Hybrid RANS/LES of Jet Surface Interaction Noise

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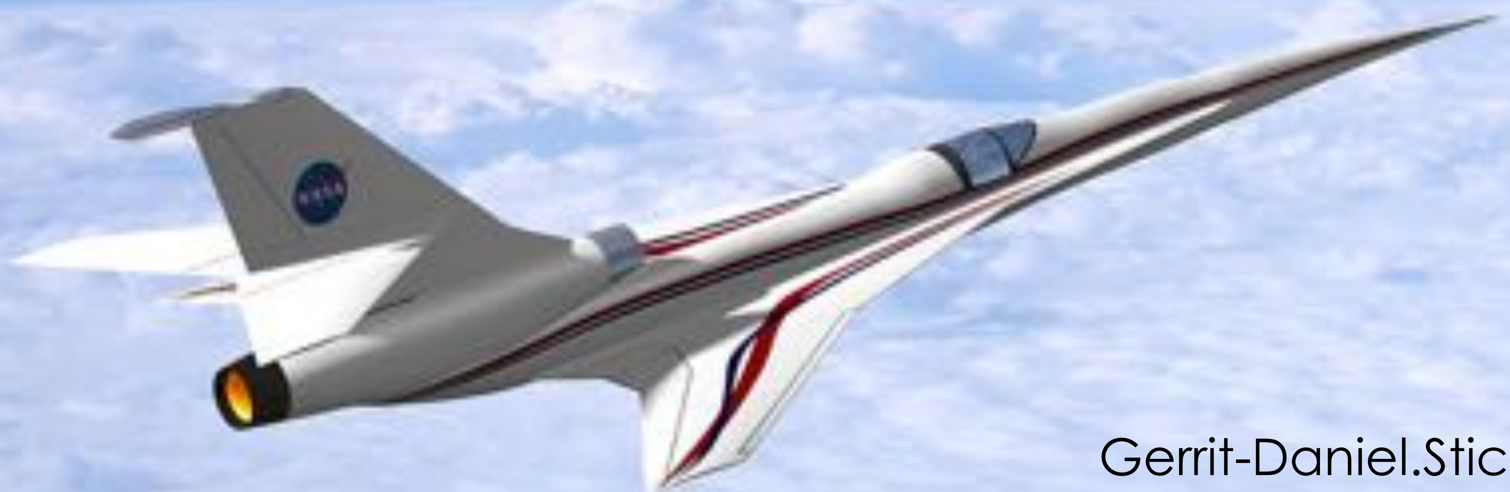
Advanced Modeling & Simulation (AMS) Seminar Series

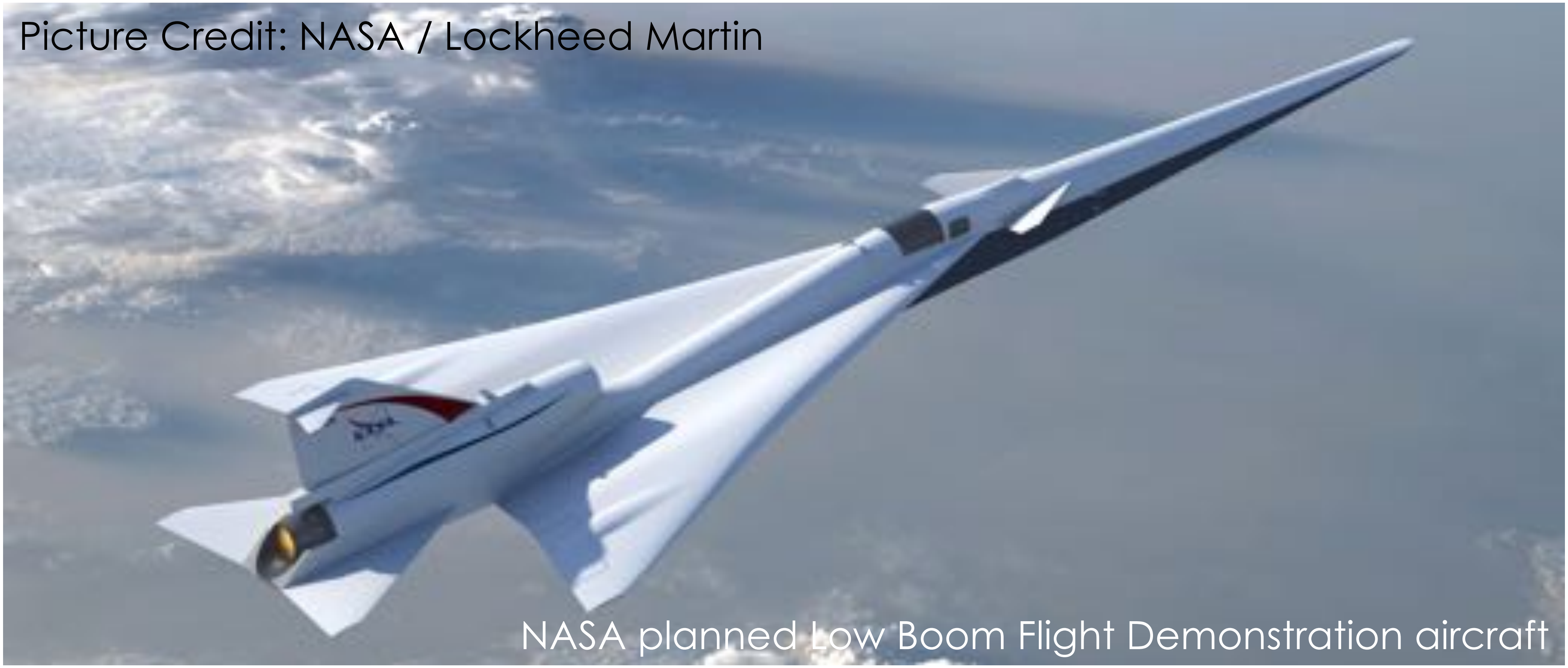
NASA Ames Research Center, June 27th , 2019

Based on AIAA 2019-2475



Gerrit-Daniel.Stich@nasa.gov

Objective
NASA's Commercial Supersonic Technologies (CST) Project



- 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.

Objective
Progress Towards Full Aircraft Noise Prediction

Utilizing Computational Fluid Dynamics (CFD) to evaluate the effects of shielding surfaces on the aerodynamic noise sources from jet flows for a full aircraft configuration "Grand Challenge"

- First systematic validation effort to asses predictive capabilities for jet-noise shielding within NASA Ames Launch Ascend and Vehicle Aerodynamics solver (LAVA)

Round Jet Validation

Picture taken from:
Test Report: Top-Mounted Propulsion Test 2017
by James Bridges

"Grand Challenge"

Shielding Concepts

Radical Installation Concepts
(chevrons, Multi-stream, Plug)

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- First systematic validation effort to asses predictive capabilities for jet-noise shielding within NASA Ames Launch Ascend and Vehicle Aerodynamics solver (LAVA)

Outline

- Motivation
- **Experimental Setup**
- **Computational Methodology**
- **Structured Overset Grid System**
- **Axisymmetric Round Jet**
  - Flow Visualization
  - Near-Field Results
  - Far-Field Results
- **Jet Surface Interaction**
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  - Far-Field Results
- **Summary and Future Work**

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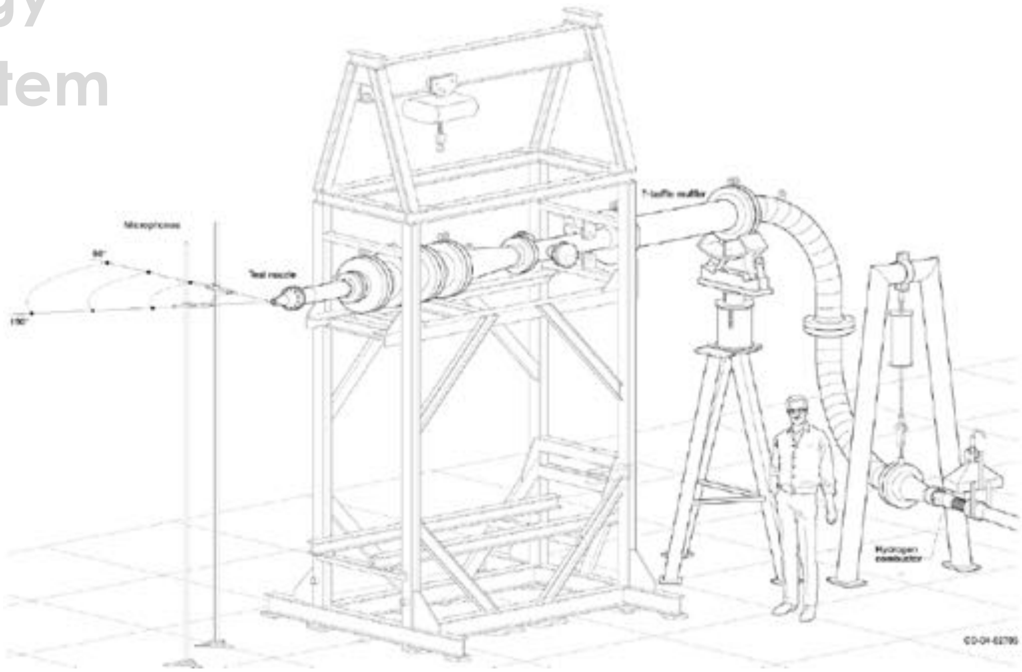
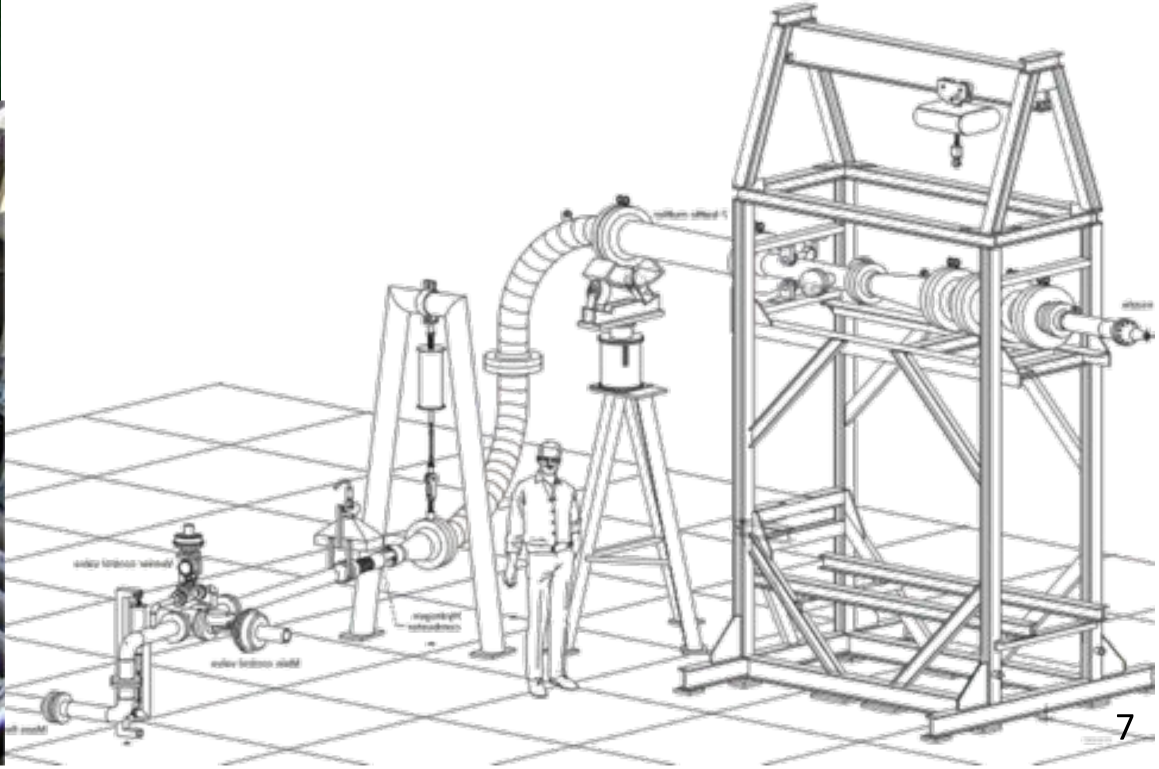


Experimental Facility
NASA Aero-Acoustics Propulsion Lab (AAPL)

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



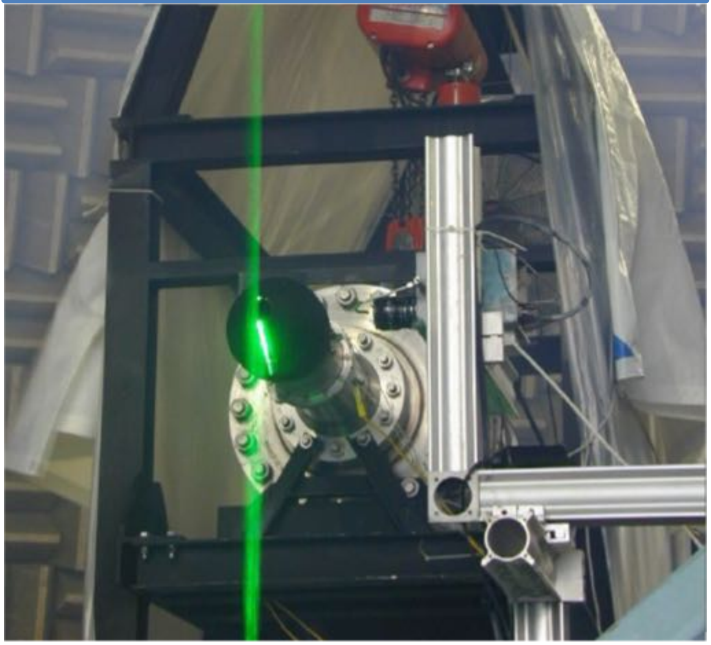
Experimental Facility

NASA Aero-Acoustics Propulsion Lab (AAPL)

- ✓ Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) with 12” extension
- ✓ Nozzle axis in downstream flow direction is marked as 180°

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

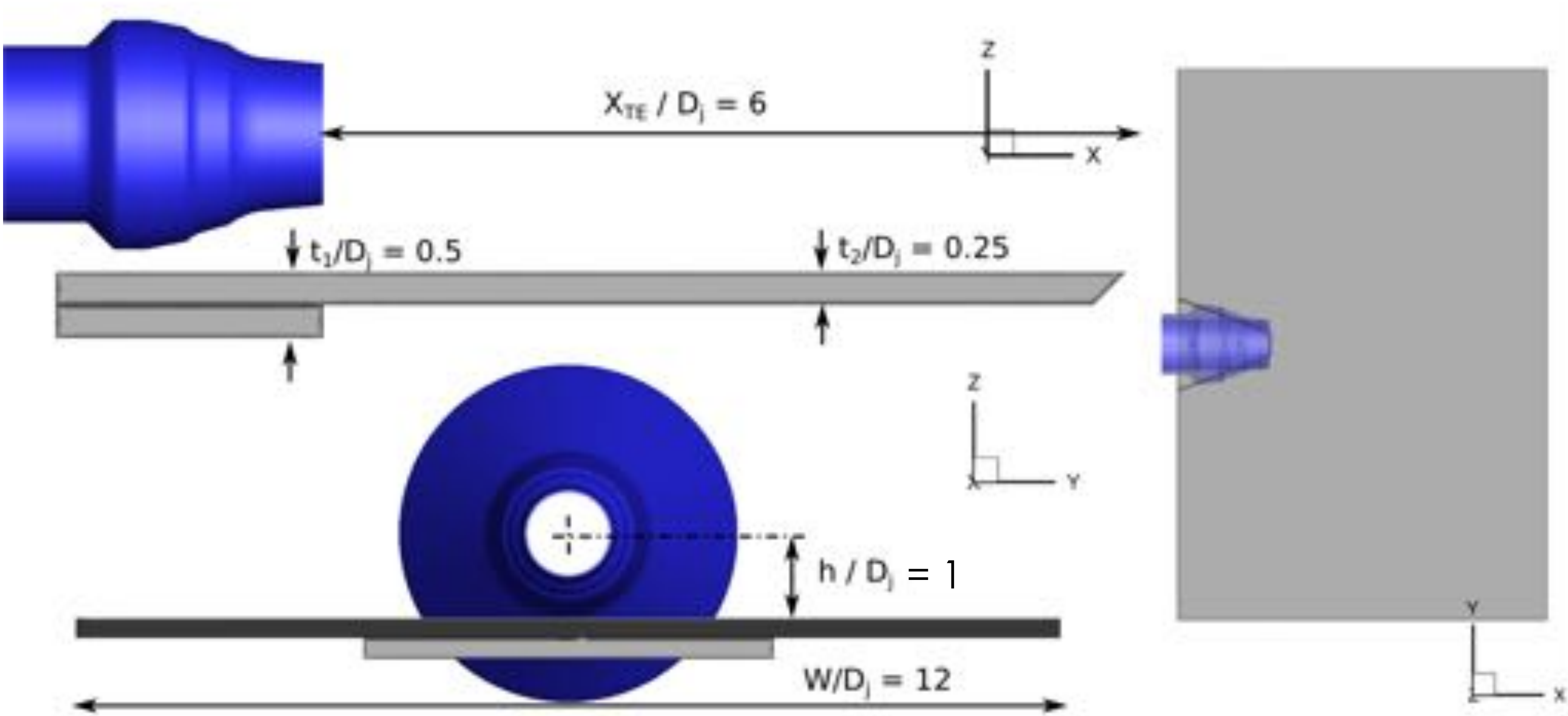
PIV measurement device

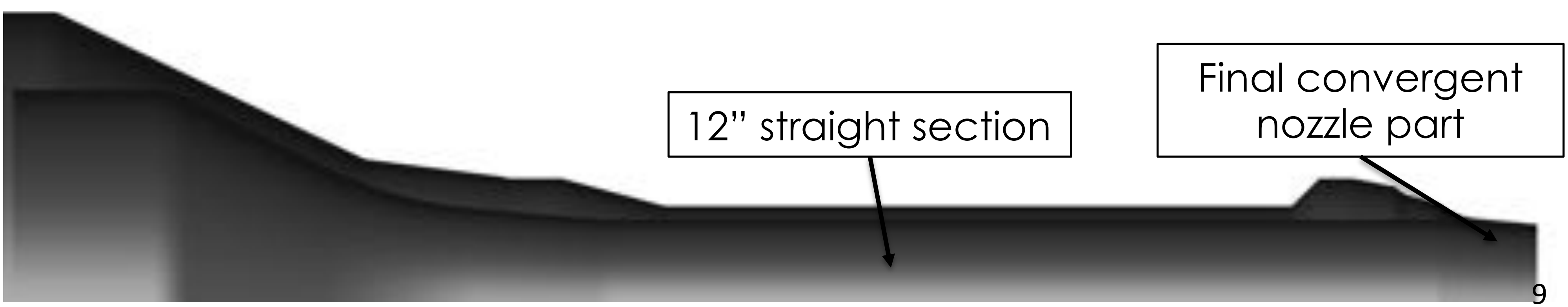


Similar conditions were analyzed in Bres *et. al.* AIAA-2015-2535, but the boundary layer thickness is 5.5 larger

