13th Symposium of VKI PhD Research 2022
23/02/2022

Steady and Unsteady Numerical Characterisation of a Highly-Loaded Low-Pressure Compressor Stage

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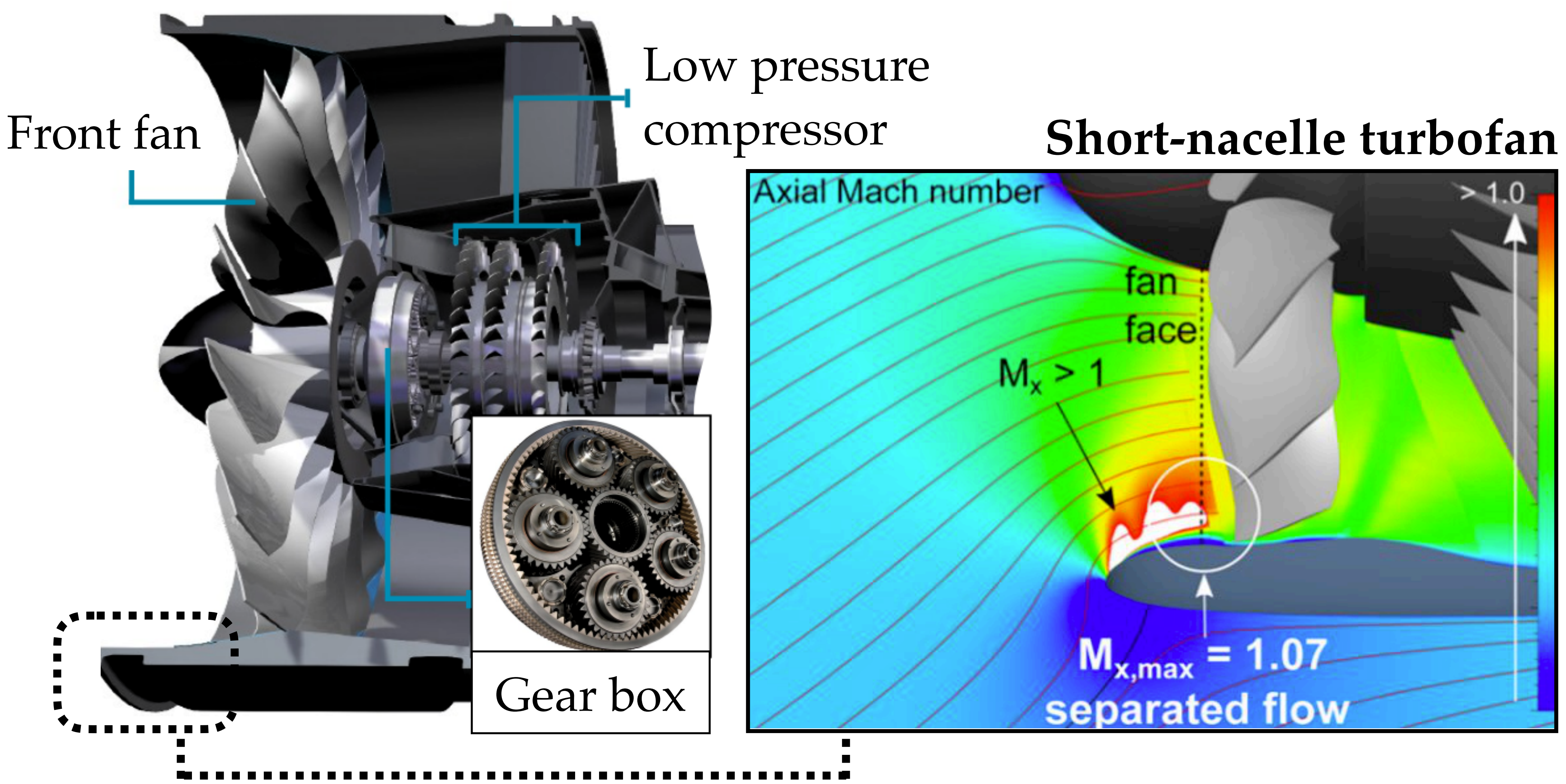
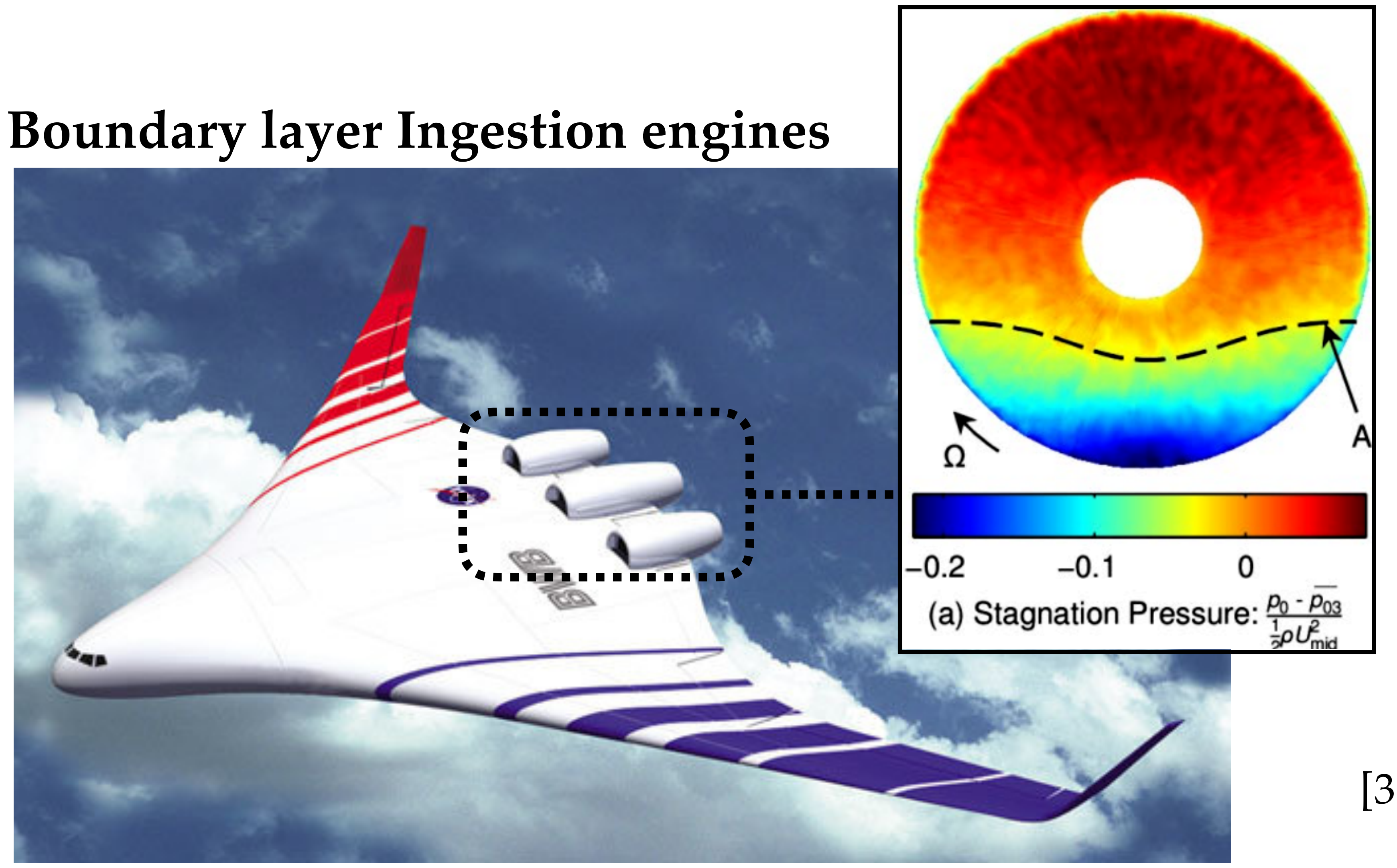
Context and PhD objectives

Solutions for emission reduction:


Short-nacelle turbofan


Boundary layer Ingestion engines

Motivations of the project: Lack of information on

- Representative geometries for LPC
- Engine-like distortions

Objectives of the project: Characterise a distorted LPC

- Assess performance and stability reduction
- Identify phenomena linked with performance and stability loss
- Characterise critical flow features and their evolution
- Identify flow mechanisms leading to stall
- Understand the role of geometrical features
- Improve design guidelines

[1] https://aerospaceamerica.aiaa.org/features/high-gear/

[2] Peters A. et al. "Ultrashort Nacelles for Low Fan Pressure Ratio Propulsors" Journal of Turbomachinery 2014

[3] Leiffson L.T. "Multidisciplinary Design Optimization of Low-Noise Transport Aircraft" PhD thesis, Virginia P&S University, 2005

[4] Gunn et al. "Aerodynamics of Boundary Layer Ingesting Fans" ASME Turbo Expo 2014

Research project overview

Timeline

1 Bibliographic research
- Distortion characterisation
- Distortion effects in transonic compressors
- Literature survey to continue all over the PhD project

In this presentation

2 Numerical simulations
- Characterisation of the clean machine
- Characterisation of the distorted machine
- Design of experiments

Current activity

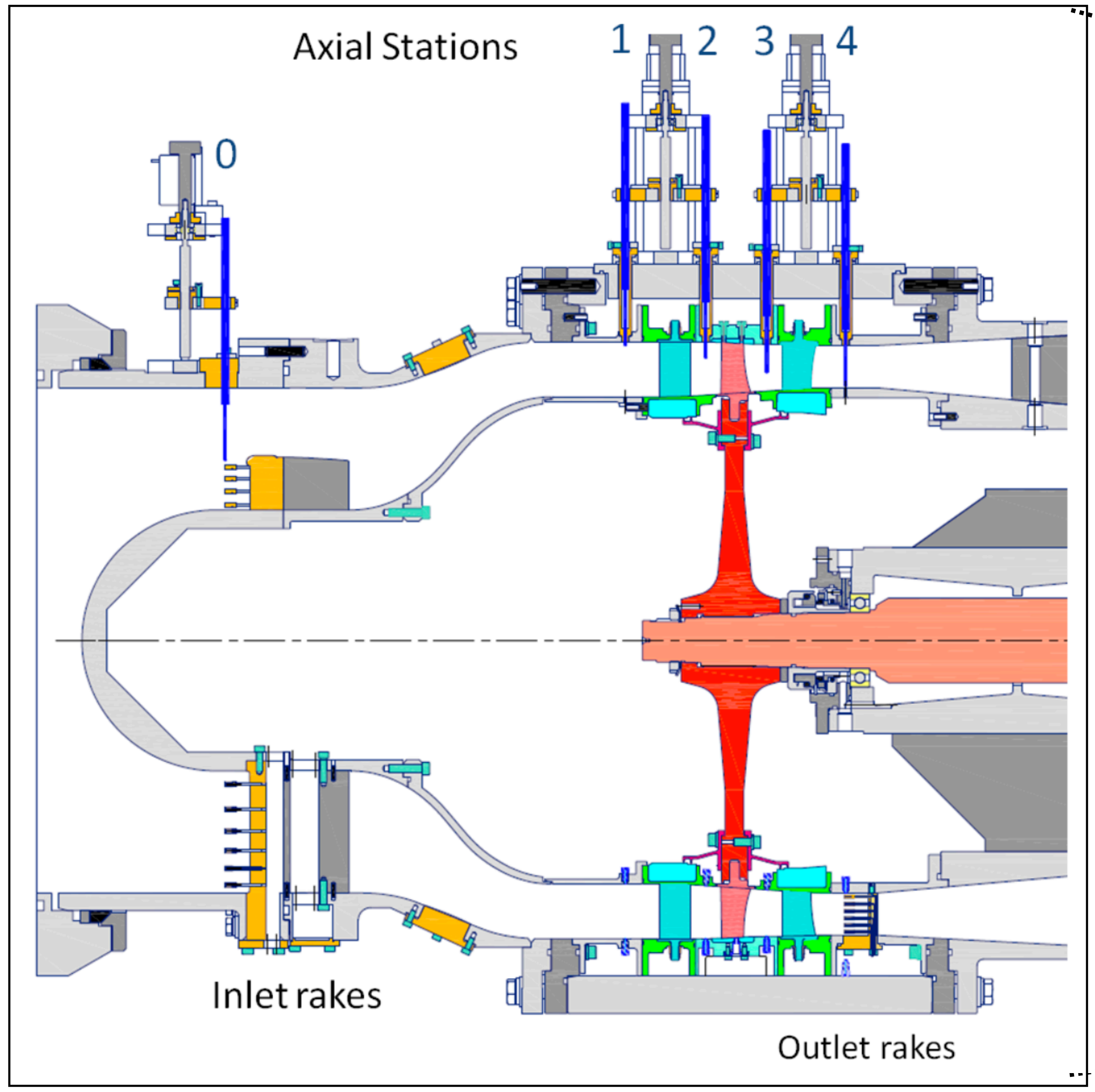
3 Measurement campaign
- Clean experimental campaign
- Distorted experimental campaign

4 Results and conclusions
- Validation of the numerical results
- Assessment of distortion effects
- Design guidelines

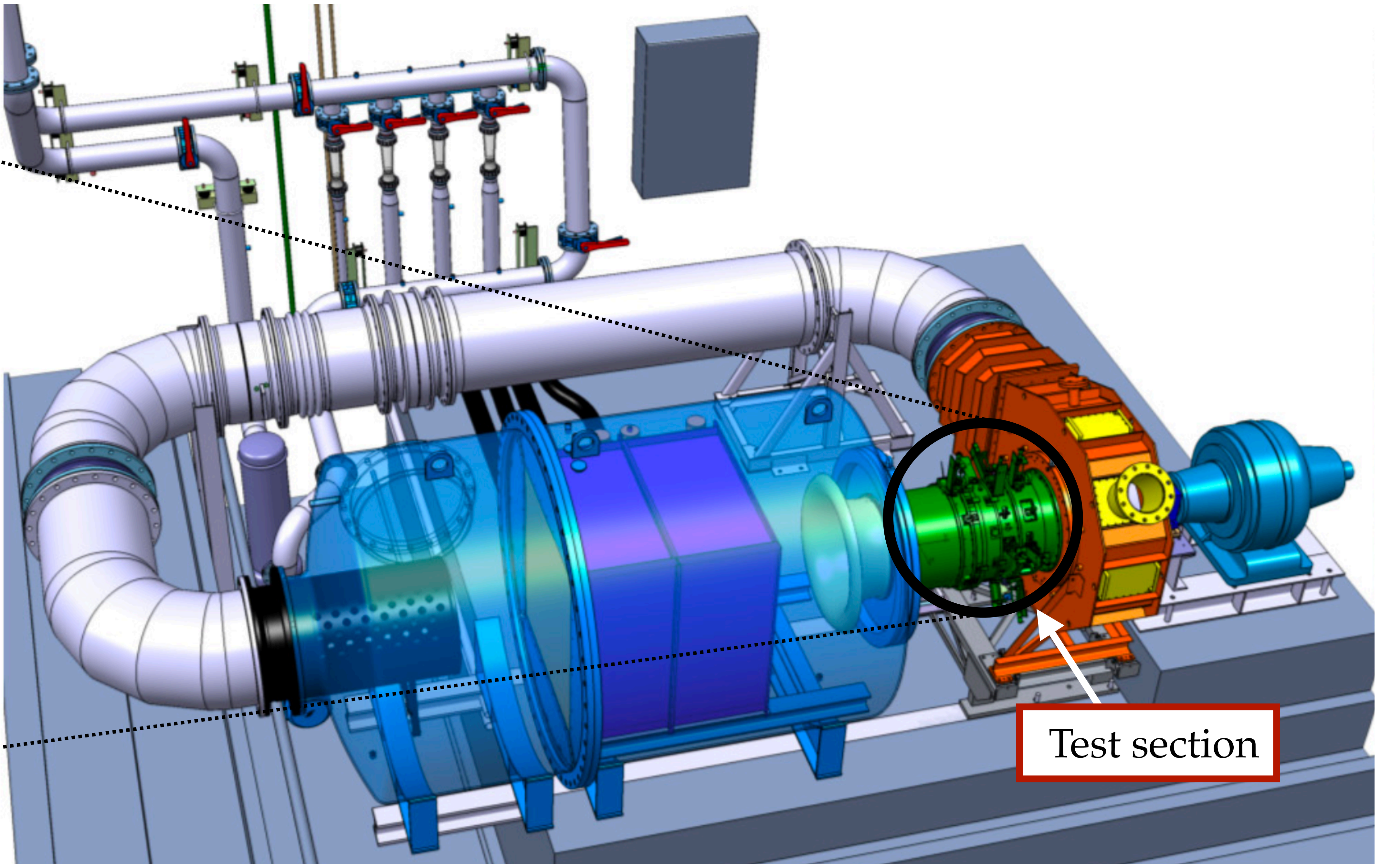
Characterisation of the clean machine:
- Define a robust numerical setup
- Reach high level of accuracy
- Support existing experimental data
- Support design of experiments
- Generate a clean reference case

