# Parallel Adaptive Detached Eddy Simulations of the EUROLIFT DLR-F11 high-lift configuration

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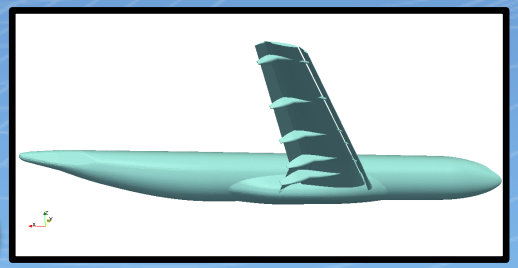
Collaborators:

Simmetrix Inc
Altair – Acusim Inc
Kitware

AIAA Aviation - Atlanta – June 18, 2014

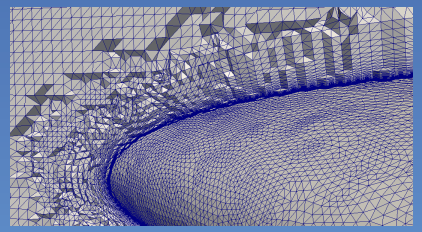
# Motivations

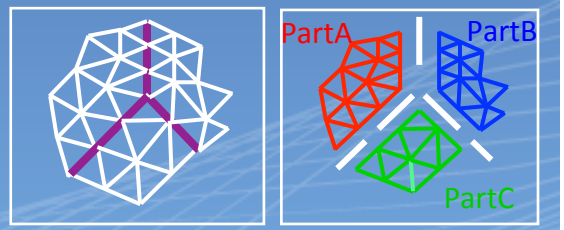
- Summary of previous results of cases 1, 2(a) and 2(b)
  - RANS-SAO
  - Overall reasonable agreement with the experimental data
  - Good velocity profiles with capturing of wakes
  - http://hiliftpw.larc.nasa.gov/Workshop2/specialsessions2014.html
  - AIAA 2014-0117
- Why moving from RANS to DDES?
  - Challenging problem on a realistic geometry, even at low AoA
  - Flow control with high frequency synthetic jets
    - Higher fidelity turbulence model required
- Geometry and case considered in this presentation
  - Configuration 4 (full geometry with slat and flap tracks)
  - Case 2a (low Reynolds number 1.35M)
  - AIAA 2014-2570

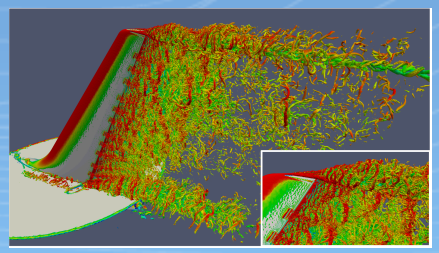


# Key ingredients

- Massively parallel CFD Flow solver PHASTA
  - Production runs: o(1) billion elements partitioned in 256k parts
- Mesh tools at extreme scale
  - 3D unstructured mesh generation in //
  - Partitioning
  - Local adaptation
  - Collaboration with RPI and Simmetrix
- Visualization with ParaView in // and Catalyst toolkits
  - Collaboration with Kitware





# PHASTA CFD Solver

- Massively parallel Navier-Stokes flow solver
- Models compressible or incompressible turbulent unsteady flows
- Turbulence models: RANS-SAO, DES97, DDES
- 3D stabilized finite element discretization in space ($2^{nd}$ -> $4^{th}$ order)
- Fully implicit in time (generalized-α time integrator)
  - Δt governed by the physics and not by the numerical scheme / grid
- Linear algebra: Krylov methods with block diagonal preconditioner
- Mesh adaptivity: => Grid matches physical scales
  => Anisotropic (boundary and shear layer)
- Used to model air flow over wing profiles, two-phase flow applied to nuclear reactor, blood flow, etc
- Scaling demonstration with 3M MPI processes on a 92B element mesh on 768k cores at Argonne (BlueGene/Q)

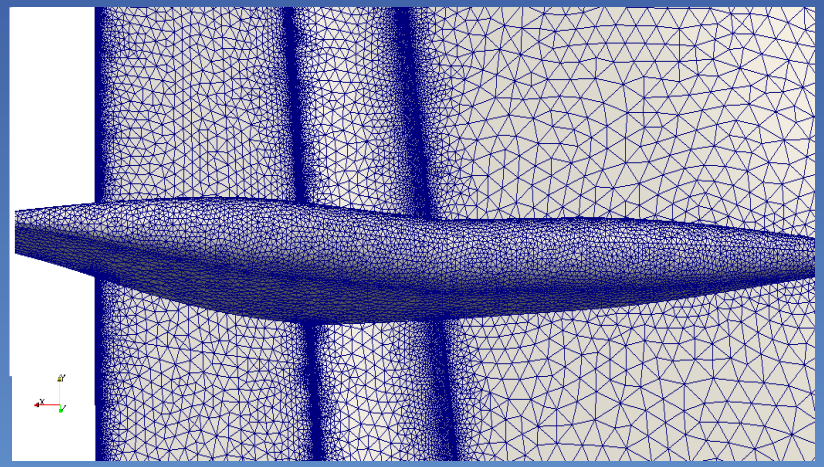
# Mesh adaptivity

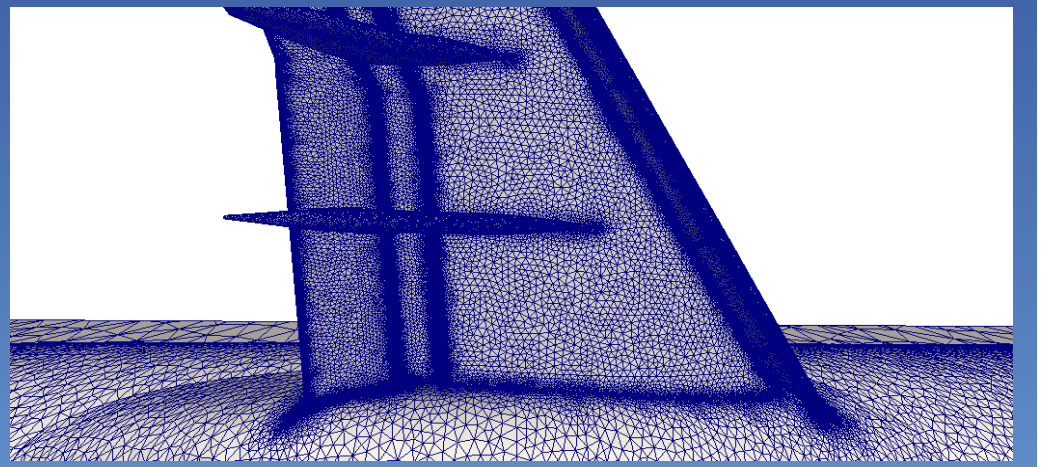
- ✓ Difficult if not impossible to generate a "good" initial mesh on complex geometries (DDES)
- ✓ Adaptation used to automatically refine the mesh in specific areas of interest
  - ➢ Gaps between the three elements of the high lift device
  - ➢ Wakes (slat tracks, flap tracks, trailing edges)
- ✓ This work: error indicator for mesh adaptivity based on the vorticity field + BL frozen
  - ➢ PDE residual and velocity RMS also good candidates for DES
- ✓ Simmetrix Inc.'s mesh adaptation software

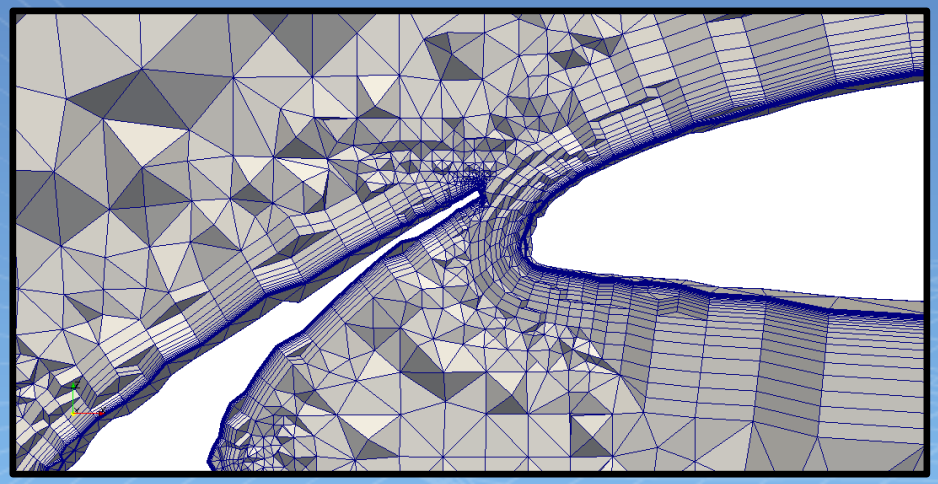
# Meshes and Cases

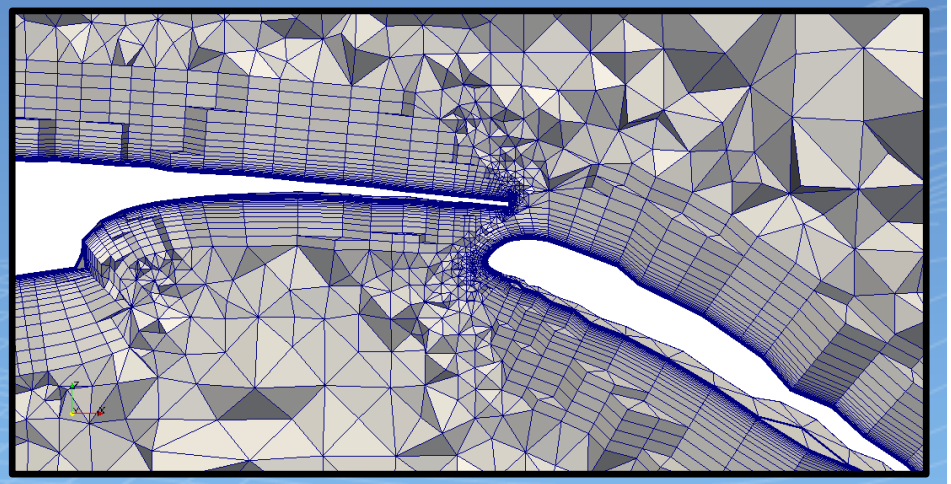
- ✓ Meshes:
  - Unstructured, with mixed element boundary layers
  - Created in-house using MeshSim software by Simmetrix Inc.
- ✓ Mesh statistics:
  - Medium M0: 98M elements – 40M nodes
  - Fine A0 (new initial mesh for DDES): 895M elements – 186M nodes
  - Fine A1 (adapted from A0): 1.3B elements – 270M nodes
- ✓ Config 4 and case 2(a): Low Reynolds number = 1.35M
  - Angles of attack: 7°
  - M0: RANS (Solved on Mira BG/Q on 32k cores)
  - A0 and A1: RANS and DDES (Solved on Mira BG/Q on 64k cores)

