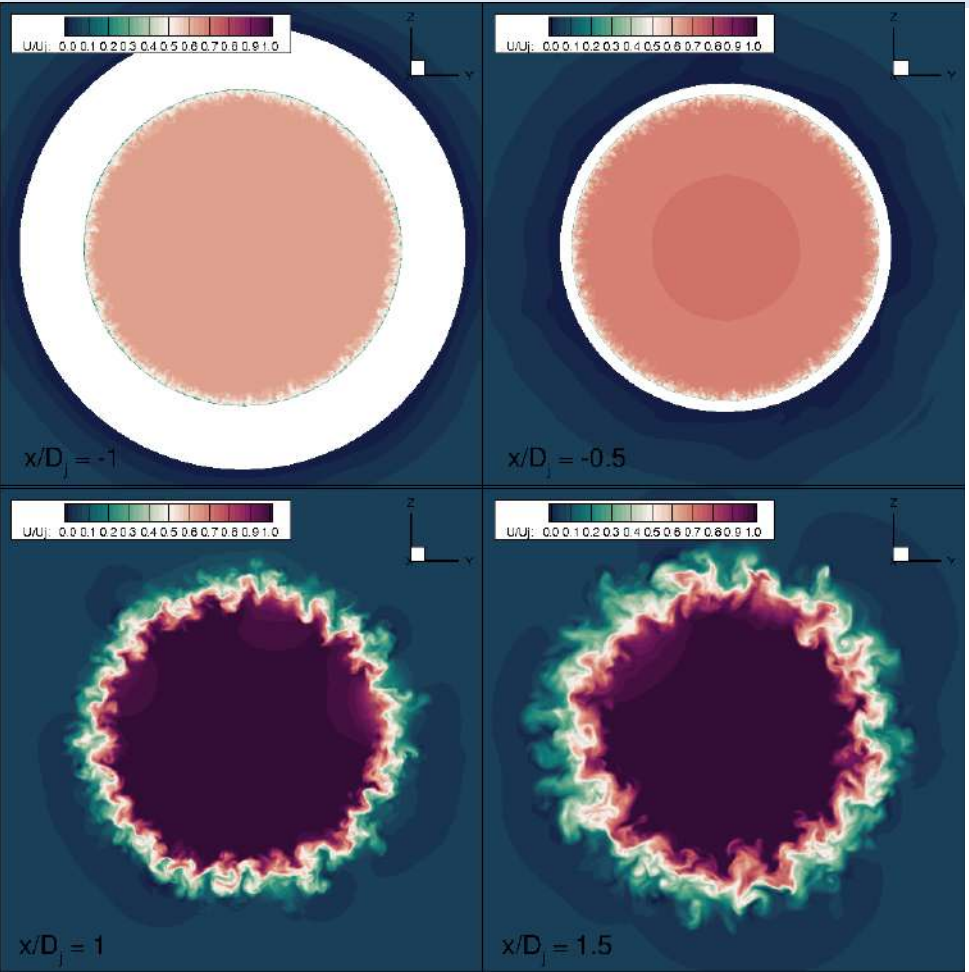
SMC001 – chevron nozzle



Clustering not aligned with solution

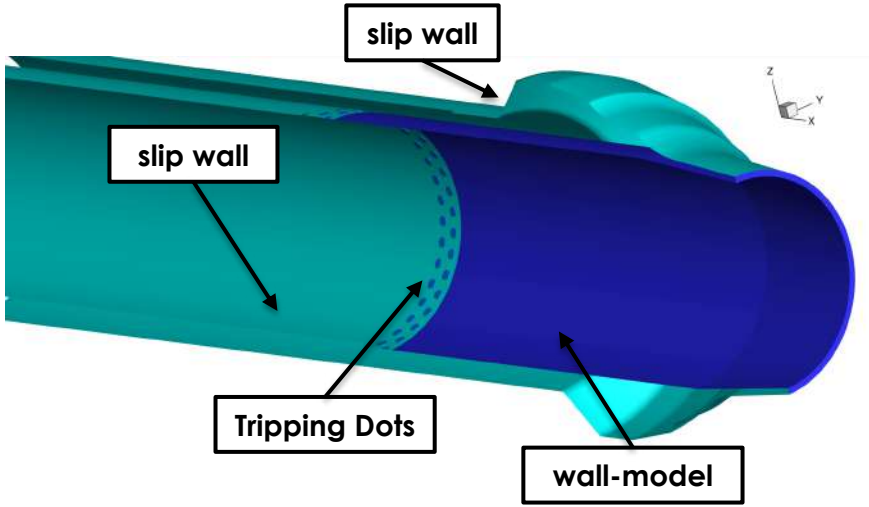
SMC000 wall-stress model (238M)