Experimental environment

DREAM test section:



VKI R4 high-speed compressor test rig:



Characteristics of the test section

- Representative of a modern GTF LPC
- 4 measurement planes available
- Characterised in clean conditions (EU FP7 DREAM project)
- Nominal speed considered for the present activity

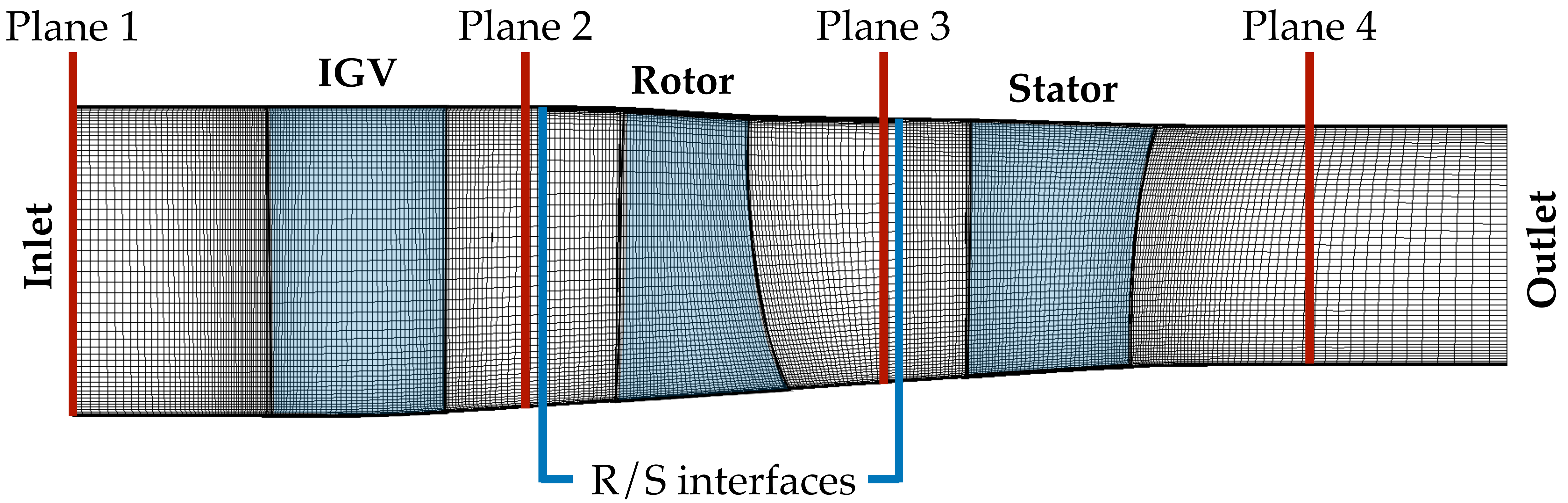
Characteristics of the facility

- Controlled temperature and pressure
- Precision throttling
- Independent variation of Re and Ma
- Different engine operating conditions (cruise, take-off)

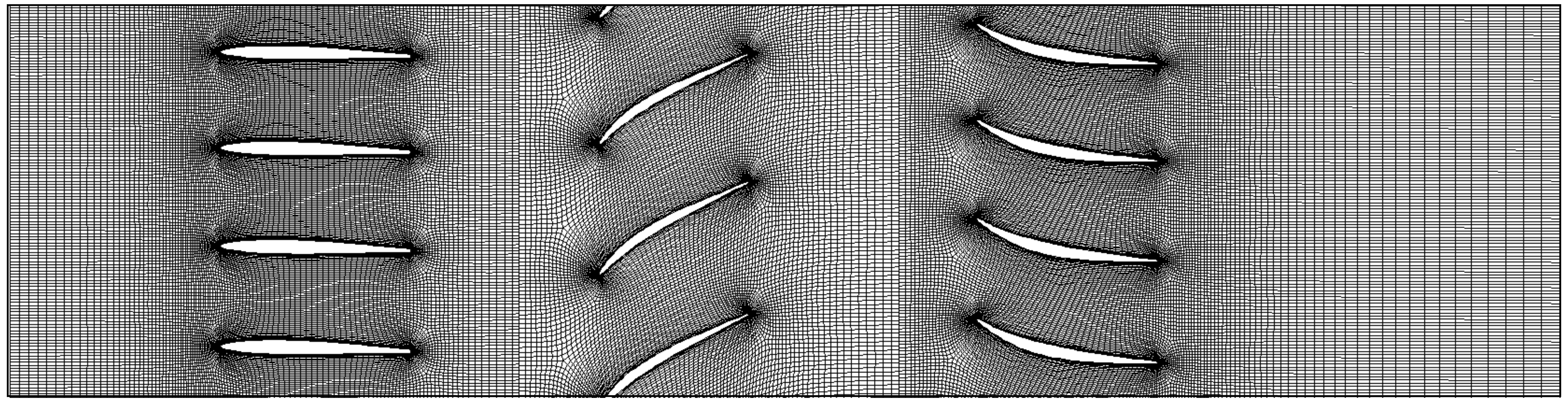
Numerical model and setup

Numerical setup and domain:

Meridional view:



B2B view:



Solver: Numeca Fine/Turbo

Grid generator: AutoGrid5 (multi-block structured)

Numerical setup:

- Simulation: RANS & URANS
- R/S int. RANS: Mixing plane + NRBC
- R/S int. URANS: Domain scaling
- Tu model: k-epsilon Chien
- Inlet Tu BC: TI = 0.35%, Tu viscosity ratio
- Inlet BC: Pt & Tt (from experiments)
- Outlet BC: Mass-flow (from experiments)
- Solid wall BC: Adiabatic
- Wall resolved simulation (y+ = 1.2)

Geometrical setup:

- Fillets and tip gaps
- Hot geometries
- Closed cavities (not included)

Chosen after assessment of real geometrical features impact

Presentation overview

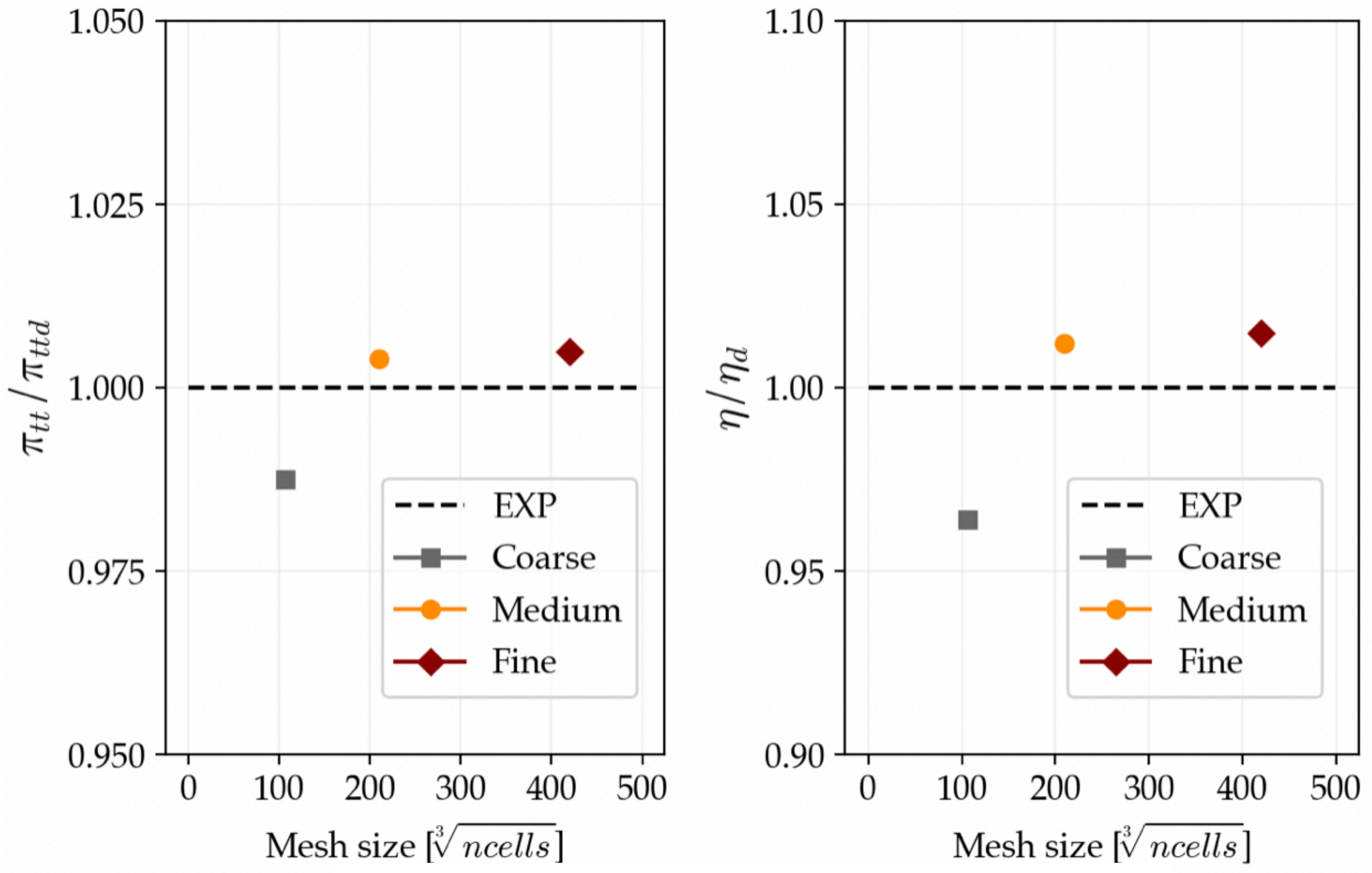
Sections of the presentation:

- Turbulence model assessment for secondary-flow characterisation (ASME Turbo Expo 2022)
- Characterisation of the machine in clean conditions
- Current activities
- Conclusions and next steps

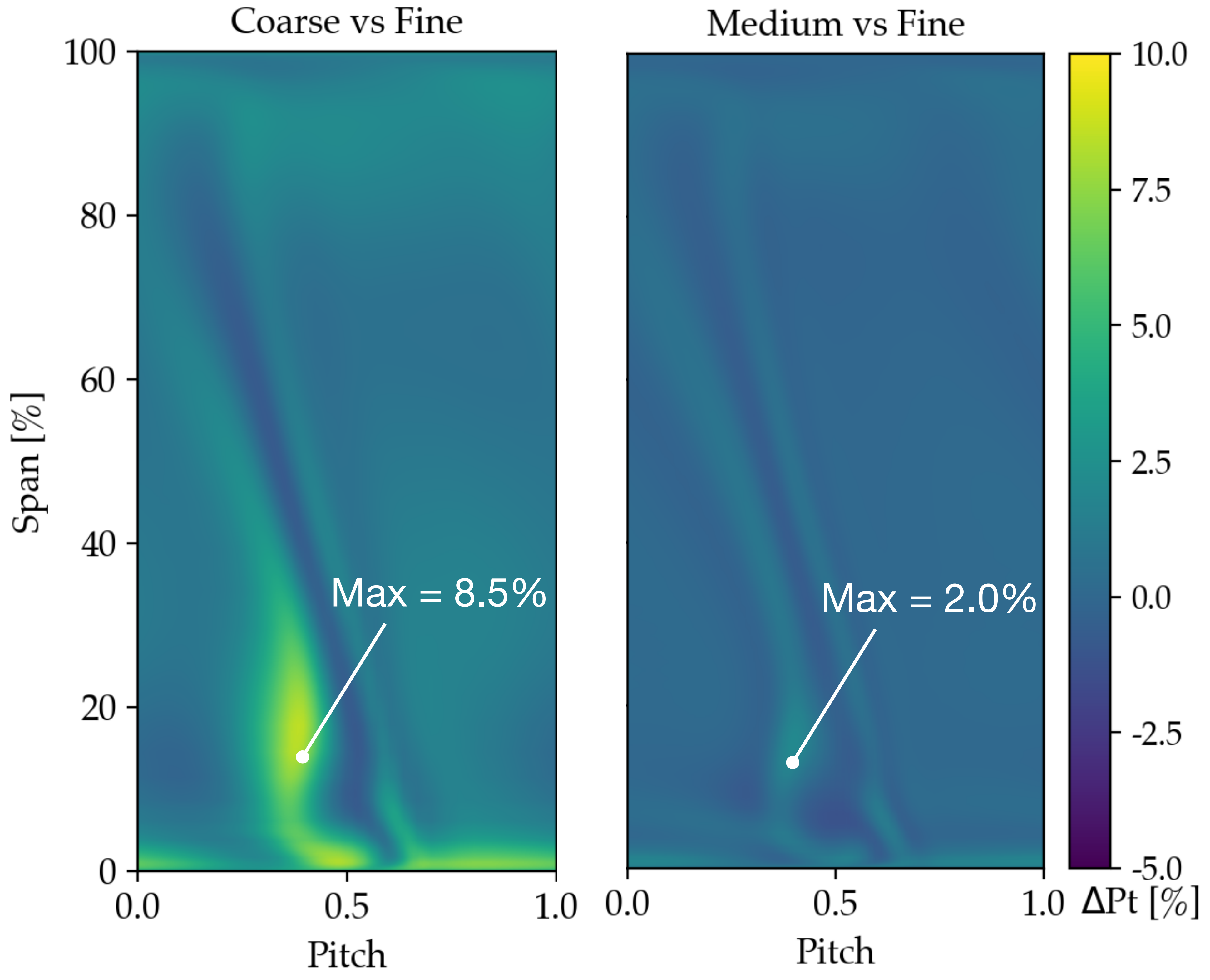
Turbulence model assessment

Grid refinement study:

Global performance



Rotor outlet flow-field

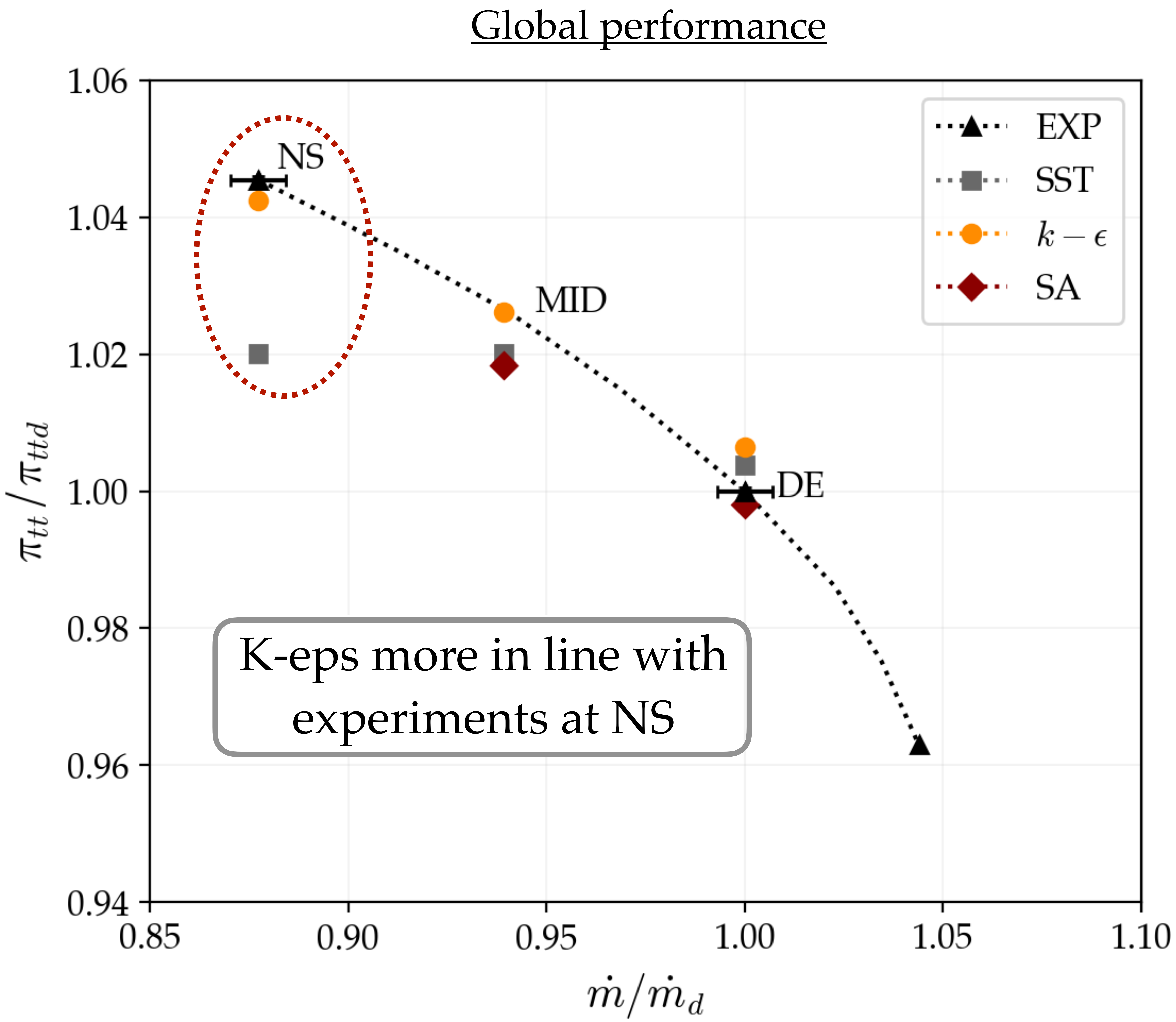


- Three mesh levels: 1.2M, 9.3M, 74M
- θ, R, Z isotropic refinement by factor 2 at each step
- Setup: RANS with k-omega SST model at DE conditions