# M0 mesh (Medium)



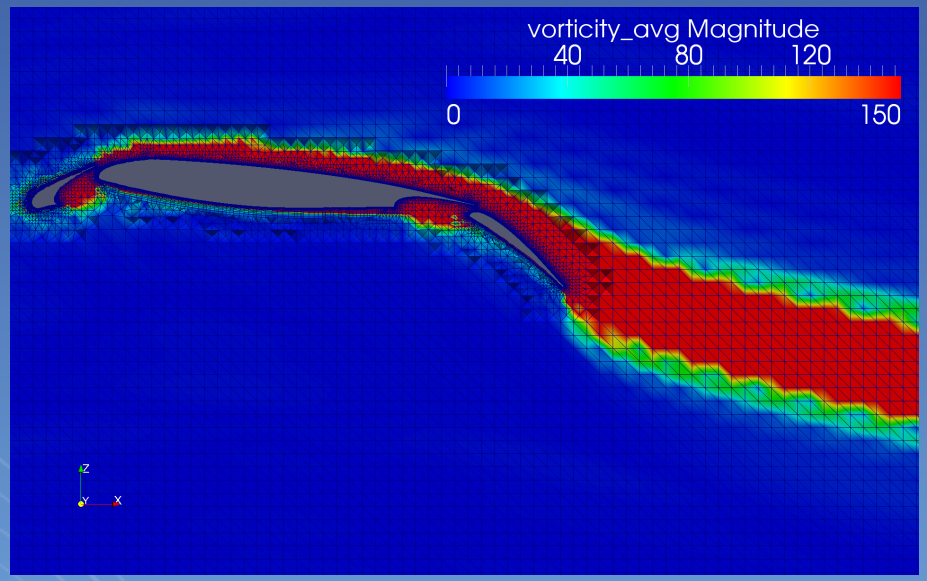


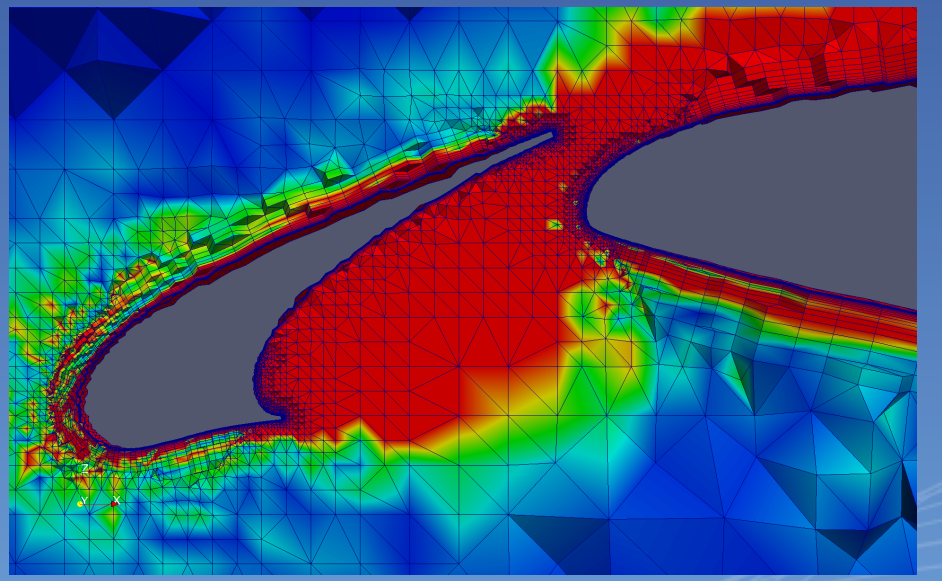


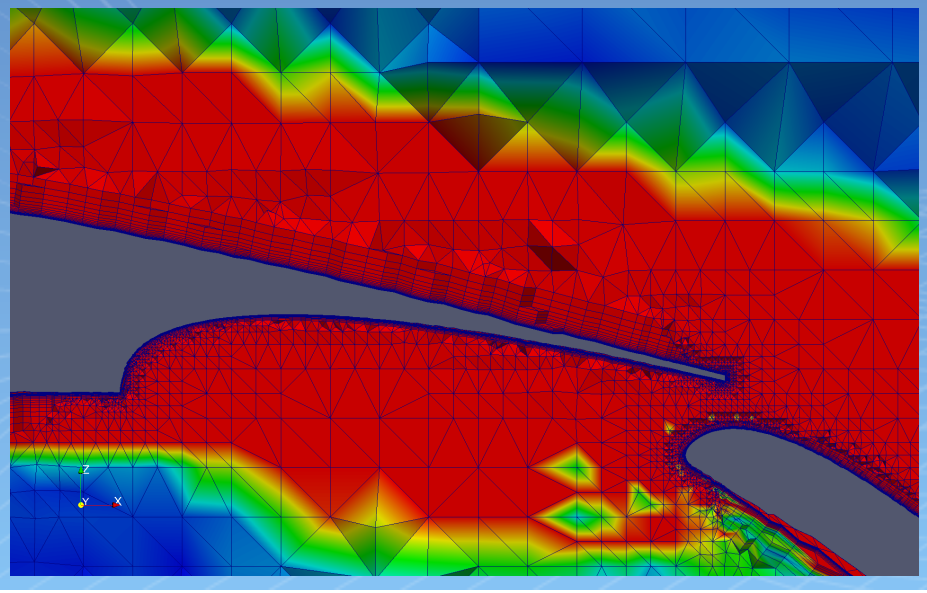


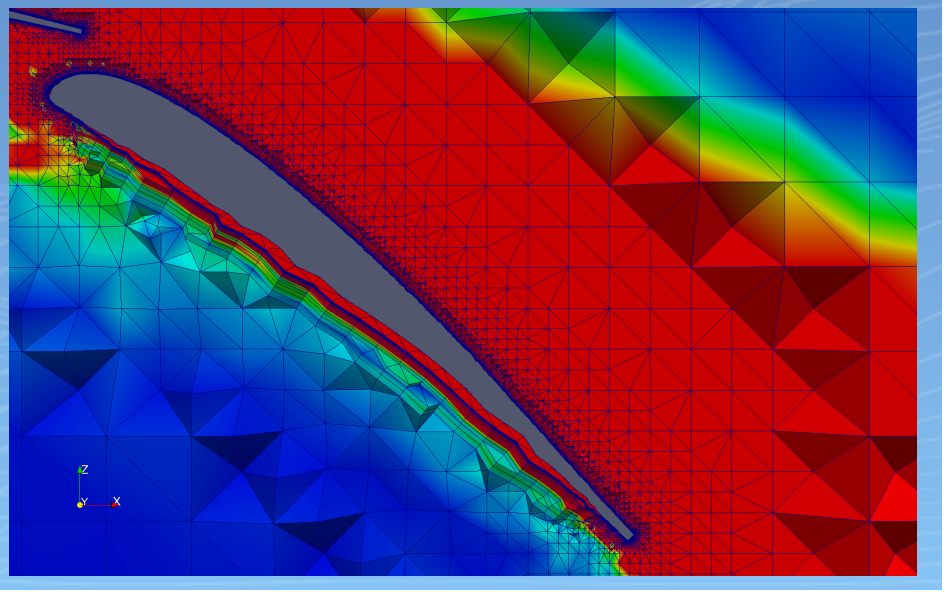
# Fine A0 Mesh

- mean vorticity field from RANS used as error indicator for mesh adaptation
- Elements in red marked for adaptation



