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EFFECTS OF UNSTEADY FLOW INTERACTIONS ON THE PERFORMANCE OF A HIGHLY-LOADED TRANSONIC COMPRESSOR STAGE

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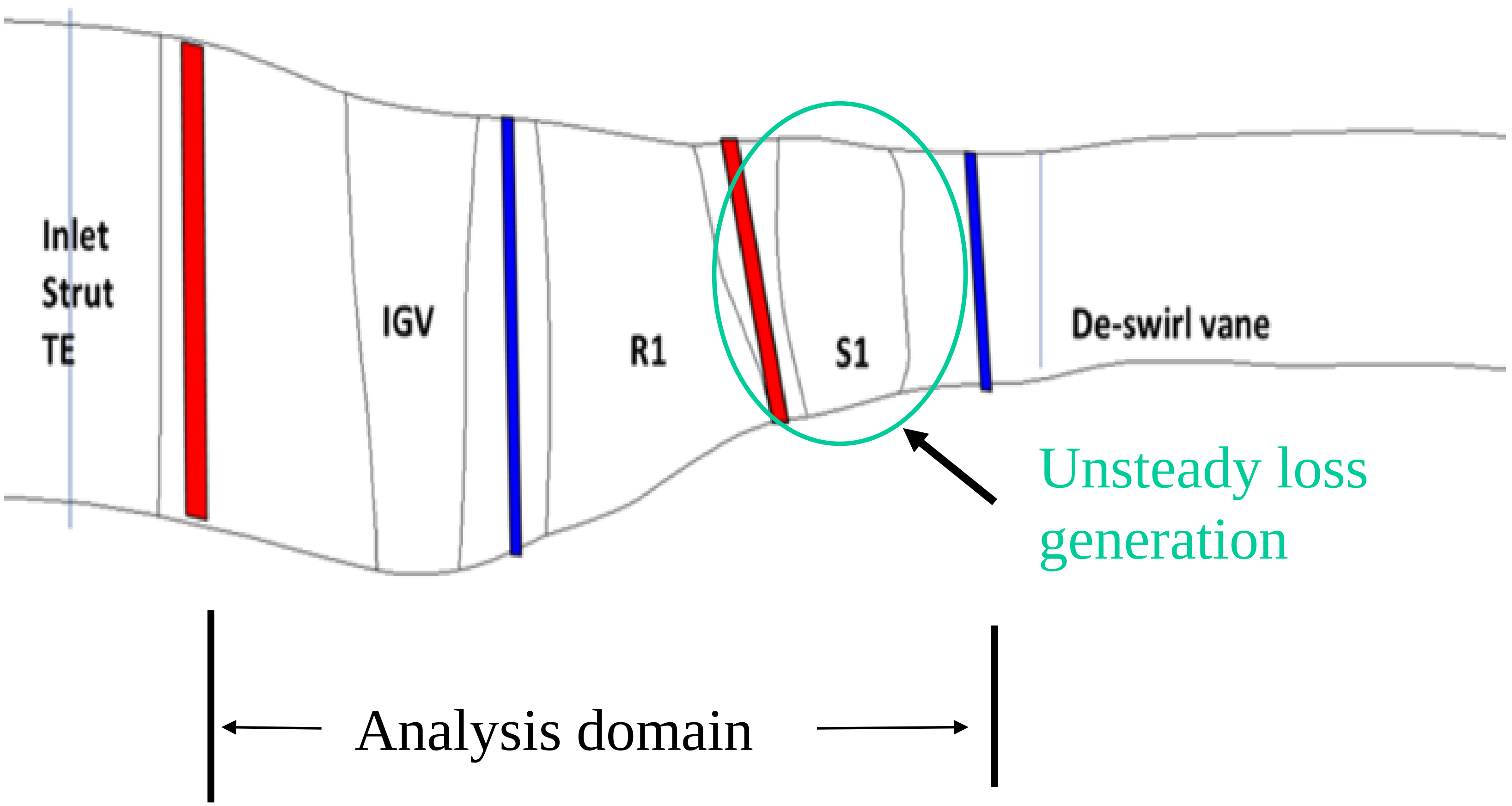
Background

- NASA ERA Program
  - Physics of Loss Generation in a GE Highly Loaded Transonic Compressor.
  - Aero Testing at NASA/Glenn W7 facility.
  - NASA Internal CFD study with RANS, URANS, LES.

CFD analysis of the first stage



Objectives

- Can a high-fidelity CFD (LES) calculate measured loss generation in Stator 1 ?
- Understand flow mechanism for this unsteady loss generation due to the incoming rotor wake.
- Possible ways to reduce loss generation ?

Order of presentation

- LES set-up and CFD grids.
- Compressor characteristics from LES.
- Unsteady loss generation in the stator passage.
- Concluding remarks.