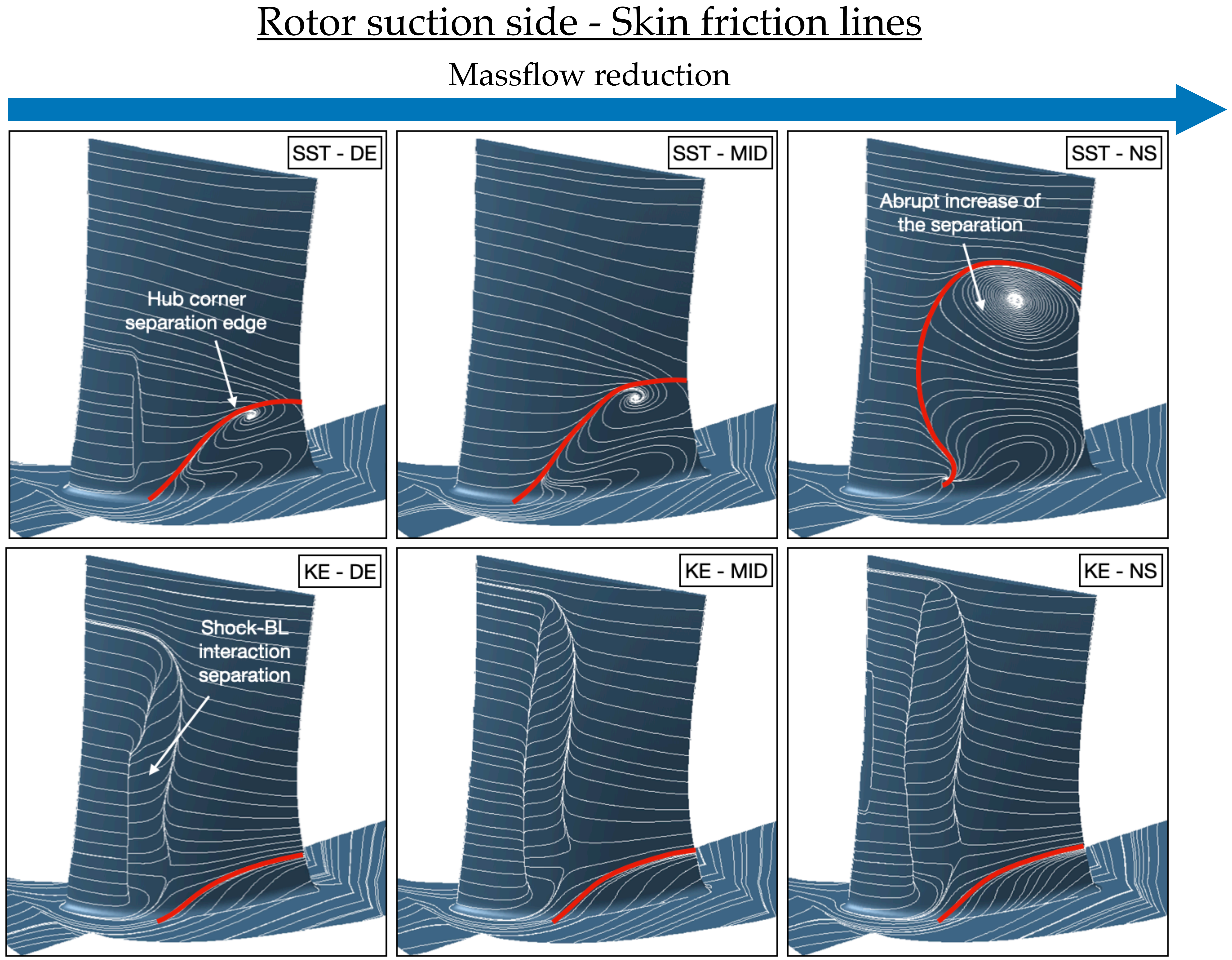
Medium mesh provides results closer to finest mesh

Turbulence model assessment

Impact on global performance and secondary structures:



K-eps more in line with experiments at NS

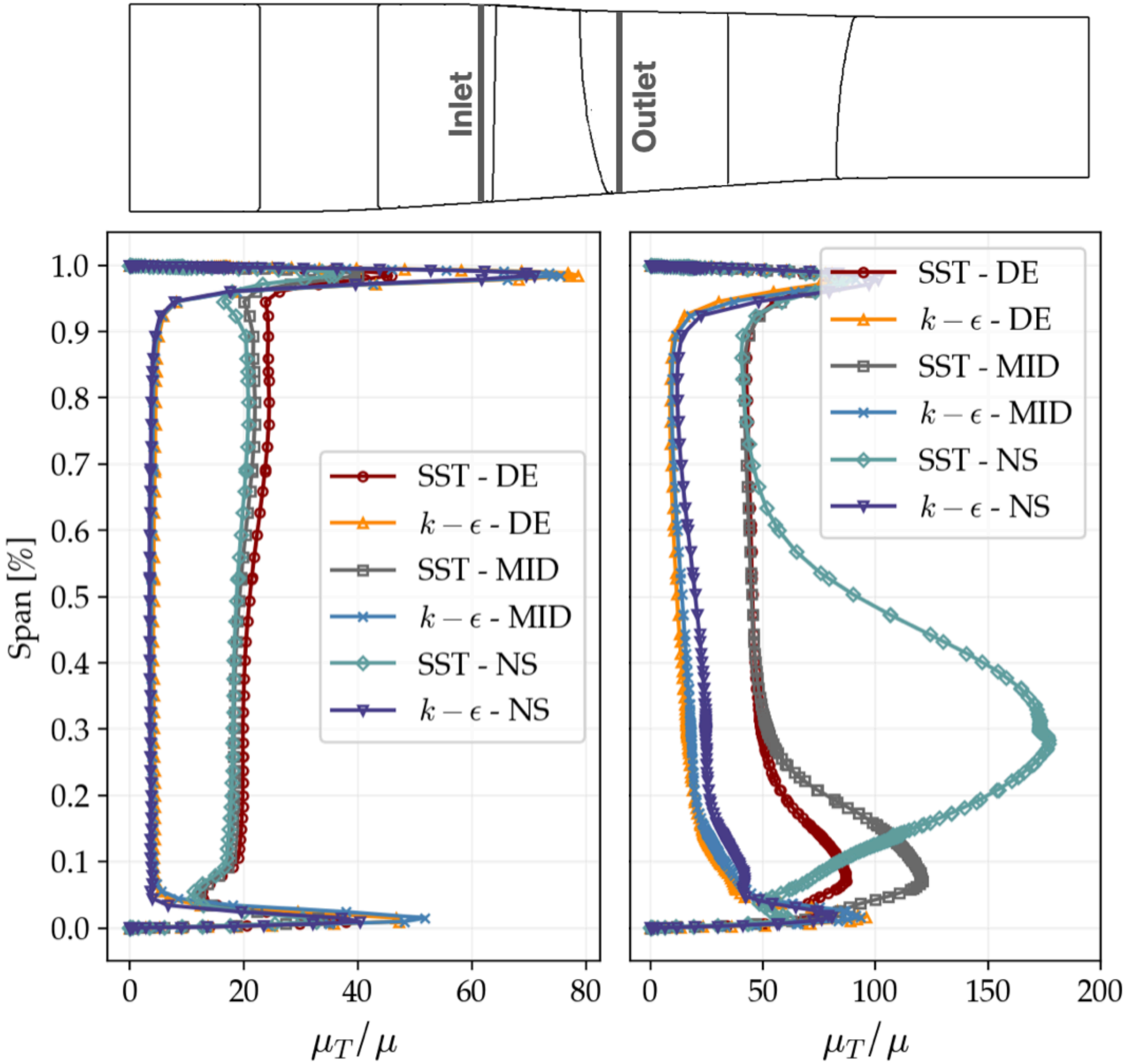


Critical flow structure at NS: Hub corner separation

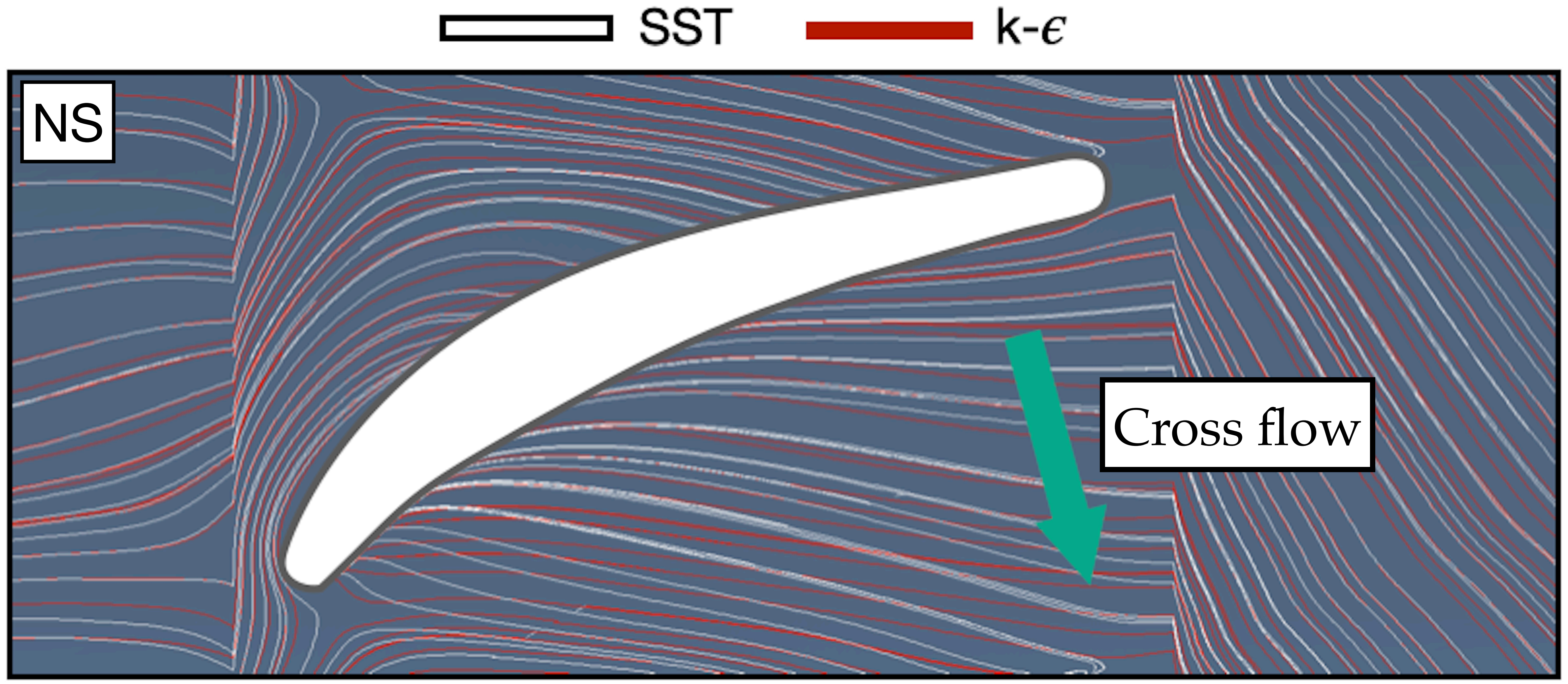
Turbulence model assessment

Overall driving mechanisms and secondary flow field evolution:

Rotor inlet/outlet conditions: eddy viscosity



Rotor hub wall - skin friction lines



1. The larger K-eps eddy viscosity into the BL decreases the crossflow and the size of the hub corner separation
2. The smaller K-eps eddy viscosity at mid-span increases the size of the shock-BL separation

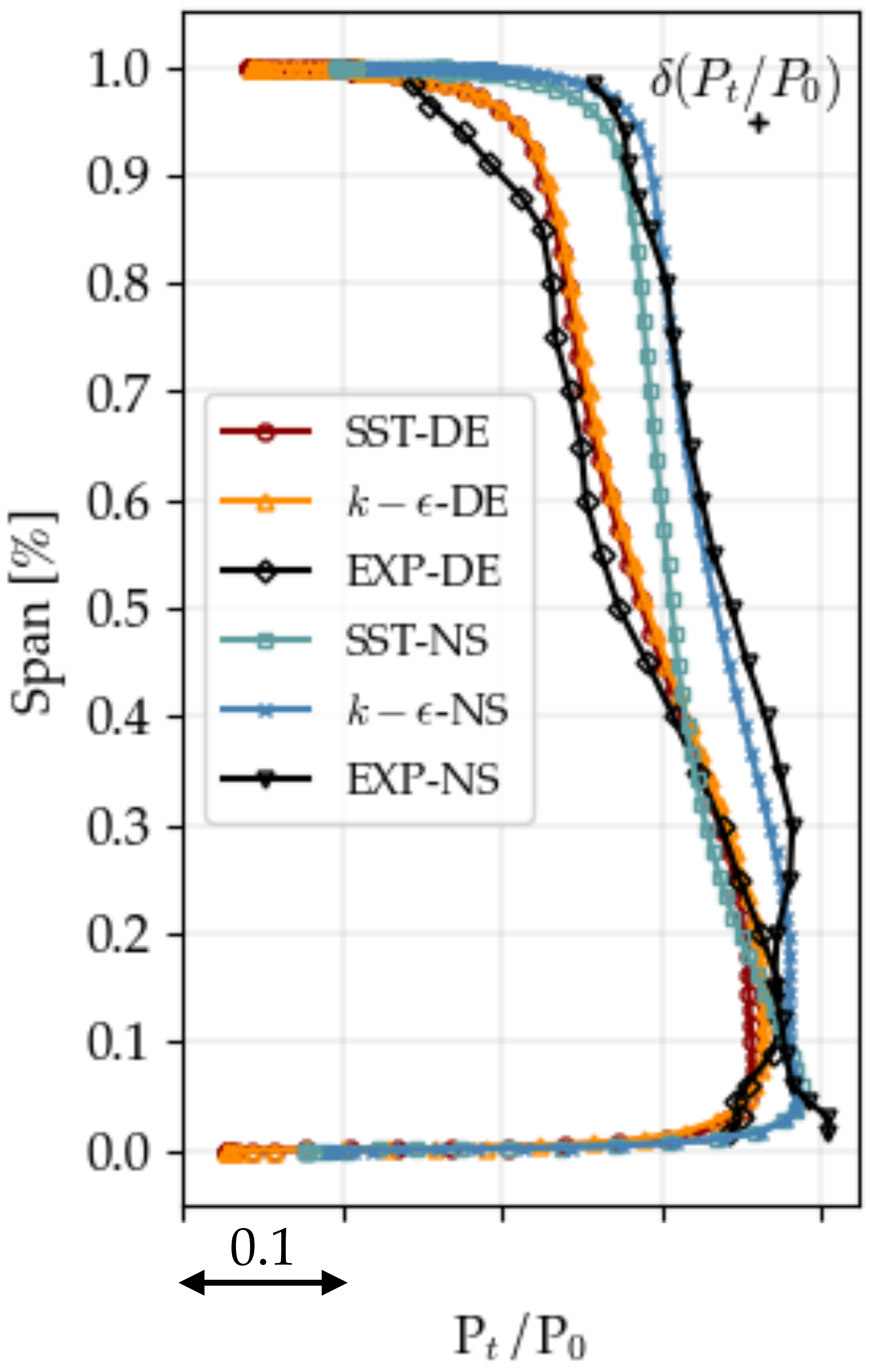
Overestimation of hub corner separation for SST is linked to the computed eddy viscosity and BL height