Geometry and Setup

Round Convergent Nozzle (SMC000) with Jet Shielding Plate





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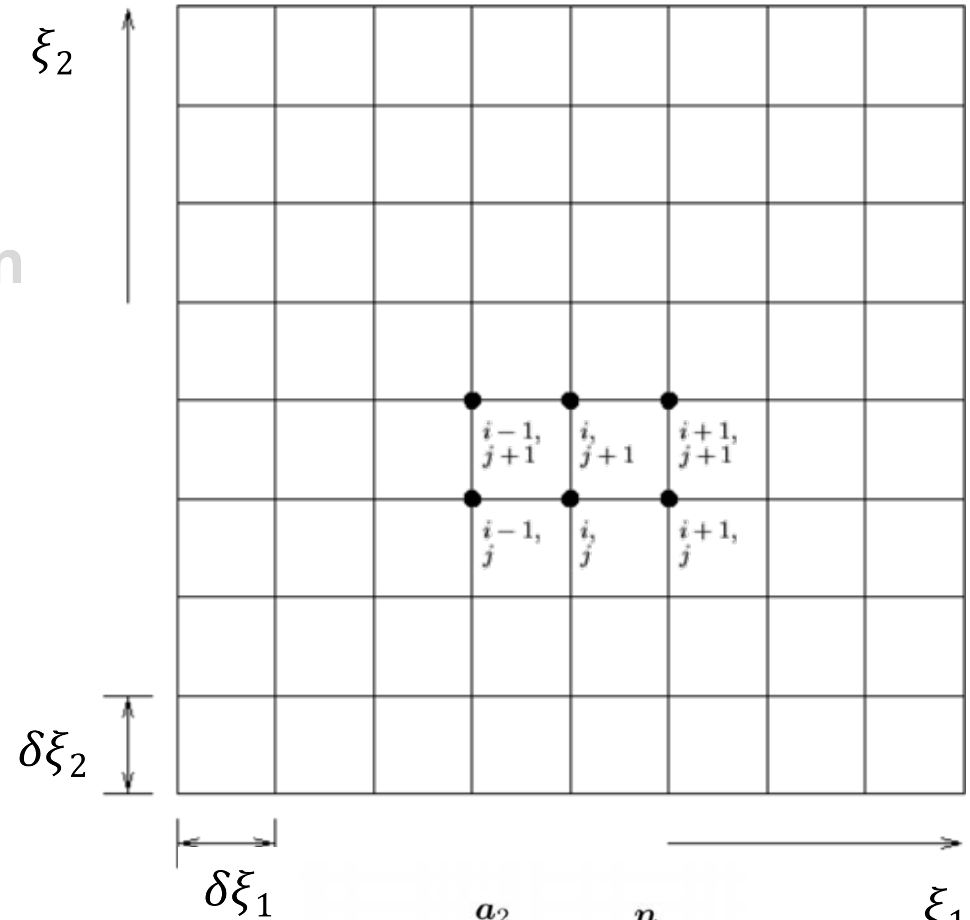
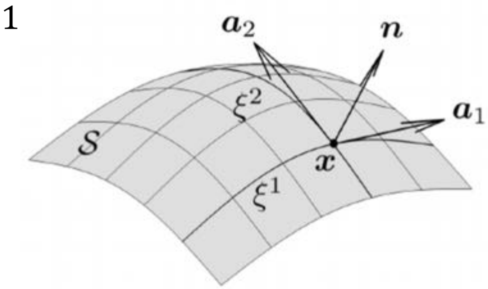
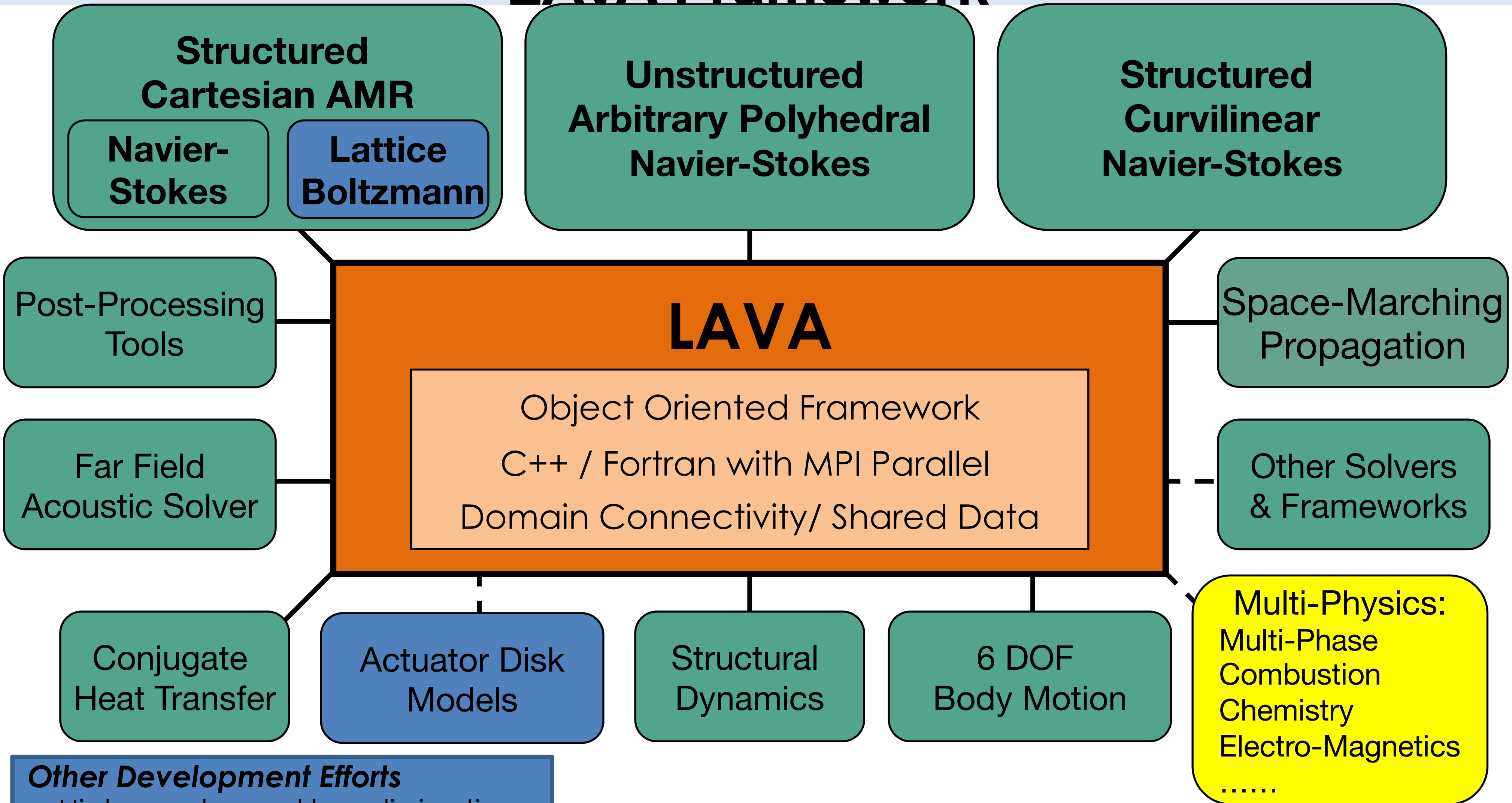




Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



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

——— Connected	Existing / Developing
– – – Not Yet Connected	Future / Framework

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

Numerical Method Used

3-D Structured Curvilinear Overset Grid Solver within LAVA framework

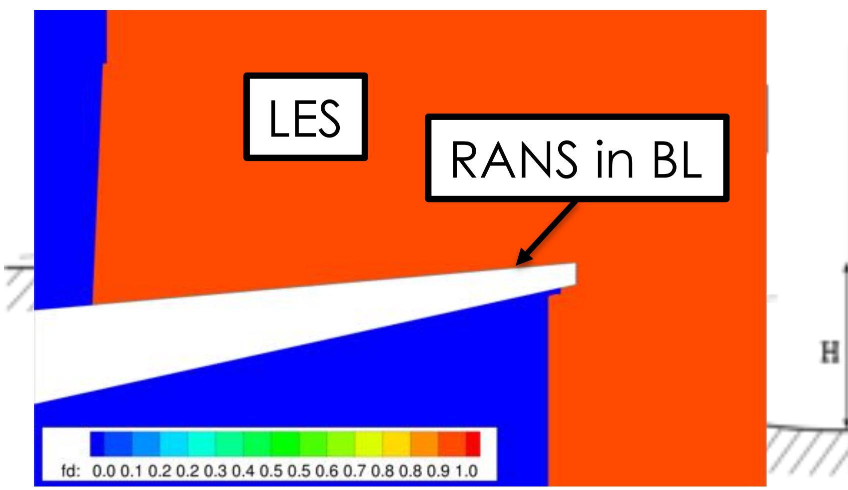
- Spalart-Allmaras turbulence model (baseline turbulence model)

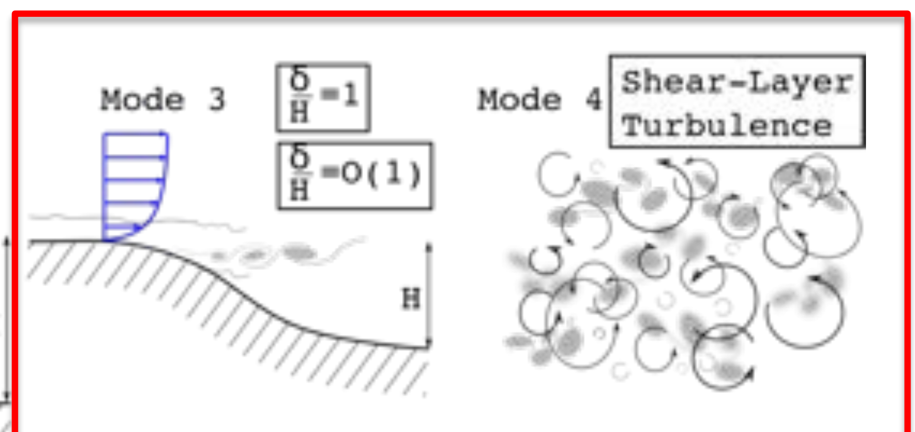
Low-Dissipation Finite Difference Method (Housman et al. AIAA-2016-2963)

- 6th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)
- Numerical flux is a modified Roe scheme
- $6^{th}/5^{th}$-order blended central/upwind biased left and right state interpolation
- 2^{nd}-order accurate differencing used for time discretization

Hybrid RANS/LES Model

- Zonal Detached Eddy Simulation (ZDES-Mode III & IV) with user selected RANS, LES, and Hybrid RANS LES zones *(Deck, S. Theor. Comput. Fluid Dyn. 2012)*





Computational Approach

uRANS

$\Delta t_{conv} = 0.5$

Initialize Hybrid RANS/LES

$\Delta t_{conv} = 0.5$

Initialize Hybrid RANS/LES

$\Delta t_{conv} = 0.05$
$\Delta t_{conv} = 0.005$

Initialize Hybrid RANS/LES

- Unsteady RANS until jet is fully developed and eddy viscosity maximum has plateaued
- Restart simulation with Hybrid RANS/LES and larger timestep
- Decrease time-step once flow is fully developed
- Ignore transients from changing model and time-step size (20,000 time-steps for this case)
- Record volume data at 100kHz sampling frequency for 30,000 steps (Δt_{conv} = 200) on isolated case and 120,000 steps (Δt_{conv} = 800) for shielding case.

$\Delta t_{conv} = \Delta t \, c_\infty / D_j$

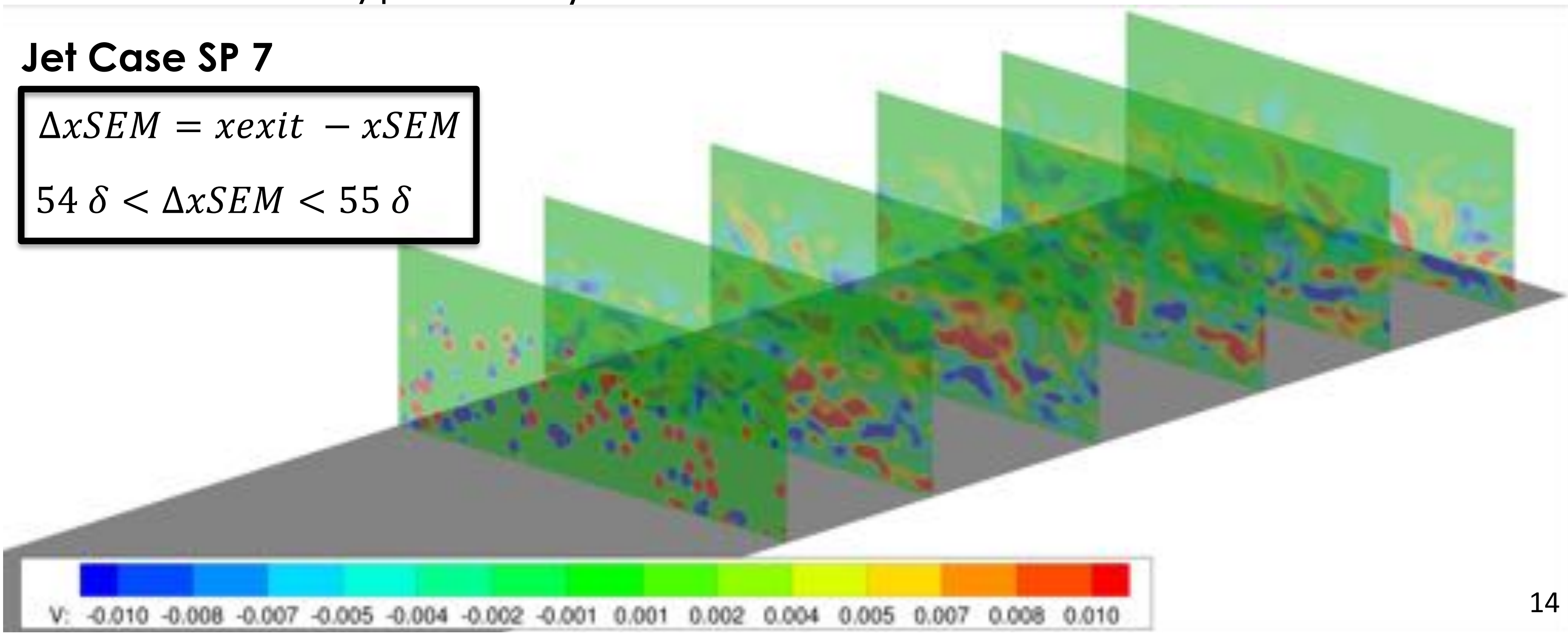
Inflow Turbulence Generation

- When transitioning from RANS to LES in wall-bounded flows it is necessary to insert meaningful three-dimensional content at the interface
- The synthetic eddy method (SEM) is one approach which adds eddies in such away that first and second order turbulent statistics can be satisfied. (approx. from the RANS solution with Bradshaw hypothesis)

Jet Case SP 7

$$\Delta xSEM = xexit \ - xSEM$$

$$54\ \delta < \Delta xSEM < 55\ \delta$$



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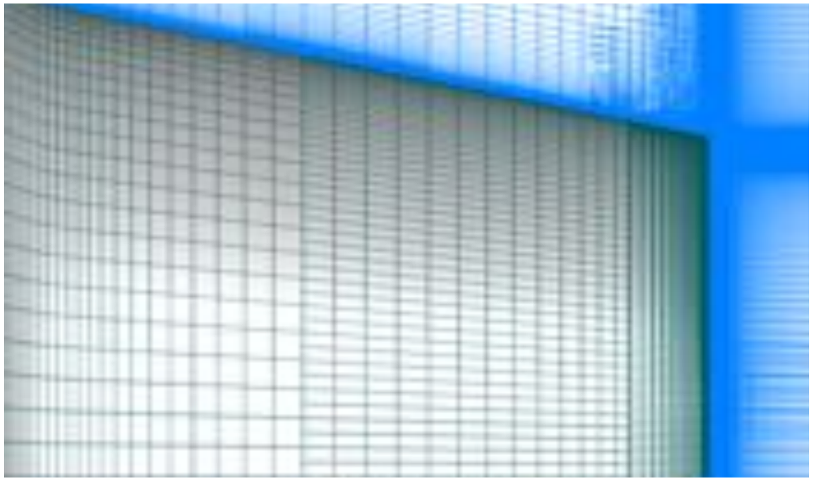
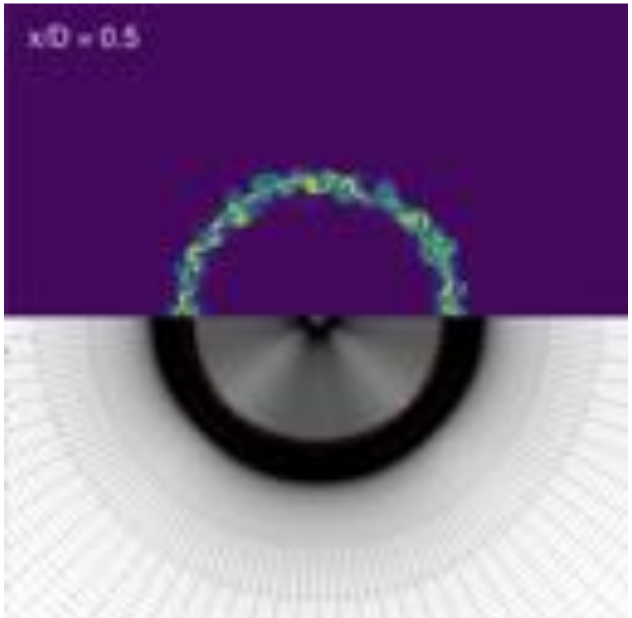
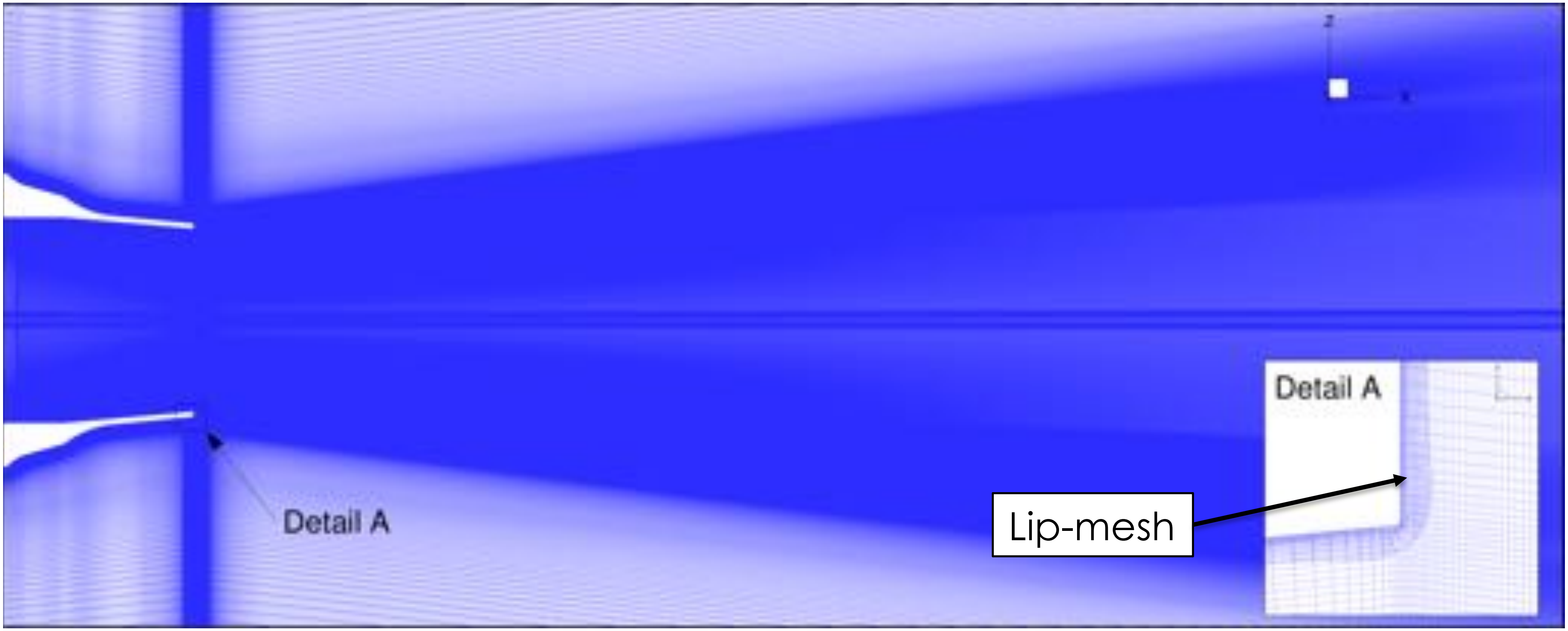




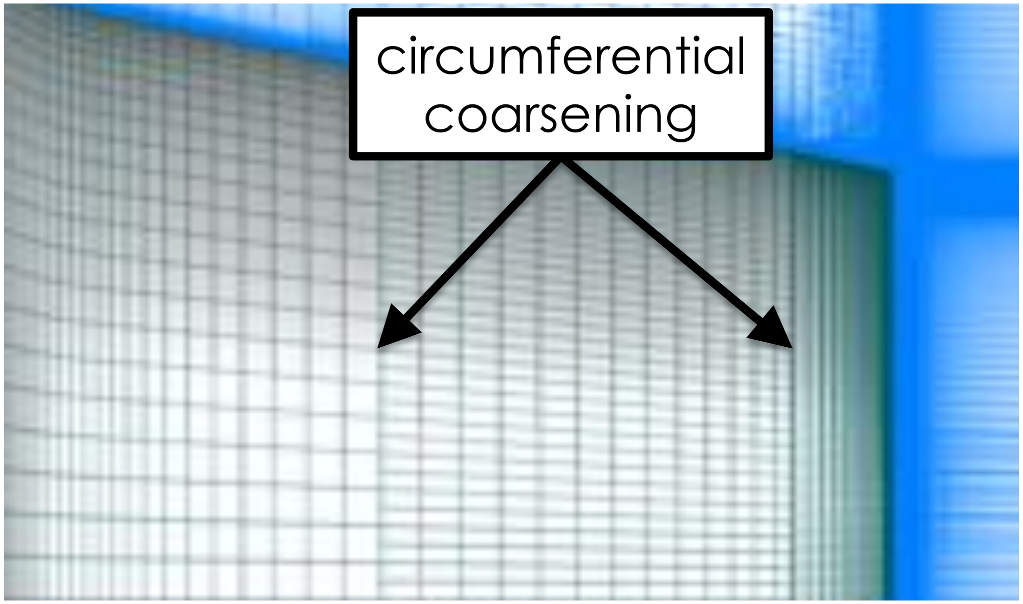
Geometry and Setup
Computational Mesh Round Jet