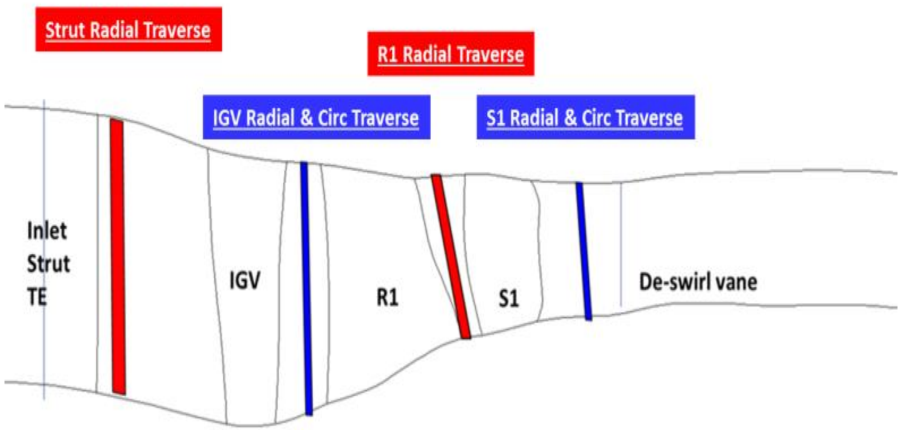
LES for turbomachinery application

- To address some shortcomings of RANS/URANS (vortex interaction, flow separation, wake development. Etc.)
- Significant increase in computing cost with large size computational grid.
- Solution depends on CFD grid.
- Good insight and knowledge required to extract physics (needs further development).

Applied LES procedure

- 3rd-order scheme for convection terms.
- 2nd-order central differencing for diffusion terms.
- Sub-iteration at each time step.
- Dynamic model for sub grid stress tensor.

