xRANS – An Engineering Approach to Extend Flow Analysis Using RANS-Simulations

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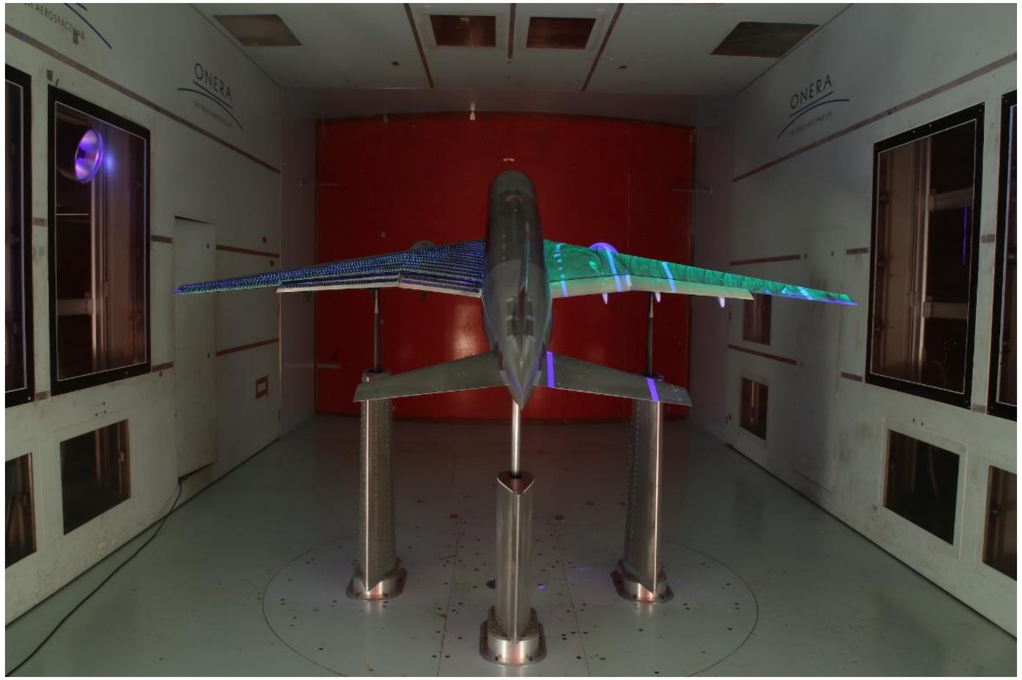
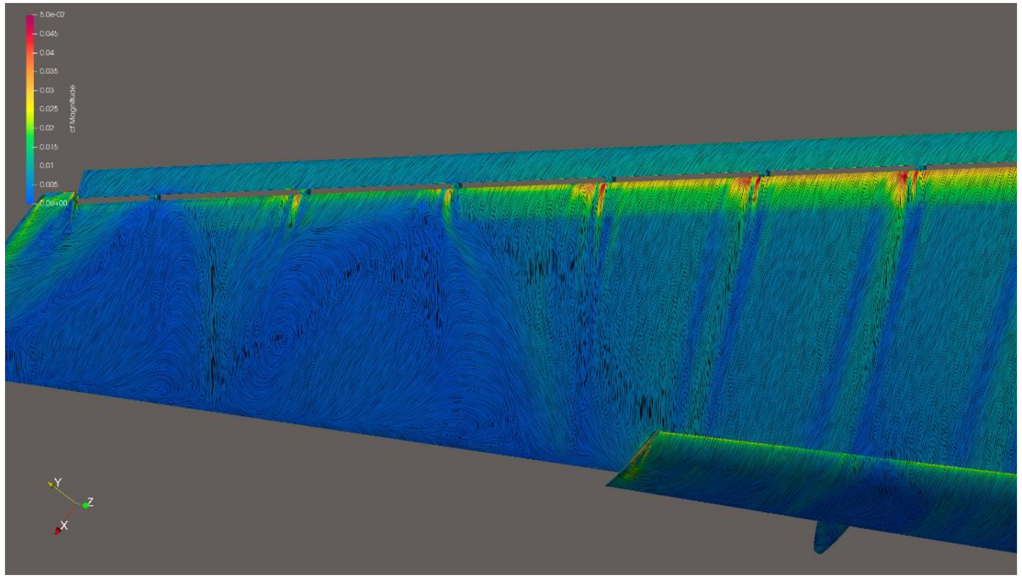
Introduction

Introduction

- 4th High Lift Prediction Workshop: Common Research Model – High Lift (CRM-HL) → major simulation challenge for RANS methods: “pizza-slice” separation:
  - lambda-shaped separation areas
  - triggered by the wake of the slat brackets
  - develop towards the trailing edge
  - expanding in size with increasing angle of attack
  - separations occur significantly earlier (AOA) compared to experiments → premature lift breakdown → inconsistent simulation of the lift breakdown e.g. for the CRM-HL
  - onset tends to occur closely downstream of the brackets & overpredicted in size → not reflected in experimental evidence
  - “pizza slice” sep.: only used for overpredicted separation areas
  - lambda-shaped separation: (measured) separation phenomena

- Starting point of this project: hybridRANS/LES are in very good agreement with experiments → compare RANS, uRANS & hybridRANS/LES simulation results in the region of “pizza slice separation” → insight in differences & identification of possible reasons



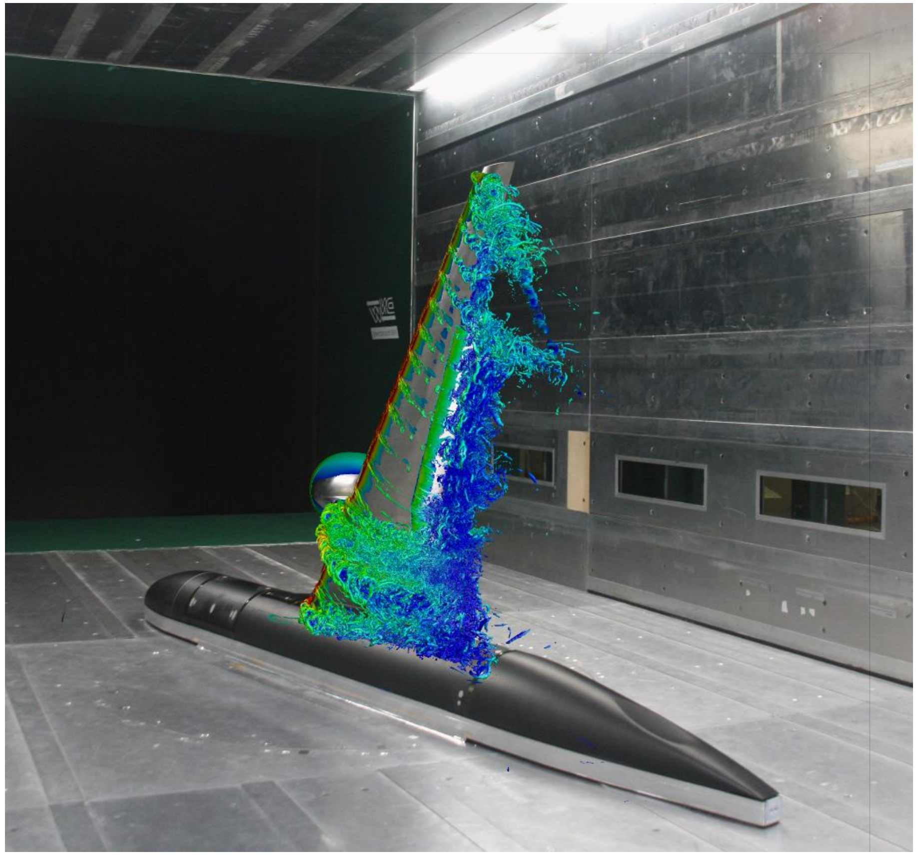


Analysis of RANS / uRANS / hybrid RANS/LES

Analysis of RANS / uRANS / hybrid RANS/LES

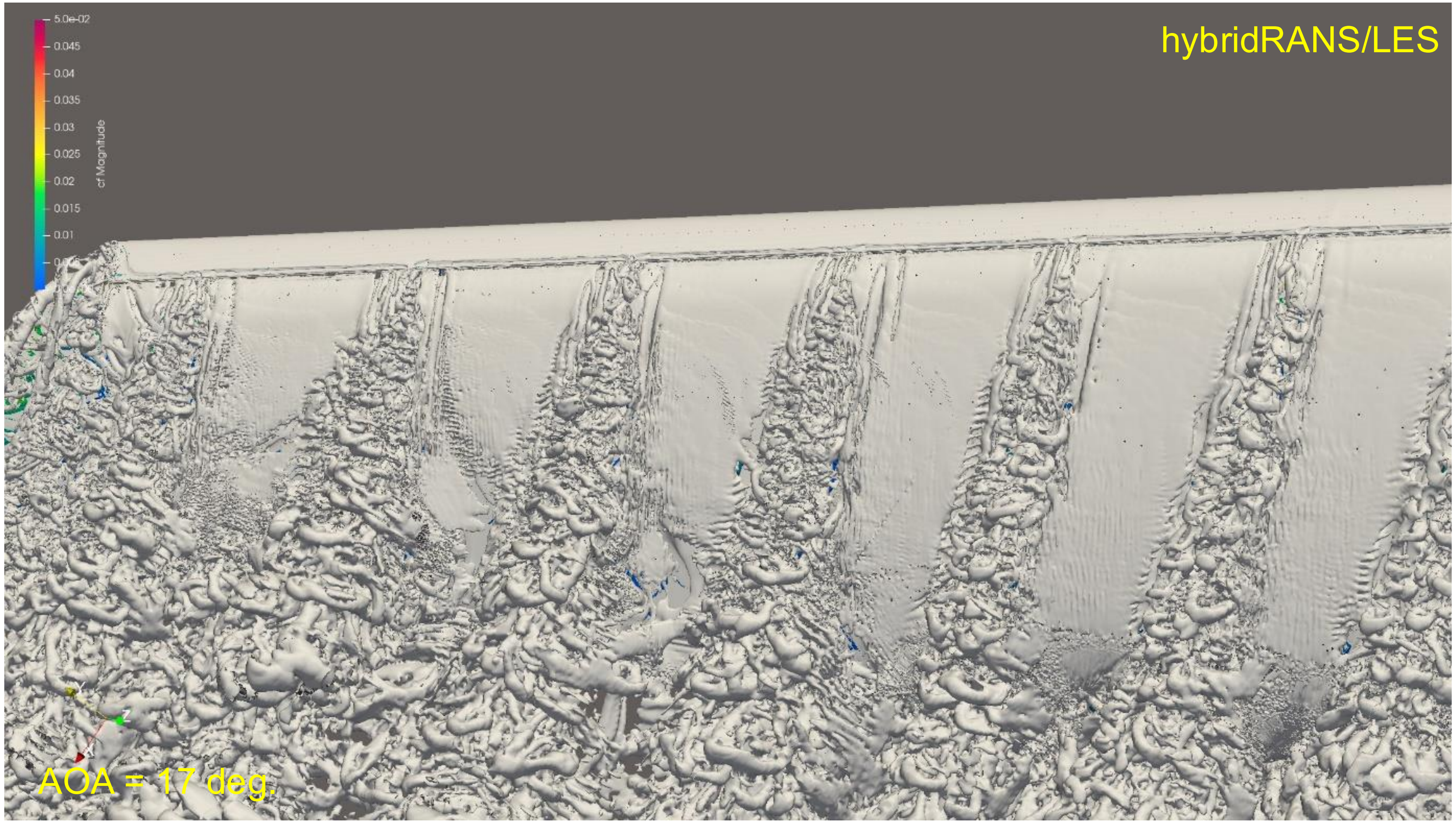
- Basis for the presented numerical results: Freeflight simulation of CRM-HL (complete aircraft):
  - DLR-Project Adamant (internal)
  - DLR TAU-Code – RANS / uRANS / hybridRANS/LES
  - AOA: 17 deg. / Mach number: 0.2 / Reynolds number: 1.7e6
  - SANeg turbulence model
  - uRANS & hybridRANS/LES → started from RANS solutions at the same AOA (including possible pizza slice separation)
  - ANSA quad / hexa dominant meshes with resolution "fine"

- Different mesh resolutions:
  - RANS: 296e6 points
  - uRANS: 215e6 points & normalized time step size: 0.001
  - hybridRANS/LES: 548e6 points & normalized time step size: 0.0004



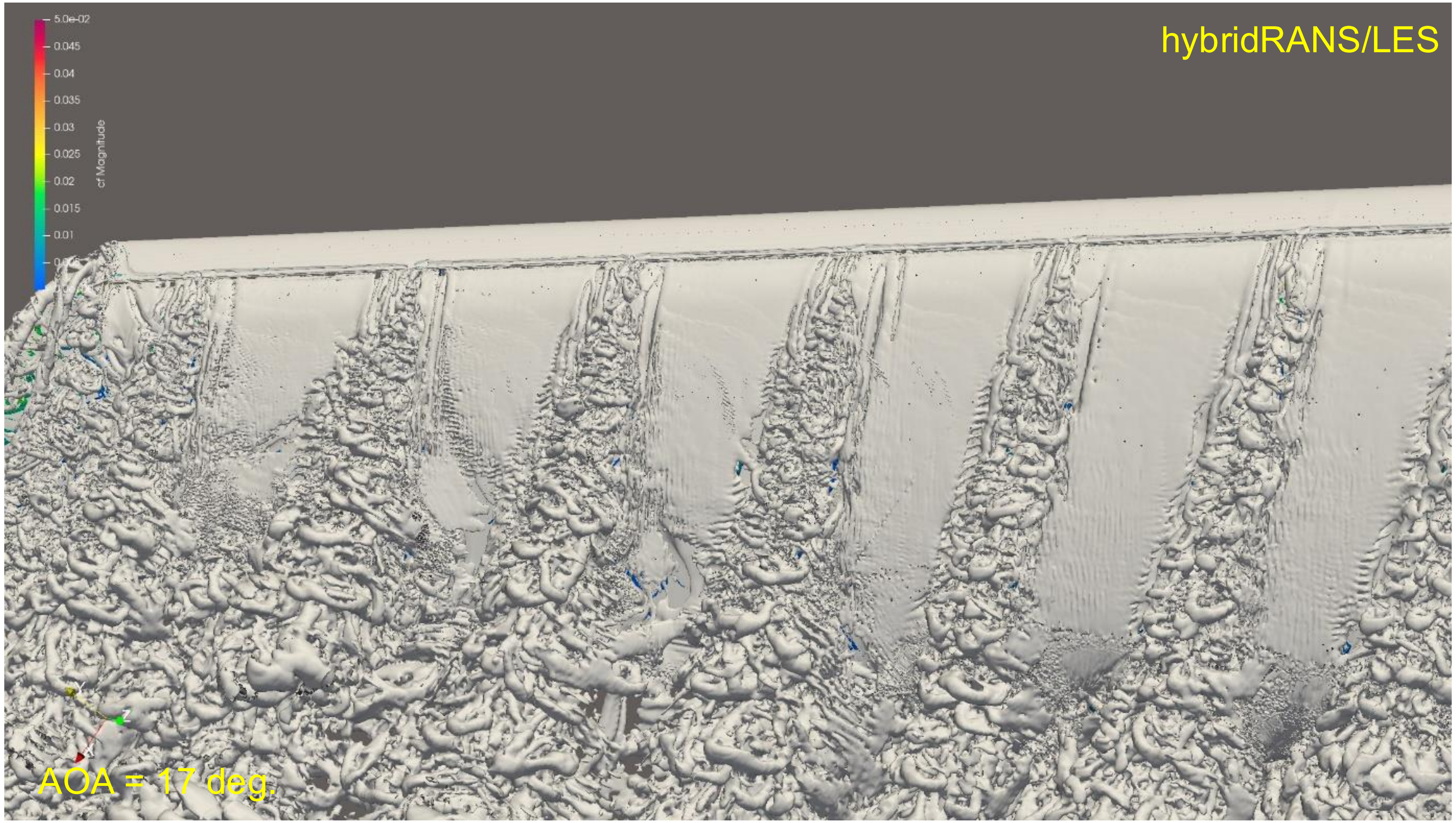
Analysis of RANS / uRANS / hybrid RANS/LES