- Three mesh resolution for isolated axisymmetric round jet: coarse (90M), medium (120M), fine (210M)



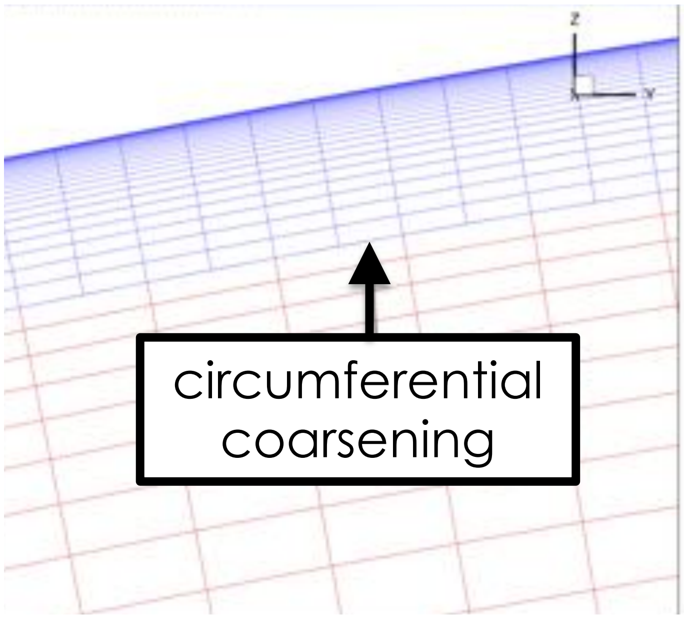
	Streamwise Points per D_j				Circumferential Points			
	$0.1D_j$	$1D_j$	$10D_j$	$25D_j$	θ_1	θ_2	θ_3	Θ_4
coarse	250	45	45	40	360	180	90	90
medium	300	61	54	45	720	360	180	90
fine	300	71	60	54	1440	720	360	180

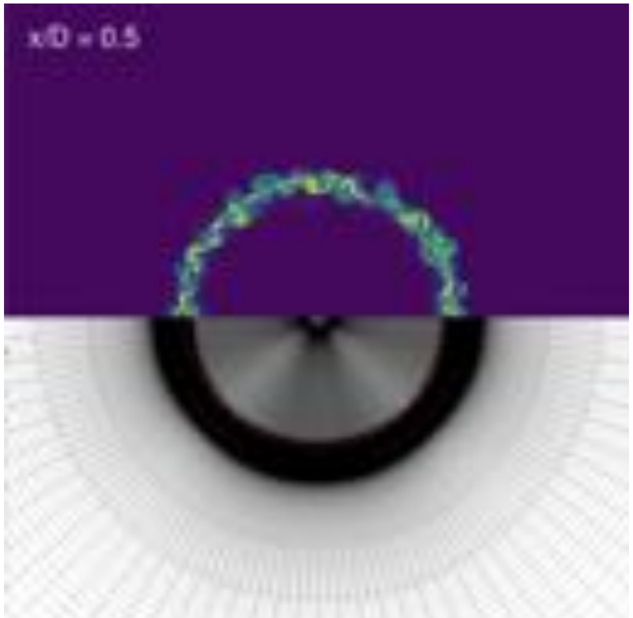
Geometry and Setup
Computational Mesh Round Jet



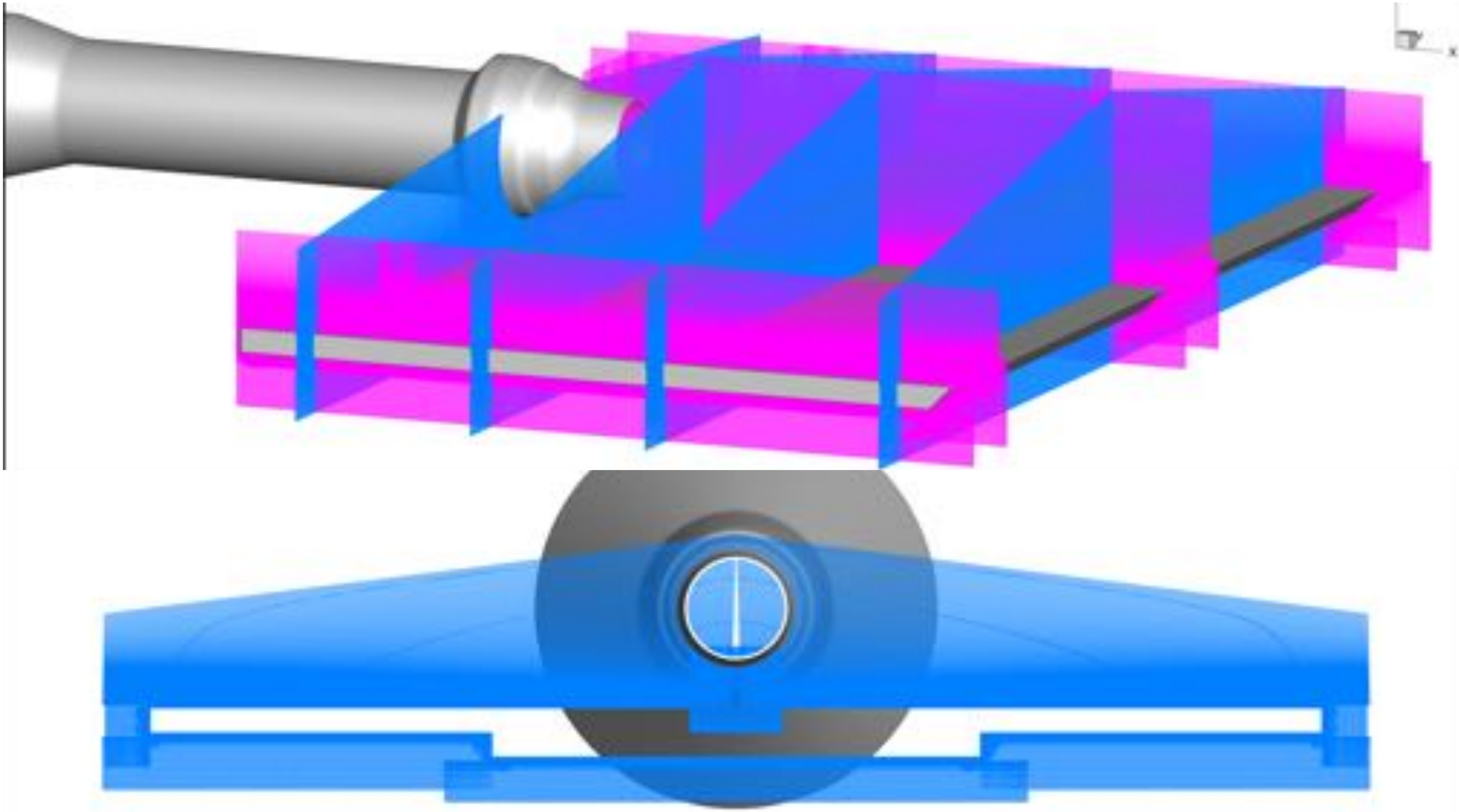
- Circumferential coarsening in axial and radial direction
  Bres *et. al.* (AIAA-2015-2535)

	Circumferential Points			
	θ_1	θ_2	θ_3	Θ_4
coarse	360	180	90	90
medium	720	360	180	90
fine	1440	720	360	180





Geometry and Setup
Computational Mesh Jet Shielding Plate



- Mesh surrounding jet shielding plate consists of 130M grid points (combined with medium isolated mesh 230M)

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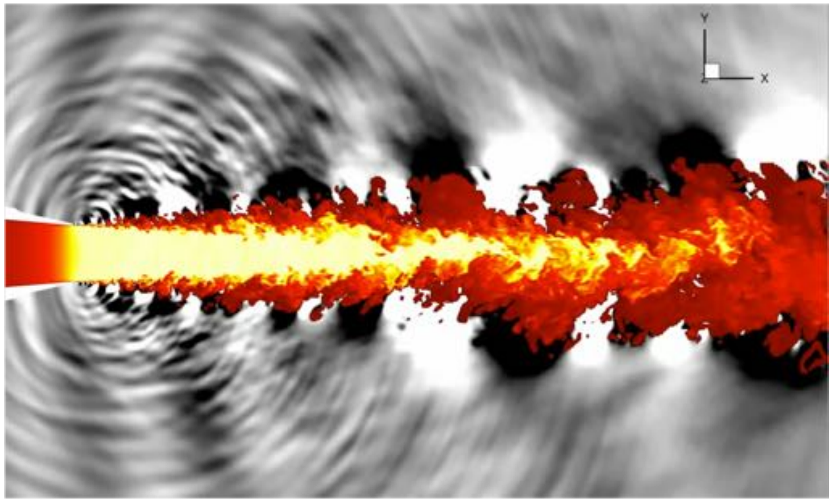
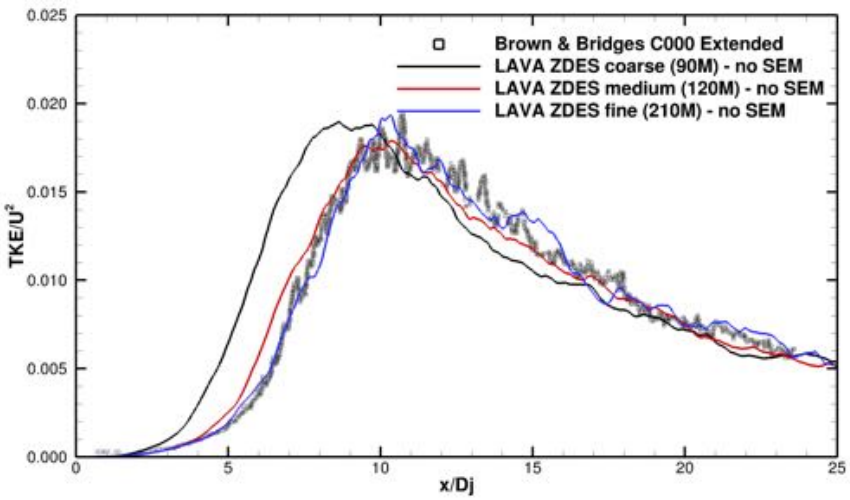
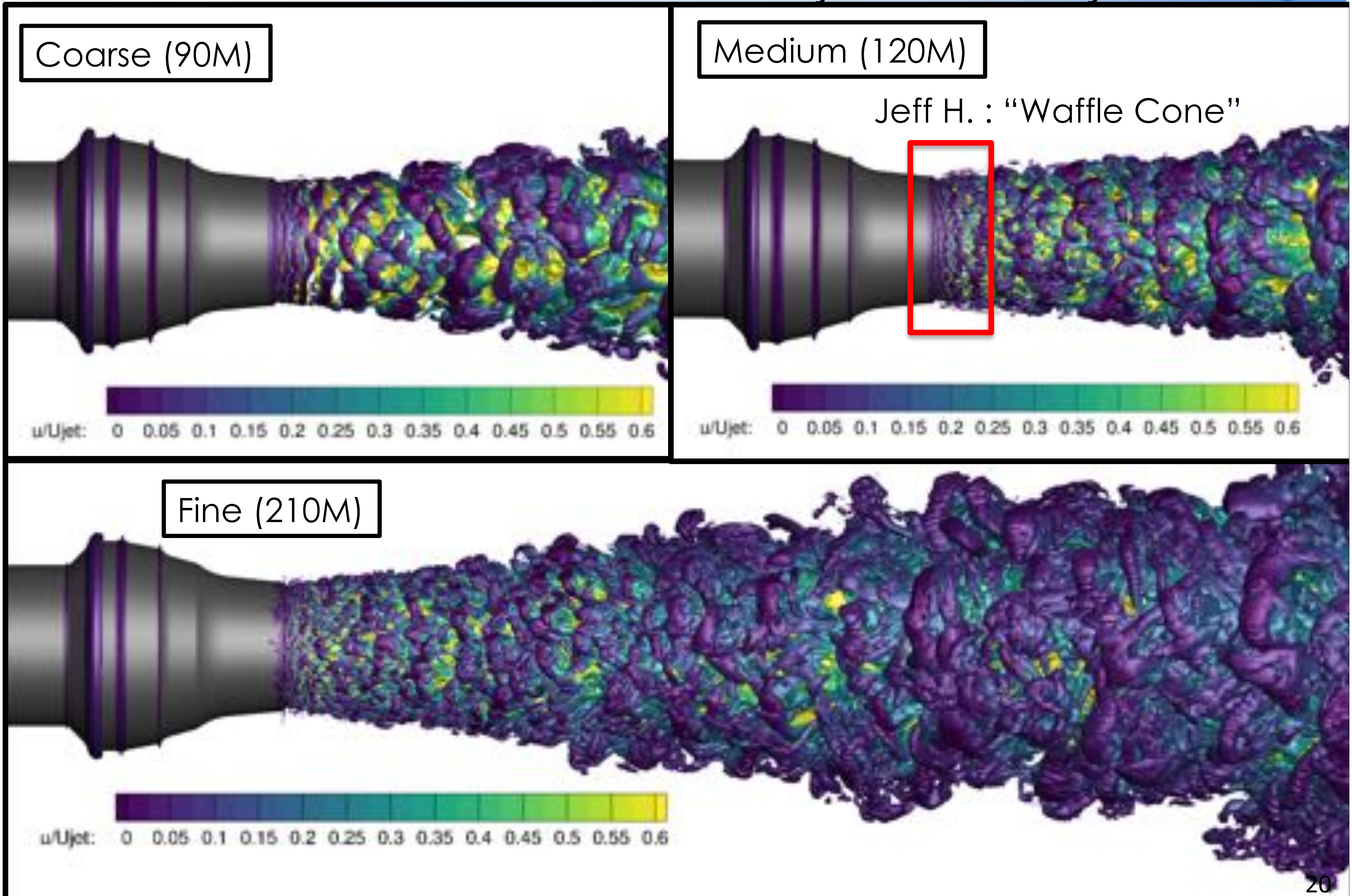
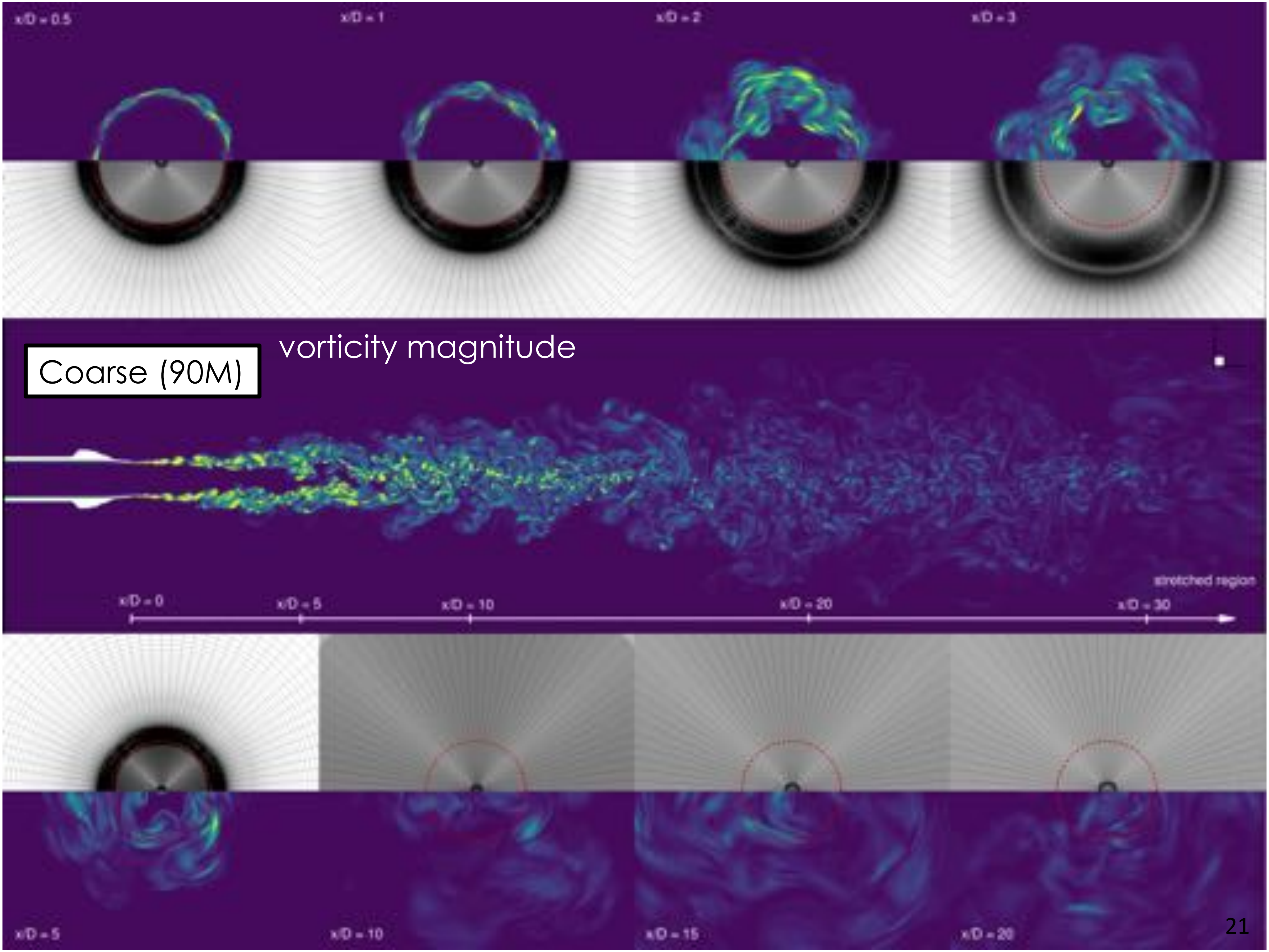