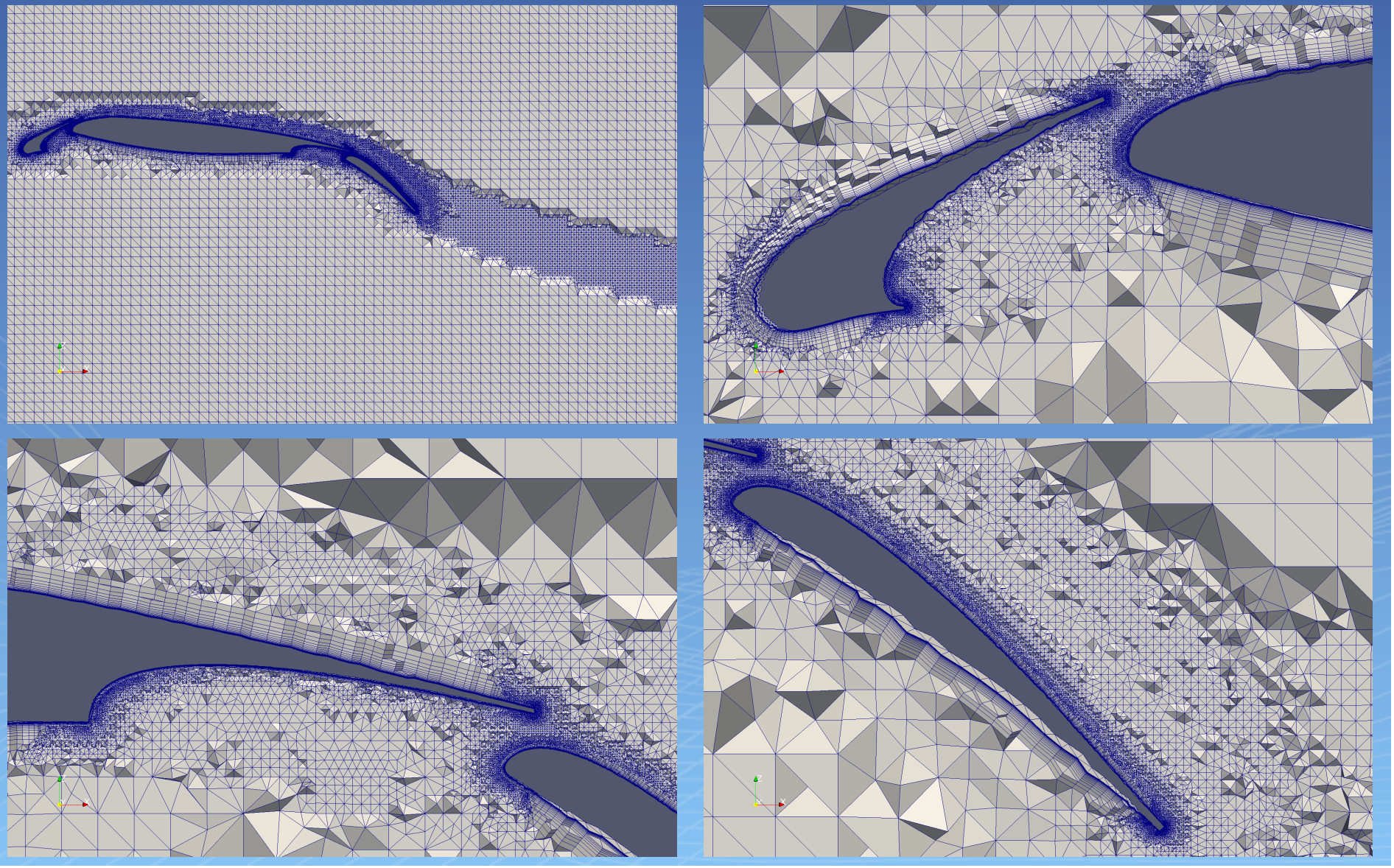







# Fine A1 Mesh (adapted from A0)

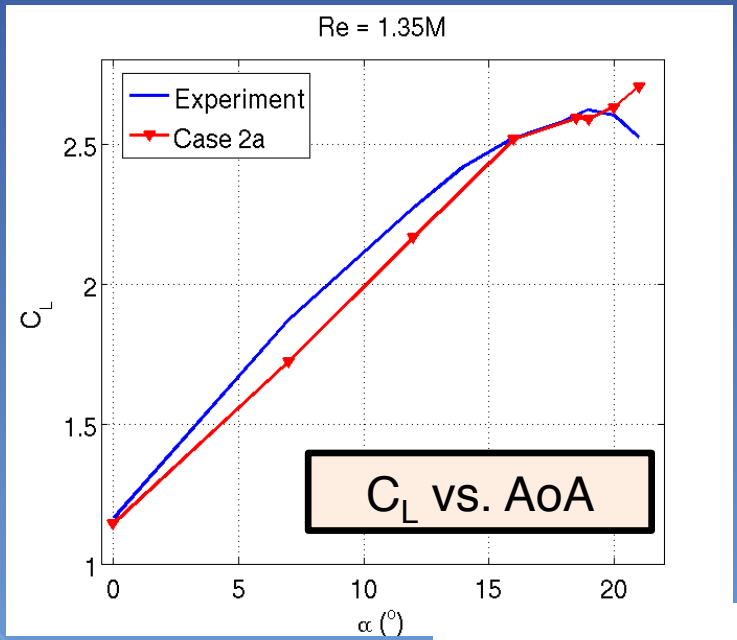


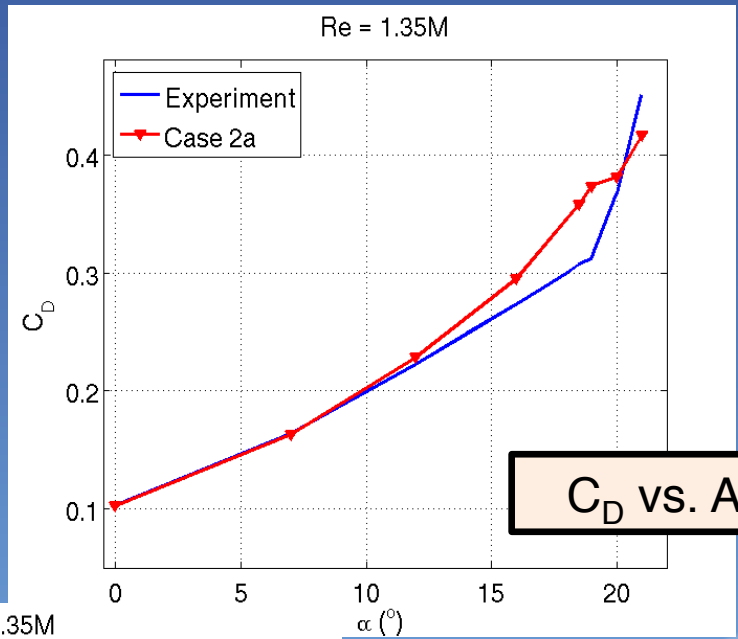


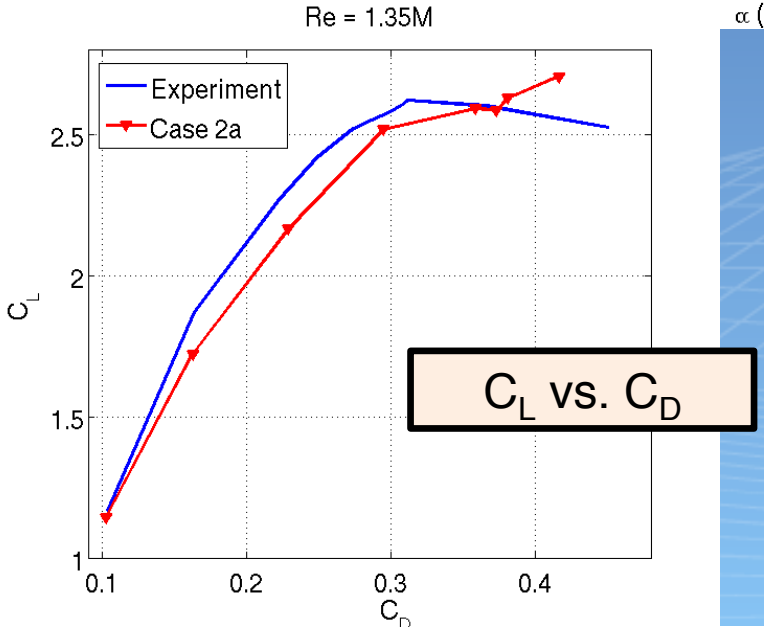
# M0 mesh

- ✓ Lift and Drag
- ✓ Velocity profiles

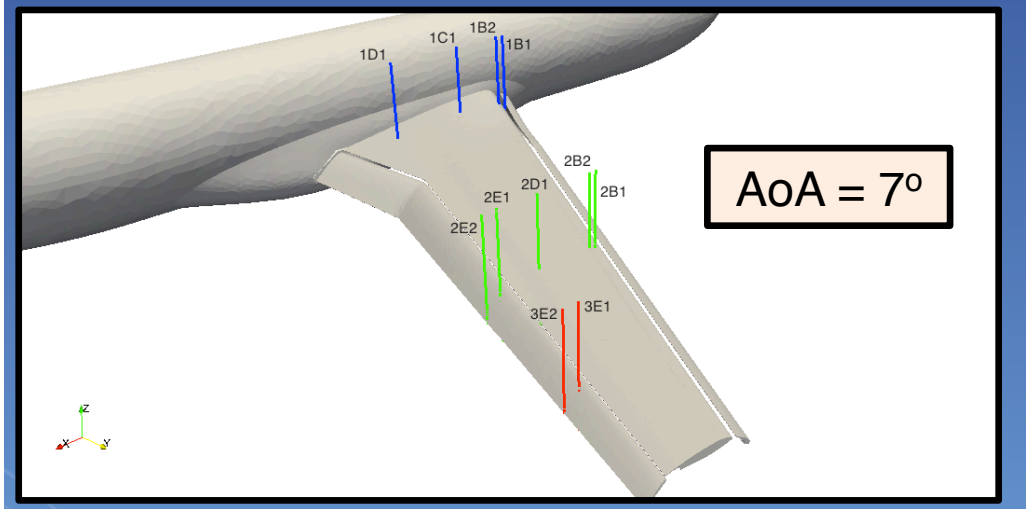
# M0 mesh: Lift and Drag

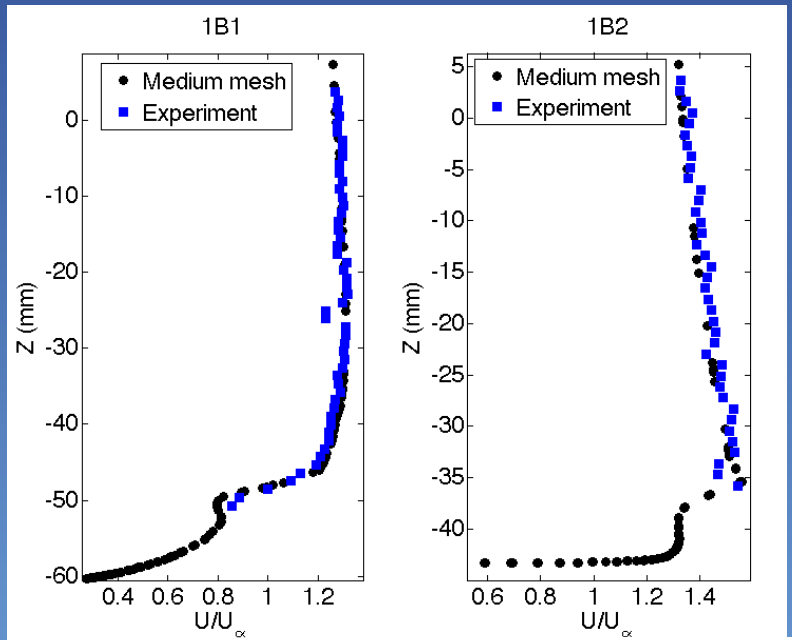


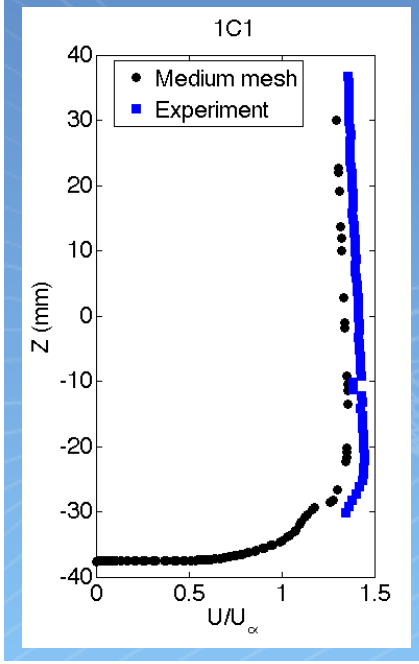



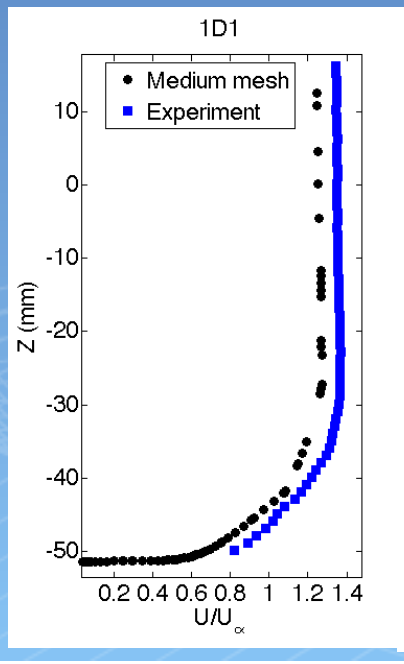



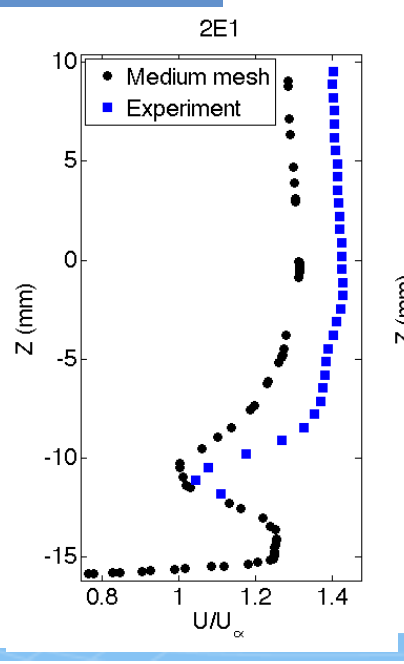
# M0 mesh: Velocity profiles

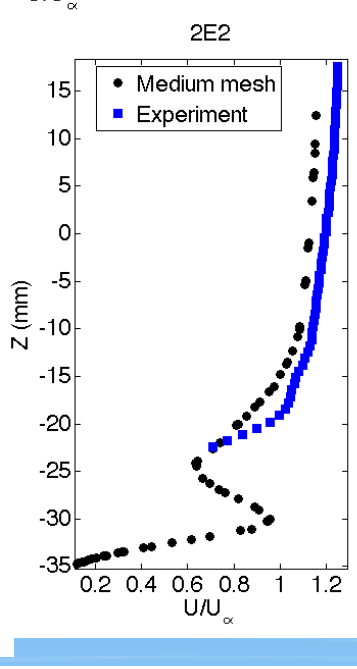


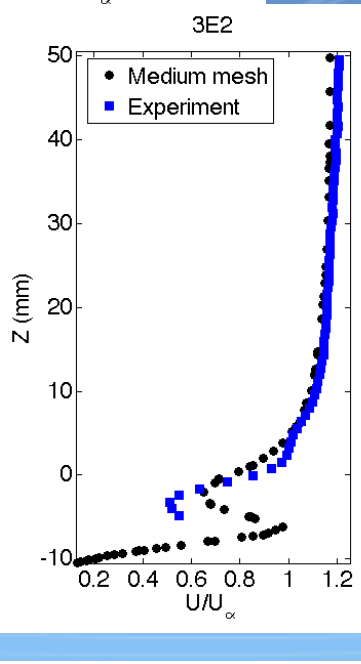



# A0 and A1 meshes

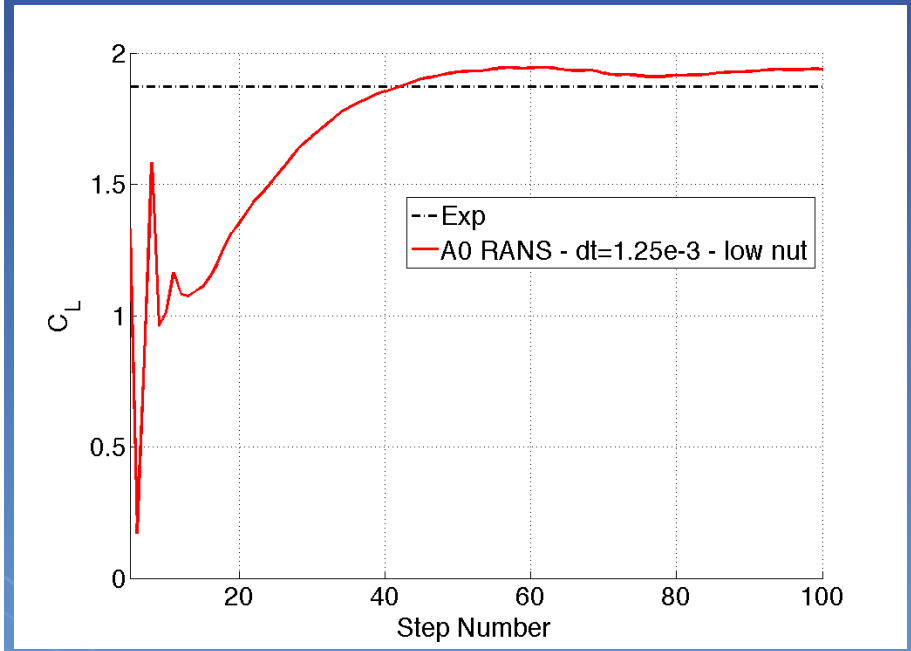
- ✓ Turbulence model: (U)RANS and DDES