- hybridRANS/LES simulations proven for very good agreement with experimental results even in the region of highly separated flow → trusted baseline to compare uRANS & RANS with
- Visualization: lambda2 criterion
- Two main flow features:
    - small-scale turbulent structures of wake-type behind blunt elements in in region of pressure rise
    - vortices (mostly) aligned with the main flow



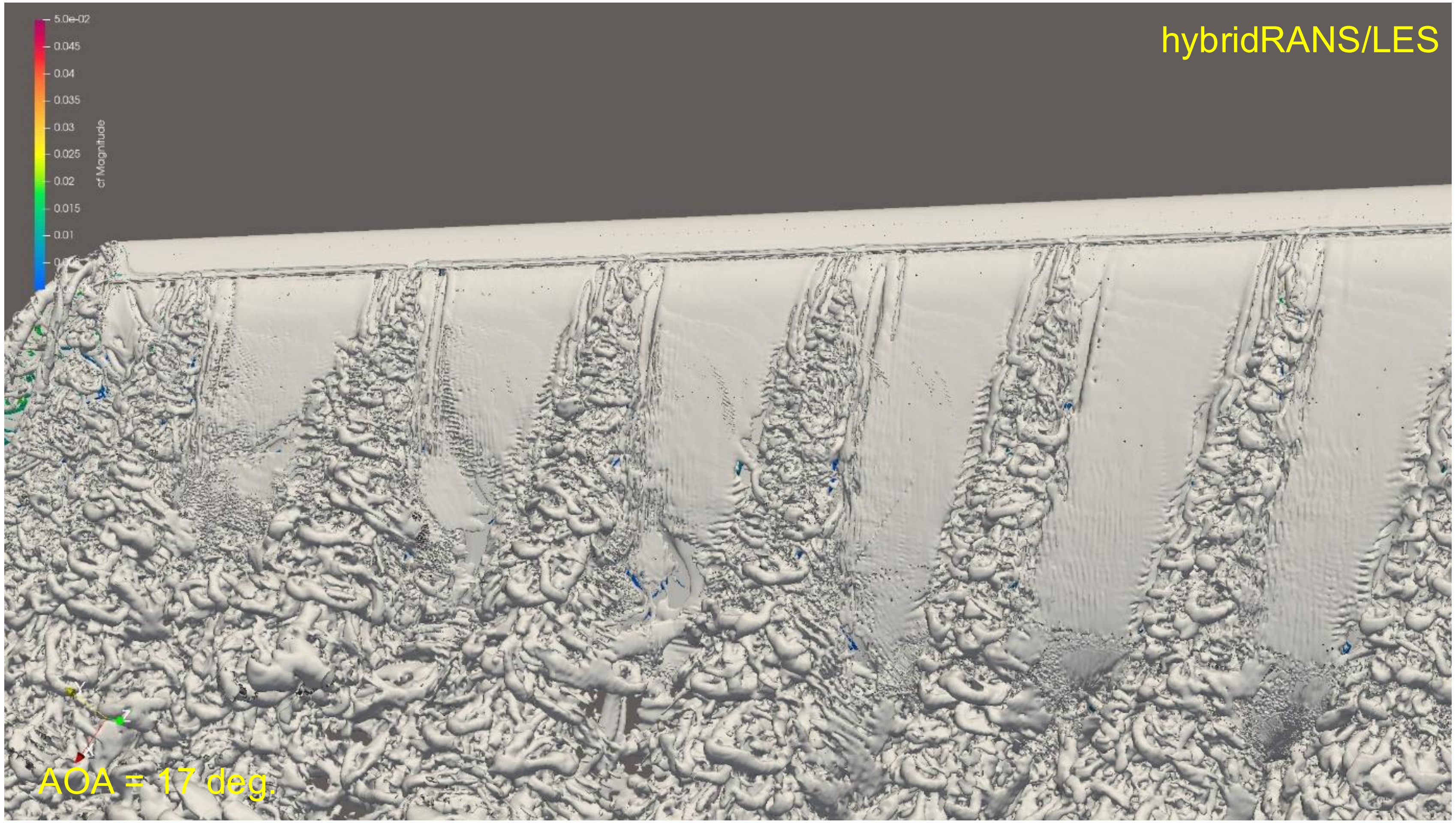
Analysis of RANS / uRANS / hybrid RANS/LES

- Primary and secondary horse shoe vortex around the slat brackets – early break-down in turbulent flowfield (compared to RANS)
- Slat cavity vortex:
    - driven by viscous forces of the flow through the slat gap
    - disturbed by the slat brackets → partially turned into flow direction
    - both for the inboard- and outboard side of a slat bracket, because vortices have no start or end in the flow field (Helmholtz's theorems)
- All vortices partially interact in the region of the slat bracket
- Depending on AOA & pressure rise on the upper wing surface → possible vortex breakdown due to pressure rise or due to turbulent structures
- All these “features” add an extra load on the boundary layer on the upper wing & additional pressure rise on the outboard wing because of “missing” flap



Analysis of RANS / uRANS / hybrid RANS/LES

- Local flow breakdown with increasing AOA:
  - local flow separation on the trailing edge (lambda-shaped) → grows upstream & spanwise direction till it reaches finally the slat bracket itself
  - Process is not abrupt in time & divides itself over some broader AOA range
- No clear distinction between turbulent flow field & vortices & fully developed flow separation in this region → trailing edge separation grows into the turbulent region against the flow direction
- The main flow passes through this region and transports the turbulent features downstream
- Time dependend flow - well confirmed by experiments (e.g. oil flow pictures, tufts, PIV, model vibrations at higher AOA…)

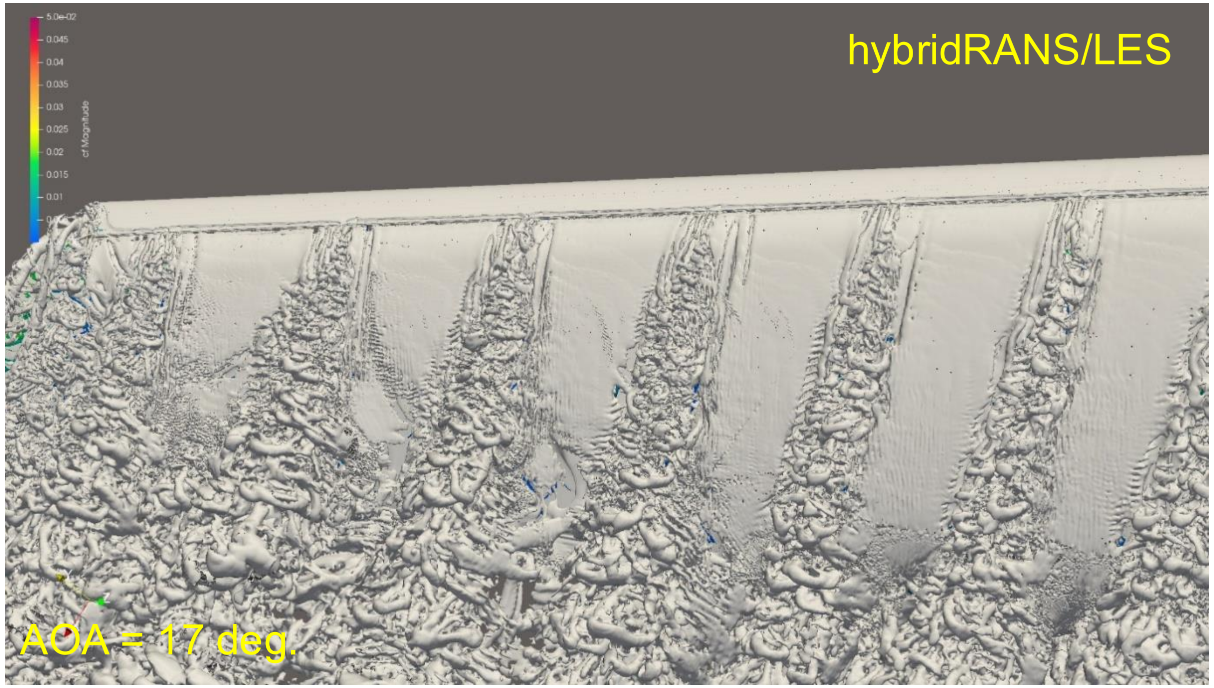


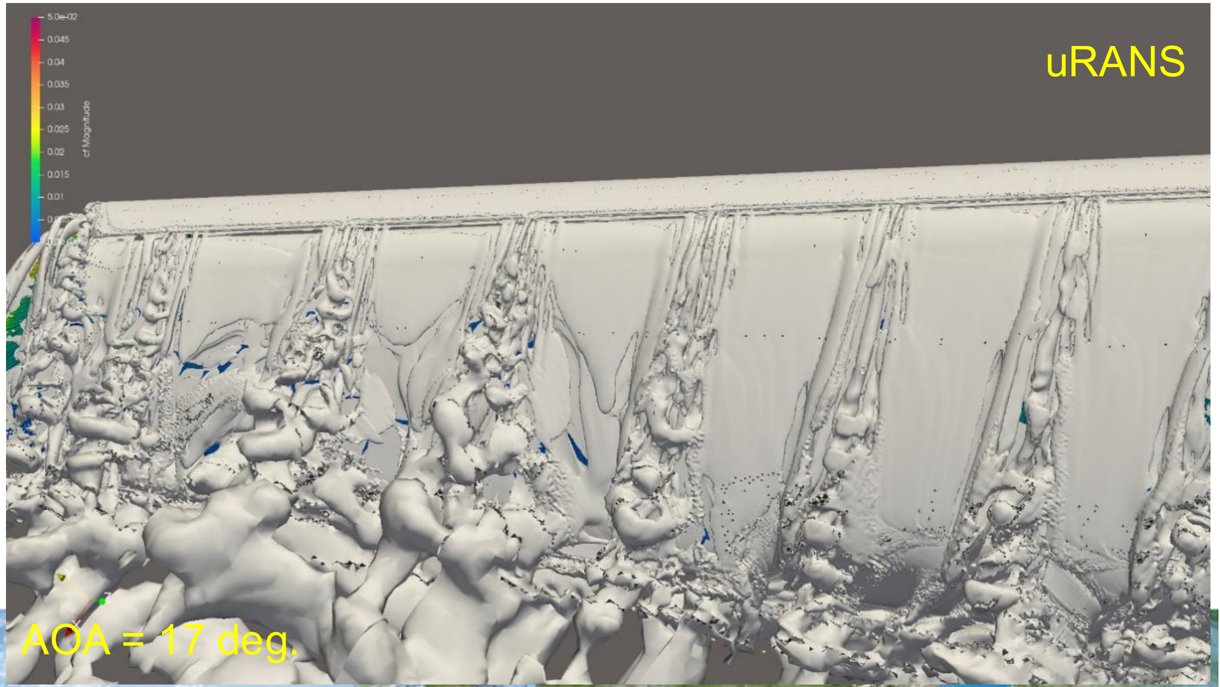
Analysis of RANS / <u>uRANS</u> / hybrid RANS/LES

- Reduced resolution in time stop (~ factor 2.5) and spatial resolution (~ factor 2.0) compared to hybridRANS/LES → resulting turbulent structures larger in size

- Overall: flow topology & the lift coefficient compares well with the hybridRANS/LES & experiments → reduction in turbulence modelling fidelity did not change the overall behavior of the flow

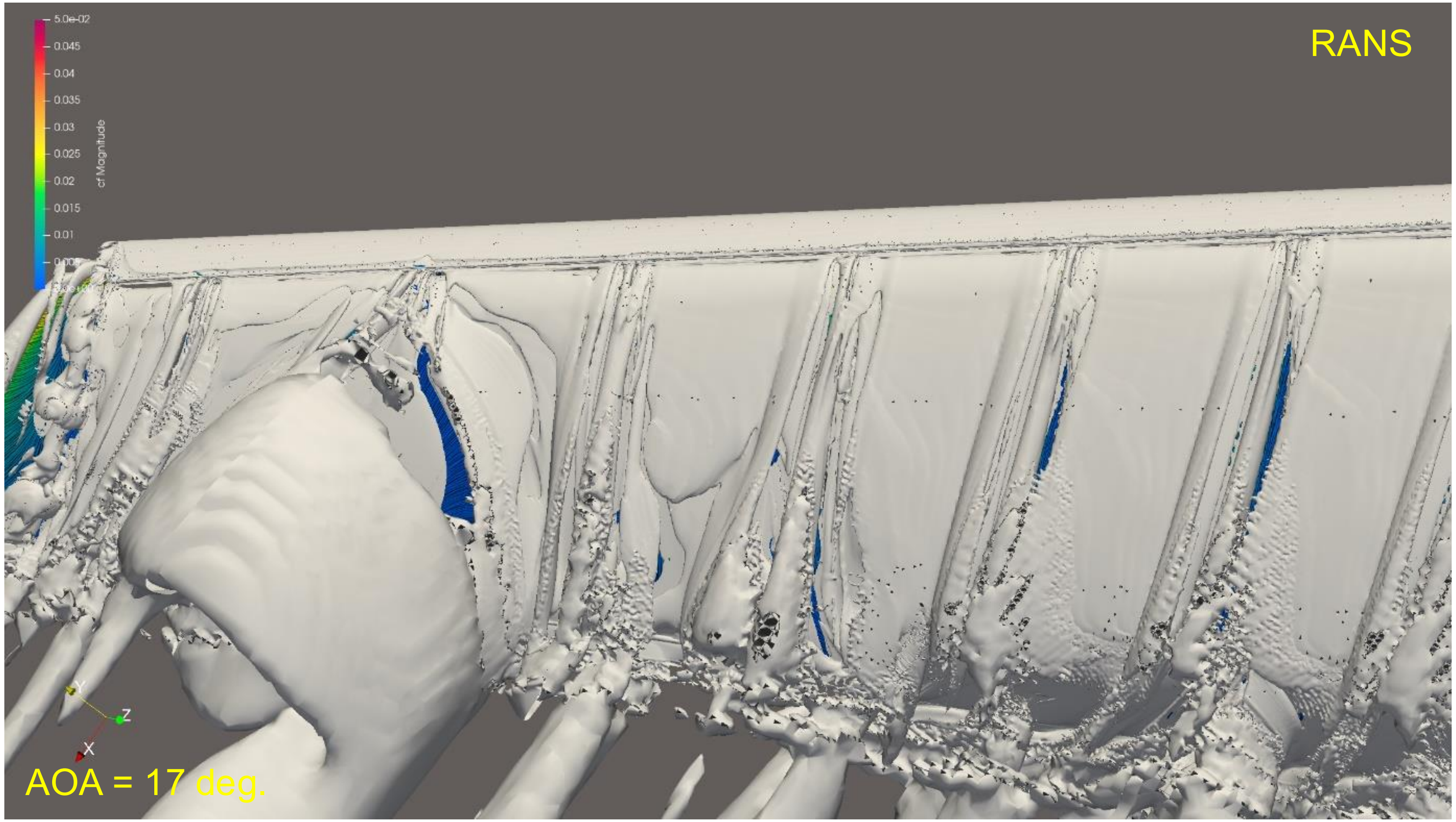
- Remark: “best practise uRANS”:
  - Adequate temporal <u>and</u> spatial resolution (remark: example already “on the edge”)
  - Start from an “physical” RANS (e.g. no “Pizza slices”) – effect shown later in lift curve (17 deg ok, 19 & 21 deg not)
  - Dual time stepping: convergence of inner iterations at least one order of magnitude, two orders are typically fine (if not converging, reduce time step)
  - “Enough” CTUs → trustable mean value