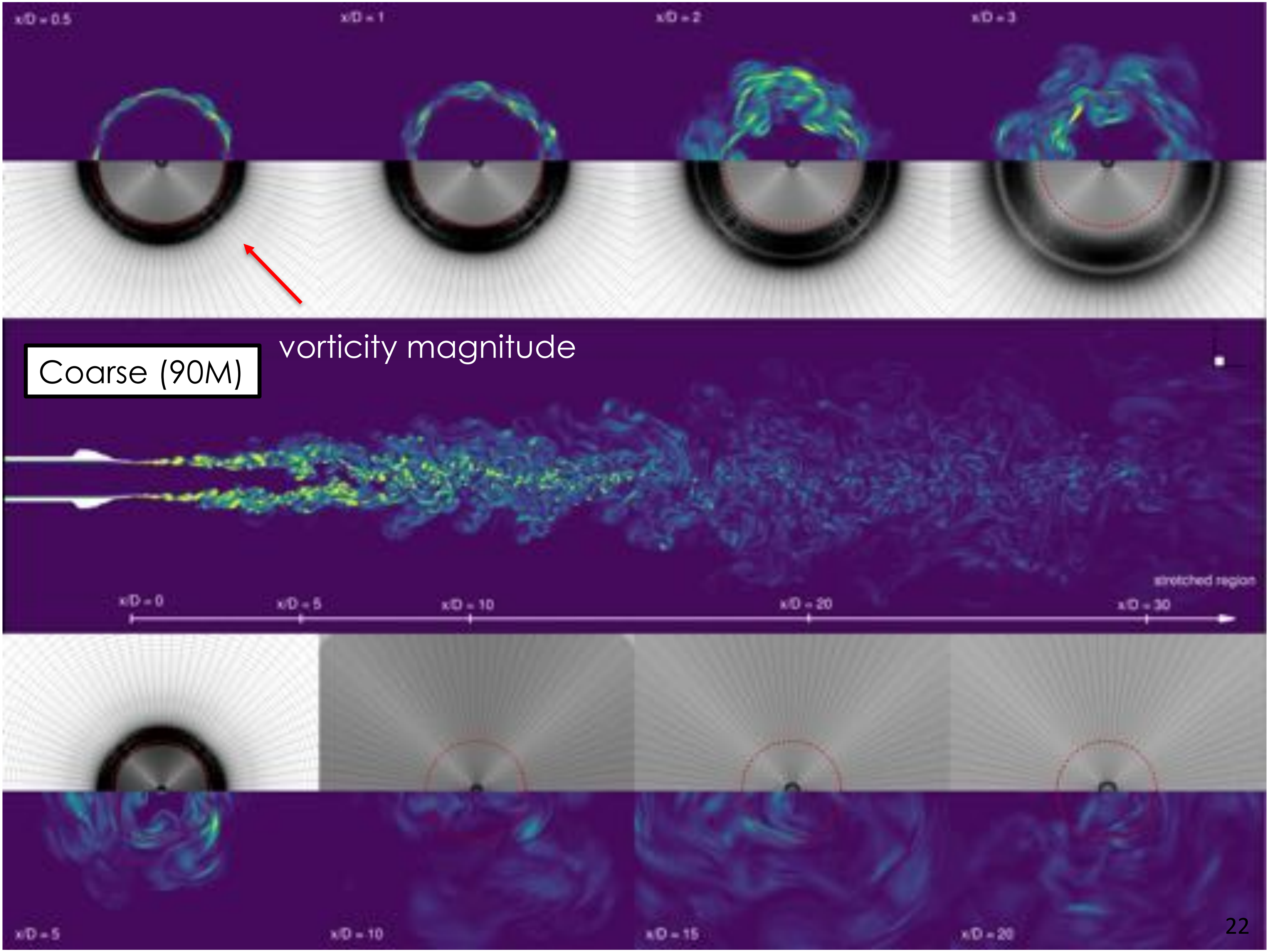
Flow Field Visualization

Isocontour of Q-Criteria colored by axial Velocity





x/D = 0.5
x/D = 1
x/D = 2
x/D = 3
Coarse (90M)
vorticity magnitude
stretched region
x/D = 0
x/D = 5
x/D = 10
x/D = 20
x/D = 30
x/D = 5
x/D = 10
x/D = 15
x/D = 20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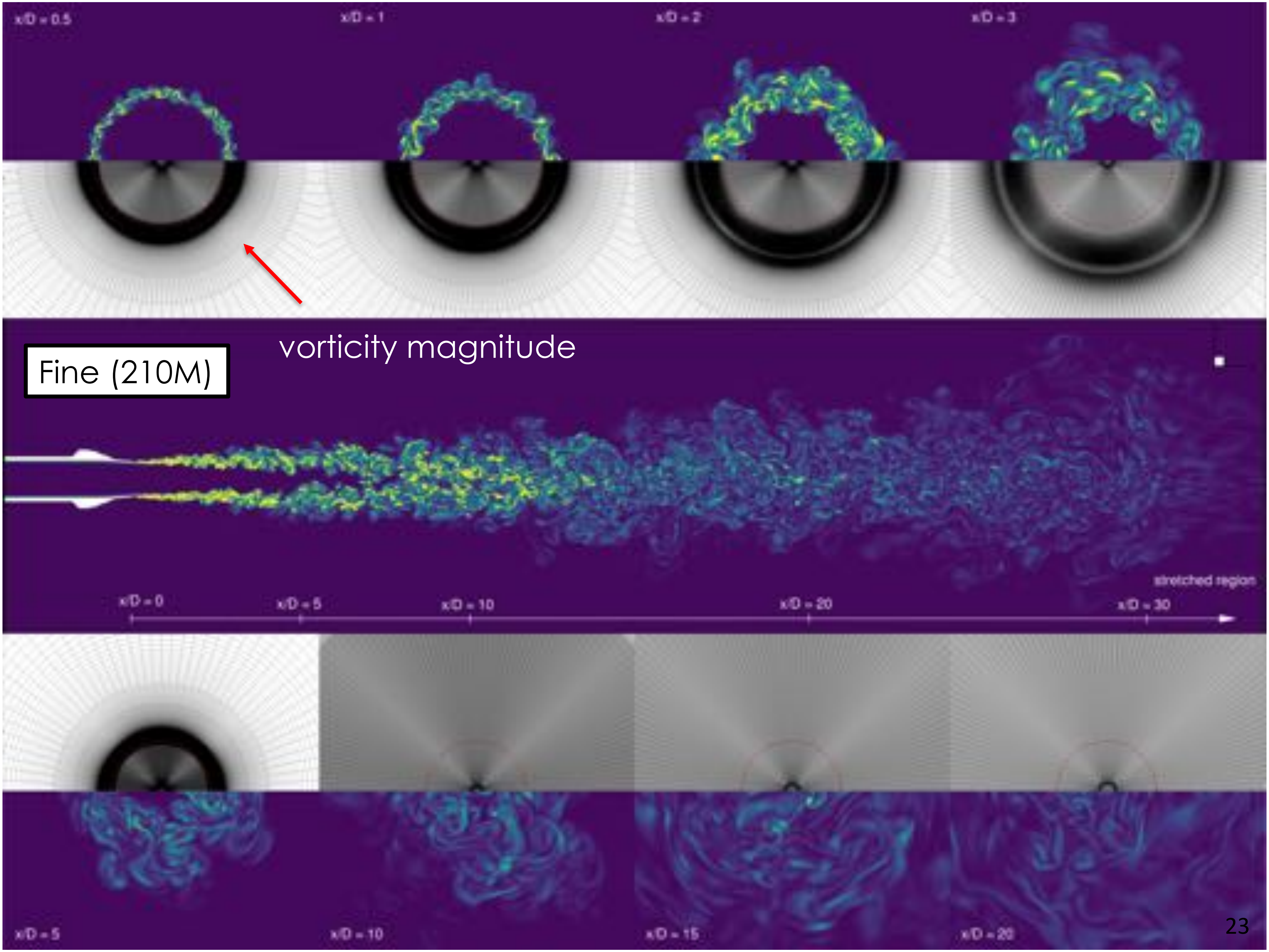
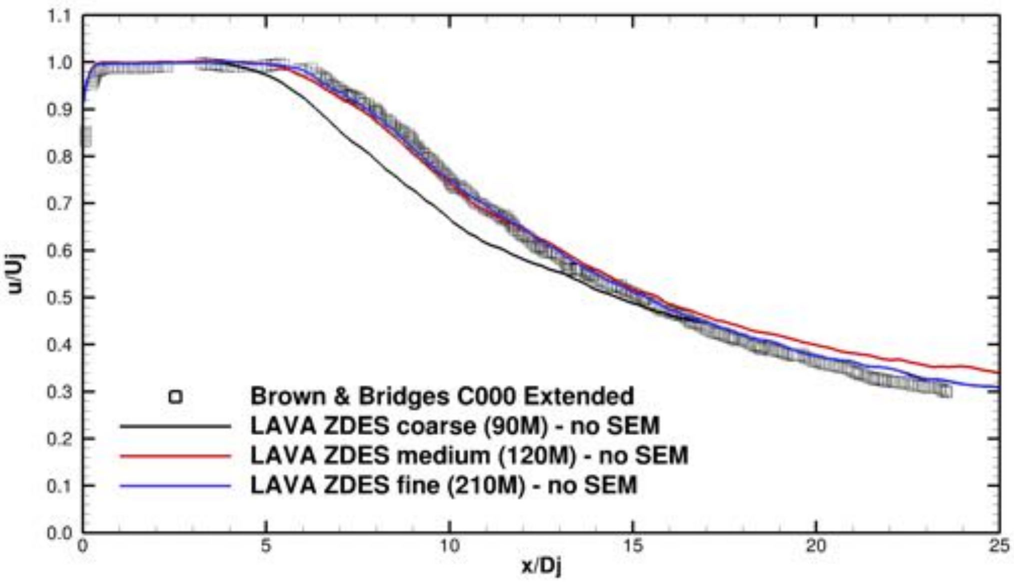
x/D = 20



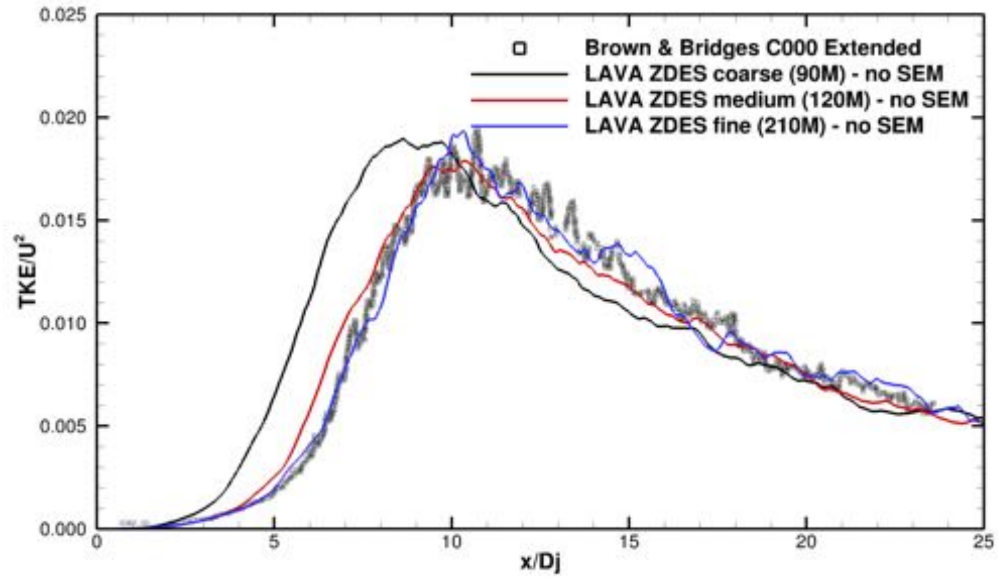
x/D = 0.5
x/D = 1
x/D = 2
x/D = 3
Fine (210M)
vorticity magnitude
stretched region
x/D = 0
x/D = 5
x/D = 10
x/D = 20
x/D = 30
x/D = 5
x/D = 10
x/D = 15
x/D = 20

Near-Field
Centerline Axial Velocity and Turbulent Kinetic Energy

(a) axial velocity



(b) turbulent kinetic energy (TKE)



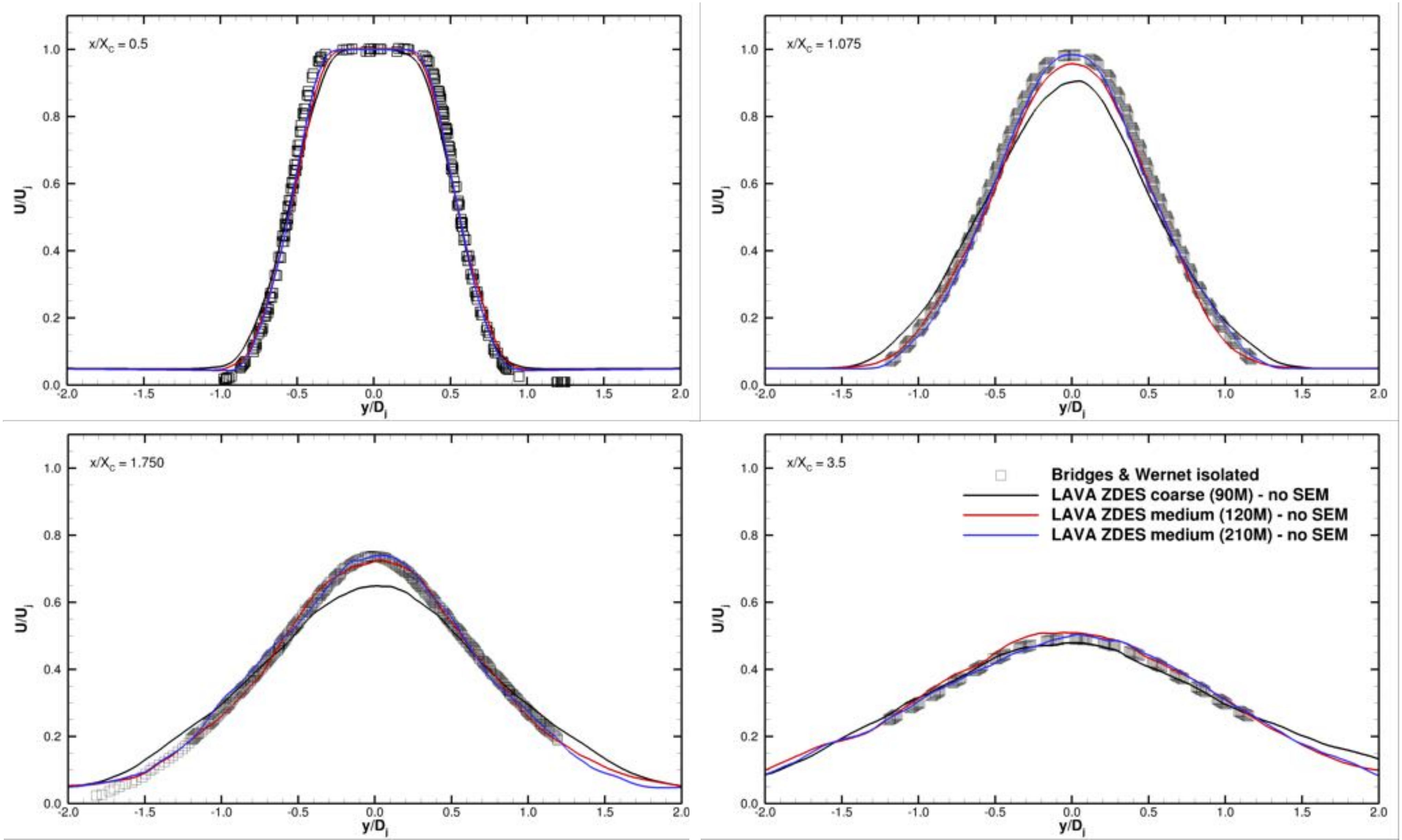
- Length of potential core X_C taken where centerline velocity 98% U_{jet}
- Prediction of medium and fine mesh within 2.5% of measured value.
- Peak and location of Turbulent Kinetic Energy (TKE) predicted very well.

Length Potential core:

Experiment	$5.9D_j$
coarse	$4.85D_j$
medium	$5.75D_j$
fine	$5.8D_j$

Near-Field

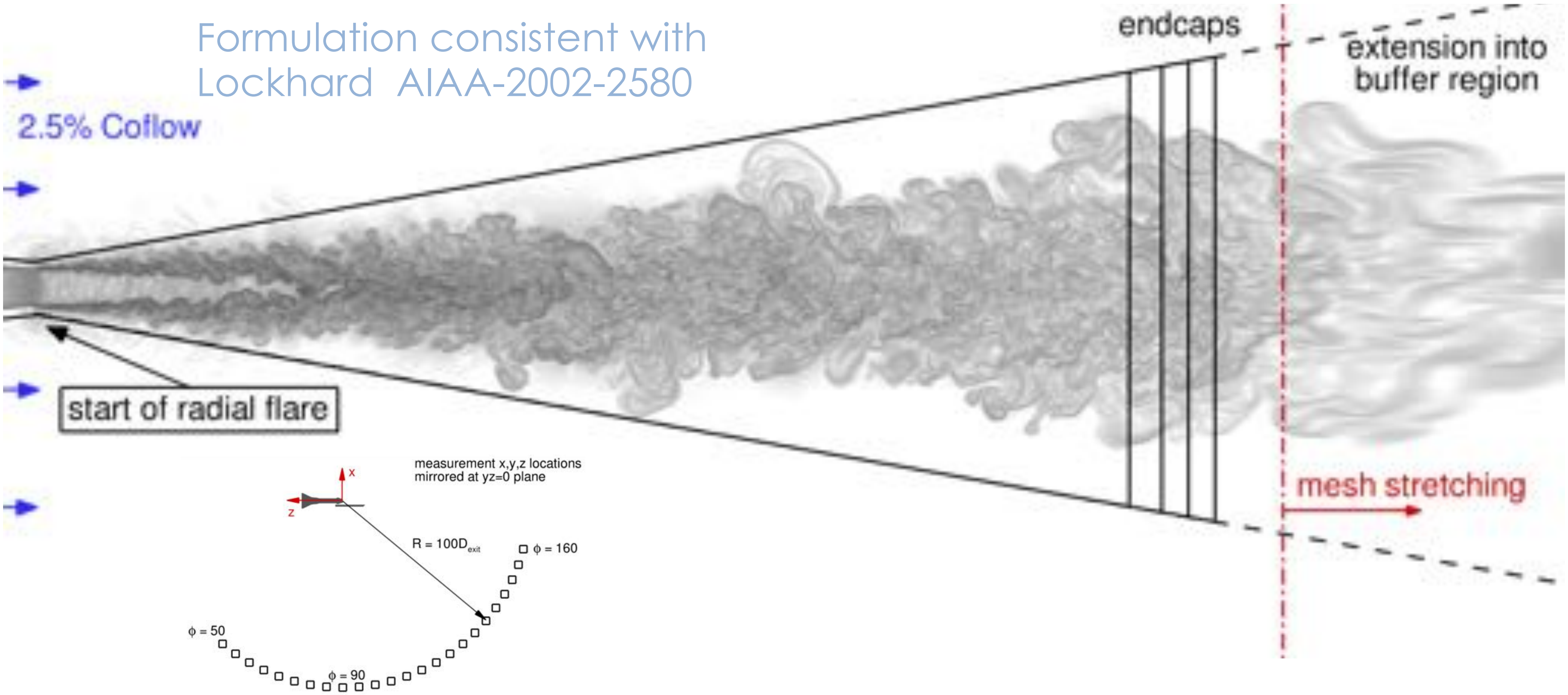
Time-Averaged Axial Velocity at Radial Slices



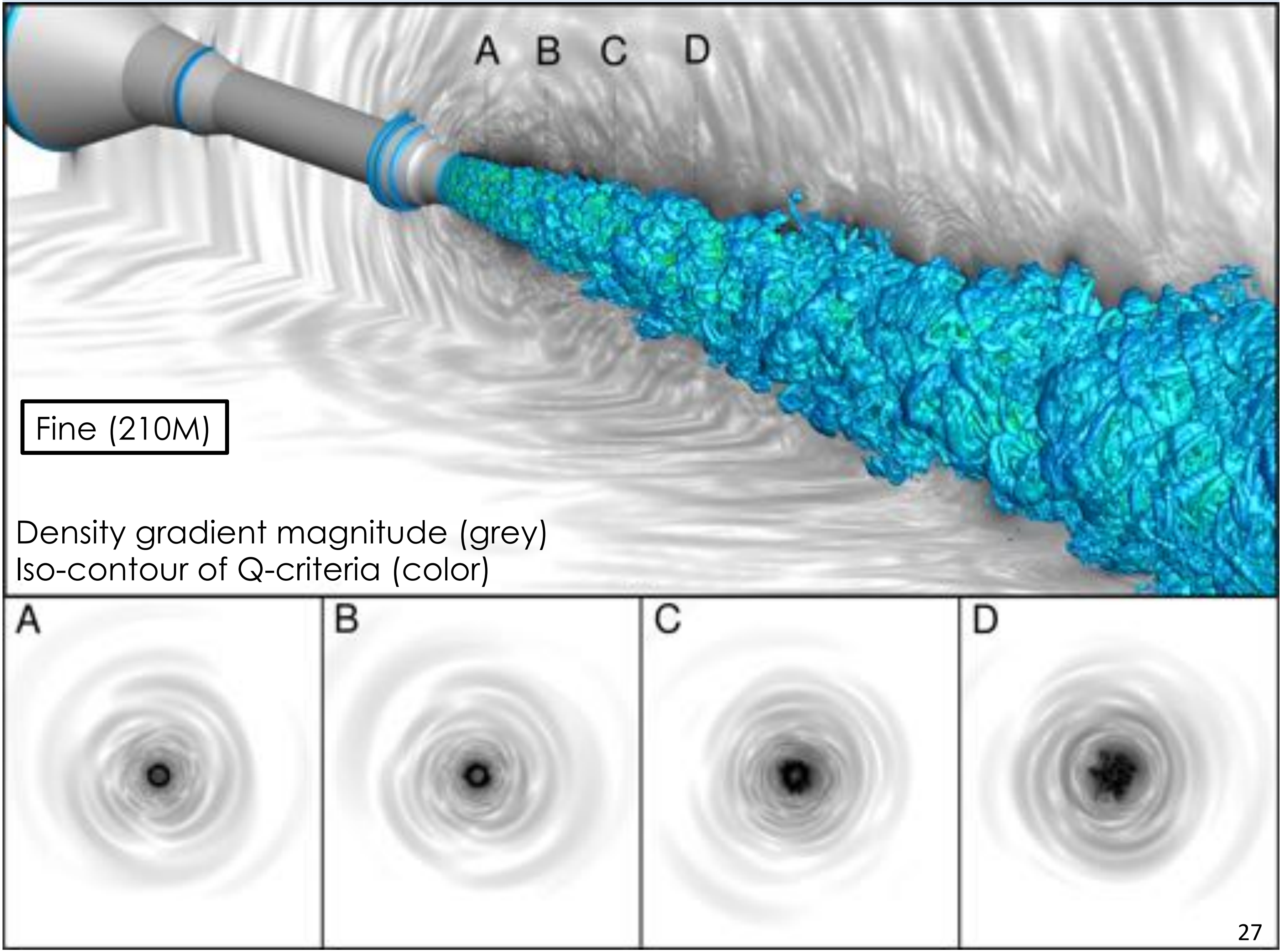
- Location of axial slice normalized by potential core length $X_C = 5.9$

