In-Tunnel CFD Simulation of the HL-CRM in the LaRC 14 x 22 ft. Wind Tunnel – Part I: Empty Tunnel Simulation Approaches and Verification Using TAU-DRSM

R. Rudnik, S. Melber-Wilkending

DLR, Institute of Aerodynamics and Flow Technology

Braunschweig, Germany

109th NIA CFD Seminar, Hampton VA, 14.03.19

NATIONAL INSTITUTE OF AEROSPACE

DLR

Outline

- Objectives and background
- In-tunnel simulation approaches
- Numerical method
  - Flow solver, turbulence modelling, boundary conditions
  - Grid generation
- Method verification / validation for empty tunnel computations
- Conceptual variations of numerical set-up (inlet boundary condition, diffusor cutback)
- Grid resolution study
- Conclusion and next steps

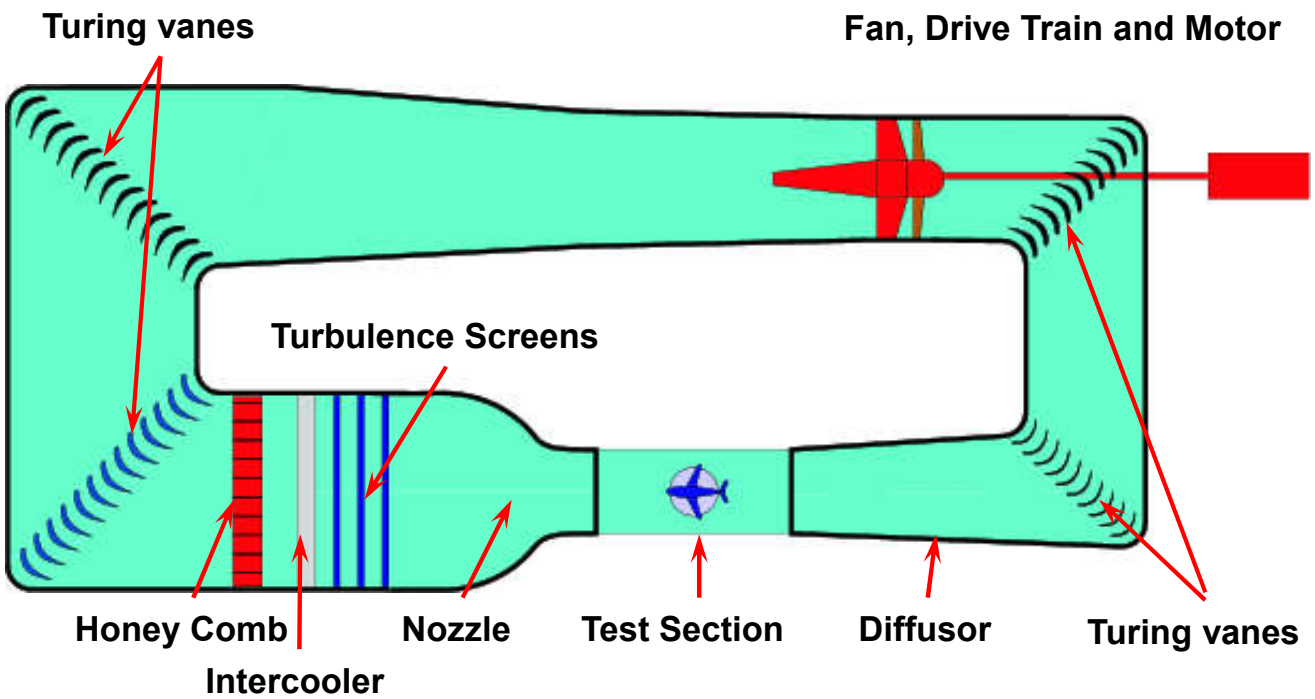
Objective and background

- **AIAA High Lift Prediction Workshop Series**
  - initiated 2010 by Boeing and NASA
  - Objective: Assess numerical prediction capability of current-generation CFD algorithms/codes commercial aircraft high-lift configurations
  - Workshops in 2010 (Chicago), 2013 (San Diego), 2017 (Denver)
  - Preparation for the HiLiftPW IV (2021) ongoing
  - Present investigation intended to prepare 1 of 8 focus problems “in-tunnel runs” (HL-Common Research Model in NASA 14 x 22 ft. wind tunnel)

- **NATO AVT-284 Workshop on Advanced Wind Tunnel Boundary Simulation**
  - held in spring 2018 (Torino, Italy)
  - Objectives: Evaluate high-fidelity CFD simulation of wind tunnel wall boundaries, installation effects (e.g. support hardware) and compare with established results
  - Develop recommendations for the use of high fidelity simulation of wall boundaries and model support hardware

In-Tunnel Simulation Approaches

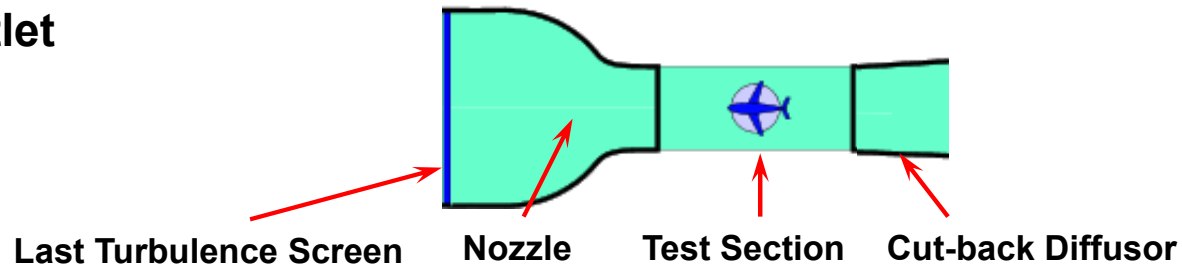
- Approach I: simulate full airline and all components
- Approach II: reduce to test section
- Approach III: simulate “essential” components (part of settling chamber, nozzle, test section, part of diffusor) adopted for DLR in-tunnel simulation approach



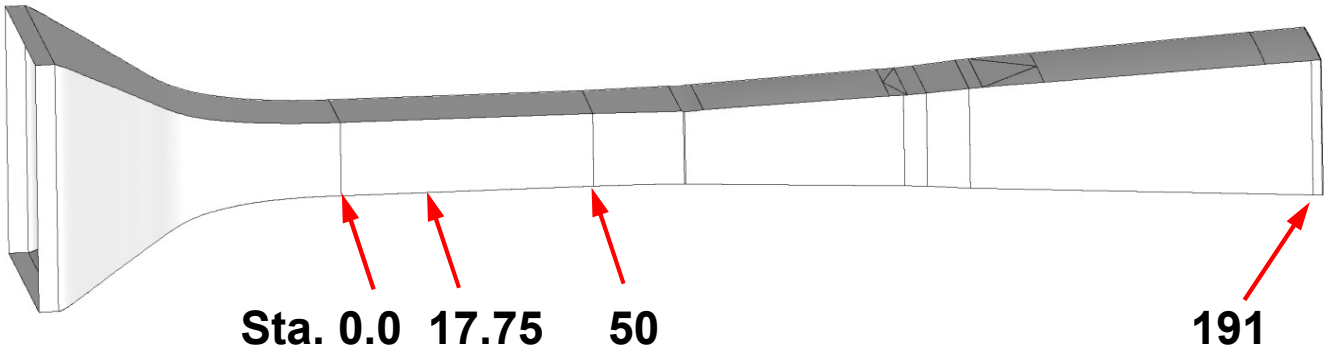
In-Tunnel Simulation Approaches

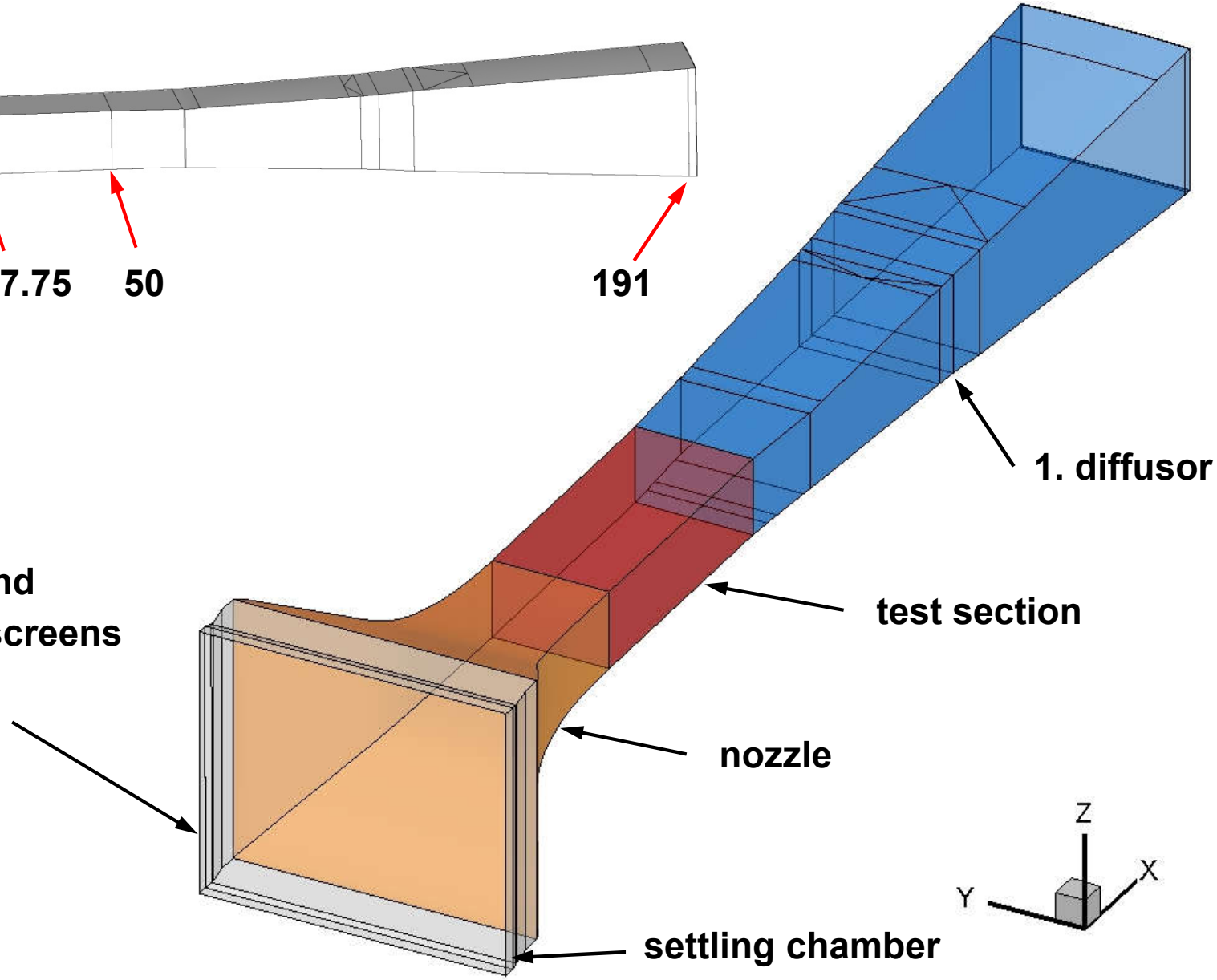
- Approach III: simulate essential components
  - pro: moderate numerical effort
  - pro: adequate specification and simulation of incoming boundary layer possible
  - pro: tunnel control inflow / outflow simulated according to real tunnel operation
  - con: inflow specification requires adaptation due to cut-off of the airline

- Sensing and control of operational conditions elaborated
  - Establish a numerical 'device' that allows b.l. to develop downstream of the last turbulence screen
  - Upstream flow condition sensors
  - Set-up sensor driven control loop to adjust flow conditions by manipulating back pressure at the outlet



NASA LaRC 14 x 22 ft. High Speed Leg





Numerical Method - Flow Solver

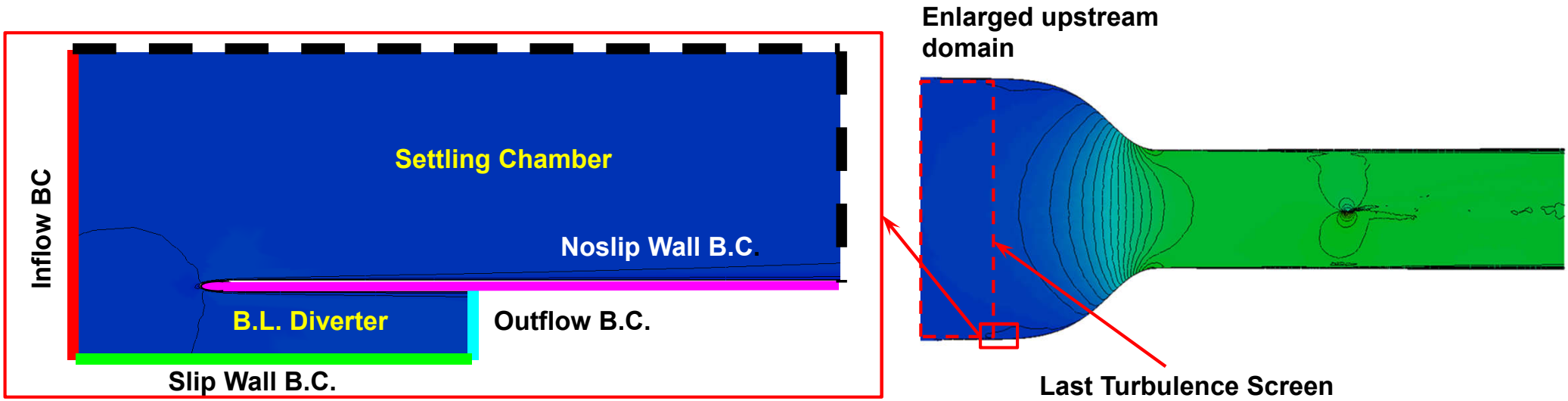
TAU flow solver and features in use for present studies

- DLR TAU code is an edge-based, finite volume, unstructured flow solver (DV 2018.1.0)
- Full NS Discretization
- Spatial Discretization - main eq.: Jameson central, 2nd order;
  blend scalar (20%) – matrix (80%) dissipation
  - turbulence eq.: AUSMDV upwind, 2nd order
- Temp. Integration: - LU-SGS Backward Euler, 2V MG cycle
- Turbulence modeled by differential SSG/LRR RSM developed at DLR (Eisfeld, Braun)
  - pressure-strain correlation is modeled by a blend of correlations derived by Speziale, Sakar, Gatski and Launder, Reece, Rodi (for near wall treatment)
  - blending accomplished by F-function according to Menter's BSL model
  - diffusion term modeled via generalized gradient diffusion model (Daly and Harlow)
  - ω- based length scale equation blended acc. to Menter's BSL formulation (ω , g)
  - present computations based on new formulation $\hat{\omega} = ln(\omega)$
    coupling to Reynolds stress equations using $\omega = e^{\hat{\omega}}$

Numerical Method - Boundary Conditions

Sensor / b.c. setup to control adequate adjustment of flow conditions: **Inlet**

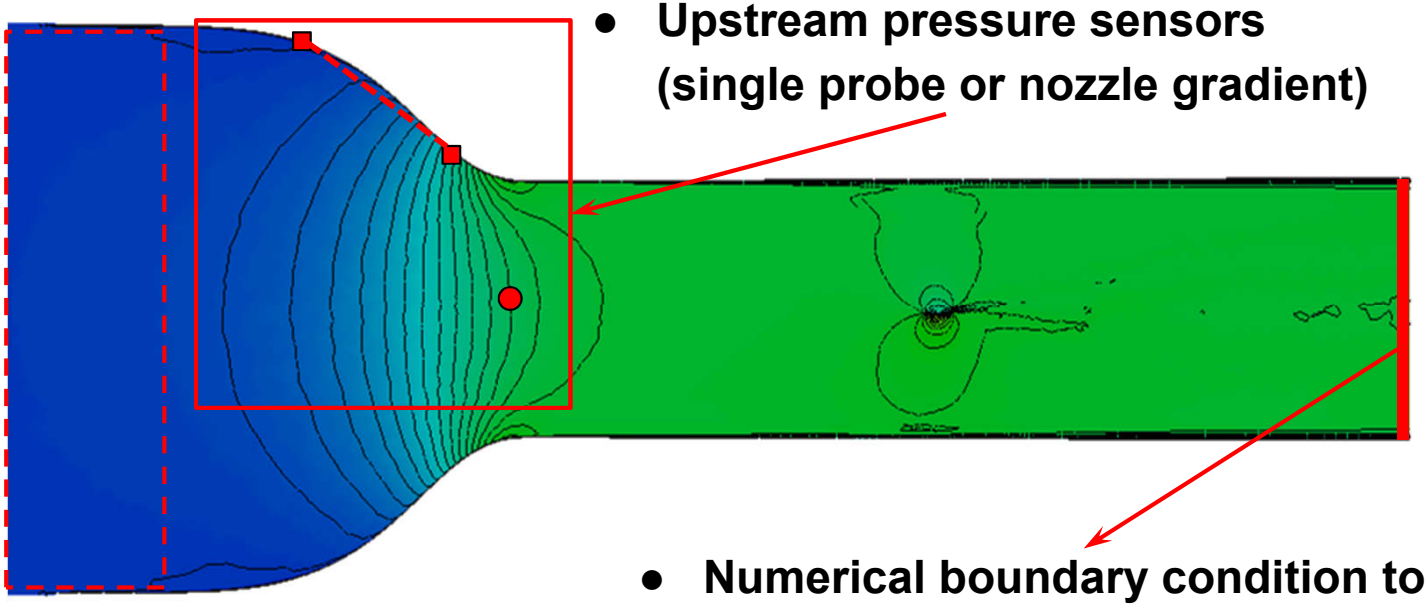
- Constant pressure across inlet plane assumed - not fulfilled for x-location at turbulence screen #3 due to upstream effects of nozzle pressure field
- Inlet plane artificially extended to justify assumption
- p_t and Tt prescribed according to w/t specification of reference flow conditions
- Adequate initializing wall boundary layer by introducing a numerical diverter controlled by outflow pressure (below diverter). Static pressure at b.c. adjusted to pressure at tunnel axis (relaxation introduced)



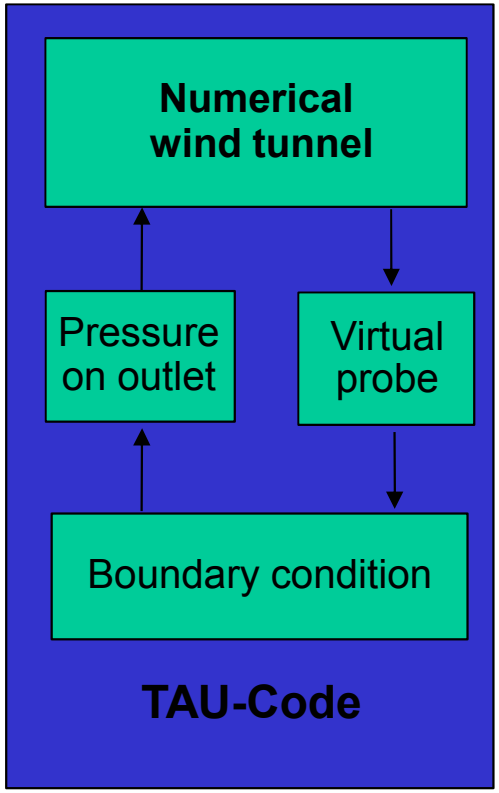
Numerical Method - Boundary Conditions

Sensor/b.c. setup to control adequate adjustment of flow conditions: **Outlet**

- **Static ("back") pressure used to adjust flow conditions according to specification and compensate losses.**
- **Control loop scenario to adjust flow conditions based on nozzle pressure sensors including PT1 damper (controlling parameters and relaxation carefully adapted)**



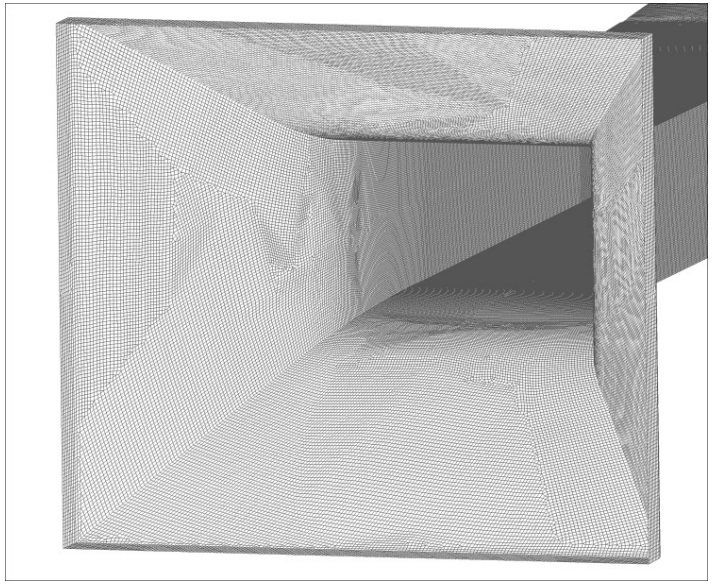
- **Upstream pressure sensors (single probe or nozzle gradient)**
- **Numerical boundary condition to adjust flow conditions by static pressure at the outlet**

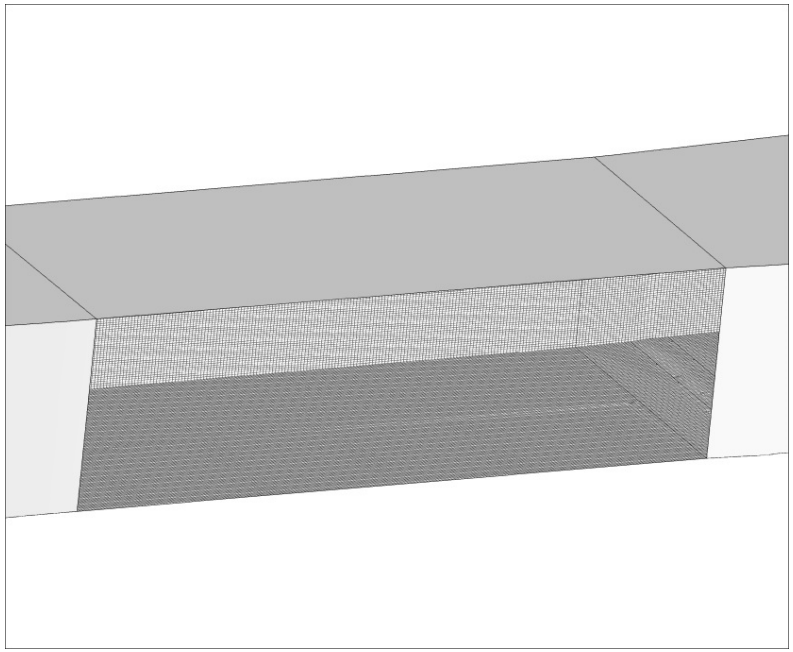


Numerical Method - Grid Generation

Commonly used SOLAR features

- Developed by ARA, QinetiQ, Airbus, BAE Systems to provide hybrid unstructured grids
- Surface discretization: mixed element, quad-dominant mesh
- Volume discretization: hex-dominant mesh near aerodynamic surfaces
- y^+ -manual adaptation, const. first cell height
- Special CAD-based treatment of grid refinement sources for improved surface discretization





Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

- **Objective Verify DLR TAU computational setup for in-tunnel CFD computations against published results of 2015 ASM, Vigyan, NASA Study of 14 x 22 ft. high speed leg Reference AIAA 2015-2022**

- **Numerical set-up used for AIAA 2015-2022:**
  - **Flow solver: NASA TetrUSS (FUN3D, USM3D)**
  - **SA-turbulence model**
  - **Grids: VGRID, hybrid unstructured, 5.6 x 10^6 grid pts., $y^* = 0.5$**
  - **Boundary conditions Inlet: subsonic inflow / jet b.c. (USM3D)**
    Outlet: backpressure b.c., p_s iterated to achieve target velocity

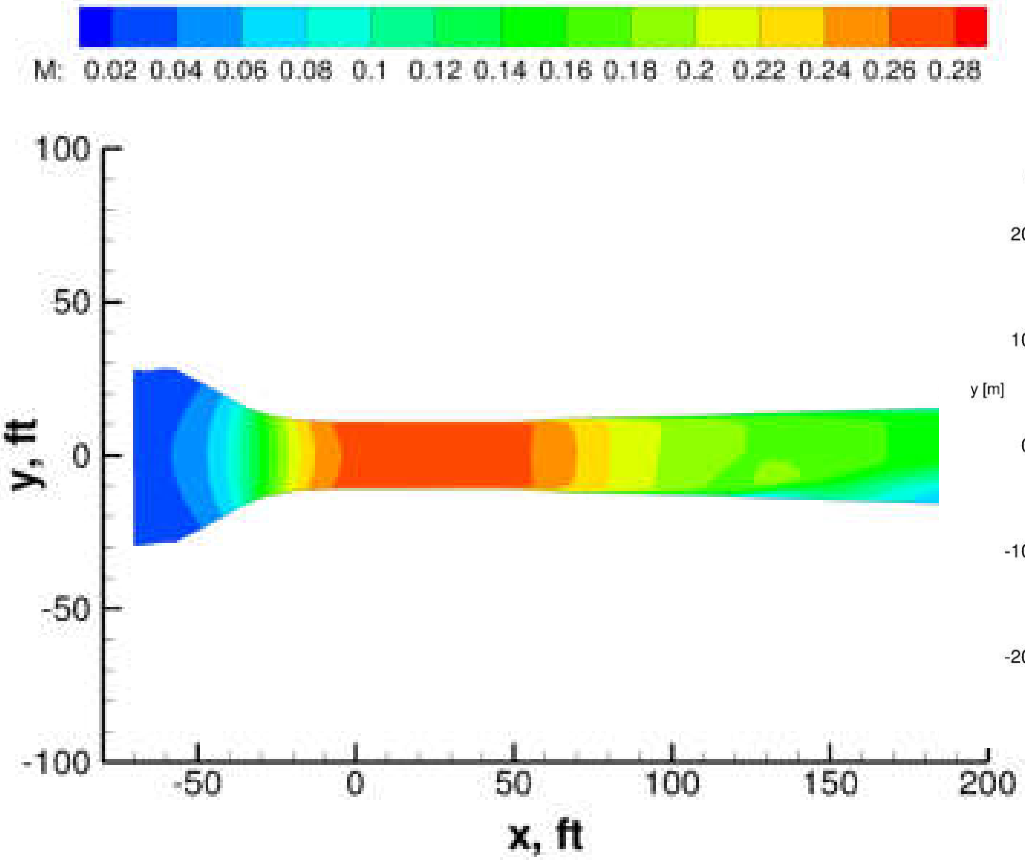
- **DLR computations:**
  - **Flow solver: TAU, set-up as described before**
  - **Grids: SOLAR hybrid unstructured, 28.0 x 10^6 grid pts. ("fine"), $y^* < 0.2$**
  - **Boundary conditions Inlet: subsonic inflow / jet b.c.**
    Outlet: backpressure b.c., p_s iterated via controller

- **Flow cons: M = 0.2678 q = 101.5 lb/ft^2 Re = 1.7108 x 10^6 per ft.**

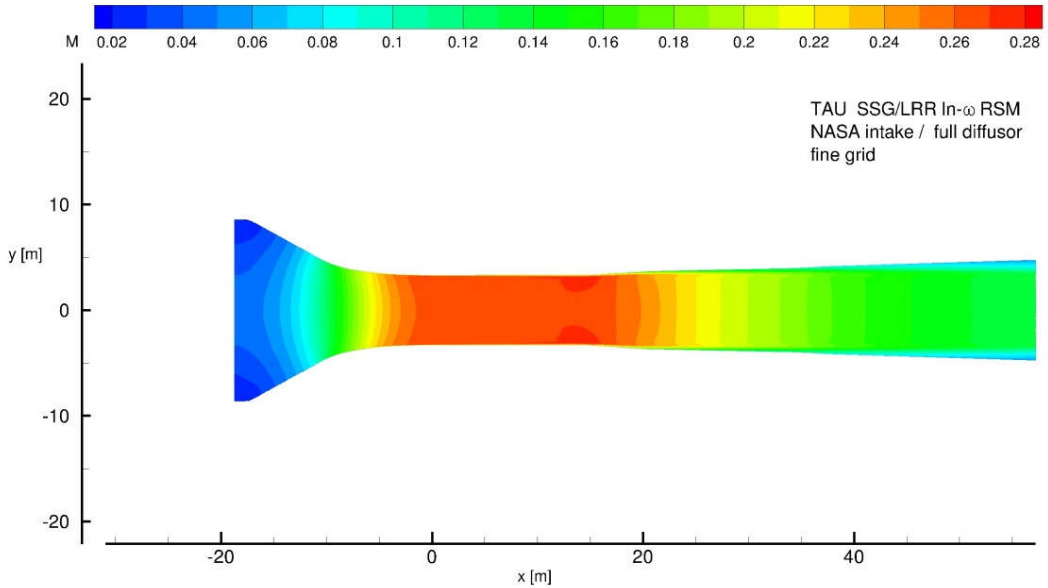
Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - FUN3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Mach conturs, horizontal plane at z = 0.0**



(a) USM3D

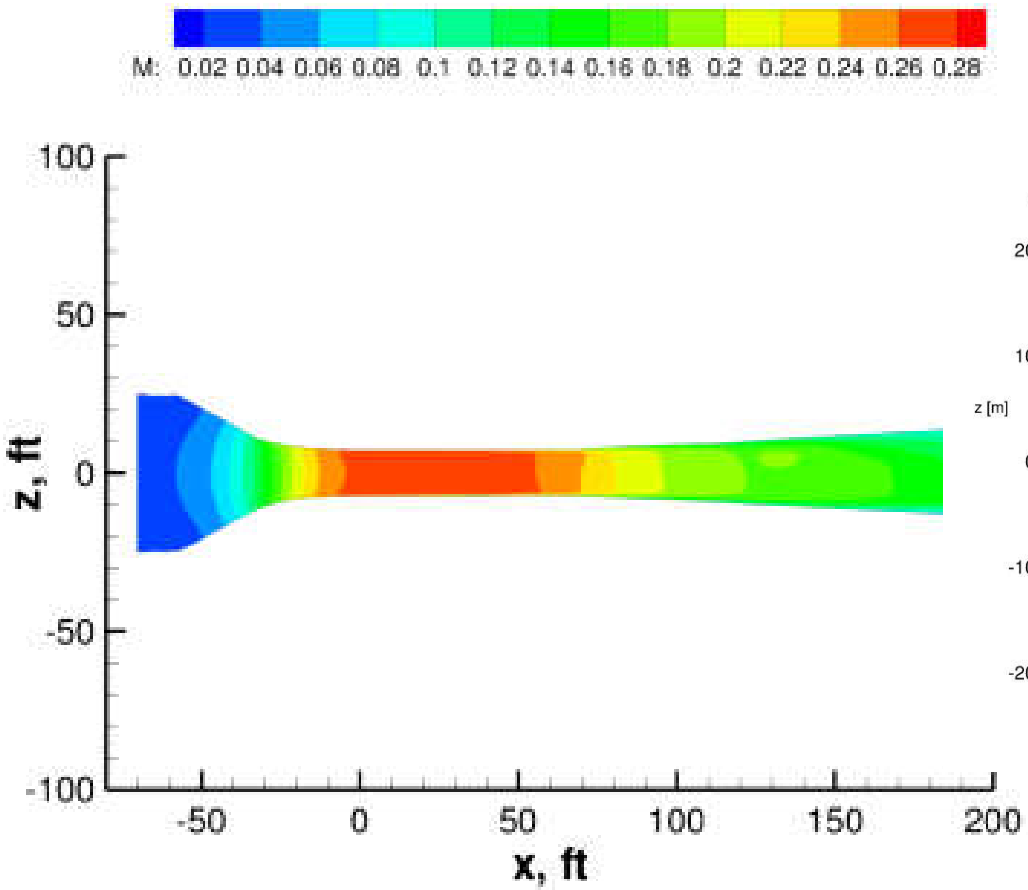


TAU DRSM

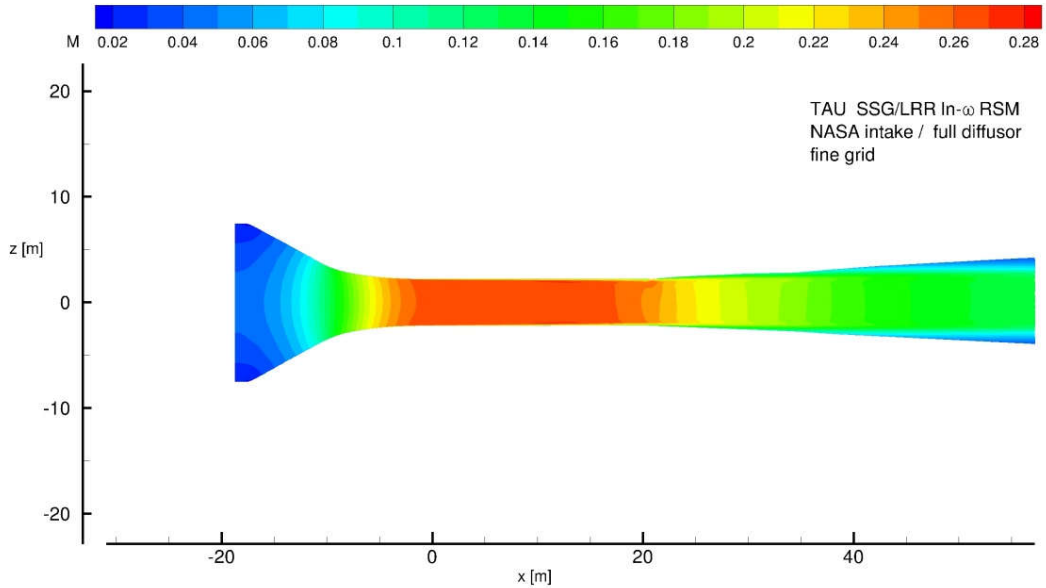
Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Mach conturs, vertical plane at y = 0.0**



USM3D

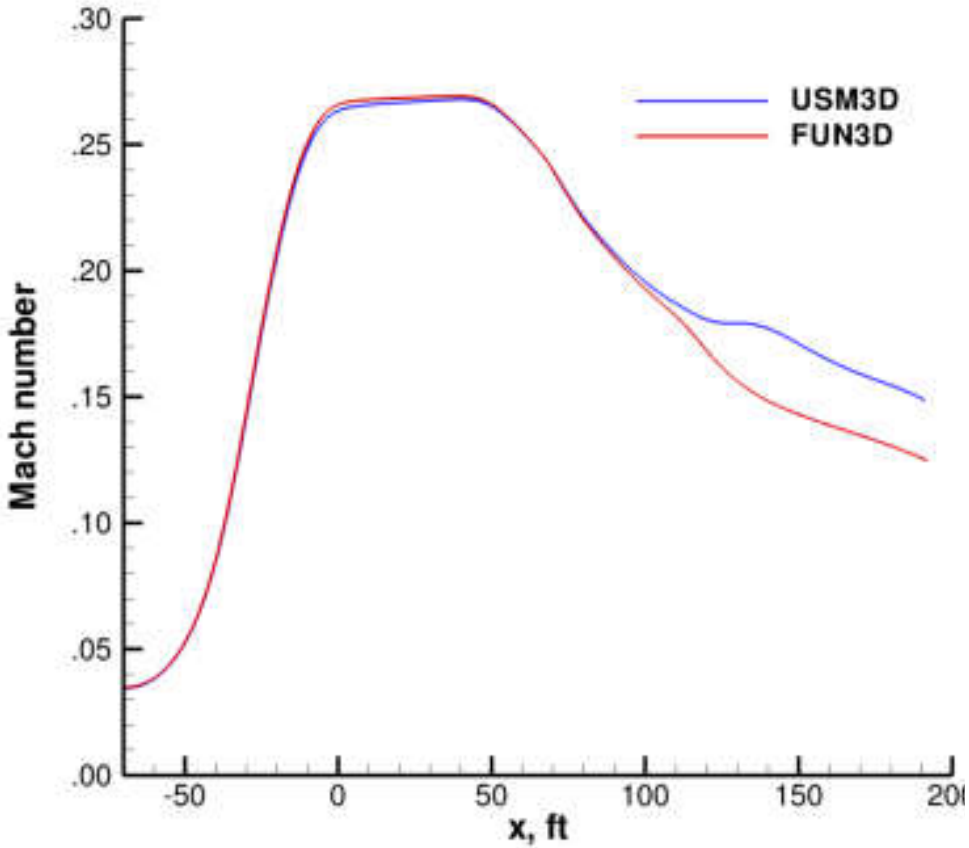


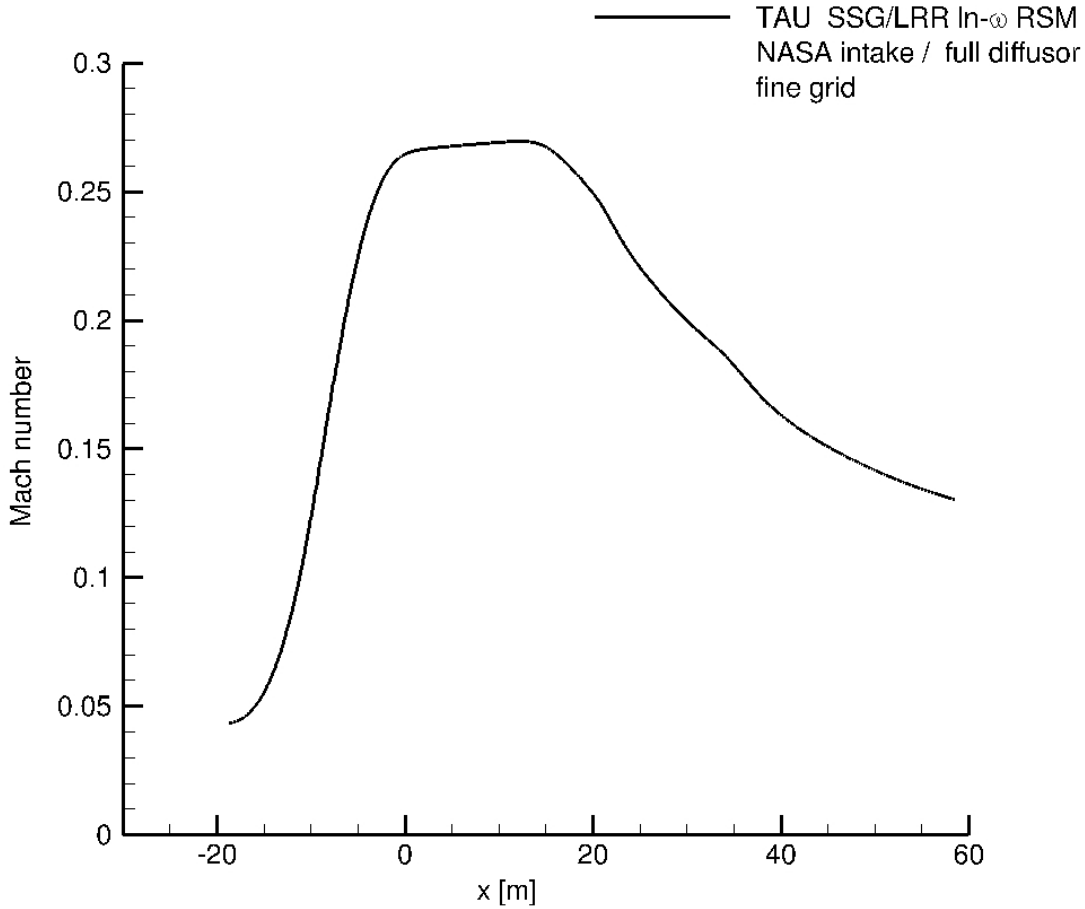
TAU DRSM

Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - FUN3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Centerline Mach profiles**

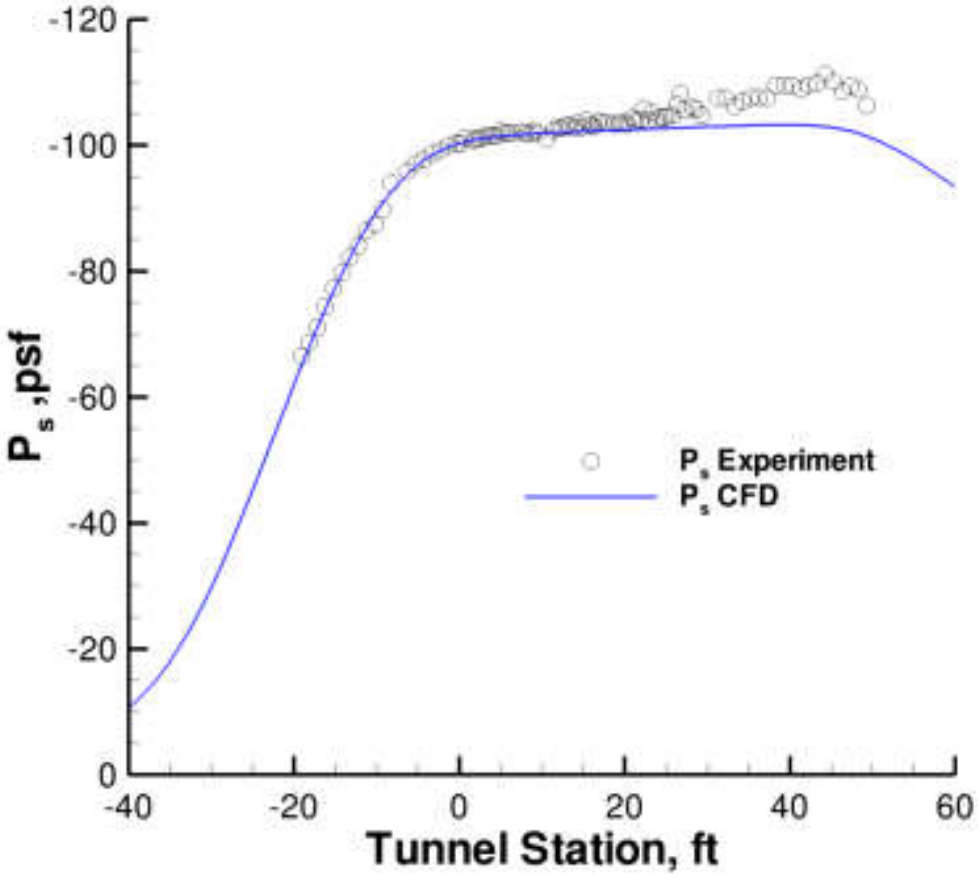


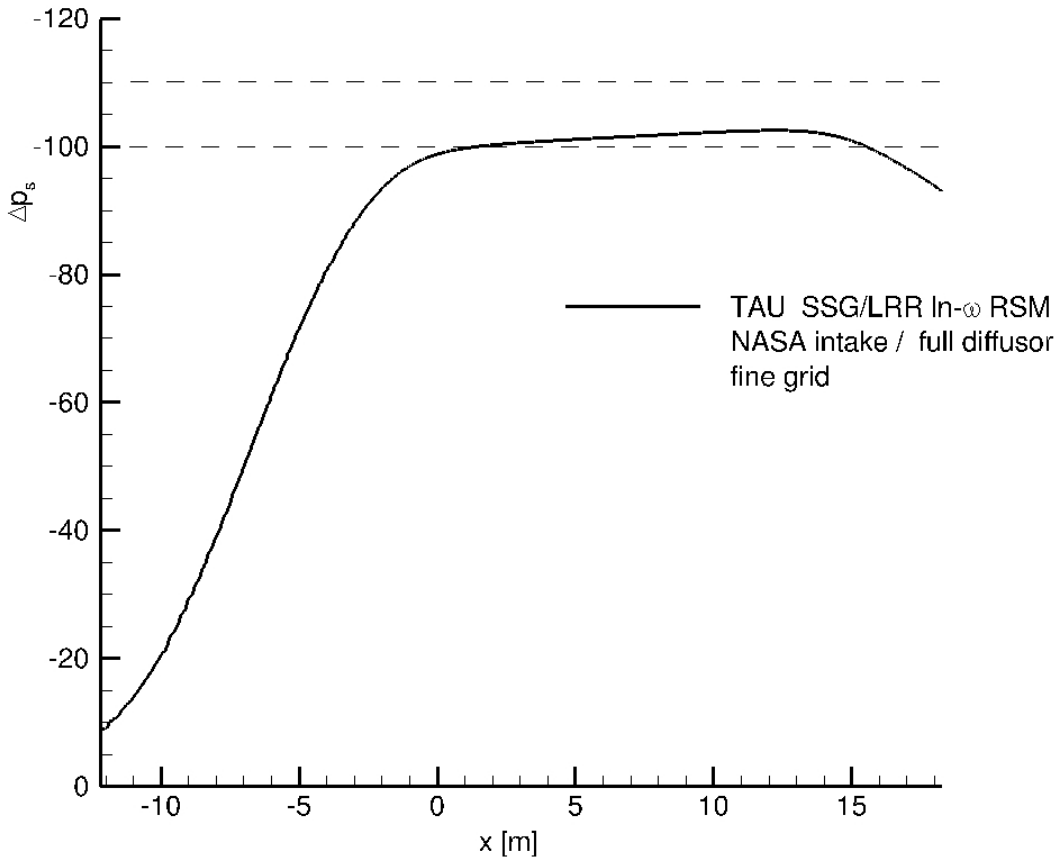


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Longitudinal pressure distribution**