Analysis of RANS / uRANS / hybrid RANS/LES

- Sharply marked flow separation region:
    - “pizza slice” shaped separation
    - nearly no “turbulent” structures, but kind a monolithic region in the flow
- starts on the trailing edge of the main wing element & with increasing AOA it grows upstream to the slat bracket
- bistable behavior: RANS solutions tend to show only not-separated or fully separated flow on the upper wing behind the slat brackets (“upper” and “lower” branch)



Analysis of RANS / uRANS / hybrid RANS/LES

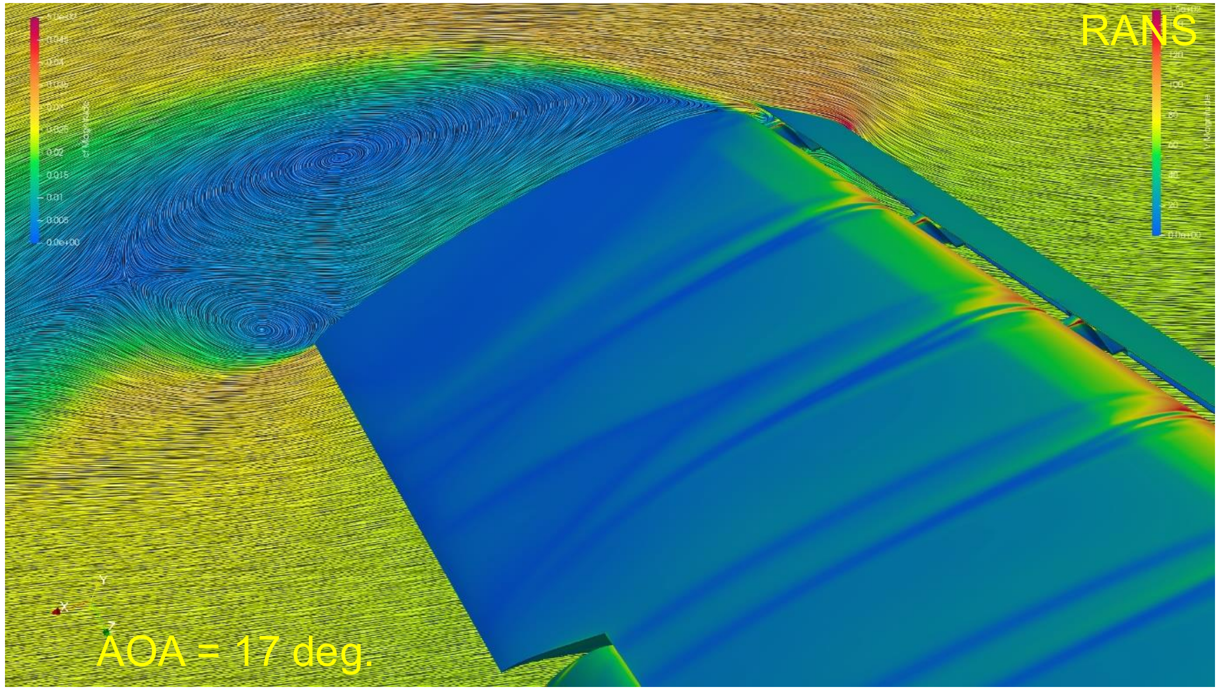
Blockage of the main flow by separated region instead of flow "through":

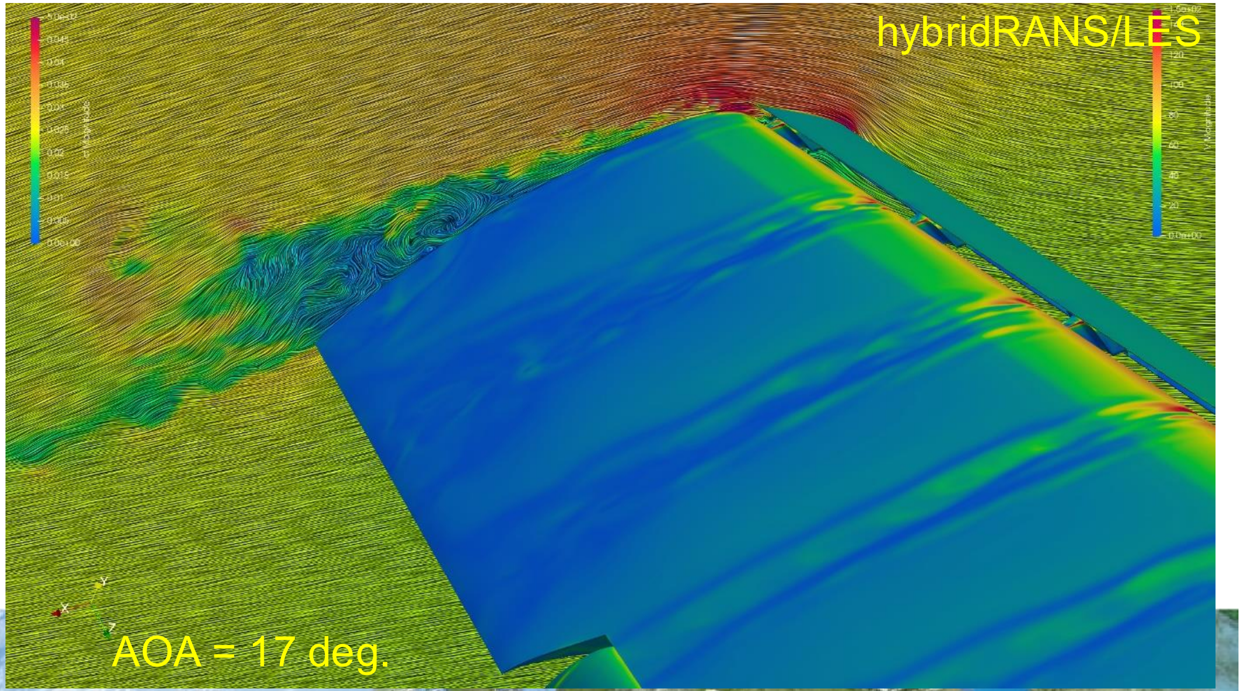
→ suppresses momentum exchange compared to uRANS & HybridRANS/LES & experiment

→ acts like an "obstacle" → additional load on boundary layer upstream of the separation

→ drives its upstream growth significantly

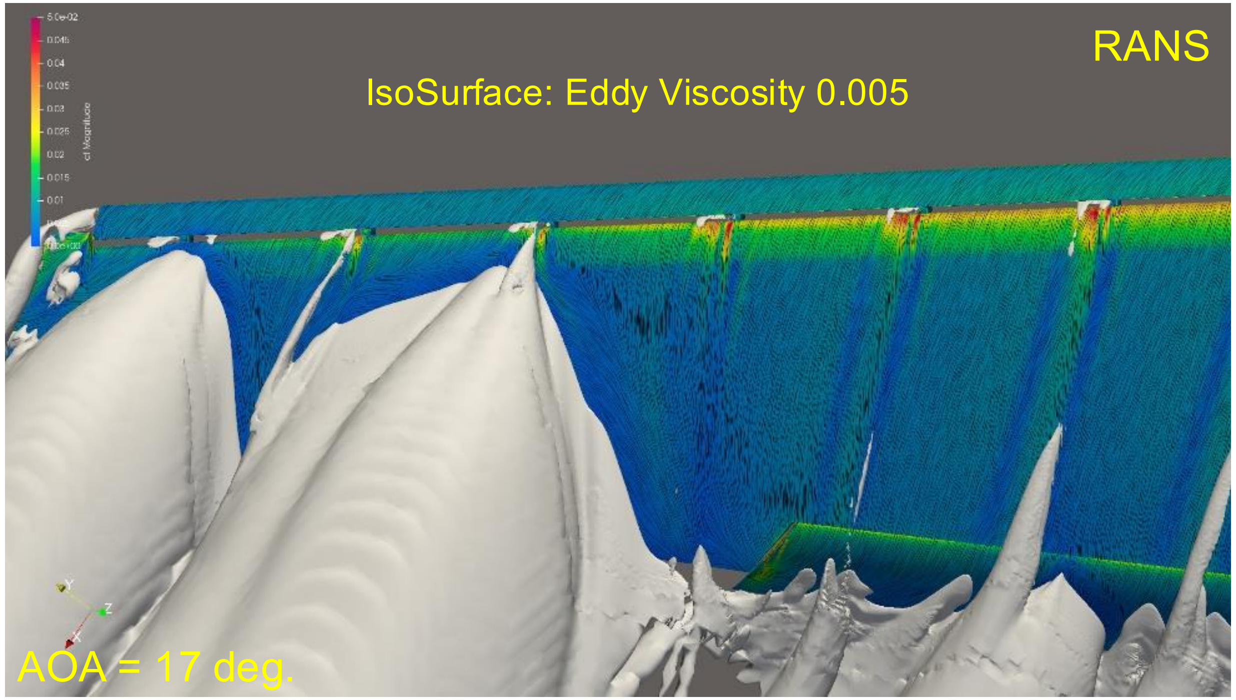
→ quite fast process in small AOA range compared with uRANS & hybridRANS/LES & experiment

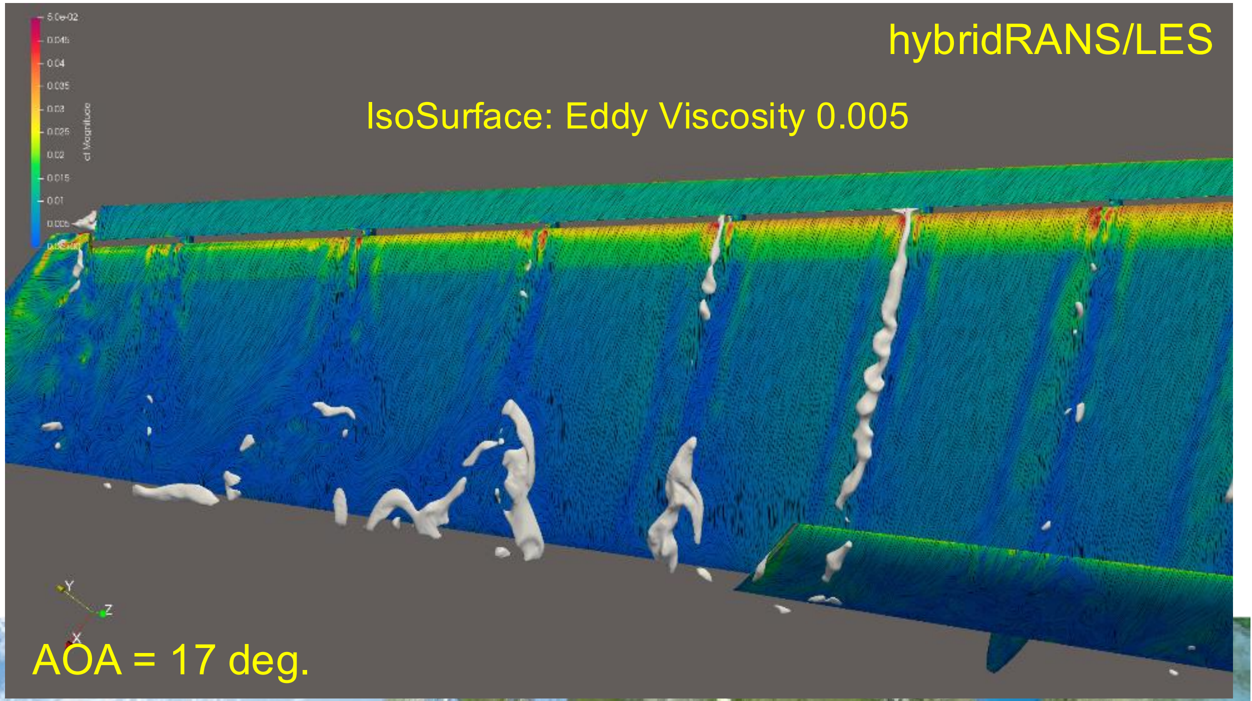




Analysis of RANS / uRANS / hybrid RANS/LES

- RANS: Inside separated region: very high values of eddy viscosity (independent of turbulence model used) → Reason?
- (Expected) input to turbulence model: spatial gradients of velocity (dV/ds)
- Time dependent flow: velocity gradients in space and time (dV/ds & dV/dt)
- uRANS: dV/ds and dV/dt are separated by numerical scheme (dual time step) and time steps are small (global time step): only dV/ds → turbulence model
- RANS & time dependent flow: dV/ds + dV/dt → TU-model:
  - → takes the sum of both gradients as “dV/ds”
  - → additional production of eddy viscosity because of dV/dt
  - → damping of time dependent fluctuations
  - → balance between dV/dt and eddy viscosity at high levels
  - → “converged” solution possible with RANS if balance is stable
- Dependency of dV/dt from time step & CFL: CFL up → dV/dt >> dV/ds
  - → different balance point for strong implicit / weak explicit solvers?
  - → different “steady” solutions?
  - → dV/dt: stability problem for strong flow solvers & high CFL?