Far-Field – Setup and Procedure
Frequency Domain Permeable Ffowcs Williams-Hawkings (FWH)

Formulation consistent with
Lockhard AIAA-2002-2580

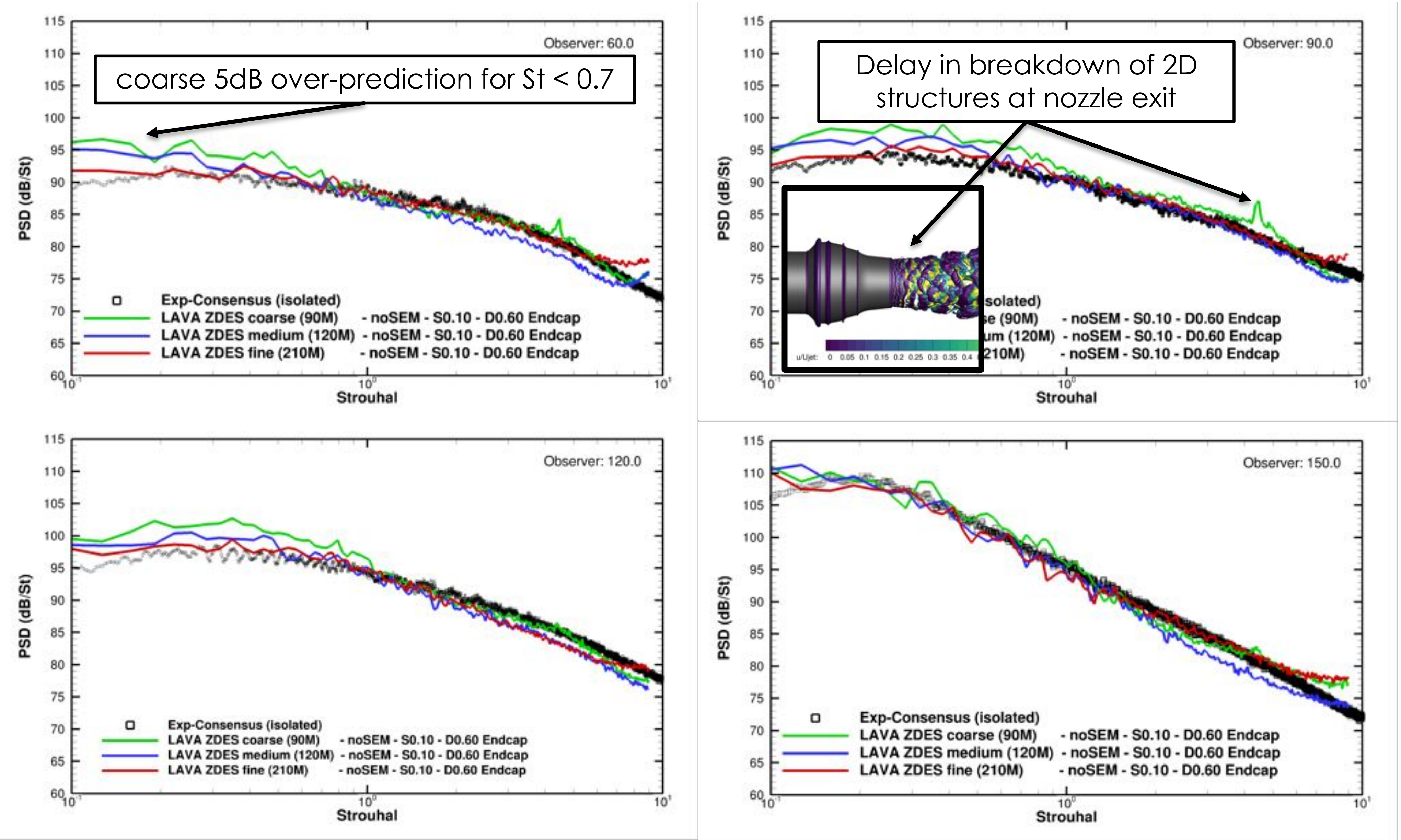


- Interpolate Volume solution to FWH surface at sampling rate 100kHz
- Samples taken over last 200 convective time units ($\Delta t\ c_\infty/D_j$)
- Time Sample Split in 5 segments with 50% overlap $St_{bin} = 0.02$
- Hanning Window is applied in the time-domain
  (PSD multiplied with sqrt(8/3) to recover energy loss from Hanning window)
- PSD data assemble averaged over 360 observers per angle (60, 90, 120, 150)
- Developed automated tool to adapt number of faces on FWH surface


A B C D
Fine (210M)
Density gradient magnitude (grey)
Iso-contour of Q-criteria (color)
A
B
C
D

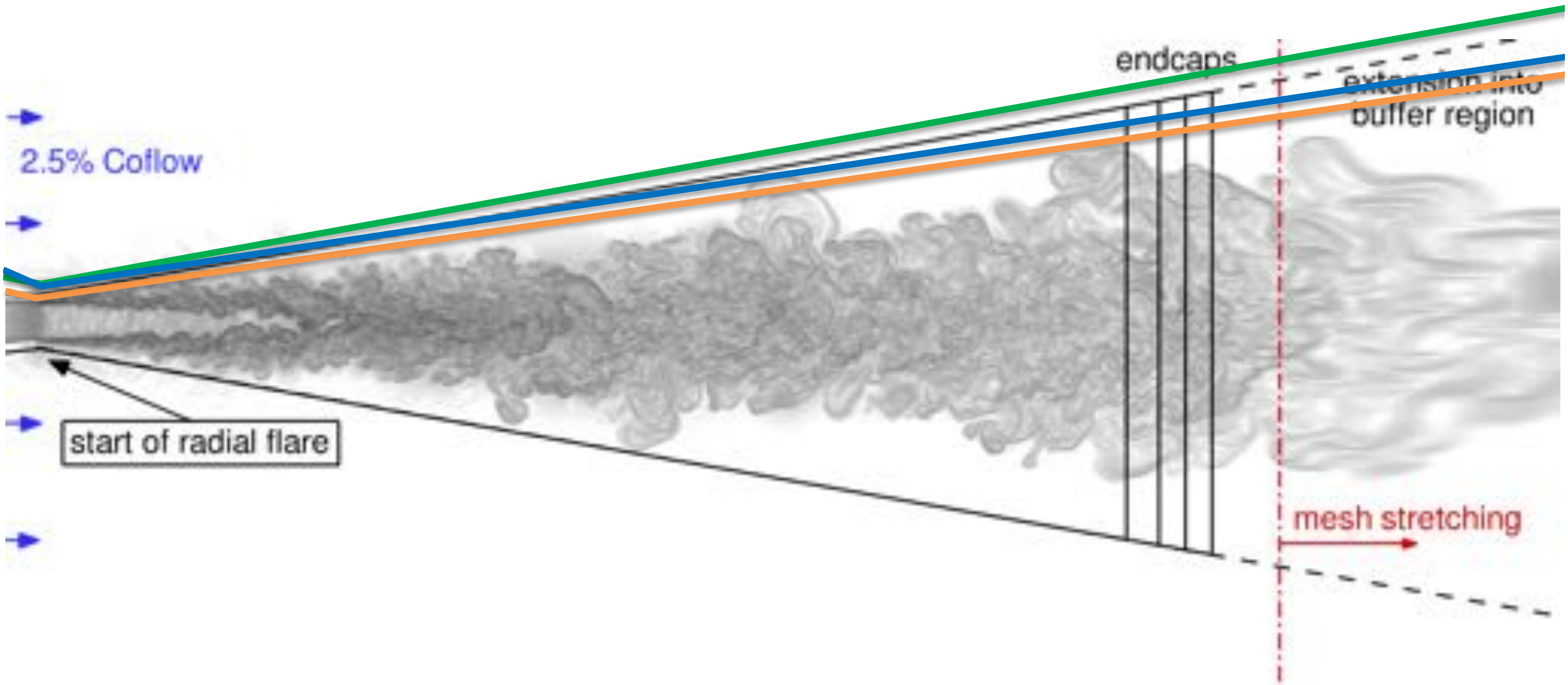
Far-Field – CFD Mesh Resolution

Comparison of PSD Spectrum 100D away from nozzle exit



- Details of selected FWH Surface can be found in paper
- Overall excellent agreement with Exp-Consensus

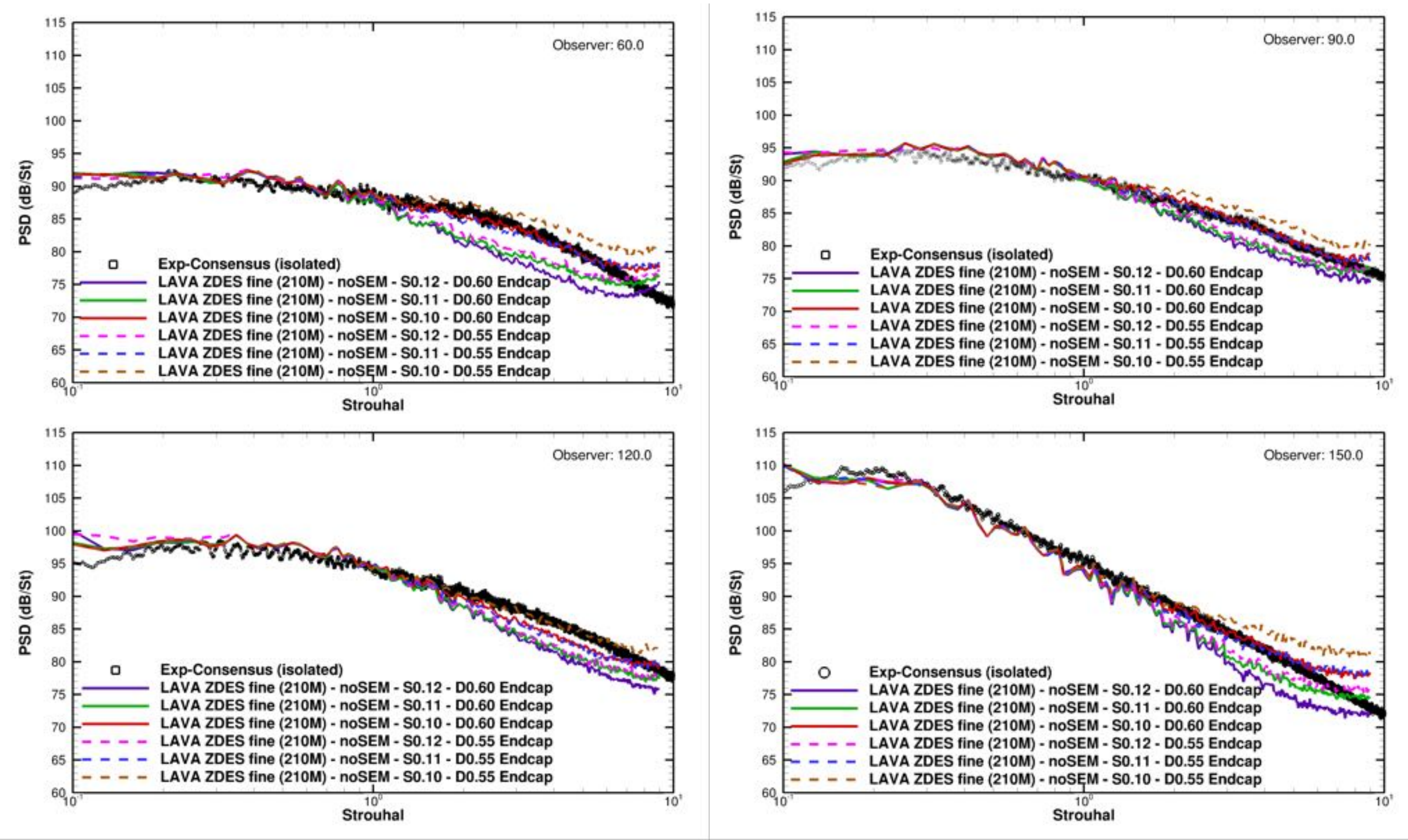
Far-Field – Choice of FWH Surface



1. Start radial Flare at $x/D_j = 0.6$ or $x/D_j = 0.55$
2. Variation of slopes S = 0.12, S = 0.11, S = 0.10
3. Combination of (1) and (2)

Far-Field – Choice of FWH Surface

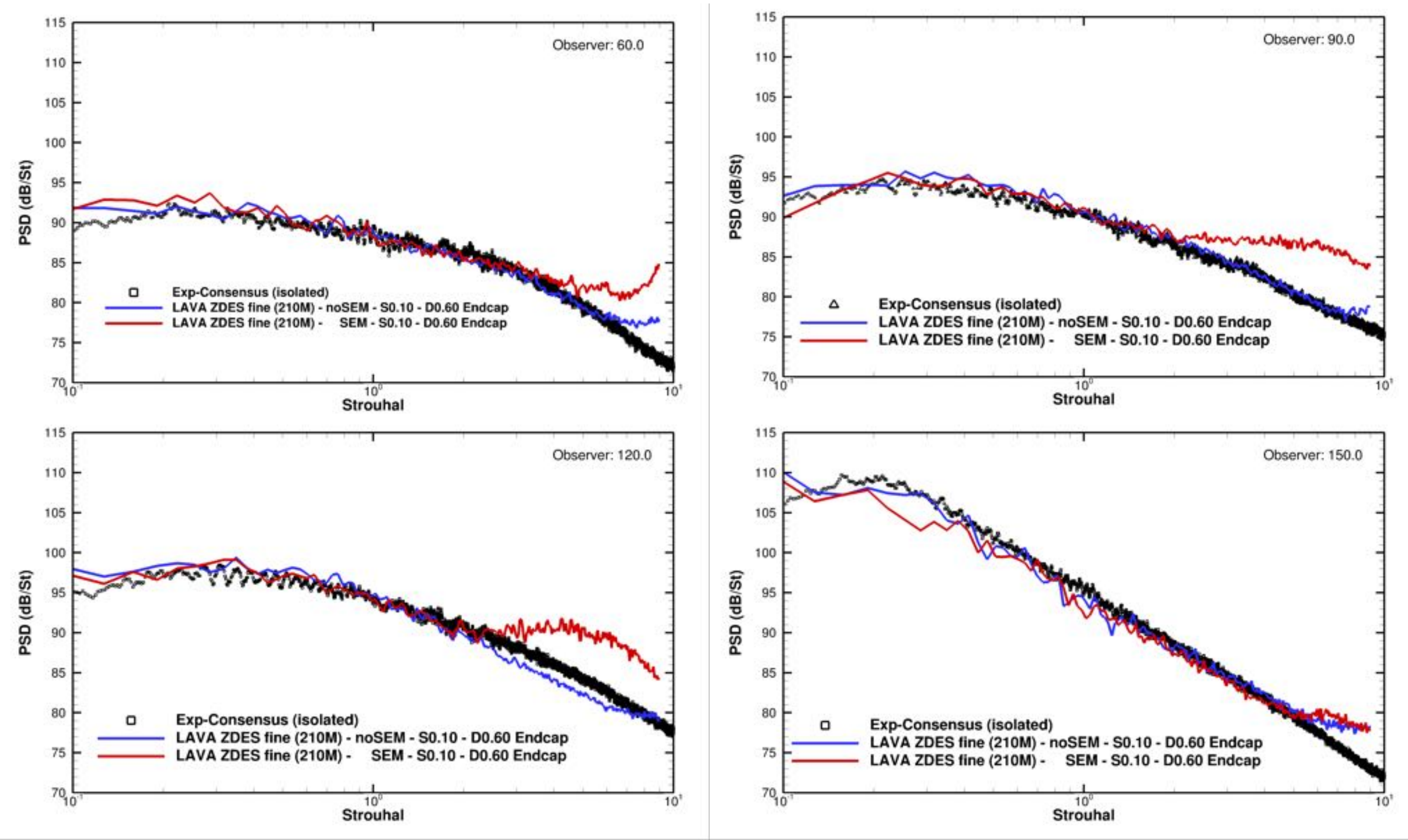
Comparison of PSD Spectrum 100D away from nozzle exit



- Results sensitive to choice of FWH surface.
- Less dissipative scheme than WCNS might reduce sensitivity

Far-Field – Inflow Turbulence (SEM)

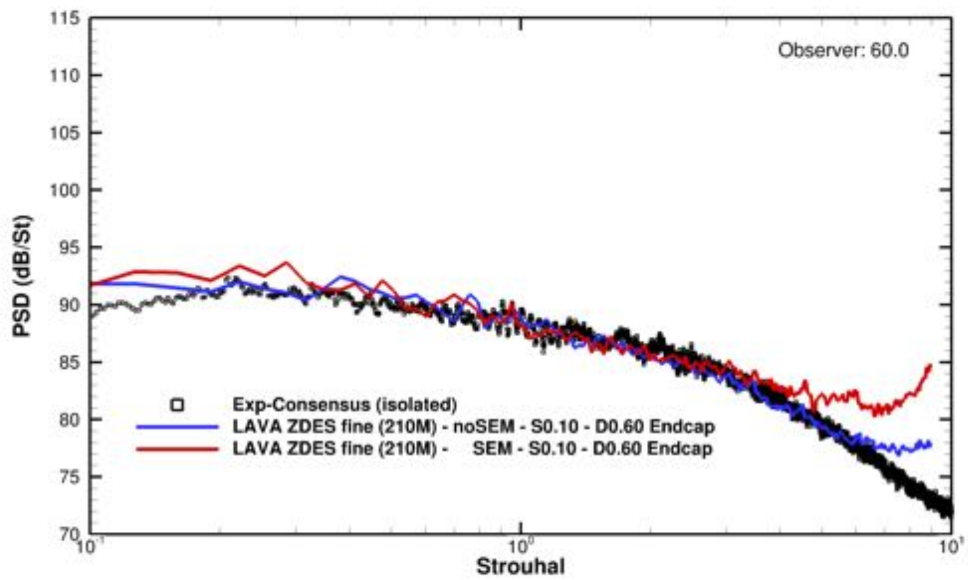
Comparison of PSD Spectrum 100D away from nozzle exit

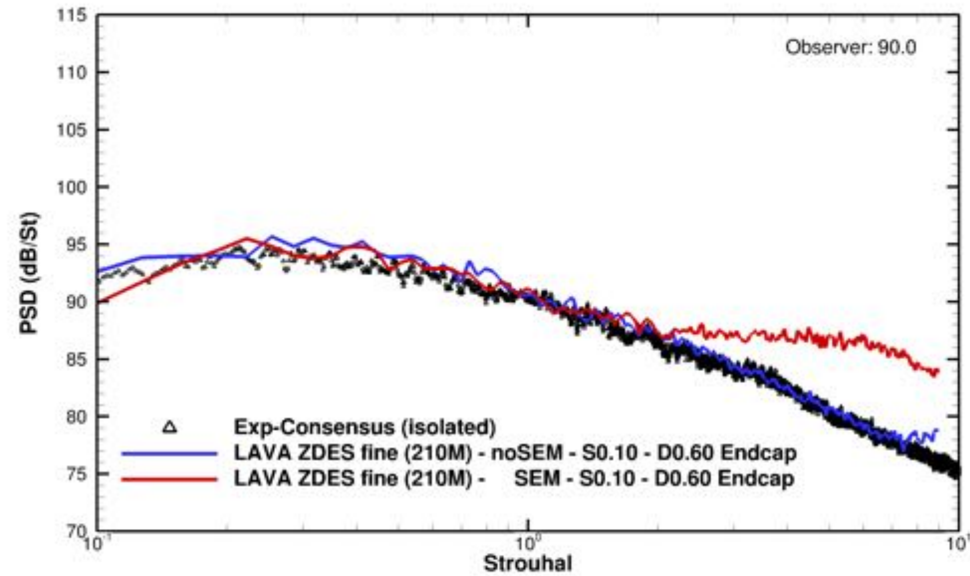


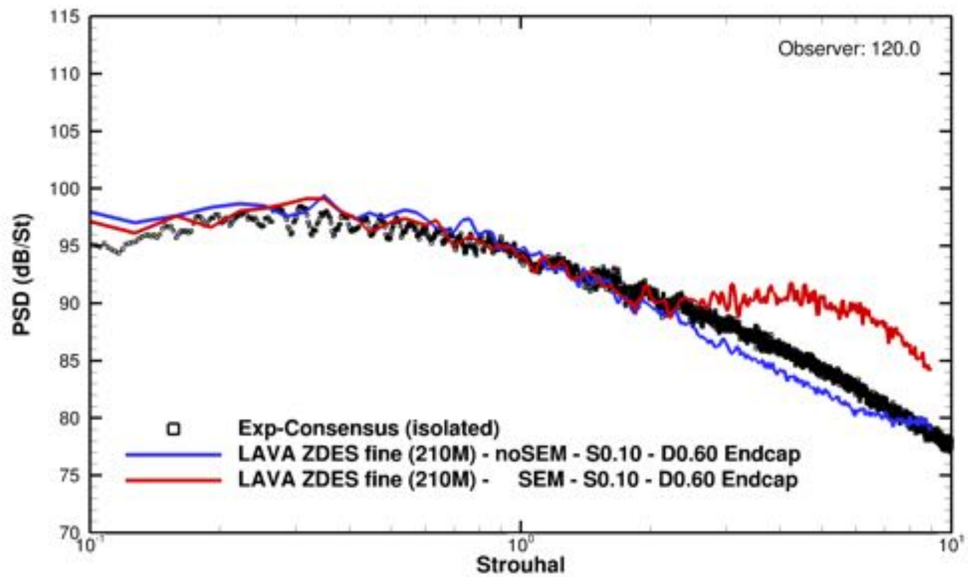
- Influence of inflow turbulence on PSD spectra.
- Smaller effect of inflow turbulence on shallower angles (150.0)

Far-Field – Inflow Turbulence (SEM)

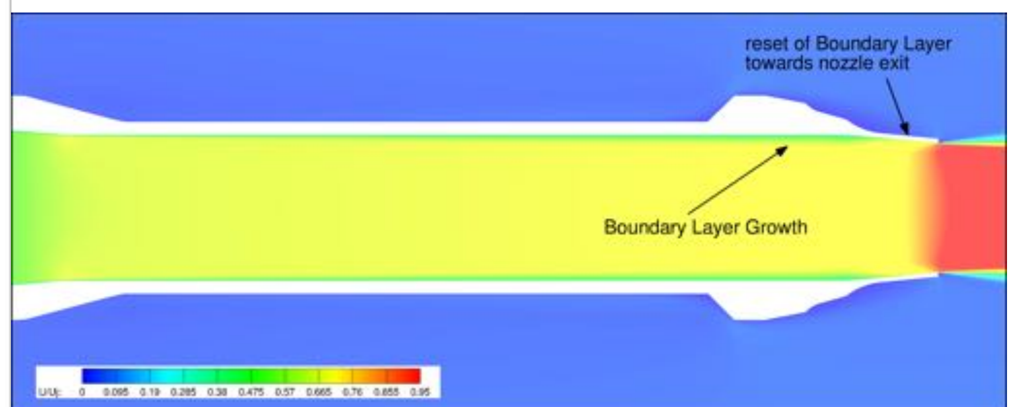
Comparison of PSD Spectrum 100D away from nozzle exit







Velocity Magnitude taken from RANS



- Enhanced influence on noise spectra for SMC000 with 12"
- Addition inflow generation methods currently under consideration.