- ✓ RANS:
  - ➢ Time step convergence
  - ➢ Influence of free stream eddy viscosity $\nu_{t\infty}$
    - $\nu_{t\infty} = \nu / 10$ ("quiet wind tunnel")
    - $\nu_{t\infty} = 3\ \nu$ (standard value)
  - ➢ Grid convergence
- ✓ DDES
  - ➢ Grid convergence
- ✓ Comparisons:
  - ➢ Force history
  - ➢ Cp
  - ➢ Q visualization

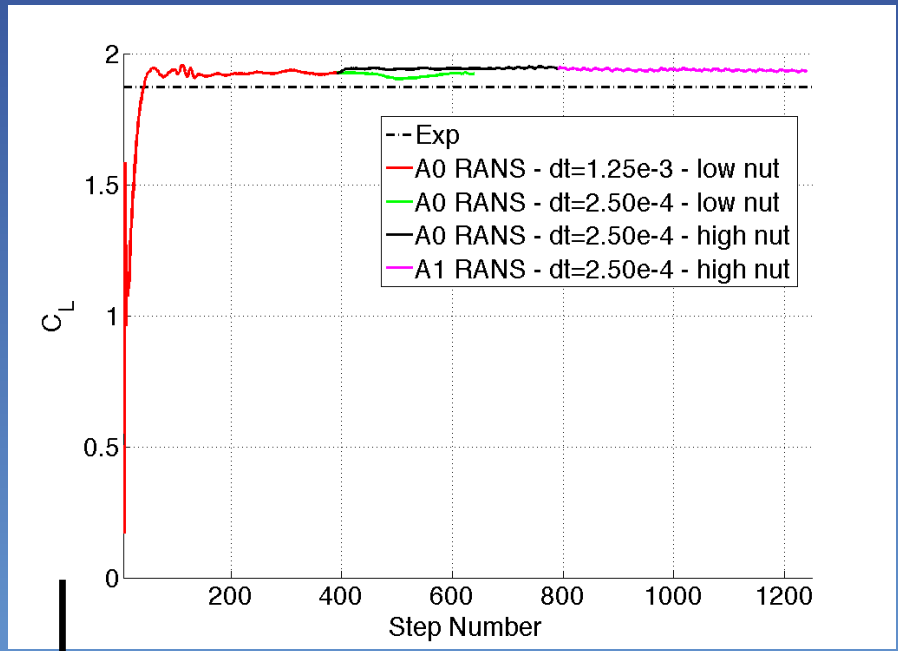
# A0 and A1 meshes

- ✓ Case nomenclature:
  - ➢ RANS
    - A0 RANS dt=1.25e-3 low nut
    - A0 RANS dt=2.50e-3 low nut (time step)
    - A0 RANS dt=2.50e-3 high nut (free stream eddy viscosity)
    - A1 RANS dt=2.50e-3 high nut (mesh resolution)
  - ➢ DDES
    - A0 DDES dt=1e-5 high nut
    - A1 DDES dt=1e-5 high nut (mesh resolution)

