Jet Noise Prediction of Chevron nozzle Flows with Wall-Modeled Large-Eddy Simulation

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*Science And Technology Corporation (STC)

NASA's Commercial Supersonic Technology (CST)



Research activities to reduce propulsion noise has been supported by NASA's Commercial Supersonic Transport (CST) Project

Jet noise is mainly produced by mixing of the turbulent high-speed jet exhaust with slower moving ambient air.

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

https://www.nasa.gov/sites/default/files/thumbnails/image/quesst_render_c.jpg

https://www.nasa.gov/sites/default/files/thumbnails/image/16-022-supersoniccontract.jpg

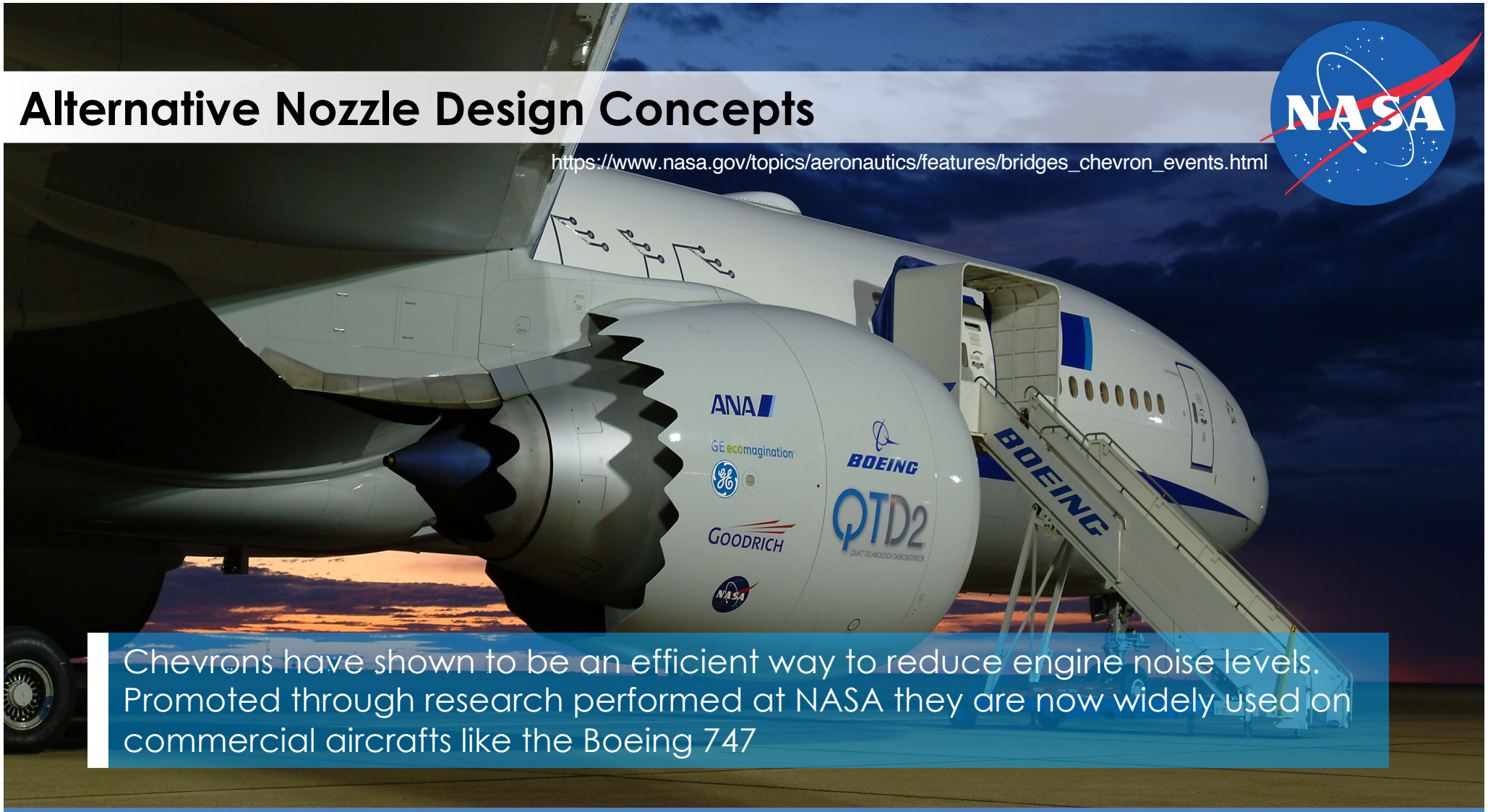
Integrated Propulsion Noise



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

Alternative Nozzle Design Concepts

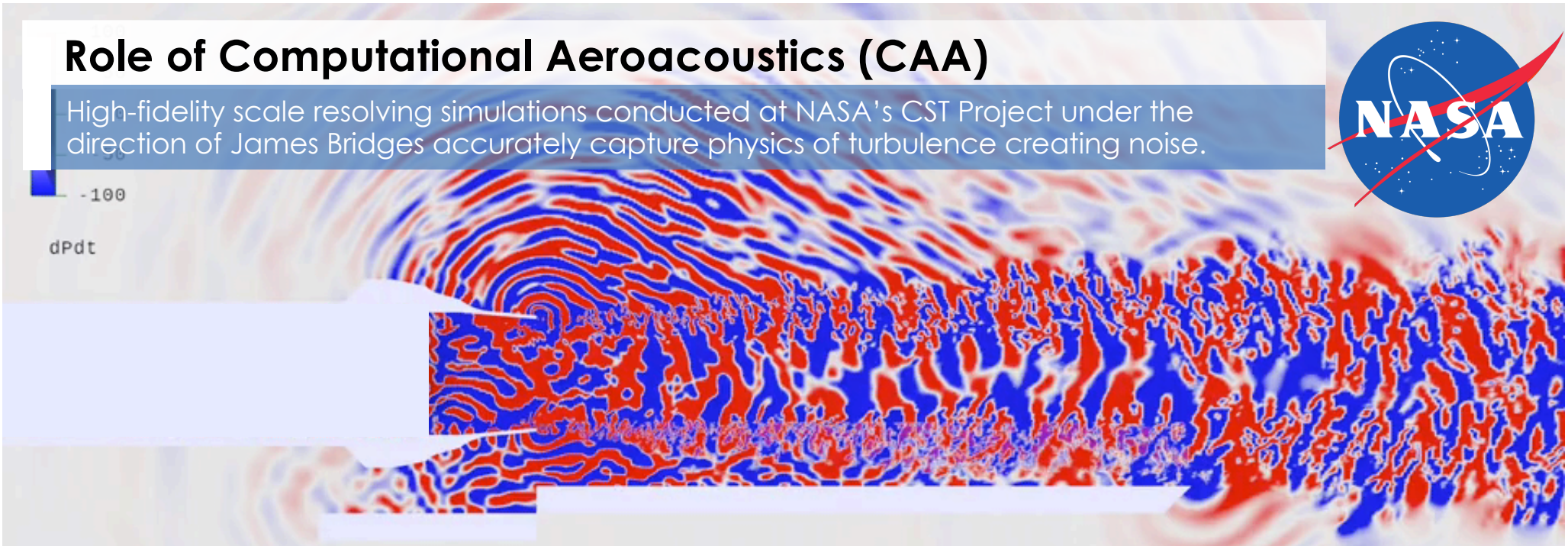
https://www.nasa.gov/topics/aeronautics/features/bridges_chevron_events.html



Chevrons have shown to be an efficient way to reduce engine noise levels. Promoted through research performed at NASA they are now widely used on commercial aircrafts like the Boeing 747

Role of Computational Aeroacoustics (CAA)

High-fidelity scale resolving simulations conducted at NASA's CST Project under the direction of James Bridges accurately capture physics of turbulence creating noise.

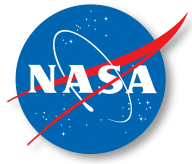


See AIAA2019-2475: Large-Eddy Simulation of Jet Surface Interaction Noise

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

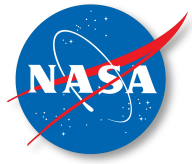
Flow Visualization by Timothy Sandstrom NASA Ames Research Center

Objective for LAVA WMLES within CST Project



- Predict jet noise **accurately** and in **short enough turnaround time** to include analysis in future propulsion integration design
- **Understand** and document **uncertainties and shortcomings** of scale-resolving wall-modeled LES for jet noise simulations
- **Future Impact:** complement wind tunnel and flight tests, reduction of associated costs, provides insight into noise reduction technology never-before available.

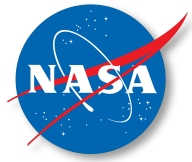
Outline



- Computational Methodology
- Experimental Setup
- Structured curvilinear overset grid systems
- Results – comparison with experiment*
- Computational Costs
- Summary and Future Work

*Experiments used for comparison: Bridges et. al.(NASA-TM-2011-216807)

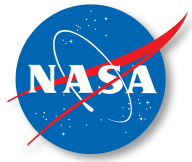
Jet Noise Simulation – Challenges of Physical and Numerical Modeling



- Nozzle and operating conditions (nozzle pressure ratio NPR, Mach number, …)
- Nozzle exit boundary layer state (turbulent, laminar)
- Entrainment and co-flow
- Installation effects

- Spatial and temporal resolution
- Correct sub-filter scale modeling
- Boundary condition treatment (resolved, modeled)
- Far-field acoustic predictions
- Managing data storage and i/o efficiently

A Brief Overview of Chevron Nozzle Simulations



- Qualitative predictions based on (u)RANS
  (Englebloom et al. 2004, Birch et al. 2006, Karubatski et al. 2009, *Birch et al. 2009)*
- First LES with chevrons emulated instead of modeled (Shur et al. 2006)
- Explicit wall resolved LES of chevron at reduced Reynolds (Uzun et al. 2007)
- 2009-present: various hybrid RANS/LES simulations with $y^+ < 1$
  (Xia et al 2009, Engel et al. 2014, Wang et al. 2017, Stich et al. 2019)
- LES at flight Reynolds number, slip + synthetic turbulence
  (Bres et al. 2012, Pauz et al. 2017)
- Wall-modeled LES at full Reynolds number of round jet $y^+ > 1$
  (Bres et al. 2018, Stich et al. 2021)

Wall-Modeled Large-Eddy Simulation (WMLES)

Basic philosophy:

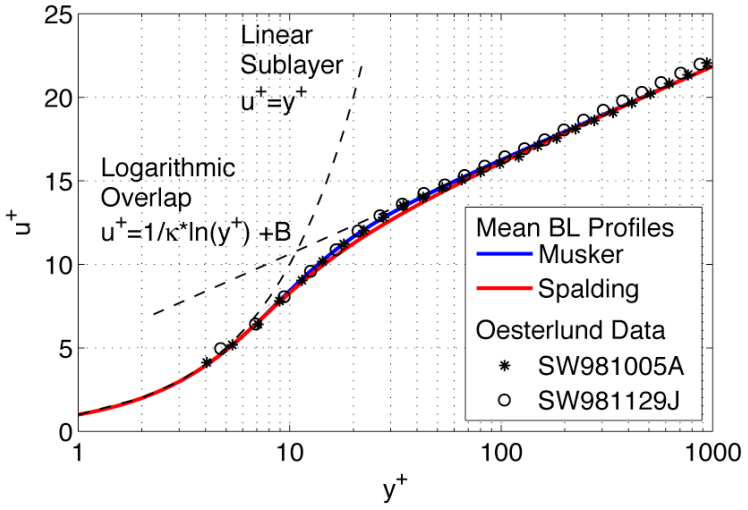
Would like to use LES everywhere but cannot resolve integral length scales for the inner-layer of a turbulent boundary layer at high Reynolds number; replace stiff-Dirichlet BCs with a wall-stress BC instead and compute the wall-stress using a wall function.

Analytical wall law:

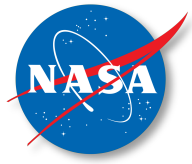
- Utilize wall functions (e.g. Musker's Law) and compute wall shear-stress based on velocity from LES
- Computationally simple and inexpensive

$$u^+ = f(y^+)$$

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



Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework



- Utilized Curvilinear Structured Overset Solver within LAVA
- Equilibrium wall-model using Musker's wall-function
- Vreman subgrid scale model
- Convective flux discretization uses:
  - Primitive variable interpolation to the half points using blending between 4^{th} order centered and 3^{rd} order upwind with shock sensor
  - HLL Riemann solver
- Boundary layer tripping with use of immersed boundary method (cylinders)
- Time discretization using TVD-RK3 (Gottlieb et. al. 1998) at CFL 1.25

More details provided in AIAA-2020-2735, AIAA-2021-1185

Experimental Setup
NASA Aero-Acoustics Propulsion Lab (AAPL)





- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) and six chevron nozzle (SMC001)

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

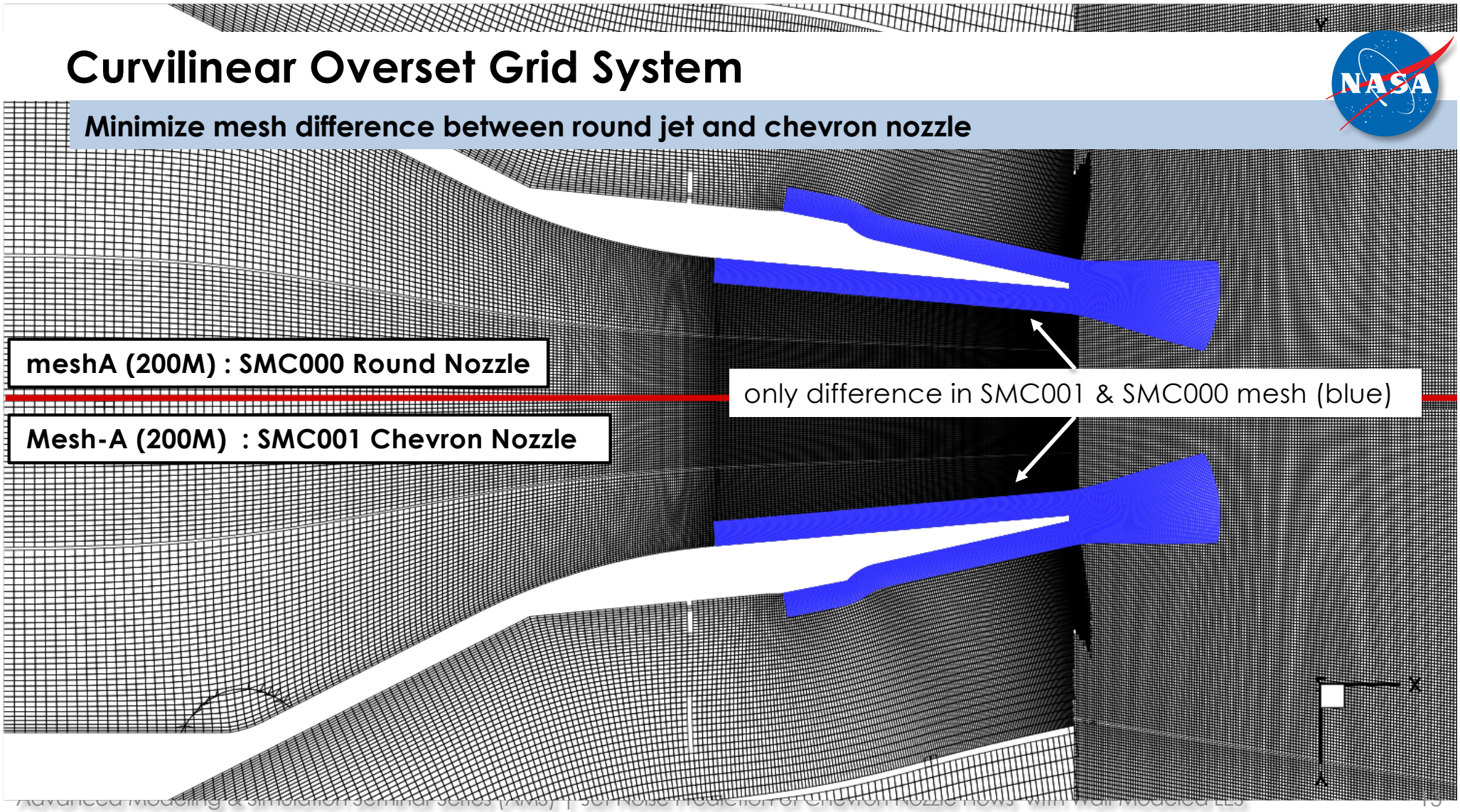
nozzle geometries



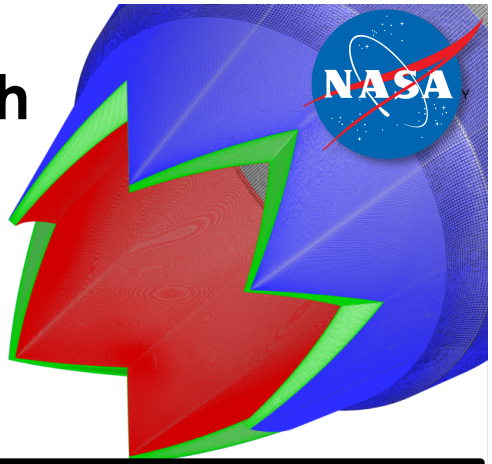
- 65" radius anechoic dome
- Located at Glenn Research Center (GRC)
- Small Hot Jet Acoustic Rig (SHJAR)
- Far-field acoustics, phased arrays, flow rakes, hotwire, schlieren, PIV, IR, Rayleigh, Raman, PSP

Curvilinear Overset Grid System

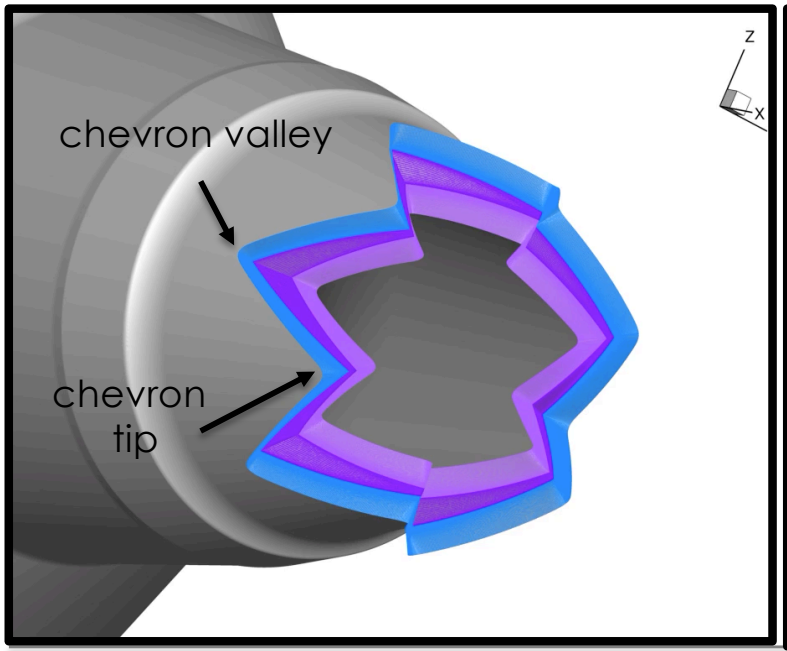
Minimize mesh difference between round jet and chevron nozzle

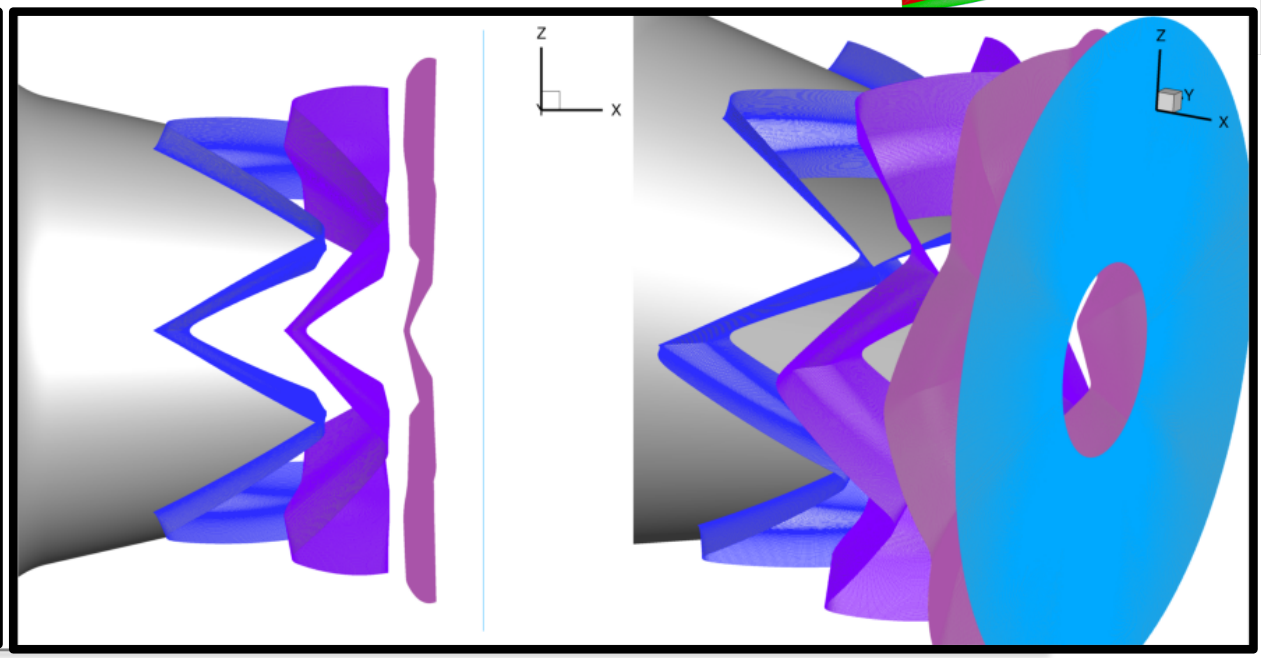


Curvilinear Overset Grid System – Near-Wall Mesh



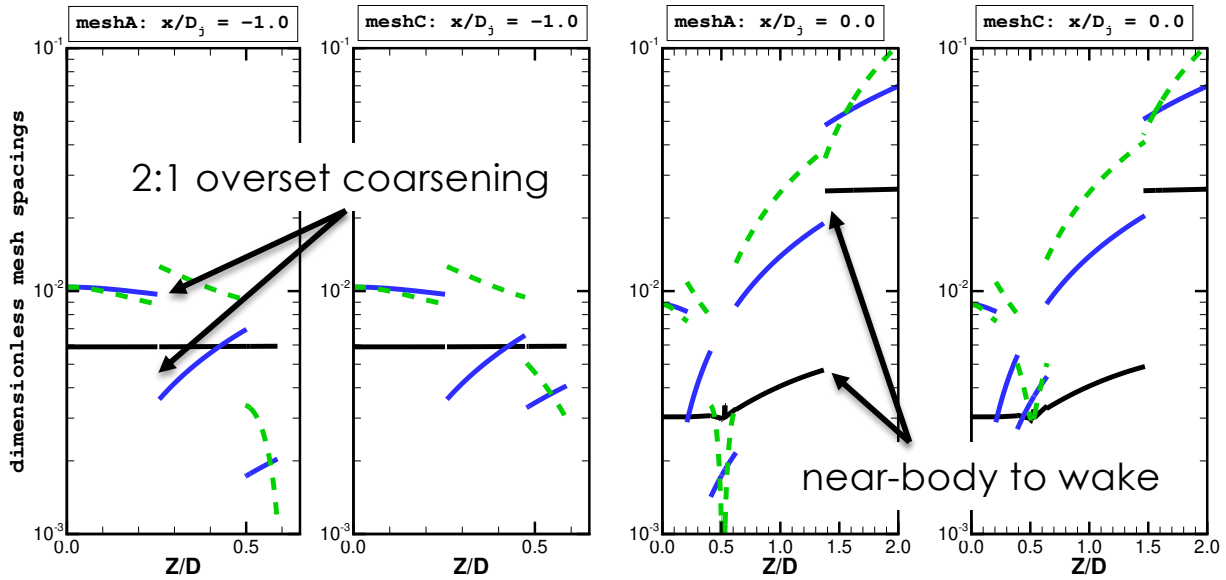
- Minimize difference in mesh between SMC000 & SMC001
- Only difference in near-wall region -0.5D < x < 0.5D