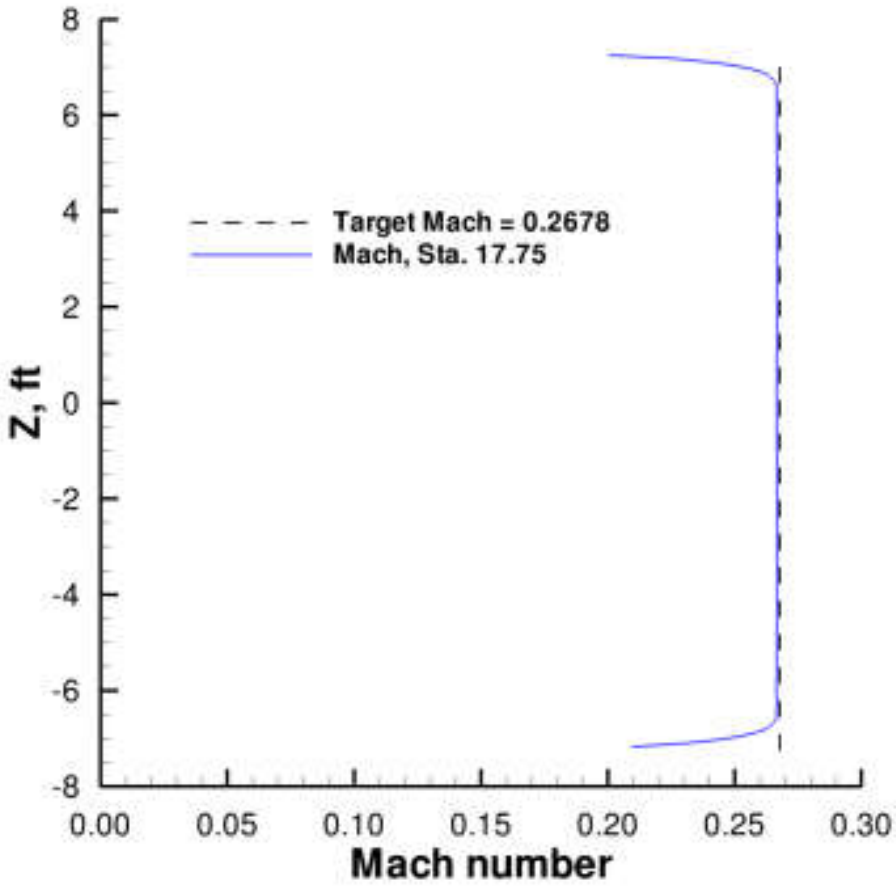




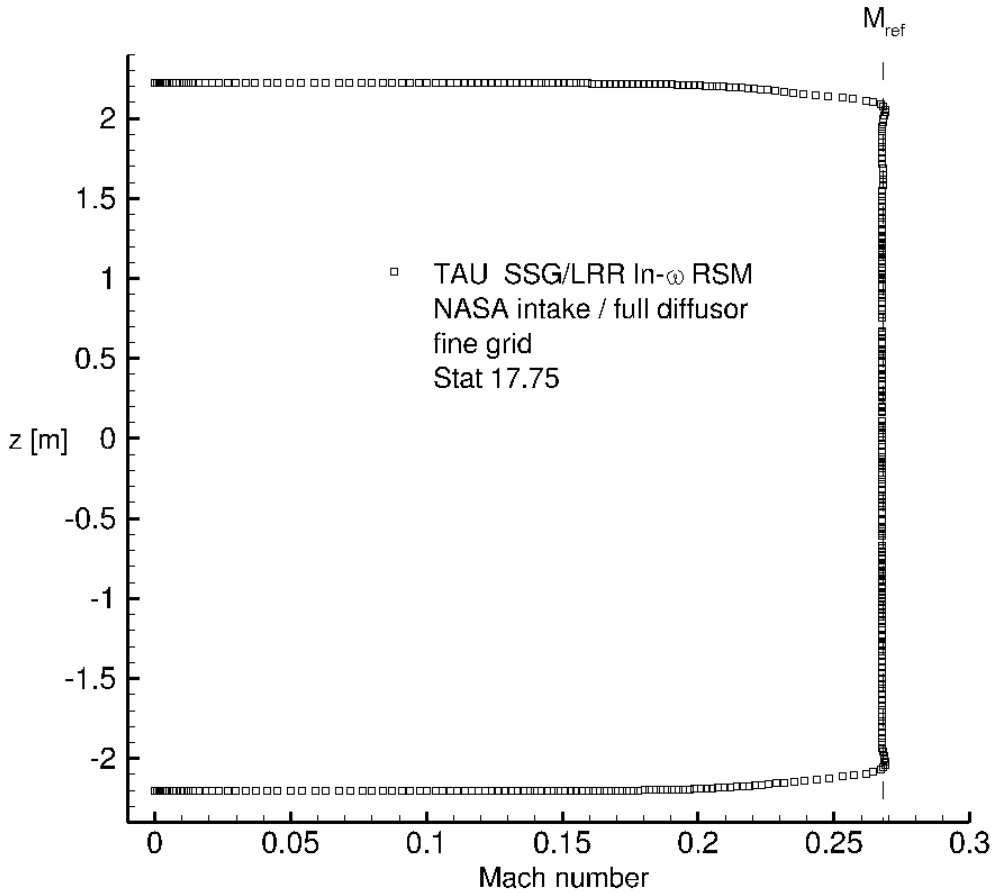
Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Wall-to-wall velocity profiles at x = 17.57 ft.**



(a) USM3D

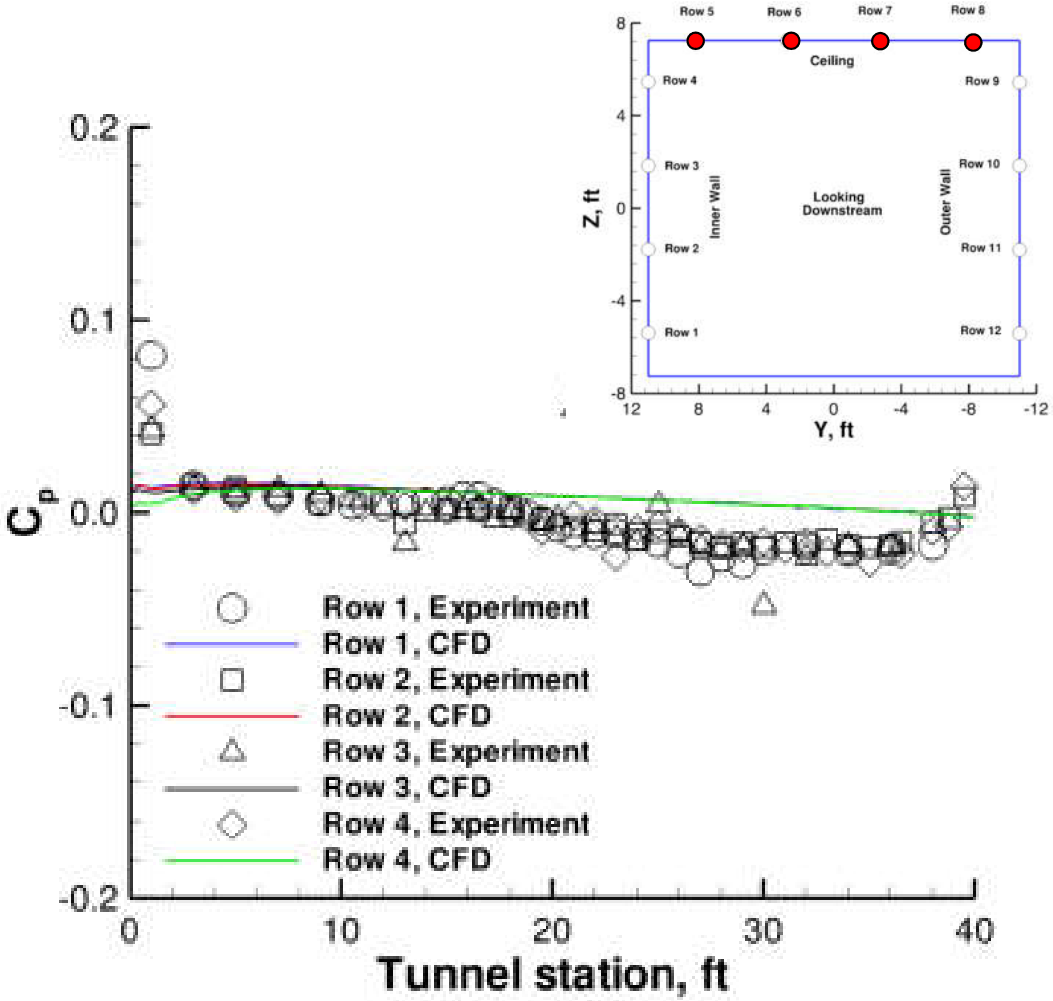


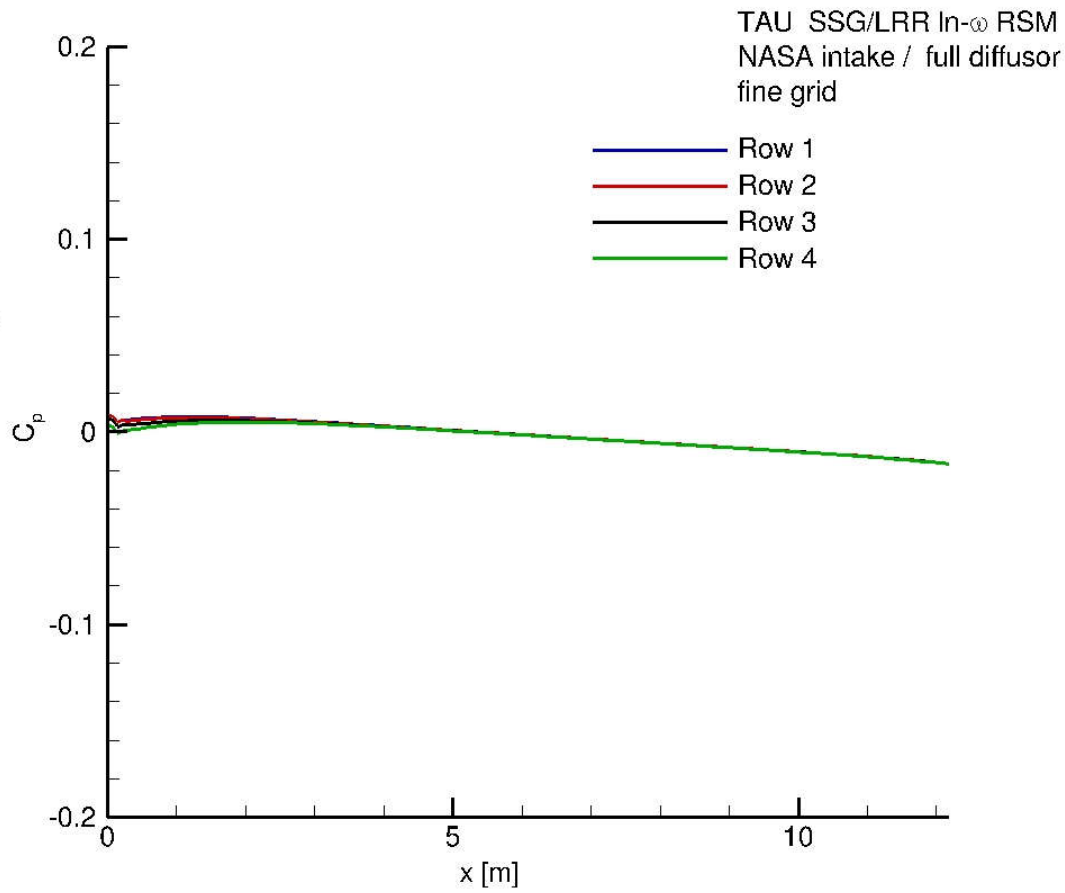
TAU DRSM

Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Wall pressure distributions: test section ceiling**

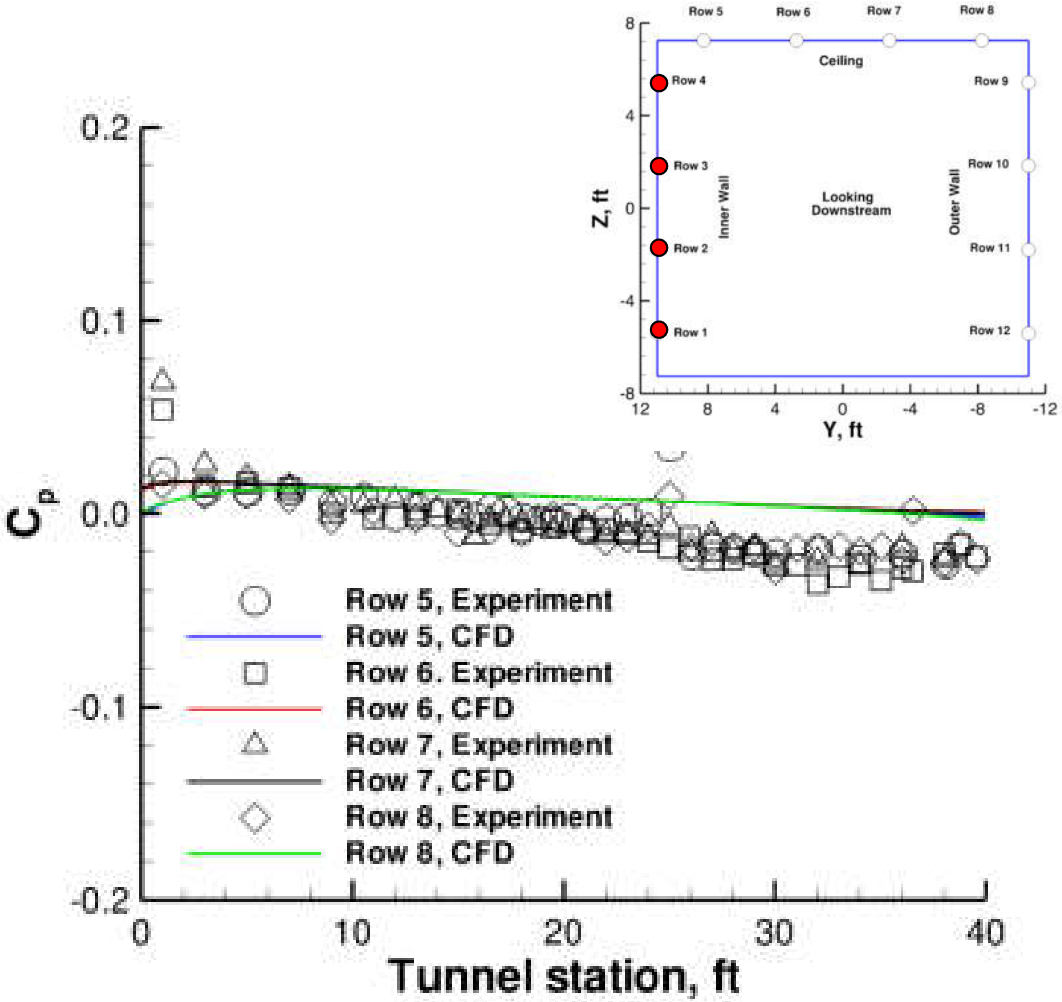


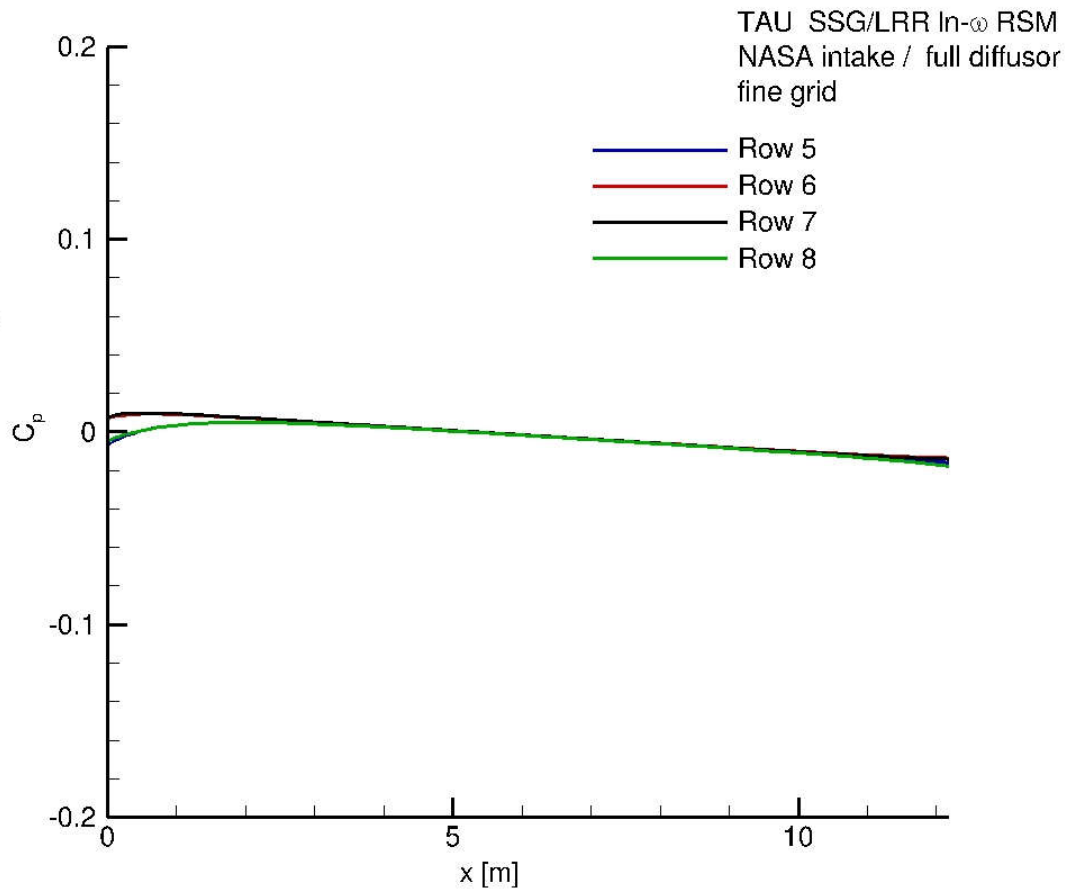


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Wall pressure distributions: test section inner wall**