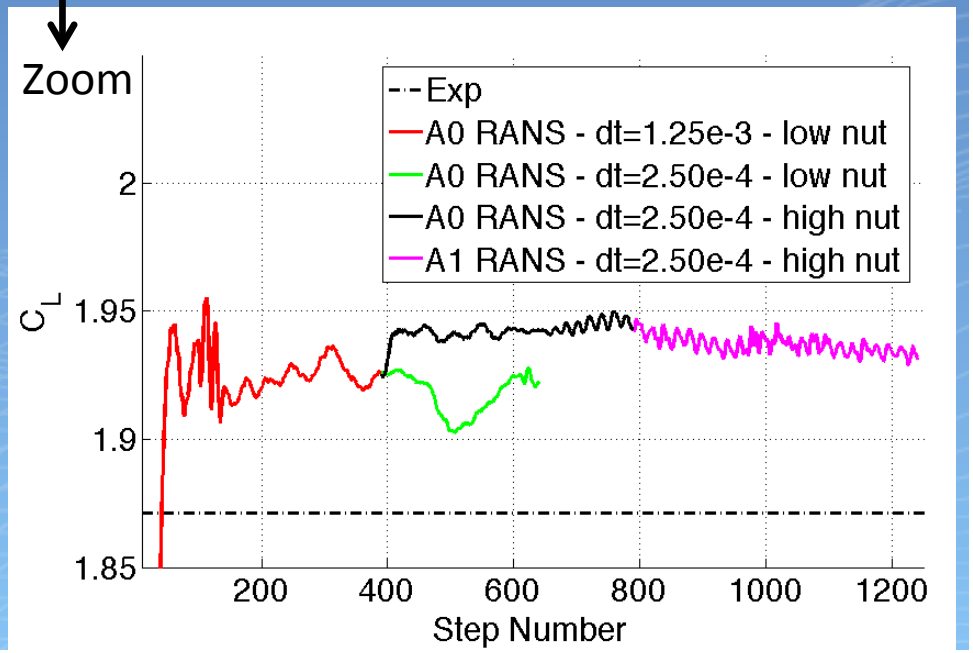
# Force history - RANS





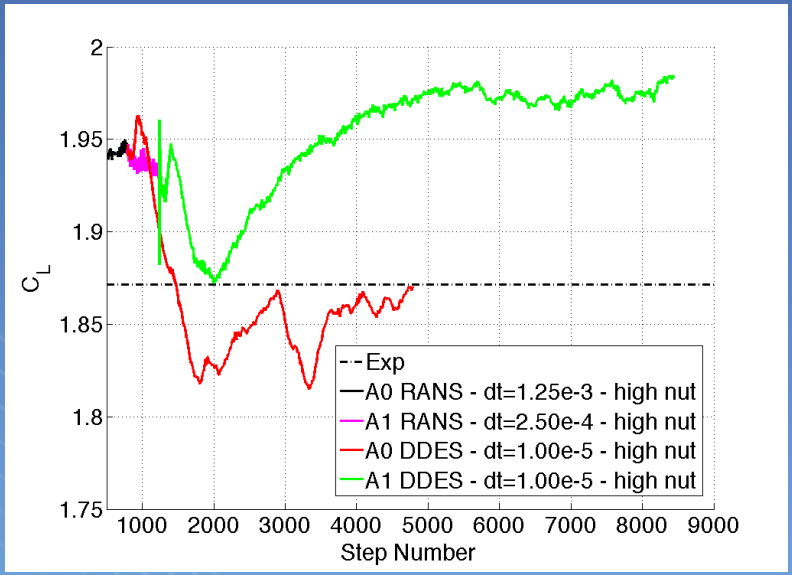




- Asymptotic value in about 50 time steps for "A0 RANS dt=1.25e-3 low nut" (see ▬ )
- Little effect of the time step for the "A0 RANS low nut" cases (see ▬ and ▬ )
- Influence of the free stream eddy viscosity on the "A0 RANS dt=2.50e-3" cases: larger force coefficient for $\nu_{t\infty}$= 3 ν (see ▬ and ▬ )
- Little effect of the mesh refinement for the "RANS dt=2.50e-3 high nut" cases (see ▬ and ▬ )



# Force history - DDES



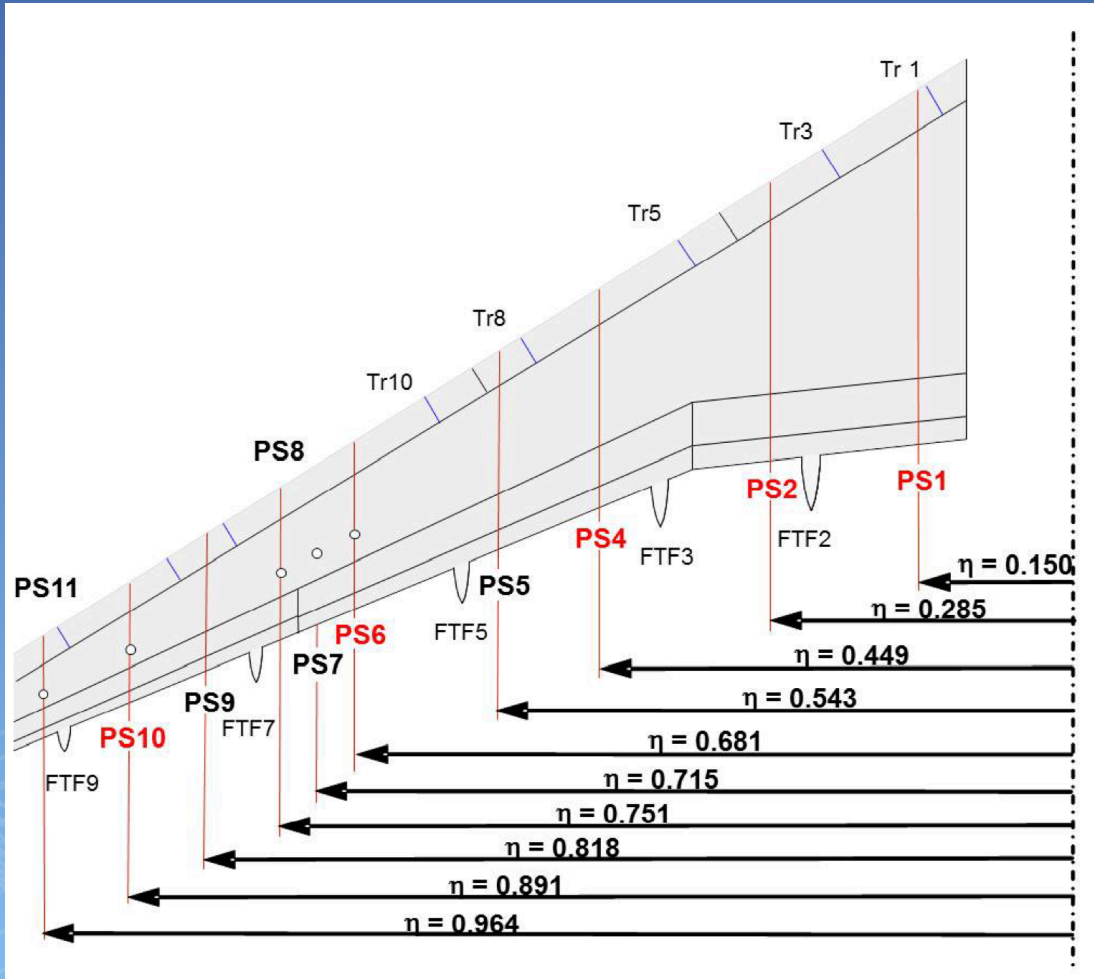



- DDES simulations on A0 and A1 mesh started from respective RANS simulations
- Strong influence of the mesh refinement for DDES (see — and —)
- A0 mesh resolution not sufficient for DDES
- Additional mesh adaptation cycle required for grid convergence

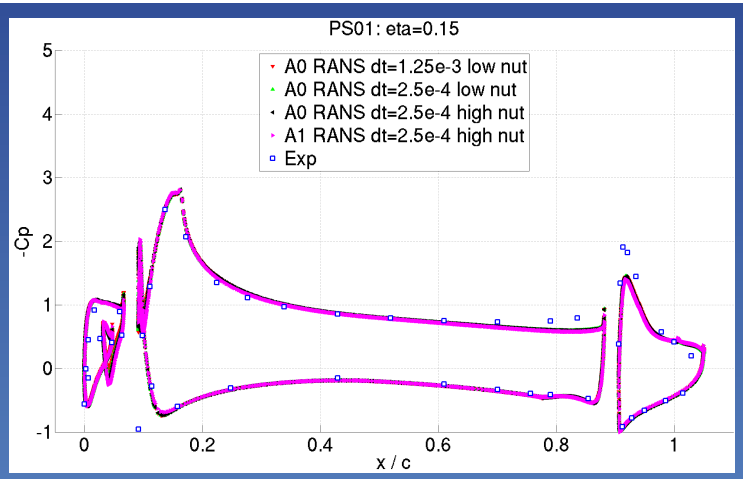
# Pressure Coefficient Cp

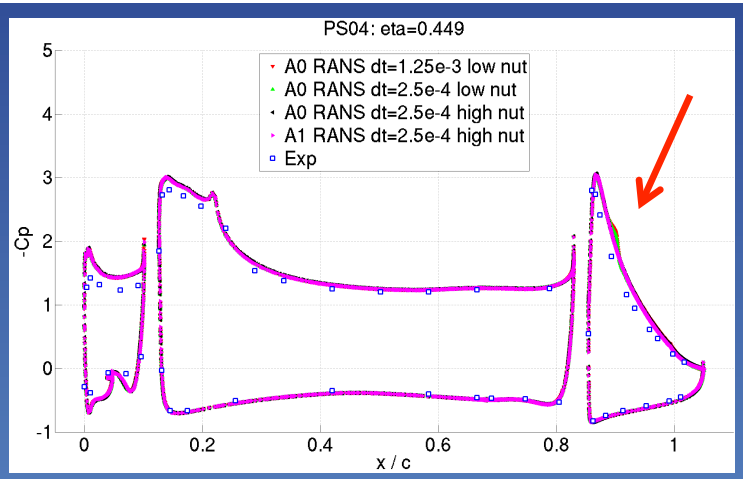


- Pressure stations considered: PS1, PS4, PS5, PS8, PS9, PS10



# Cp - RANS


PS01: eta=0.15
A0 RANS dt=1.25e-3 low nut
A0 RANS dt=2.5e-4 low nut
A0 RANS dt=2.5e-4 high nut
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c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A0 RANS dt=1.25e-3 low nut
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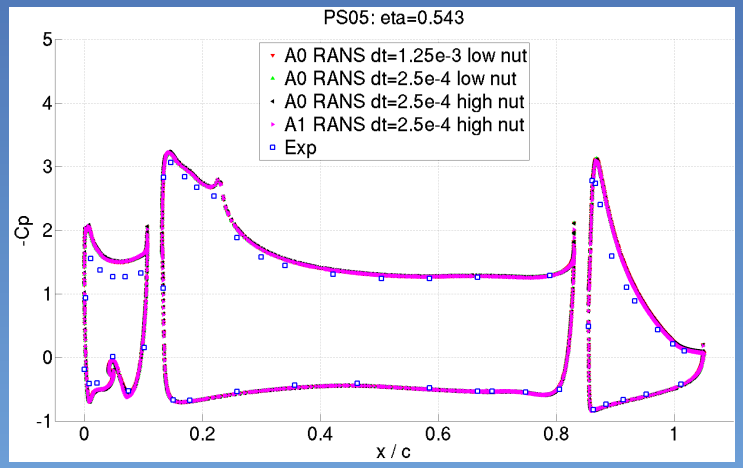
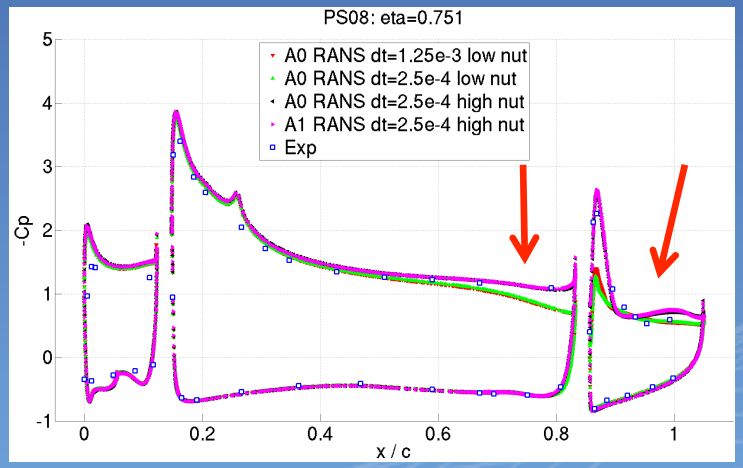
A0 RANS dt=2.5e-4 high nut
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c