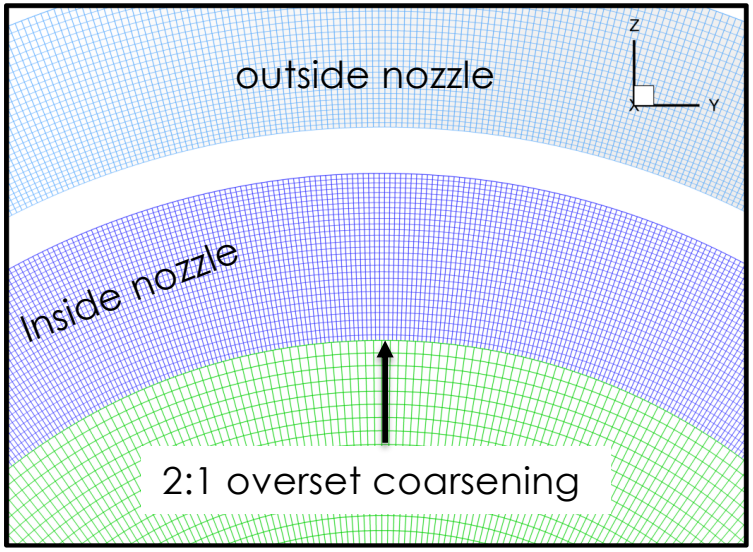


Curvilinear Overset Grid System – Mesh Resolution Study

- Coarsening of near-wall baseline mesh-A (200M) to mesh-C (110M)
- Number of points in azimuth: mesh-A/B (1918), mesh-C (918)
- Medium mesh-C (110M) used for round jet SMC000 only



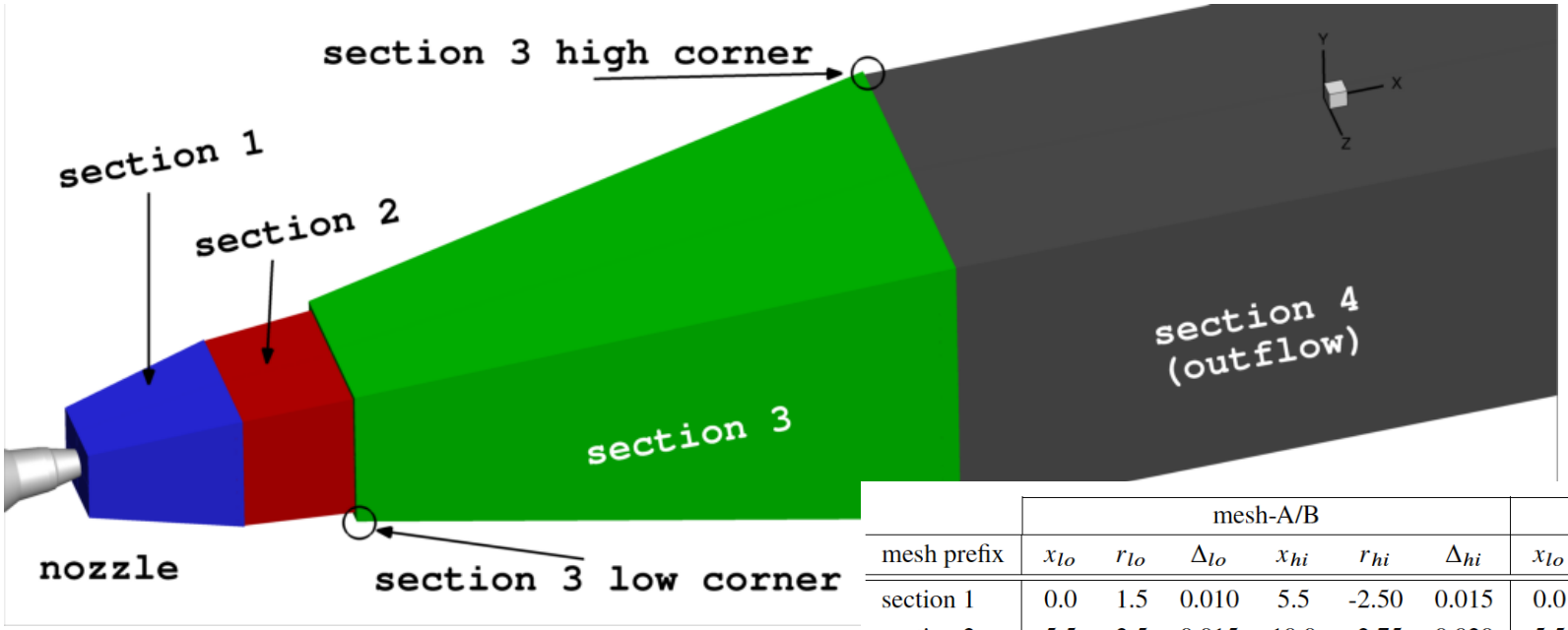
cut through nozzle mesh at x/D = 0.0



(black) streamwise, (blue) azimuthal, (green) wall-normal

Curvilinear Overset Grid System – Isotropic Jet Mesh

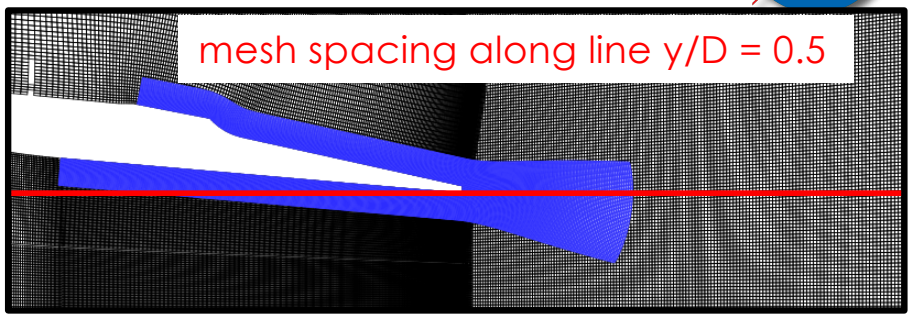
- Keep mesh cells in main jet region as isotropic as possible to minimize grid effects
- Minimal stretching in all three coordinate directions (less than 1%)



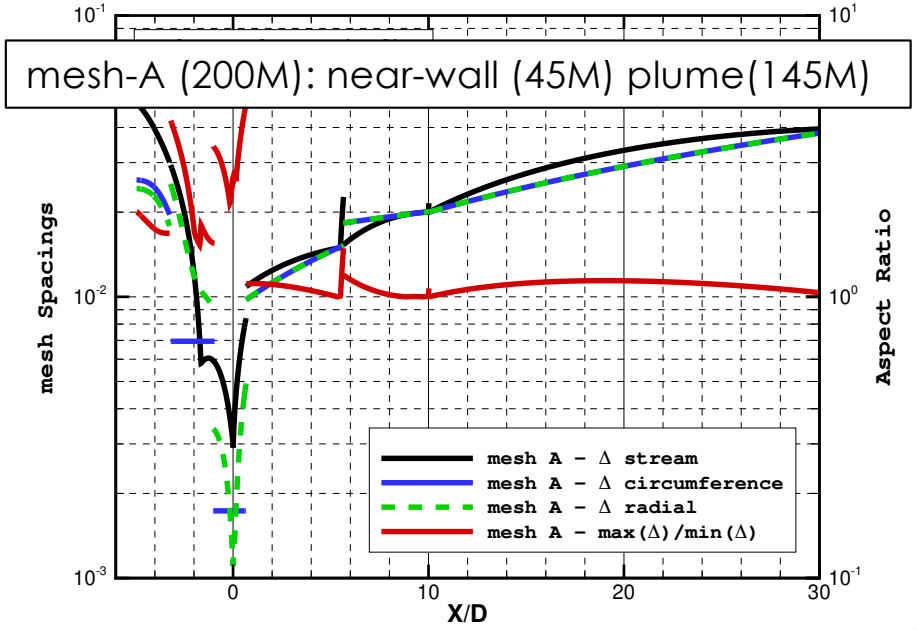
	mesh-A/B						mesh-C					
mesh prefix	x_{lo}	r_{lo}	Δ_{lo}	x_{hi}	r_{hi}	Δ_{hi}	x_{lo}	r_{lo}	Δ_{lo}	x_{hi}	r_{hi}	Δ_{hi}
section 1	0.0	1.5	0.010	5.5	-2.50	0.015	0.0	1.5	0.010	5.5	-2.50	0.020
section 2	5.5	2.5	0.015	10.0	-2.75	0.020	5.5	2.5	0.020	10.0	-2.75	0.030
section 3	10.0	3.0	0.020	32.0	-6.00	0.040	10.0	3.0	0.030	32.0	-6.00	0.050
section 4	32.0	6.0	0.080	60.0	-6.00	1.500	32.0	6.0	0.080	60.0	-6.00	1.500

Curvilinear Overset Grid System – Lip-line Resolution

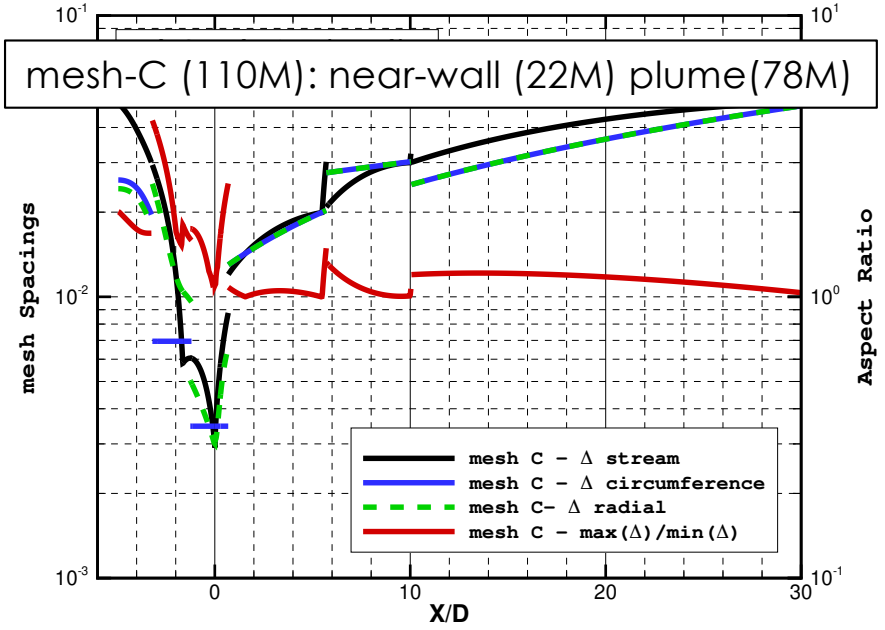
- Almost isotropic (AR=1) cells in potential core mesh to reduce grid anisotropy effects
- Spacings along nozzle lip-line y/D = 0.5



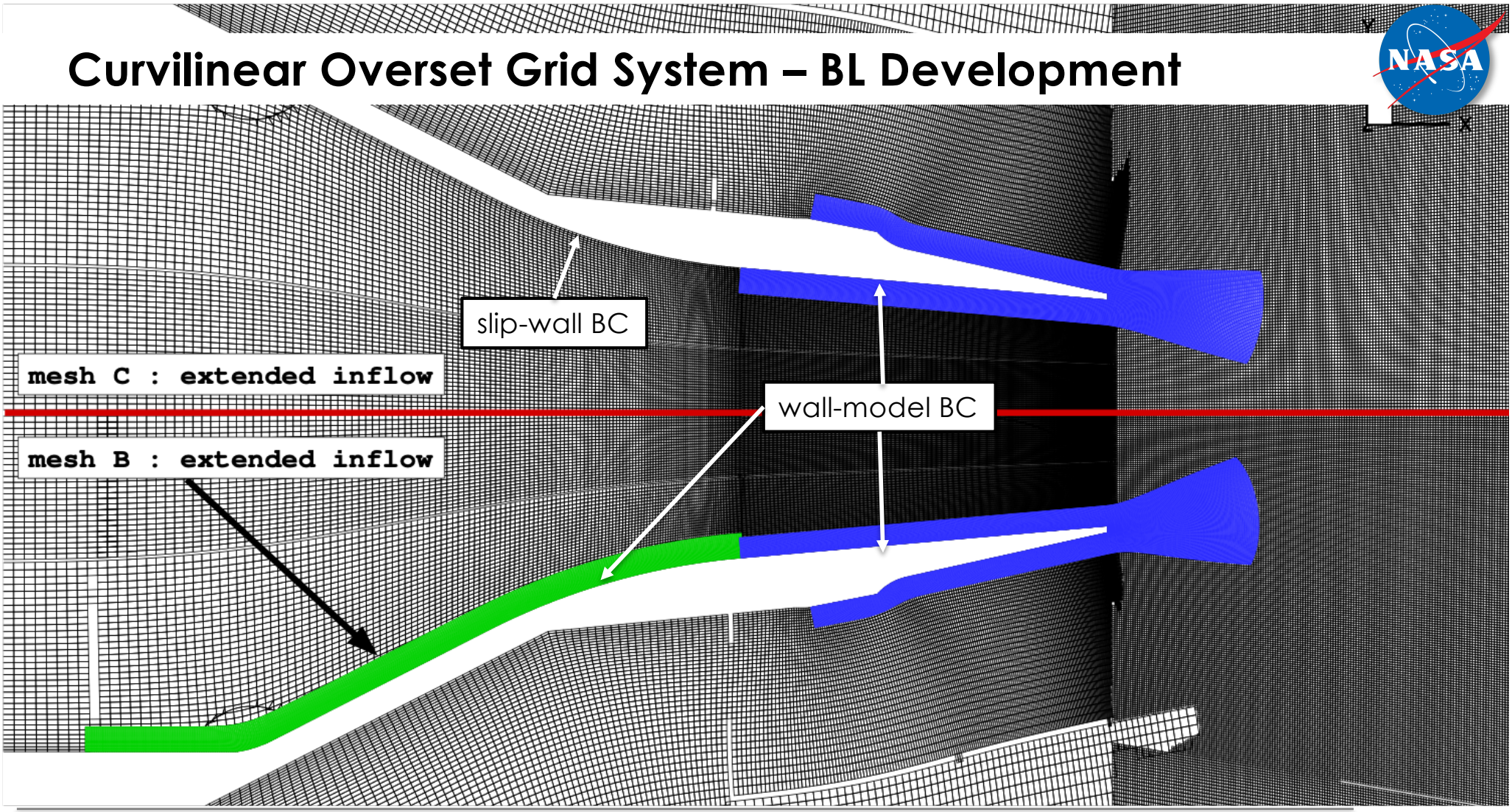
mesh-A (200M): near-wall (45M) plume(145M)



mesh-C (110M): near-wall (22M) plume(78M)

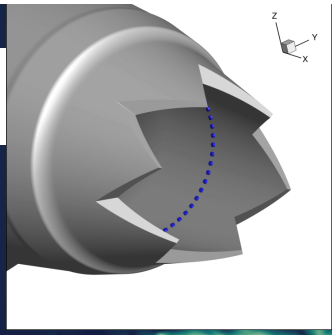


Curvilinear Overset Grid System – BL Development



Forced transition towards turbulent BL inside of nozzle

- Tripping dots represented using a penalty (immersed boundary) method

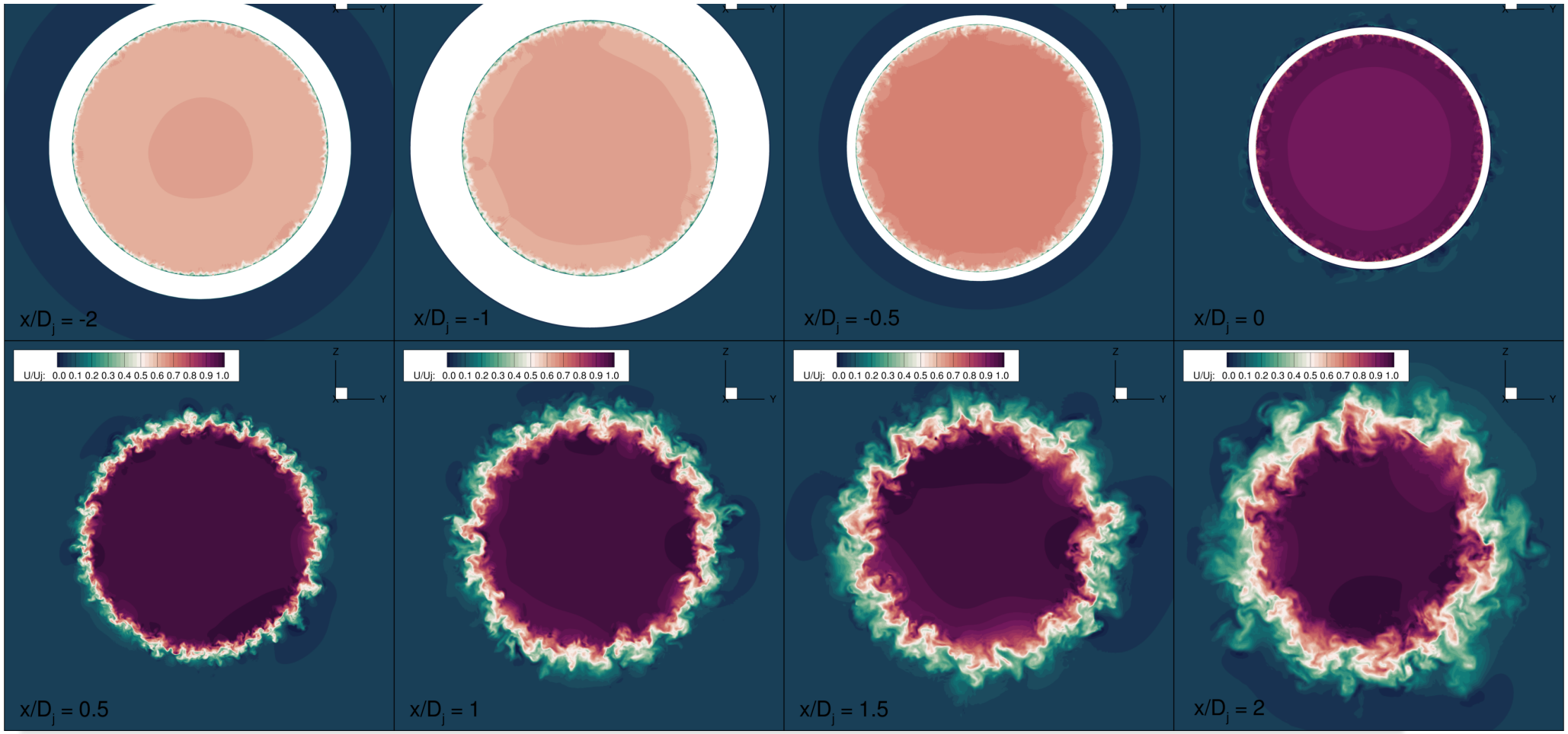


mesh-A (short trip)