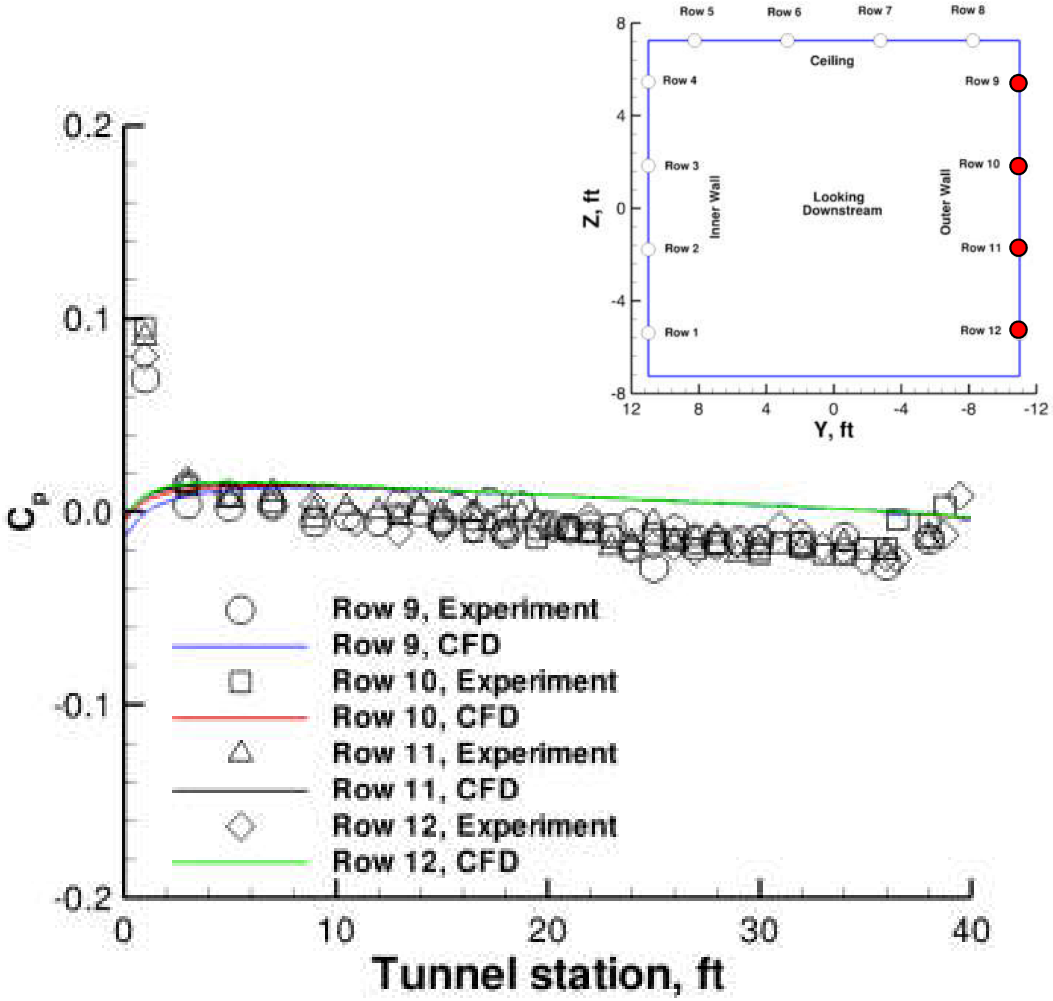


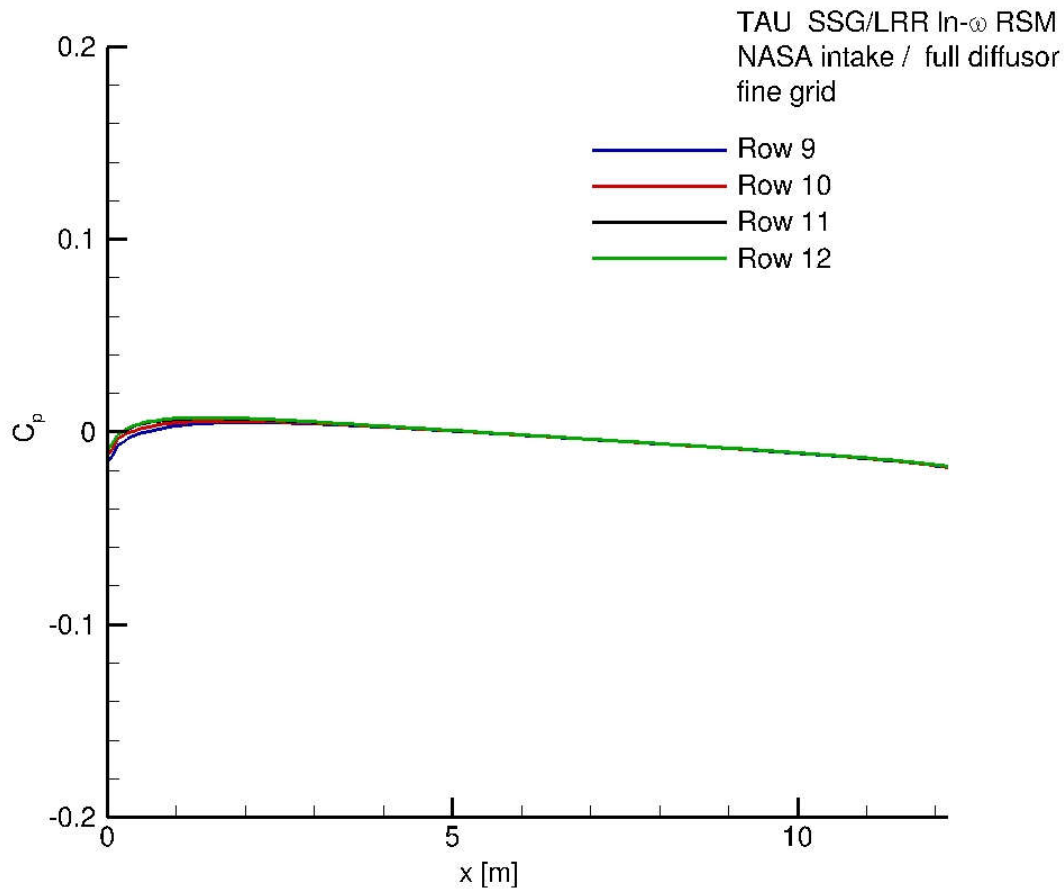


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Wall pressure distributions: test section outer wall**

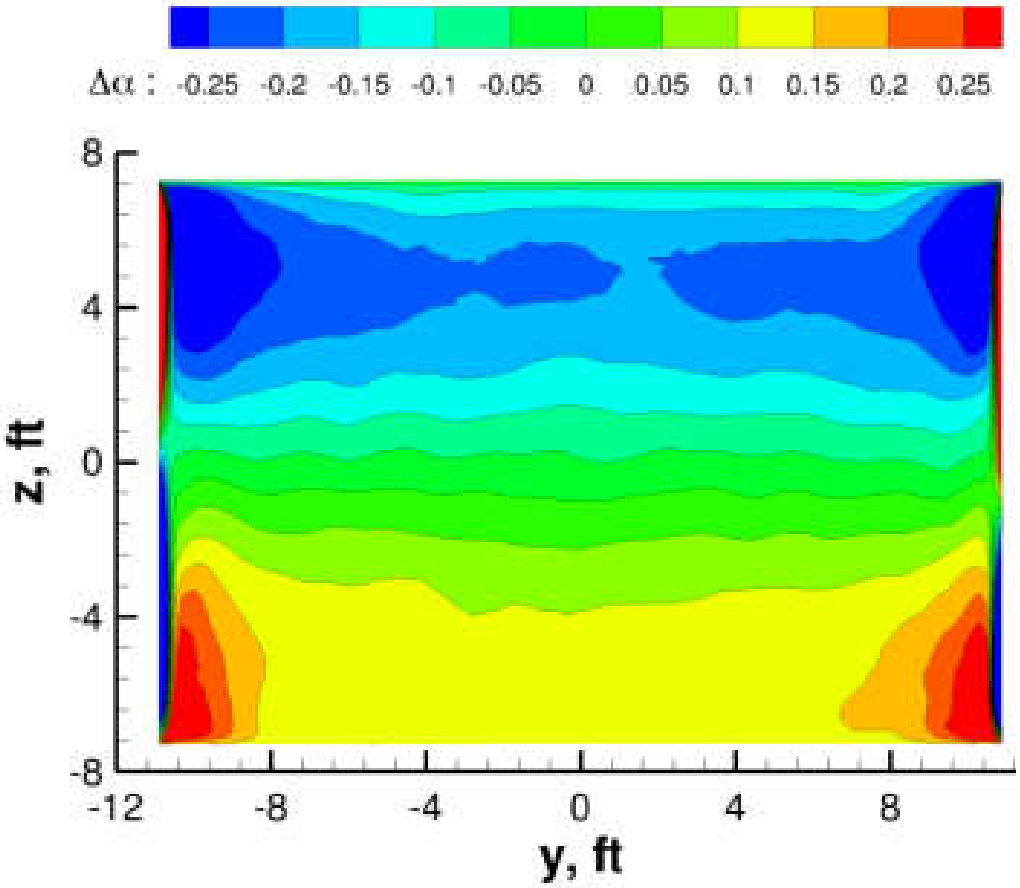


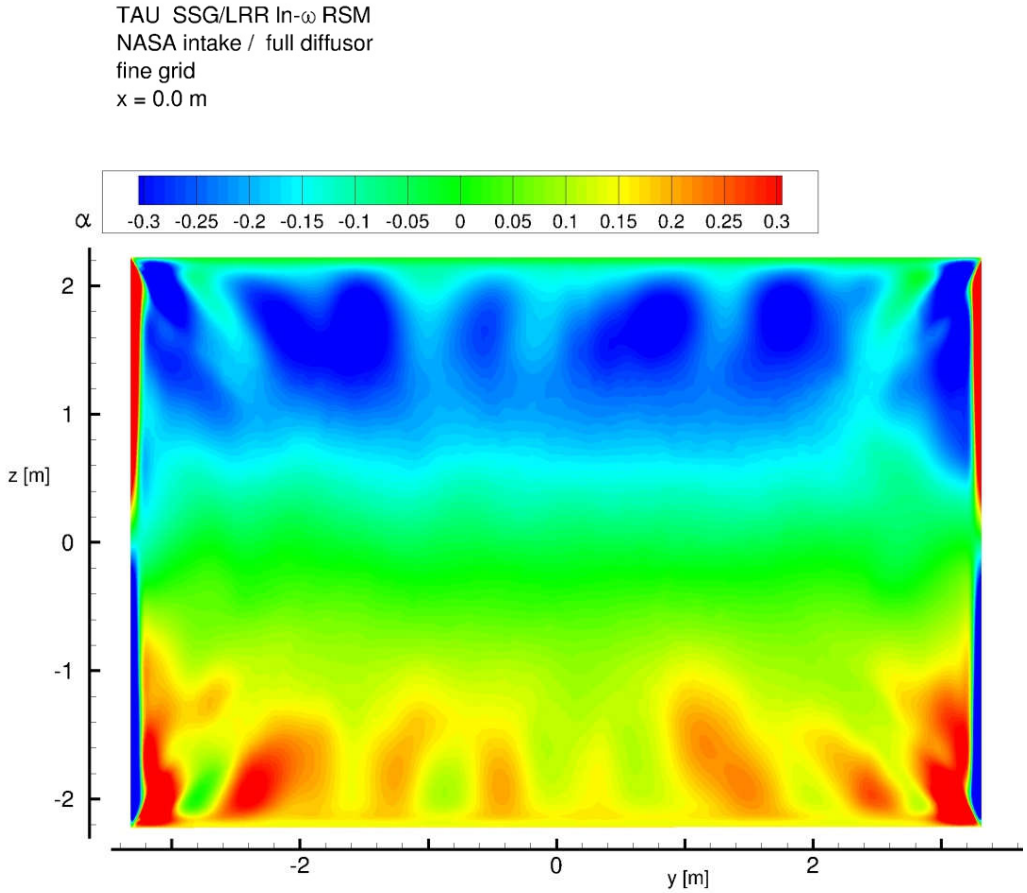


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Contours of upwash angle along test section at Sta 0.0**

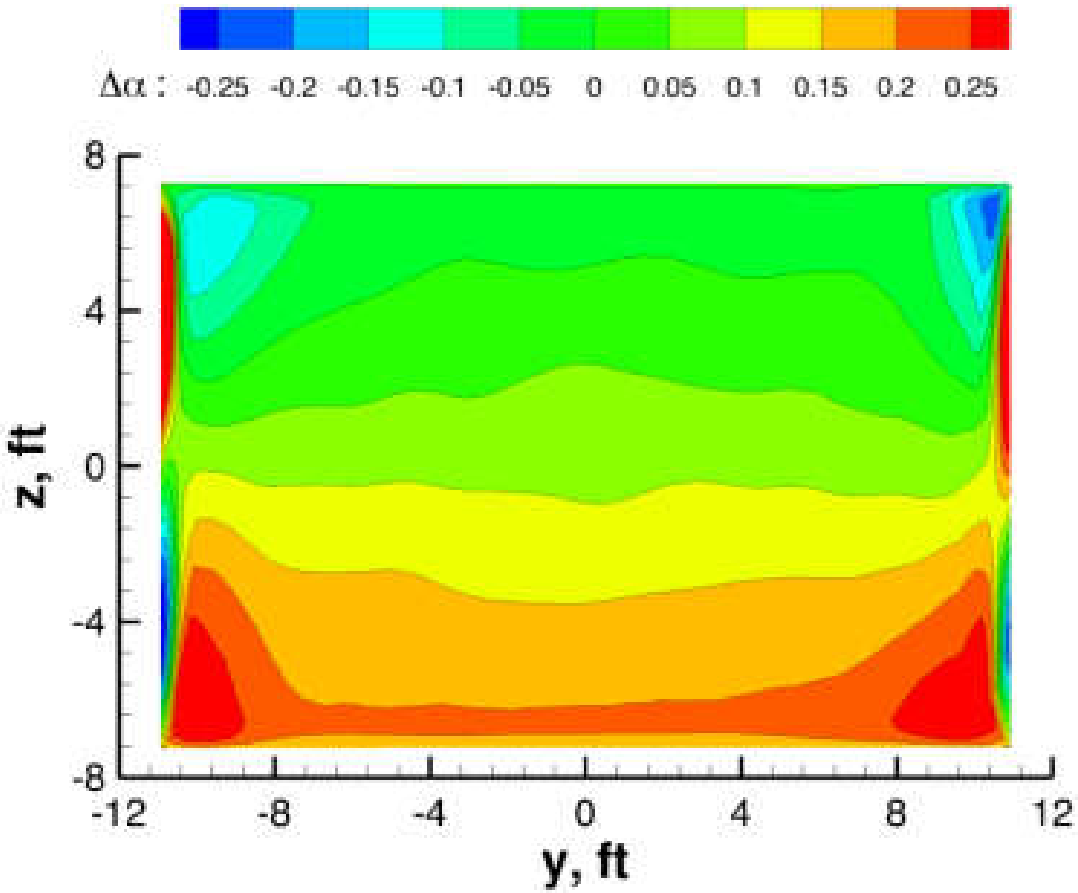


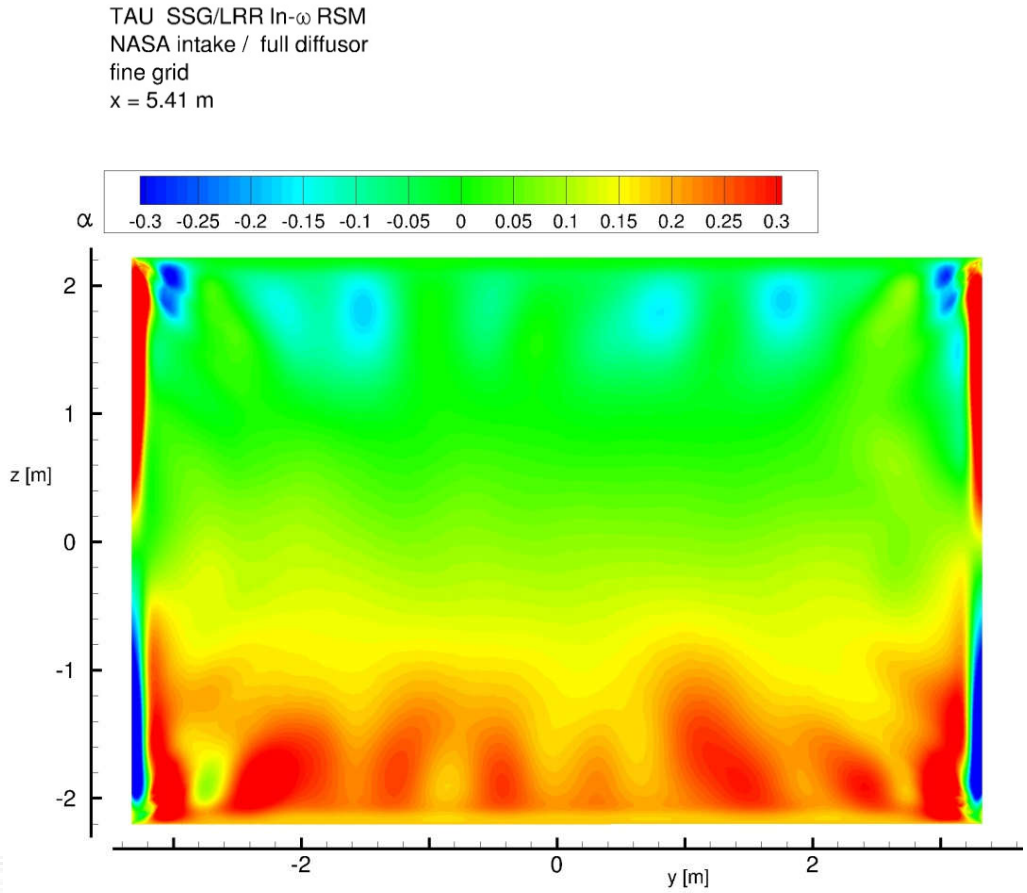


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Contours of upwash angle along test section at Sta 17.75**

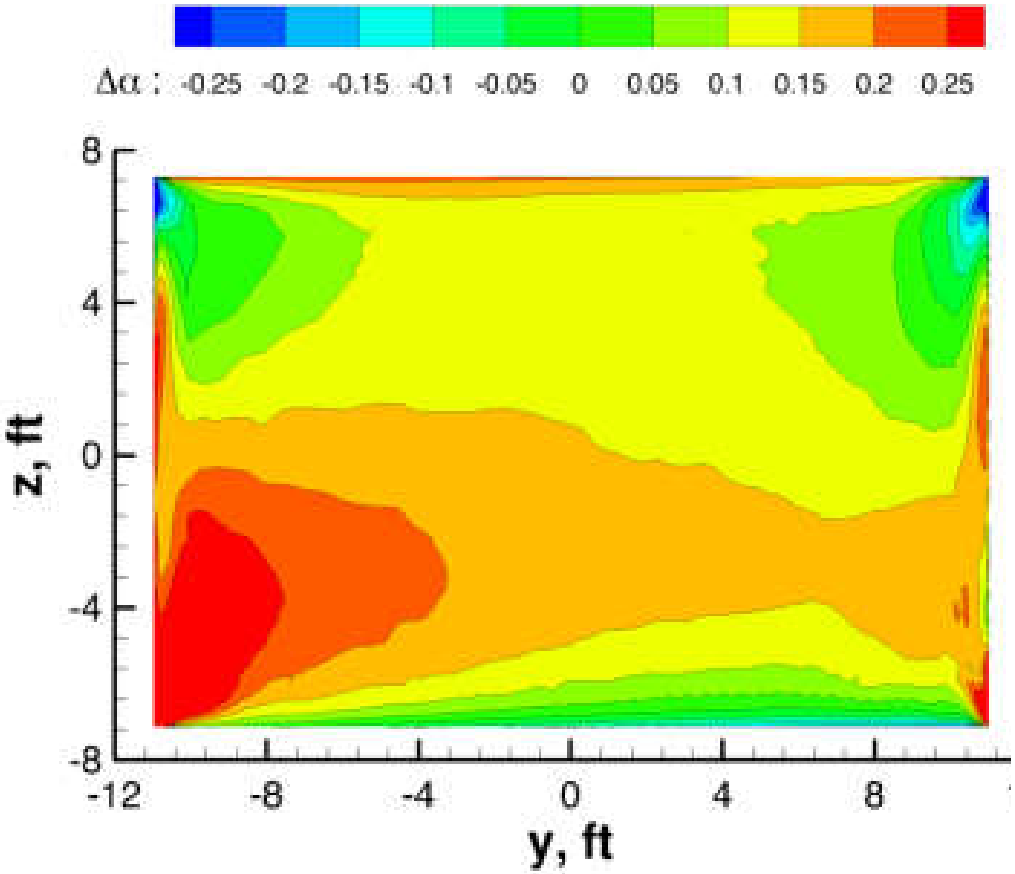


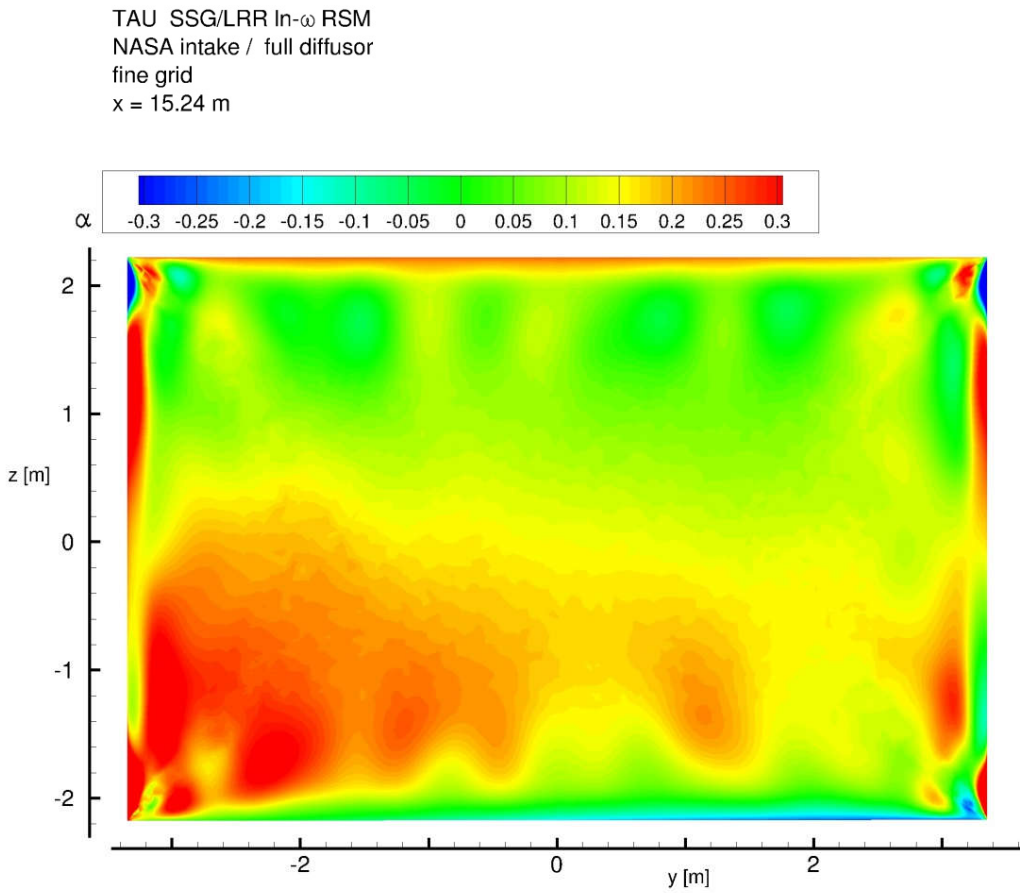


Verification / Validation TAU ET vs. ASM, Vigyan, NASA Study (AIAA 2015-2022)

USM3D (SA) - TAU (DRSM) using fine grid / NASA intake / full diffusor

- **Contours of upwash angle along test section at Sta 50**





Conceptual Variations of Numerical Set-up

- **Objective: analyze the impact of variations in the geometrical and numerical set-up on the numerical results for the empty-tunnel simulation**

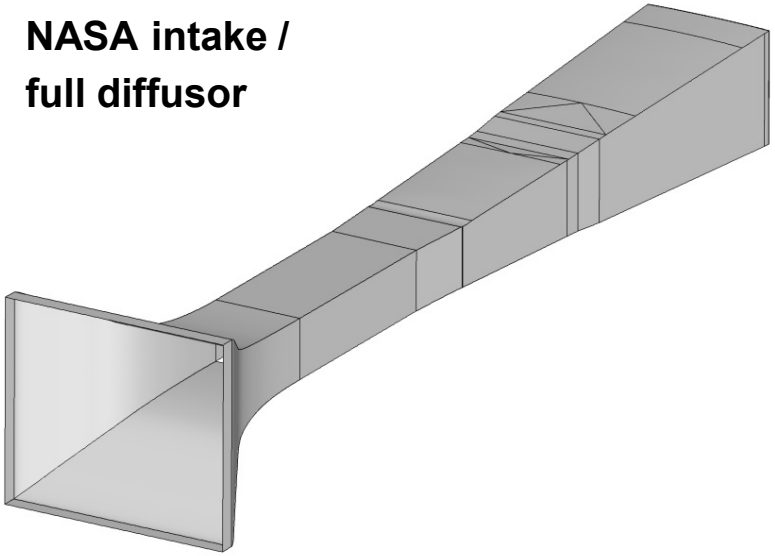
- Numerical set-up
  - Flow solver: TAU, set-up as described before
  - Grids: SOLAR hybrid unstructured, 28.0 x 10^6 grid pts. ("fine"), $y^* = < 0.2$
  - Boundary conditions Inlet: subsonic inflow
    Outlet: backpressure b.c., p_s iterated via controller

- **Variations considered**
  - **DLR inlet: extension to account for homogeneous flow assumption**
  - **Cut-back of the 1. diffusor from 192 ft. to 72 ft.**

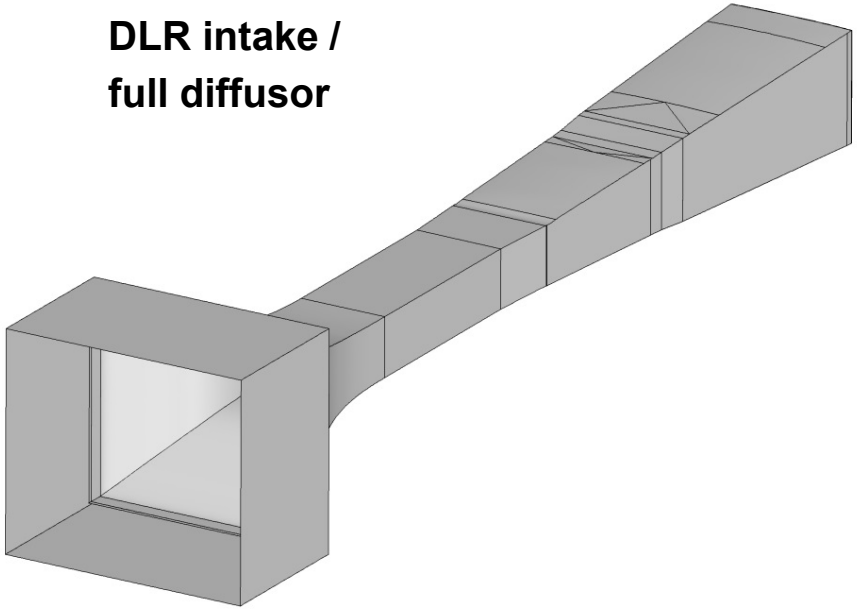
- Flow cons: M = 0.2678 q = 101.5 lb/ft^2 Re = 1.7108 x 10^6 per ft.

Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

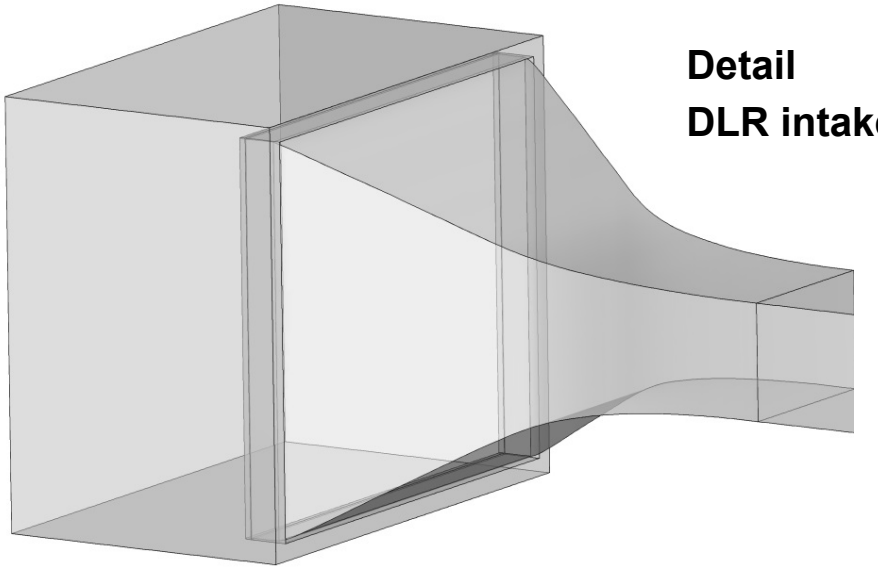
NASA intake / full diffusor



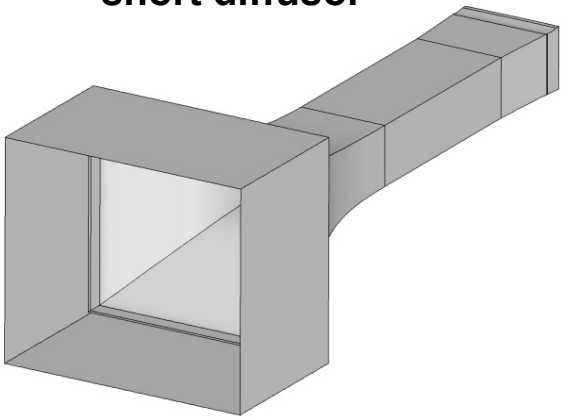
DLR intake / full diffusor



Detail DLR intake



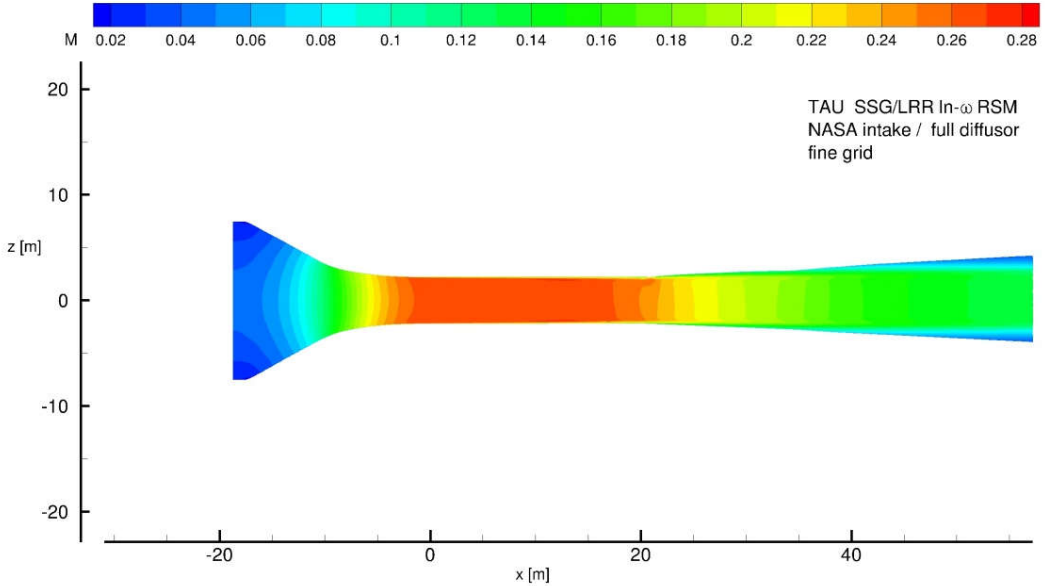
DLR intake / short diffusor

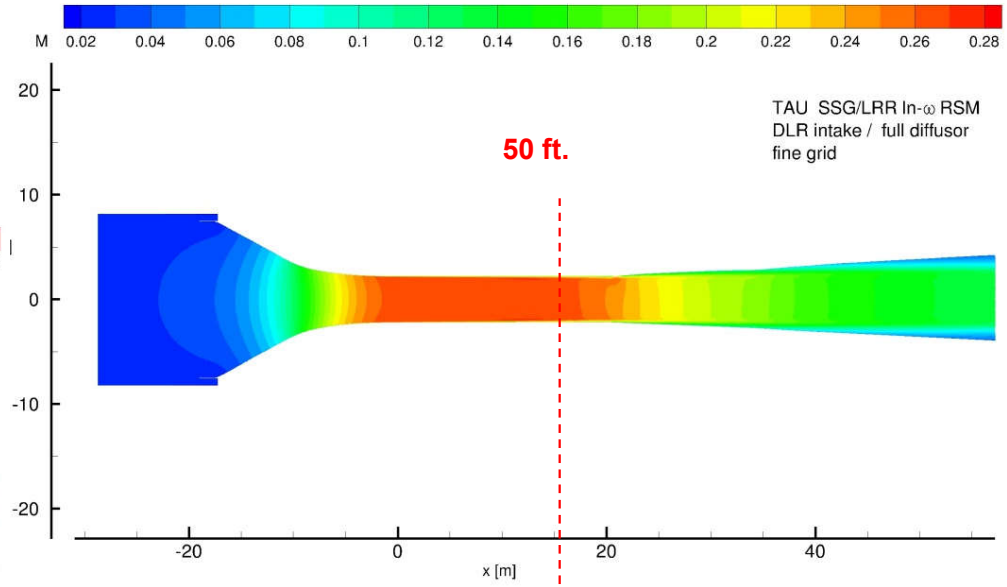


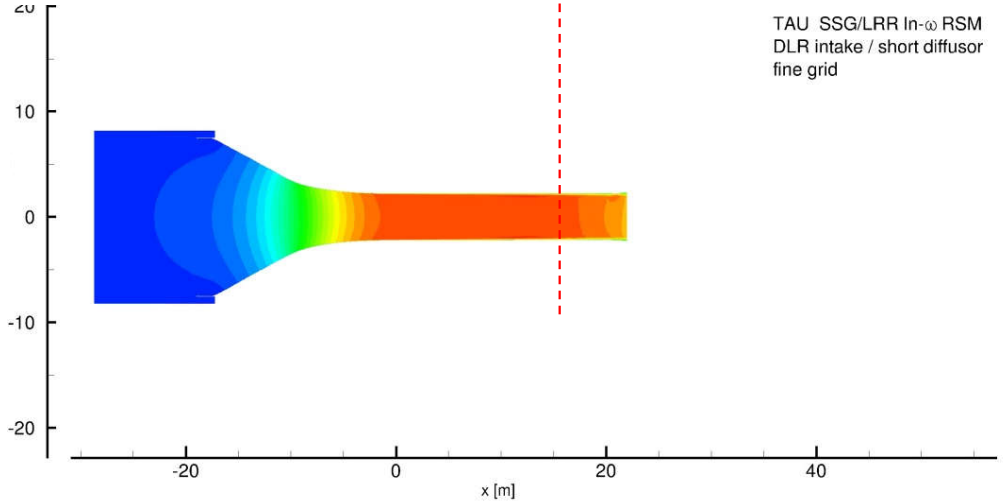
Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

TAU (DRSM) using fine grid for variations of intake and diffusor

- **<u>Mach conturs, vertical plane at y = 0.0</u>**



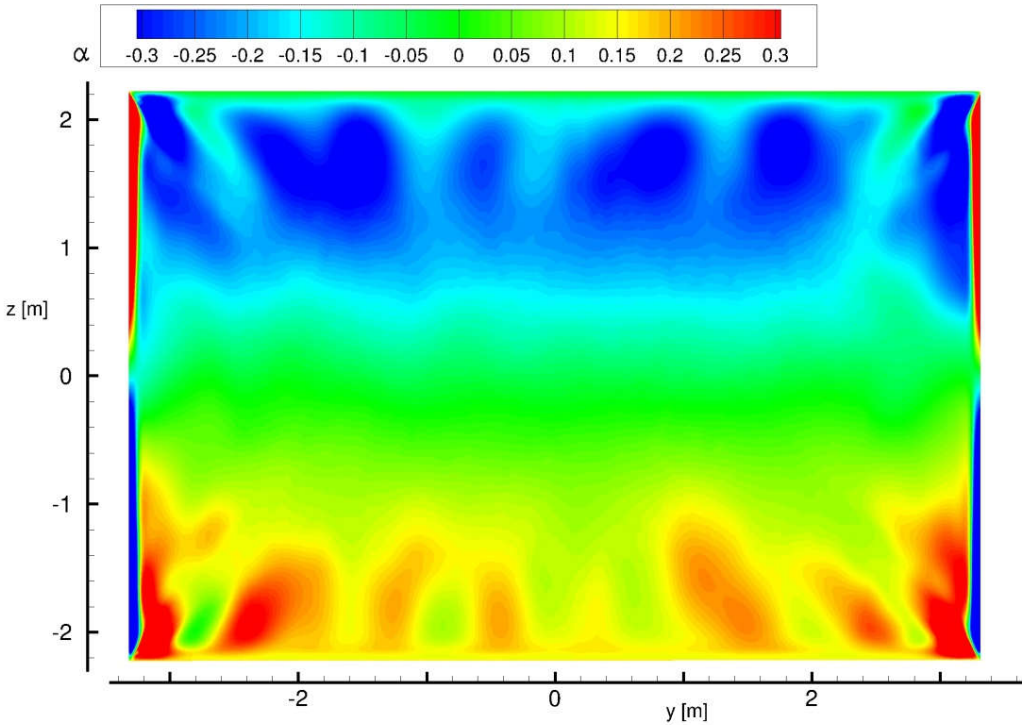




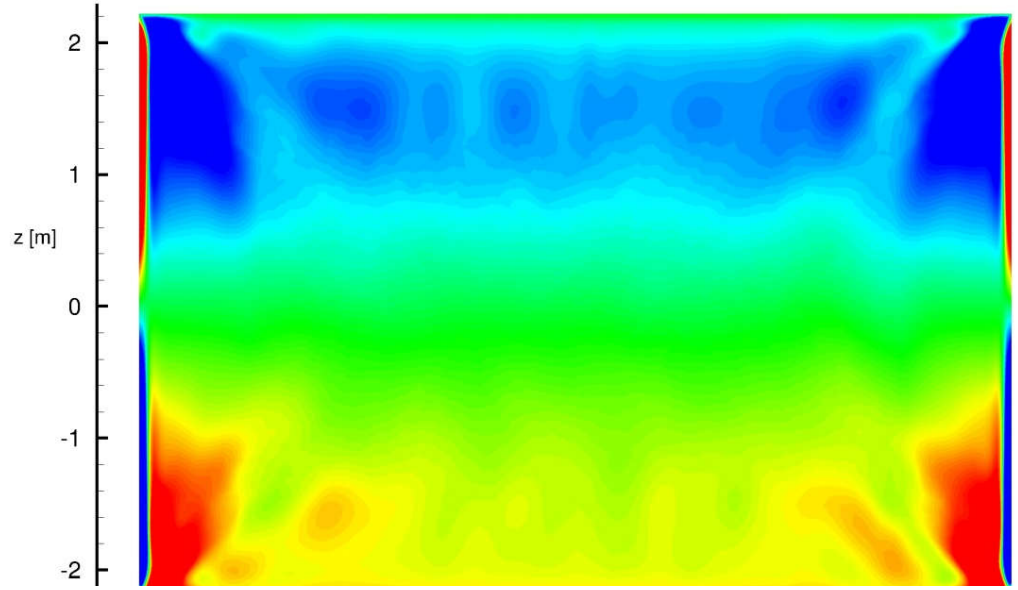
Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

- **Contours of upwash angle along test section at Sta 0.0**

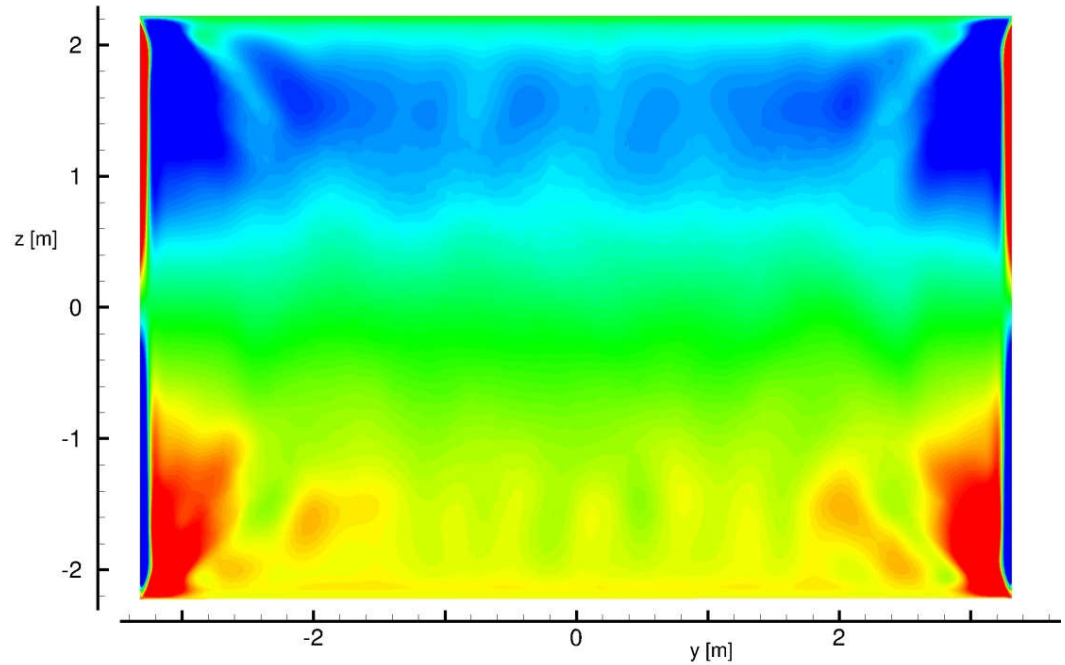
NASA intake / full diffusor



DLR intake / full diffusor



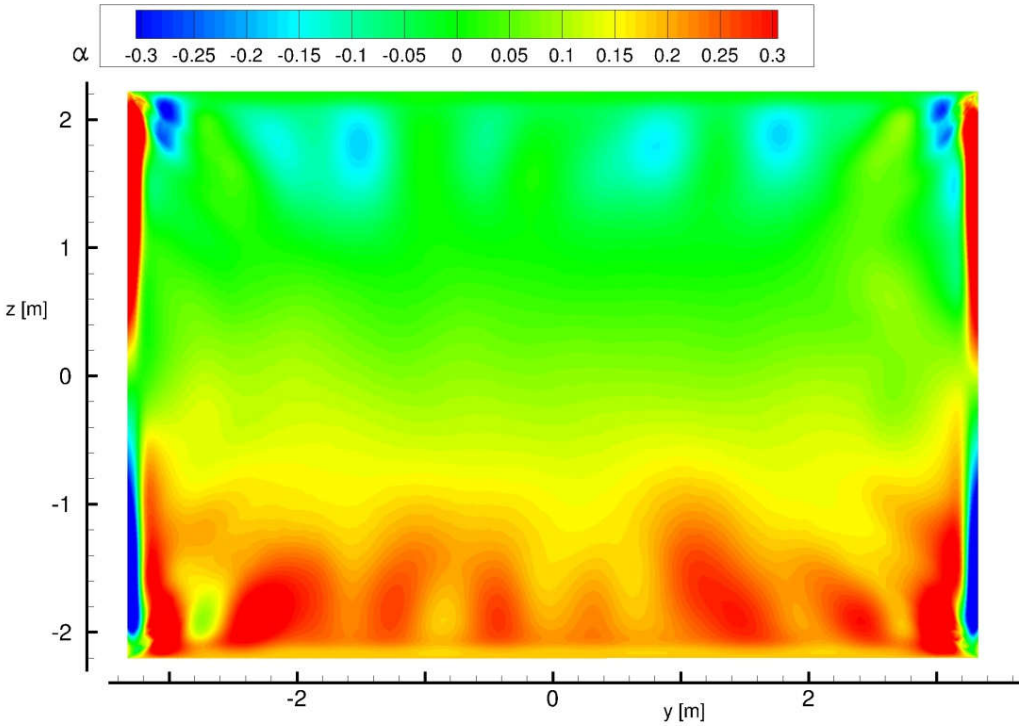
DLR intake / short diffusor



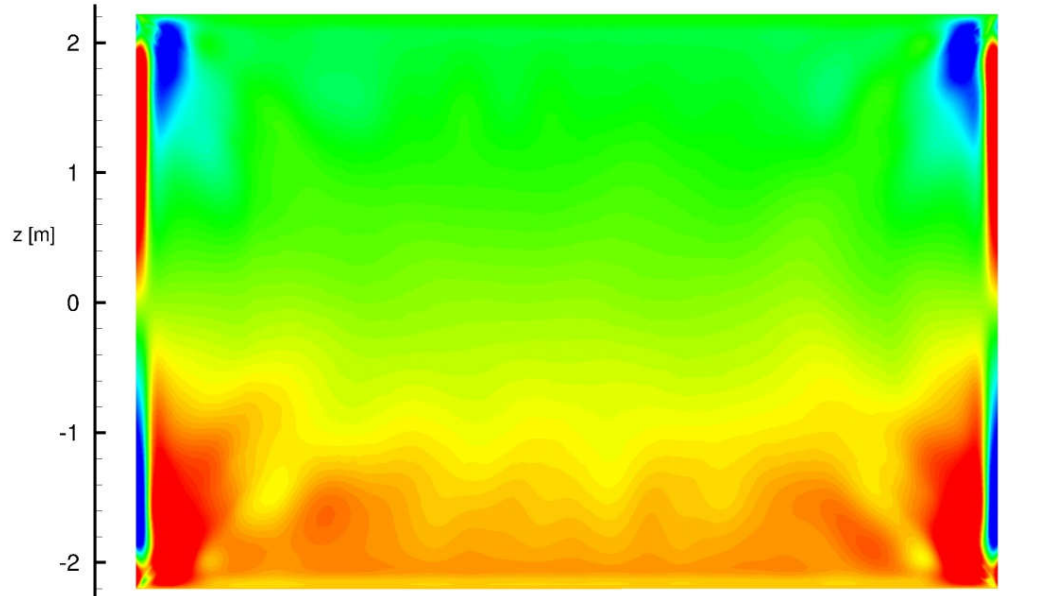
Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