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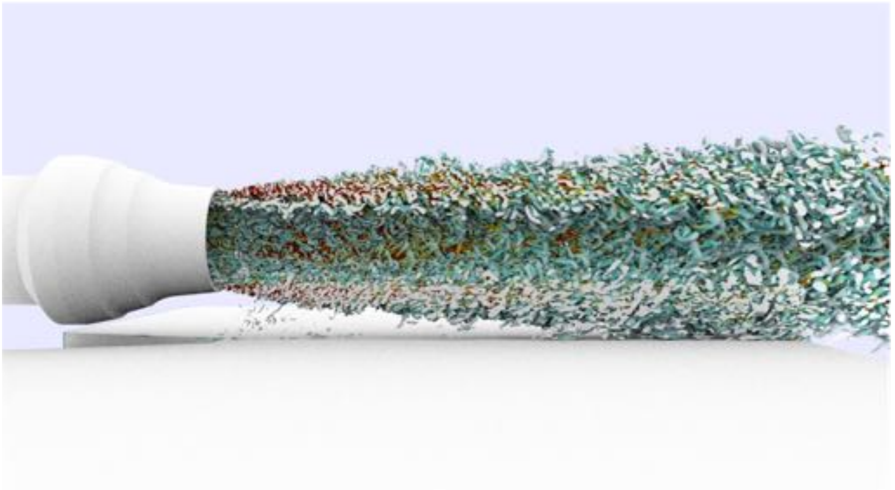
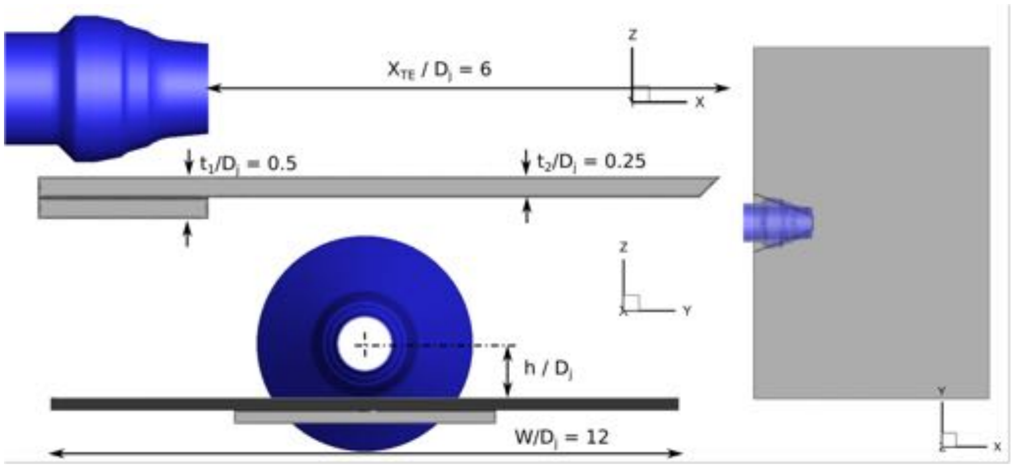
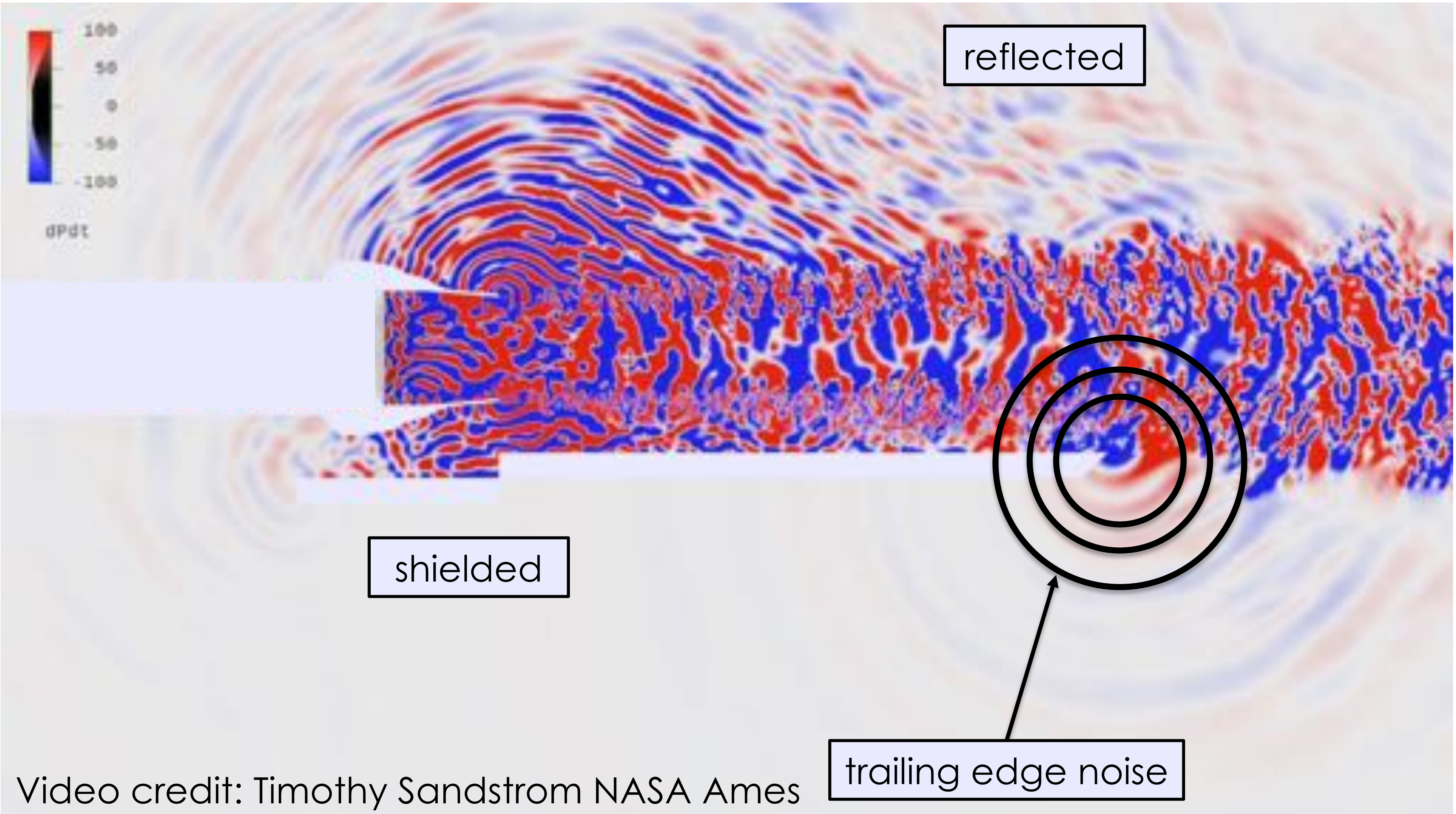
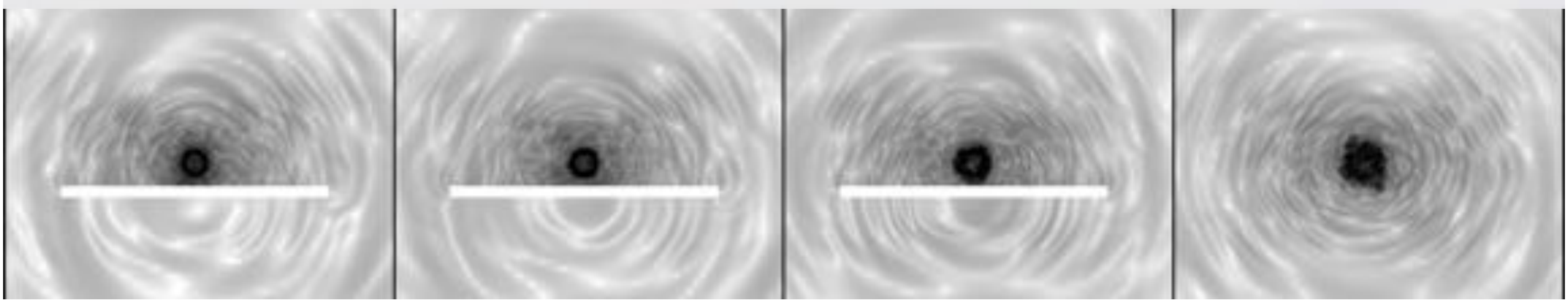
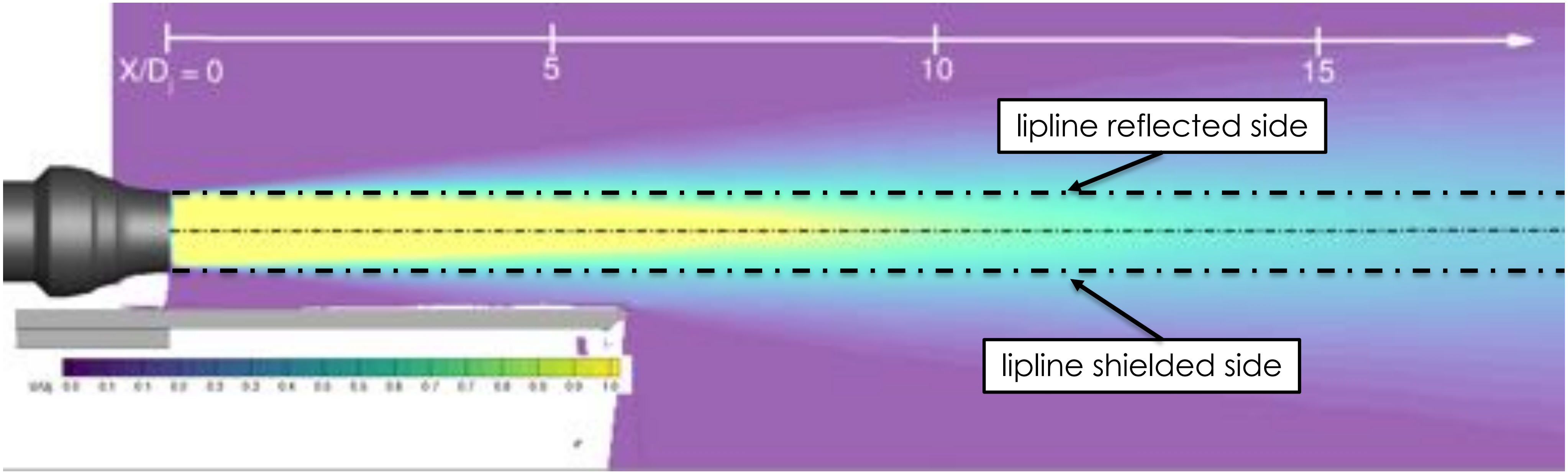


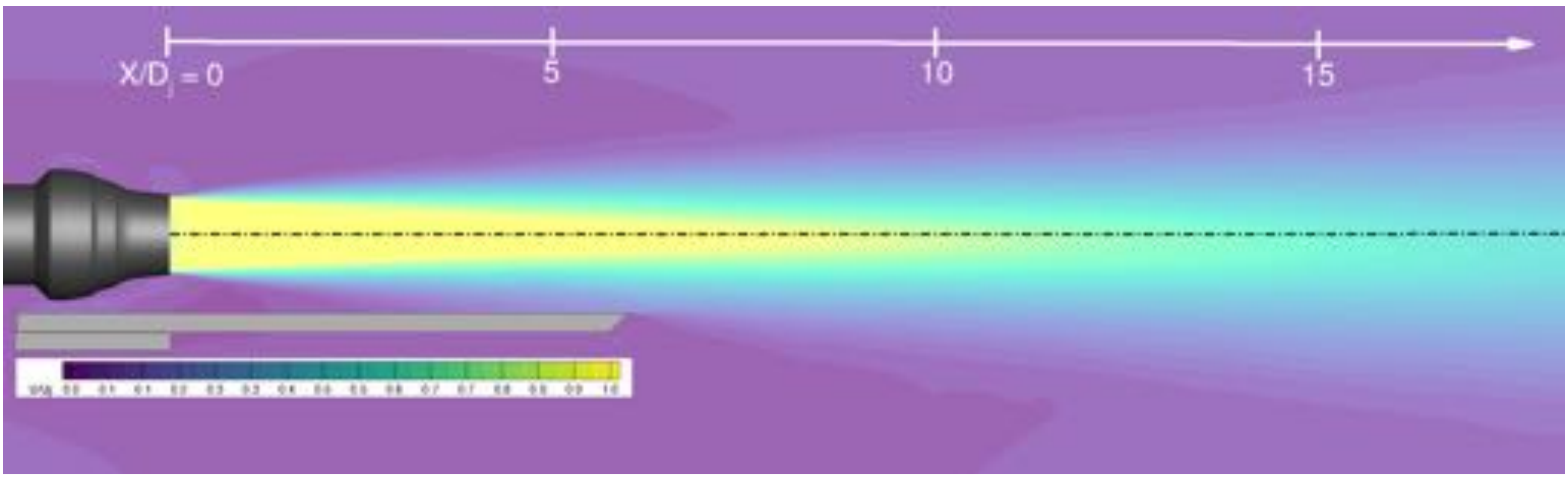



100
50
0
-50
-100
dPdt
reflected
shielded
trailing edge noise
Video credit: Timothy Sandstrom NASA Ames


Near-Field Comparisons

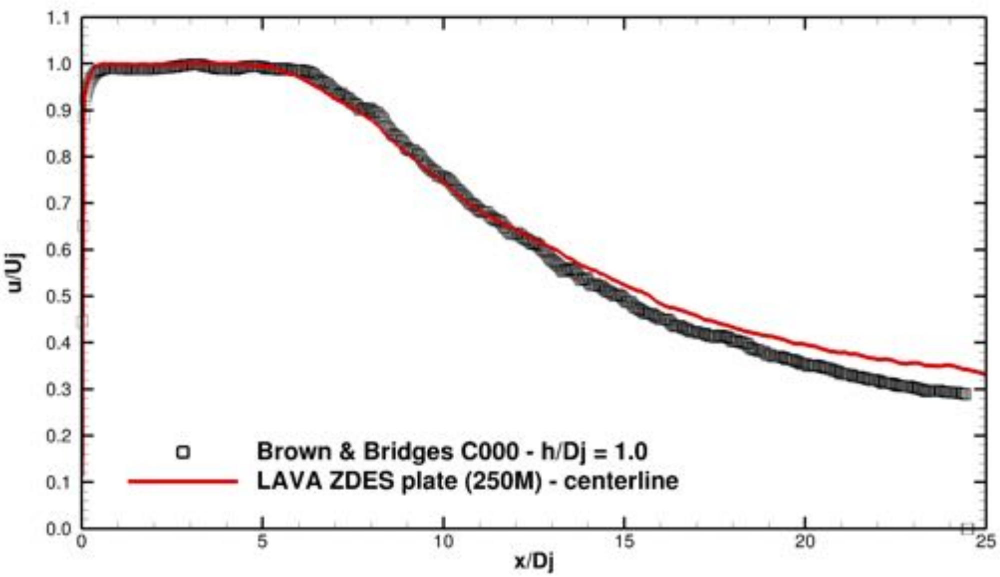


(a) PIV measurements from Experiment

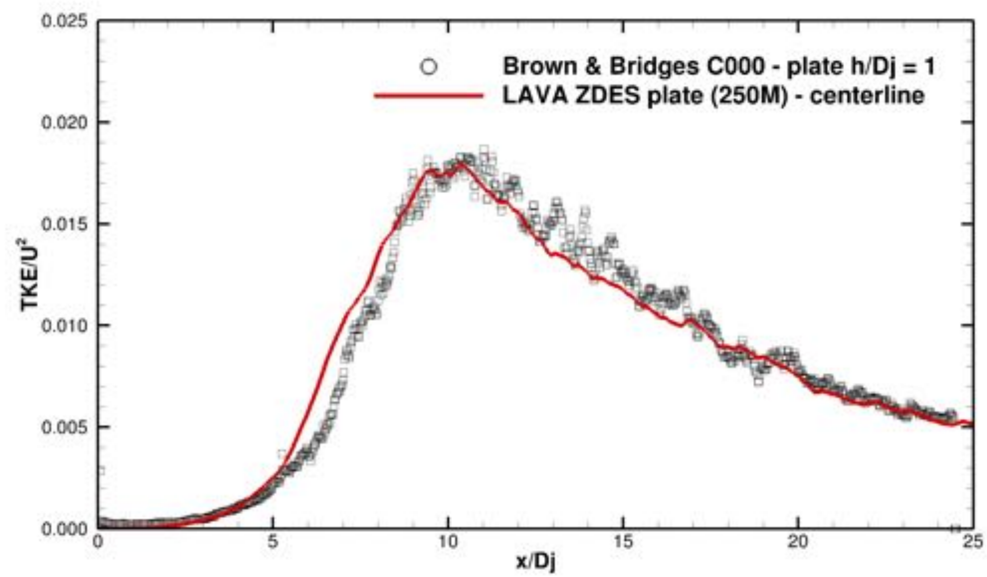


(b) Contour plot from CFD

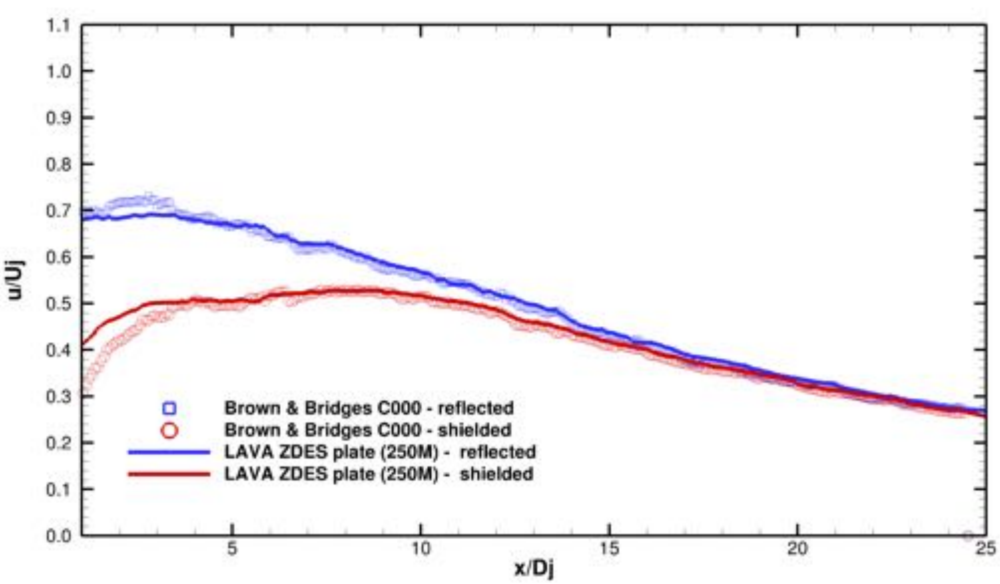
Near-Field
Time-Averaged Axial Velocity and Turbulent Kinetic Energy