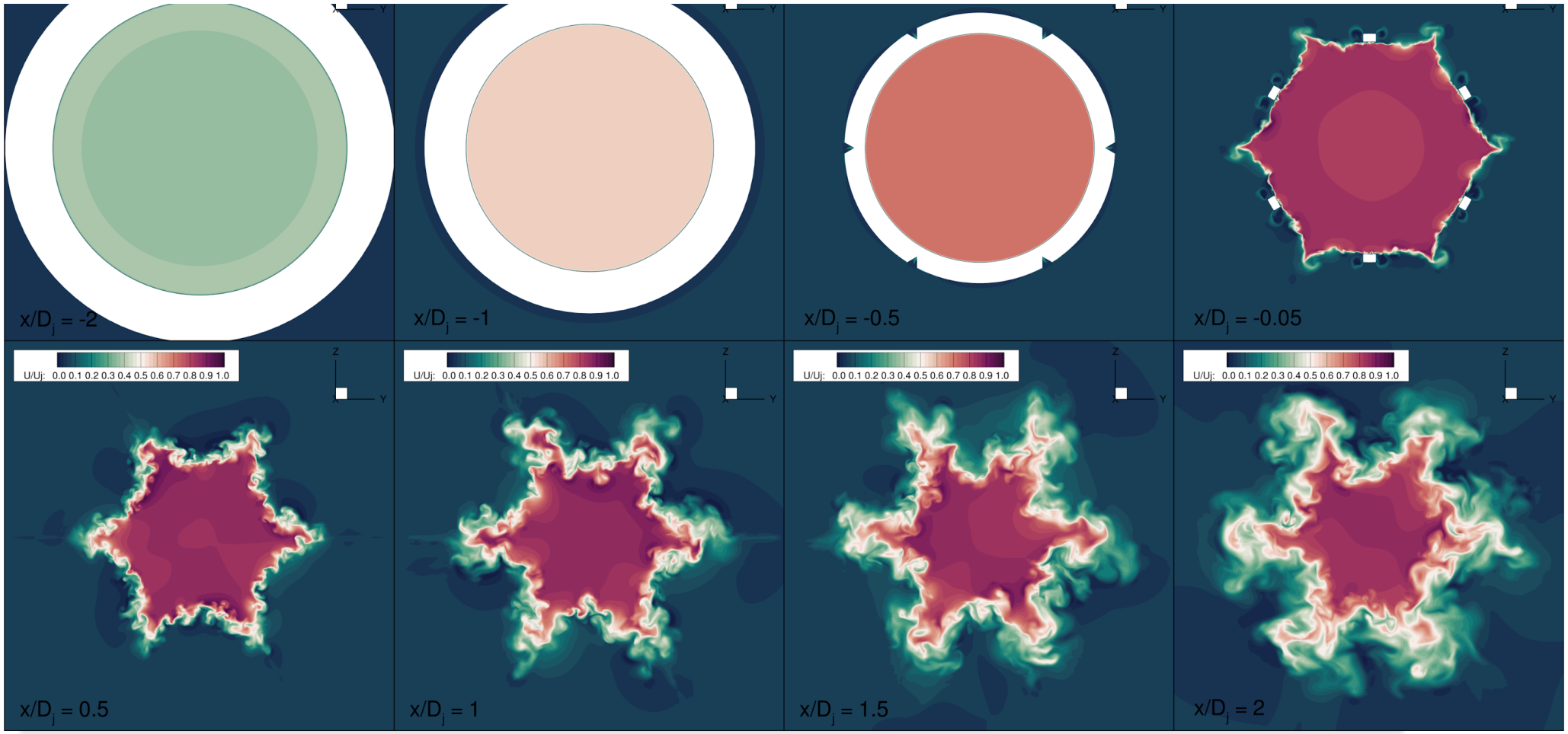
mesh-B (long trip)

velocityx: 0 75 150 225 300

Flow field and Features – Round Jet Nozzle SMC000

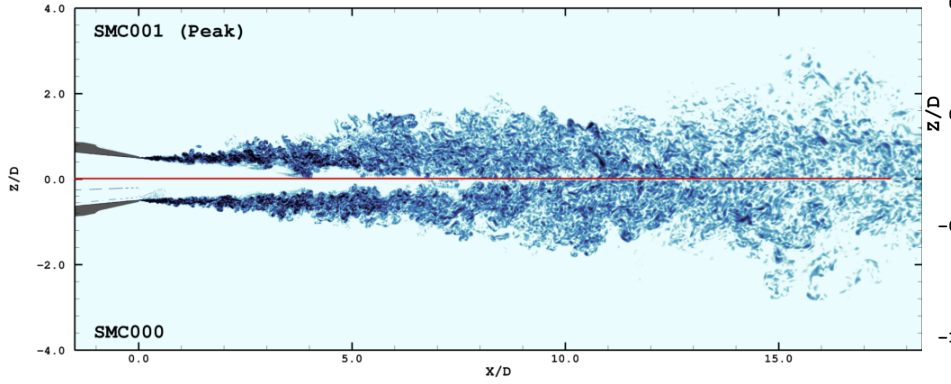


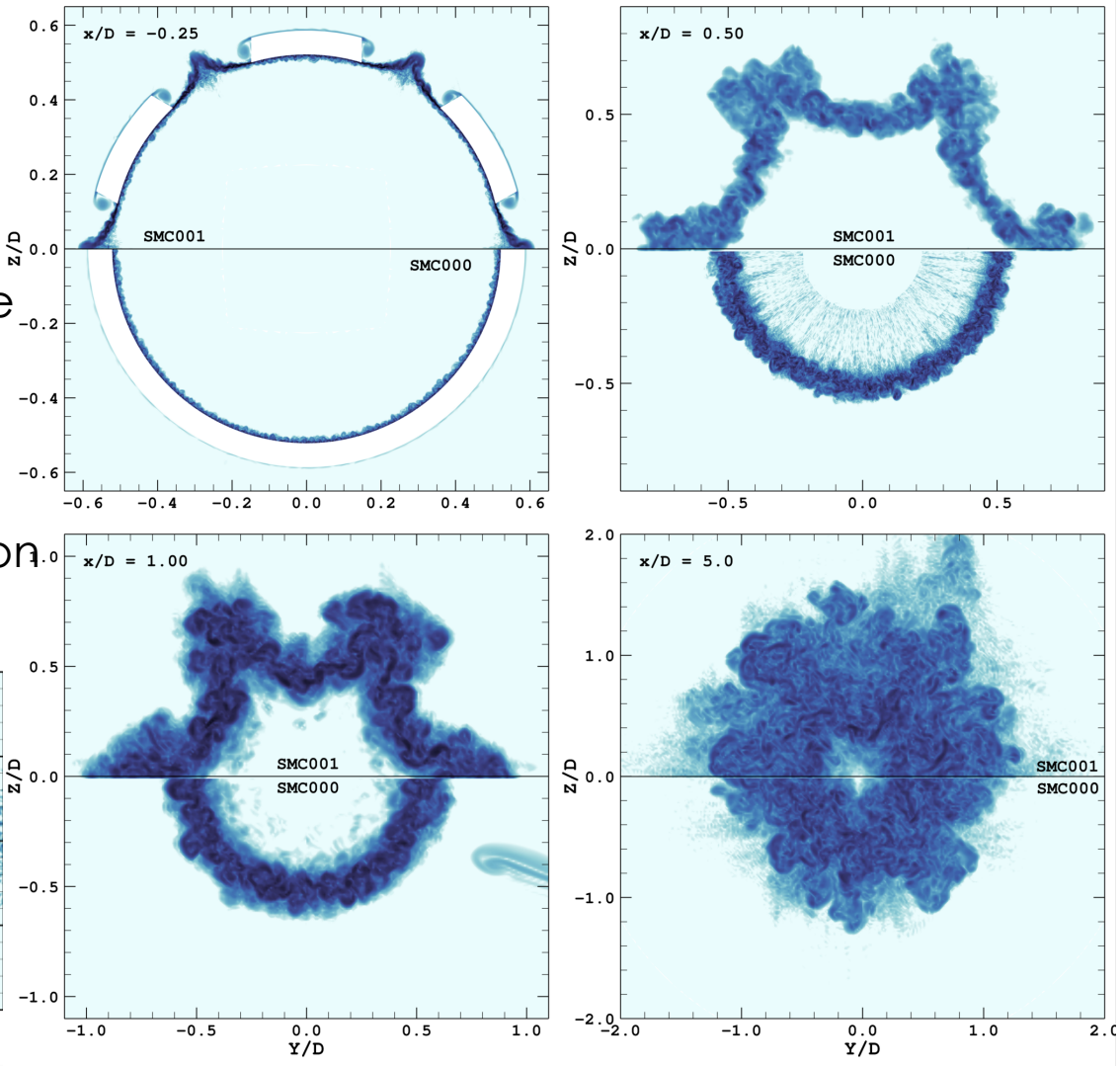
Flow field and Features – Chevron Nozzle SMC001



Flow Field Comparison SMC000 vs SMC001

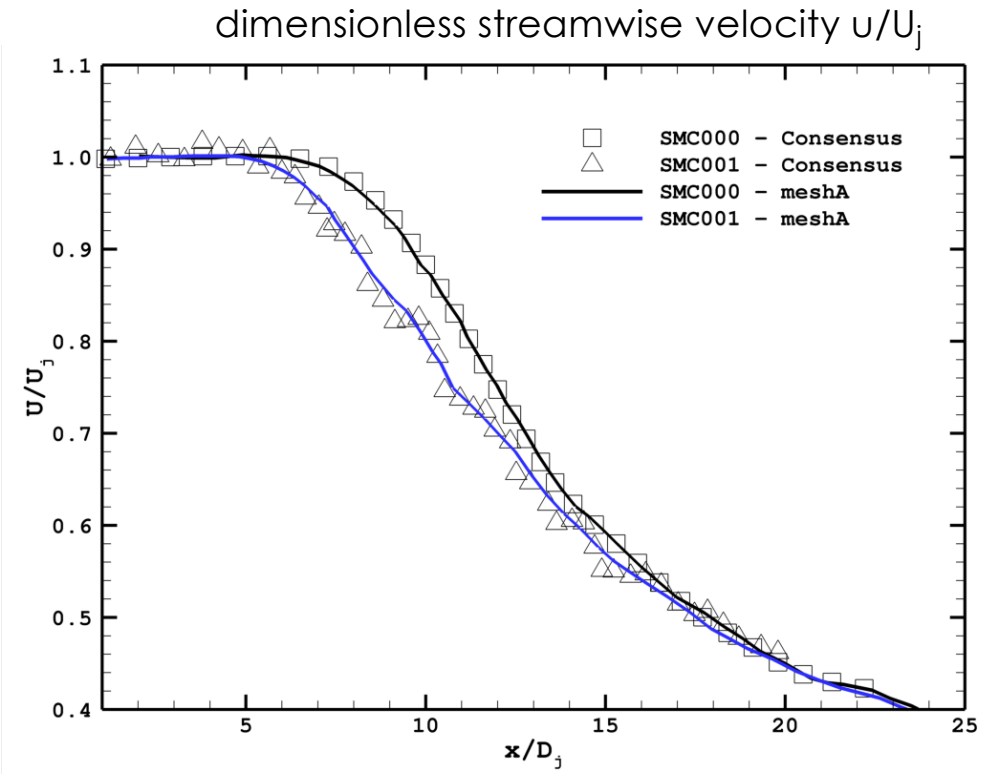
- Vorticity magnitude for chevron nozzle (top) round-jet (bottom)
- Stronger jet spreading in chevron compared to round jet
- Vorticity roll-up at nozzle exit at chevron

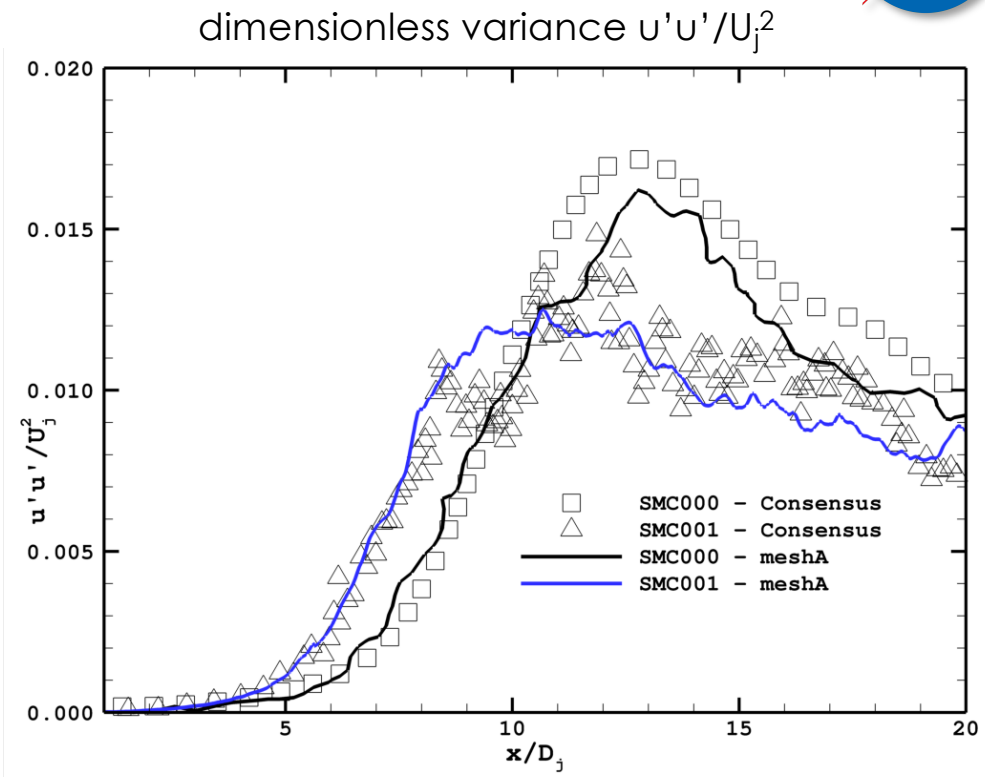




Near-Field Comparison: Centerline

SMC000: Round
SMC001: Chevron

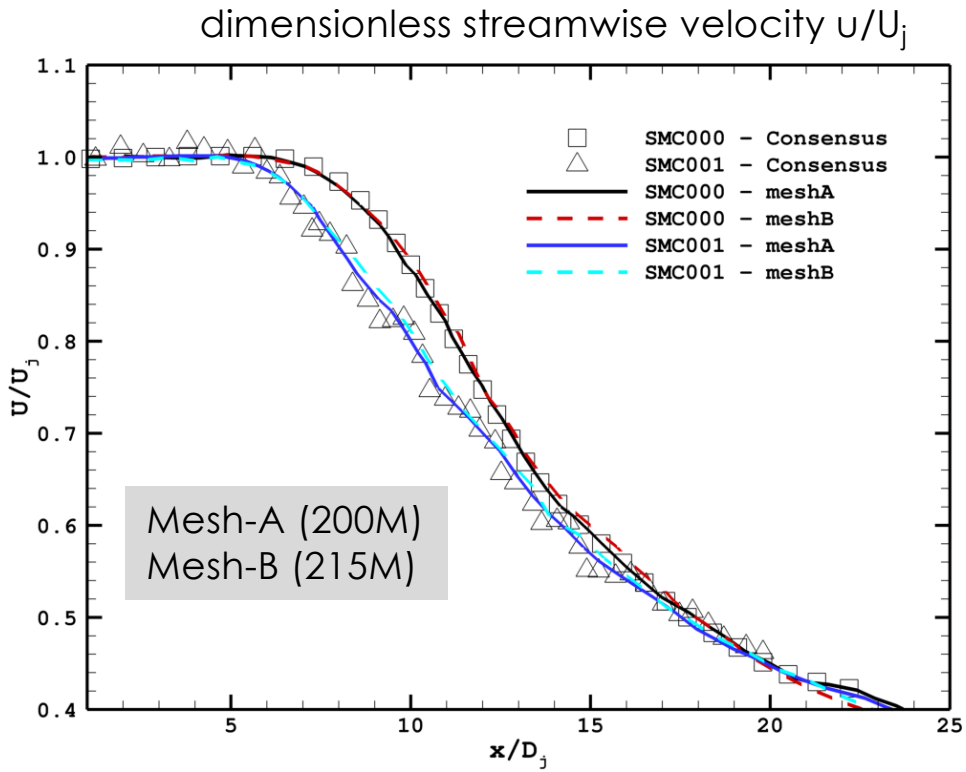


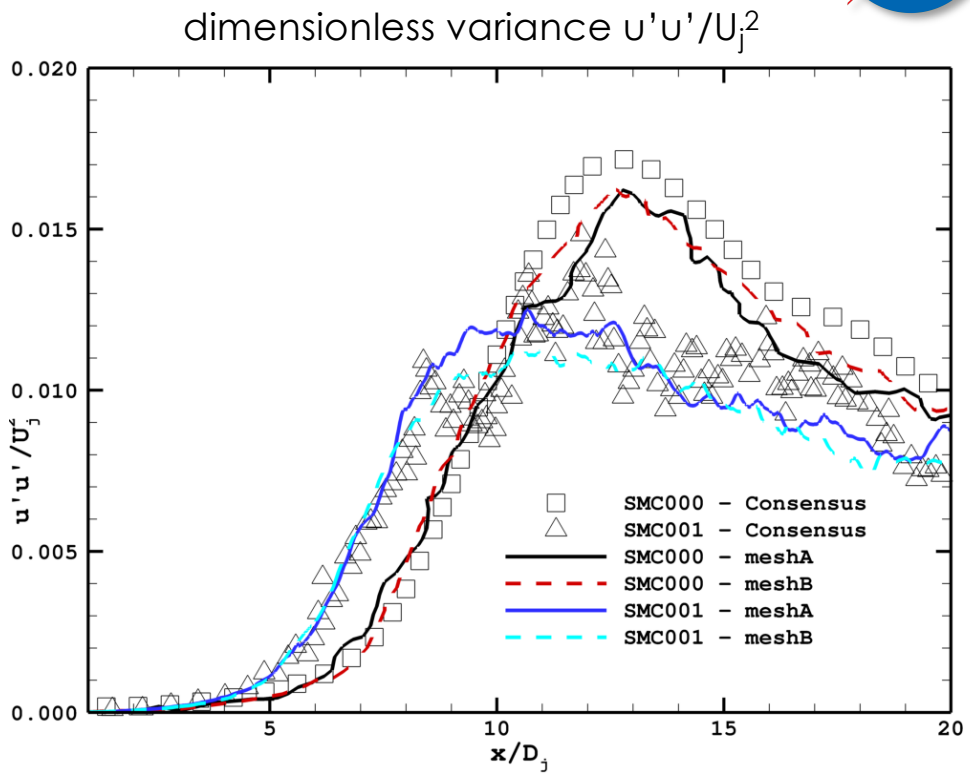


- Length of potential core predicted accurately ($U/U_j = 0.98$)
- Location and magnitude of normal stress agrees well with experiment

Near-Field Comparison: Centerline

SMC000: Round
SMC001: Chevron



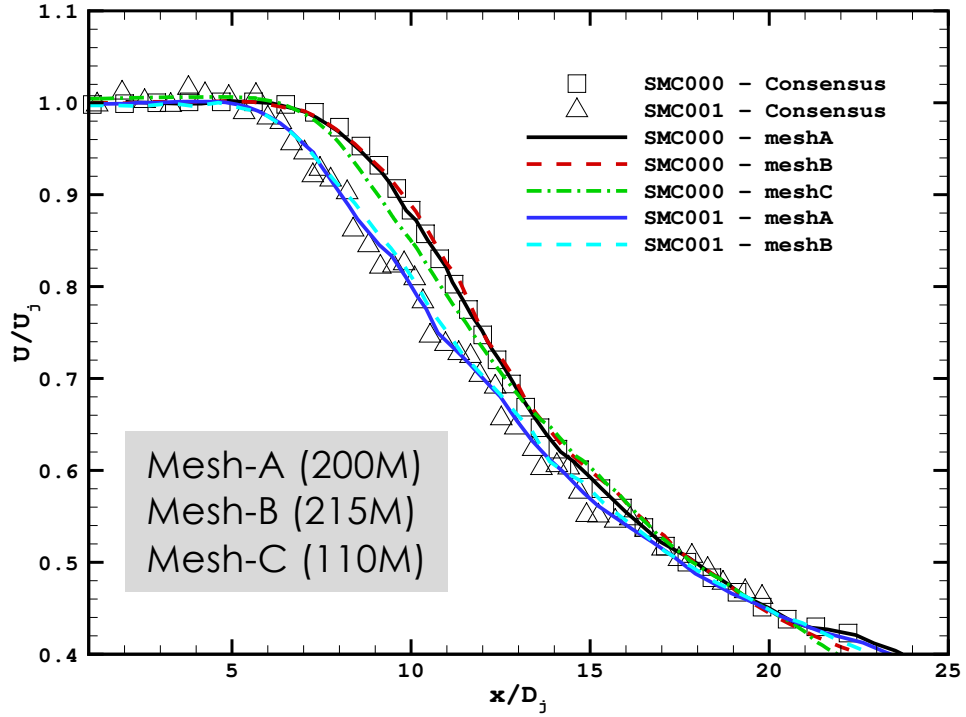


- Length of potential core predicted accurately
- Location and magnitude of normal stress agrees well with experiment
- Both different virtual origins of BL show comparable result