- **Contours of upwash angle along test section at Sta 17.75**

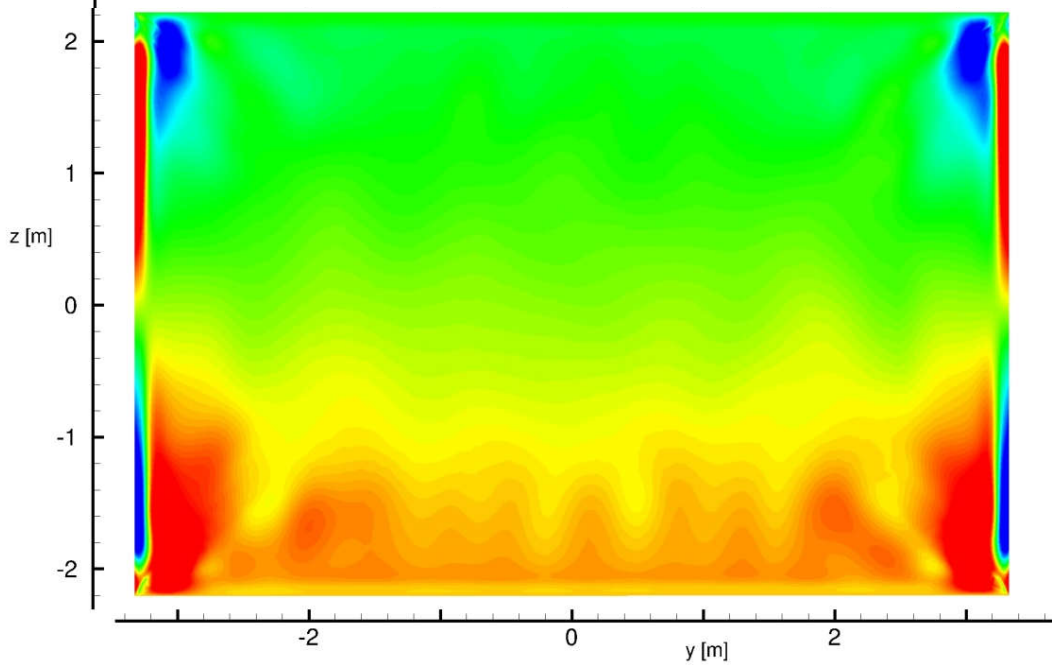
NASA intake / full diffusor



DLR intake / full diffusor

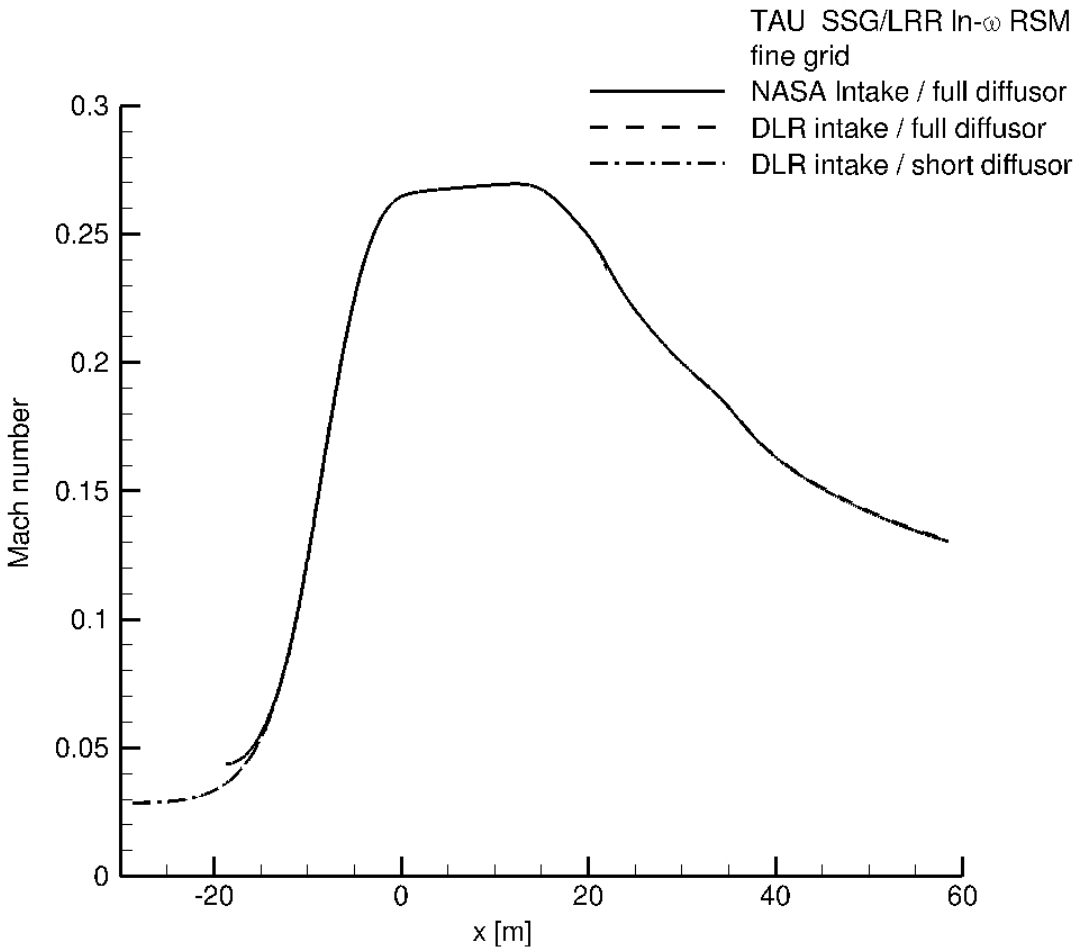


DLR intake / short diffusor

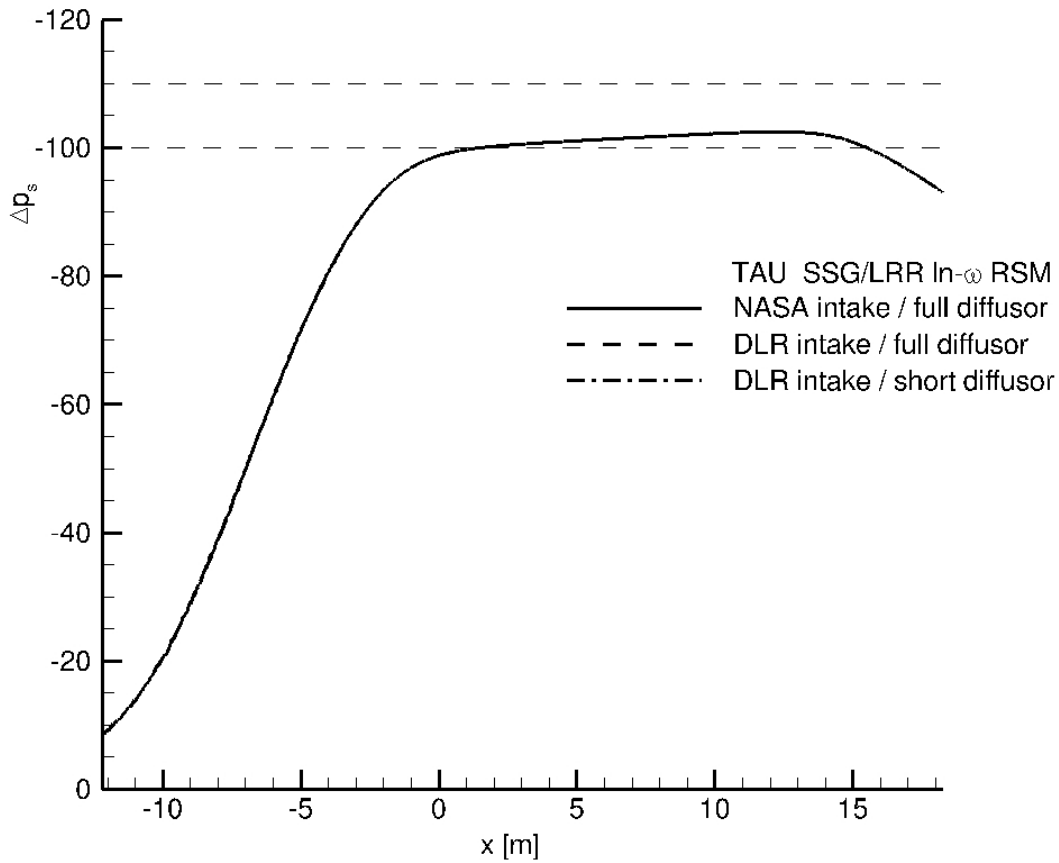


Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

- **Centerline Mach profiles**

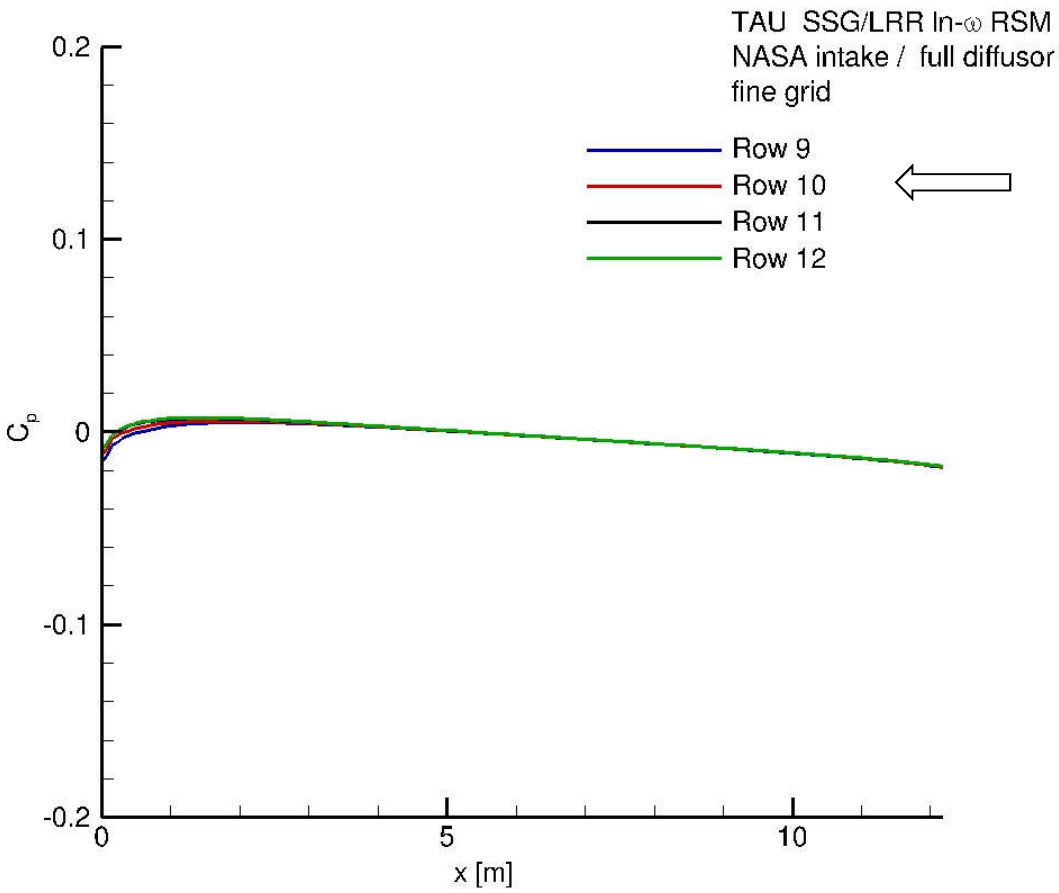


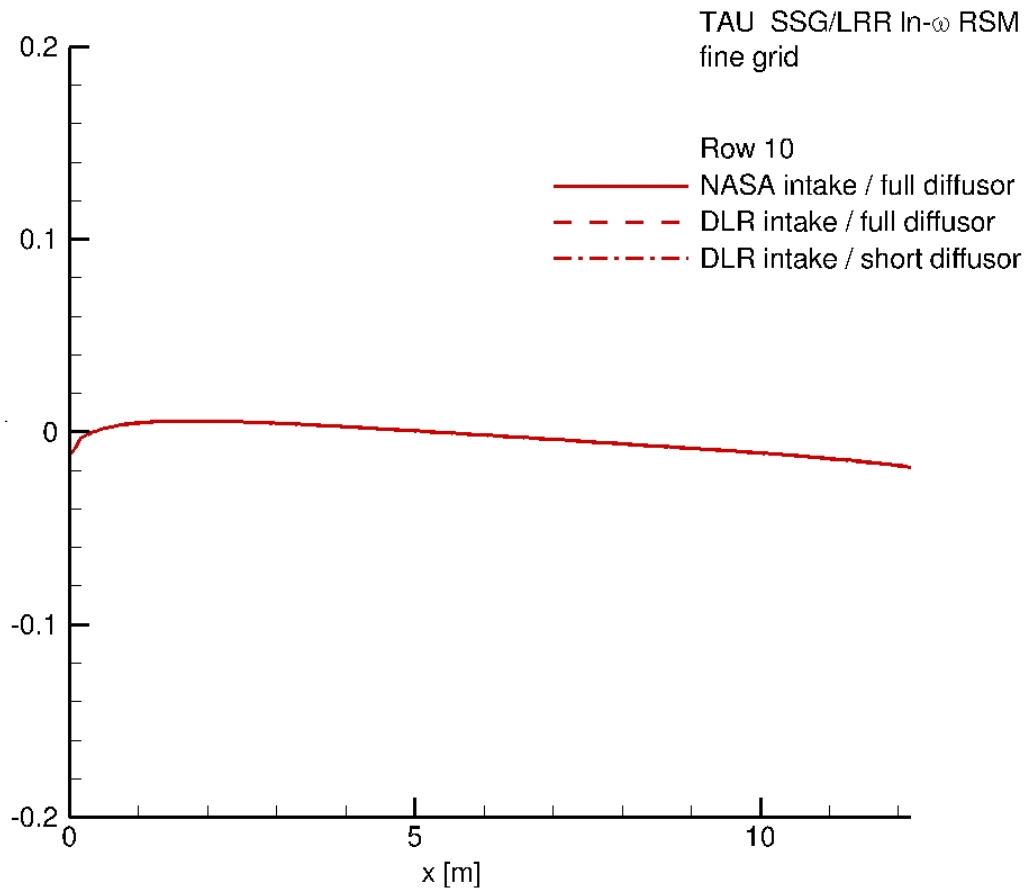
- **Longitudinal pressure distribution**



Conceptual Variations of Numerical Set-up - Geometry / B.C. Variants

- **Wall pressure distributions in test section outer wall**





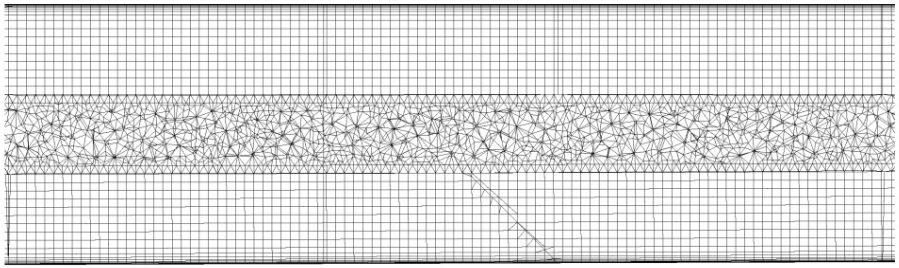
Grid Resolution Study

- **Objective:** analyze the impact of grid resolution on the test section characteristics and diffusor flow
- **Numerical set-up:** DLR Intake / full diffusor
- **4-level grid resolution study**

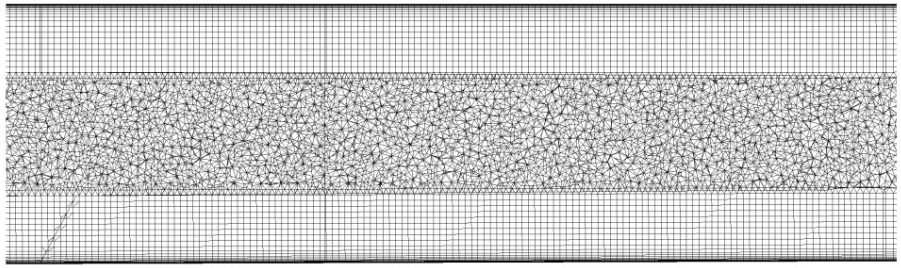
Grid	coarse	medium	fine	x-fine
Grid Points	3.94×10^6	11.03×10^6	32.09×10^6	92.95×10^6
Hexahedra	$3{,}60 \times 10^6$	10.14×10^6	$29{,}43 \times 10^6$	$84{,}96 \times 10^6$
Surface Elements	0.16×10^6	0.32×10^6	0.67×10^6	$1{,}39 \times 10^6$
Total Elements	$4{,}95 \times 10^6$	14.2×10^6	42.77×10^6	127.72×10^6
No. struct. Layers	29 + 9	40 + 9	57 + 9	81 + 9
1st wall spacing, y_n	2.080e-6 m	1.442e-6 m	1.000e-6 m	0.693e-6 m
y_n^+	< 0.42	< 0.29	< 0.2	< 0.14