Turbulence model assessment

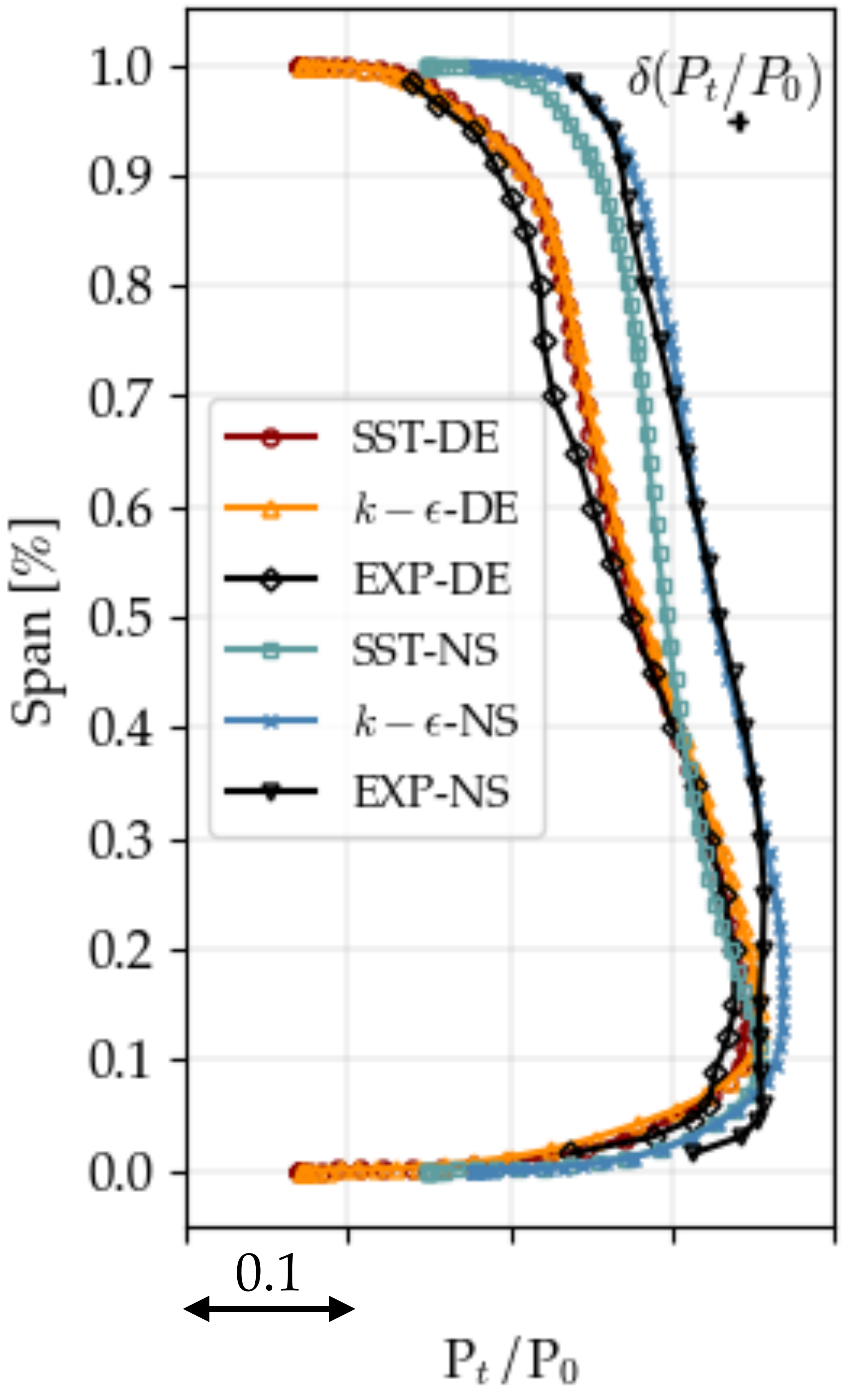
Validation against experimental results:

Spanwise validation

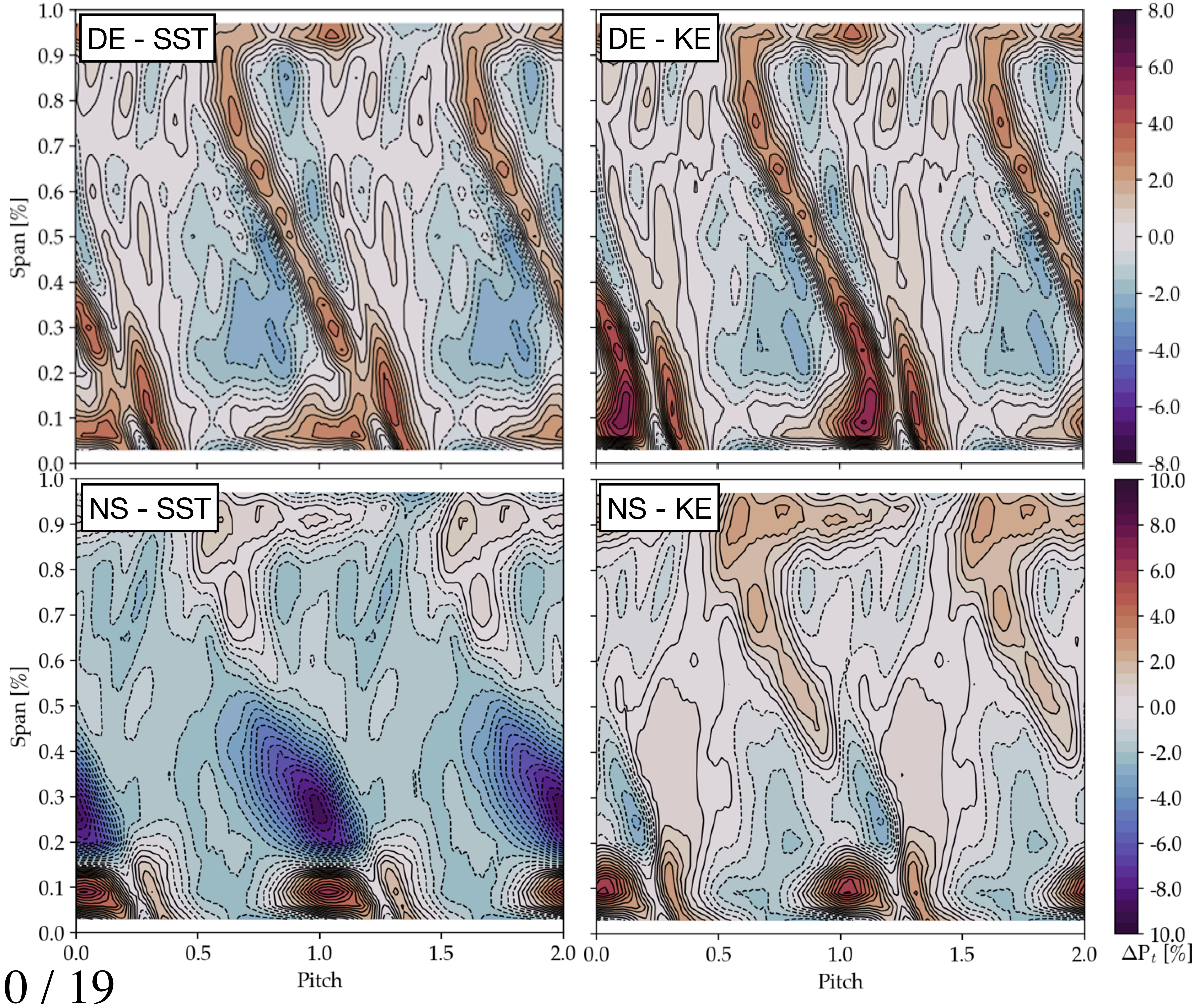
Rotor outlet



Stator outlet



2D map validation: rotor outlet



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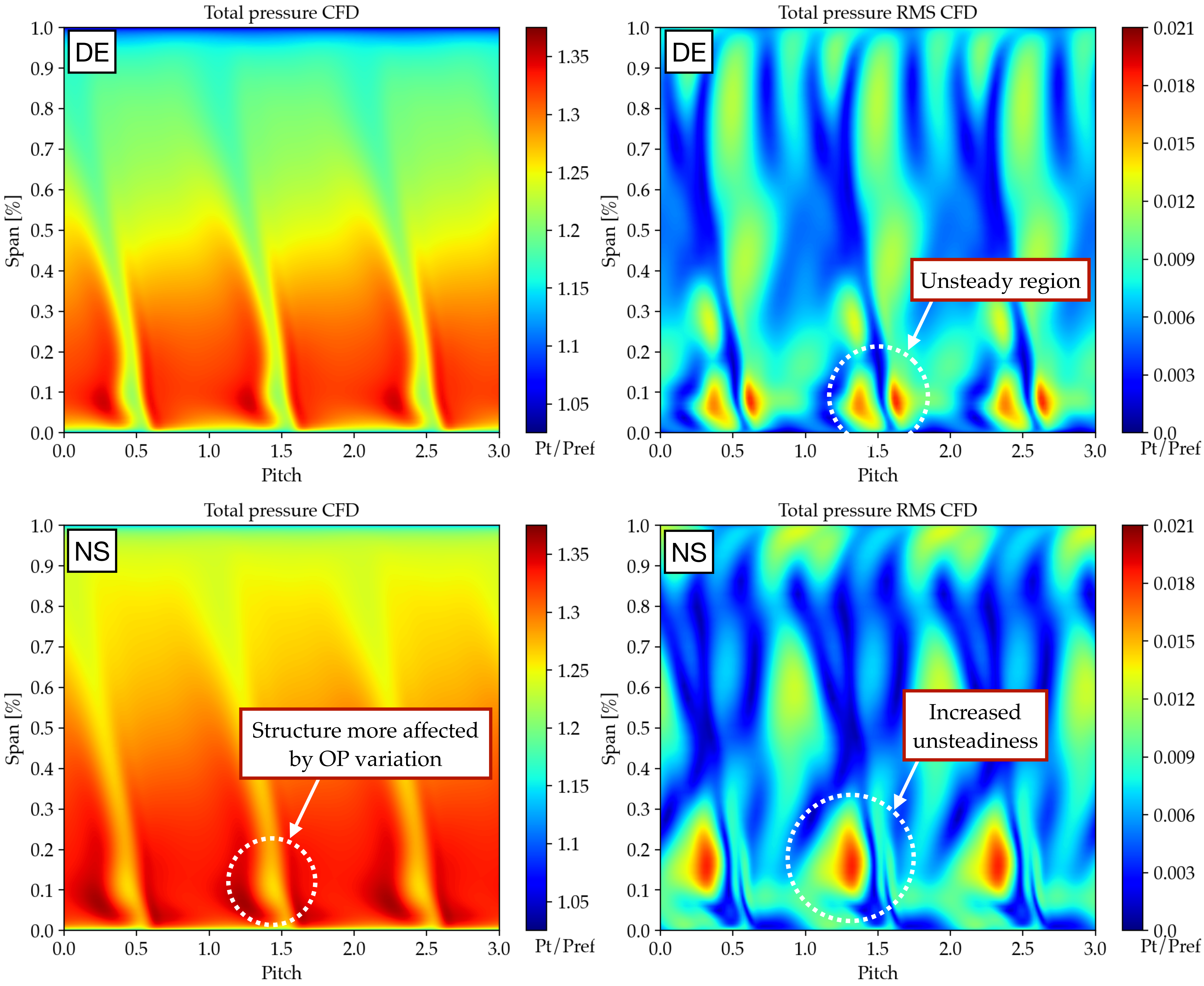
Critical flow regions and phenomena

Rotor hub corner separation:

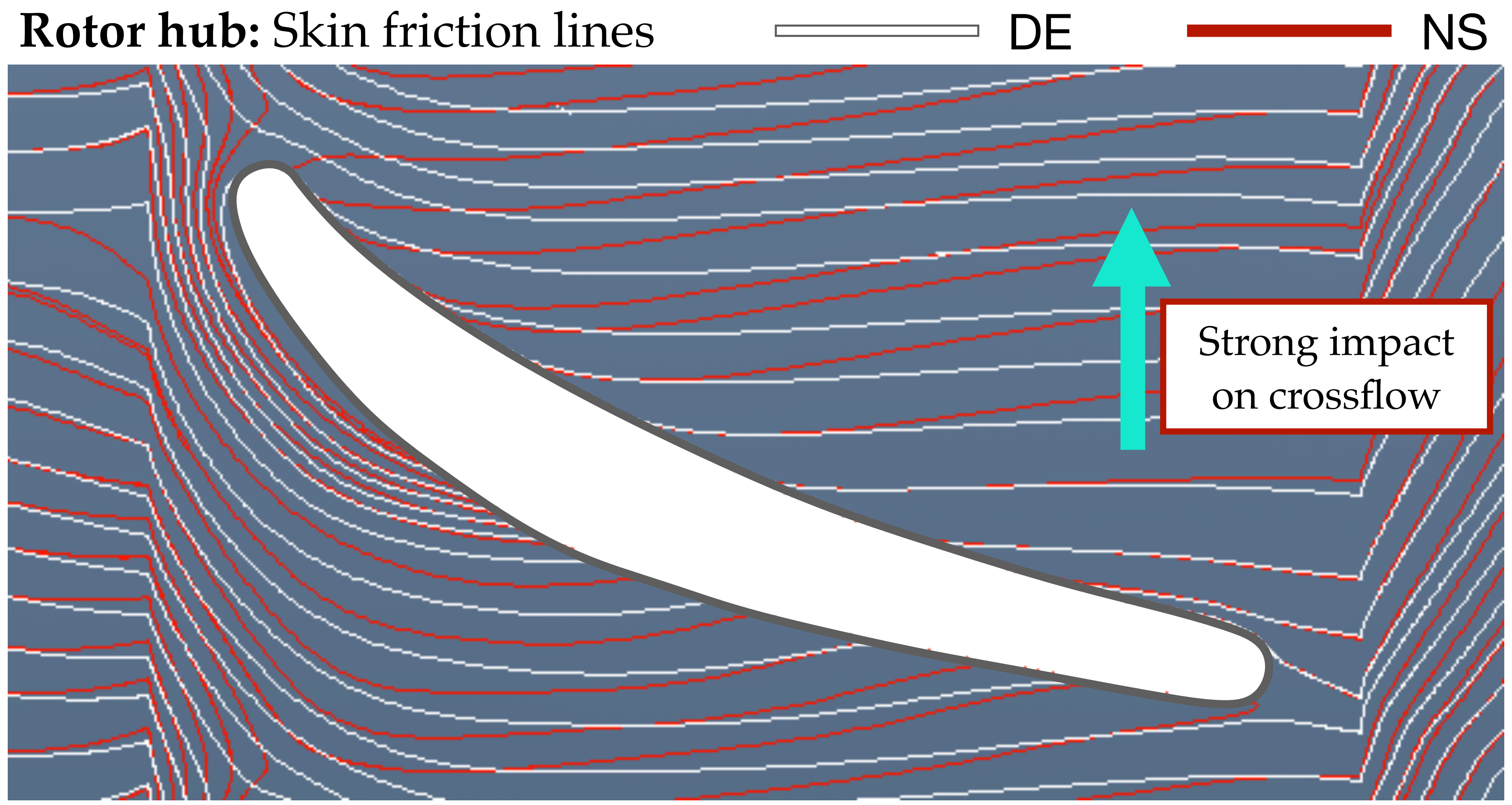
- Critical behaviour visible from Tu-model analysis
- Low-momentum flows impacted by large loading
- Criticality confirmed by unsteady results
- Hub corner sep. largely impacted by OP variation (unsteadiness already filtered by RANS)