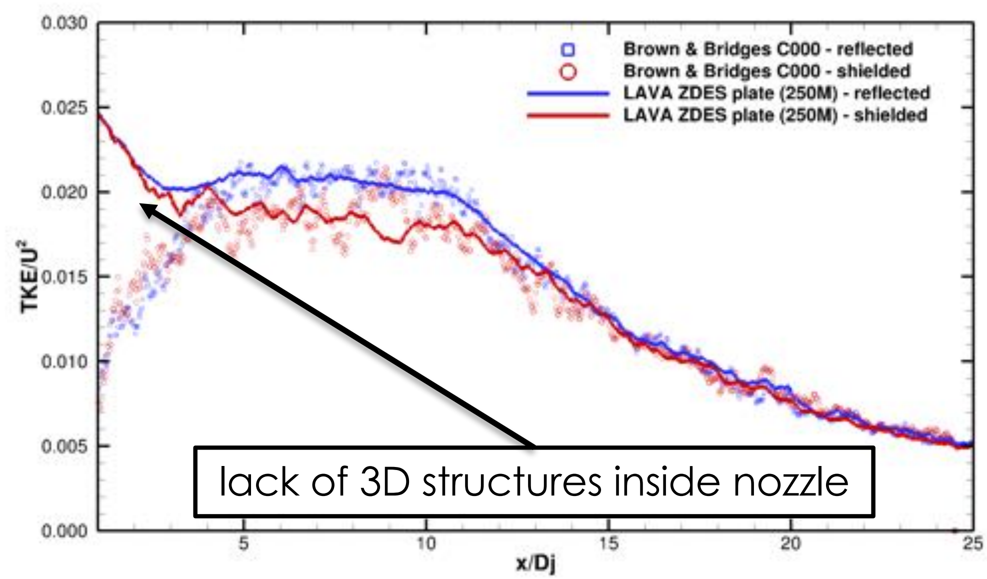
(a1) Centerline Velocity



(a2) Centerline TKE



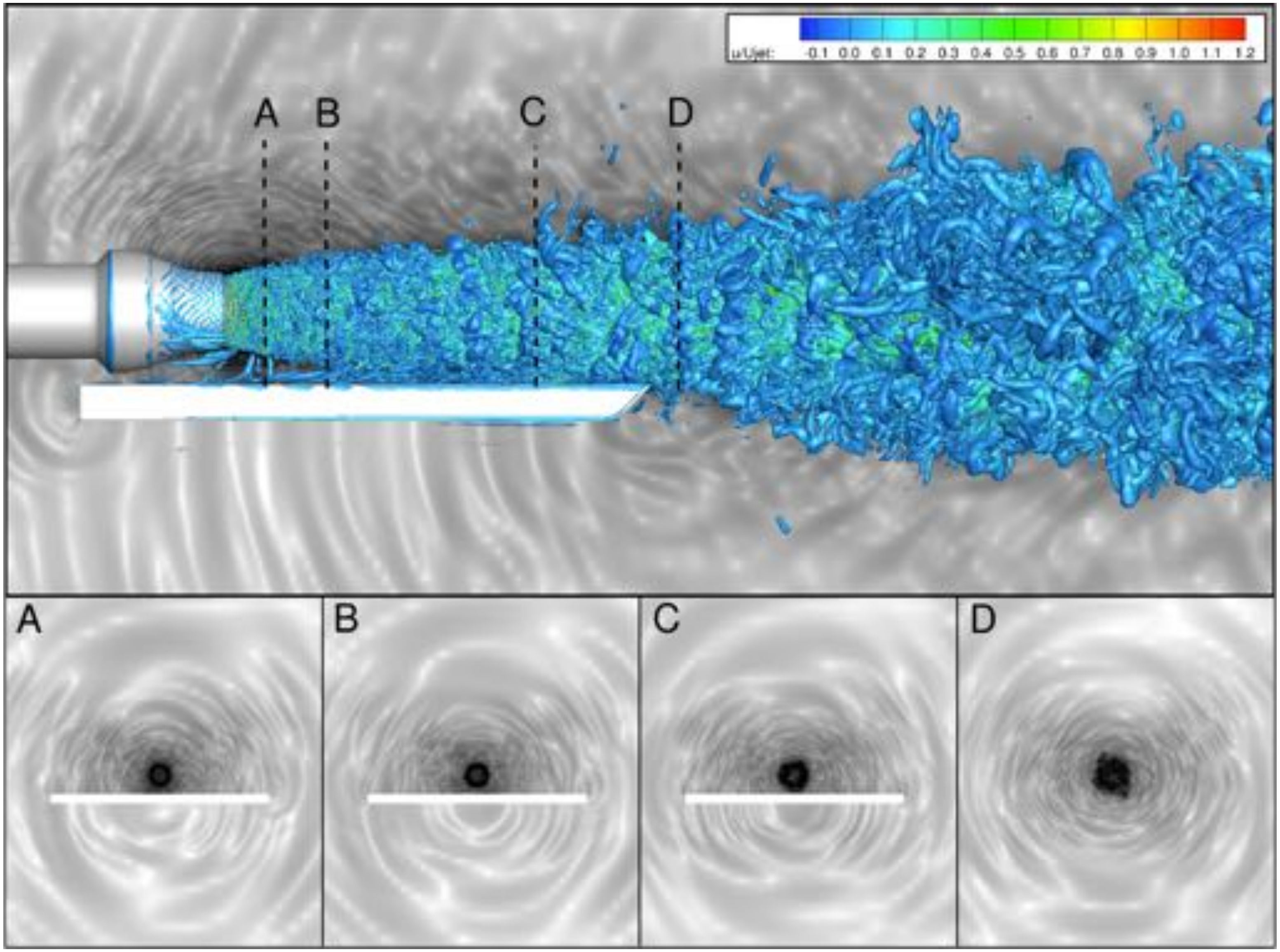
(a1) Lipline Velocity



(a2) Lipline TKE

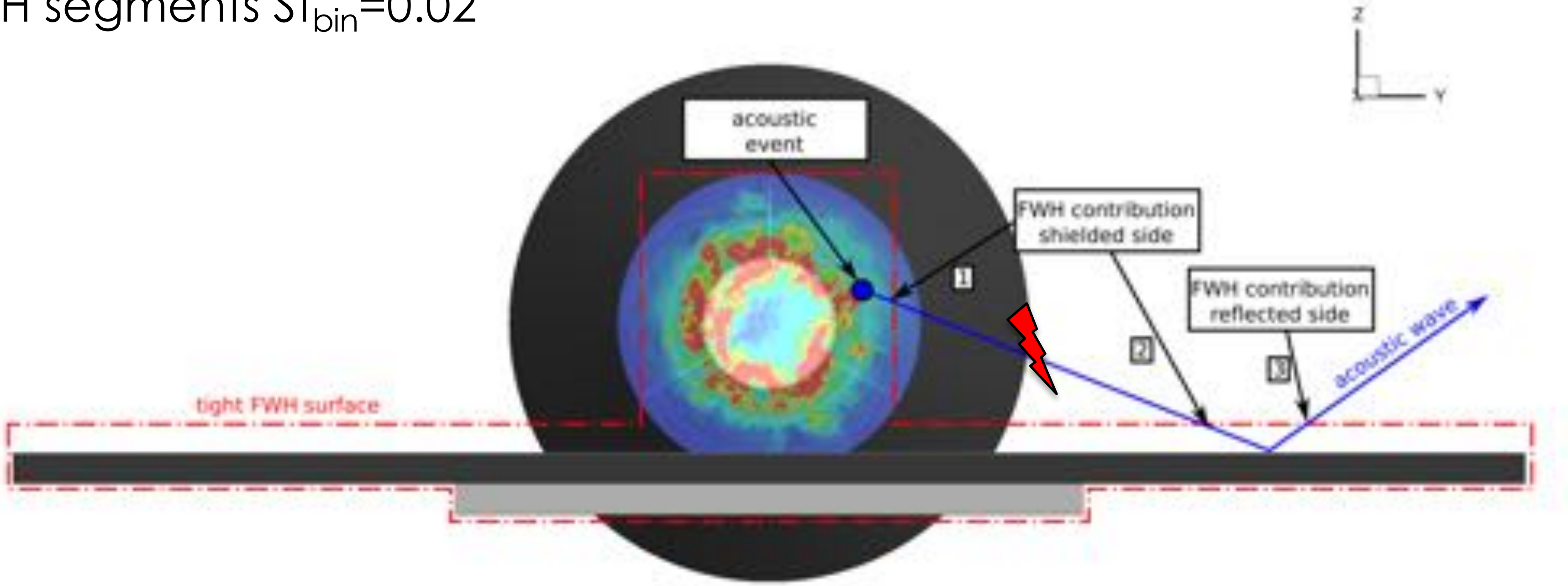
Far-Field – FWH Surface Definition
Tight FWH Surface

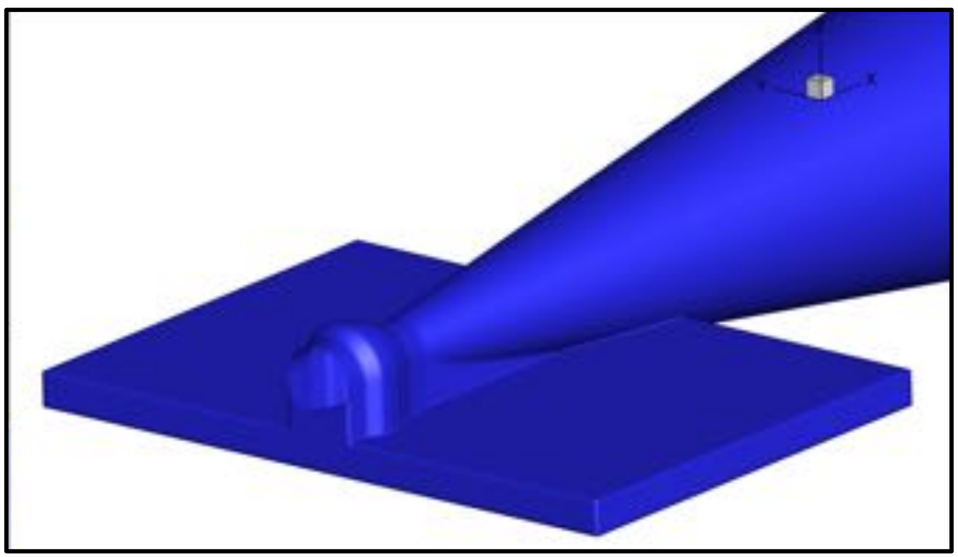
- Best practice guidelines established for isolated round-jet do not apply directly on case with enclosed surface (non-symmetric)
- Inclusion of all necessary sources important to predict noise spectra correct

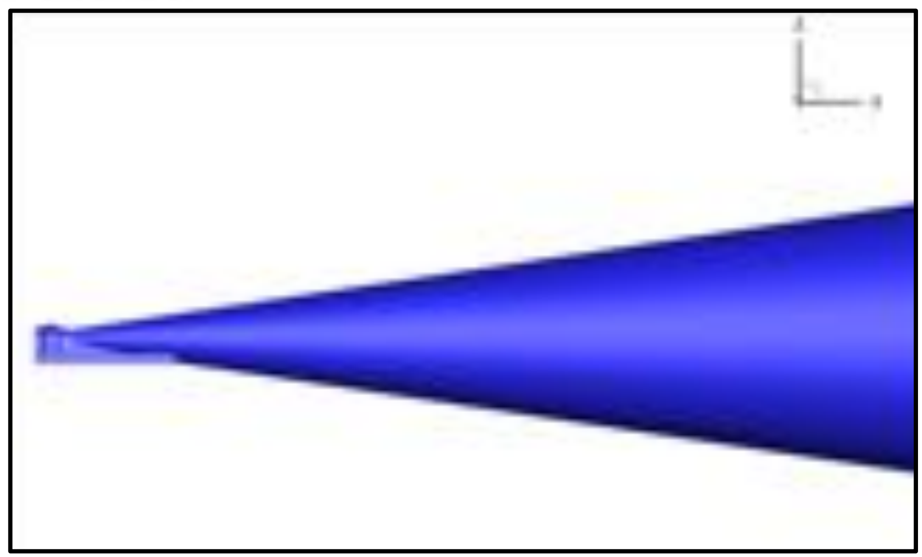


Far-Field – FWH Surface Definition
Tight FWH Surface

- 1000 convective time units
- 25 FWH segments St_{bin}=0.02

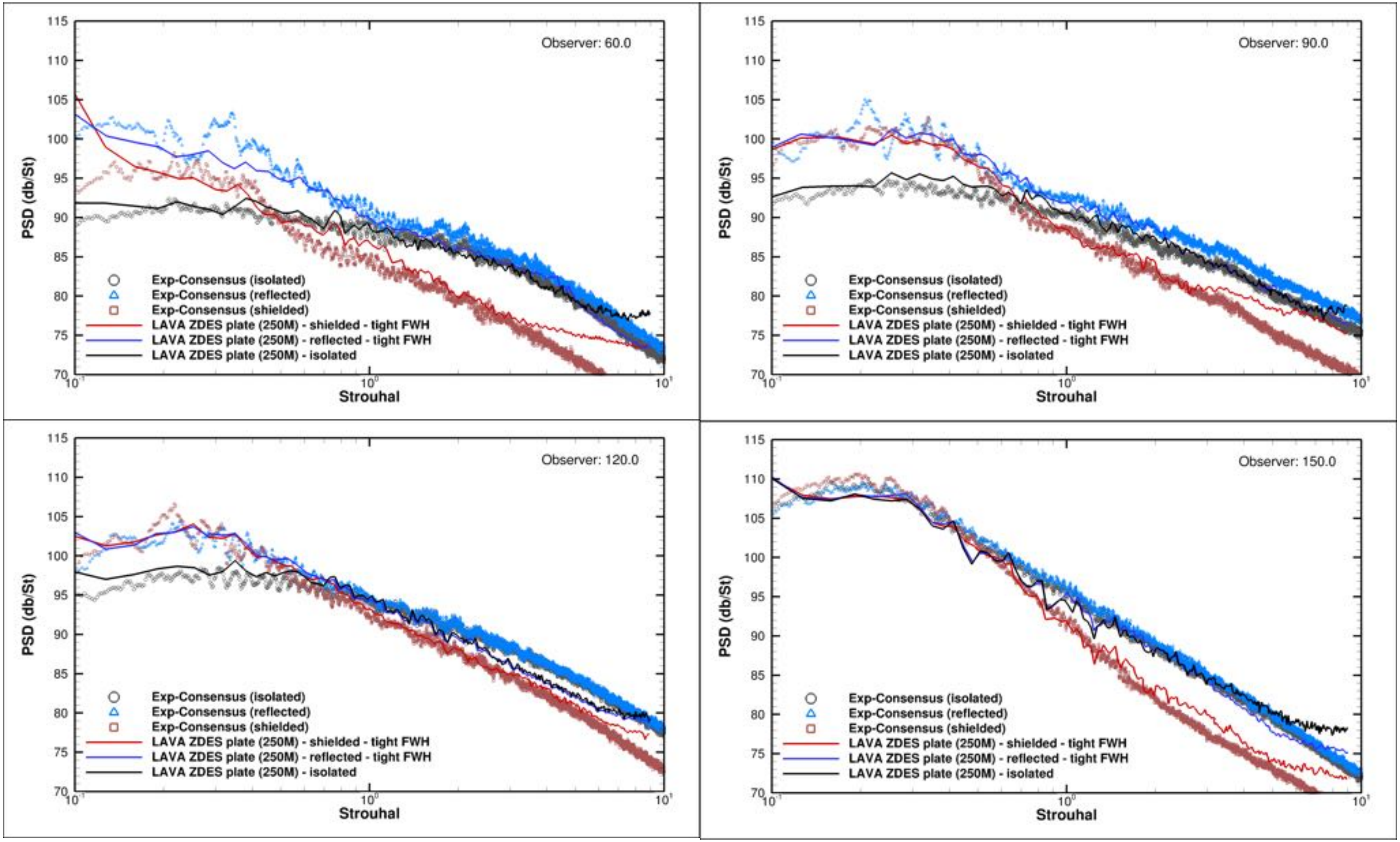






Far-Field – Tight FWH Surface

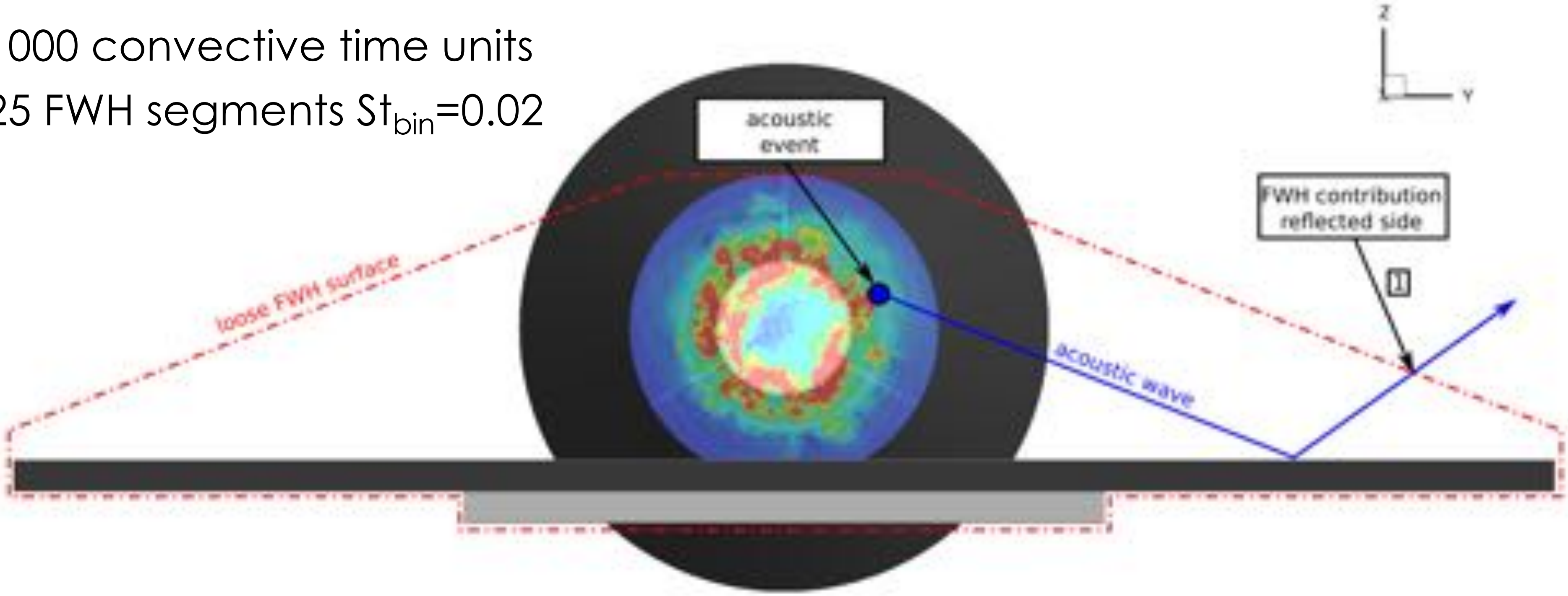
Comparison of PSD Spectrum 100D away from nozzle exit