PS05: eta=0.543
A0 RANS dt=1.25e-3 low nut
A0 RANS dt=2.5e-4 low nut
A0 RANS dt=2.5e-4 high nut
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c


PS08: eta=0.751
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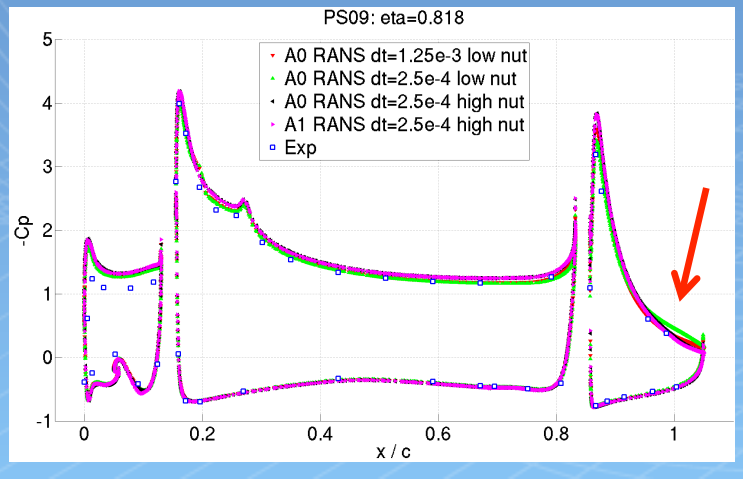
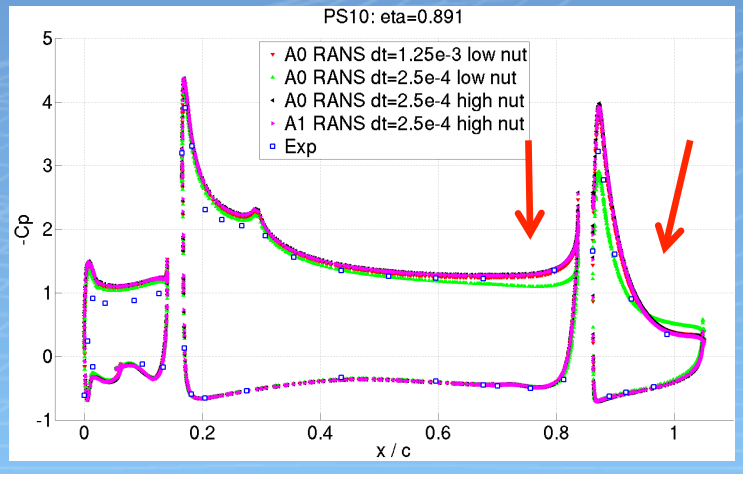
A0 RANS dt=2.5e-4 low nut
A0 RANS dt=2.5e-4 high nut
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c


PS09: eta=0.818
A0 RANS dt=1.25e-3 low nut
A0 RANS dt=2.5e-4 low nut
A0 RANS dt=2.5e-4 high nut
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c


PS10: eta=0.891
A0 RANS dt=1.25e-3 low nut
A0 RANS dt=2.5e-4 low nut
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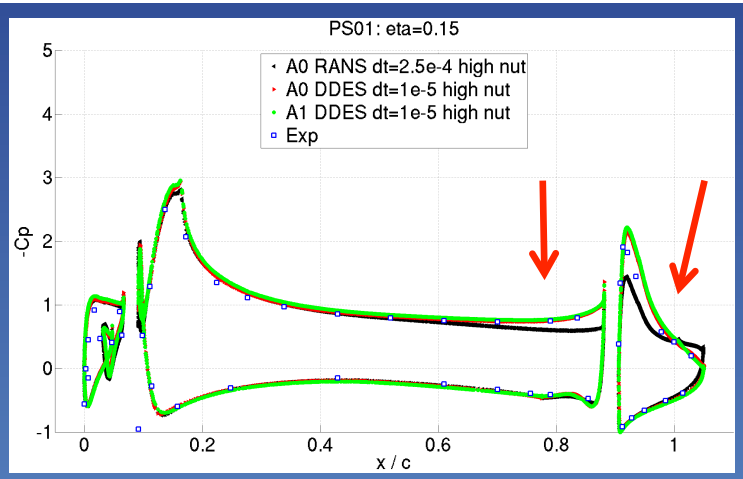
A1 RANS dt=2.5e-4 high nut
Exp
-Cp
x / c

# Cp - DDES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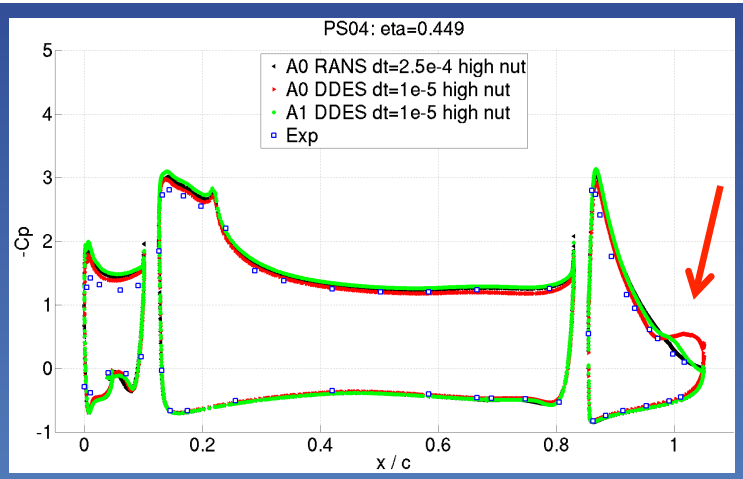
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c


PS04: eta=0.449
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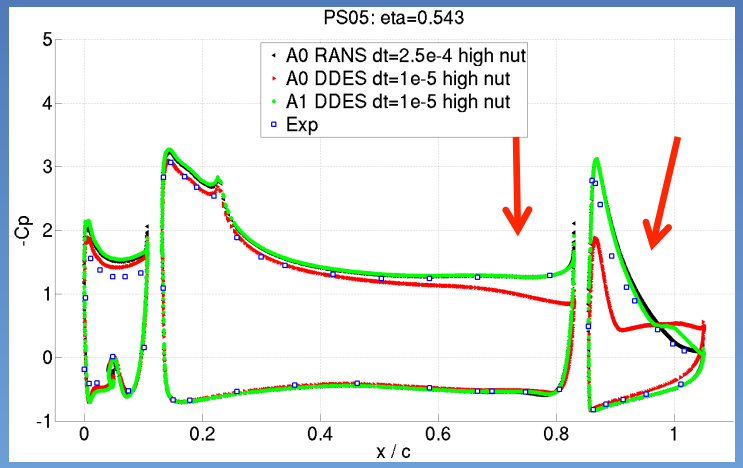
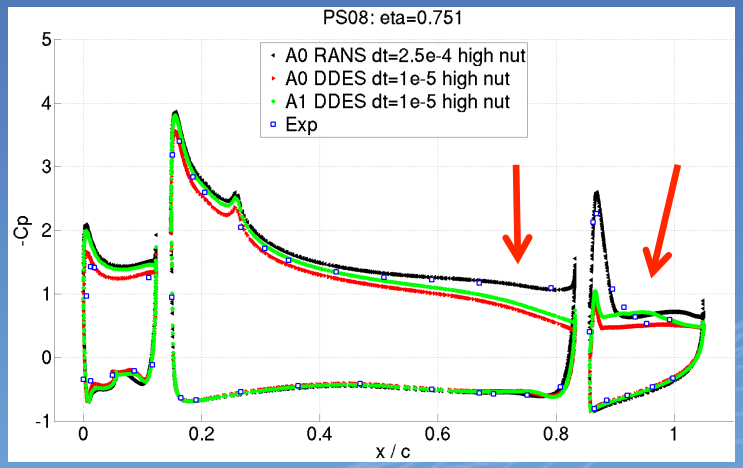
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c


PS05: eta=0.543
A0 RANS dt=2.5e-4 high nut
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c