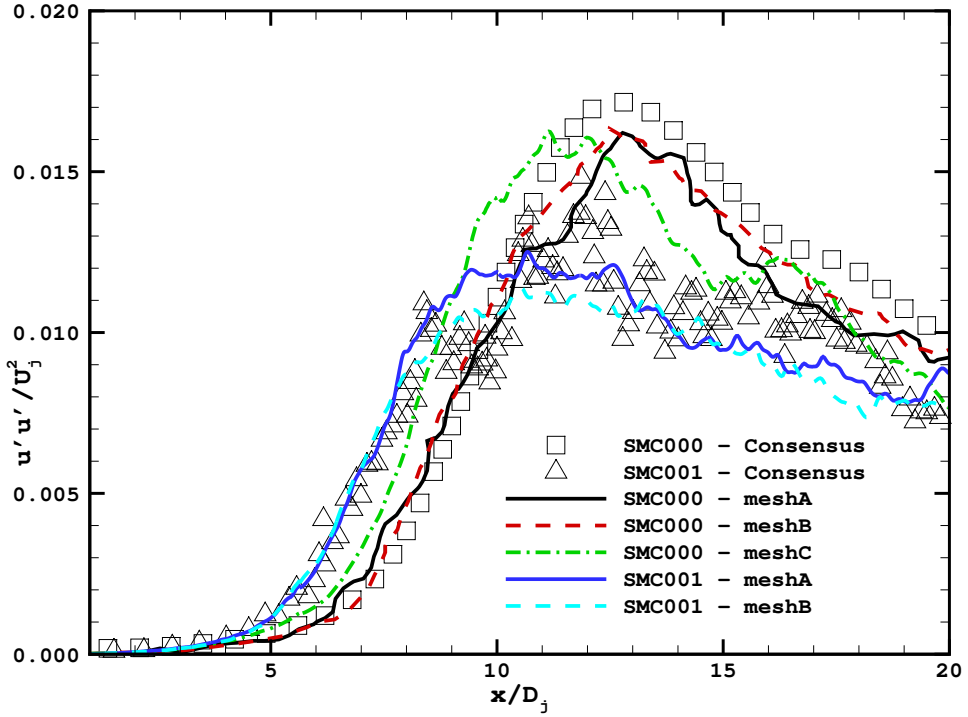
Near-Field Comparison: Centerline

SMC000: Round
SMC001: Chevron

dimensionless streamwise velocity u/U_j



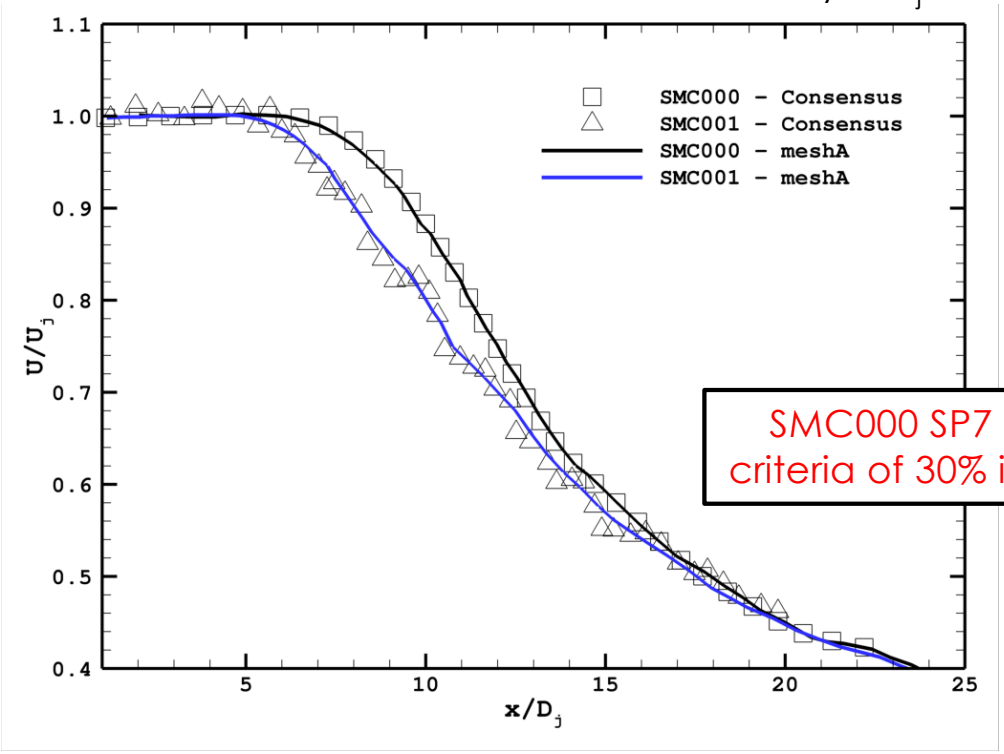
dimensionless variance $u'u'/U_j^2$



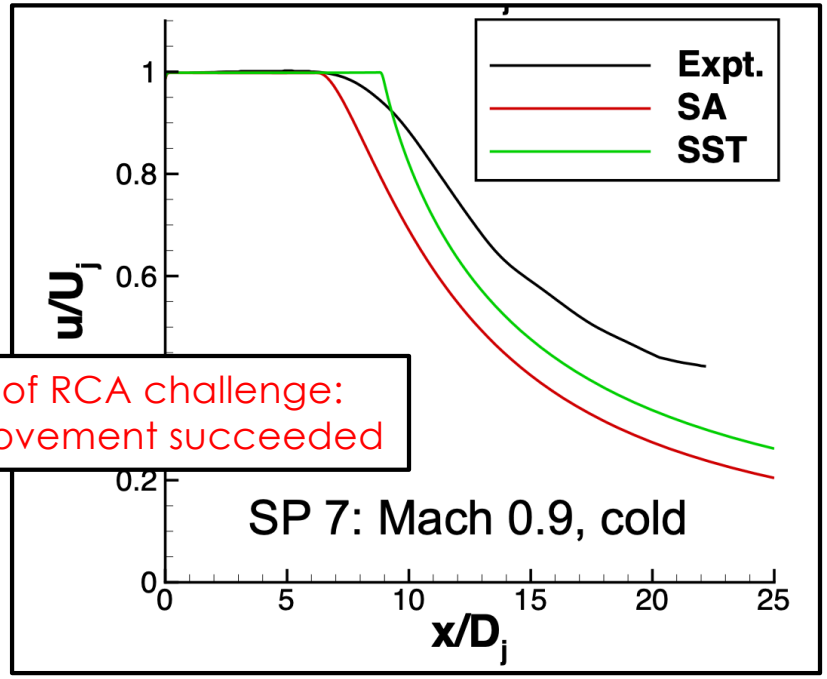
- Length of potential core predicted accurately
- Location and magnitude of normal stress agrees well with experiment
- Medium mesh-C slightly under-predicts potential core length and premature rise in u'u'

Near-Field Comparison: Centerline

dimensionless streamwise velocity u/U_j



NASA RCA (Vision2030)
Improvements in Jet Predictions



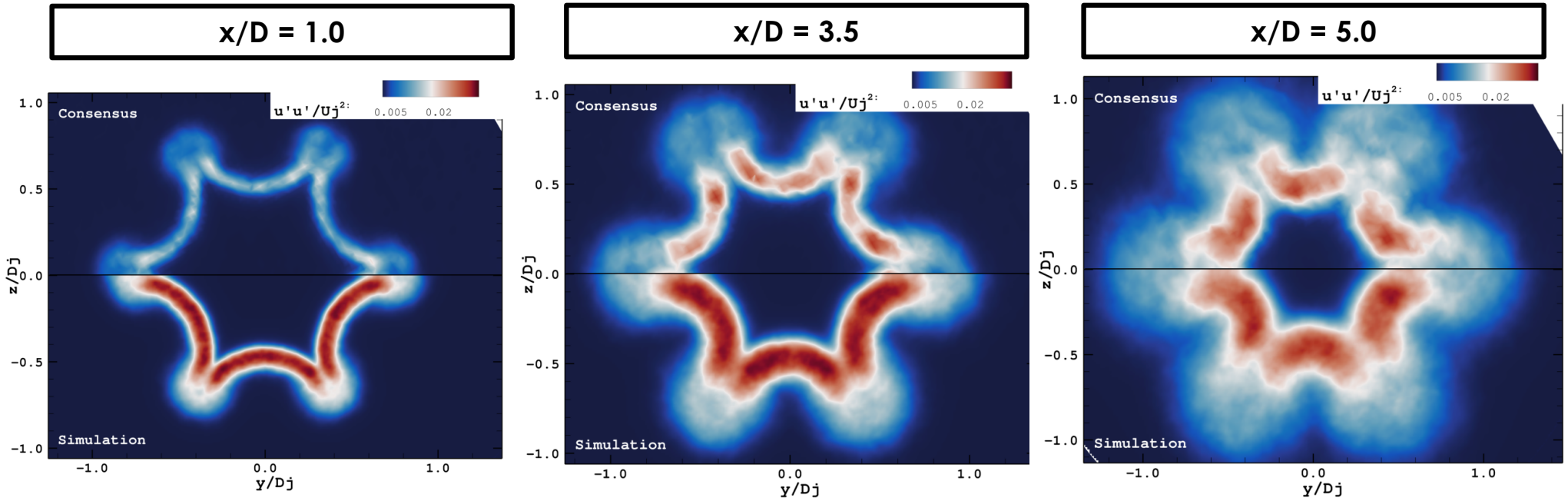
https://turbmodels.larc.nasa.gov/StandardTestCasesFinal6.pdf

SMC000 SP7 part of RCA challenge:
criteria of 30% improvement succeeded

- Length of potential core predicted accurately ($U/U_j = 0.98$)
- Location and magnitude of normal stress agrees well with experiment

Qualitative Comparison of Variance with experimental PIV

Chevron nozzle SMC001

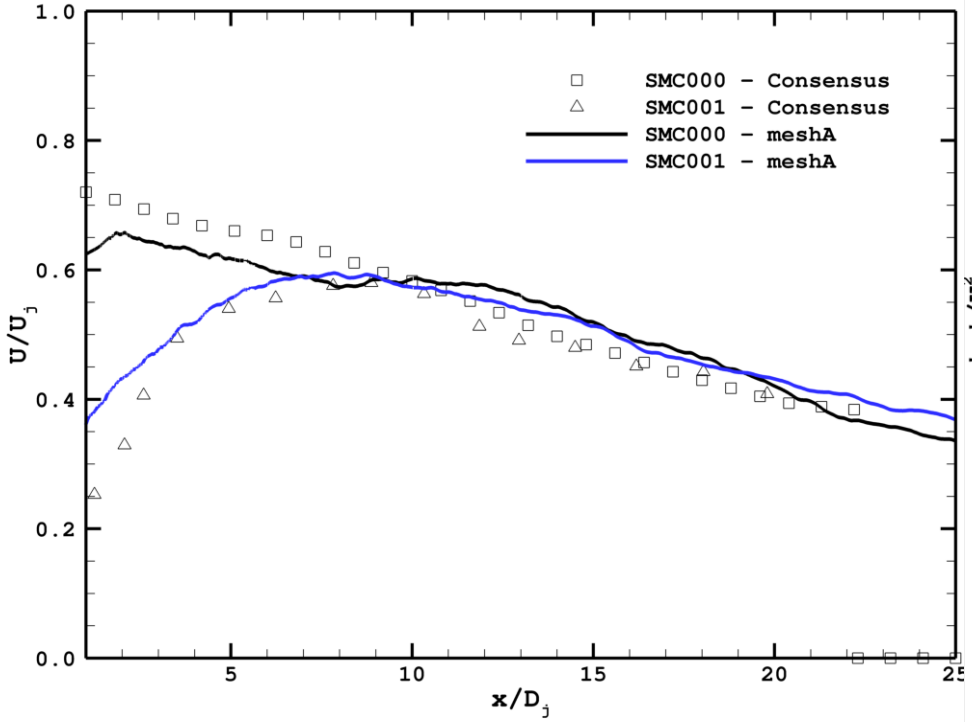


- Capture shape and spreading of nozzle shear layer accurately
- Overprediction of variance along nozzle shear layer up to x < 4D

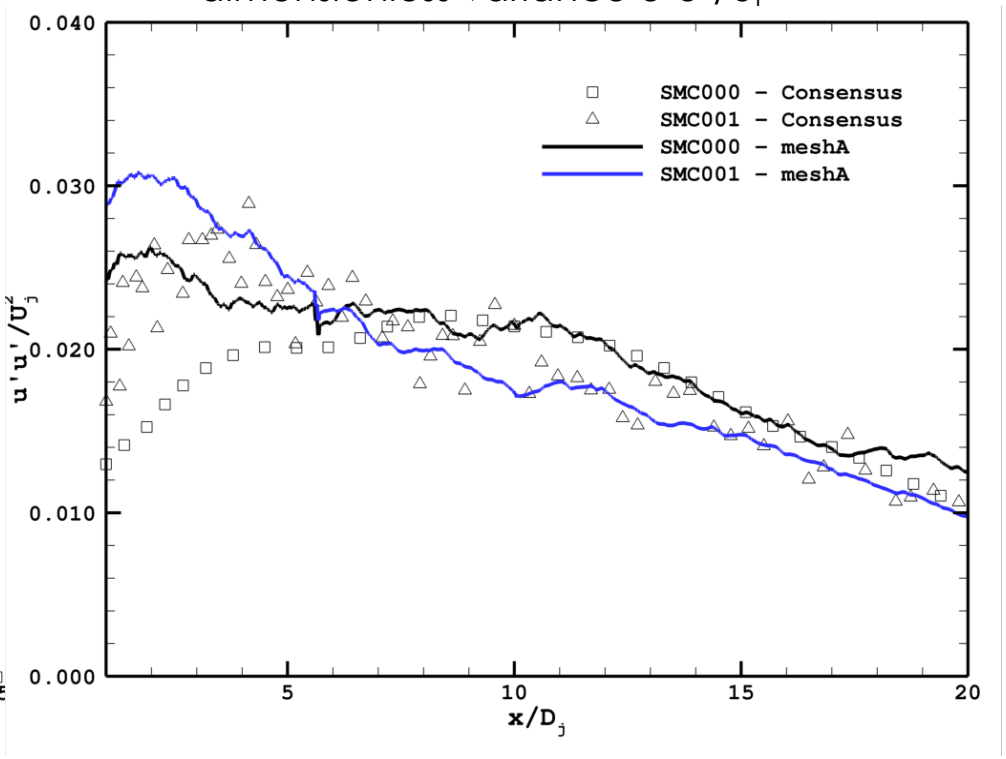
SMC000: Round
SMC001: Chevron

Near-Field Comparison: Lipline

dimensionless streamwise velocity u/U_j



dimensionless variance $u'u'/U_i^2$

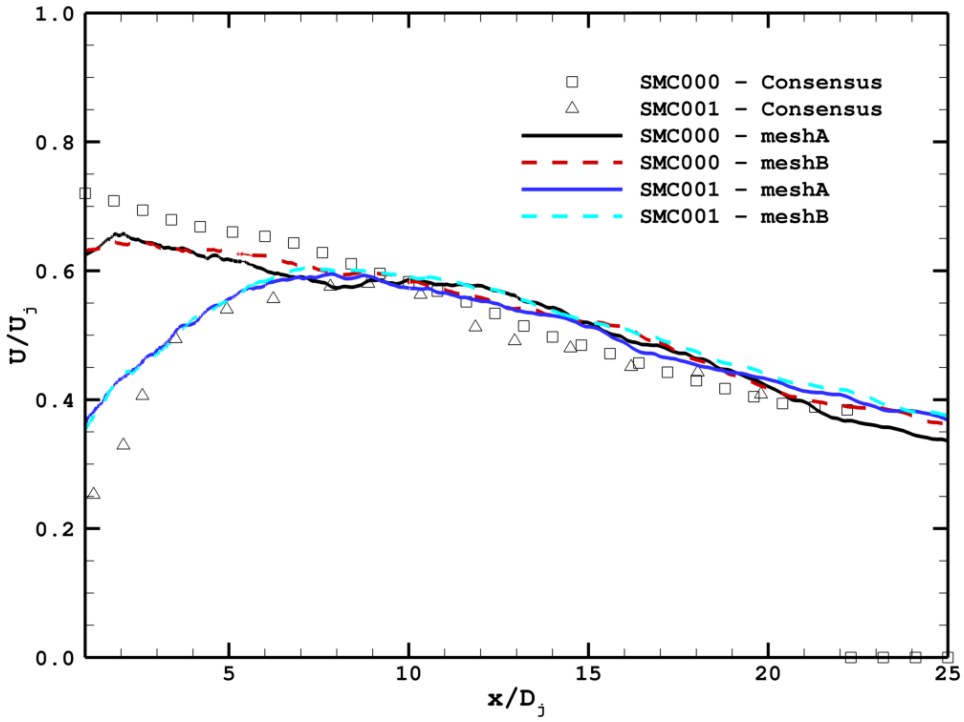


- Overprediction of normal stress at nozzle exit up to 4D
- Overall good agreement with experiment for all grid levels

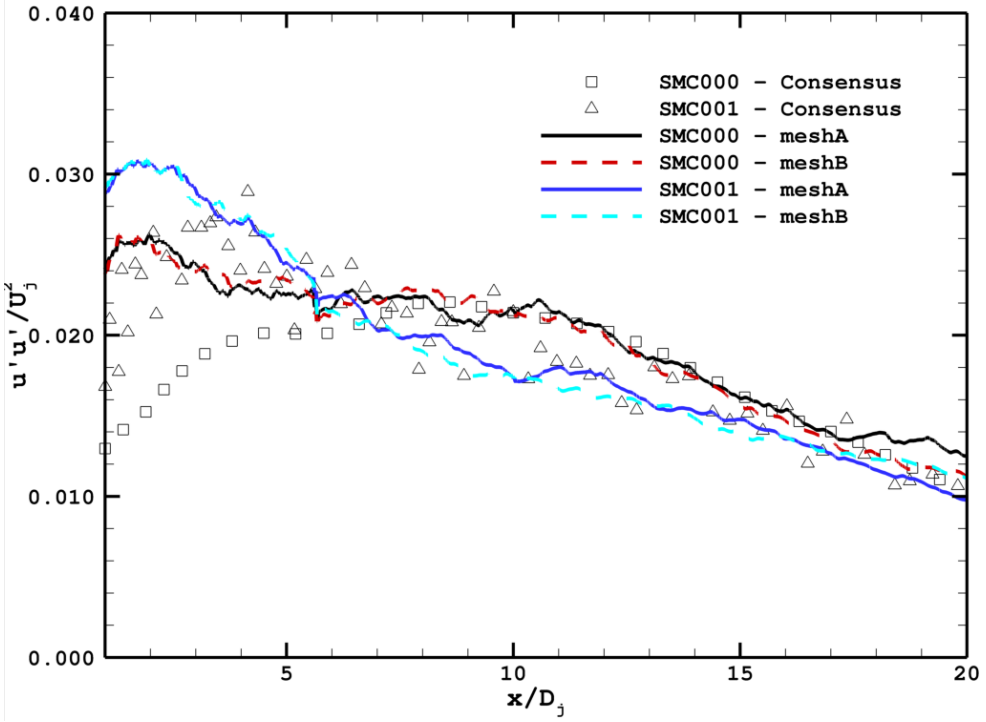
SMC000: Round
SMC001: Chevron

Near-Field Comparison: Lipline

dimensionless streamwise velocity u/U_j



dimensionless variance $u'u'/U_j^2$

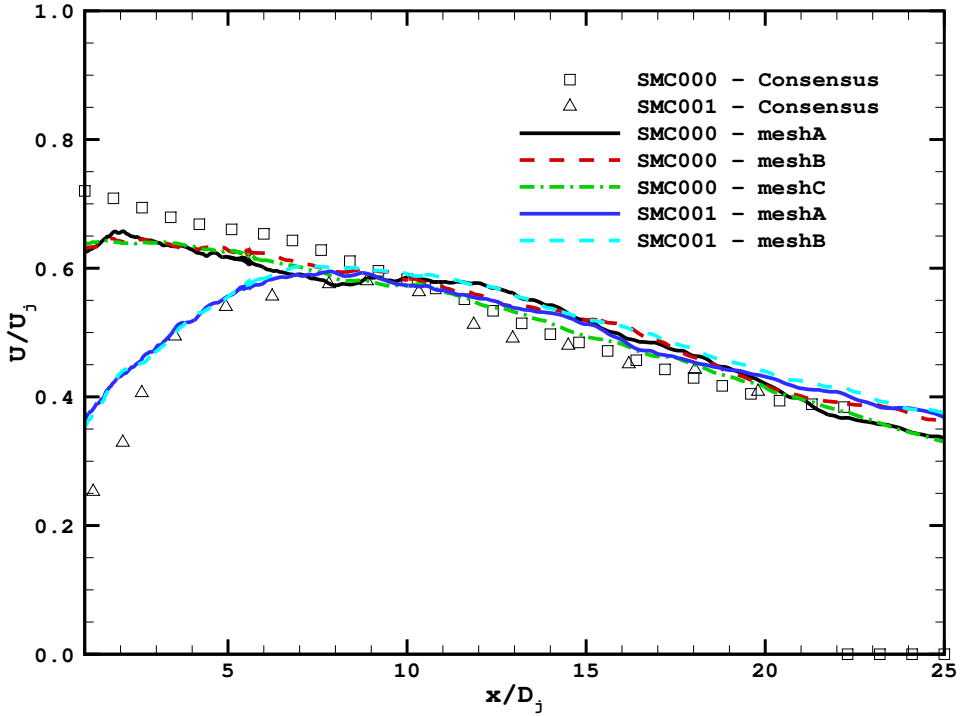


- Overprediction of normal stress at nozzle exit up to 4D
- Overall good agreement with experiment for all grid levels
- Both mesh-A (short trip) and mesh-B (long trip) show comparable result

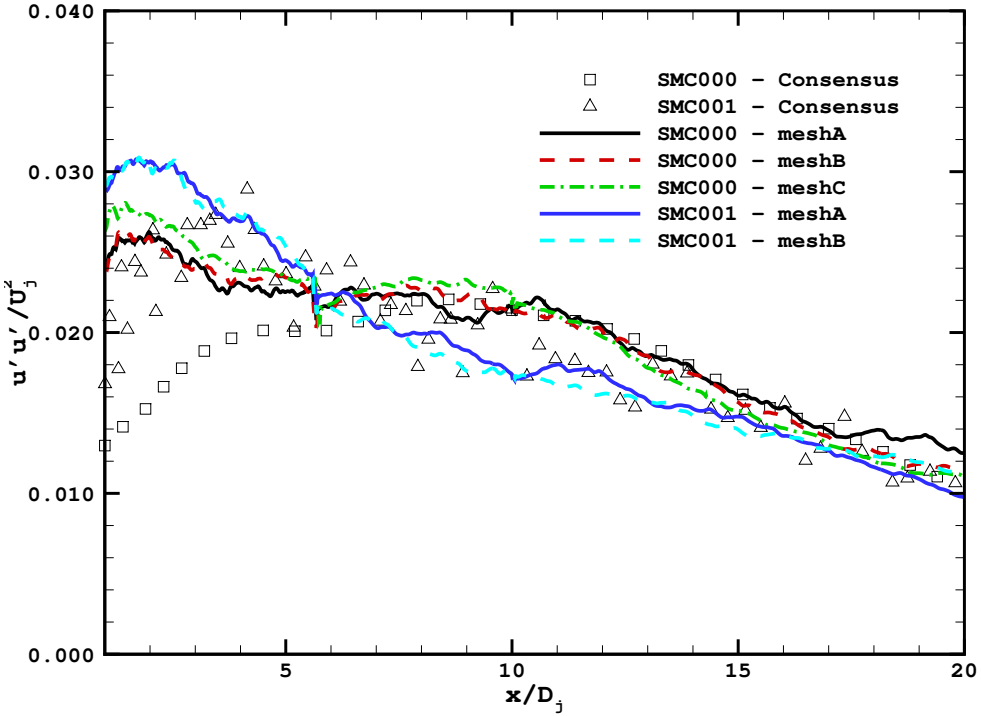
SMC000: Round
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Near-Field Comparison: Lipline

dimensionless streamwise velocity u/U_j



dimensionless variance $u'u'/U_j^2$

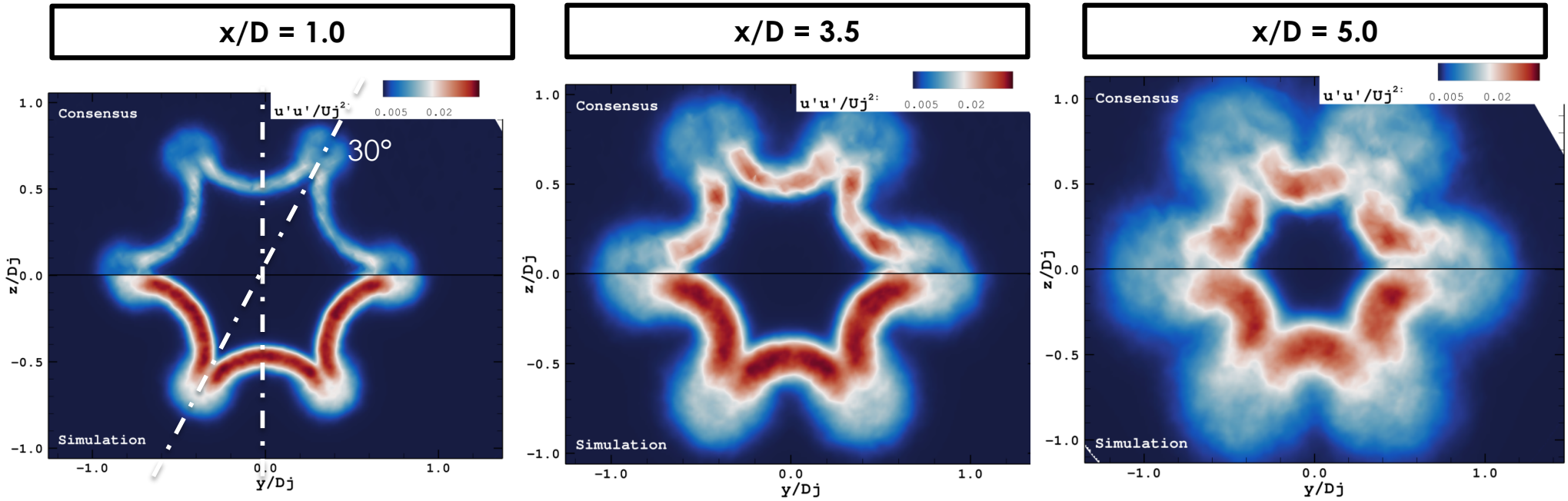


- Overprediction of normal stress at nozzle exit up to 4D
- Overall good agreement with experiment for all grid levels
- Slightly larger u'u' at lipline for mesh-C