Unsteady region

Structure more affected by OP variation

Increased unsteadiness

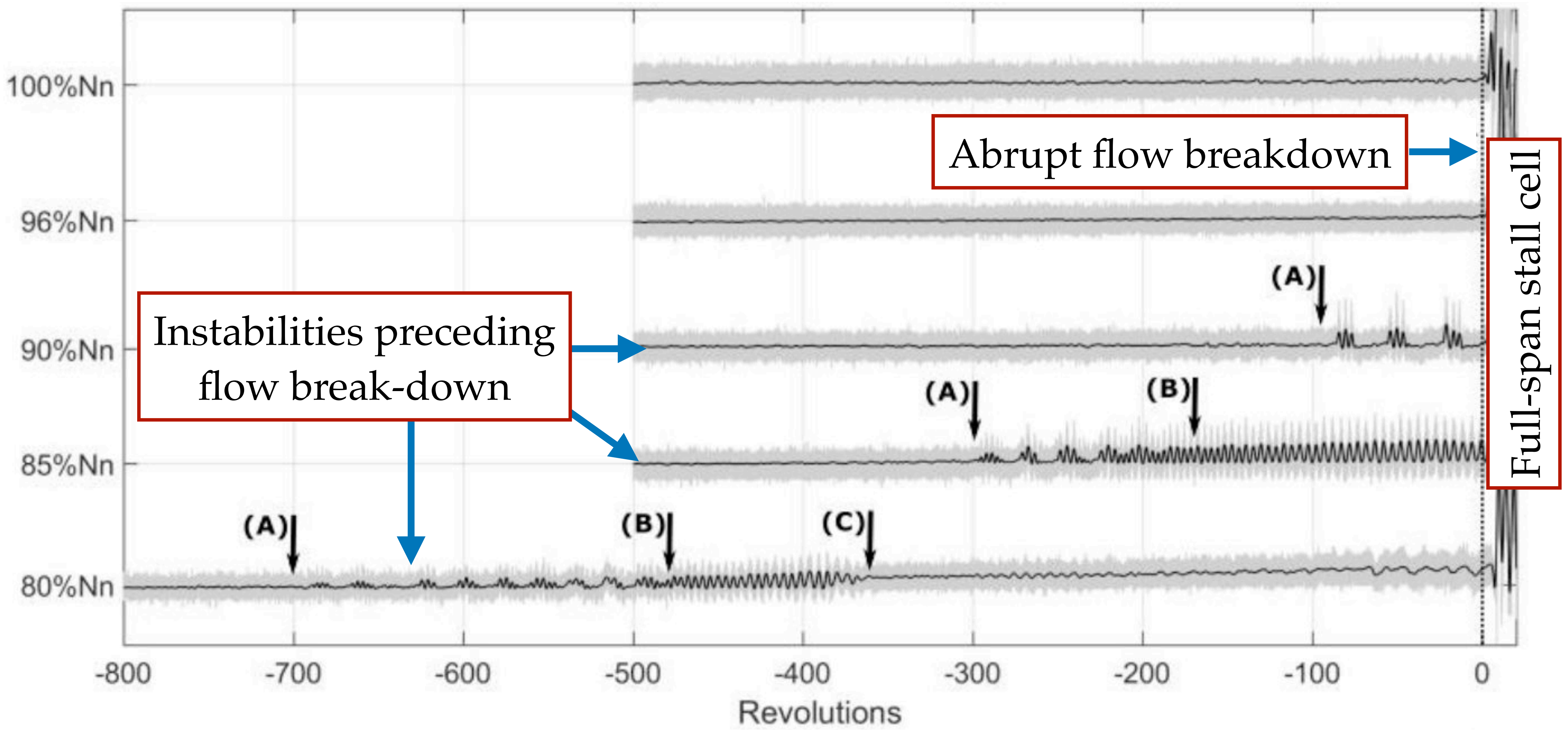


Strong impact on crossflow

Critical flow regions and phenomena

IGV-rotor wake propagation: experimental evidence

Static pressure at casing rotor inlet - From near stall to flow break-down

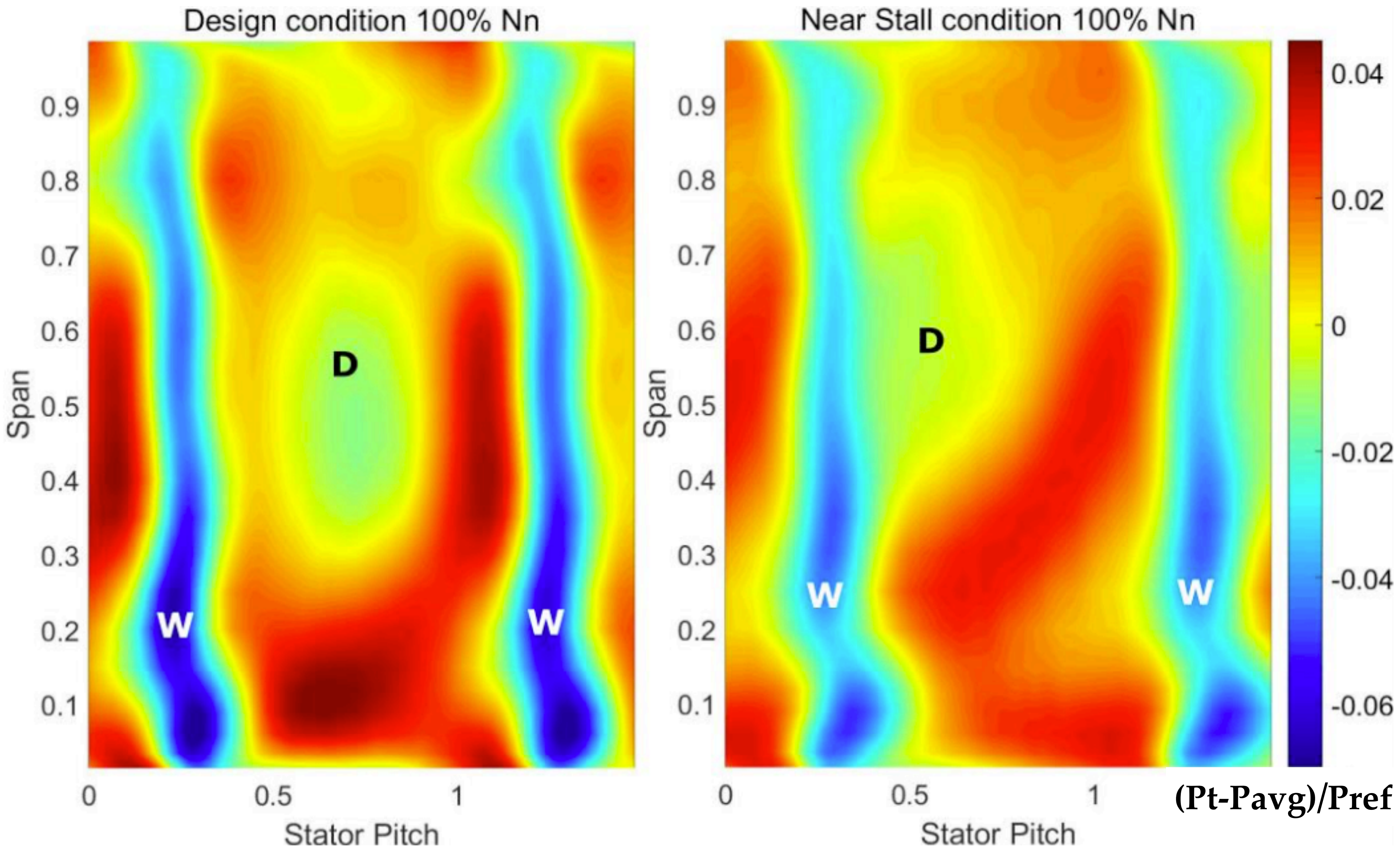


Abrupt flow breakdown

Full-span stall cell

Instabilities preceding flow break-down

Stator outlet total pressure maps - EXP:



Experimental observation

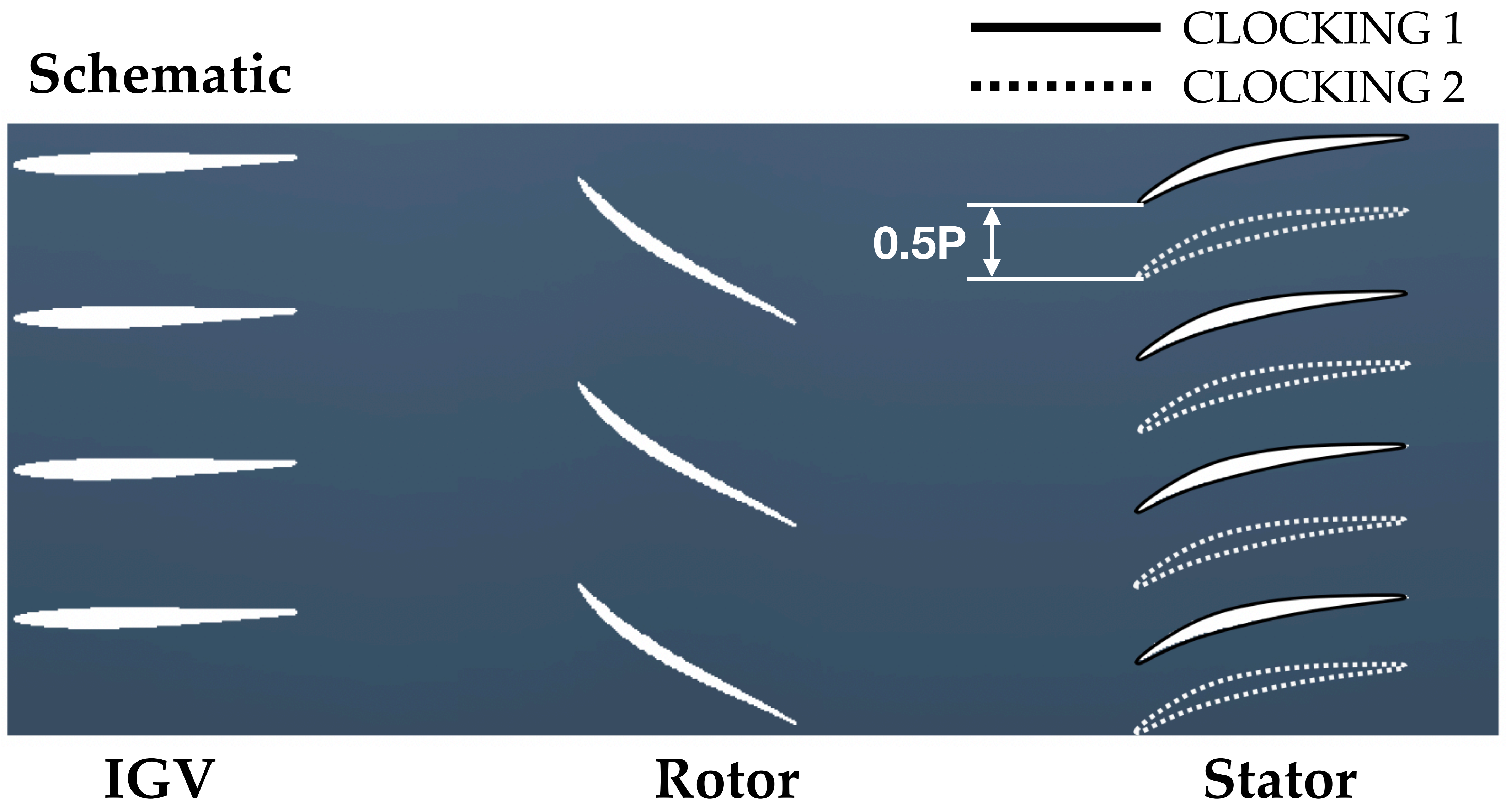
- 5, 27Hz components appear prior to flow breakdown
- IGV wakes through rotor generate a Pt "hole" at stator outlet
- Pt reduction moves toward stator SS at reduced mass-flow
- Stator midspan separation induced by increased incidence
- Such separation is thought to be at the origin of the instability

- Role of IGV-rotor wake interaction?
- Improve stability modifying IGV-stator clocking?

[5] Dell'Era G. et al. "Experimental Characterisation of the Unstable Range of a High Speed Booster" Draft version

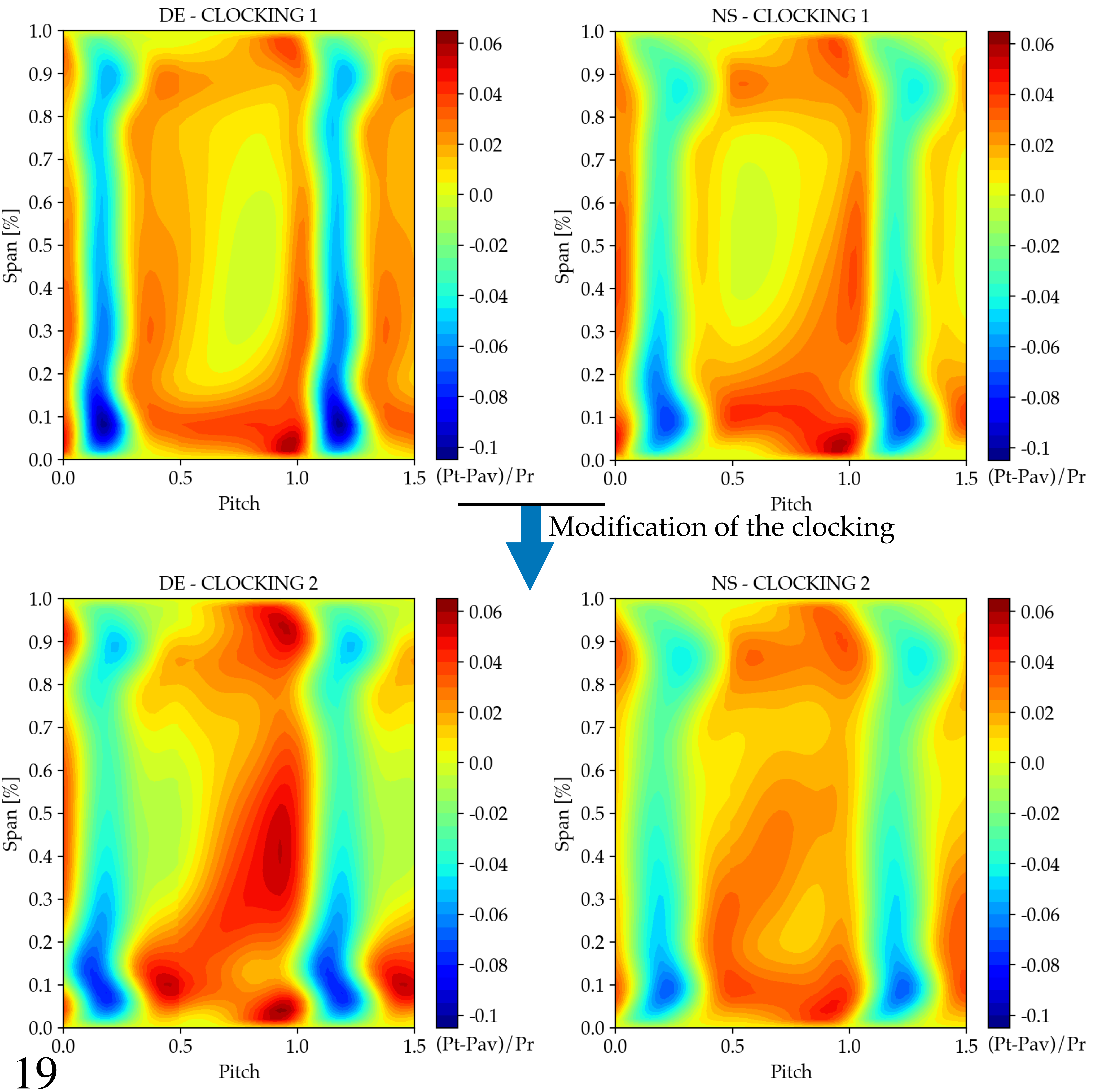
Considerations about the loss of stability

Effect of the clocking on the stator outlet field:



- Correspondence 1:1 IGV-stator clocking on DREAM
- Modification of Pt "hole" position with different clocking
- **Machine stability** possibly **improved** at reduced speed **with modified clocking**
- **In the test section the clocking can not be modified**

Stator outlet total pressure maps - CFD:



Presentation overview

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- Turbulence model assessment for secondary-flow characterisation (ASME Turbo Expo 2022)
- Characterisation of the machine in clean conditions
- Current activities
- Conclusions and next steps

Current activities

Full-annulus simulations in clean conditions:

Motivations behind the use of a full annulus domain:

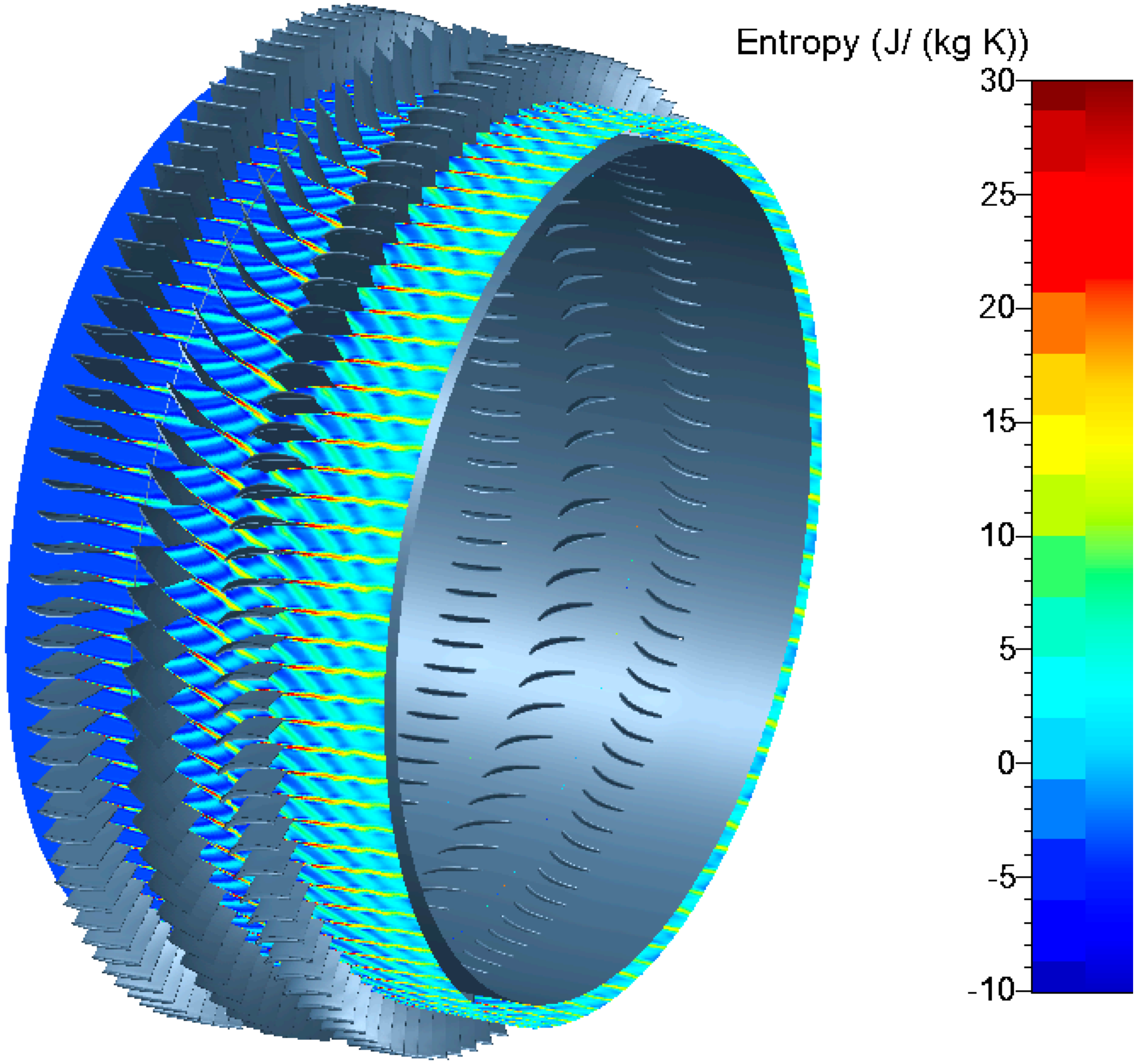
- To avoid impact on secondary flow structures
- To capture low-frequency modes and instabilities

Numerical setup and mesh:

- Same setup and mesh of previous URANS (domain scaling)
- Analysis at DE and NS operating points
- Computational cost: 0.75M CPU hours/simul on 350M cells

Infrastructure:

- Access to Tier-1 Zenobe cluster (Consortium CÉCI)



Current activities

Experimental campaign in clean conditions:

Tasks:

- Steady and unsteady characterisation of the machine in stable operating range
- Characterisation of the unstable operating range (critical features for stability)

Lessons learned from CFD:

- Need of high instrumentation resolution at rotor and stator outlet
- Analyse axial correlation for IGV wakes propagation and clocking effects

Realised so far:

- Definition of experimental setup and instrumentation to employ
- Calibration of 3 hole virtual fast-response pressure probe: static, dynamic, aerodynamic

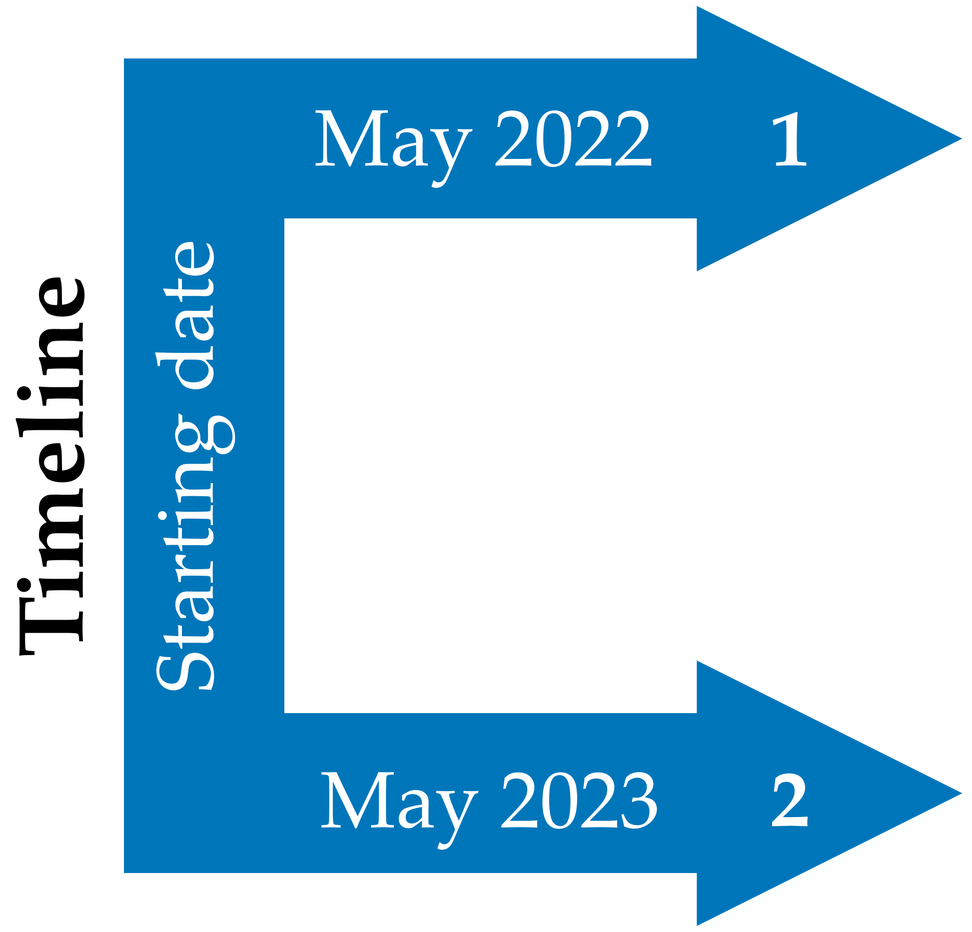
The complementary interpretation of numerical and experimental results will allow a full-characterisation of the DREAM test section in clean conditions

Conclusions and next steps

Outcome of the presented activity:

- Geometrical features included into the domain (fillets, tip gaps and hot geometries)
- No general Tu-model better than others (K-eps better at NS, while SST at DE)
- Two critical flow structures detected in clean conditions:
  1. Rotor hub corner separation: structure most affected by OP variation
  2. Propagation of IGV-rotor wakes: phenomena impacting on the stability

Next steps:



Timeline

Starting date

May 2022 **1**

- <u>Full-annulus simulations in distorted conditions</u> (*Tier-1 Zenobe cluster):*
  - Understand distortion effects on compressor performance and stability
  - Characterise pre-existing and new critical phenomena
  - Distortion pattern considered: *Under definition* - targeting as realistic as possible pattern

May 2023 **2**

- <u>Experimental campaign in distorted conditions:</u>
  - Modification of the test section for installation of distortion screen on target pattern
  - Steady and unsteady data in both stable and unstable operating range

Acknowledgments

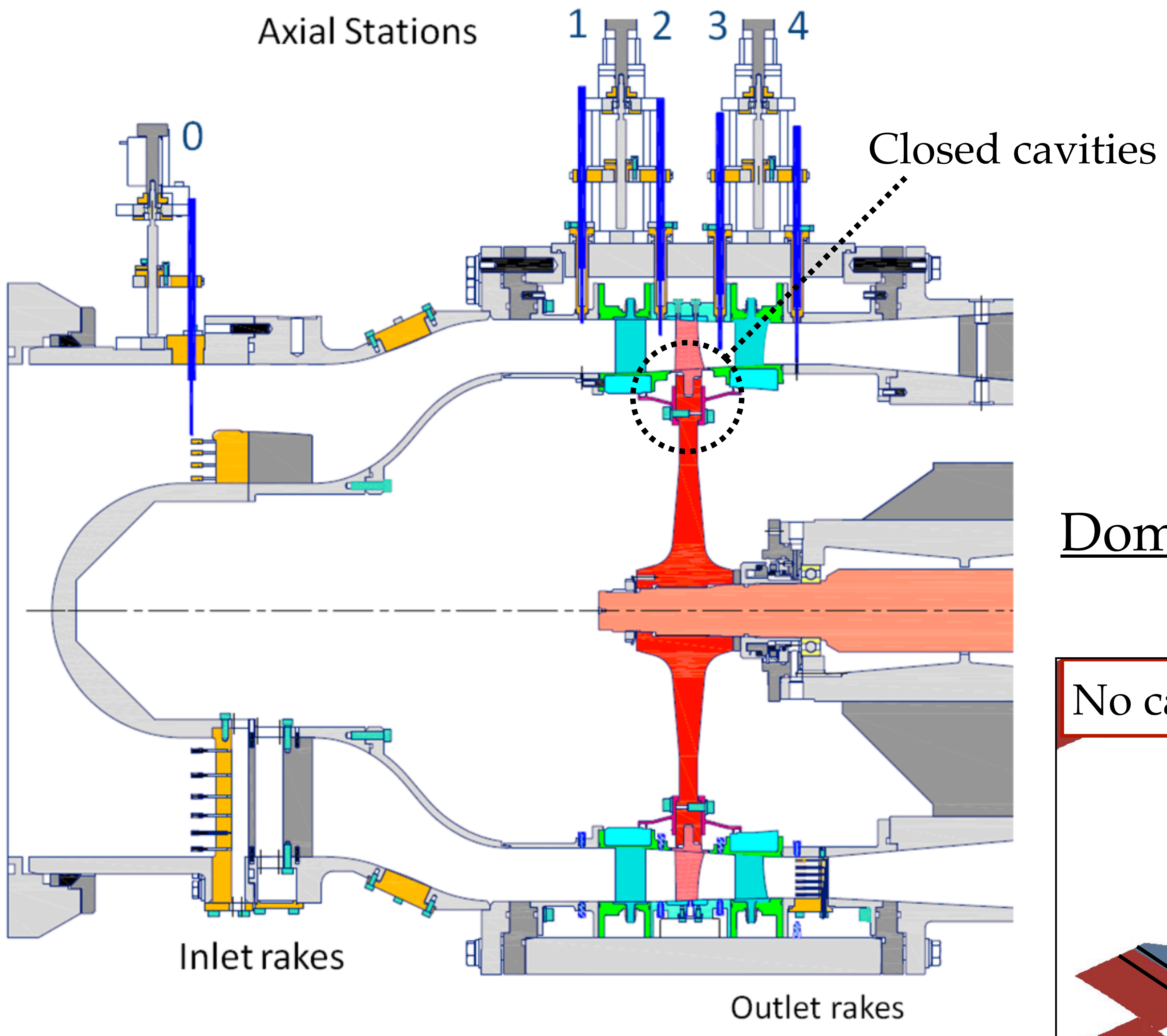
This work is supported by:

- FRS-FNRS FRIA fundings - PhD fellowship
- Consortium CÉCI - Access to Tier-1 Zenobe cluster

Numerical domain - geometrical features

Backup slide

List of geometrical features of interest:



Features to investigate:

- Fillets
- Tip gaps
- Hot geometries

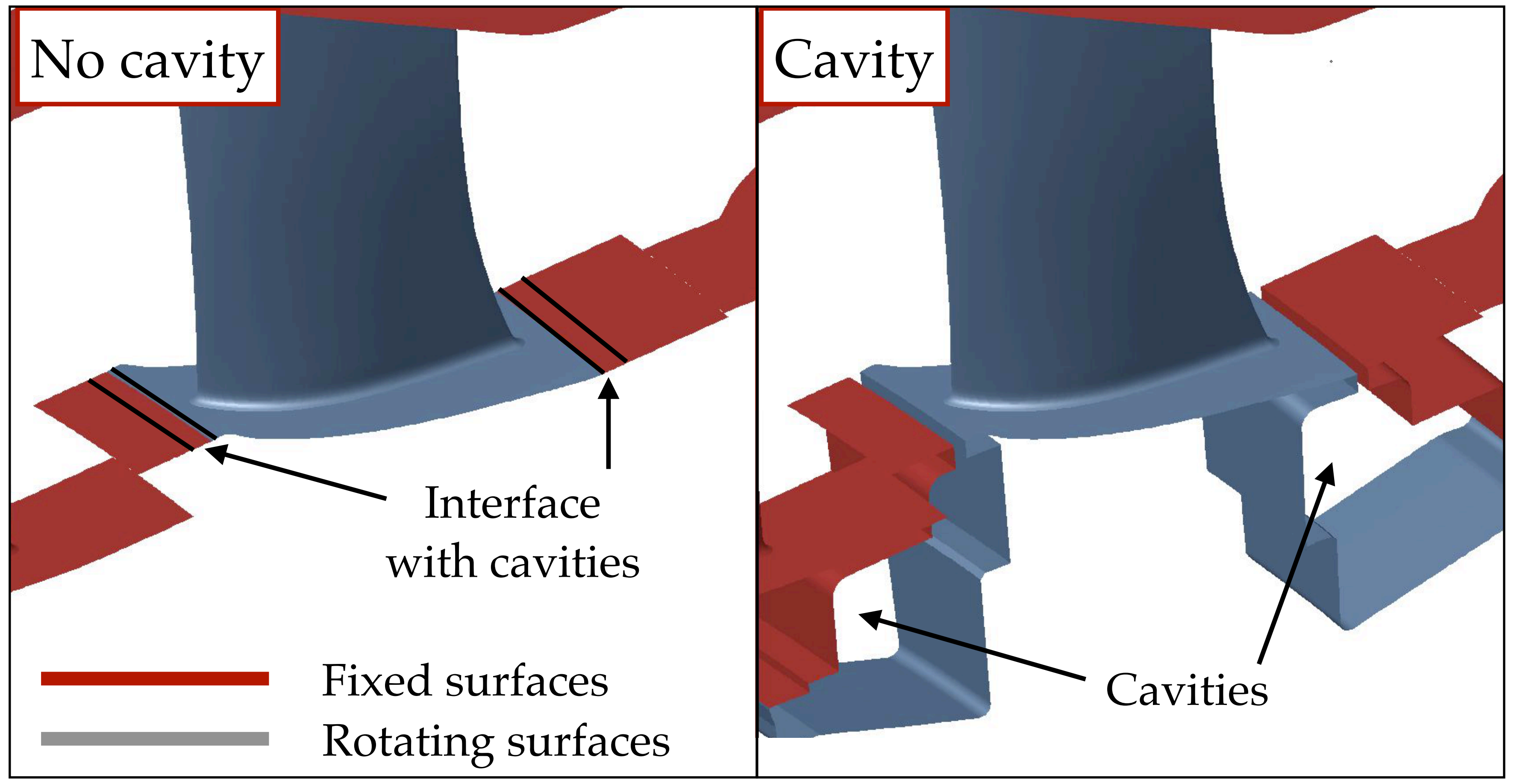
Limited impact on mesh size

- Closed cavities

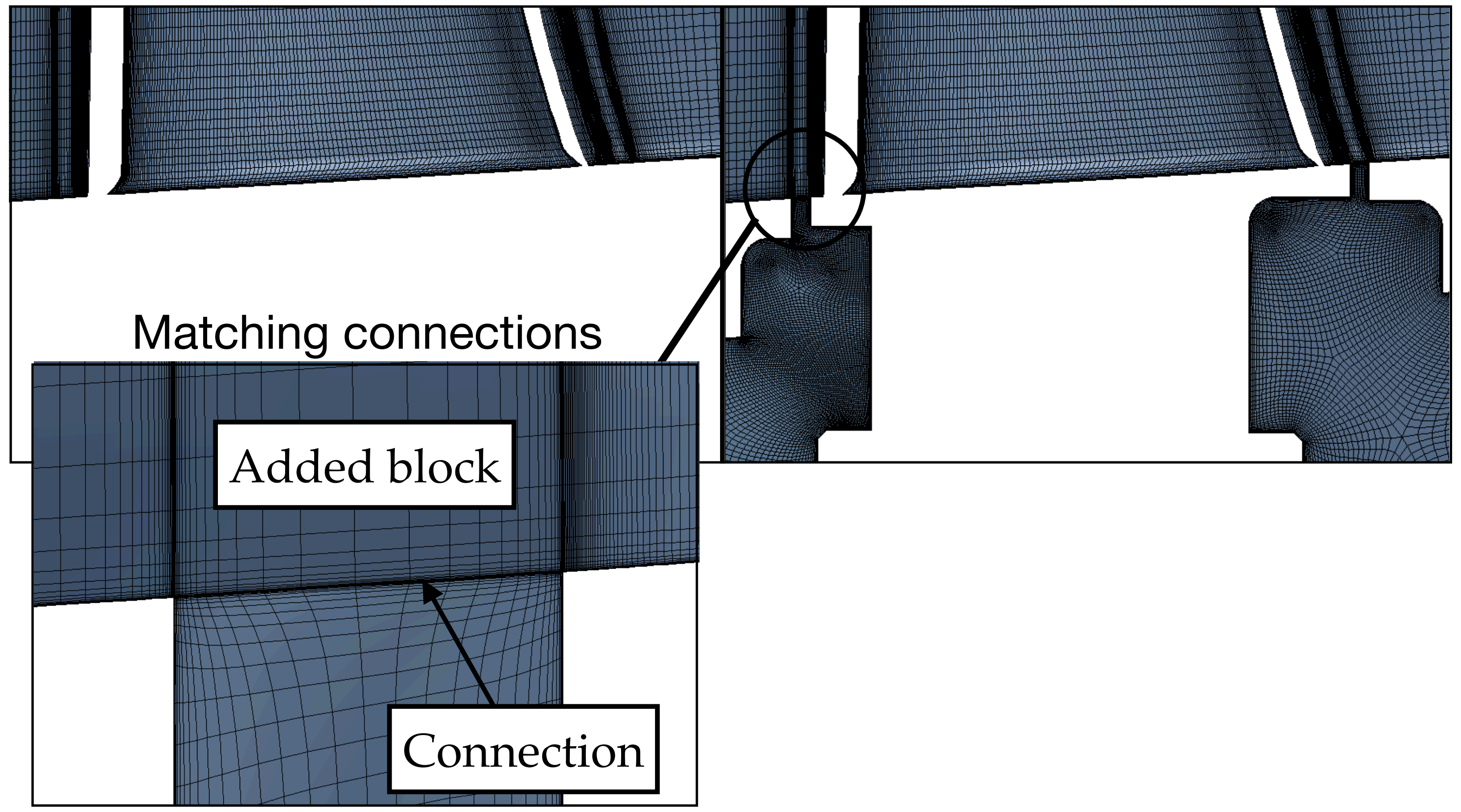
Large impact on mesh size
(to further investigate)

Domain and mesh for cavity and no-cavity case:

Solid wall boundary conditions



Mesh topology



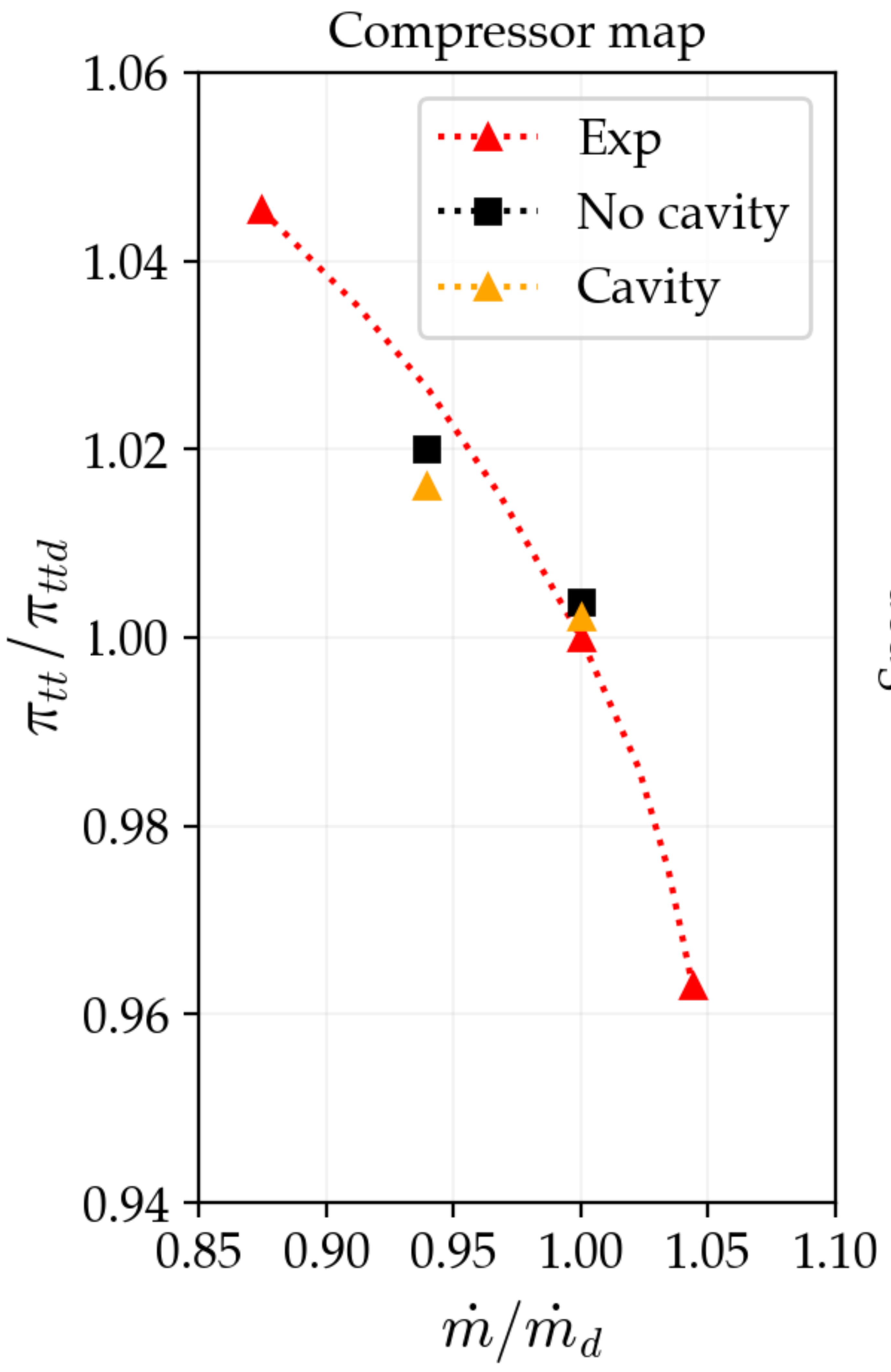
Interfaces substituted with non-rotating solid walls in the no-cavity configuration

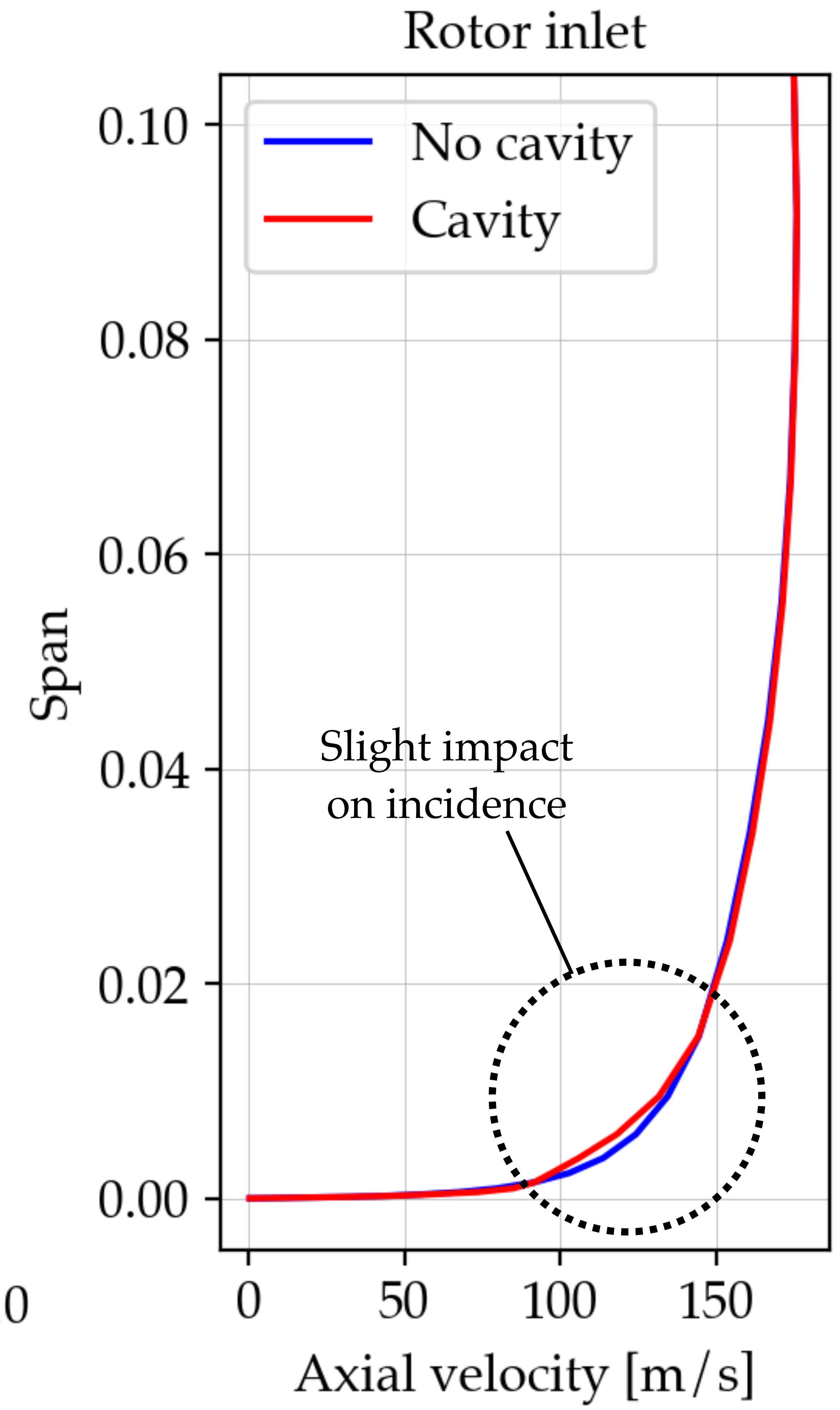
Same topology for the 2 configurations

Numerical domain - geometrical features

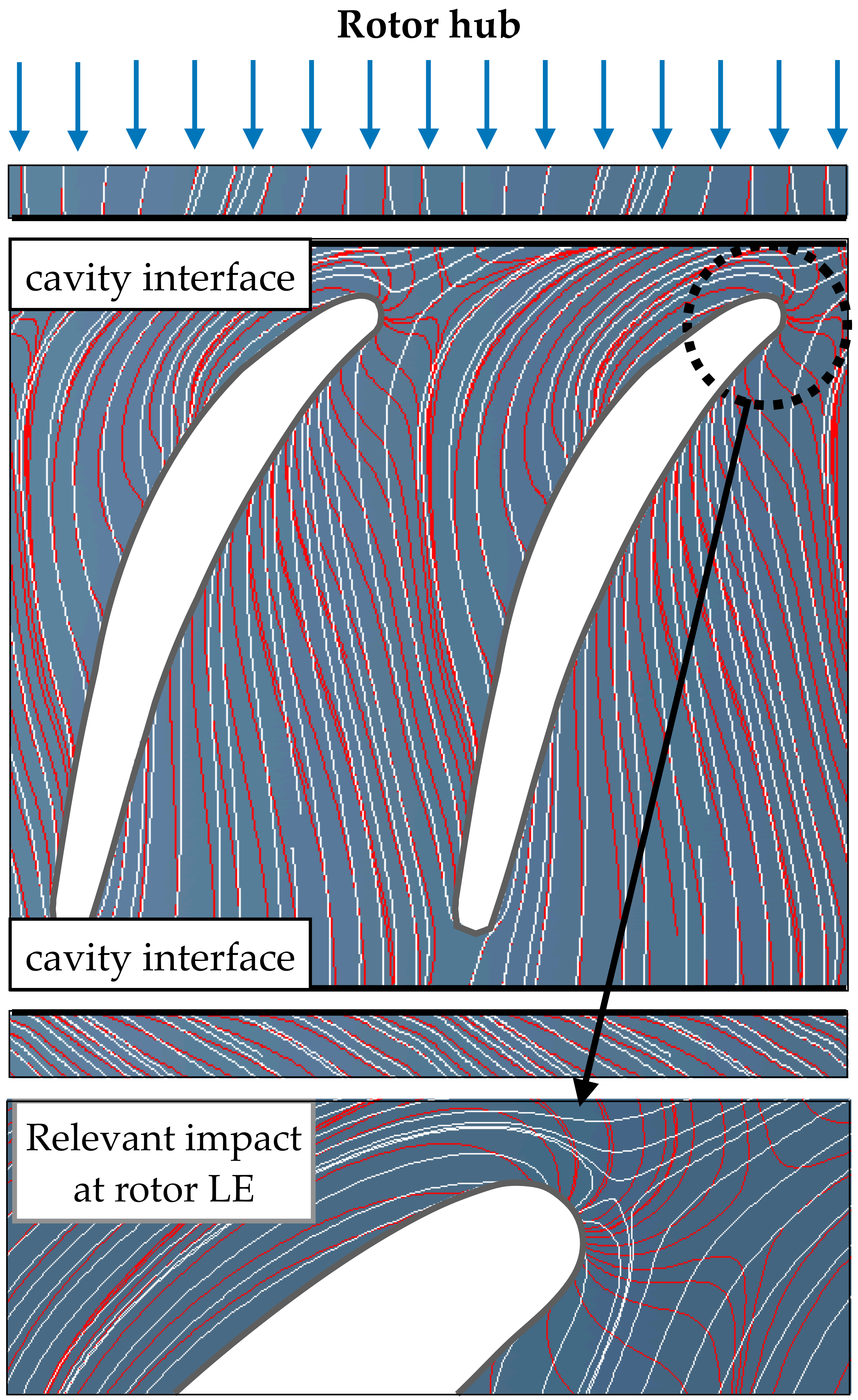
Backup slide

Impact of cavities on the main channel flow:

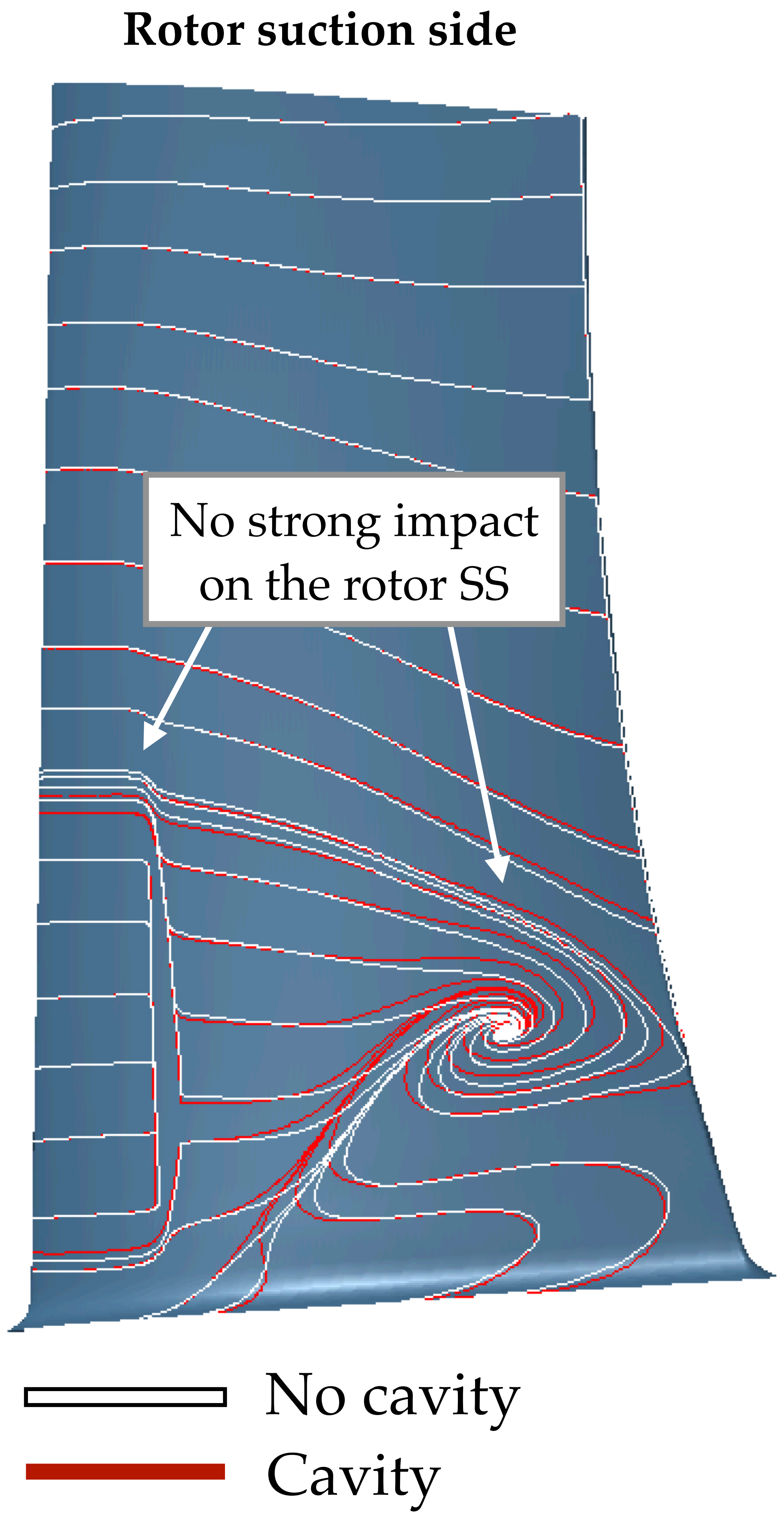

Compressor map


Rotor inlet

Slight impact on incidence


Rotor hub

Relevant impact at rotor LE

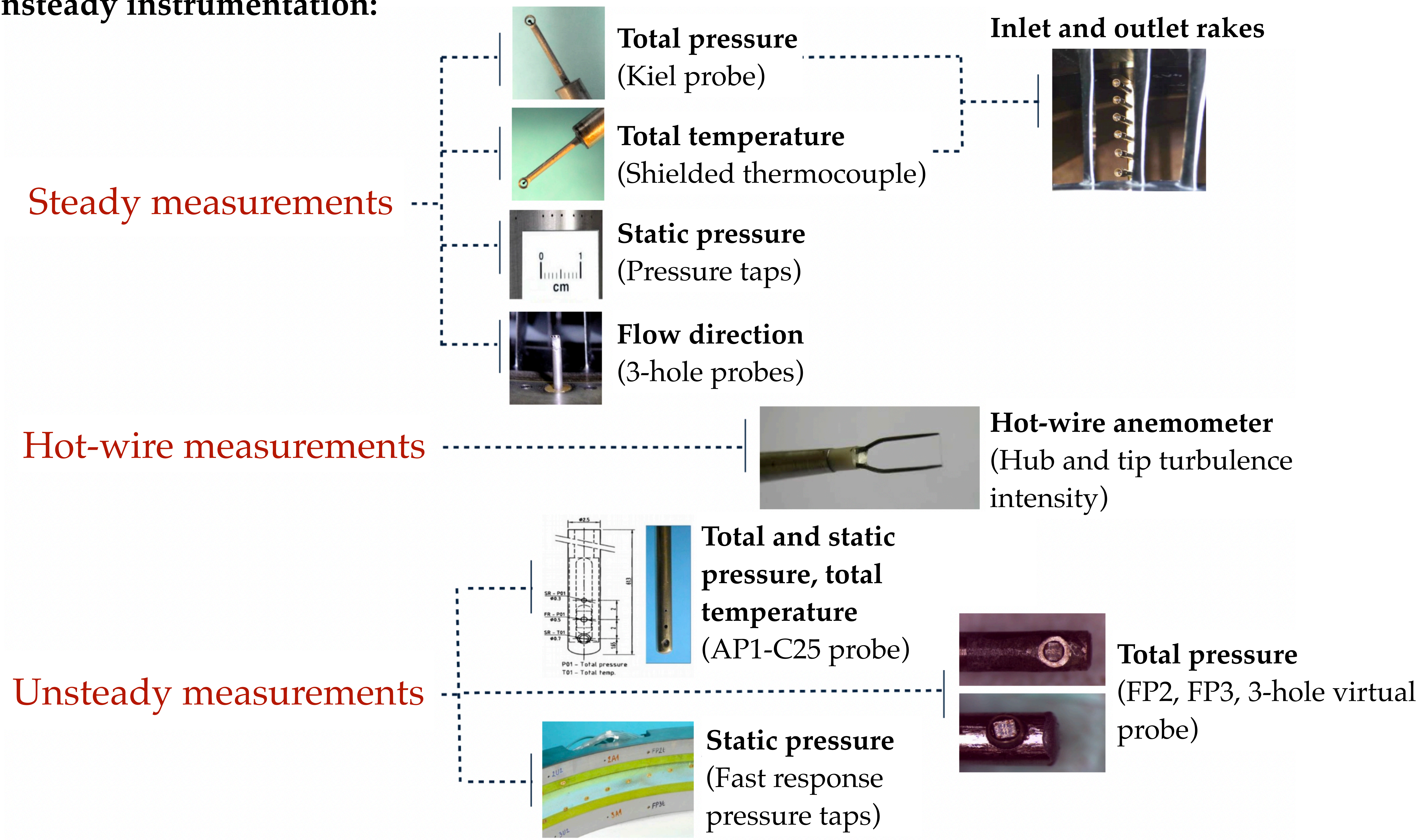

Rotor suction side

No strong impact on the rotor SS

Experimental instrumentation

Backup slide

Steady and unsteady instrumentation:



Steady measurements

- **Total pressure** (Kiel probe)
- **Total temperature** (Shielded thermocouple)
- **Static pressure** (Pressure taps)
- **Flow direction** (3-hole probes)

Inlet and outlet rakes

Hot-wire measurements

- **Hot-wire anemometer** (Hub and tip turbulence intensity)

Unsteady measurements

- **Total and static pressure, total temperature** (AP1-C25 probe)
- **Total pressure** (FP2, FP3, 3-hole virtual probe)
- **Static pressure** (Fast response pressure taps)

Experimental instrumentation

Backup slide

Quantities to measure:

Steady measurements:

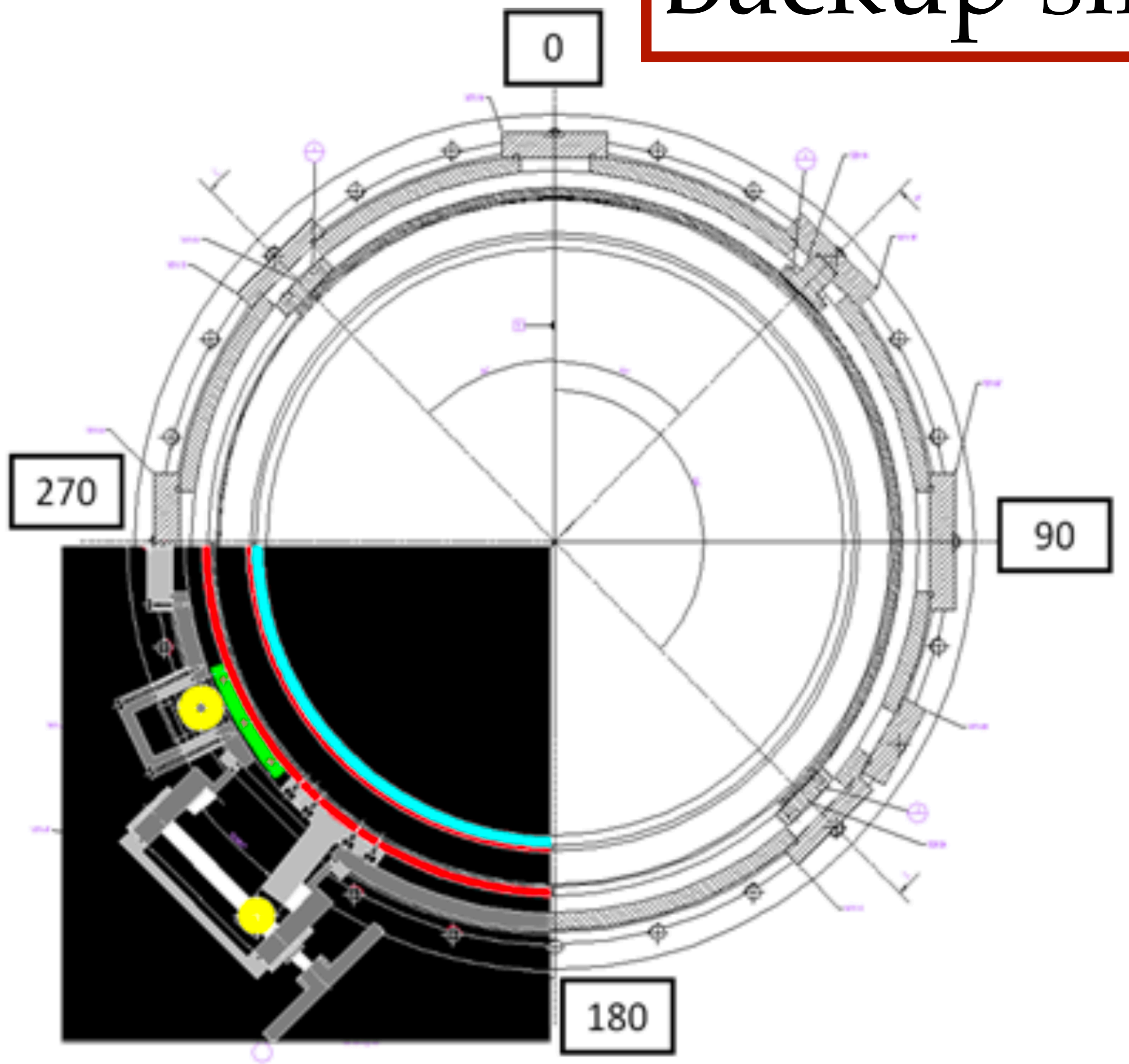
- Compressor map:
  - Total to total pressure ratio
  - Static to total pressure ratio
  - Efficiency
  - Massflow
- Spanwise distributions:
  - Total pressure in planes 1,2,3,4
  - Total temperature in planes 1,2,3,4
  - Ma in planes 1,2,3,4
  - Flow angle in planes 1,2,3,4
- Maps:
  - Total pressure in plane 4
  - Total temperature in plane 4
  - Ma in plane 4
  - Flow angle in plane 4

Unsteady measurements:

- Spanwise distributions:
  - Total pressure in planes 3,4
- Maps:
  - Total pressure in planes 3,4
  - Flow angles in planes 3,4
  - Static pressure at casing

Unstable operating range:

- Stall inception and post-stall:
  - Hub, midspan and casing velocity in planes 1,2
  - Pressure signals at casing inlet, midchord and outlet
  - Pressure signal at rotor outlet hub, midspan and tip
  - Pressure signal at stator outlet hub

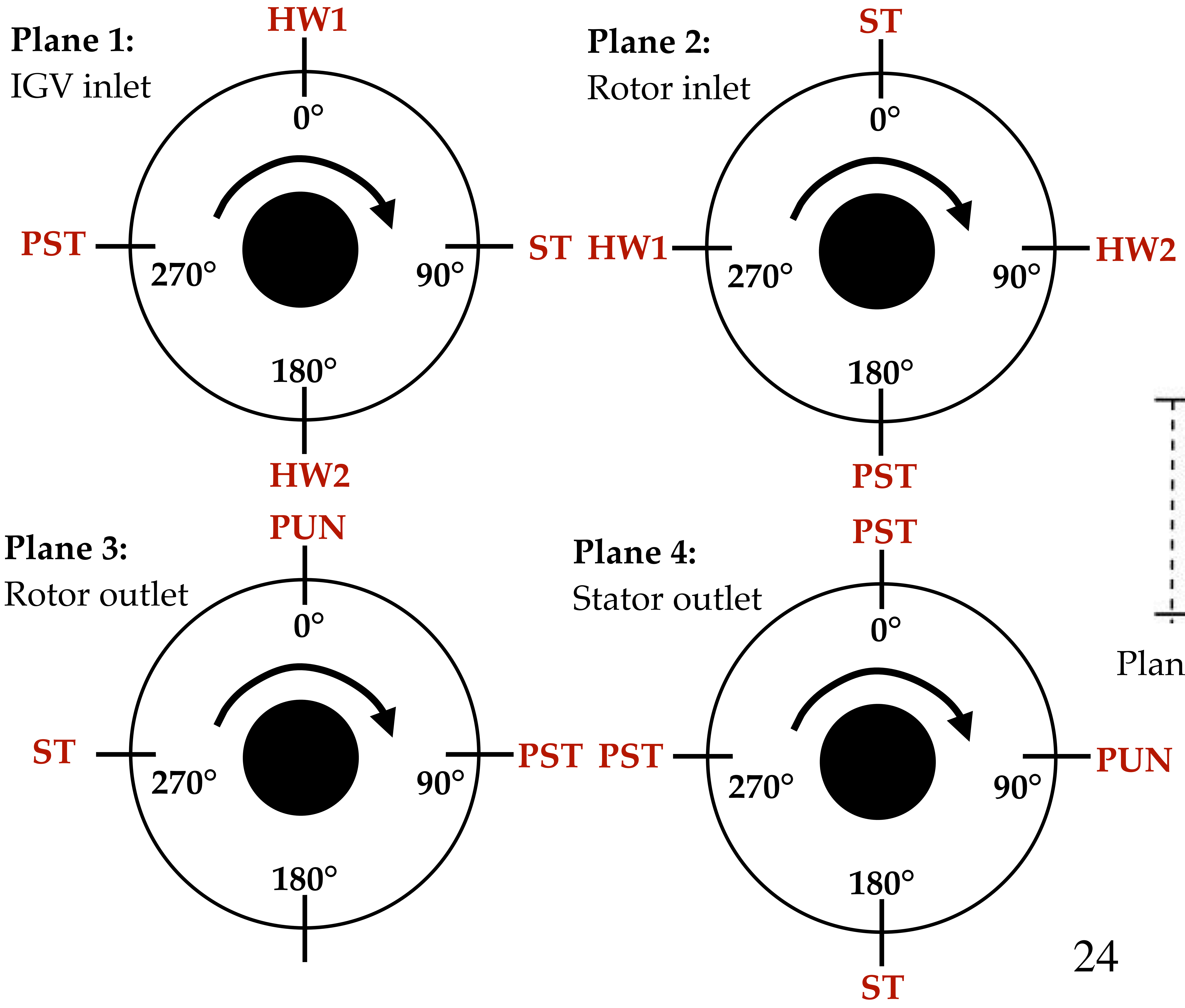


(Circumferential locations where it is possible to perform radial traversing)

Experimental setup

Backup slide

Plane by plane and meridional experimental setup:



Plane 1: IGV inlet

Plane 2: Rotor inlet

Plane 3: Rotor outlet

Plane 4: Stator outlet

Nomenclature:

- HW: Hot-wires
- PST: 5 Hole Steady
- PUN: 3 Hole Virtual Unsteady
- ST: Shielded Thermocouple