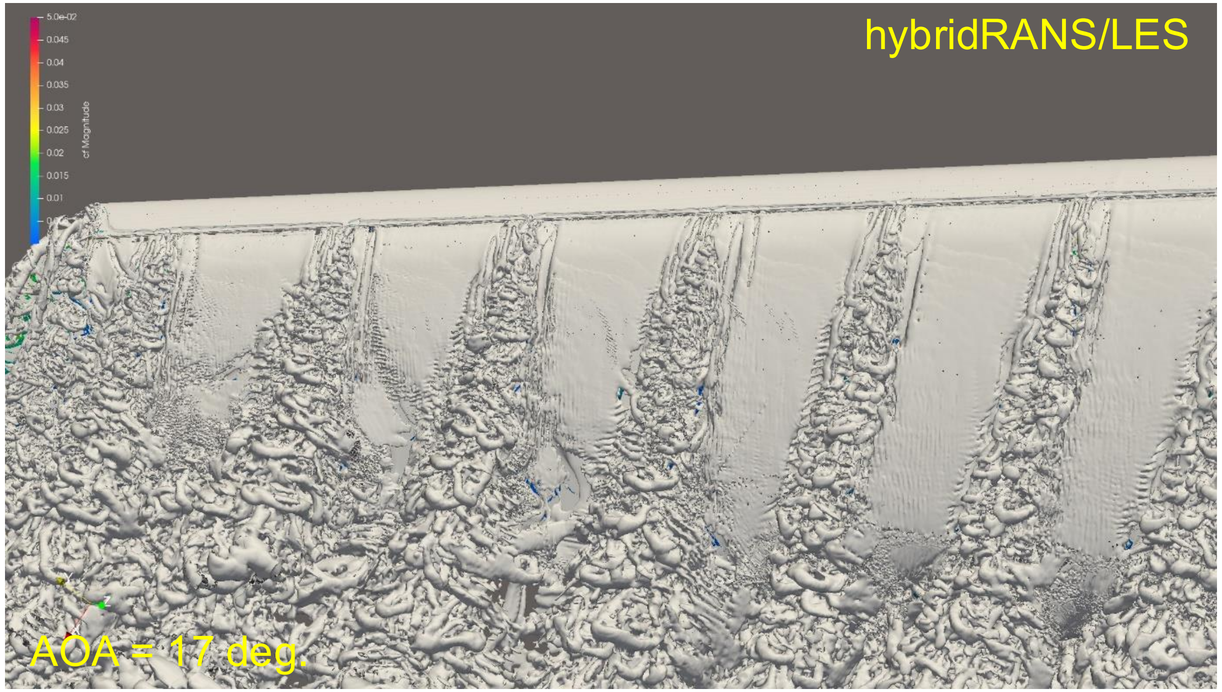


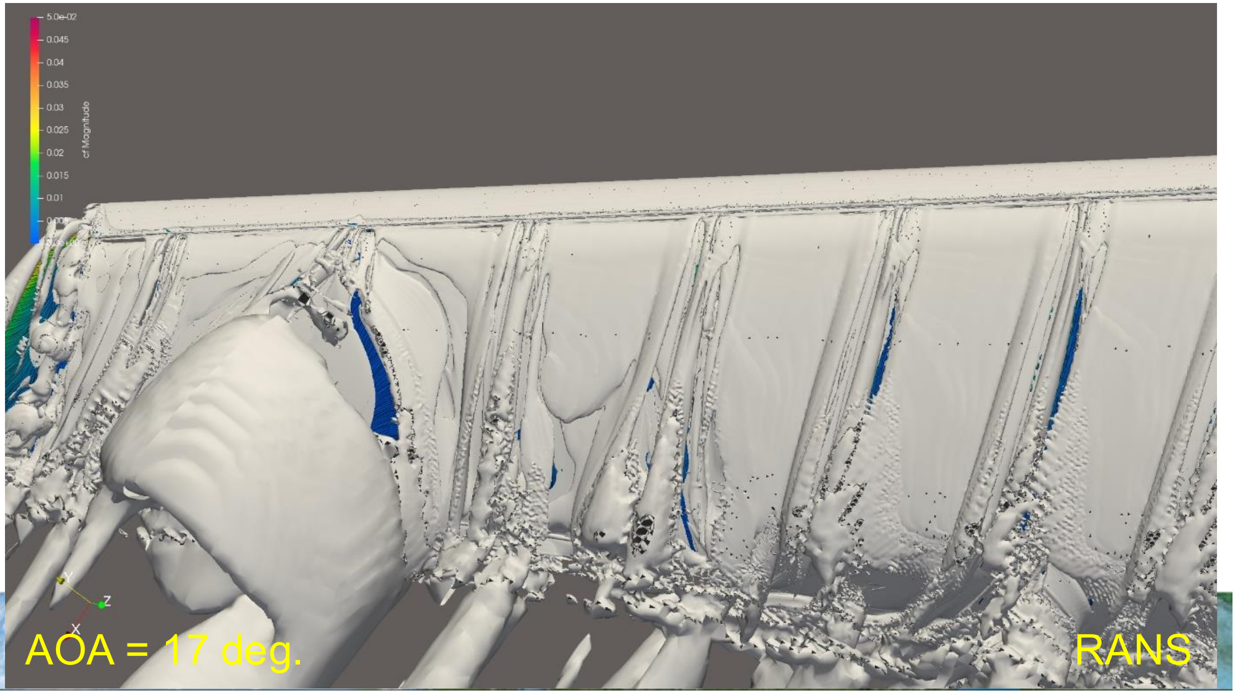


Analysis of RANS / uRANS / hybrid RANS/LES

- RANS timestep calculation → local time stepping based on CFL condition:
  - Steady state flow: time depended fluctuations occur only in transient phase of convergence → local time stepping does not change the converged result
  - Time dependent flow: physical dispersion of a time dependency in time & space → “smoothing out” of any time dependent structures:
    - as stronger the type of time integration
    - as higher the CFL number

- CRM-HL “pizza slice” separation due to RANS:
  - Local time stepping → treating local time dependent flow as “steady state flow”
  - uRANS or HybridRANS/LES resolving time dependent flow → physical solution of the problem



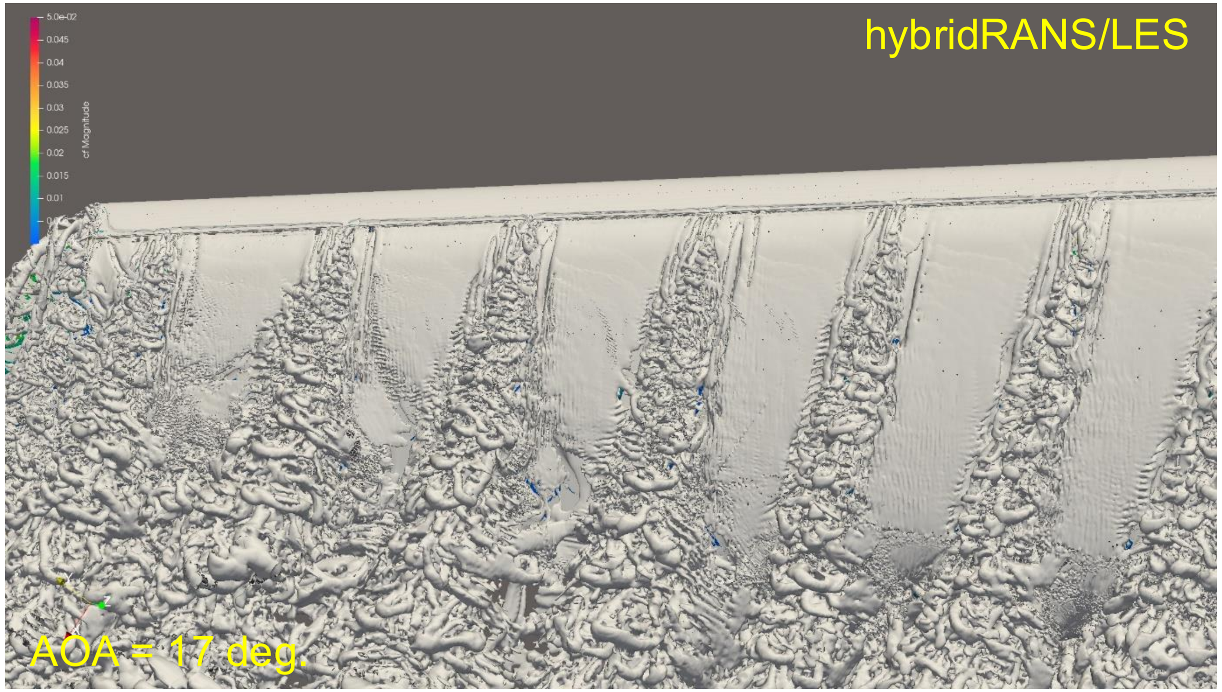


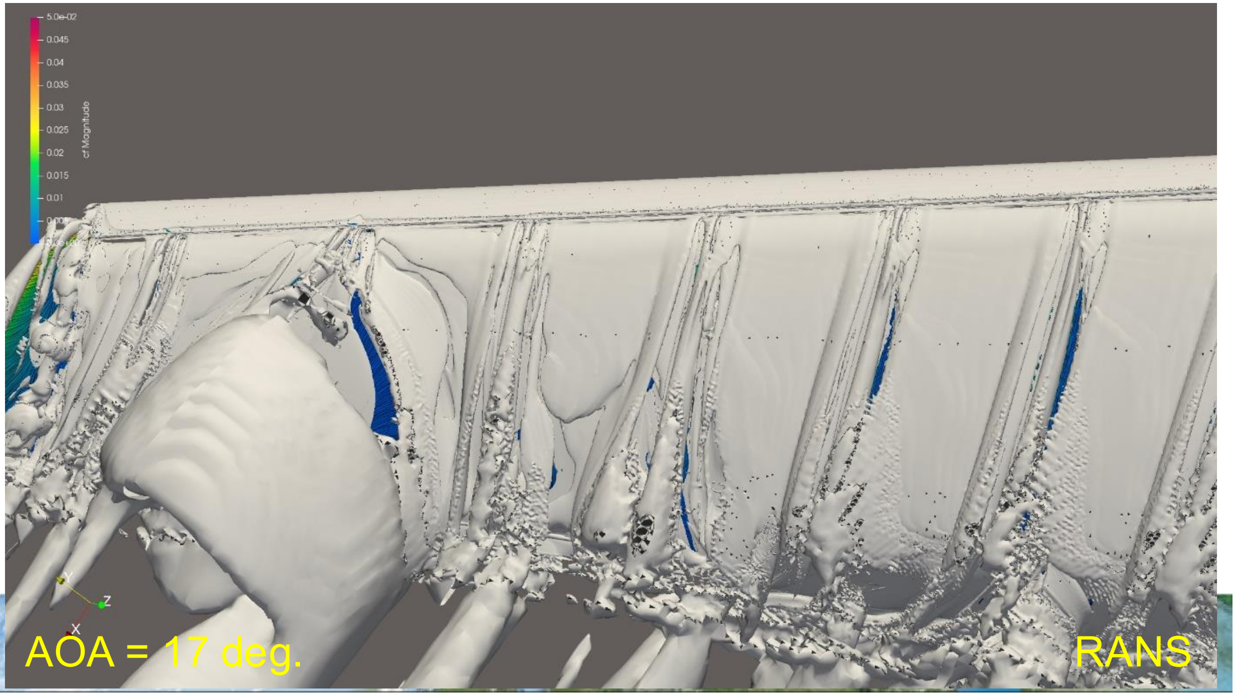
Analysis of <u>RANS</u> / uRANS / hybrid RANS/LES

- Objection: But what if a RANS flow solver is able to converge to machine accuracy including lambda-shaped separations of “pizza slice” type – is this solution “physical”?

A RANS converged solution of an mixed steady/unsteady flow field is an <u>artificially forced steady state interpretation</u> of an overall physically time dependent flow field → result is not physically relevant as soon the time dependent flow influences in any way the global solution of the problem

- This holds true for <u>any</u> steady state RANS solution if local time dependent regions occur and so the findings here are not limited to high lift flows with lambda-shaped separation patterns – they are true for any flow with partial or full time-dependency





Development of xRANS-Method

Development of xRANS-Method

- Main result: all local time dependent flow needs to be treated time dependent → unacceptable costs for typical industrial applications or numerical optimization
- (Try to) reduce costs to level of a steady state RANS: a new method is proposed → extended RANS or xRANS

- Main difference between RANS and uRANS is treatment of the time step for each cell:
  - RANS: local (variable) time steps → just a mathematical tool - physical time is meaningless here
  - uRANS: global (= physical) time steps → time advances uniformly, events happen at their physical rate
- **Basic idea of xRANS: identify domains of time dependent flow & limit time step in this regions to uniform global time step → fully automatic switching from RANS to uRANS in regions of time dependent flow**

- Identification of time dependent regions: using already available variable in RANS solvers → eddy viscosity → high values in time dependent regions due to dV/dt
- Upper time step limit:
  - free parameter of xRANS
  - needs to be chosen depending on numerical and physical characteristics
  - can be possibly "some "order of magnitudes larger than physical time step needed to resolve the time dependent flow – ongoing work …
  - needs just to be small enough to prevent "RANS behavior" in such regions → possible substantial advantage regarding wall clock time for xRANS compared to uRANS
  - only limitation to an upper limit to prevent numerical instability for small cells in such regions

- xRANS: freely tunned between RANS (no limitation) and uRANS (limitation to physical time step size) → new tool for numerical simulation of mixed steady and time dependent problems

Development of xRANS-Method

- Current implementation of xRANS (in TAU-Code):
  - First loop for all Cells:
    - If time step > xRANS time step limit → time step = xRANS time step limit
    - If time step > maximum time step → time step = maximum time step (~ 10^3 to 10^4 of xRANS time step limit)
      - Limit the overall time step range – the smaller time steps limit the overall convergence in any case
      - Possibly increase CFL number without instabilities
  - Second loop for all Cells:
    - Time step smoothing by given factor of maximum change between neighboring cells (e.g. 1.2 – 1.4)
      - Smoothed time step distribution seems to stabilize the convergence

- Initial tests: starting from already separated RANS solution → switching to xRANS → not reliably remove the “pizza sliced” separations
- Requirements for a successful application of xRANS:
  - Start xRANS from a non-separated RANS solution & increase the AOA then by moderate steps – or even better: use xRANS for complete lift curve because of its automatic switching between uRANS & RANS
  - Reliable mark all time dependent flow features → eddy viscosity
  - Choose a reasonable time step limit

- Some solutions of the slat bracket problem “just with RANS” to be reviewed based on the ideas of this talk:
  - (excessive) grid adaptation or initially significant refined grids: small cell volume & possibly even constant cell volume → time step is limited because of the CFL condition → global time step → uRANS in these regions
  - time step smoothing (increase convergence stability for complex problems - meaning in many cases – locally time dependent): limits the maximum change of the time step between two neighboring cells to a given factor → small factor → kind of uRANS behavior

Demonstration of xRANS-Method, Results and Discussion

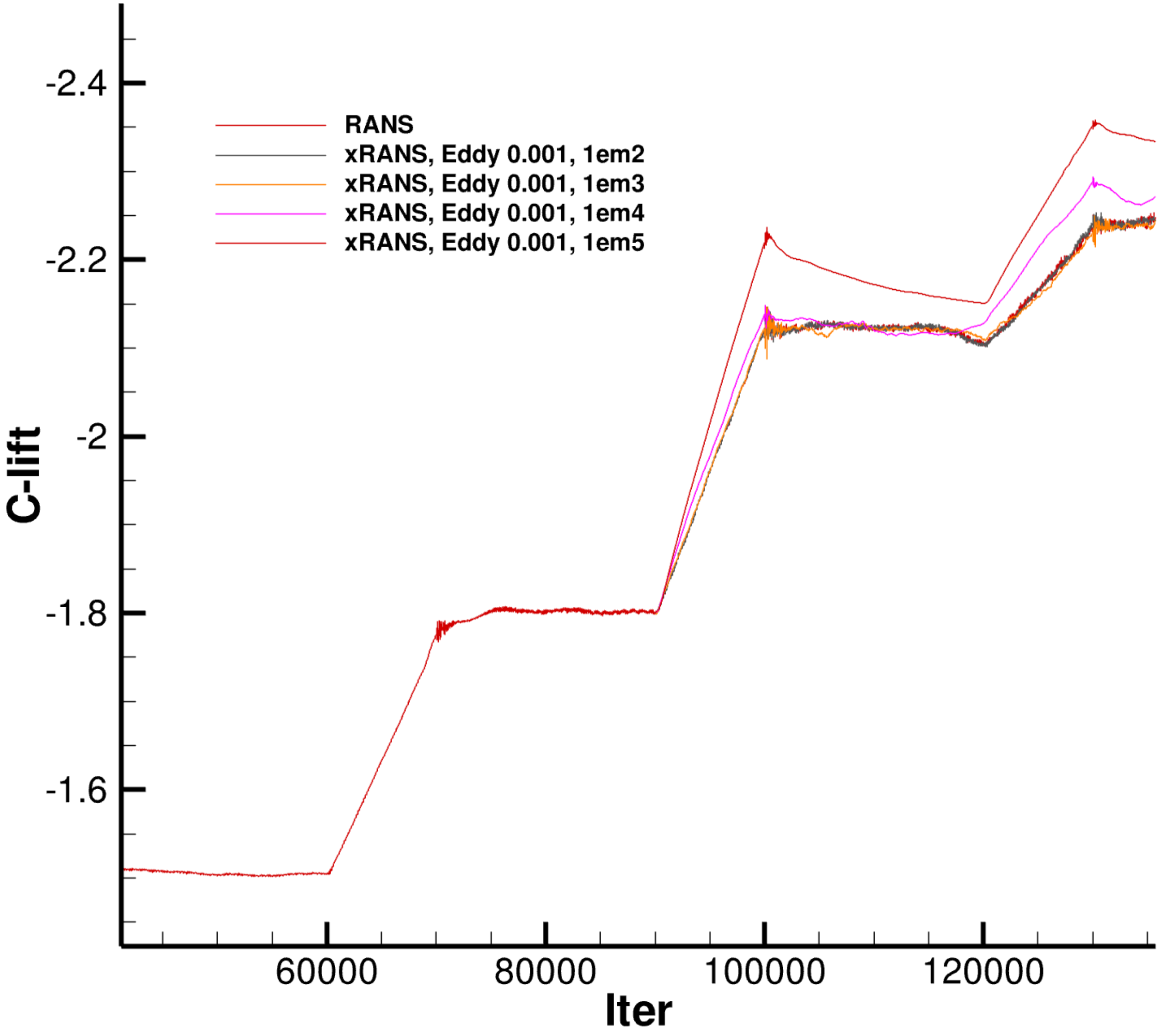
Demonstration of xRANS

- All presented results: Work in progress …

- Best practice RANS lift curve: Prevent any kind of possible flow hysteresis
  - cold start at AOA 5 degrees
  - pitching up by warm start of the previous AOA
  - steps between simulated AOAs reduced from 3 till finally 0.5 degrees in the range of maximum AOA
  - AOA changes: smoothly variation with small increments (~ 1/10000 degree) by rotating the mesh block with CRM configuration in background mesh (chimera)
  - Same as in experiment