Assessment of Jet Noise with wall-shear stress WM



- Stress-based equilibrium wall-model
- Explicit time-stepping method (RK3-TVD)
- Timestep size approx. 0.0004 dt^*c_{inf}/D (7.0e-8 s) (previous ZDES: 0.007 (1.0e-6))

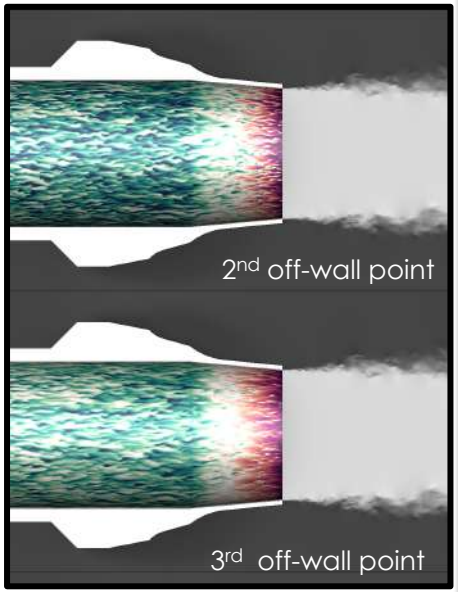
- Two rows of small tripping dots at x/D_j = -2.0
- Tripping dots resolved with immersed boundary method



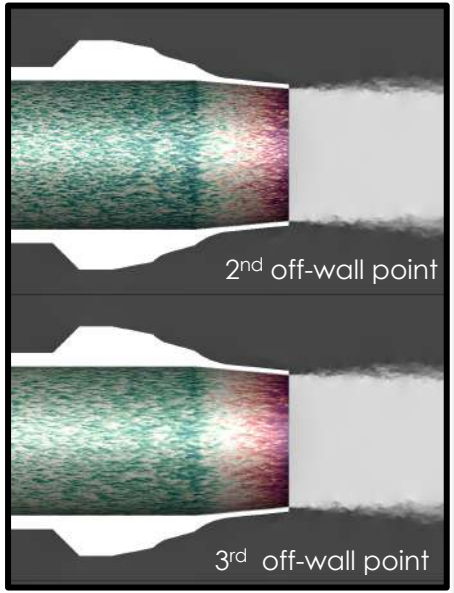
Assessment of Jet Noise with wall-shear stress wall-model

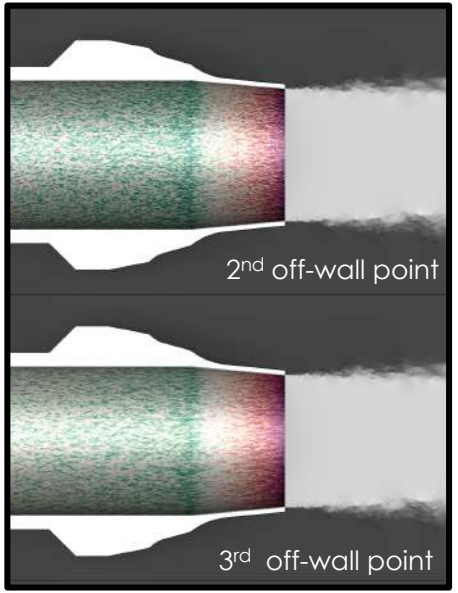
Influence of Dissipation on nozzle boundary layer

Blending– 10%	Blending– 5.0%	Blending– 2.5%	Blending– 0.2% inside – 2.5% outside









- Elongated, coherent structures inside of nozzle.
- Artificially large azimuthal coherence because of numerical dissipation

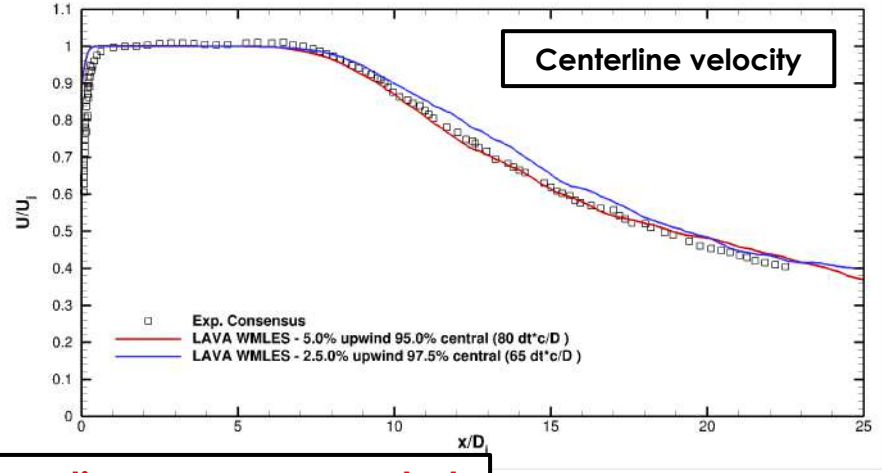
- Reduced numerical dissipation results in reduction of azimuthal length scales (more realistic boundary layer turbulence)