SMC000: Round
SMC001: Chevron

Qualitative Comparison of Variance with experimental PIV

Chevron nozzle SMC001

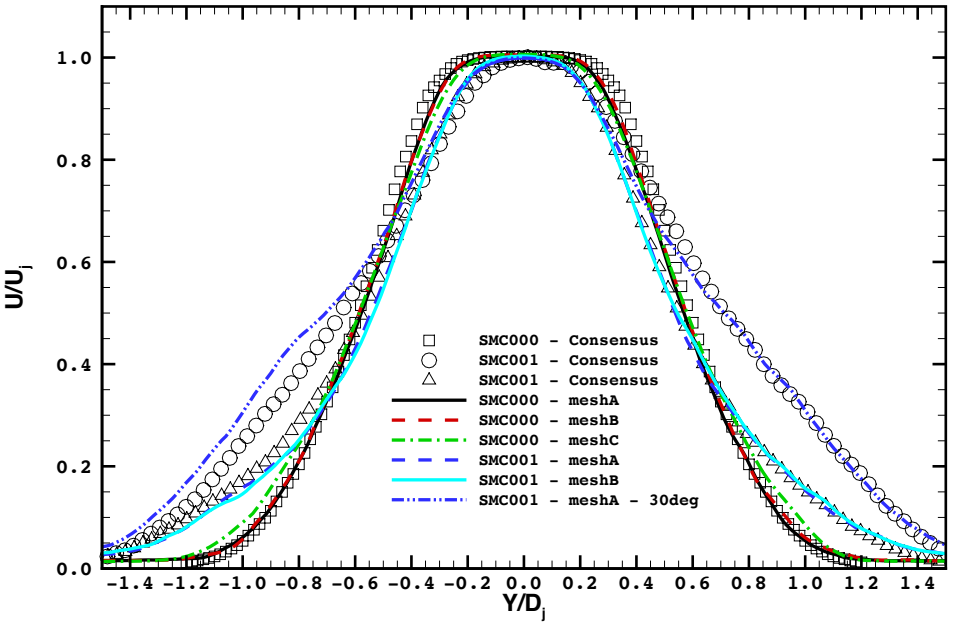


- Capture shape and spreading of nozzle shear layer accurately
- Overprediction of variance along nozzle shear layer up to x < 4D

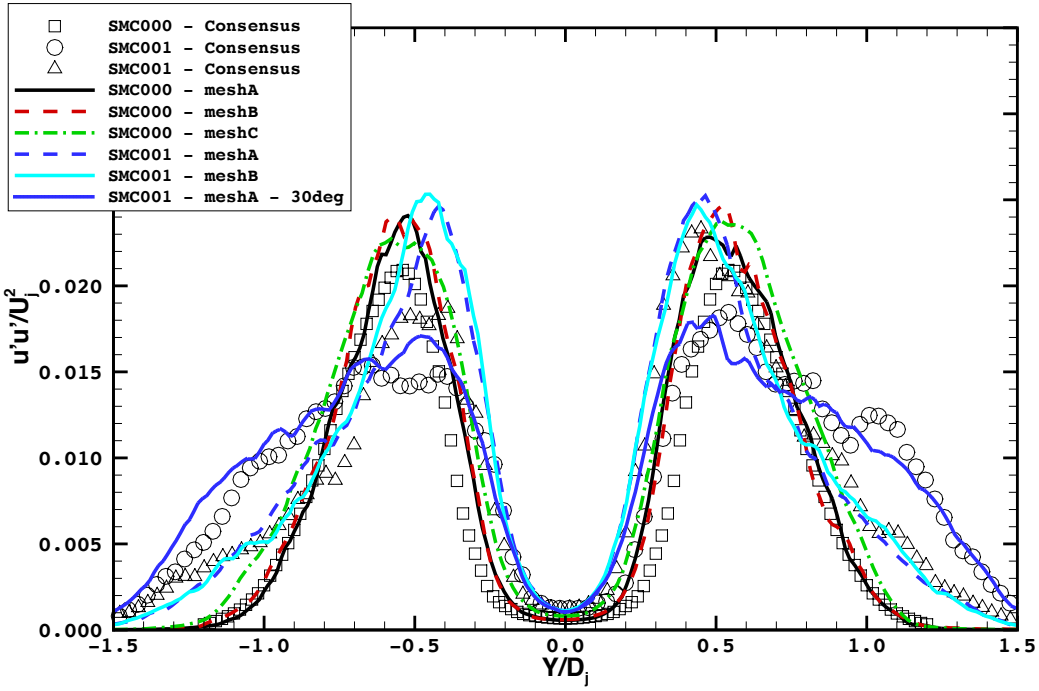
SMC000: Round
SMC001: Chevron

Near-Field Comparison: Axial Profiles x = 5.0D

dimensionless streamwise velocity u/U_j



dimensionless variance $u'u'/U_j^2$

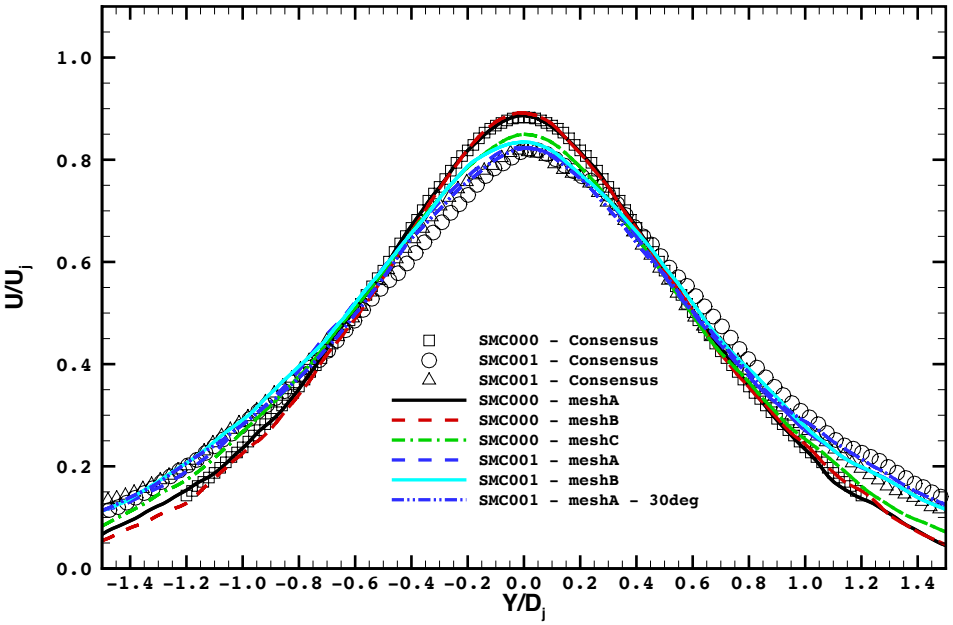


- Width of jet well captured in simulations
- Medium mesh-C and fine mesh-A consistent with each other

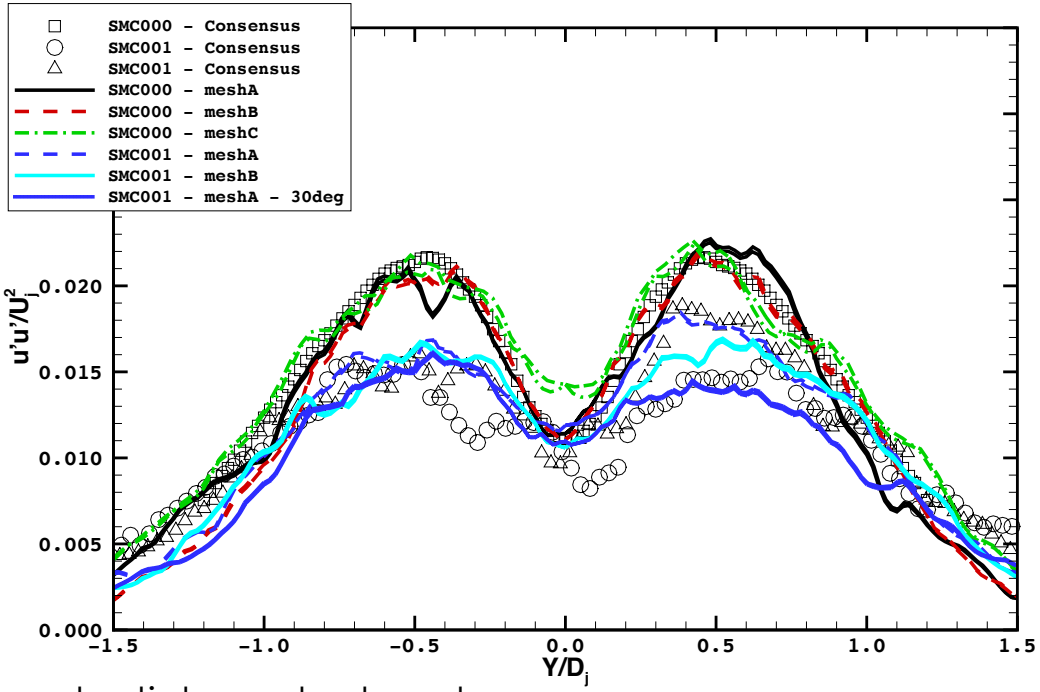
SMC000: Round
SMC001: Chevron

Near-Field Comparison: Axial Profiles x = 10.0D

dimensionless streamwise velocity u/U_j



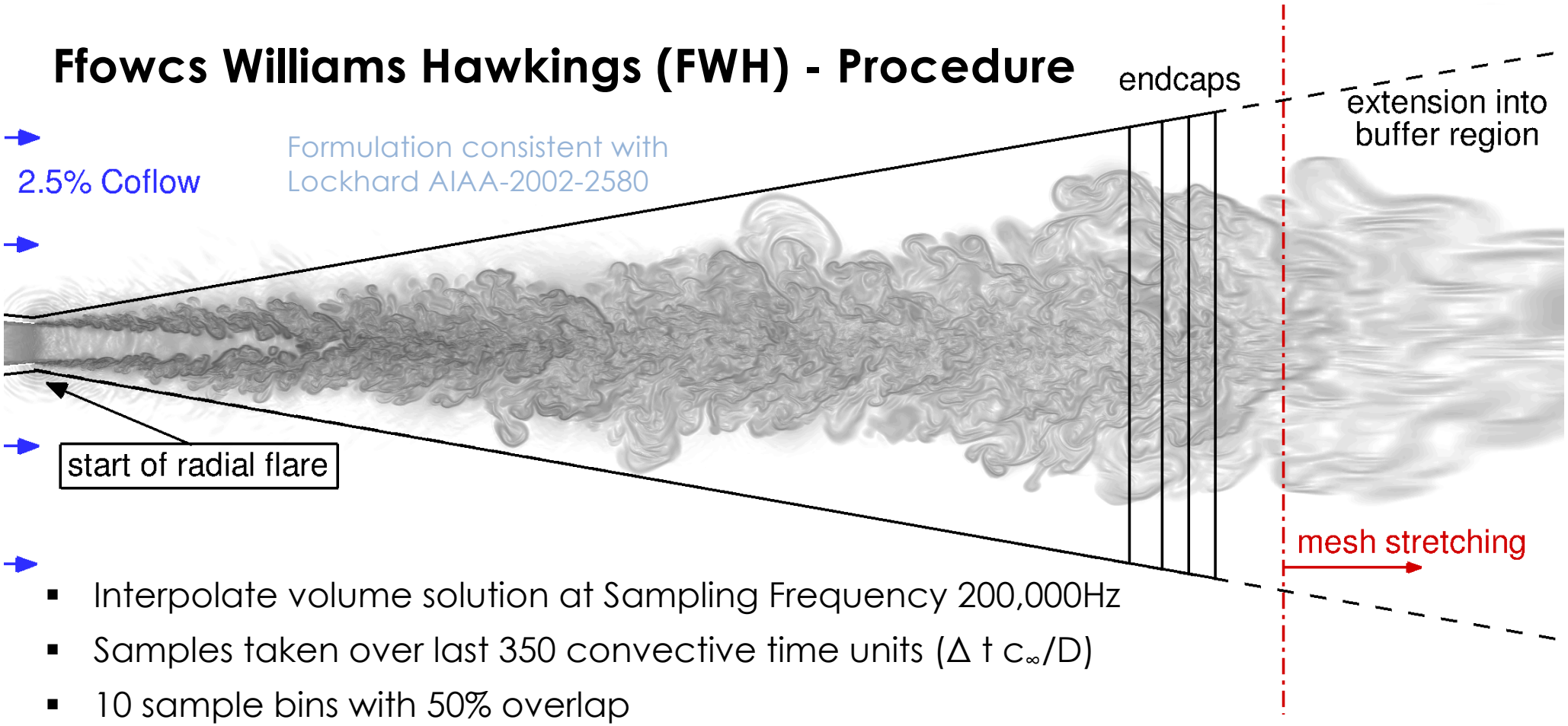
dimensionless variance $u'u'/U_j^2$



- Consistent results with all mesh resolutions after potential core broken down
- Slightly larger u'u' at jet center for medium mesh-B
- Overall good agreement with experiment

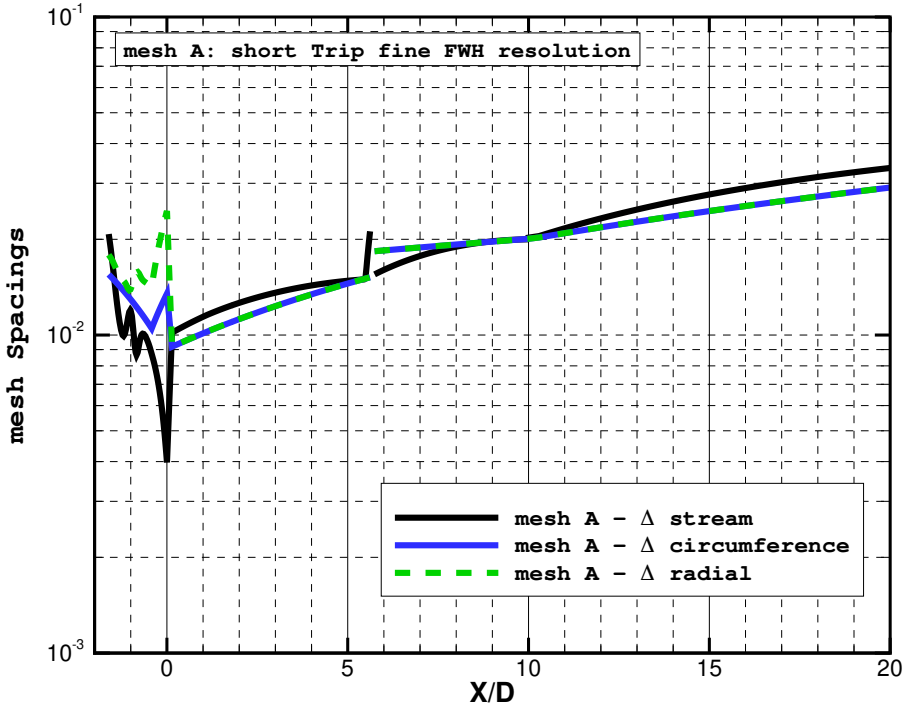
SMC000: Round
SMC001: Chevron

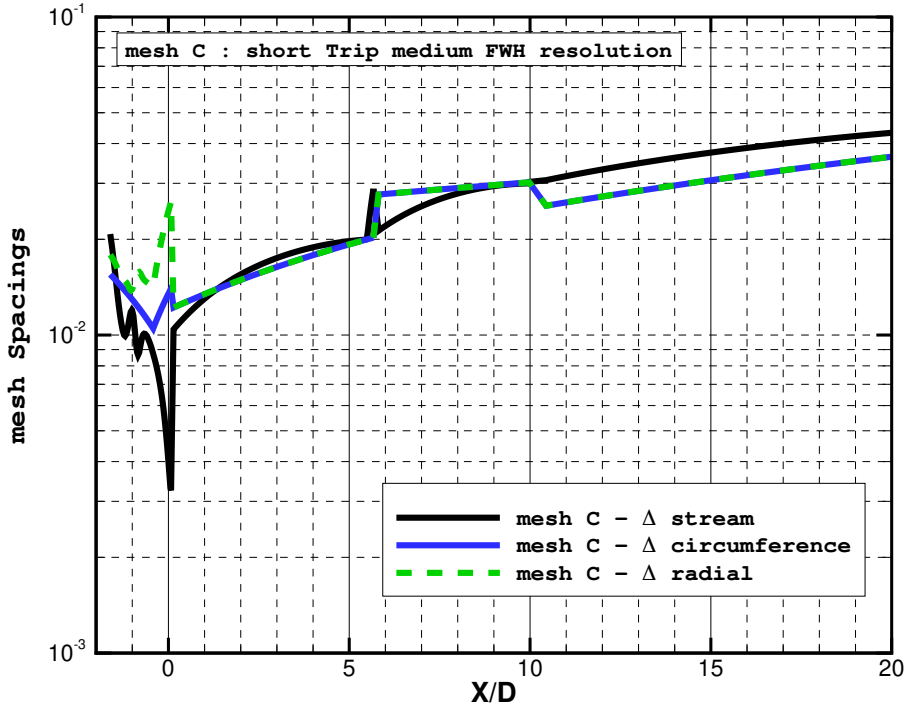
Ffowcs Williams Hawkings (FWH) - Procedure



- Interpolate volume solution at Sampling Frequency 200,000Hz
- Samples taken over last 350 convective time units ($\Delta t\, c_\infty/D$)
- 10 sample bins with 50% overlap
- Hanning window applied
- Averaged over 6 observers in azimuth

Ffowcs Williams Hawkings (FWH) - Mesh Resolution

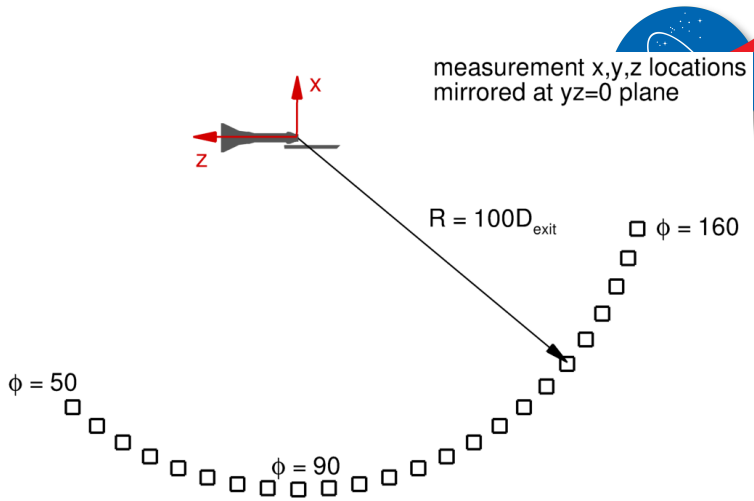


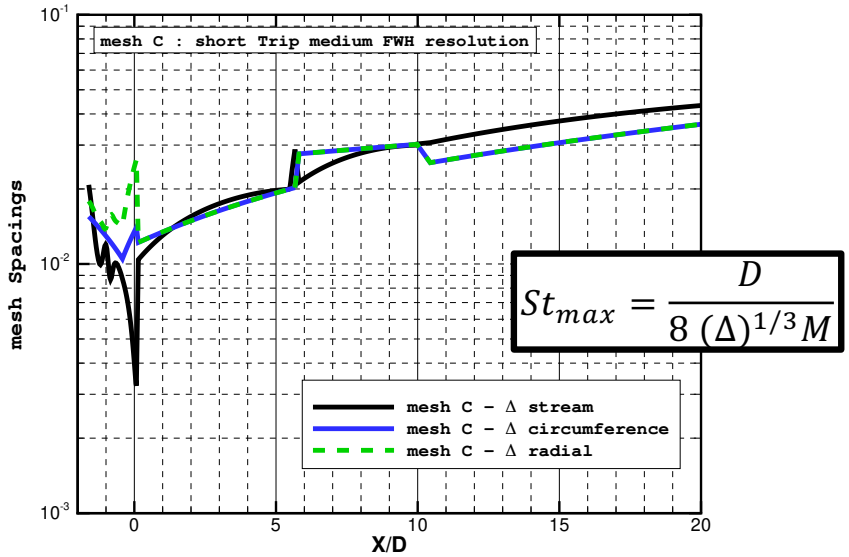


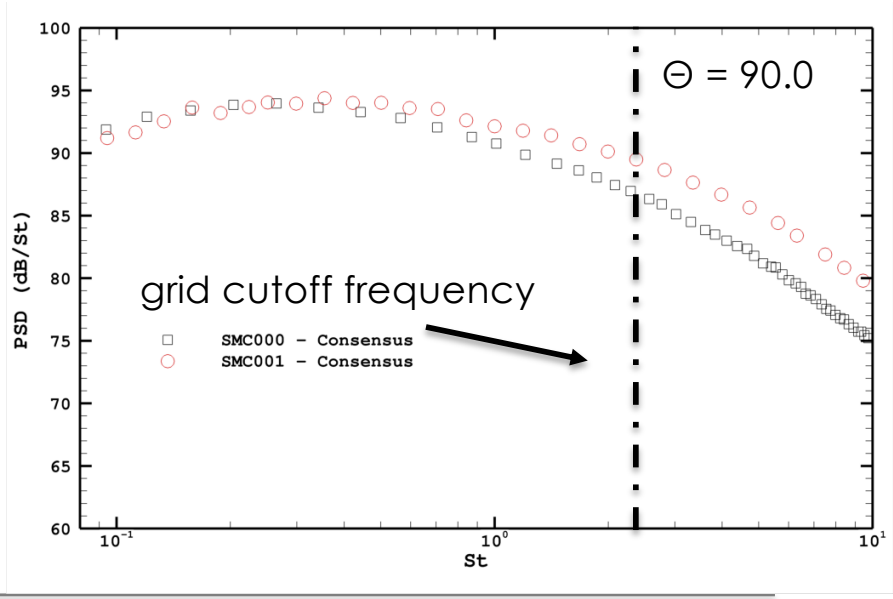
- Underlying CFD mesh resolution along FWH surface triangulation
- Utilized in order to assess resolvable frequency assuming 8 pnts per wavelength