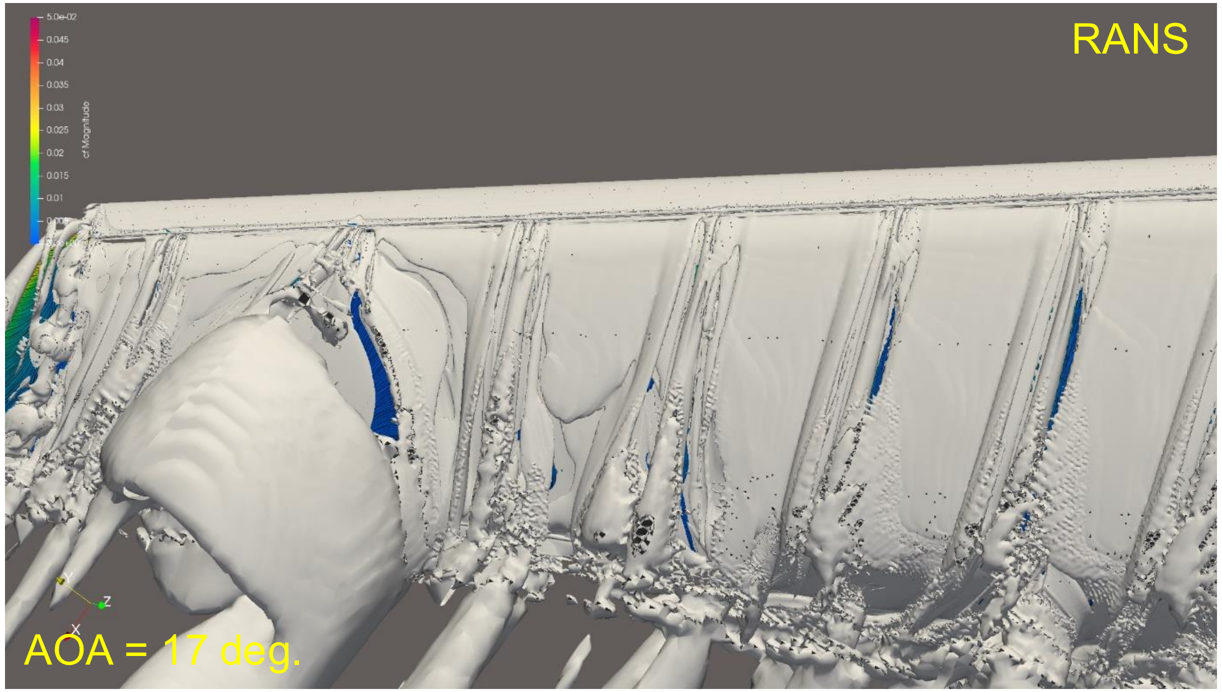
- Time step / Time step limit:
  - uRANS: 0.004226 sec
  - hybrid RANS/LES: 0.000169 sec
  - xRANS: 1.284 - to 0.00128 sec

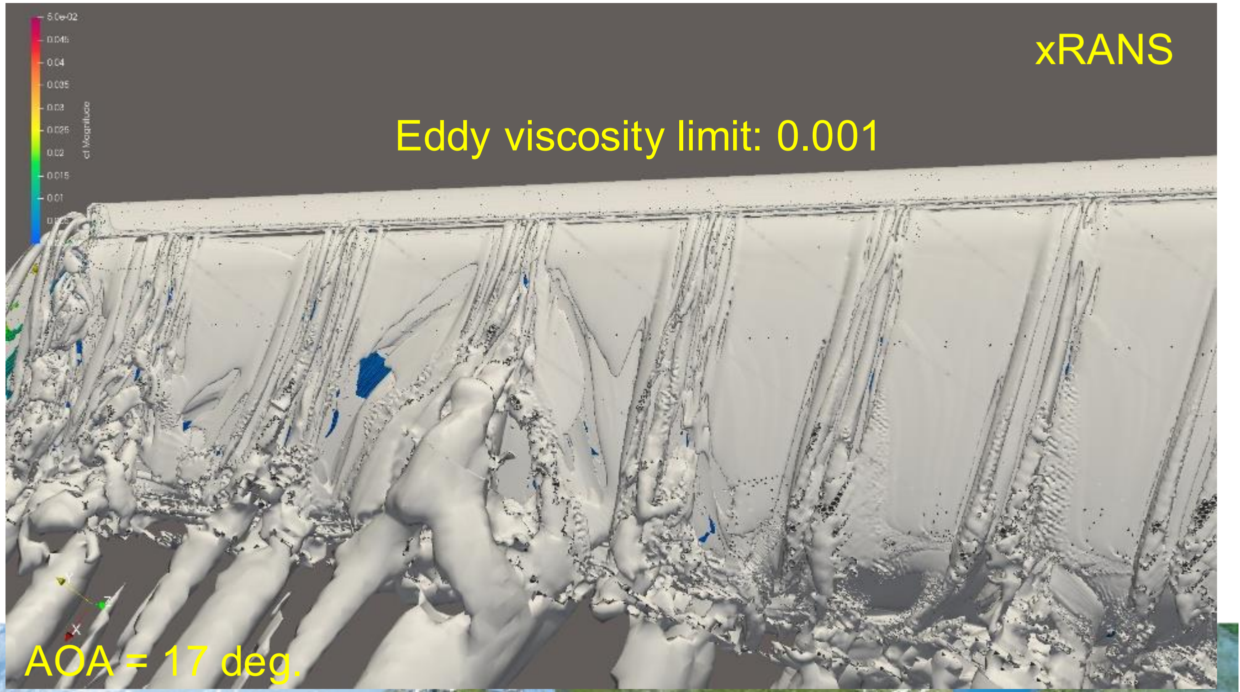
- Eddy viscosity limit:
  - 0.005 is based on analysis RANS at 17 deg. AOA.
  - Later on: 0.001 – because 0.005 did not mark “all” time dependent areas in full detail



Demonstration of xRANS

- Even with “very big” time step limit of 0.0128 sec compared to uRANS time step → xRANS improves RANS results significant → clear demonstration of time dependent features are the reason for the “pizza slices”
- Remark: xRANS limited points: 4 – 13% of the grid

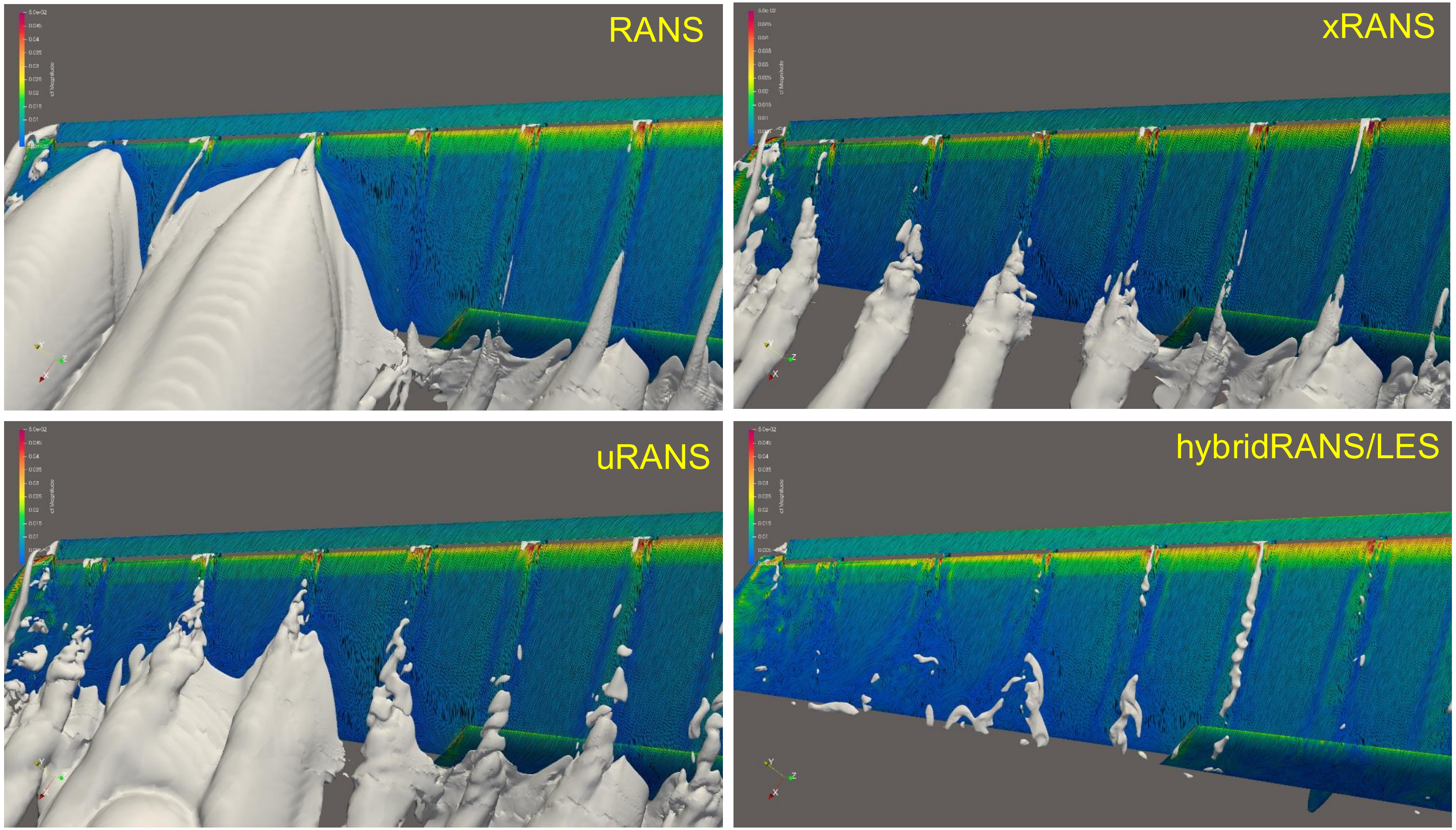




Demonstration of xRANS

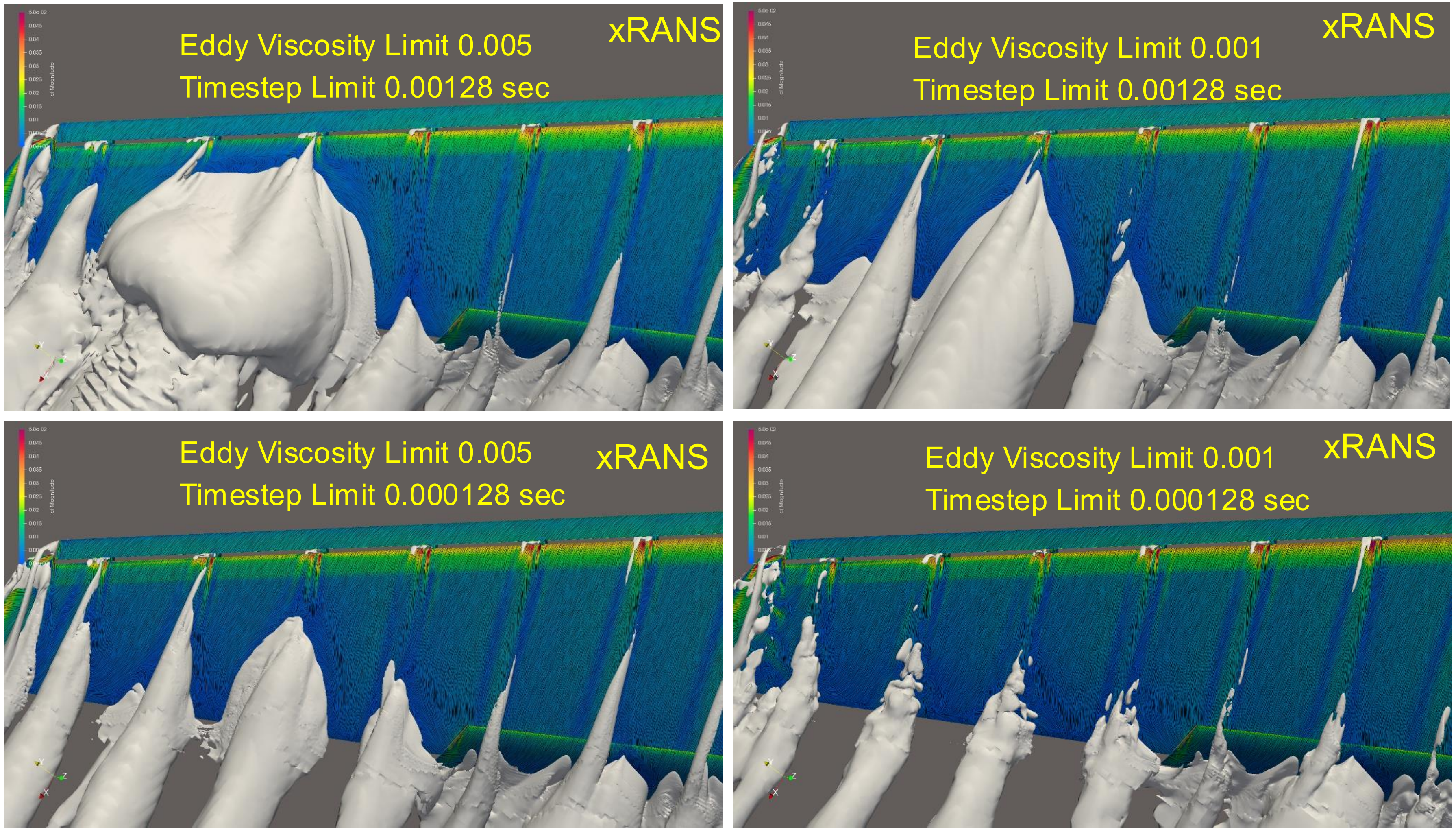
- Visualization: isosurface of eddy viscosity = 0.005 → direct effect of xRANS
- Example: AOA 17 deg
- xRANS: time step limit 0.00128 sec, eddy viscosity limit 0.001

- xRANS time step limitation effective to reduce the excessive eddy viscosity production found in RANS simulations down to the same level and distribution as of uRANS → pizza slices “removed”
- eddy viscosity level of an hybridRANS/LES is still lower: – possibly an effect of the LES simulation, but at the same time at a finer grid and a smaller timestep