- 0.2% upwind only within nozzle boundary layer and shear layer (up to 0.5D). 2.5% upwind in jet region.
- All sub-grid dissipation controlled by physics based sub grid scale (Sigma SGS) modeling

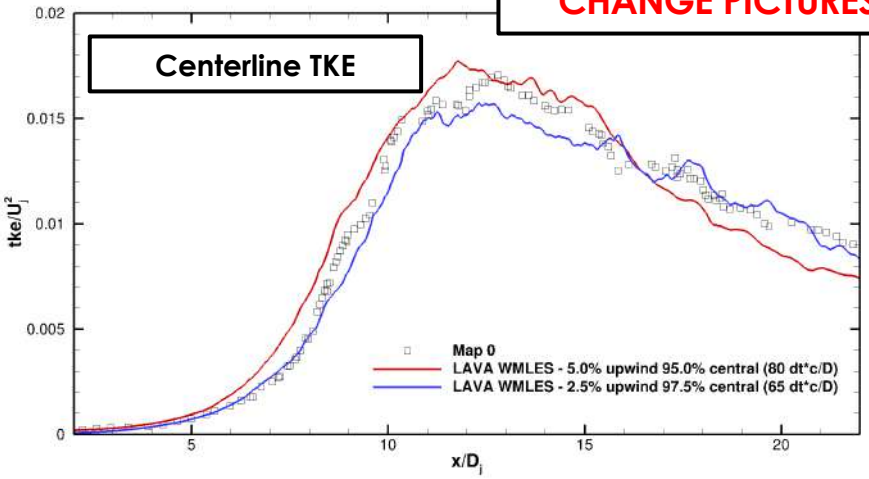
Assessment of Jet Noise with wall-shear stress wall-model

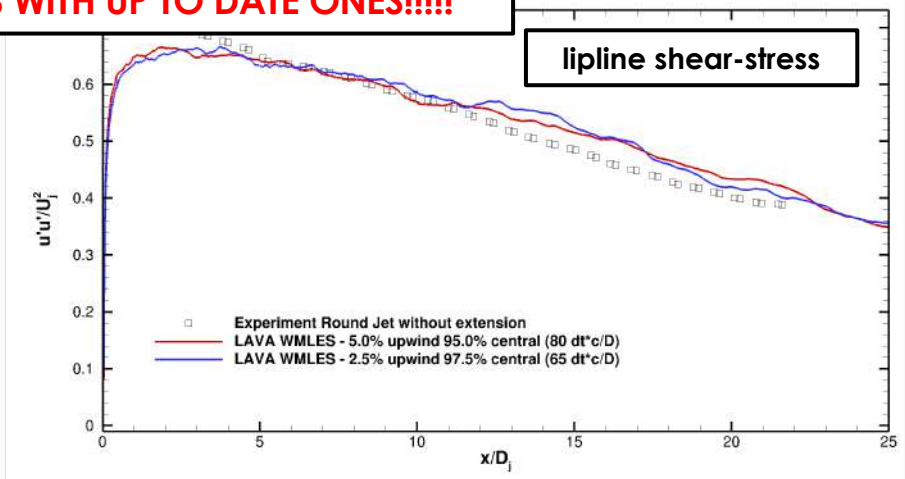
Near-Field Results





preliminary results, more time-average needed
CHANGE PICTURES WITH UP TO DATE ONES!!!!!