Far-field Noise Spectrum at 100D

- Good agreement with microphone data until grid cutoff frequency
- Cutoff frequency estimated from mesh resolution along FWH surface assuming 8 pnts/wavelength

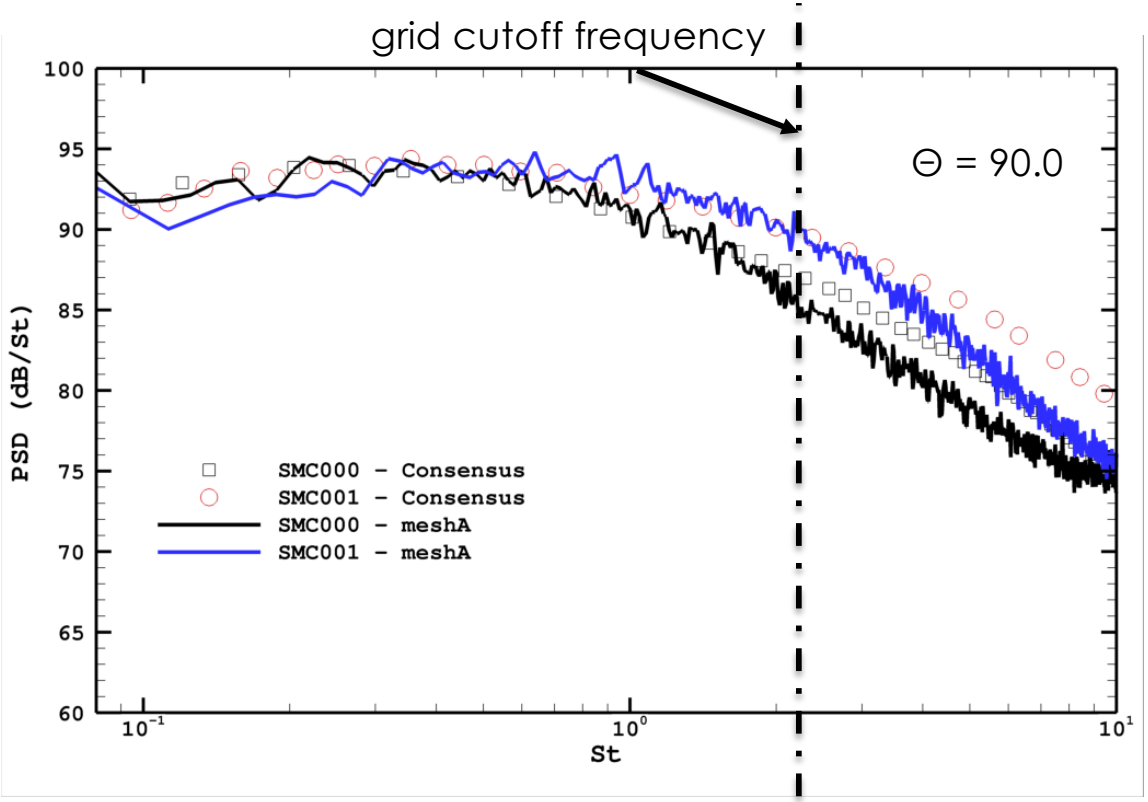






Far-field Noise Spectrum at 100D

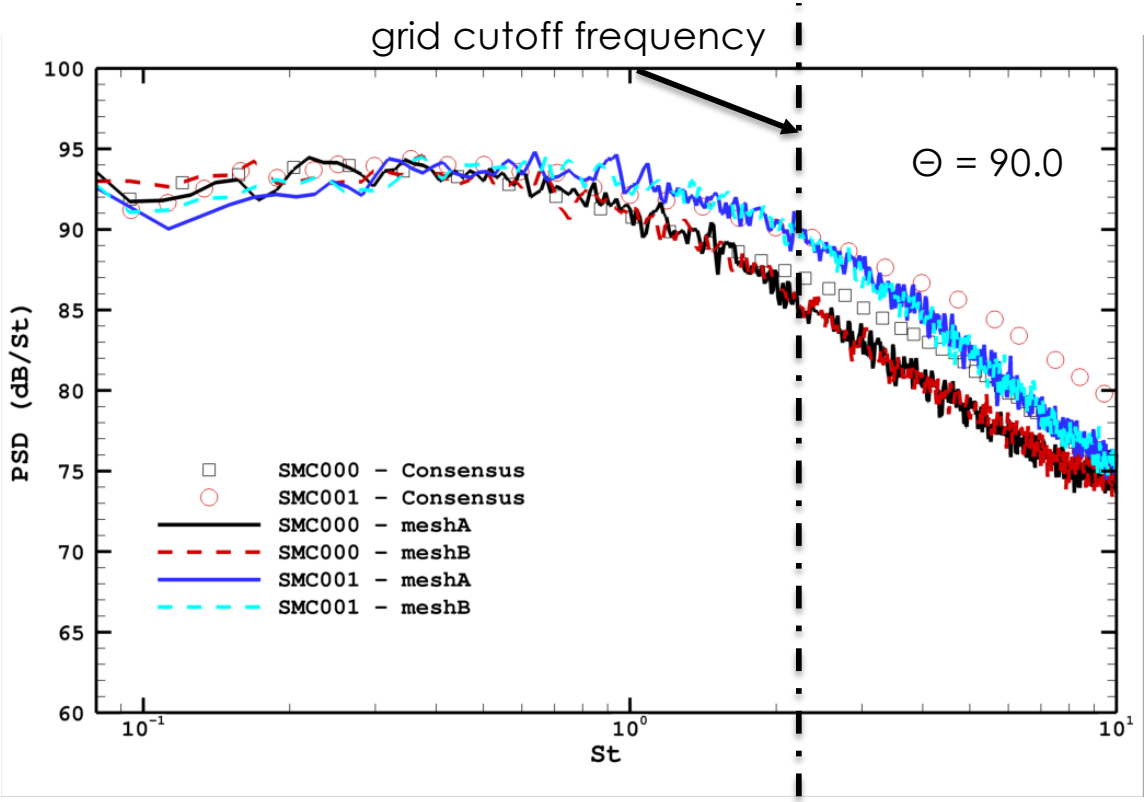
SMC000: Round
SMC001: Chevron



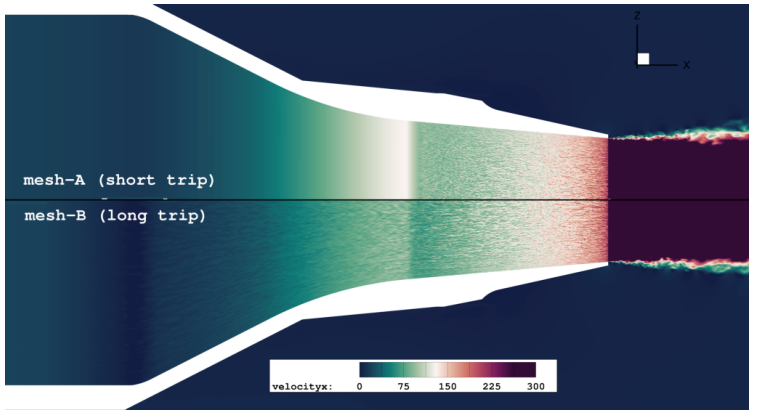
- Good agreement with microphone data until grid cutoff frequency

Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

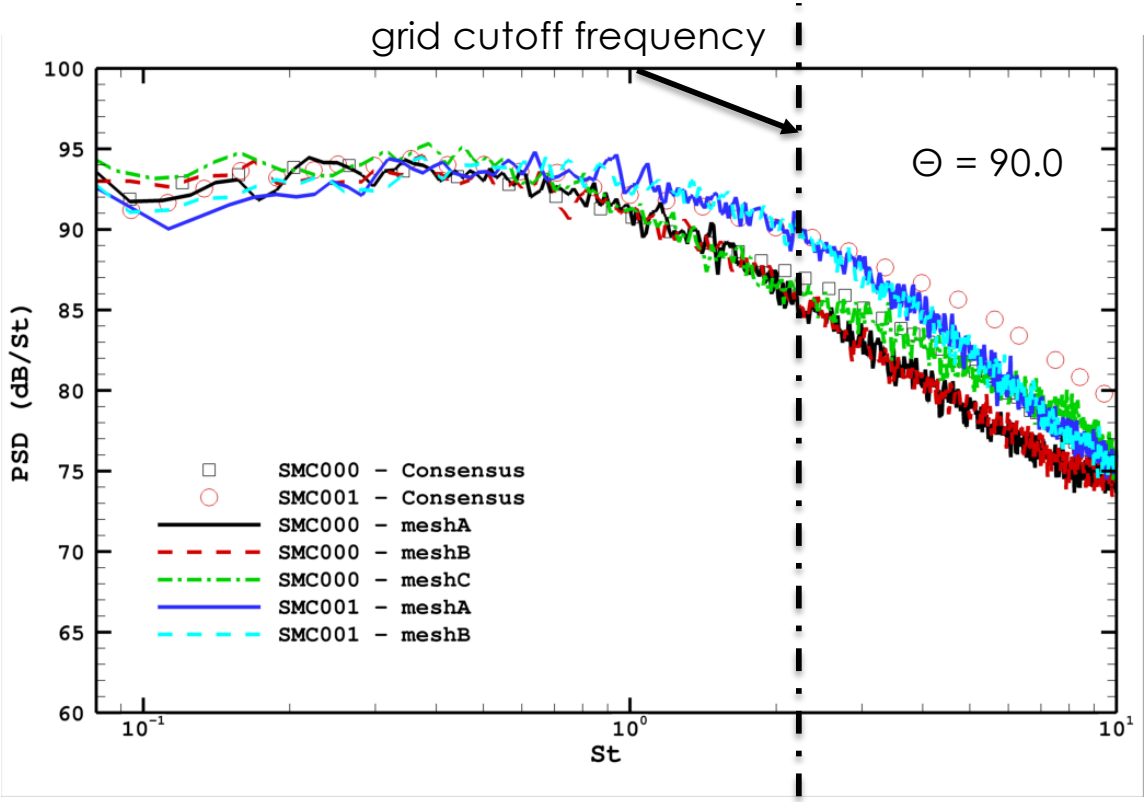


- Difference virtual origin of BL has no impact on noise

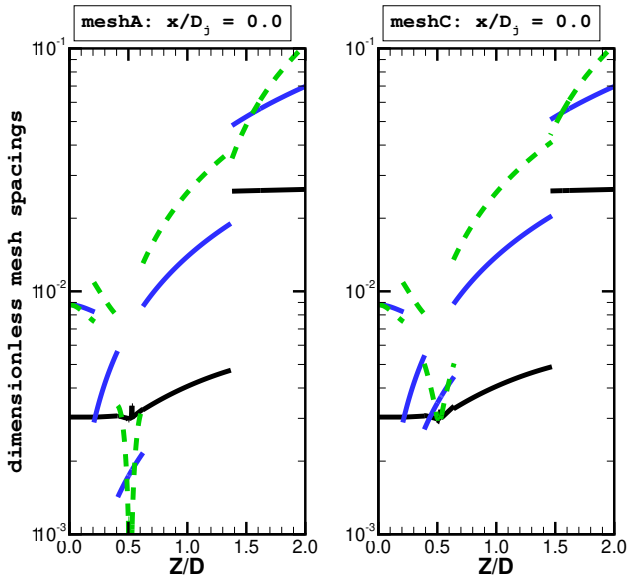


Far-field Noise Spectrum at 100D

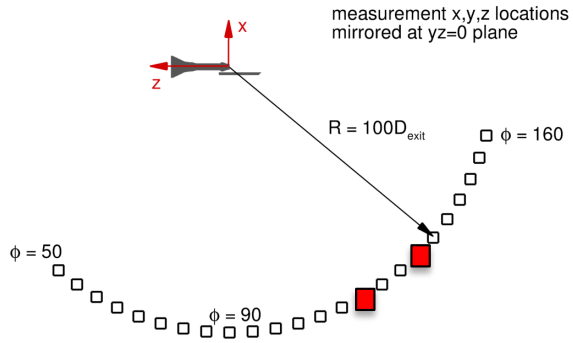
SMC000: Round
SMC001: Chevron

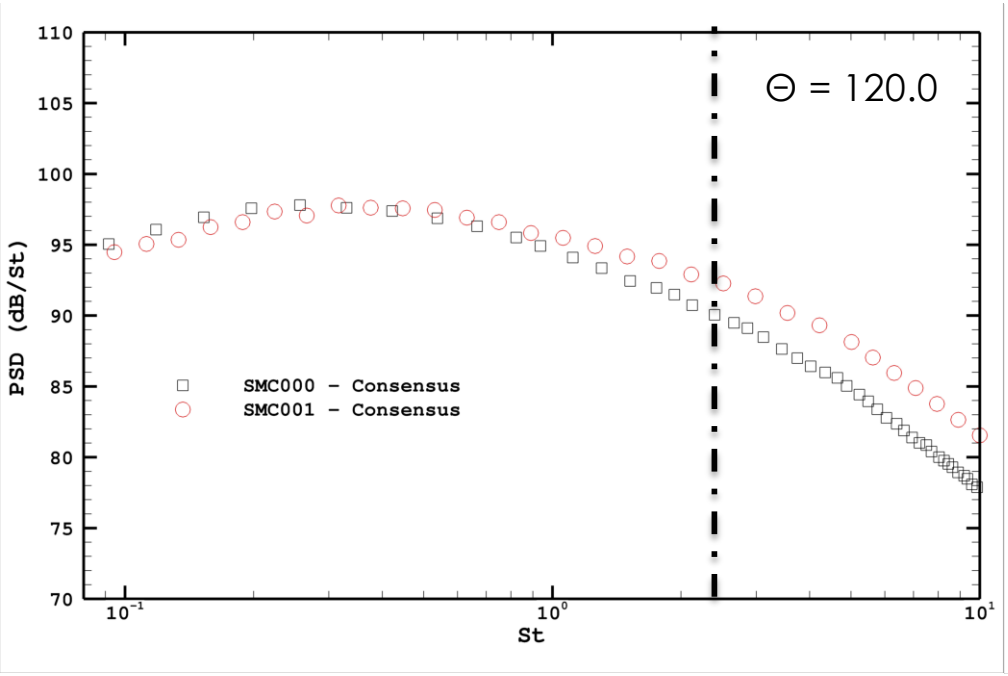


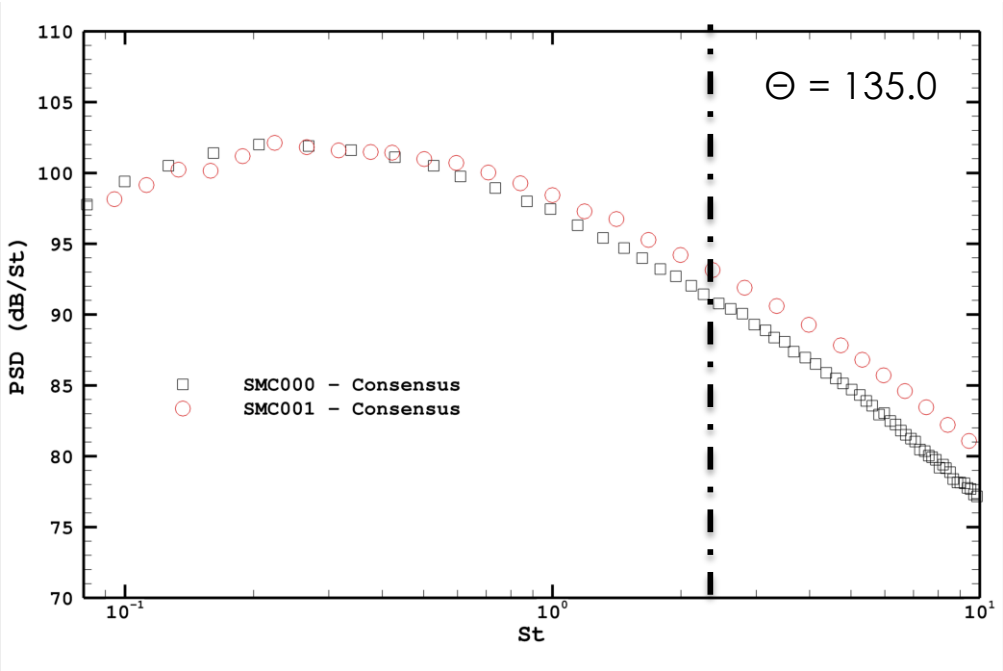
- Good agreement with medium mesh-C
- Higher PSD at St > 1.5 due to more coherent structures at nozzle exit



Far-field Noise Spectrum at 100D



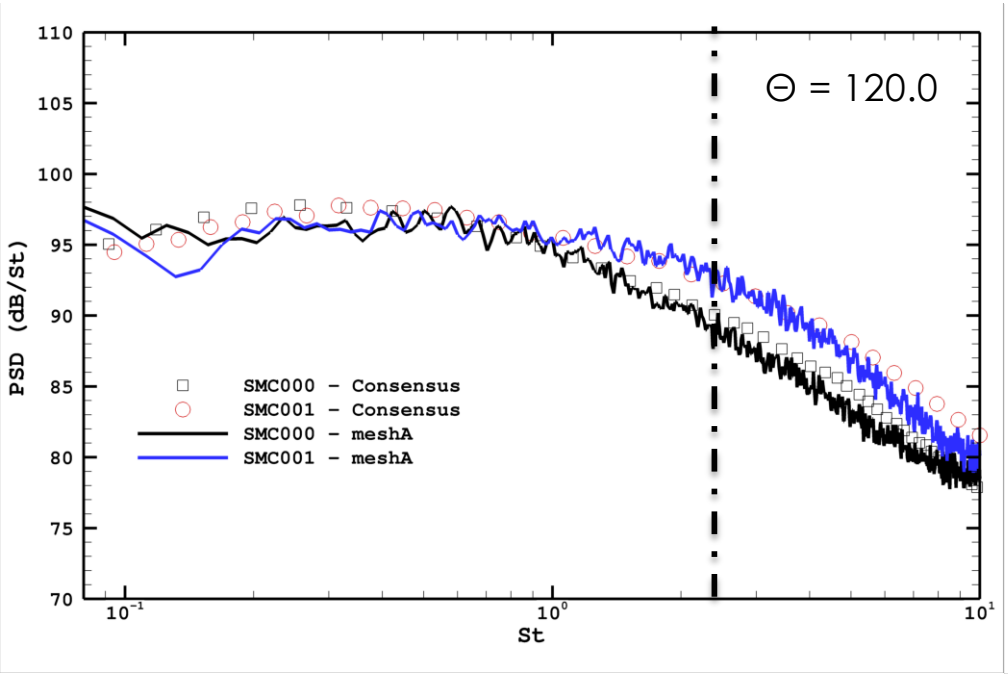


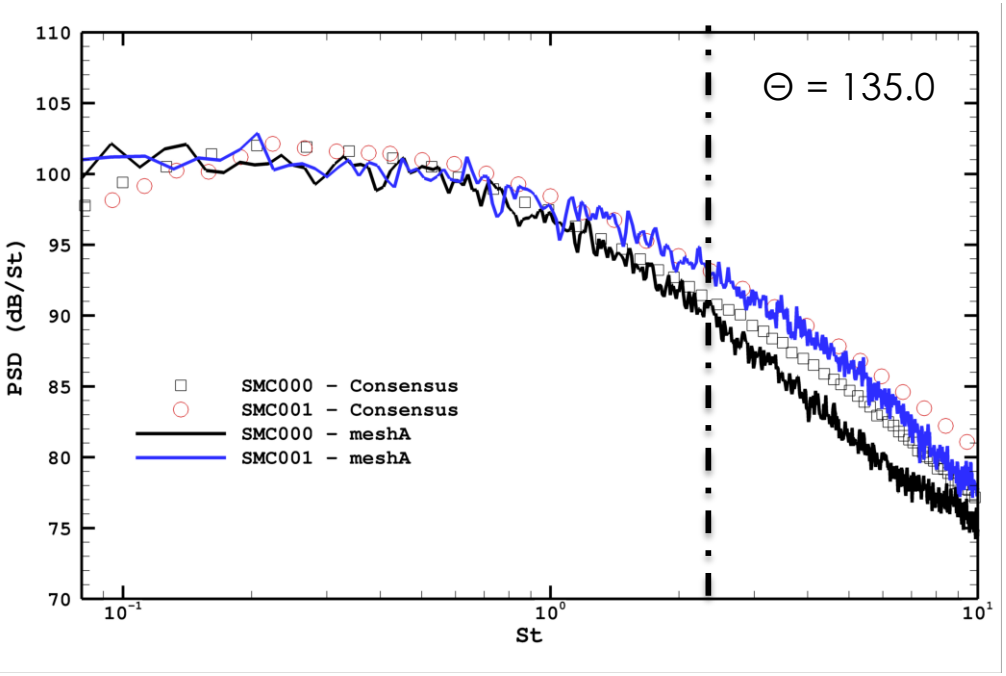


Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

- Difference between round jet and chevron for St > 1 captured in simulation
- Slight underprediction of noise at lower frequencies
- Overall good agreement with experiment