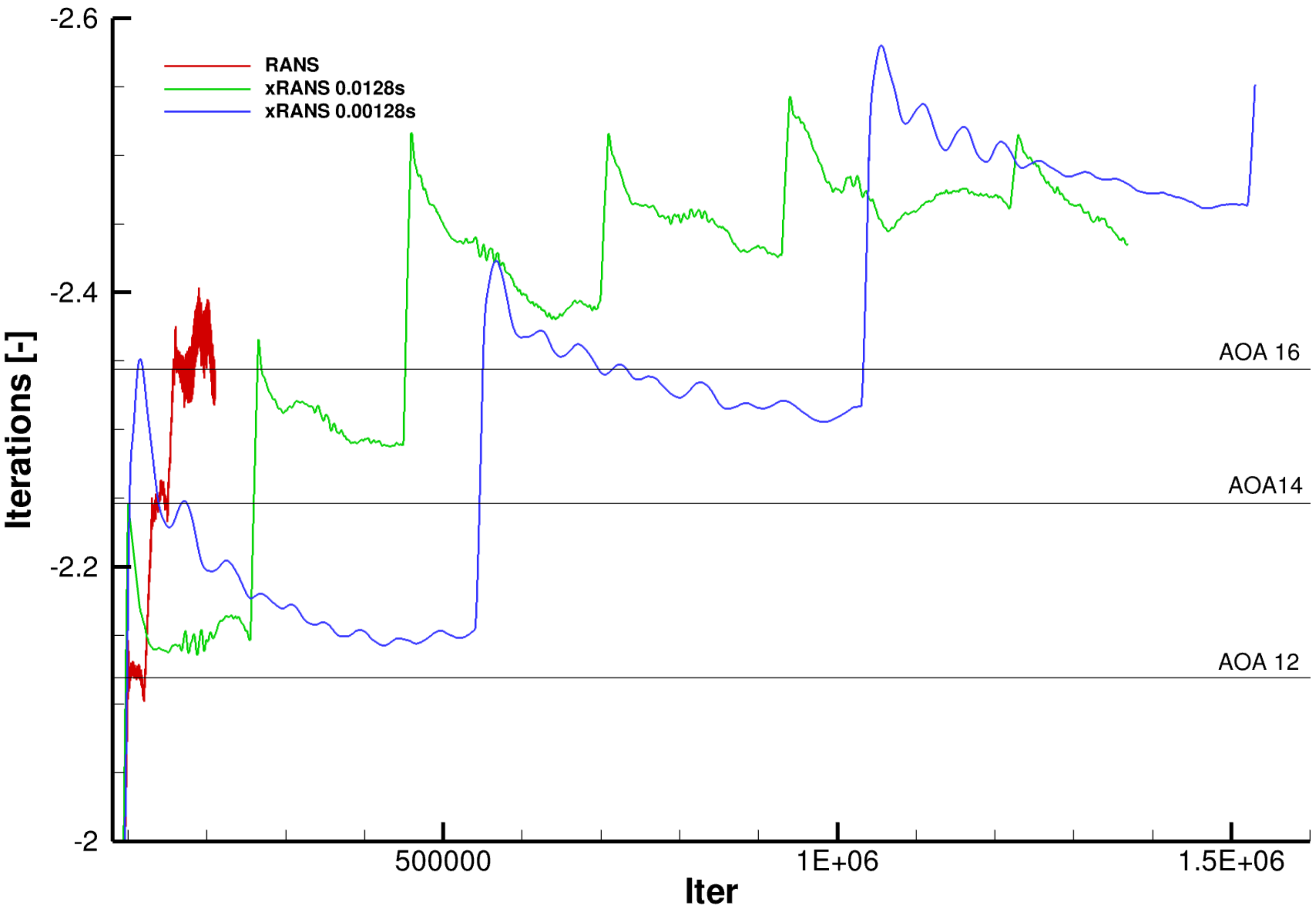
Demonstration of xRANS

- Visualization: isosurface of eddy viscosity = 0.005
- Example: AOA 17 deg
- Variation of time step & eddy viscosity limit
- Stronger effect of time step limit compared to eddy viscosity limit



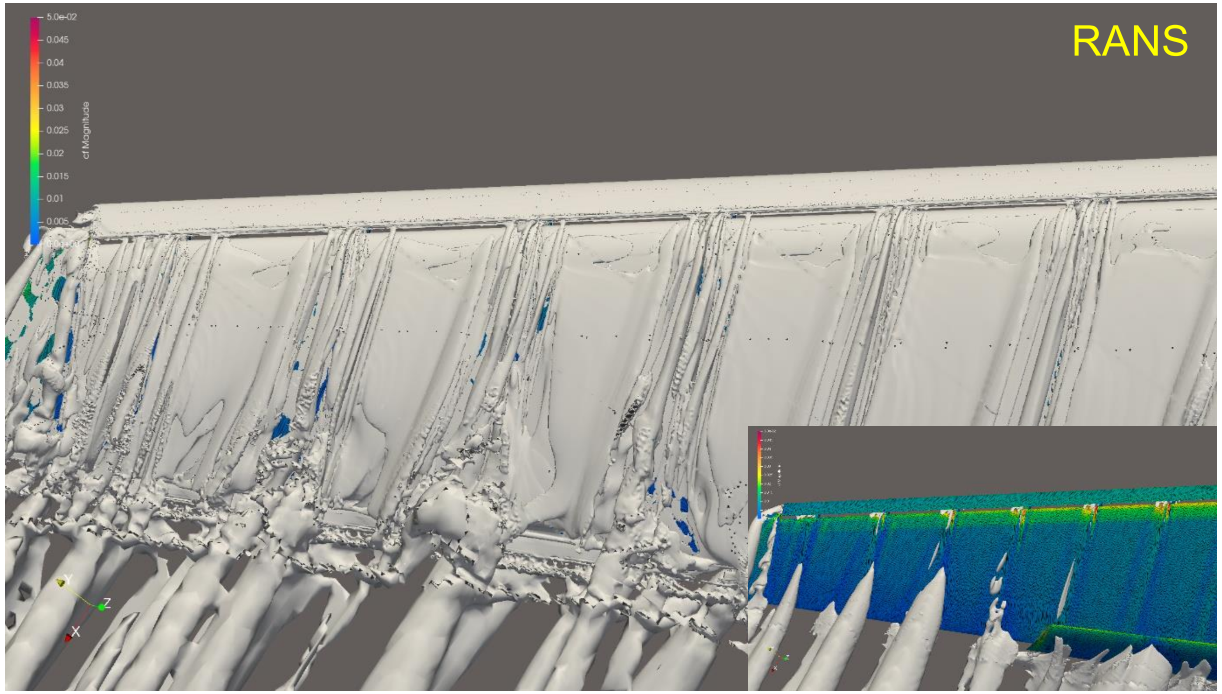
Demonstration of xRANS

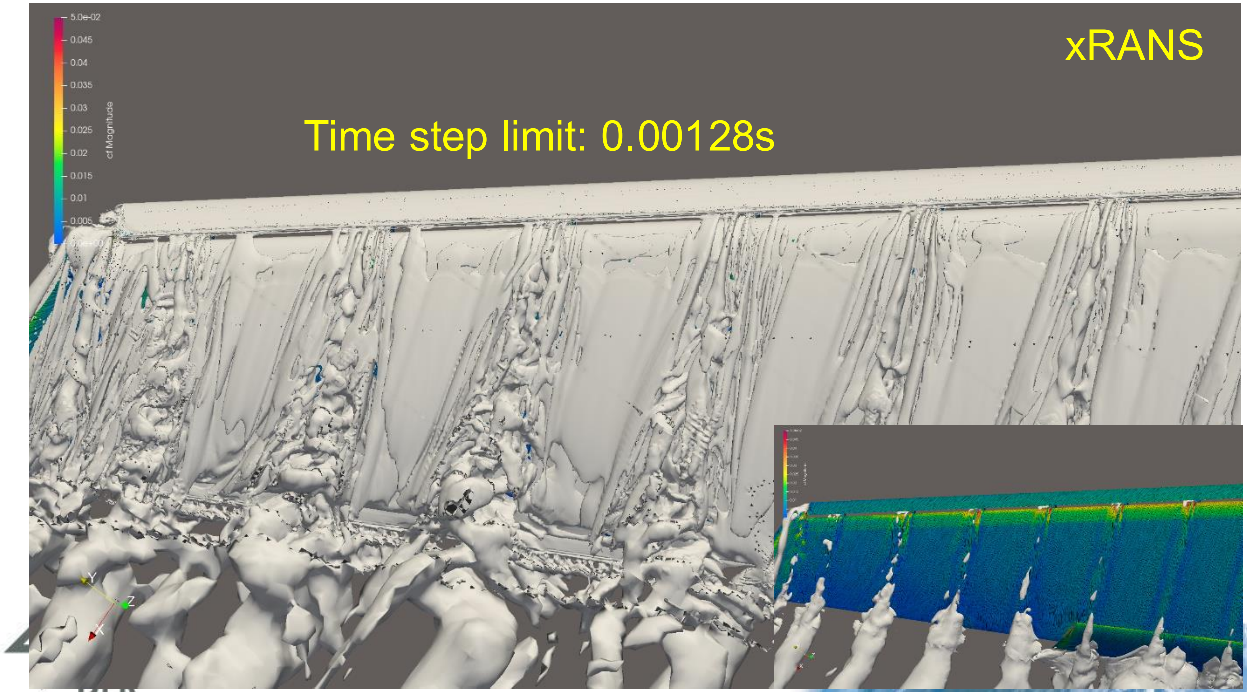
- Converged xRANS simulations with current best practice:
  - Eddy viscosity limit 0.001
  - Time step smoothing 1.4
  - Time step limits of 0.0128s and 0.00128s
  - Maximum time step 10k of free stream value
- All polars started from RANS solution at AOA 8 deg.
- Convergence behavior of xRANS turns from “RANS type” to “uRANS type” as smaller the time step limit is → more iterations needed for smaller time step limit
- Overall higher lift level of xRANS results → pizza slices removed – compare next slides

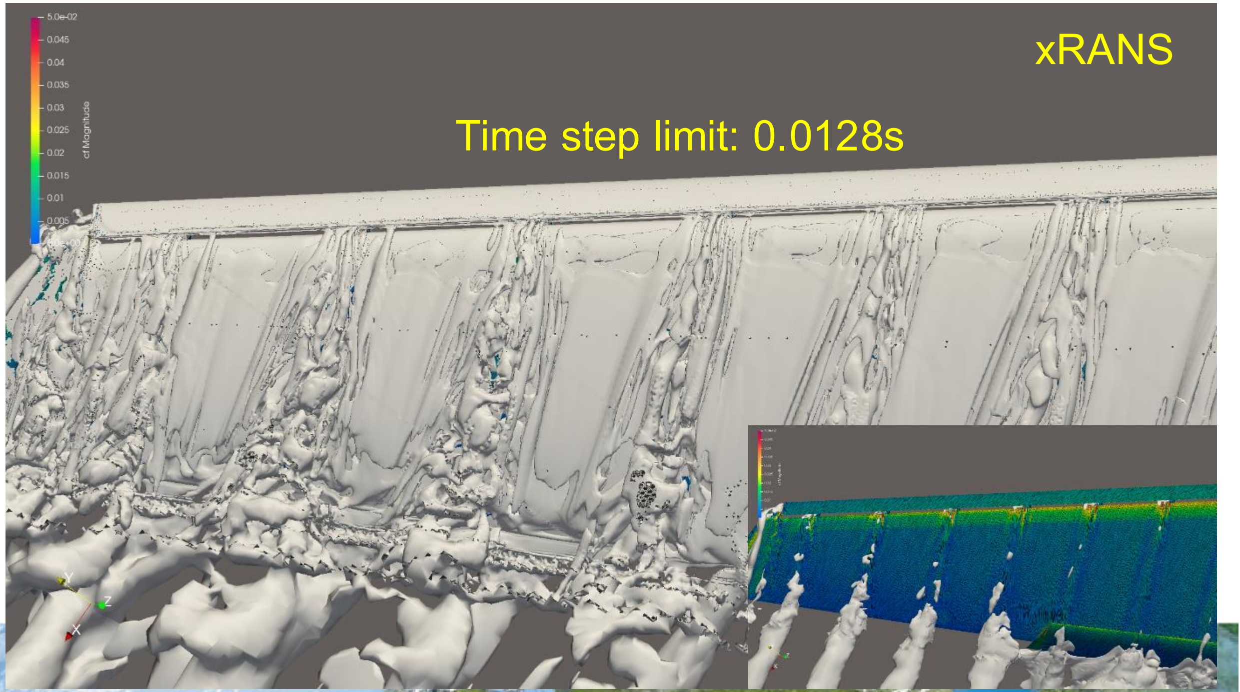


Demonstration of xRANS: AOA 12 deg

- No “pizza slices” at AOA 12
- Much more “vortices” in RANS solution?!