PS08: eta=0.751
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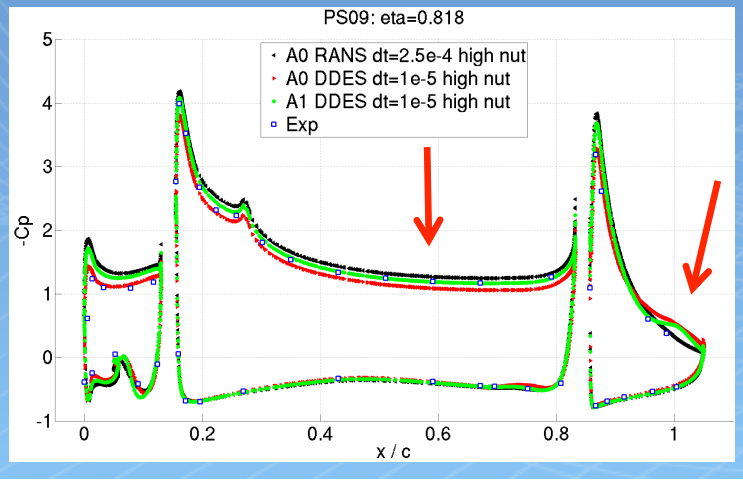
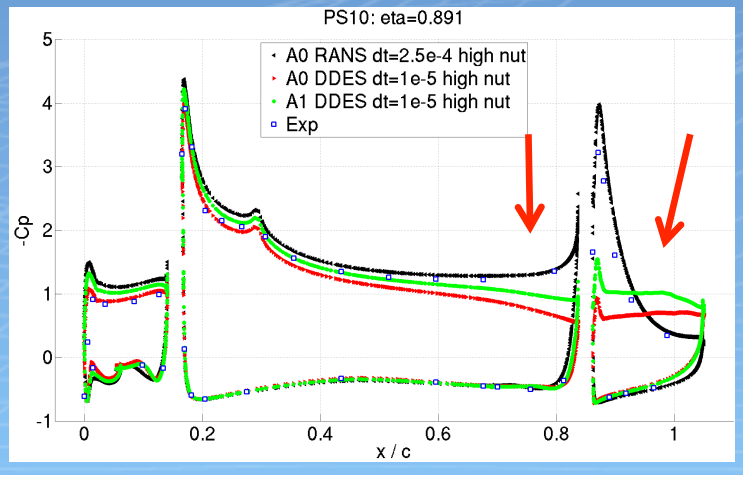
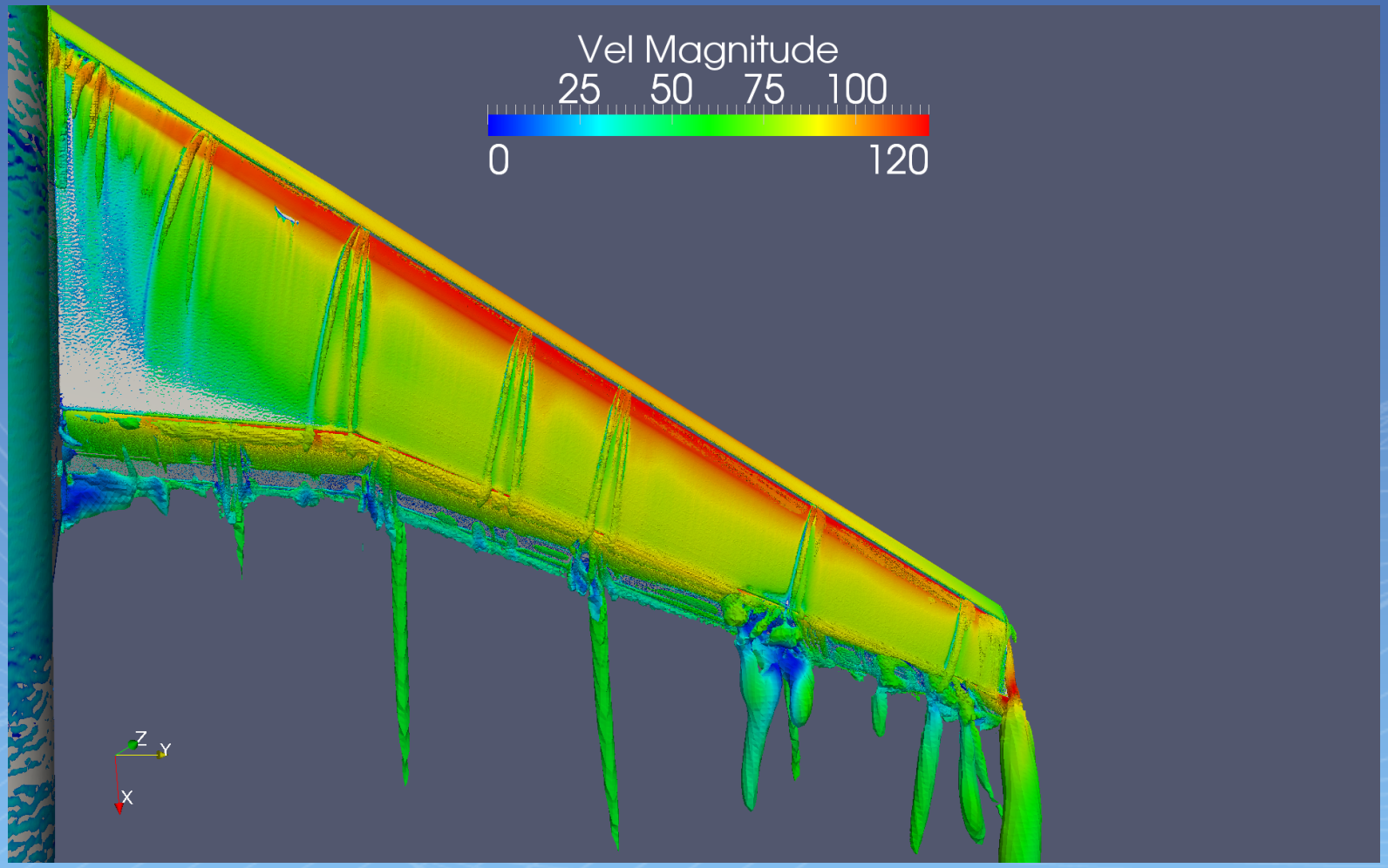
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c


PS09: eta=0.818
A0 RANS dt=2.5e-4 high nut
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c


PS10: eta=0.891
A0 RANS dt=2.5e-4 high nut
A0 DDES dt=1e-5 high nut
A1 DDES dt=1e-5 high nut
Exp
-Cp
x / c

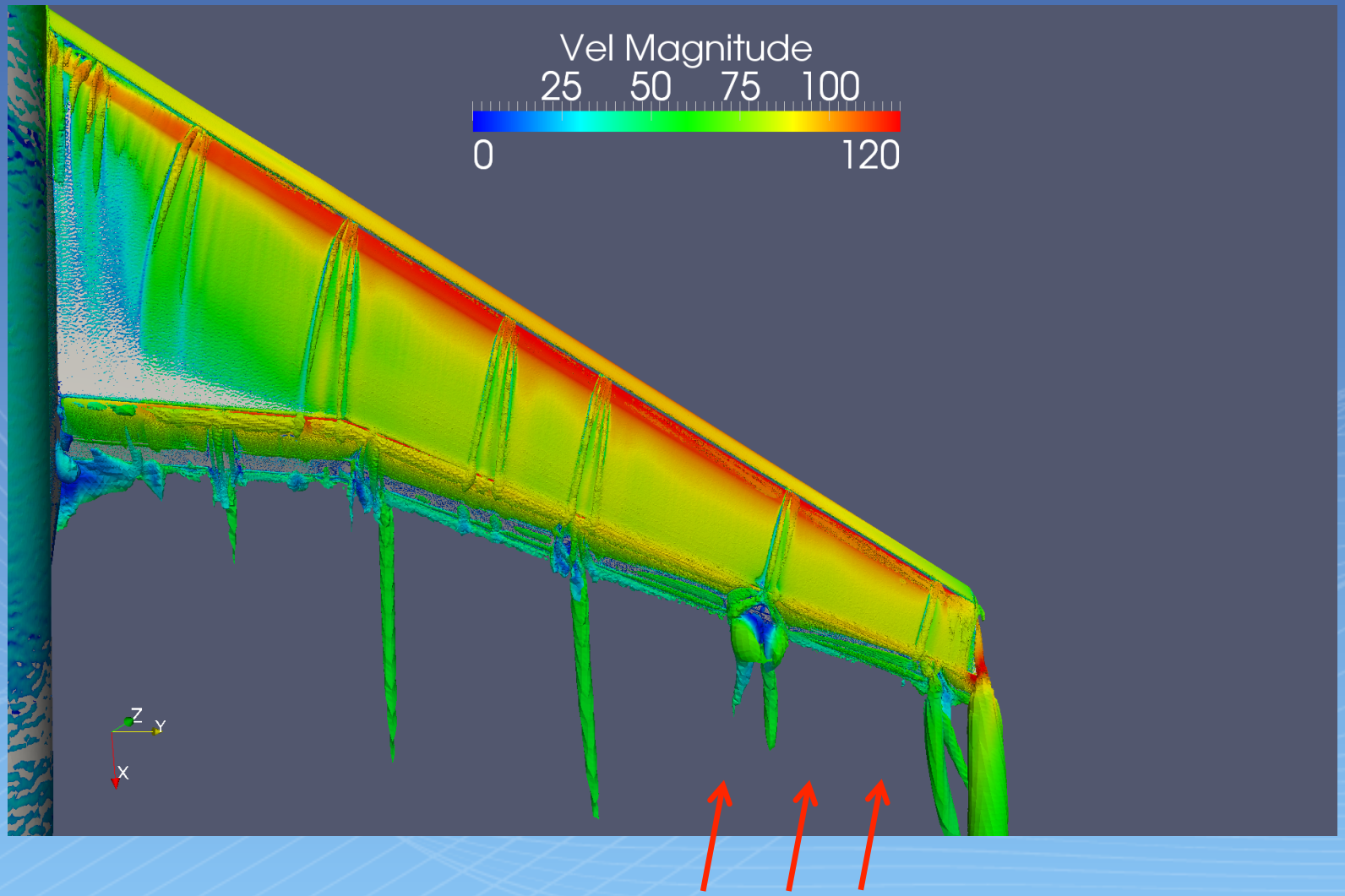
# Instantaneous Q visualization: RANS

A0 RANS dt=2.50e-3 low nut



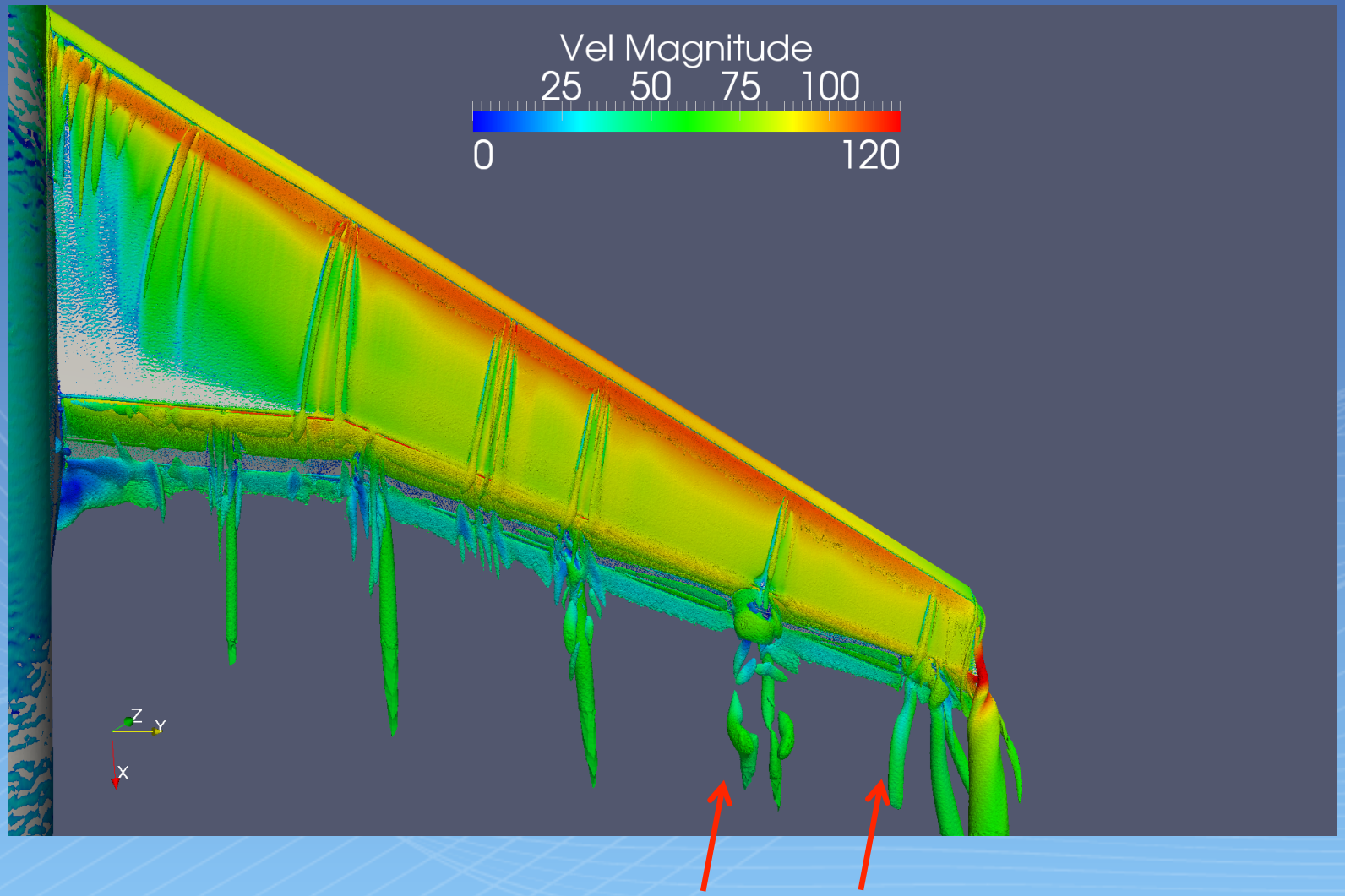
# Instantaneous Q visualization: RANS

A0 RANS dt=2.50e-3 high nut (free stream eddy viscosity)