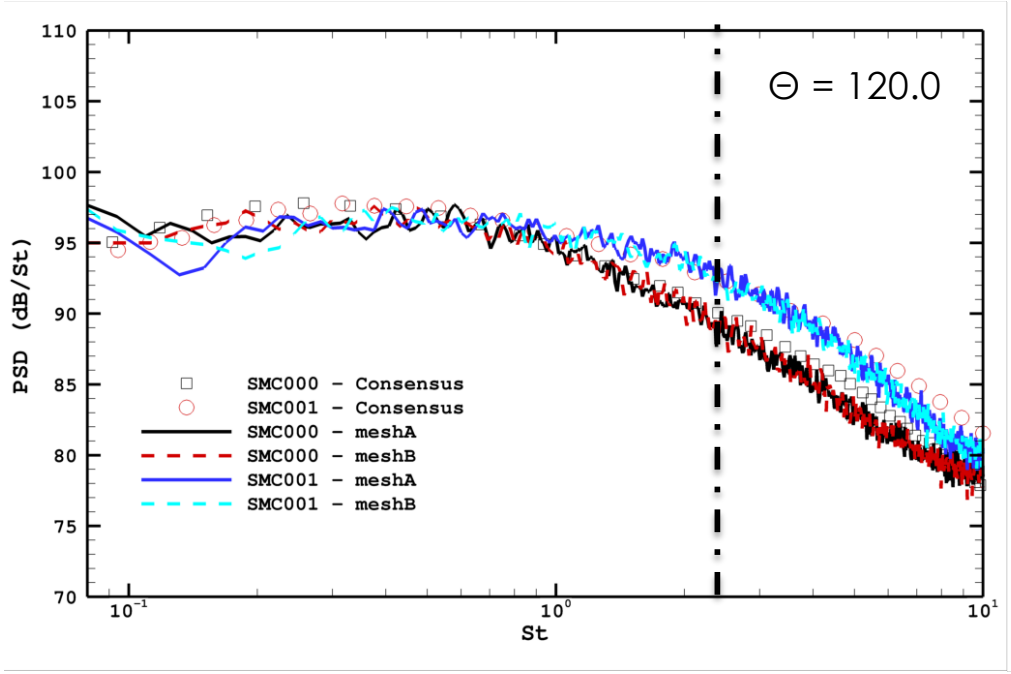


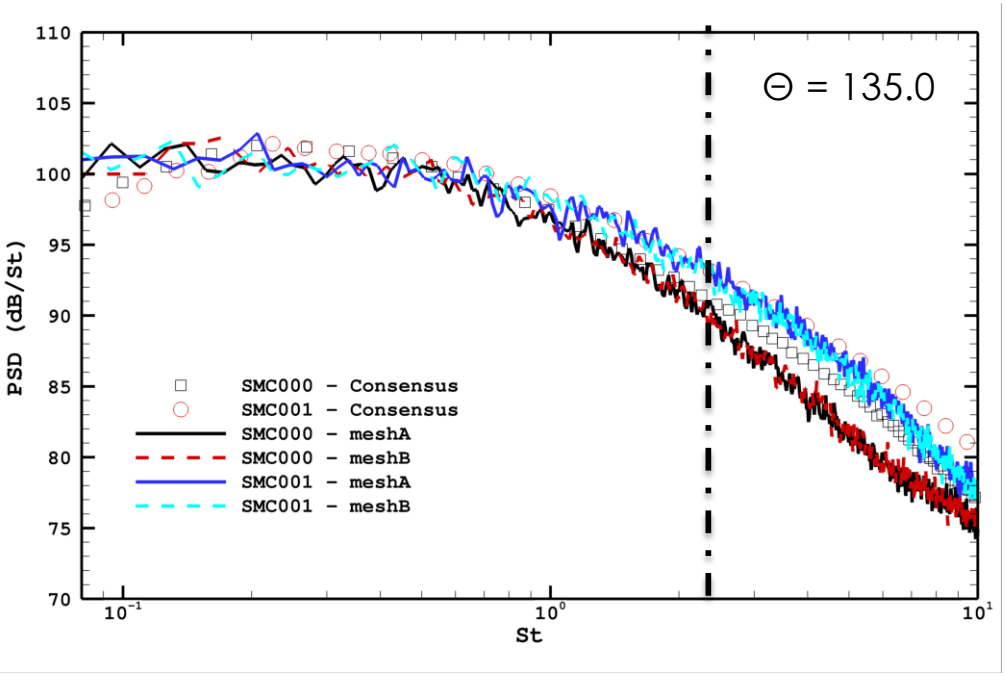


Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

- Difference between round jet and chevron for St > 1 captured in simulation
- Slight underprediction of noise at lower frequencies
- Difference of virtual origin has little to no impact on noise spectrum

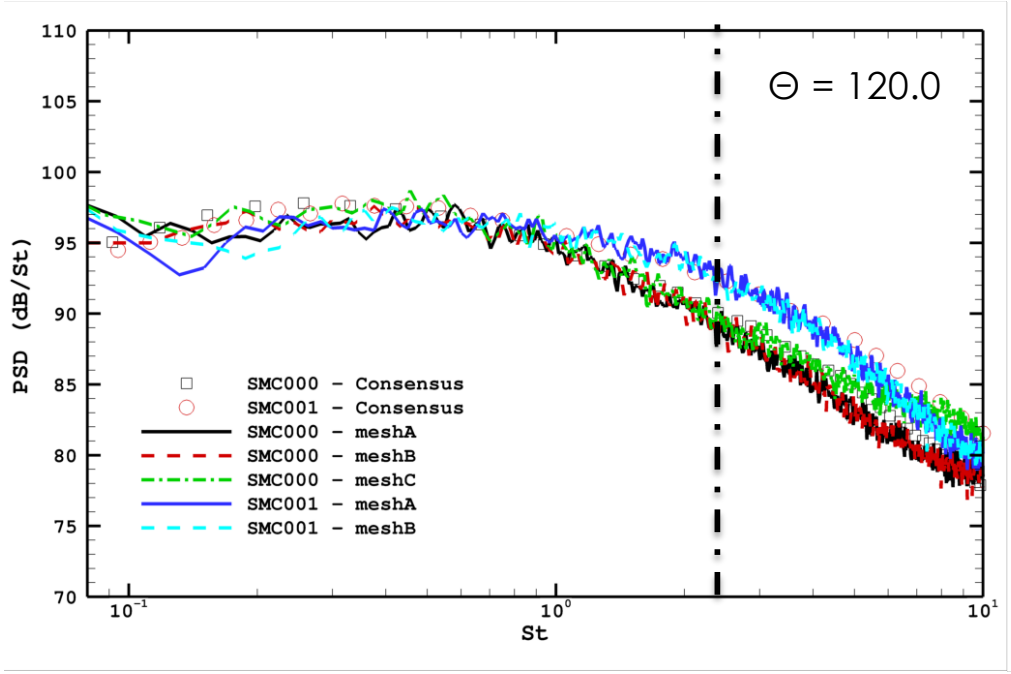


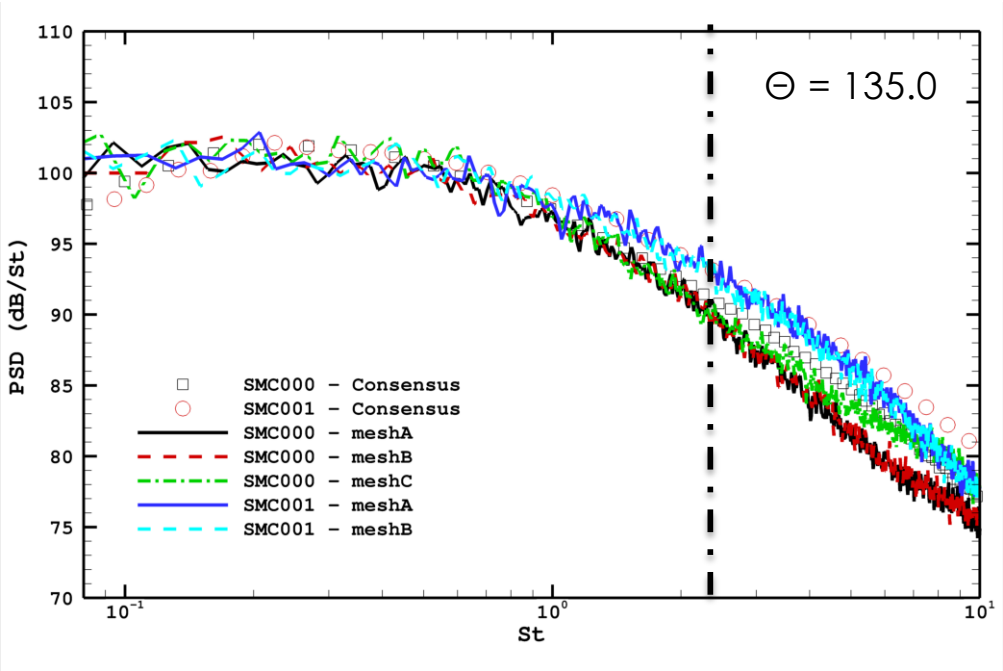


Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

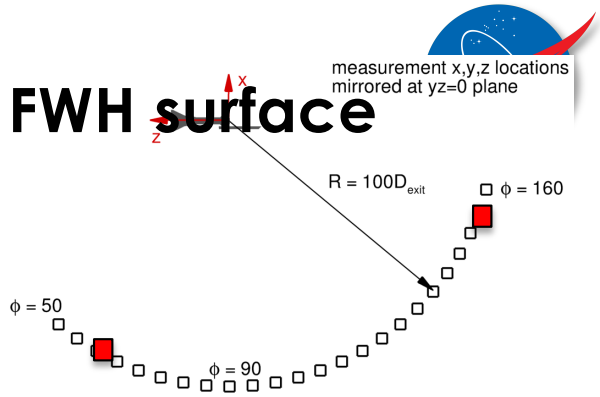
- Difference between round jet and chevron for St > 1 captured in simulation
- Slight underprediction of noise at lower frequencies
- Larger eddies inside of nozzle result in rise of high frequency noise

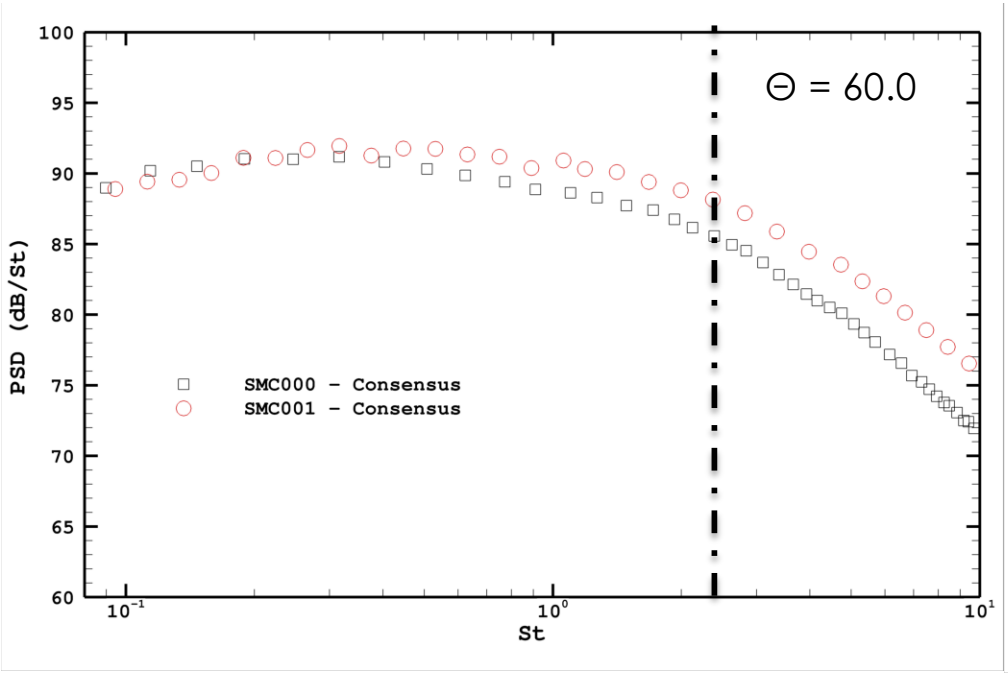


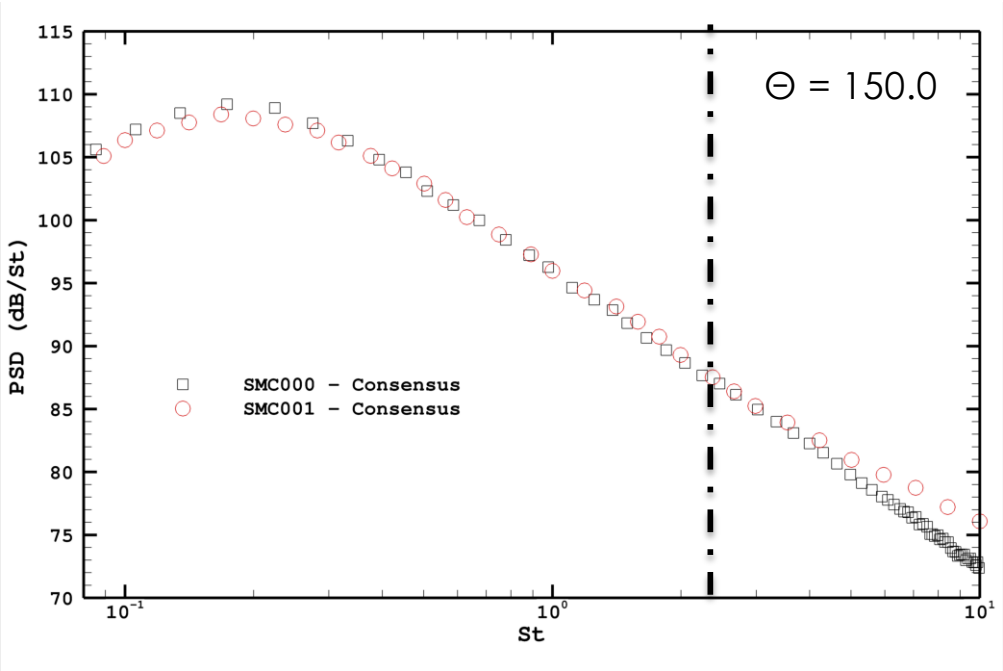


Far-field Noise Spectrum at 100D – Ends of the FWH surface

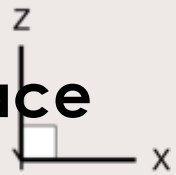
- FWH method assumes we contain all relevant noise sources within our FWH triangulation







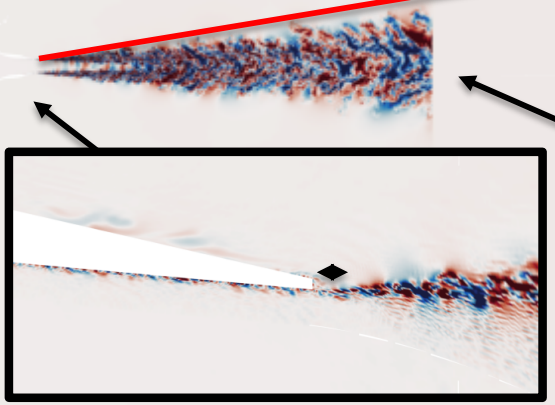
Far-field Noise Spectrum at 100D – Ends of the FWH surface



Domain size for jet 35D (standard size in literature)

Length scale: 0.02D
Sweeping Timescale: 0.05 D/U

165° observer



Length scale: 2.0D
Sweeping Timescale: 15.0 D/U



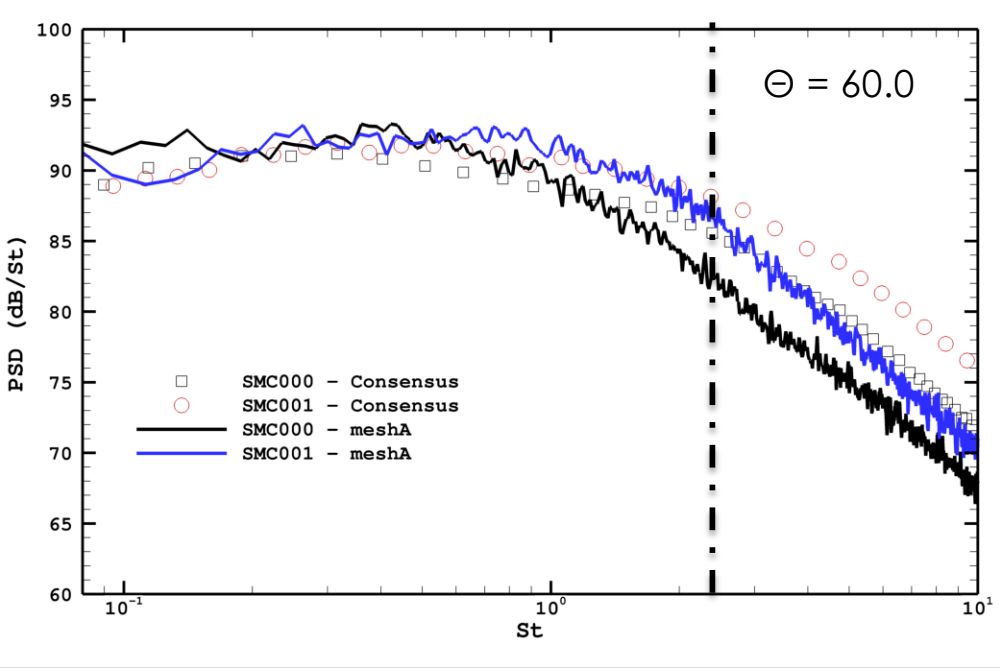
VVel: -25 -20 -17.5 -15 -10 -5 0 5 10 15 17.5 20 25

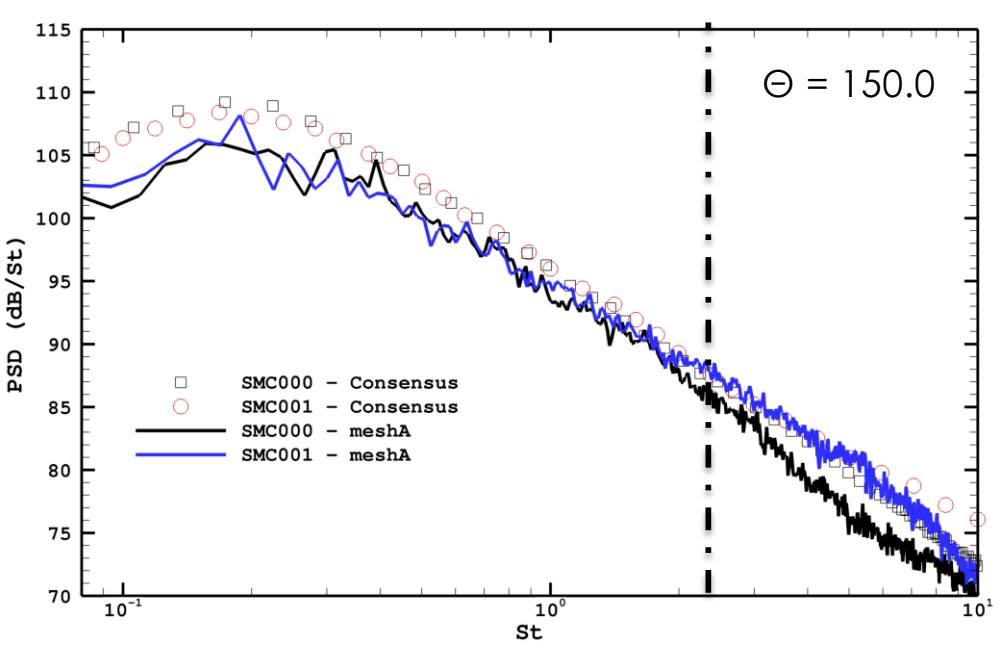
45

Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

- For upstream and far aft-angles we assume that we captured all relevant sound sources within our FWH triangulation
- Underprediction of noise at far aft-angles for low frequency

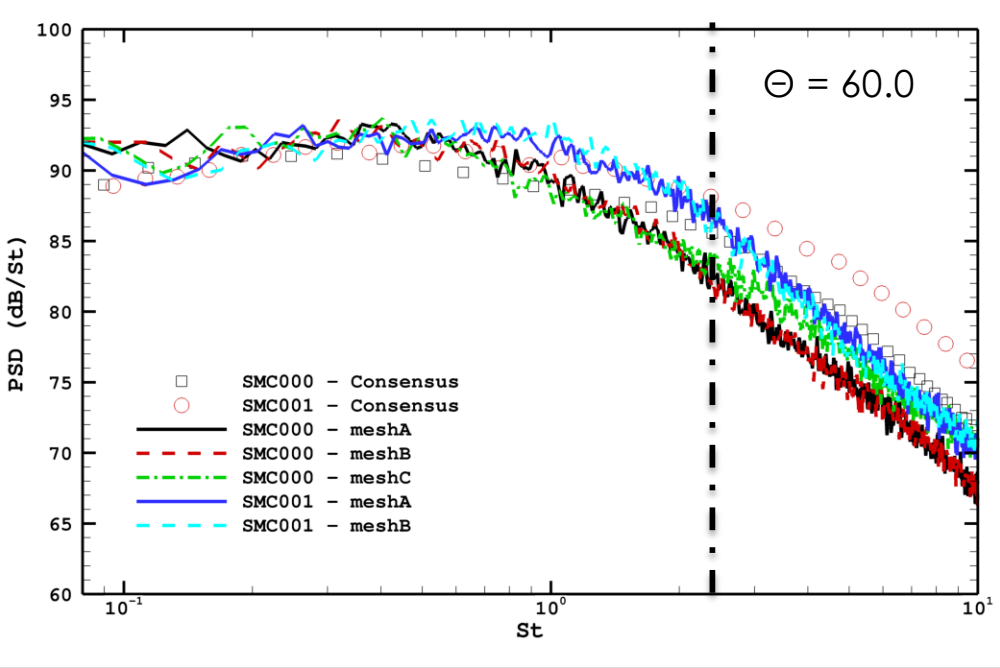


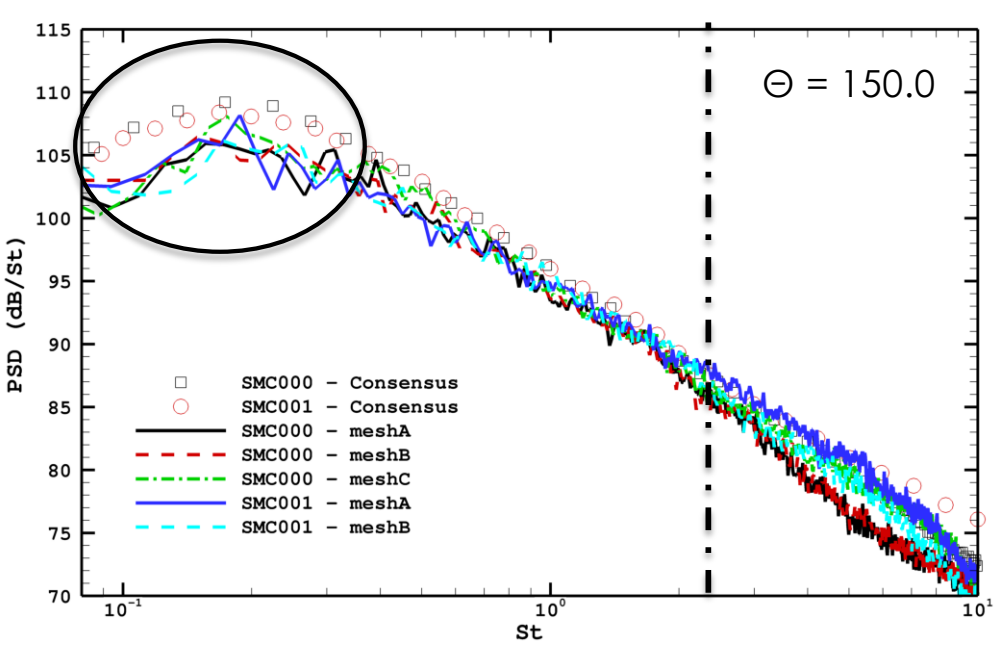


Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

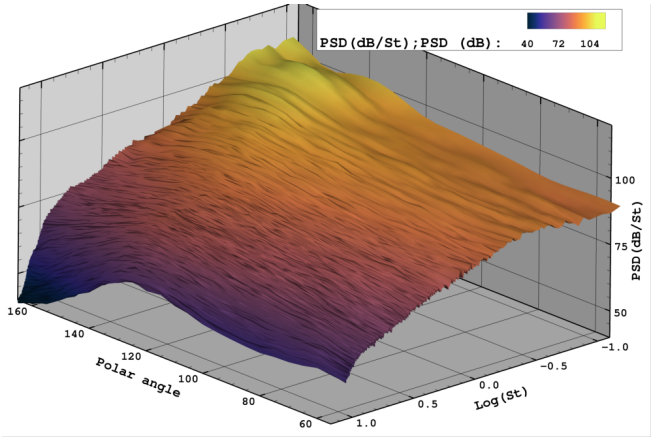
- For upstream and far aft-angles we assume that we captured all relevant sound sources within our FWH triangulation
- Underprediction of noise at far aft-angles for low frequency