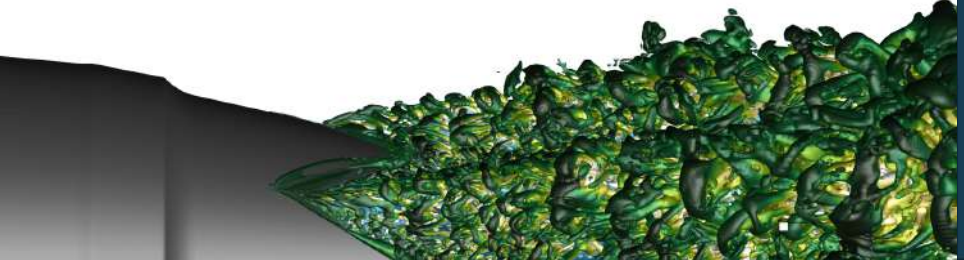


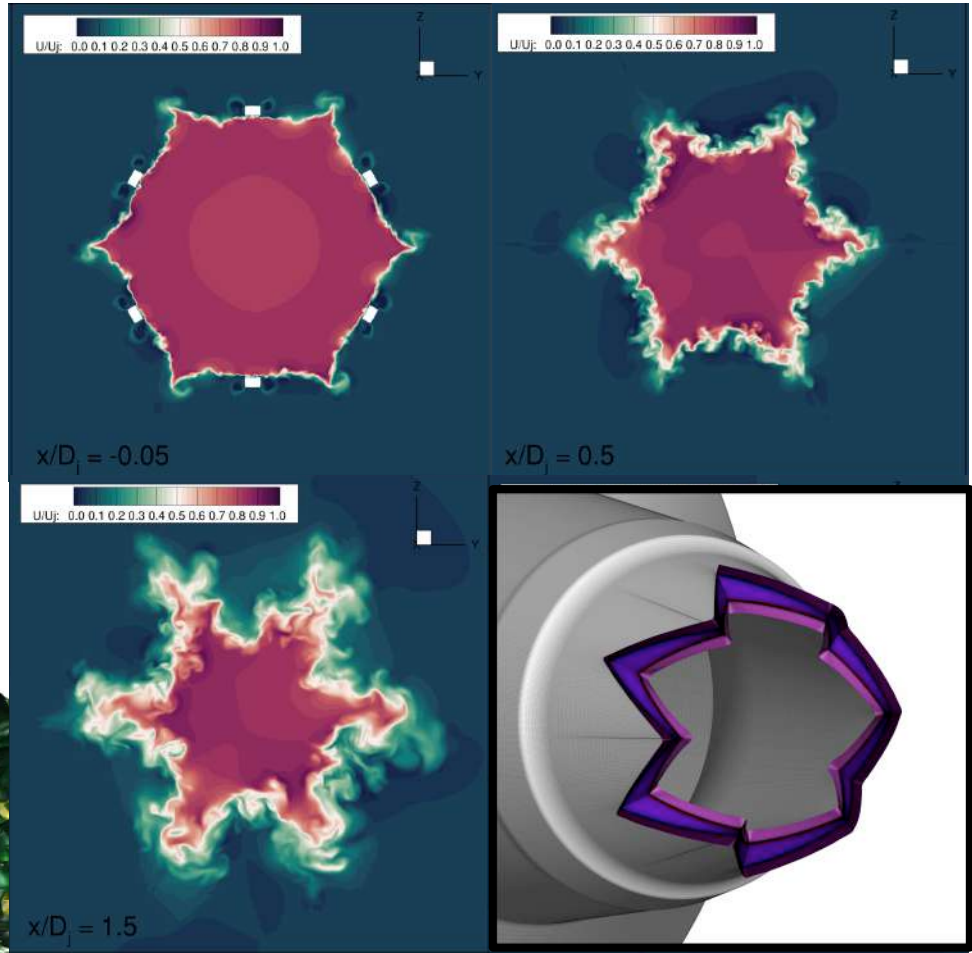


Next Steps: Assessment of Jet Noise with wall-shear stress wall-model

Chevron nozzle SMC001 SP7

- Progress towards prediction of noise with wall-shear stress Model for complex geometries

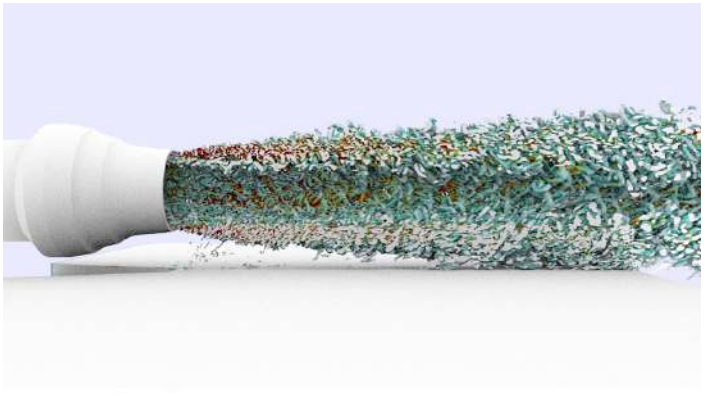




Summary

- Hybrid RANS/LES within the LAVA framework using structured curvilinear overlapping grids is successfully applied to predict jet noise.
- Good comparison with experiments for both near-field and far-field achieved for round-jet as well as surface interaction noise case.
- Wall-shear stress equilibrium wall-model was implemented within the LAVA framework
- Initial results with wall-shear stress equilibrium model look promising
- BL needs to be resolved better inside of nozzle for further improvements.





Acknowledgments

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- Timothy Sandstrom from NASA Ames visualization team for particle flow visualizations.
- Team members of LAVA group for helpful discussions and advice

Questions?