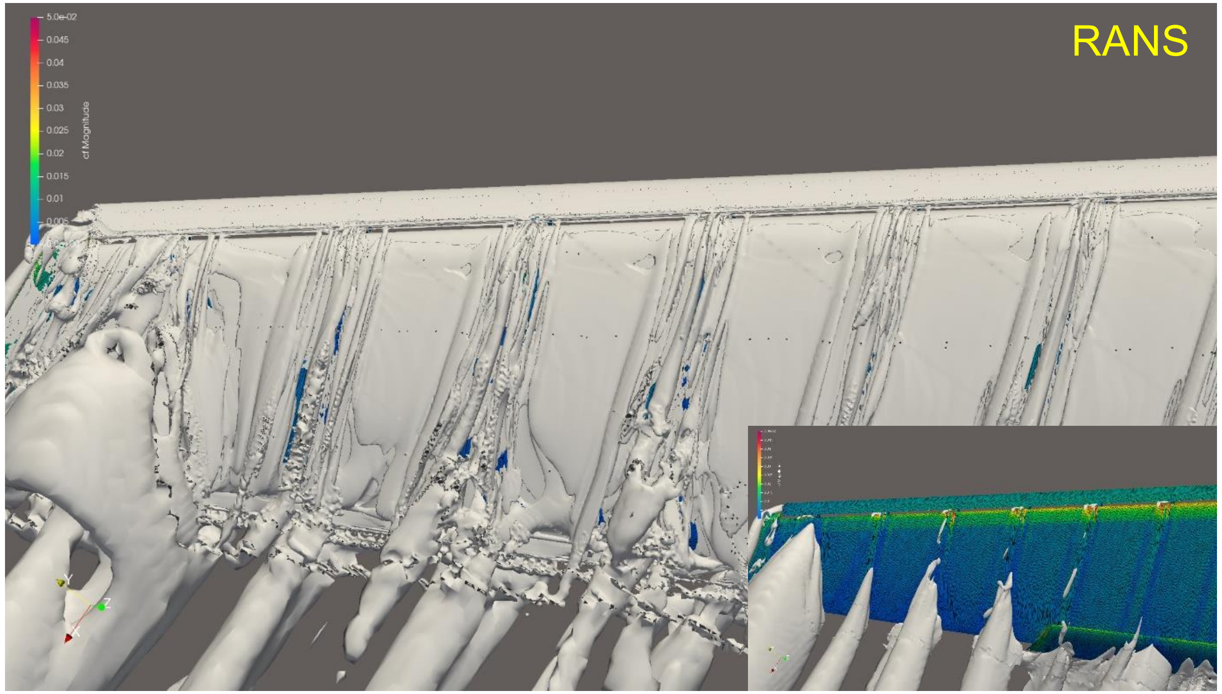


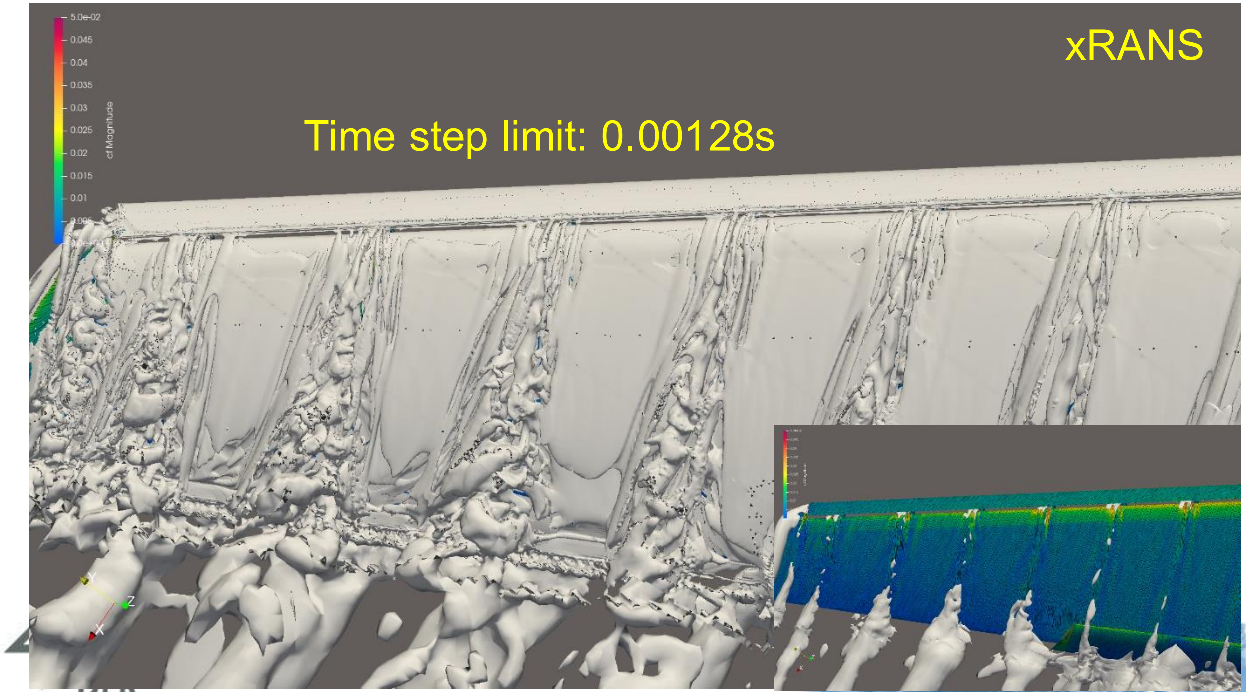


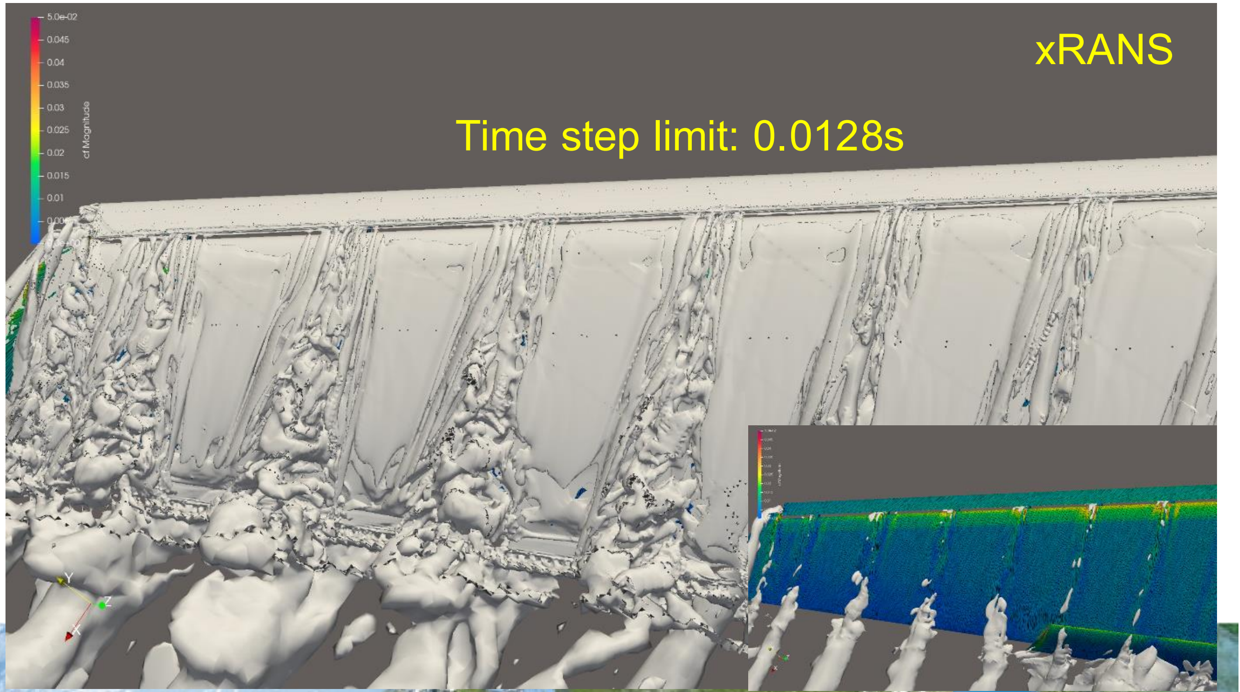


Demonstration of xRANS: AOA 14 deg

- RANS simulation develops pizza slice separation
- xRANS even with time step limit of 0.0128 sec (~ 10x uRANS time step) successfully removes pizza slice separation & flow field has the same features as uRANS