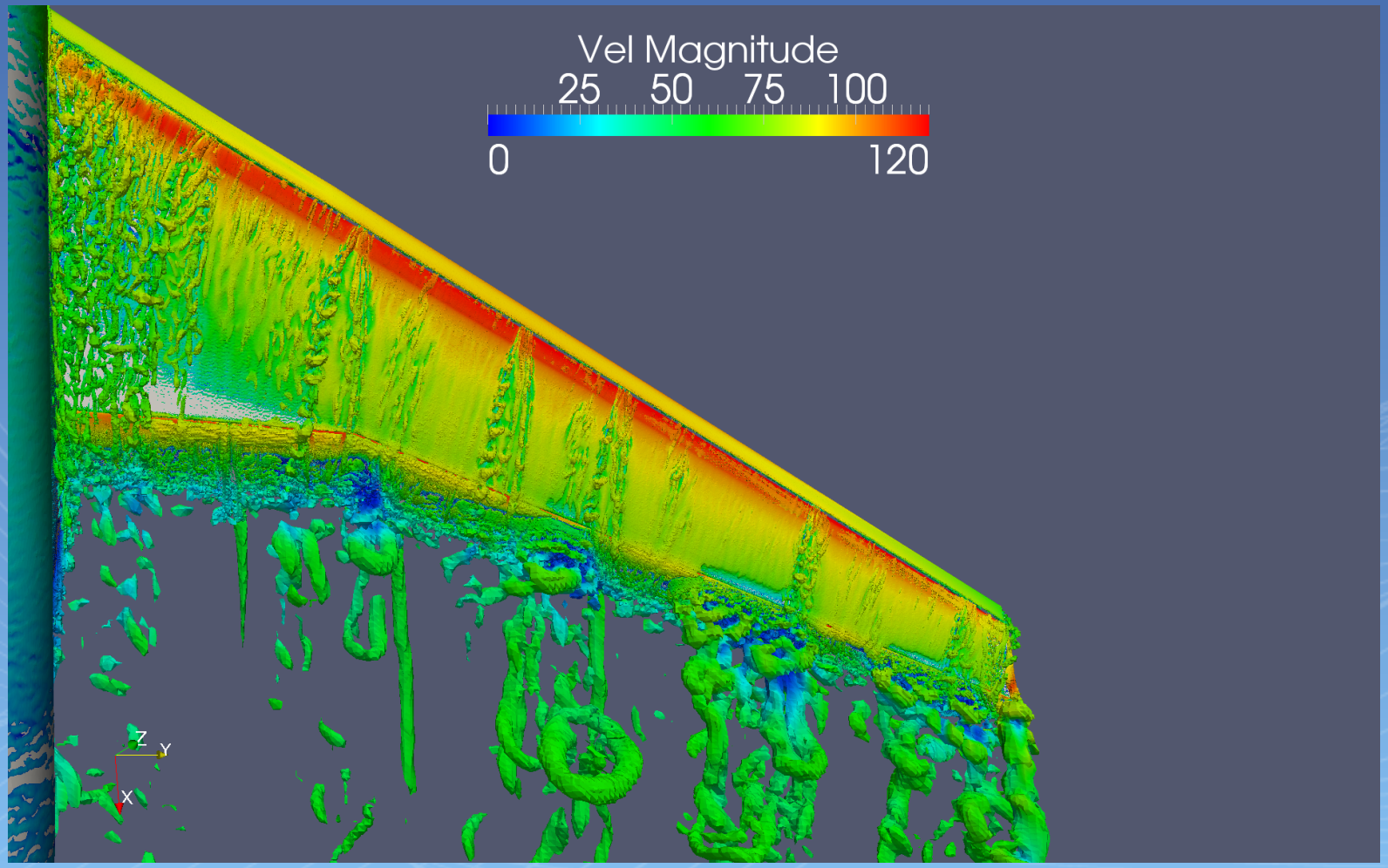
# Instantaneous Q visualization: RANS

A1 RANS dt=2.50e-3 high nut (mesh resolution)



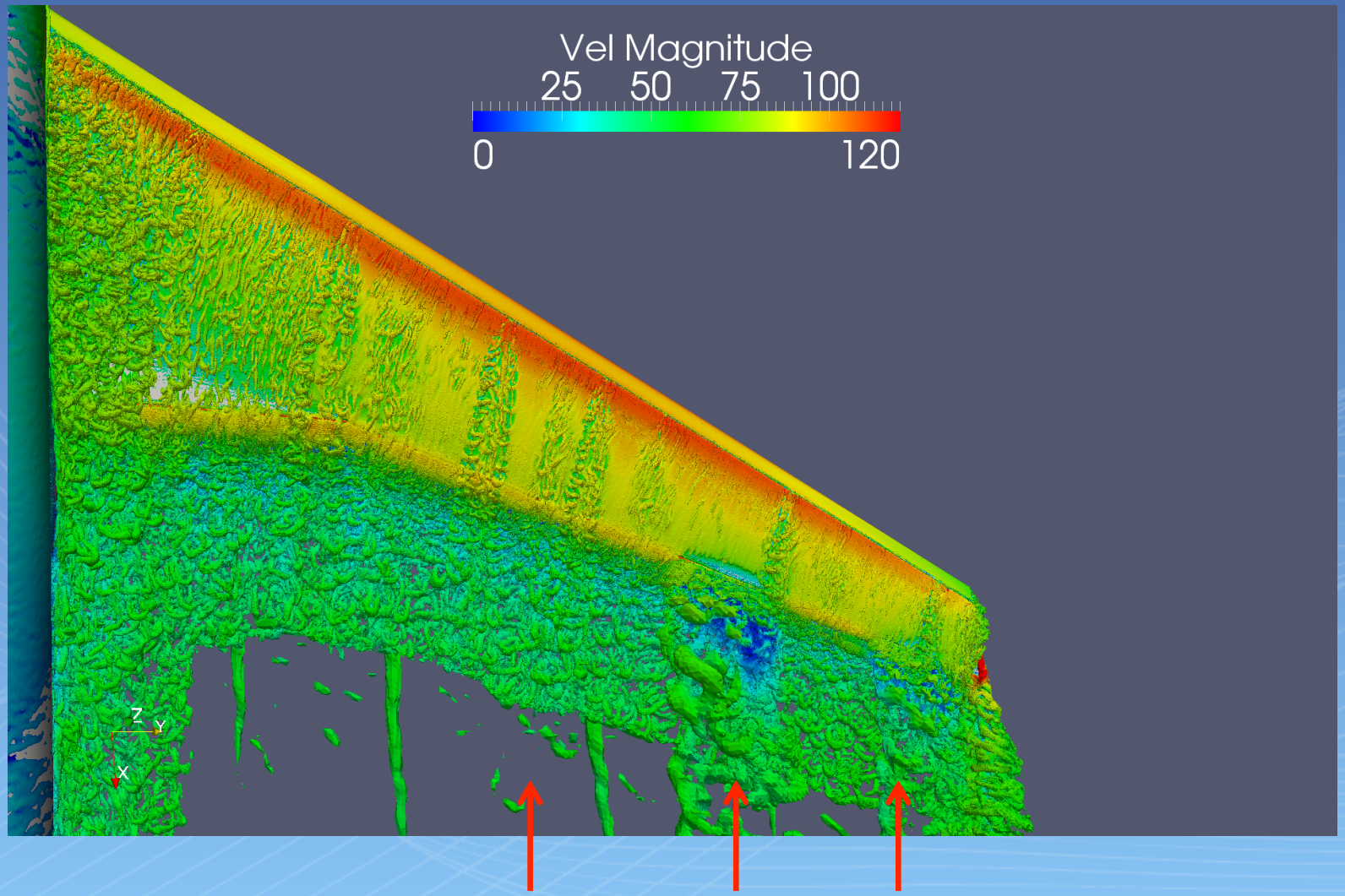
# Instantaneous Q visualization: DDES

A0 DDES dt=1e-5 high nut



# Instantaneous Q visualization: DDES

A1 DDES dt=1e-5 high nut (mesh resolution)



# Conclusions and future work

- (U)RANS: Overall reasonable agreement with the experimental data
  - Better agreement with standard value of $nu_t$ (fully turbulent)
  - Little effect of the time step and mesh refinement (A0 fine enough for RANS)
- DDES and RANS: Over prediction of the suction peak on the slap
  - Compressibility effect
- DDES:
  - Better Cp agreement inboard w.r.t. RANS (on the flap and main wing)
  - Influence of the mesh resolution
    - Too low resolution in key locations can lead to wrong prediction of flow detachment, even at low AoA
    - Better agreement for Cp on the A1 mesh w.r.t. the A0 mesh
    - Additional adaptation cycles required for better agreement and grid convergence
- Mesh resolution and adaptation are keys
  - Slat and flap track wakes
  - Trailing edges
  - Gaps
- Higher AoA

# Parallel Adaptive Detached Eddy Simulations of the EUROLIFT DLR-F11 high-lift configuration

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AIAA Aviation - Atlanta – June 18, 2014