Grid Resolution Study - Longitudinal and Cross Section

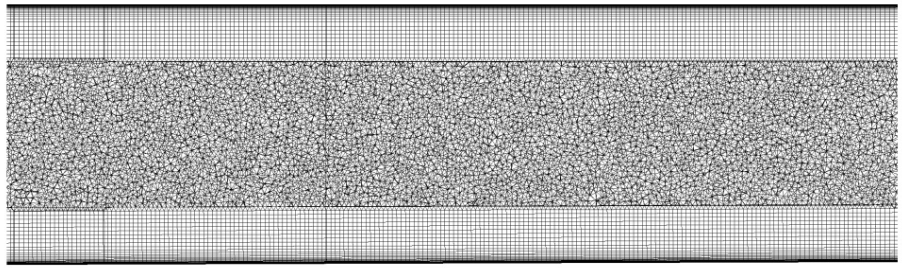
Test section **Sta 17.75**



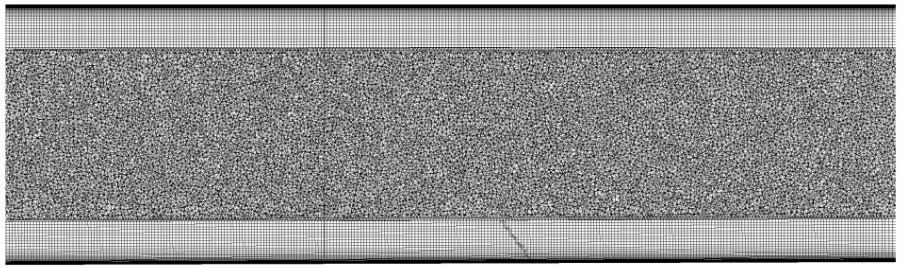
coarse



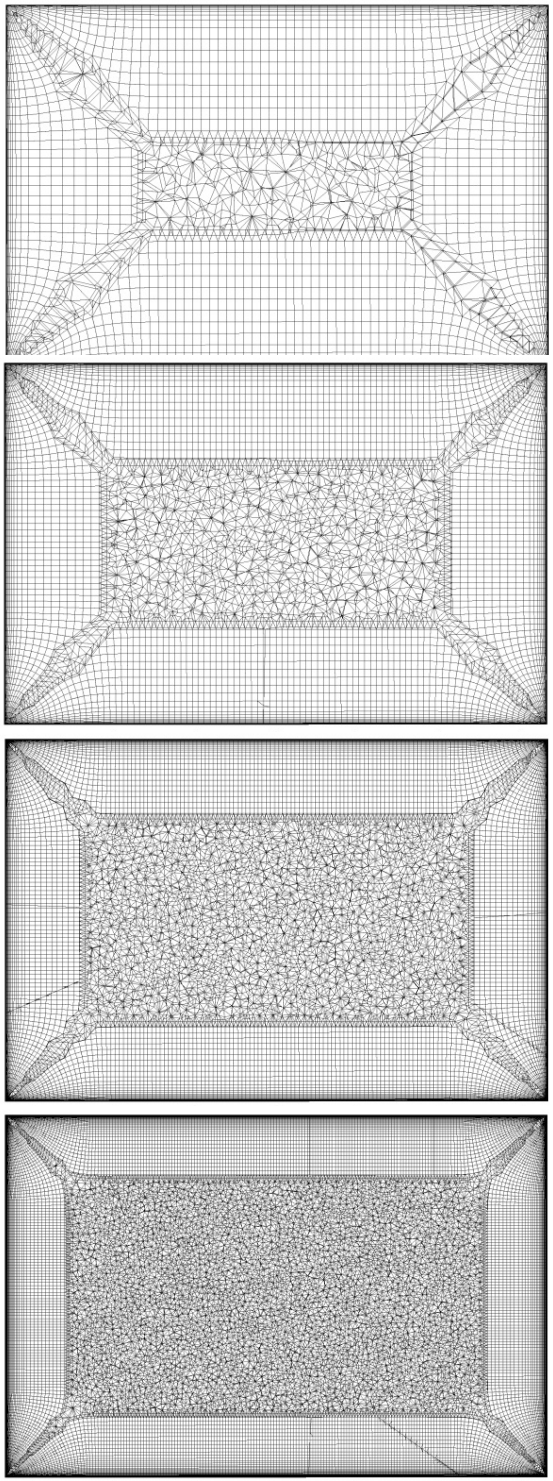
medium



fine

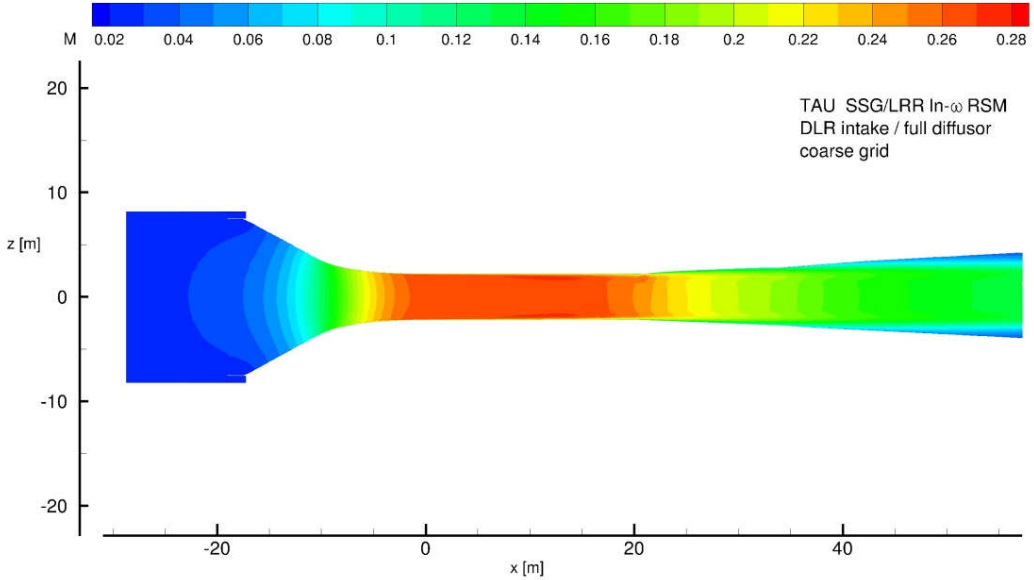


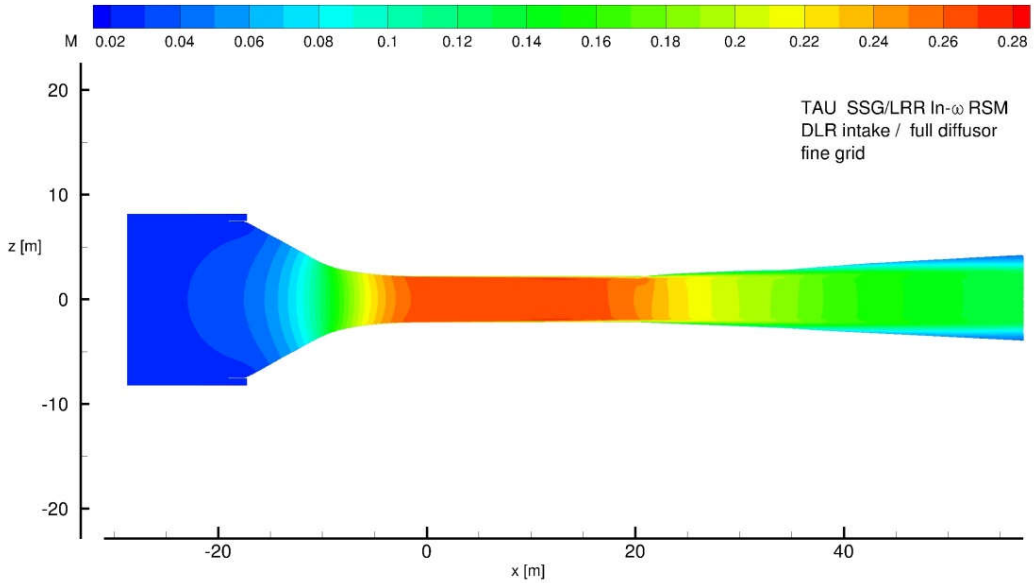
x-fine

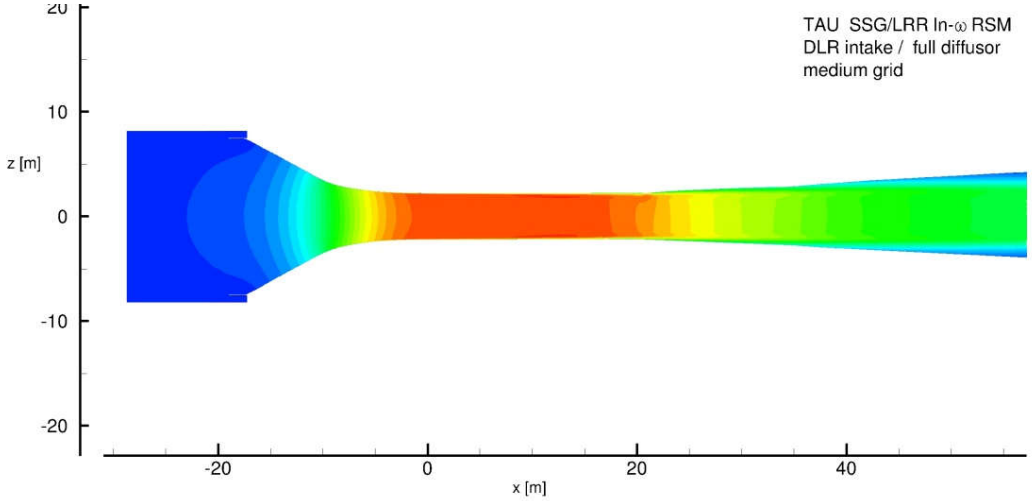


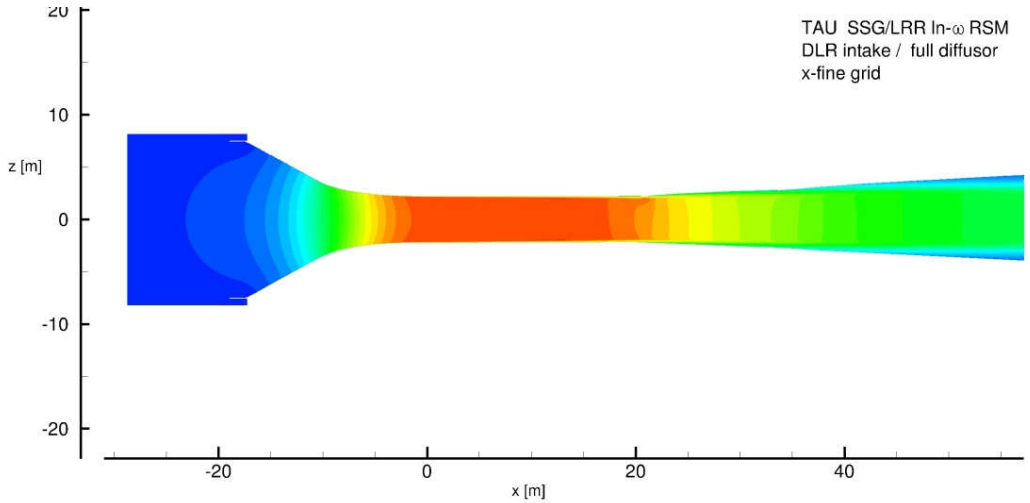
Grid Resolution Study - Flow Field Results

- **Mach conturs, vertical plane at y = 0.0**



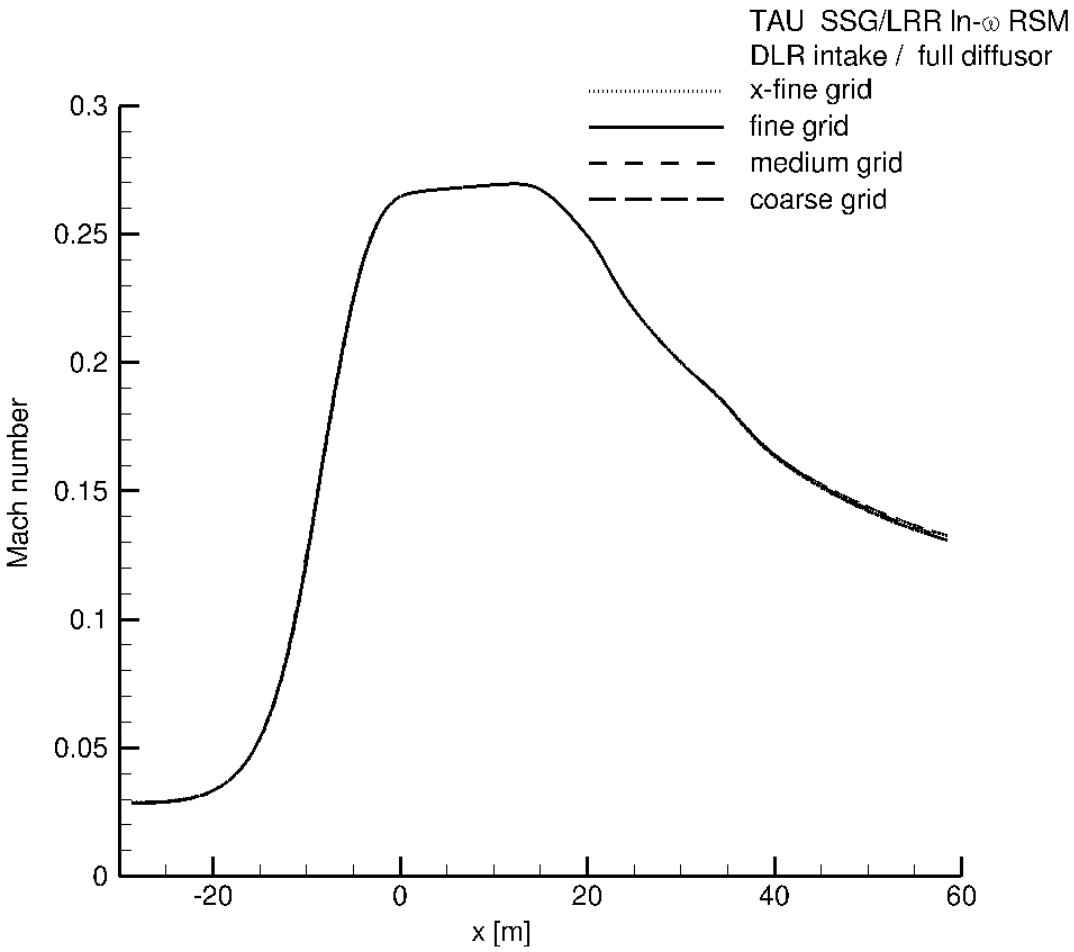




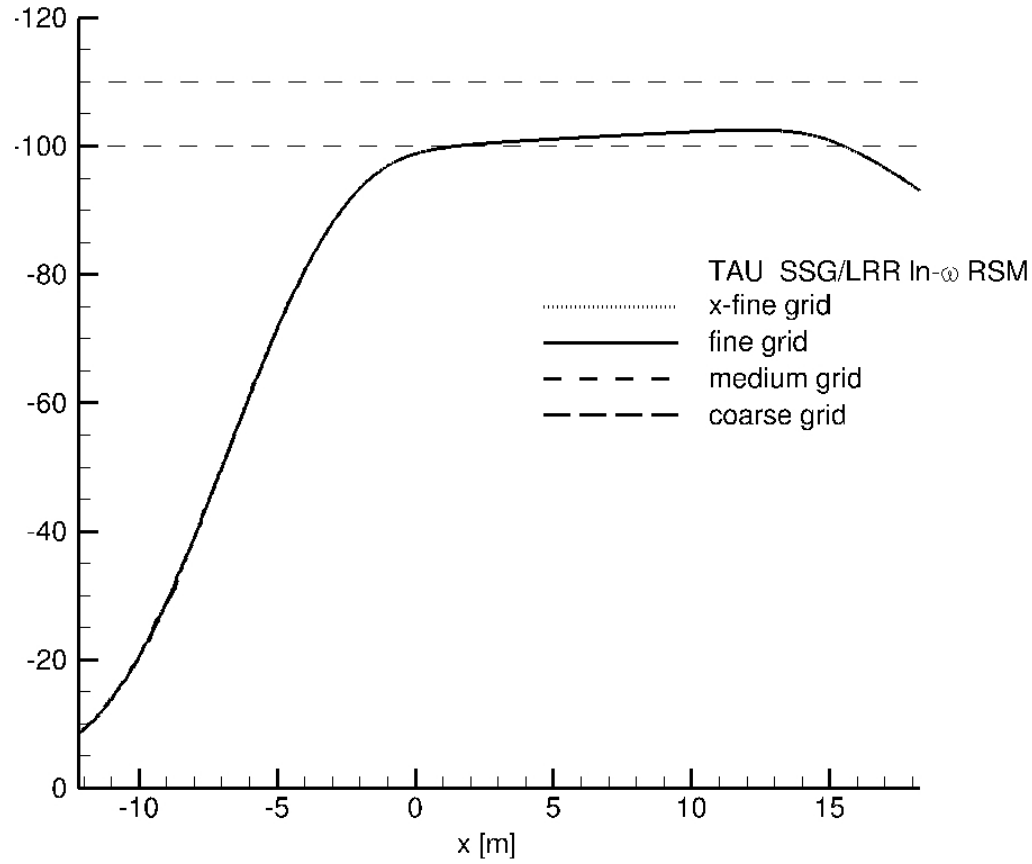


Grid Resolution Study - Centerline Distributions

- **Centerline Mach profiles**

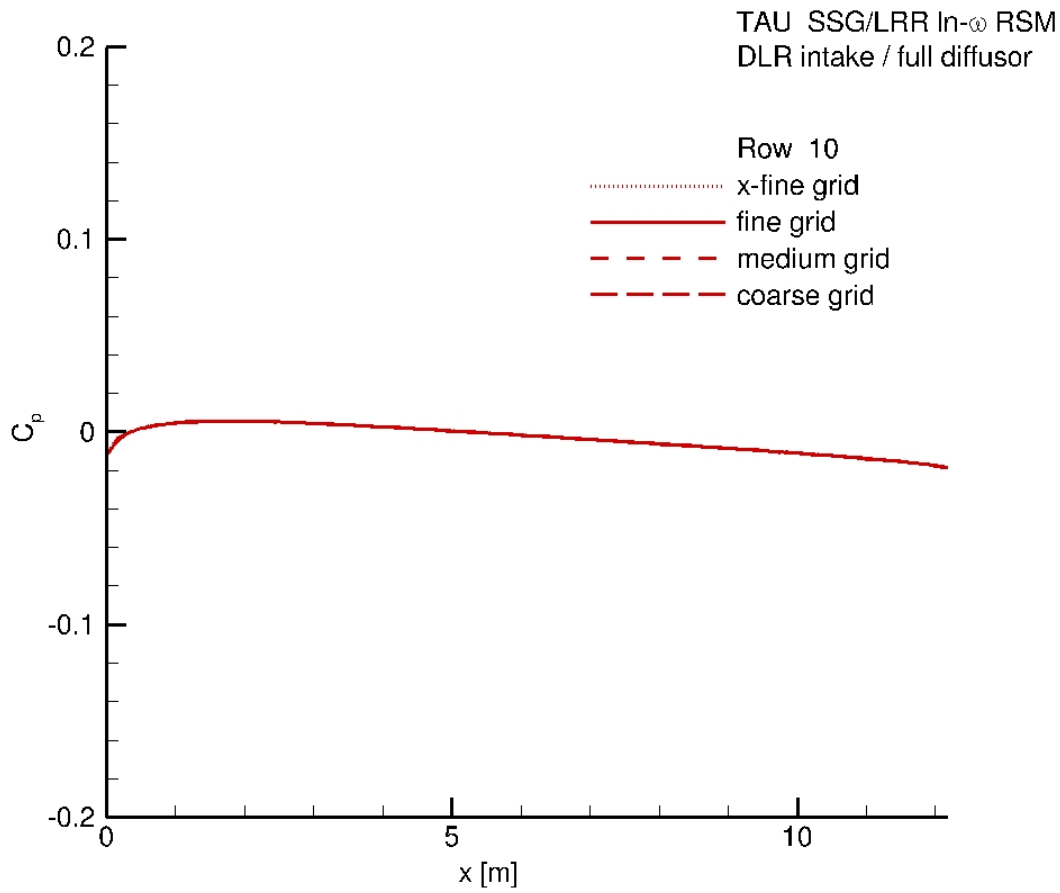


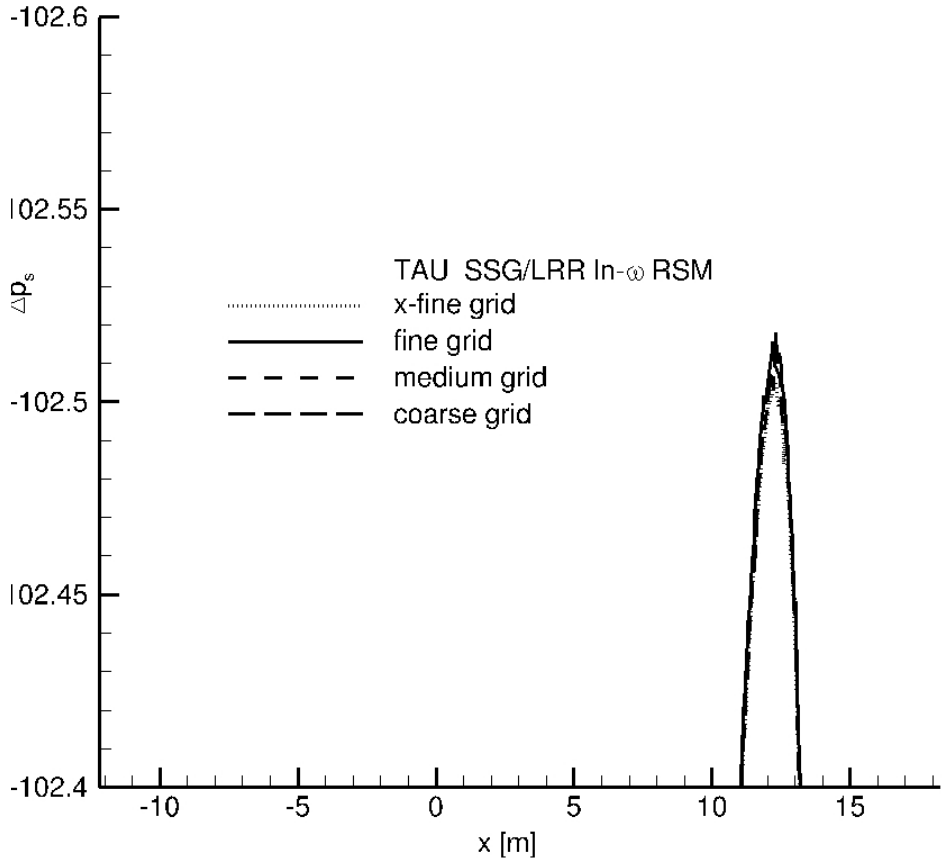
- **Longitudinal pressure distribution**



Grid Resolution Study - Wall Pressure Distribution

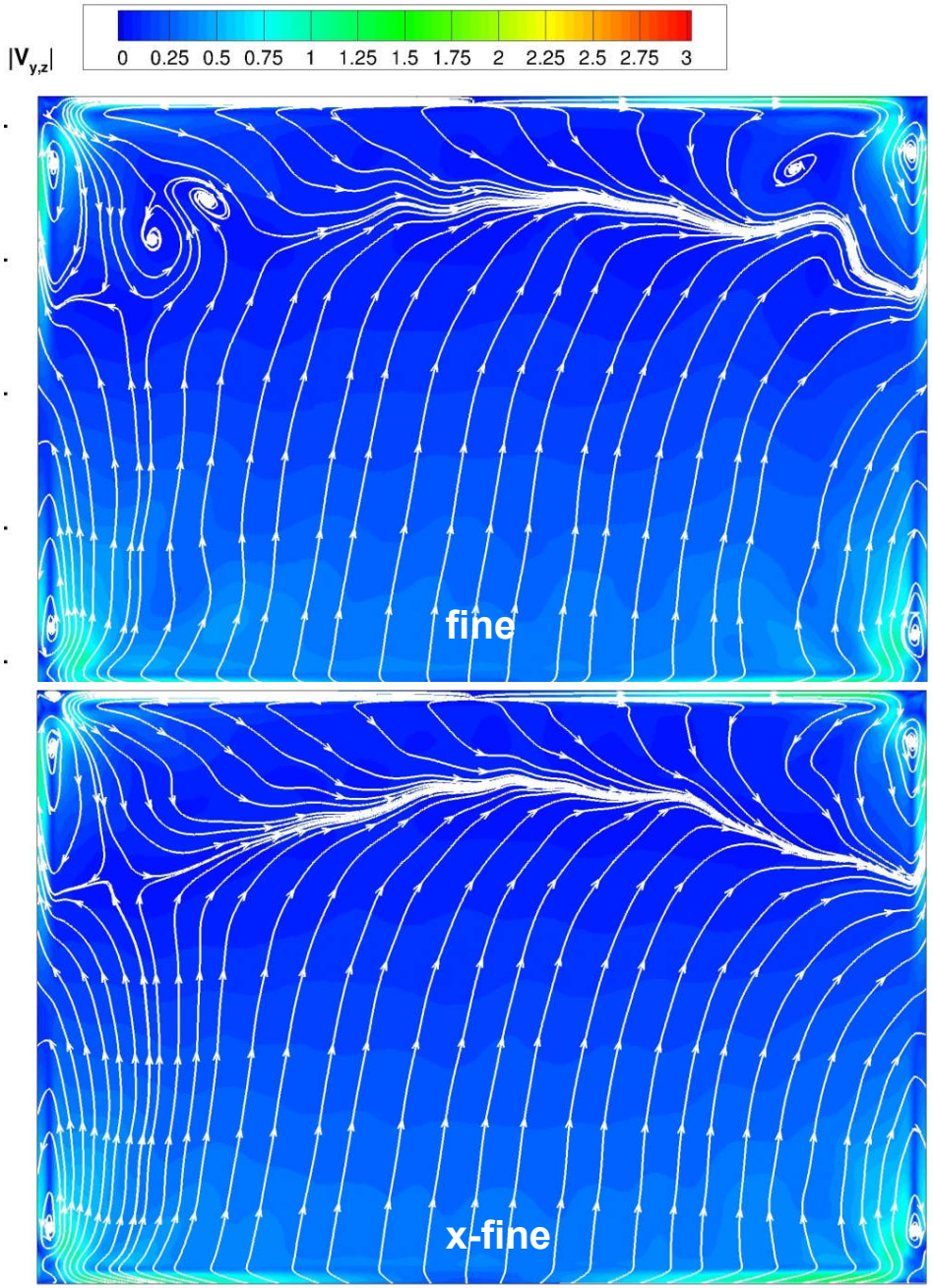
- **Wall pressure distributions in test section outer wall**