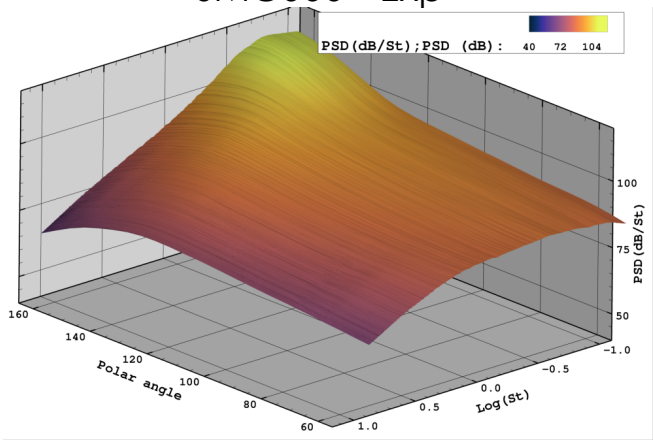


Far-field Noise Spectrum at 100D: Directivity

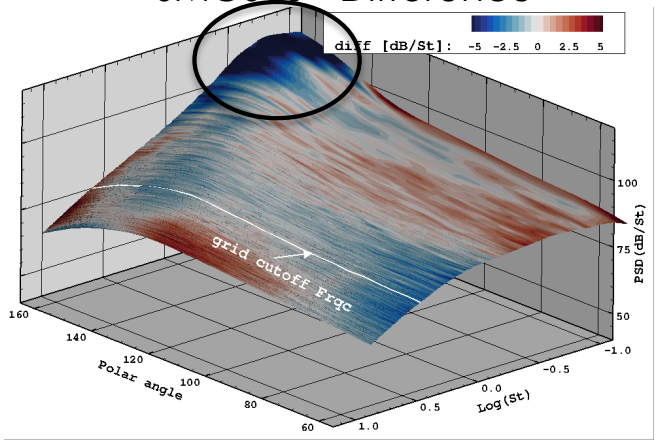
SMC000 - CFD



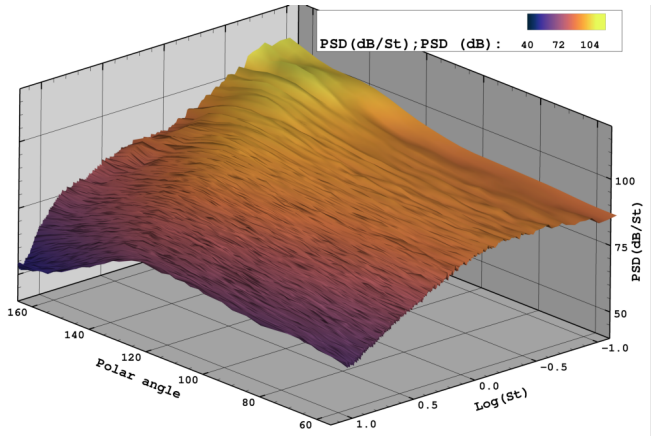
SMC000 - Exp



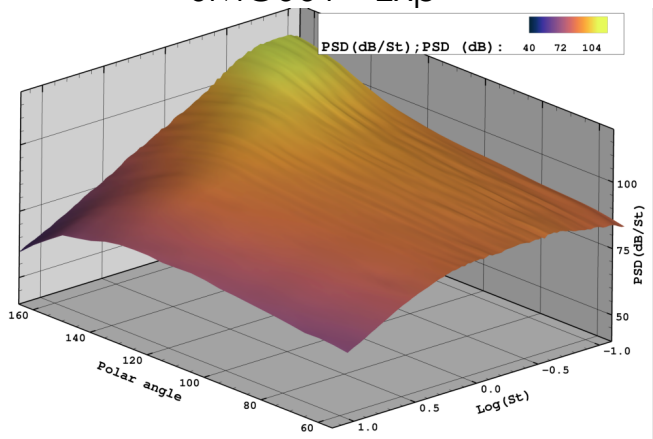
SMC000 - Difference



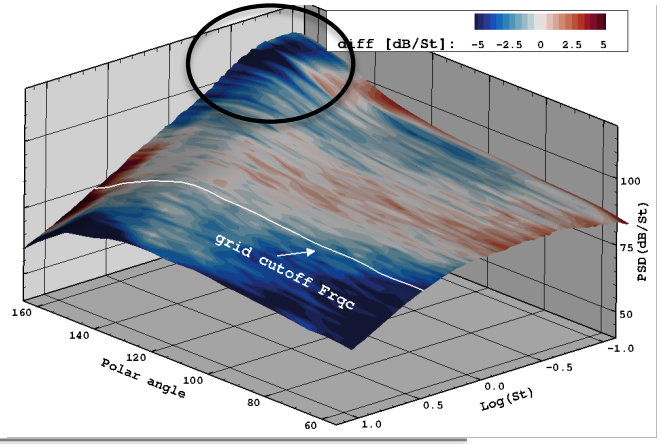
SMC001 - CFD



SMC001 - Exp



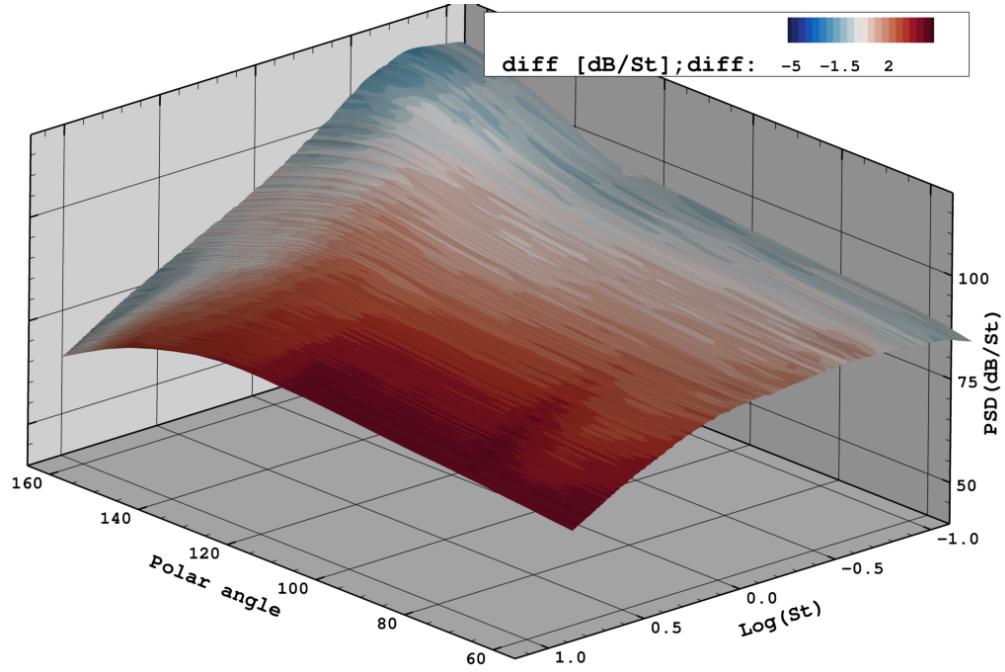
SMC001 - Difference



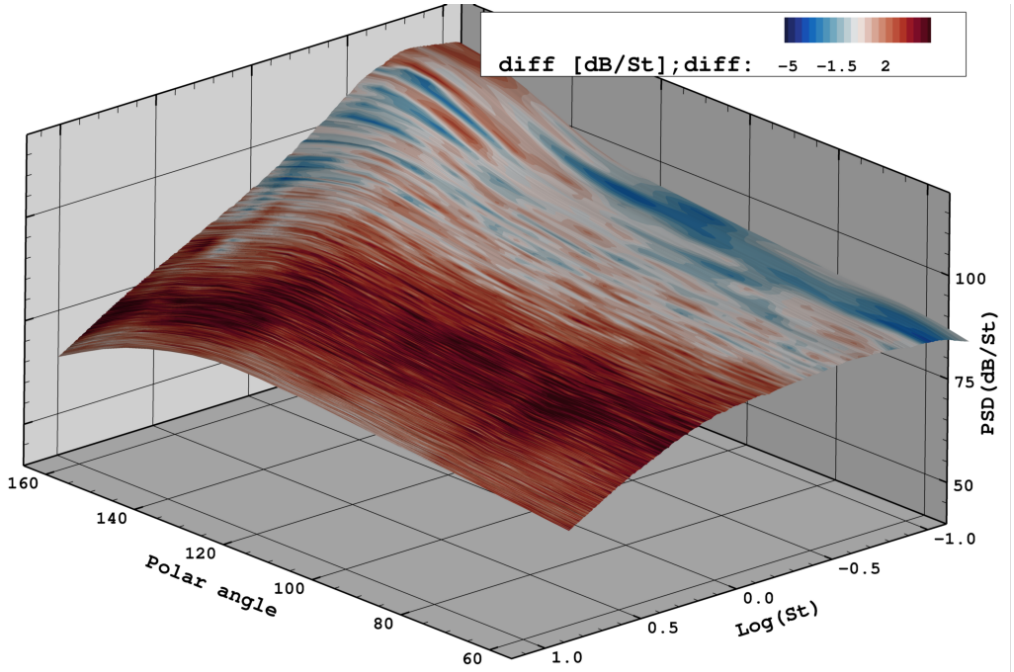
Far-field Noise Spectrum at 100D: Directivity

SMC000: Round
SMC001: Chevron

Difference SMC000 vs SMC001: Experiment

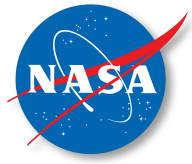


Difference SMC000 vs SMC001: CFD



- Overall good agreement in prediction of noise reduction due to chevron nozzle
- Difference in PSD at very low frequencies and large angles due to statistical uncertainty of few data samples in signal

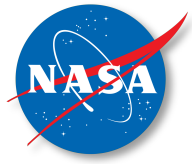
Computational Costs of Simulation



- Simulation initialized from steady-state RANS to speed up transients on coarsest mesh
- Initial flush out of transients for about 100CTU to fully develop jet
- Subsequent simulations started from interpolated solution of coarse mesh

case name	mesh size	$\frac{\Delta r_w}{D}$	trip location	$\frac{dt \cdot c_\infty}{D}$	$\frac{\Delta t \cdot c_\infty}{D}$	$\frac{T \cdot c_\infty}{D}$	cost (kCPUh)	CTU (CPUh)
mesh-A	200M	0.0015	-1.5D	0.0005	0.017	345	84	249
mesh-B	220M	0.0015	-5.0D	0.0005	0.017	345	84	249
mesh-C	110M	0.0030	-1.5D	0.0010	0.017	685	47	69
Stich *et.al* [14]	210M	<0.0001	-	0.0070	0.06	300	298	995

Timings and Code Improvements



Time savings due to algorithm, code improvements and development

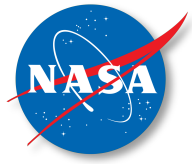
Date	Method	Mesh size [10^6]	$\Delta t/c_\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
November 2019	Hybrid RANS/LES (ZDES III)	225	0.007	60 Skylake (2400 cores)	995	3.2 day / 6.5 day	--
March 2020	Wall-stress WMLES	254	0.0005	60 Skylake (2400 cores)	430	26.8 hr / 2.3 day	**2.8x**
November 2020	Wall-stress WMLES	110	0.001	60 Skylake (2400 core)	69	**4.3 hr / 8.6 hr**	**18x**

CTU: Convective Flow Through Unit

** Timings include high frequency (sampling rate 200kHz) i/o output for solution*

*** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019*

Timings and Code Improvements



Time savings due to algorithm, code improvements and development

Date	Method	Mesh size [10^6]	$\Delta t/c_\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
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March 2021	Wall-stress WMLES	250	0.0007	100 Rome (12800 core)	106	**75min / 150 min**	

CTU: Convective Flow Through Unit

** Timings include high frequency (sampling rate 200kHz) i/o output for solution*

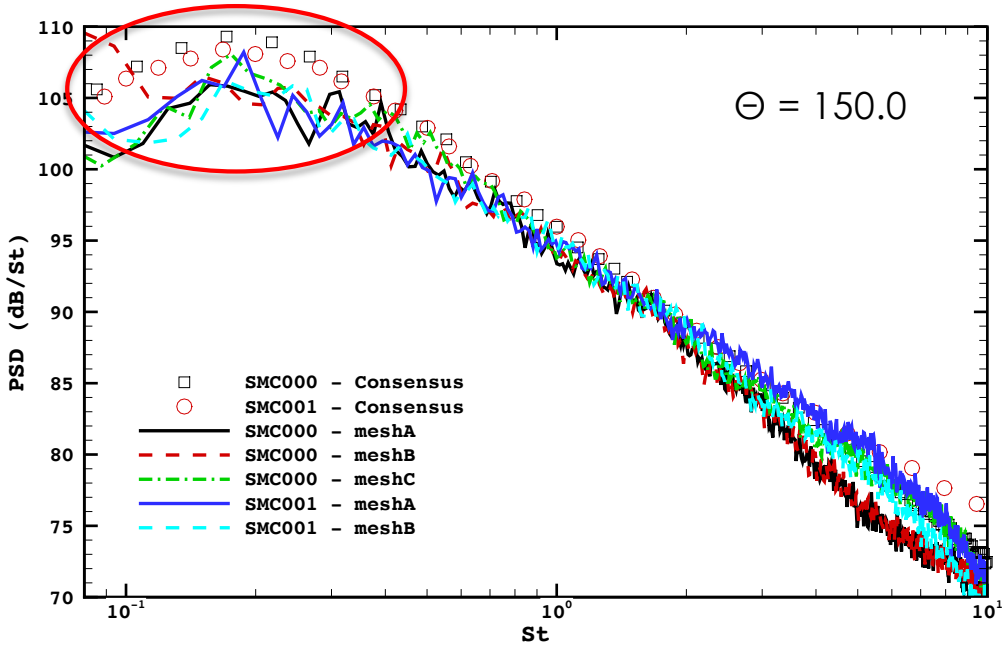
*** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019*

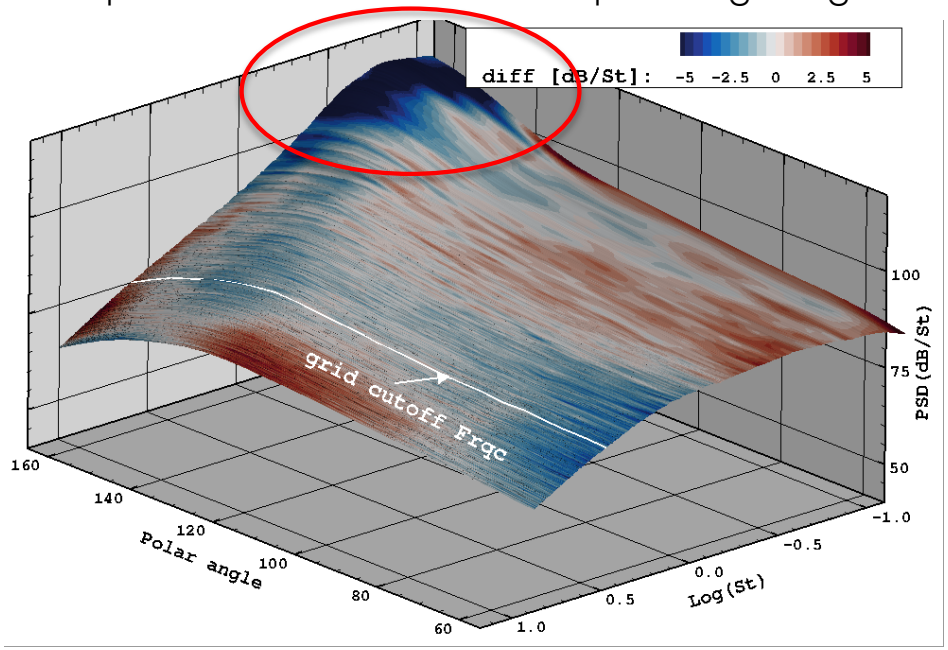
Conclusions

- WMLES performed for round jet SMC000 and chevron nozzle SMC001
- Accurate prediction of near-field quantities with PIV experimental data
  - Breakdown of potential core predicted within 1%
  - Rise and peak of turbulent kinetic energy (TKE) along centerline predicted accurate, Overprediction of TKE at Lipline
- Good comparison with far-field noise microphone array data
  - Good agreement in the resolved frequency range
  - Qualitative and quantitatively predicted noise reduction of chevron nozzle compared with experiment
  - Underprediction of noise at far aft angles
- Demonstrated capability to perform jet noise simulations in reasonable turnaround time *(from weeks, to days, to hours)*

Future and ongoing work

- Scale resolving simulations will play an increasing role in jet noise prediction for supersonic Configurations in the near future
- For this reason, strength and deficiencies of WMLES for jet noise need to be well understood and the uncertainties quantified
- As a first step we are trying to understand the observed under-prediction of noise at low freq and large angles

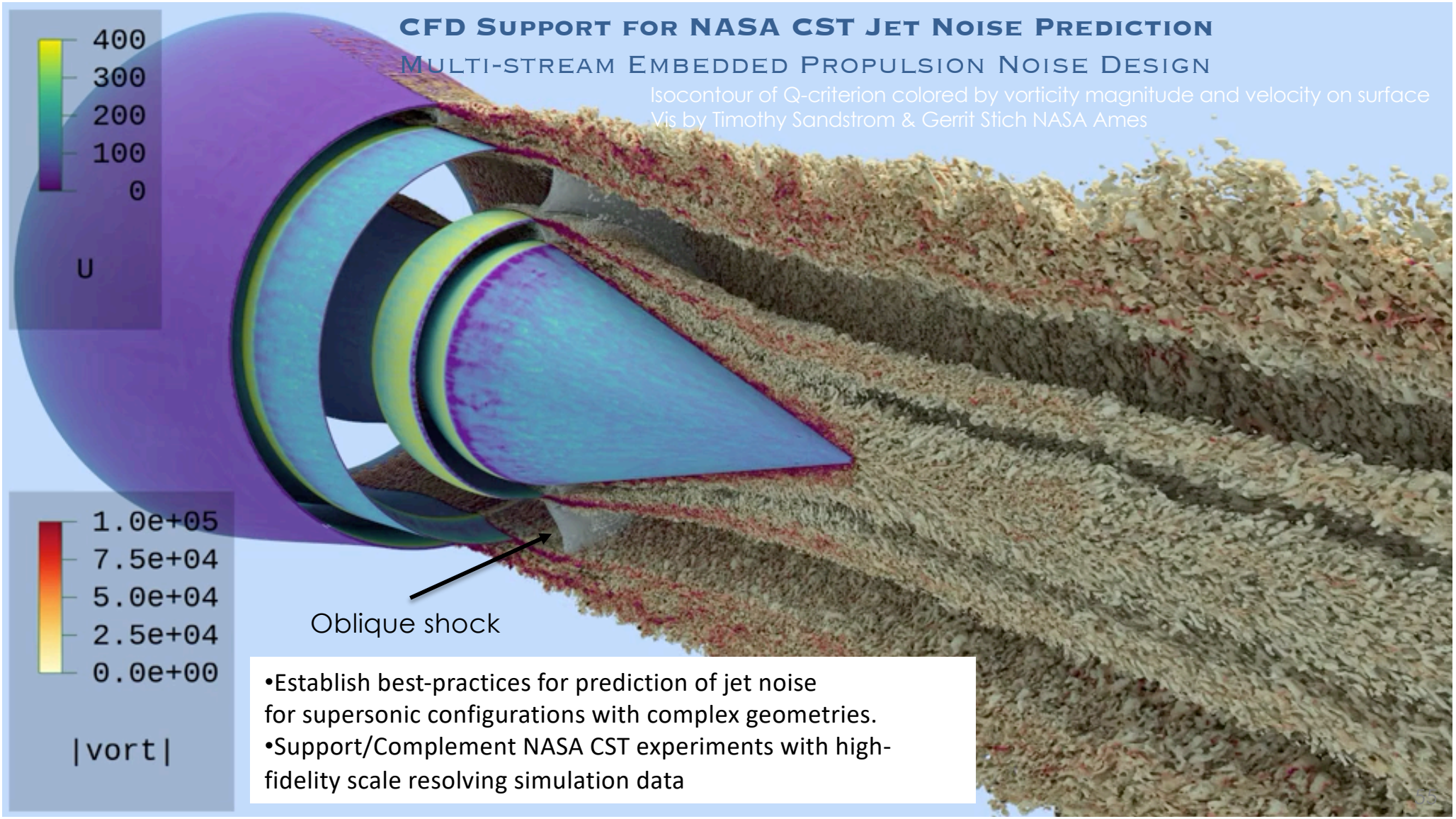




CFD Support for NASA CST Jet Noise Prediction

Multi-stream Embedded Propulsion Noise Design

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface
Vis by Timothy Sandstrom & Gerrit Stich NASA Ames

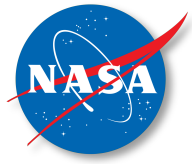


- Establish best-practices for prediction of jet noise for supersonic configurations with complex geometries.
- Support/Complement NASA CST experiments with high-fidelity scale resolving simulation data

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Questions?



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