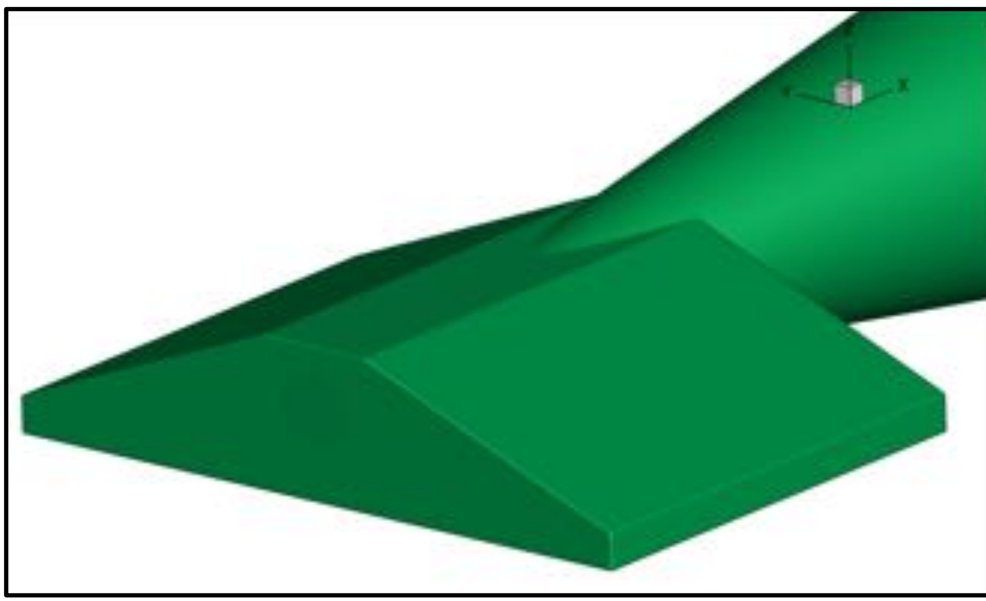


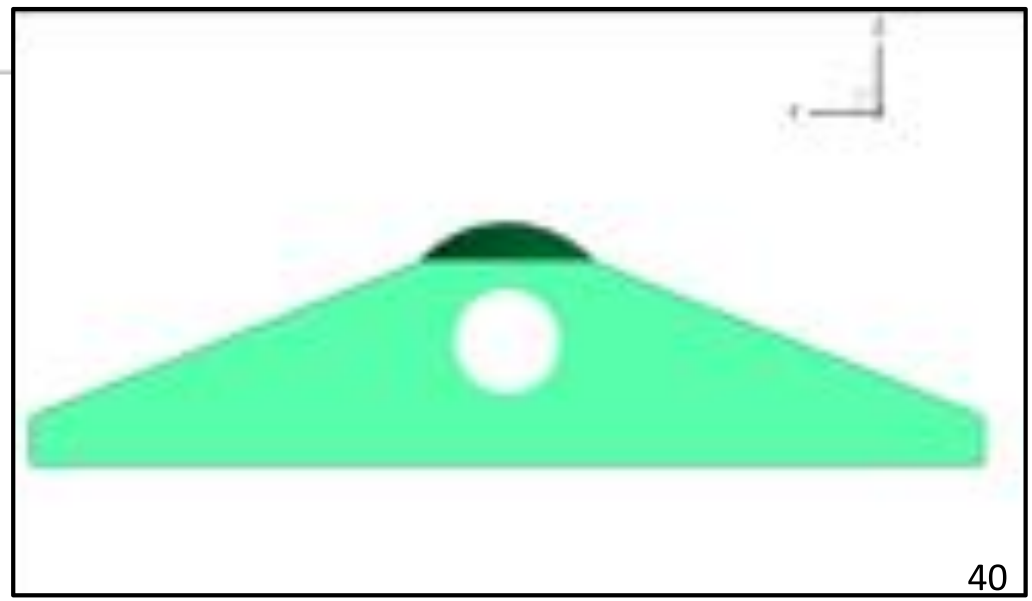
- Excellent agreement with measurements, split captured accurately.
- Resolution in plate region not sufficient for high-frequencies.

Far-Field – FWH Surface Definition
Loose FWH Surface

- 1000 convective time units
- 25 FWH segments St_{bin}=0.02

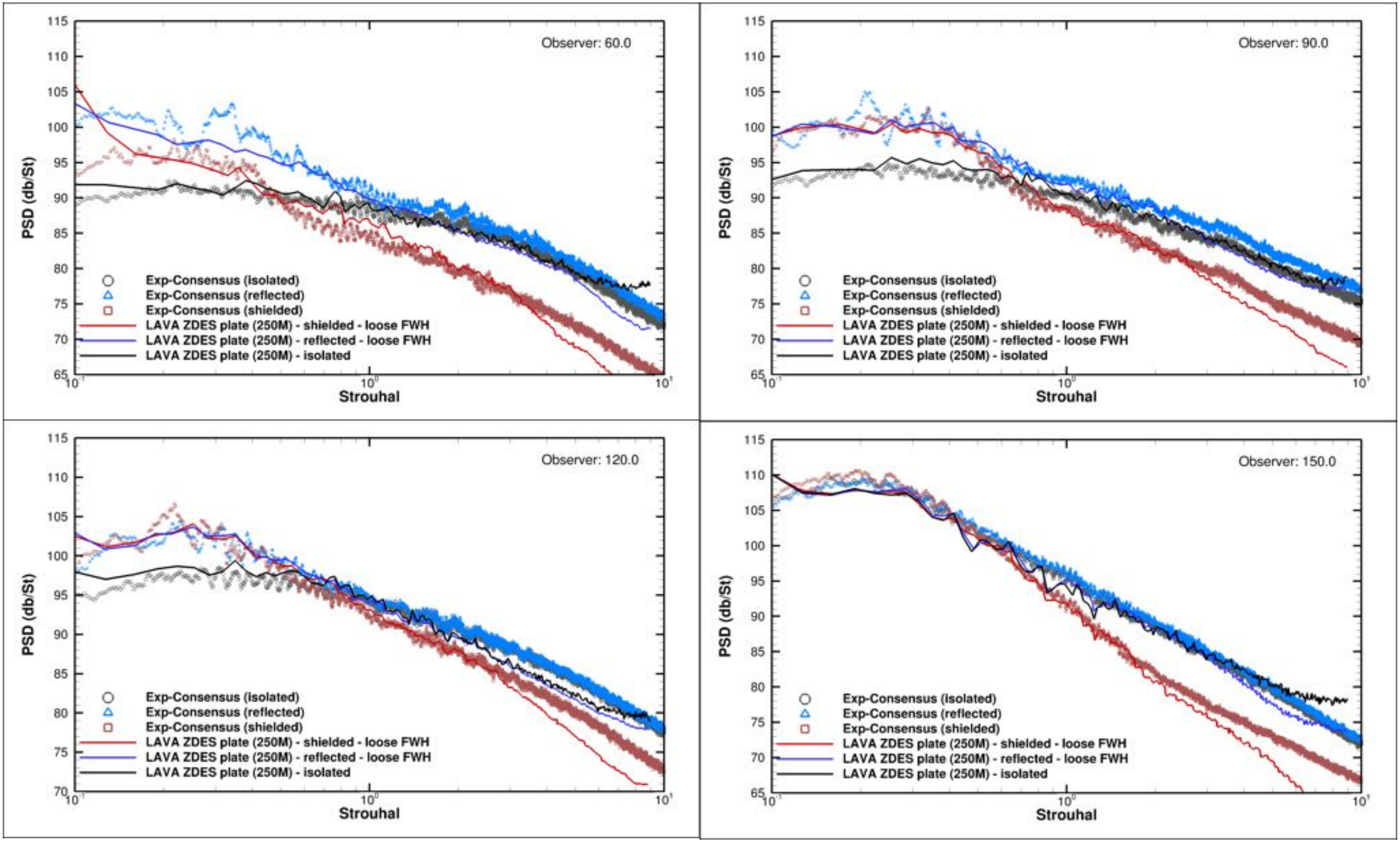






Far-Field – Tight FWH Surface

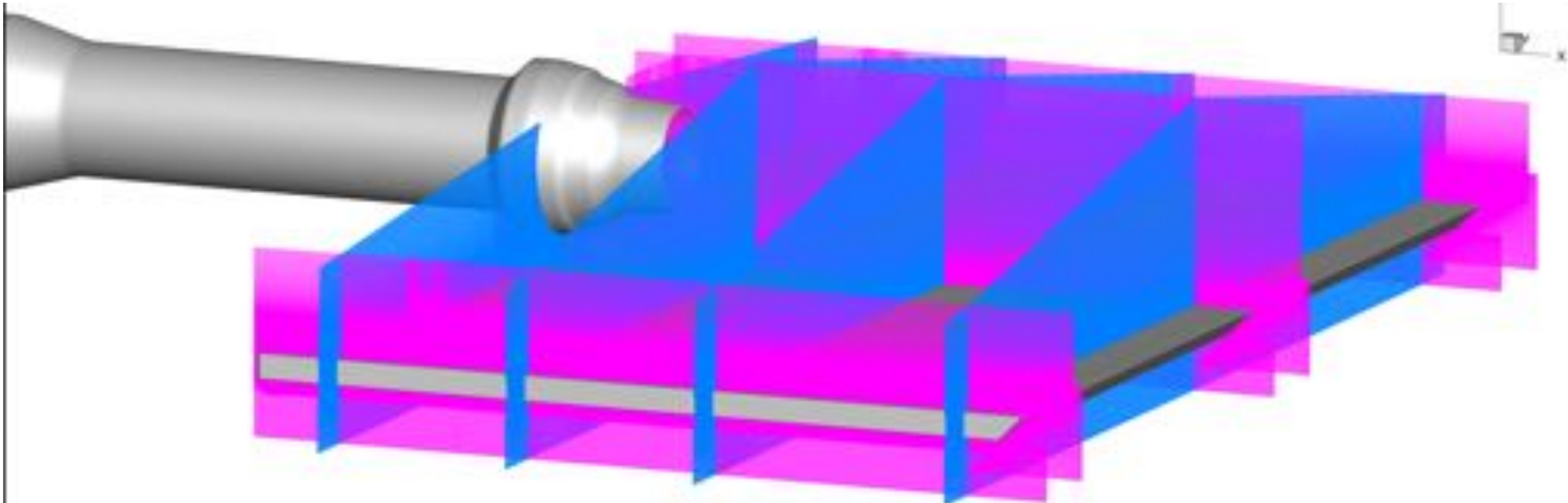
Comparison of PSD Spectrum 100D away from nozzle exit



- Excellent agreement with measurements, split captured accurately.
- Resolution in plate region not sufficient for high-frequencies.

Geometry and Setup

Computational Mesh Jet Shielding Plate



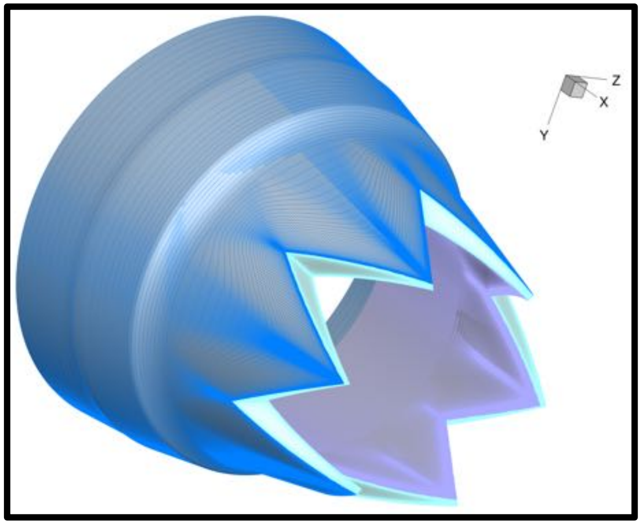
- Mesh surrounding jet shielding plate consists of 130M grid points (combined with medium isolated mesh 230M)

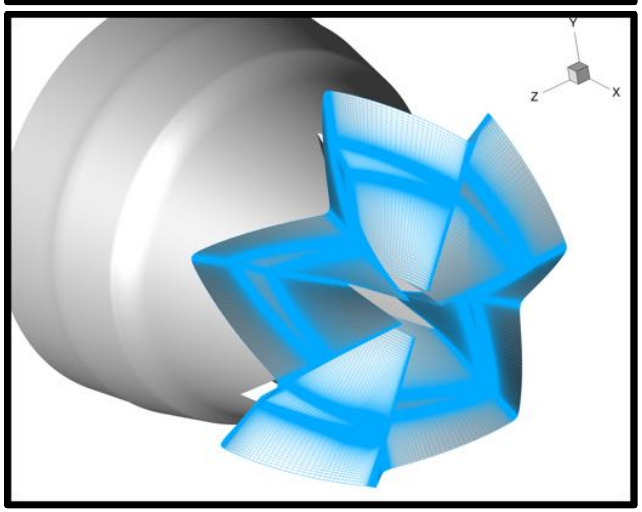
Future Work
Progress towards the ”Grand-Challenge”

Future Work
Progress towards the ”Grand-Challenge”

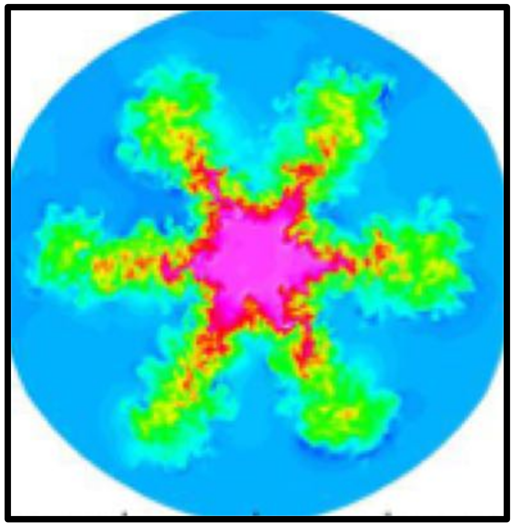
Round Jet with chevron nozzle SMC001

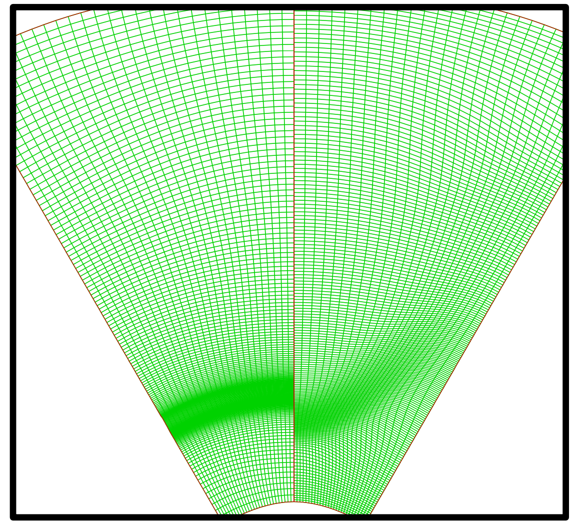
- Completed structured curvilinear mesh for complex chevron nozzle design.





Uzun et al. 2012





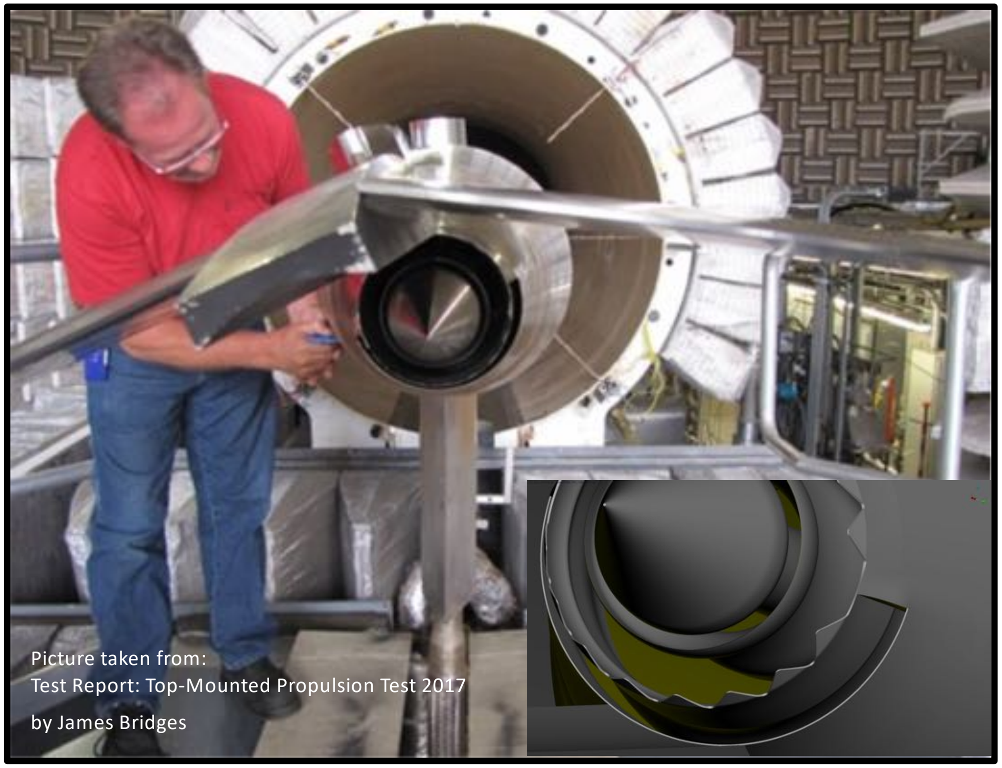
- Automated mesh refinement/ redistribution to track flow features of chevron nozzle (see Uzun et.al. 2012)

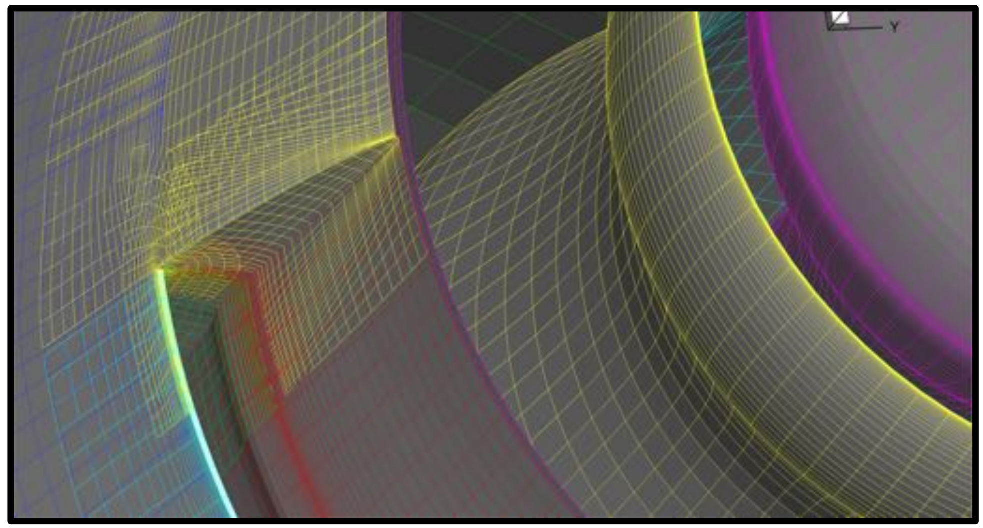
Future Work
Progress towards the ”Grand-Challenge”

Combination of isolated problems into one nozzle TMP17

(Multi-stream, Plug, Chevron, Shielding)

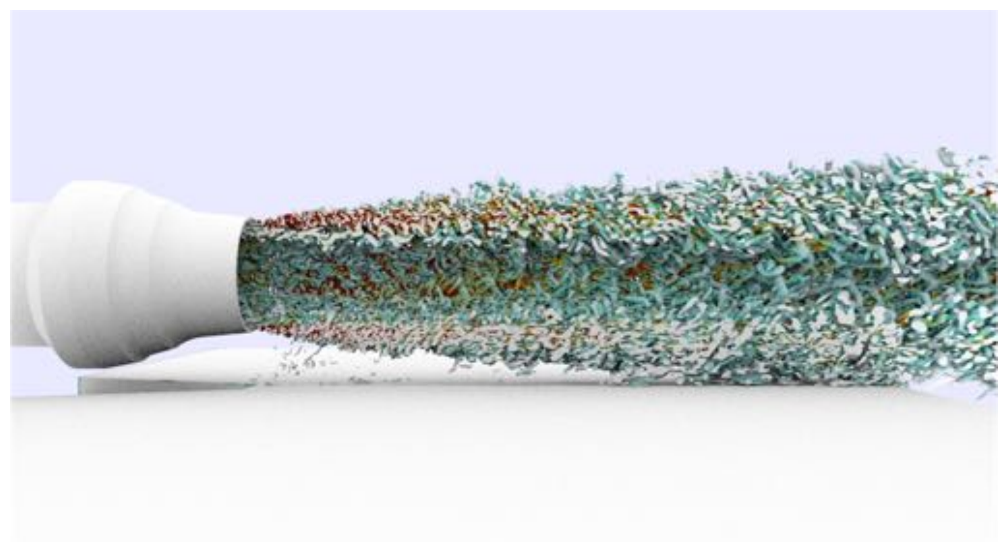
- Surface meshing for TMP17 almost completed





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.
- Completed far-field acoustic propagation
  - Mach wave radiation noise in the jet direction is well-captured
  - Strong influence on utilized SEM investigated, further improvements necessary (tripping, quitter inflow)
- 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?