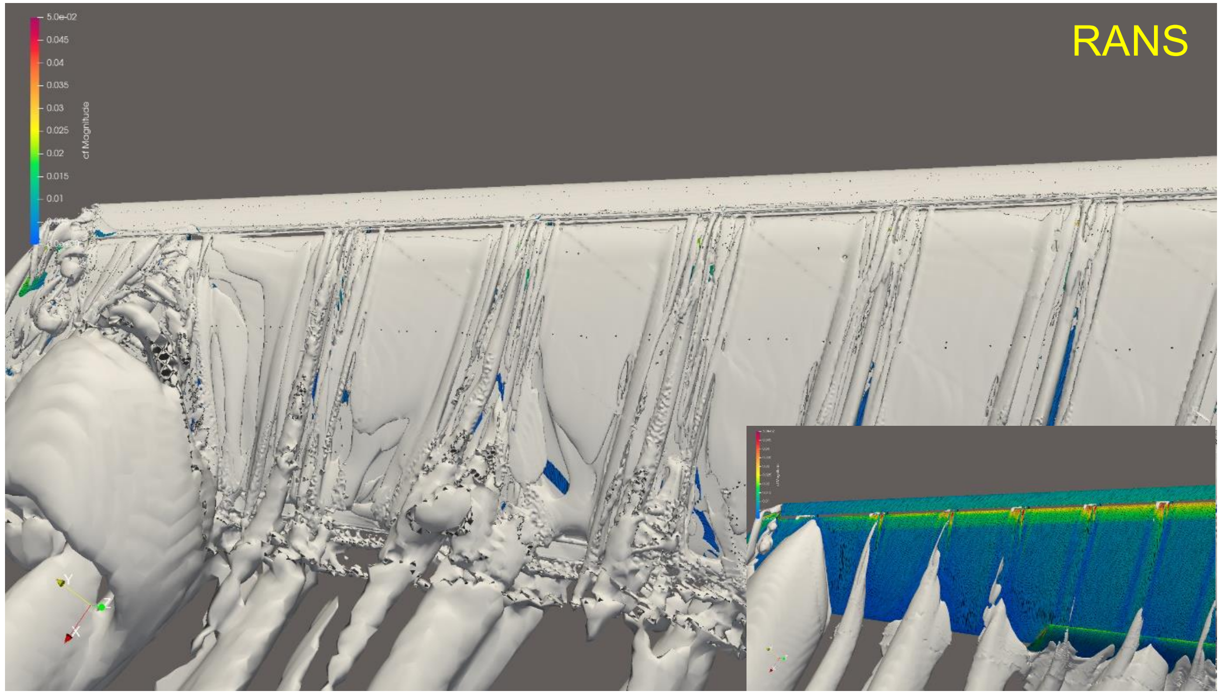


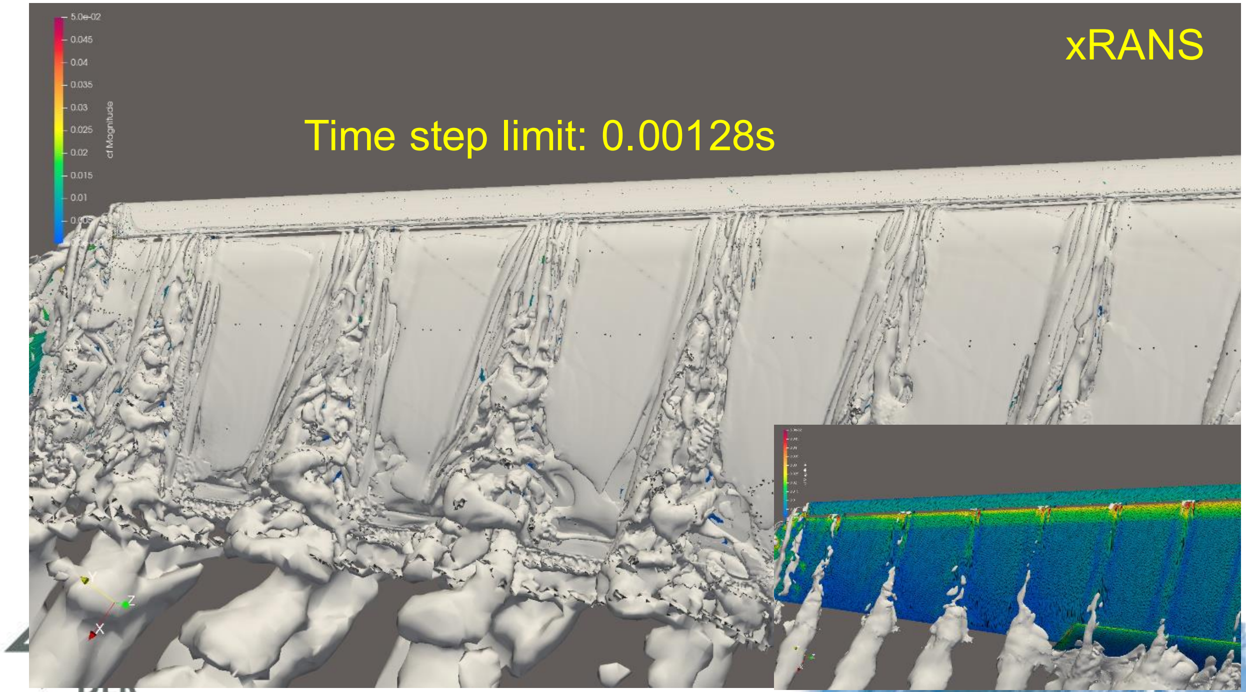


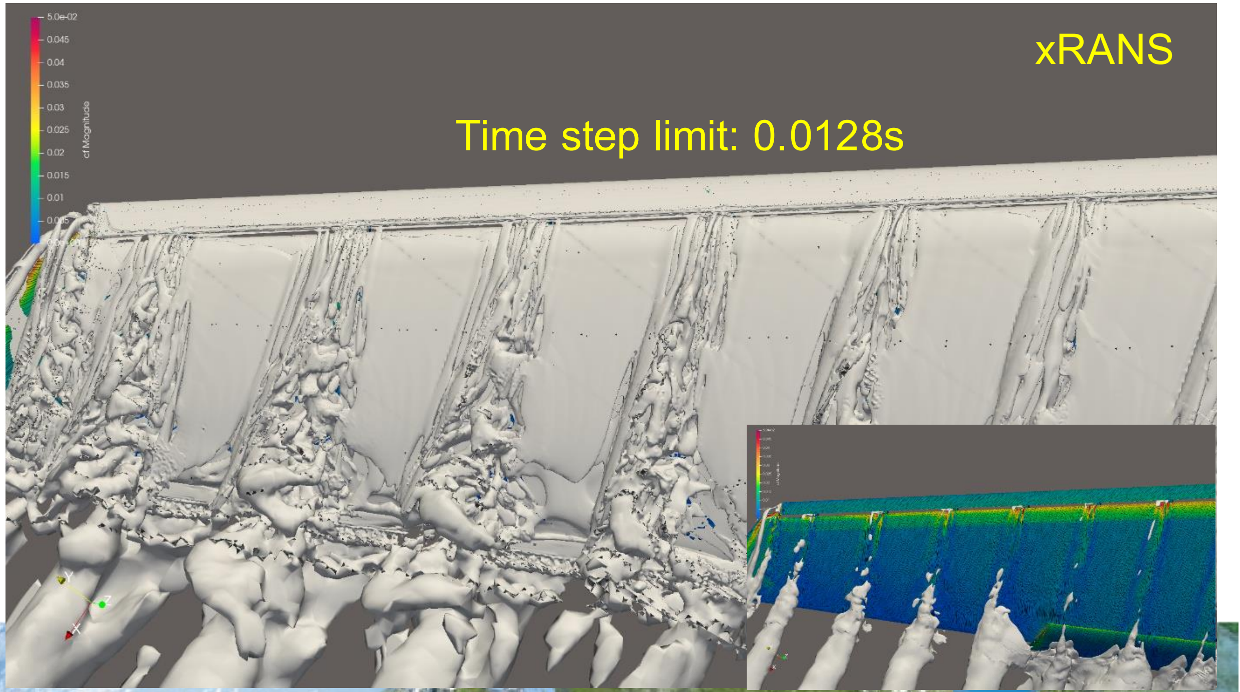


Demonstration of xRANS: AOA 16 deg

- xRANS still without “pizza slice” separation

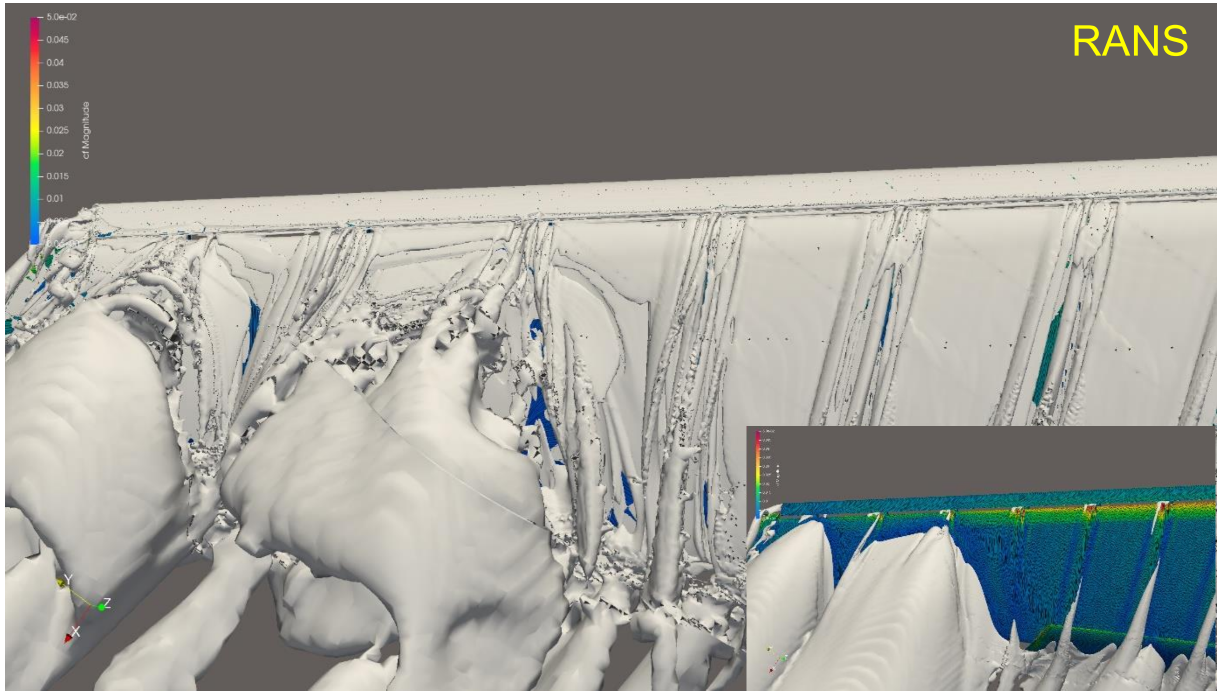


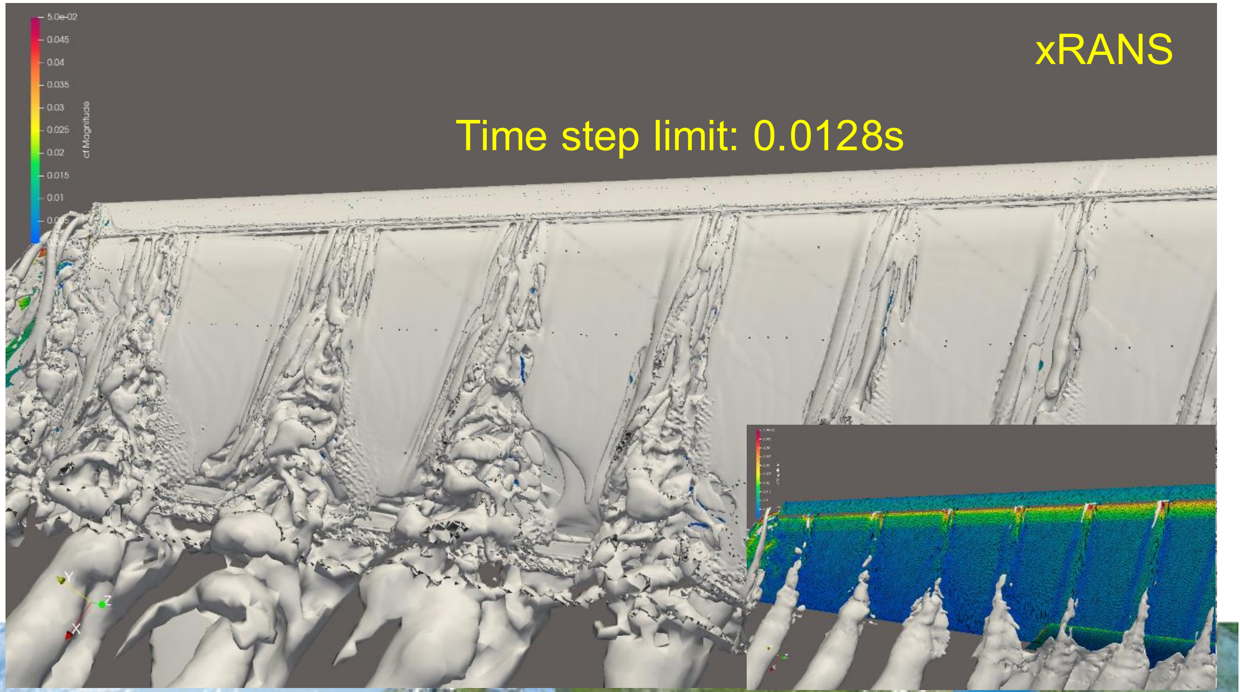




Demonstration of xRANS: AOA 18 deg

- xRANS still without “pizza slice” separation





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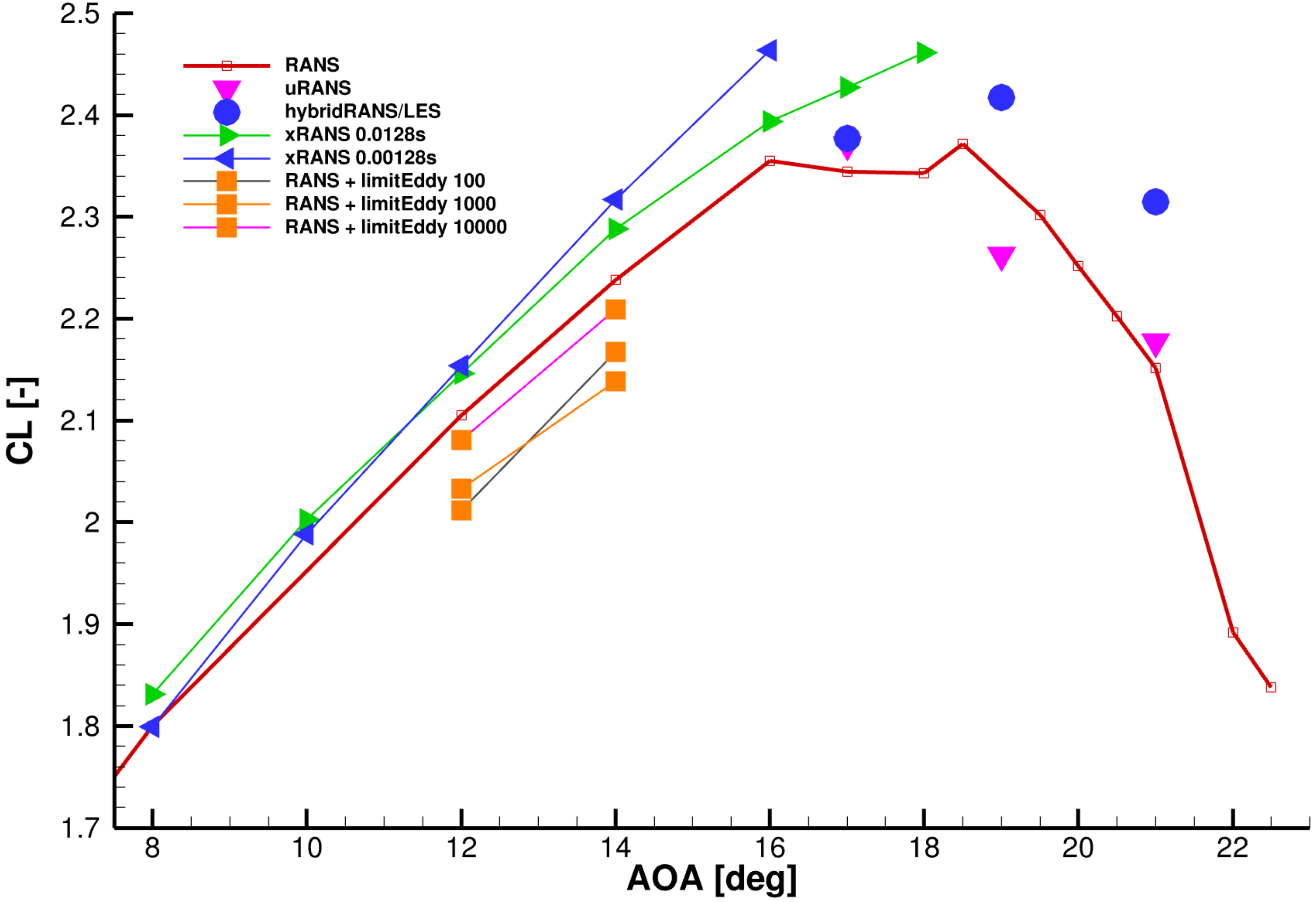
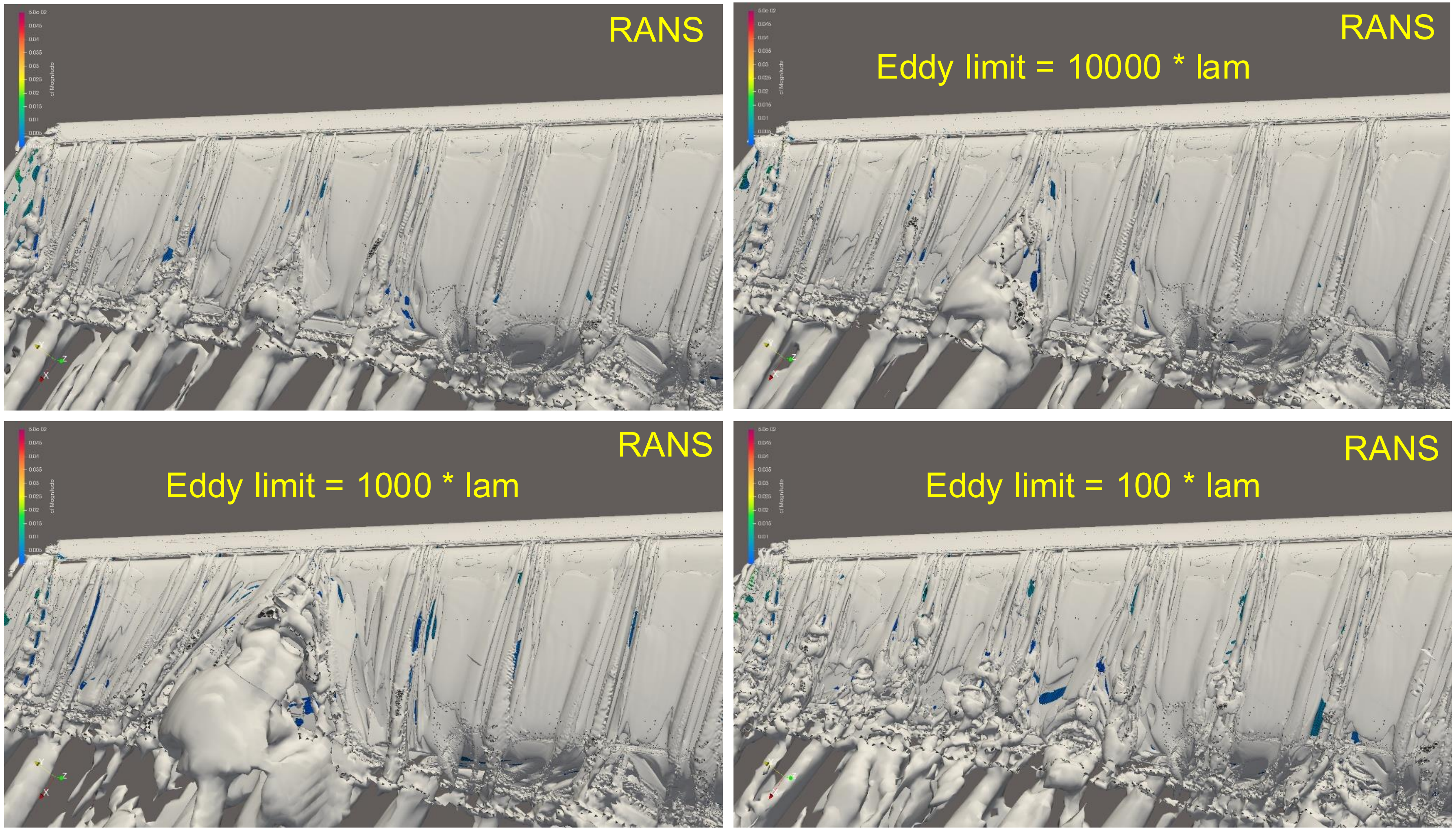
Demonstration of xRANS

- Remark: uRANS at 19 and 21 deg → not recovering from “pizza slices” → new best practice uRANS…
- xRANS: Pizza slice type of separation removed → additional lift
- Additional lift compared to hybridRANS/LES – possible reason:
    - more iterations for xRANS needed because of limited time step → more “CTUs” & mean values
    - Clear effect of time step limit
- xRANS simulations still running …



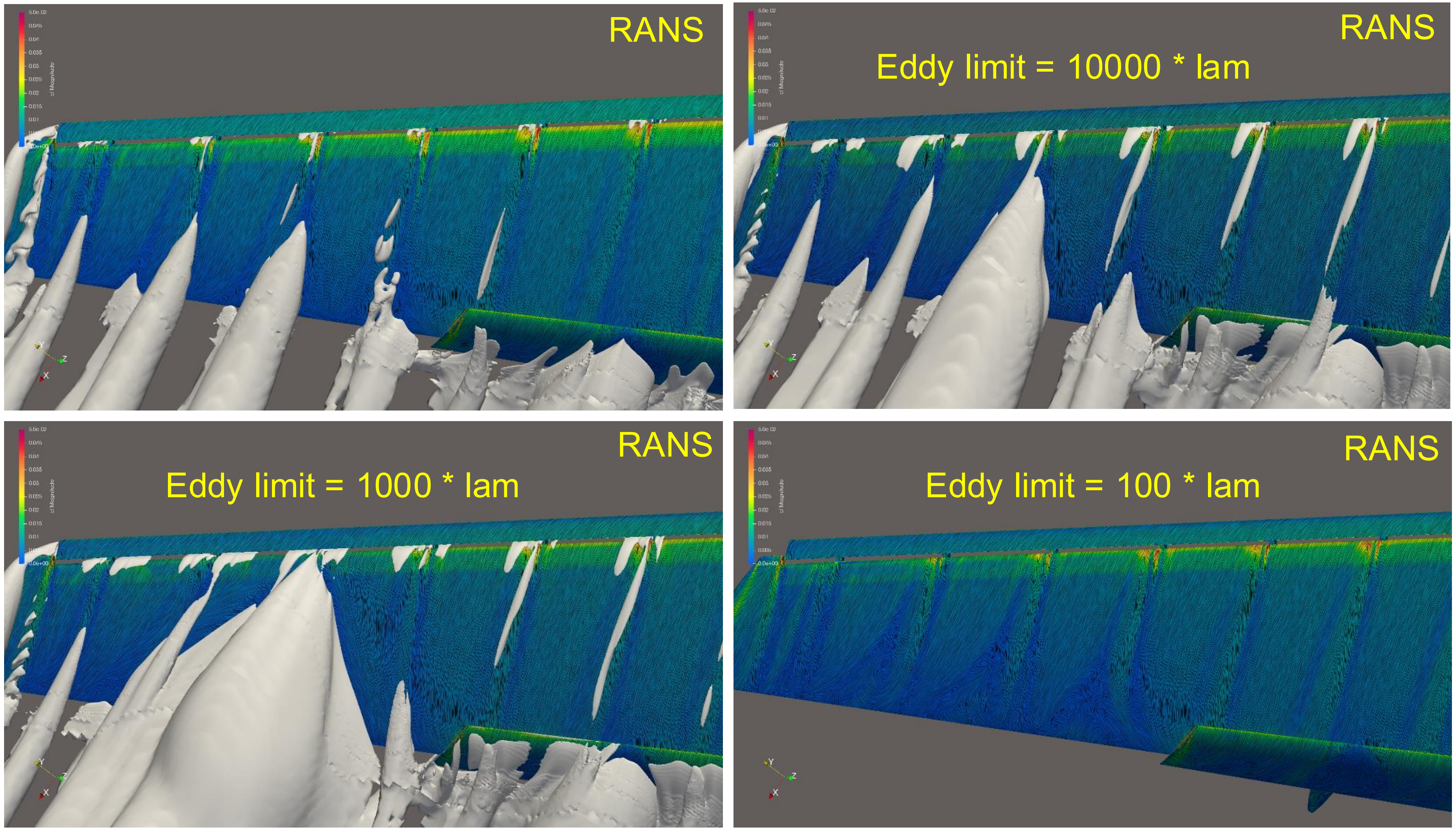
Limit of Eddy viscosity

- Plan B: Instead of using xRANS "just" limit eddy viscosity to a given factor of the reference value in farfield
- AOA: 12 deg
- Pictures: lambda2 criterion
- Limitation to factor of 10k and 1k increases the pizza slice separation – possible reason (much) more iterations in case of eddy limited simulations compared to "pure" RANS → pizza slice creeping up quite slow
- Limitation to factor of 100: seems to create more a kind of LES-result?



Limit of Eddy viscosity

- Comparison of the eddy viscosity in the field: stronger limitation reduces the (not vortex corrected SANeg) results in the vortex cores …
- Overall:
    - Limitation of eddy viscosity “to small” → pizza slice structures shows up
    - Limitation of eddy viscosity enough to suppress pizza slices → complete flow field is changed - already effect on lift → <u>not useable</u>
    - As more eddy viscosity is limited as more the convergence breaks down → Eddy viscosity limitation creates kind of LES type simulation but without needed small time steps and spatial resolution…



Conclusion

Conclusion

- Comparison of RANS, uRANS & hybridRANS/LES simulation results (HL-CRM): complex flow field with turbulent structures and vortex interaction behind the slat brackets → <u>locally time dependent flow:</u>
  - resolved by uRANS & hybridRANS/LES
  - RANS creates a non-physical solution: Artificial eddy viscosity created by time dependent gradients dV/dt in time dependent regions (independent of the turbulence model)

- Solution of that kind of problem:
  - uRANS or hybridRANS/LES → computational costs
  - xRANS → identify domains of time dependent flow & limit time step in this regions to uniform global time step → <u>automatic</u> switching from RANS to uRANS in regions of time dependent flow
  - Successful demonstration of the xRANS method

- (Current) Open questions:
  - What is the maximum time step limit still getting physical results → walltime speedup compared to uRANS
  - Is there an RANS solution of an unsteady flowfield which is exactly the same as a mean uRANS solution?
  - Fast uRANS-solver – the “better way to go”?

- Paper at SciTech 2027, extended abstract available