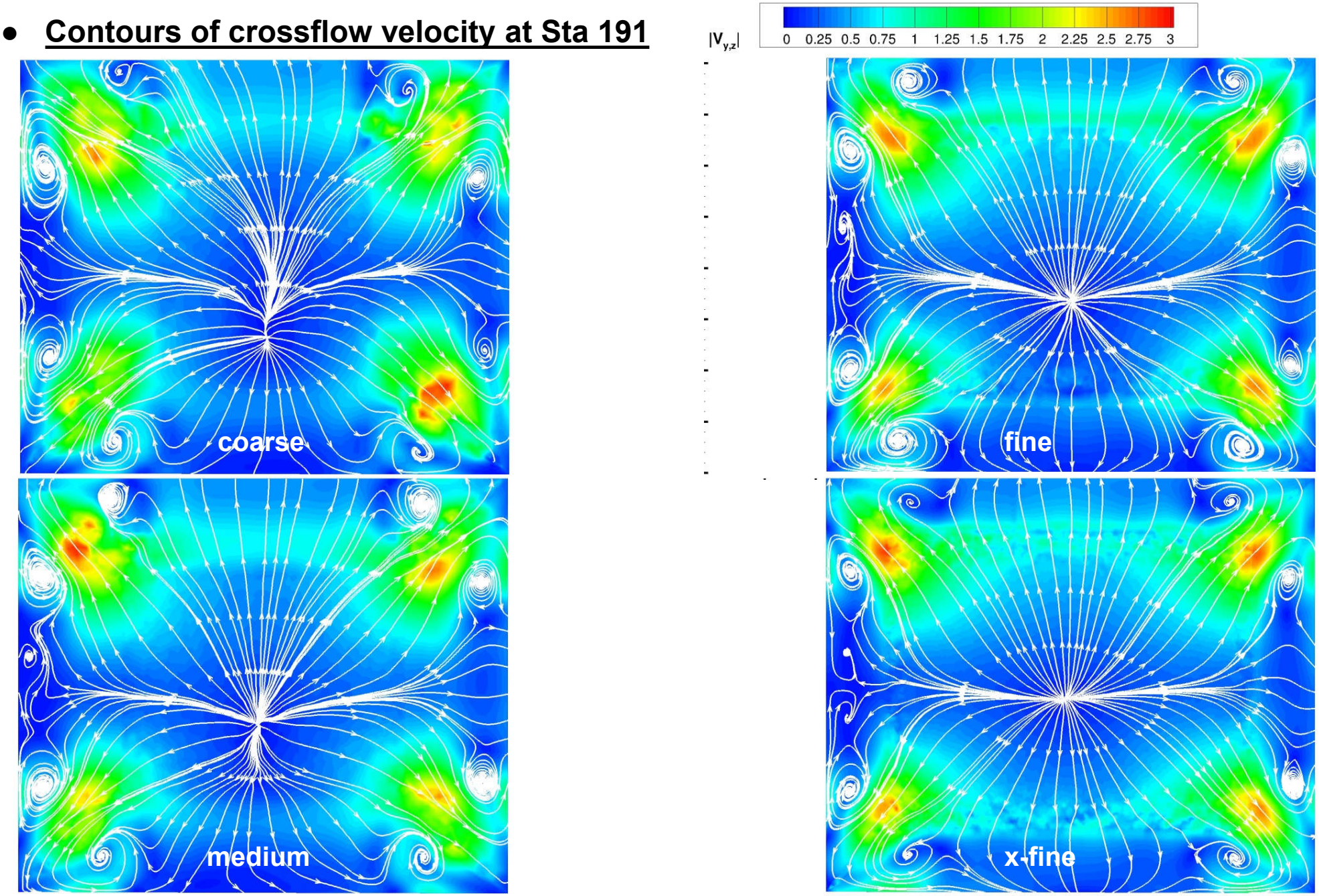
Grid Resolution Study - Flow Field Results in Test Section

- **Contours of crossflow velocity at Sta 17.75**

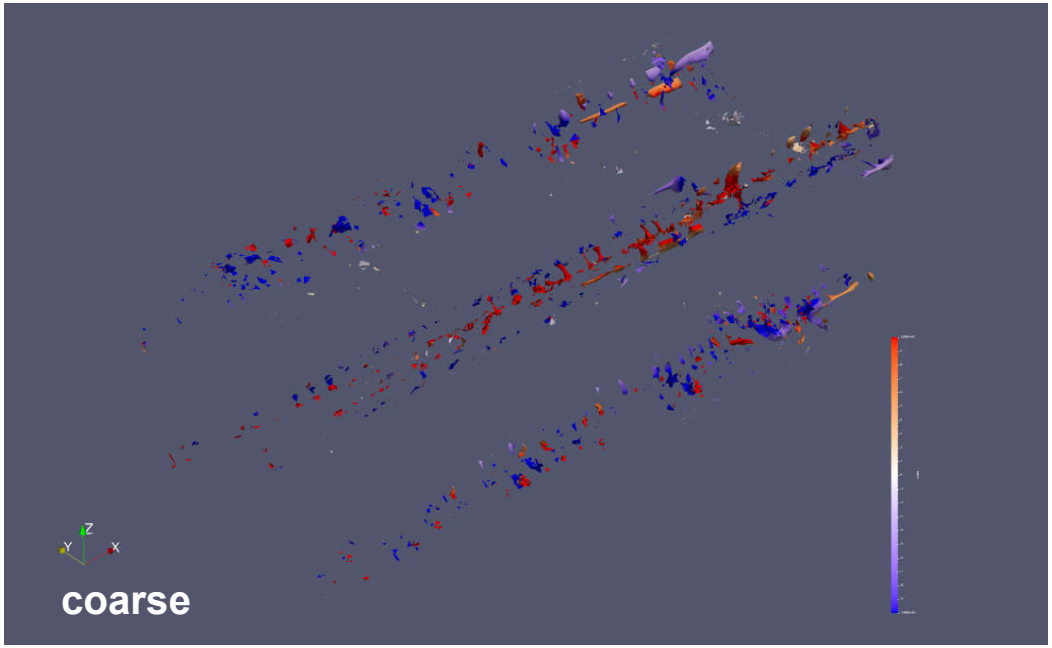


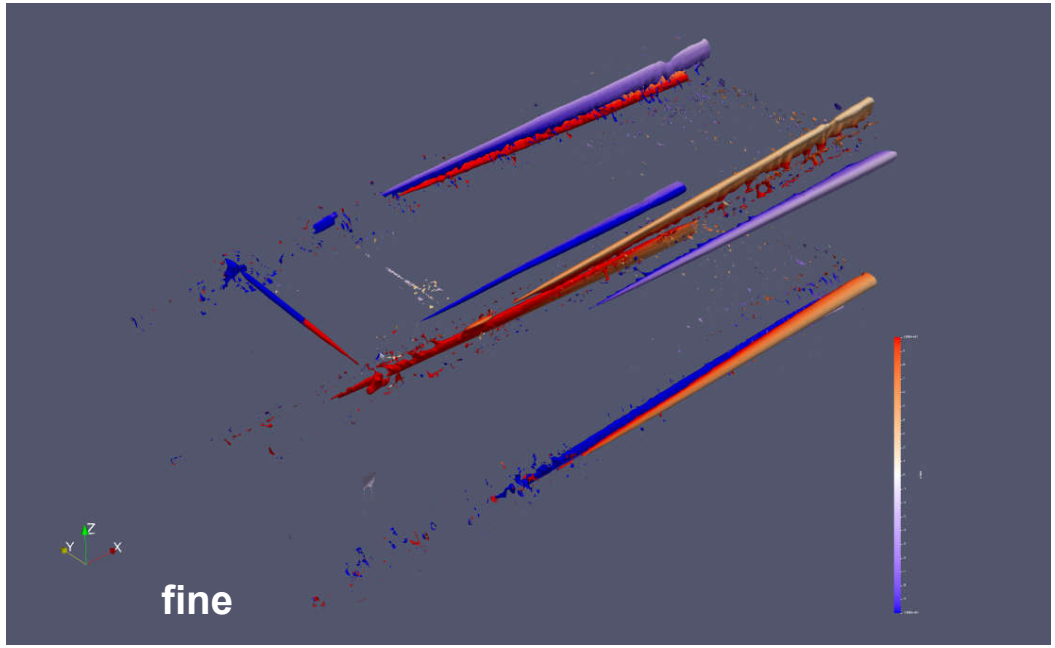
Grid Resolution Study - Flow Field Results at Diffusor Exit

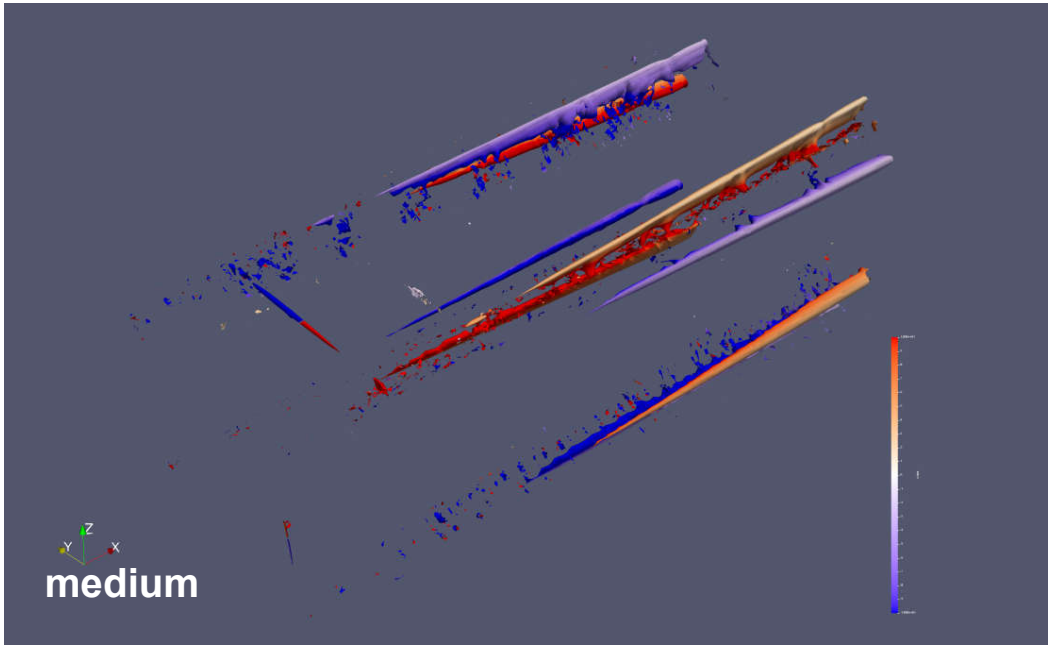
- **Contours of crossflow velocity at Sta 191**

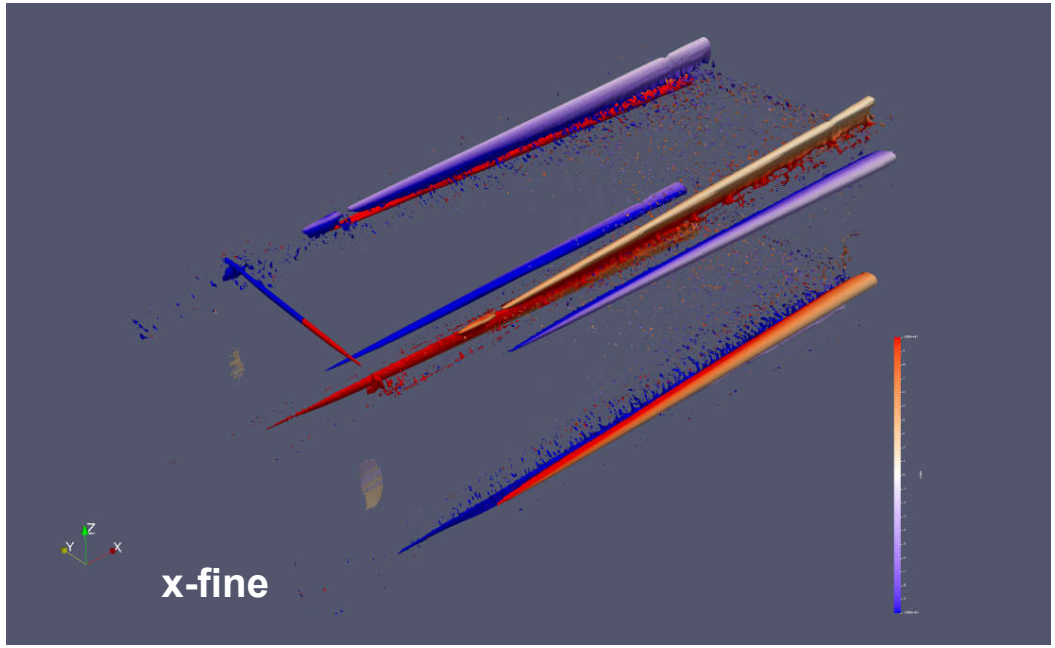


Grid Resolution Study - Flow Field Results in the Diffusor









Conclusion and next steps

- A numerical study of the empty high speed leg of the NASA 14 x 22 ft. low speed wind tunnel has been presented addressing different aspects of in-tunnel simulation.
- The DLR TAU/SOLAR package has been used with a differential SSG-/LLR ln(ω) model.
- An indirect validation and verification with numerical and experimental results from a previous study reveals close agreement to the existing CFD results and fair agreement to experimental evidence with discrepancies supposed to be caused by simplifications of geometrical wind tunnel details.
- Vortex formation in the test section and diffuser is observed, which underlines the capability of the DRSM to resolve such type of phenomena.
- Conceptual variations of numerical set-up w.r.t inlet boundary simulations and a diffusor cutback doesn't affect the main characteristics of the flow in the test section.
  - for the inlet modification some effects were observed in the uniformity of the test section inflow
  - for the diffusor cut-back very minor differences were found due to the diffusor cut-back (empty section !)

Conclusion and next steps

- **Grid resolution study featuring an order of magnitude variation in total grid point number and a widely identical grid topology shows basically no visible effect on the main characteristics of the flow in the (empty !) test section**
  - **for the vortex formation, effects of reduced numerical dissipation are found leading to more distinct vortices of reduced extent for higher resolved grids**

***Next steps*:**

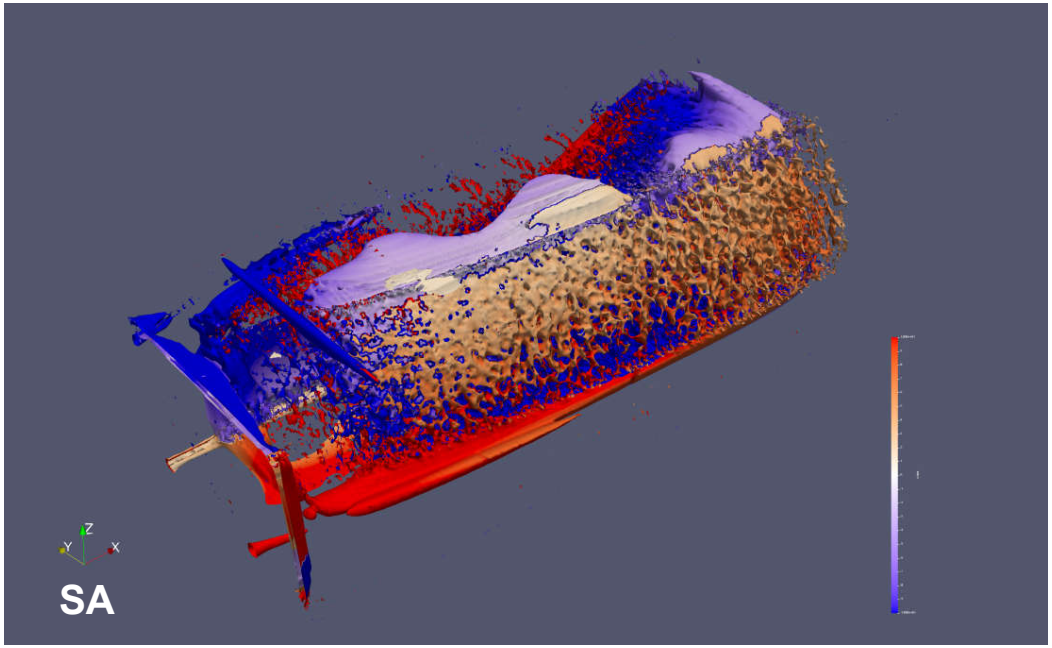
- **Integration of the HL-CRM WB CAD model into the tunnel set.up**
- **Grid generation based on an Chimera approach for the model vicinity with high a resolution near wall area**
- **Computation of the HL-CRM in-tunnel an free air using the DRSM**
- **Evaluation of results and assessment of installation impact on the aerodynamic characteristics**

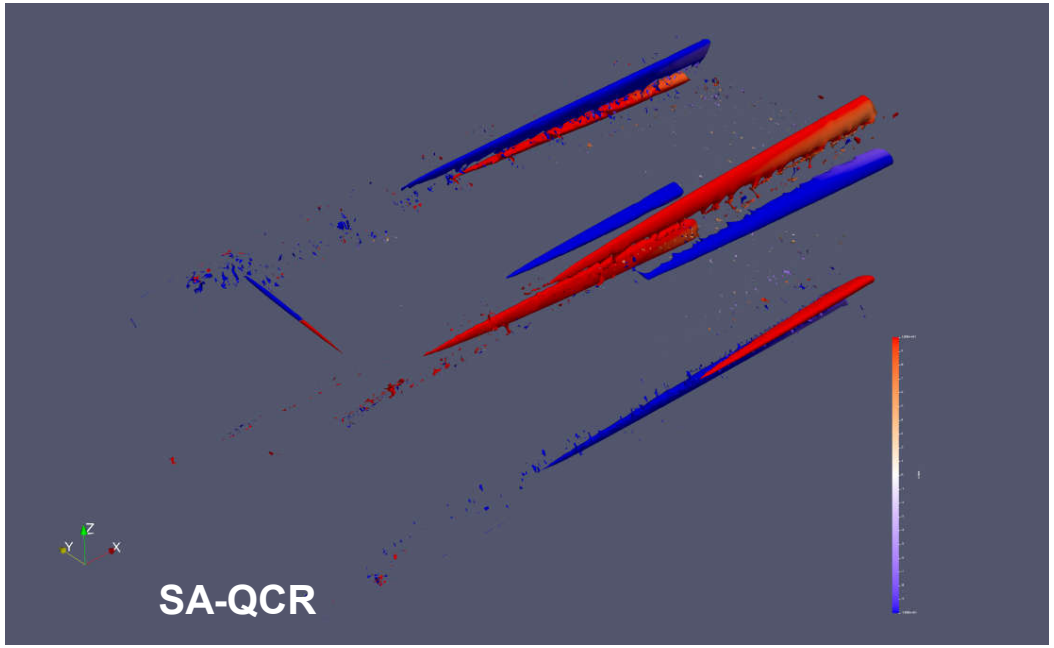
Thanks for your attention !

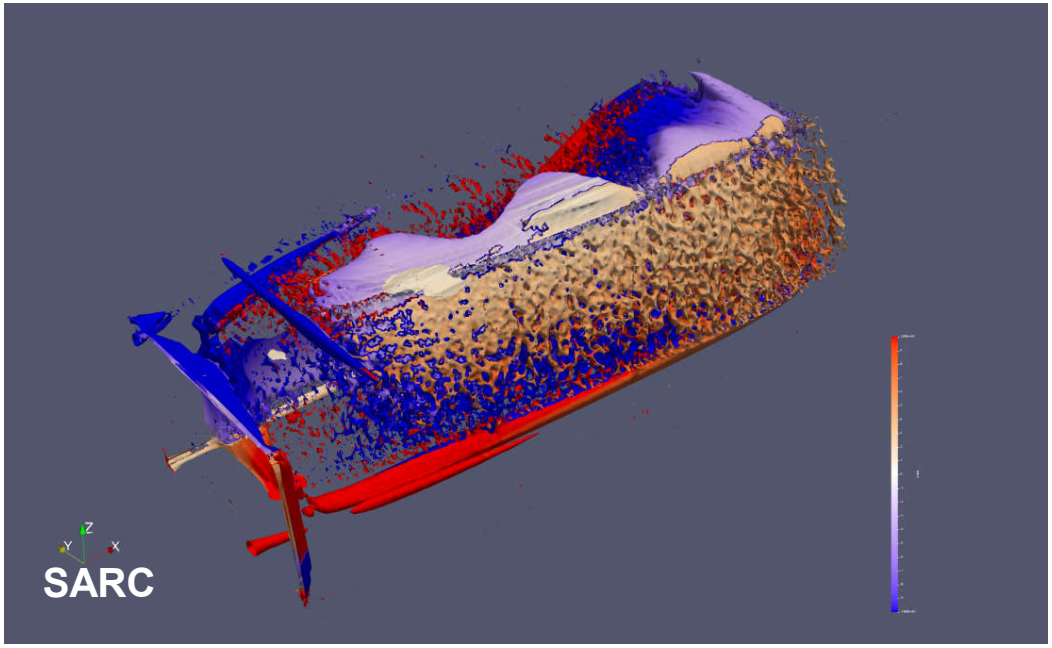
The authors like to acknowledge the support of

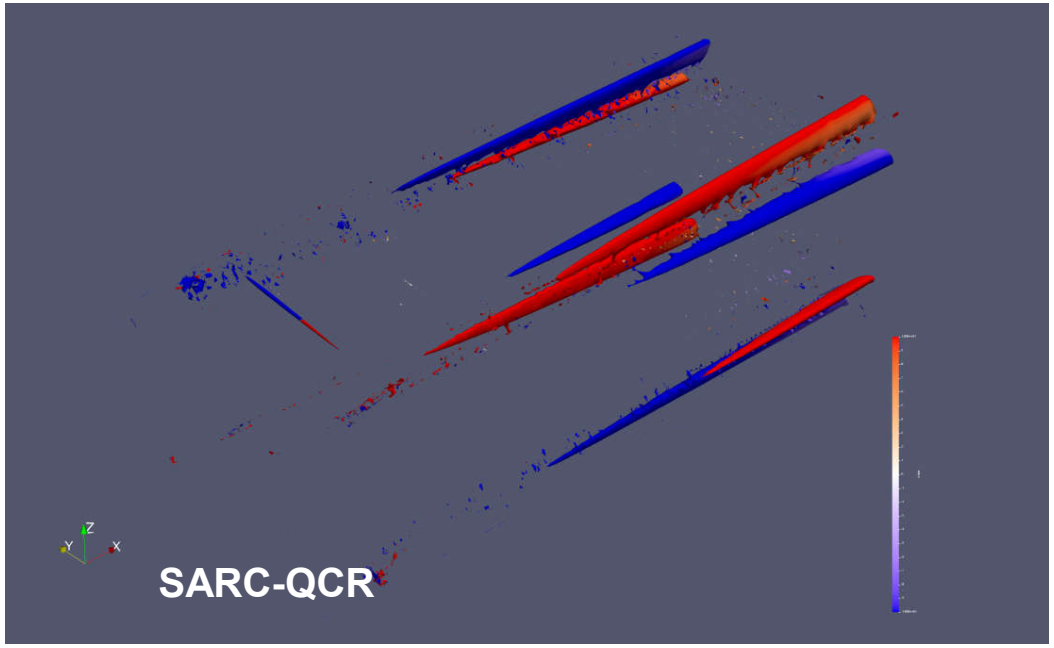
NIA and NASA for conducting this research

Turbulence Model Study – SA Variants on fine grid level









Turbulence Model Study - SARC-QCR vs. SSG/LRR ln(ω) on fine grid level