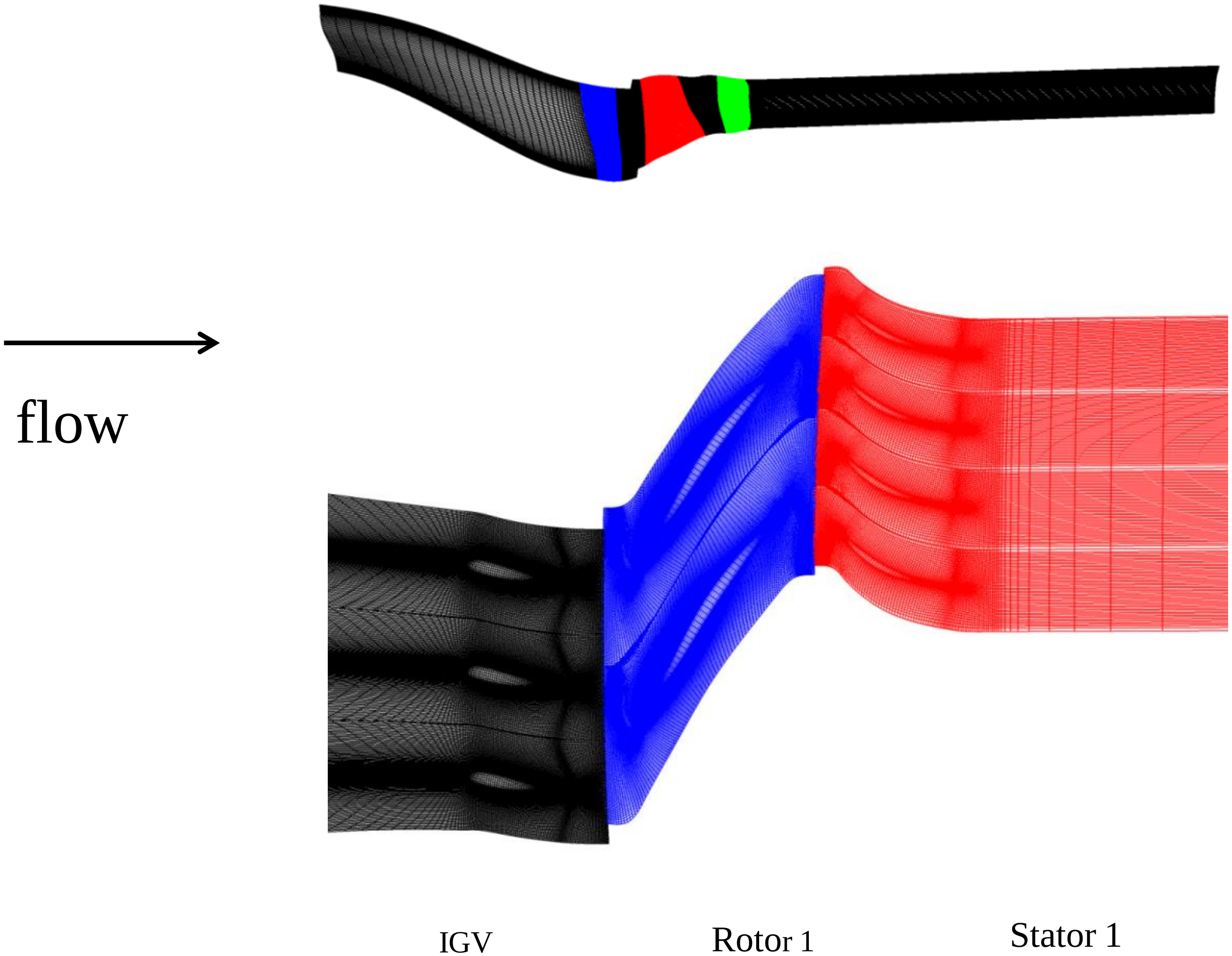
LES Set-Up



- Original Blades : 42 IGV, 28 R1, and 58 S1.

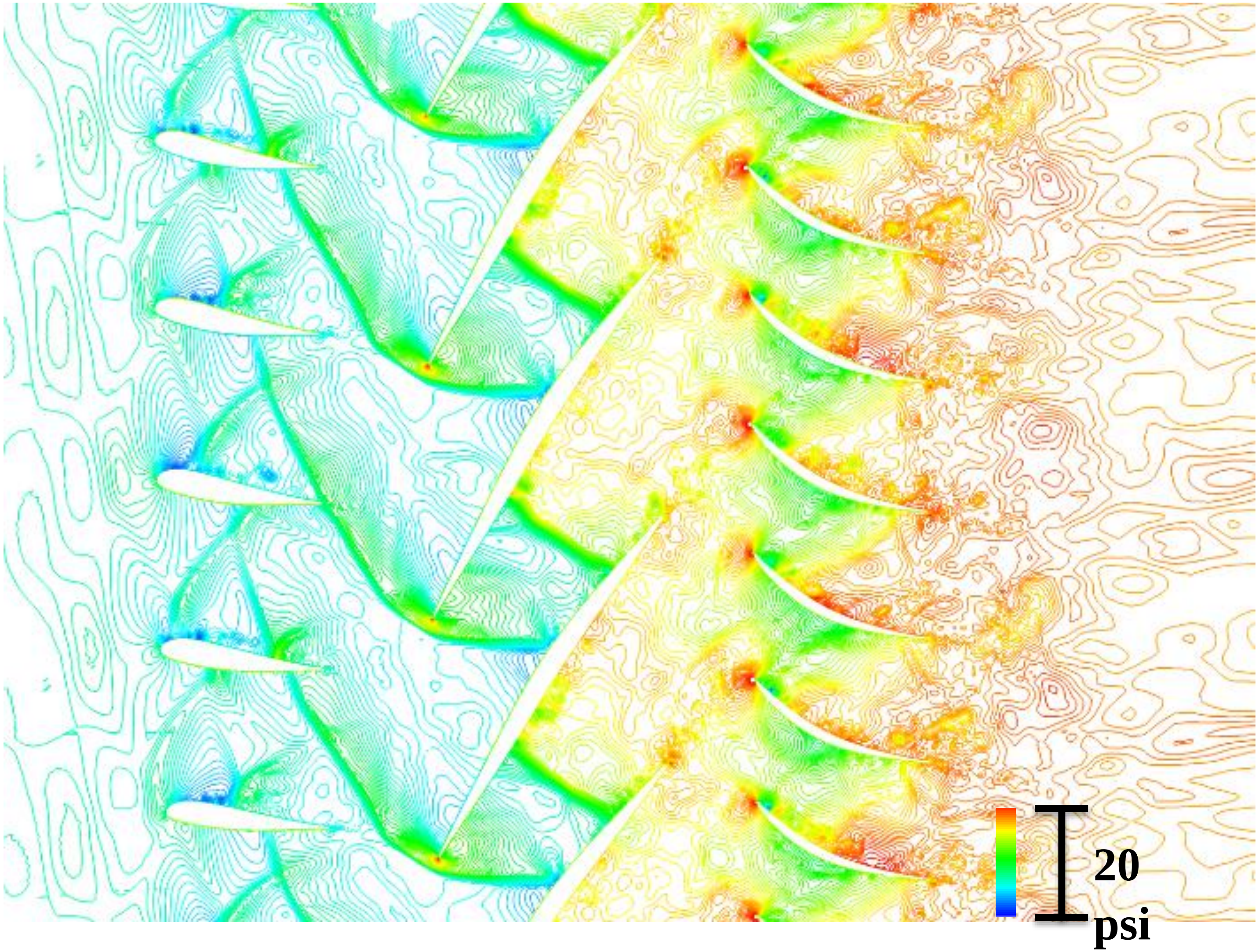
  Scaled to 42 IGV, 28 R1, and 56S1.
- 3 IGV , 2 R1 , and 4 S1 passages analyzed with periodicity condition.
- 500 million CFD nodes for 9 passages (for S1, 384x356x650 in B to B, Spanwise, axial direction for each passage)

Computational grid and domain

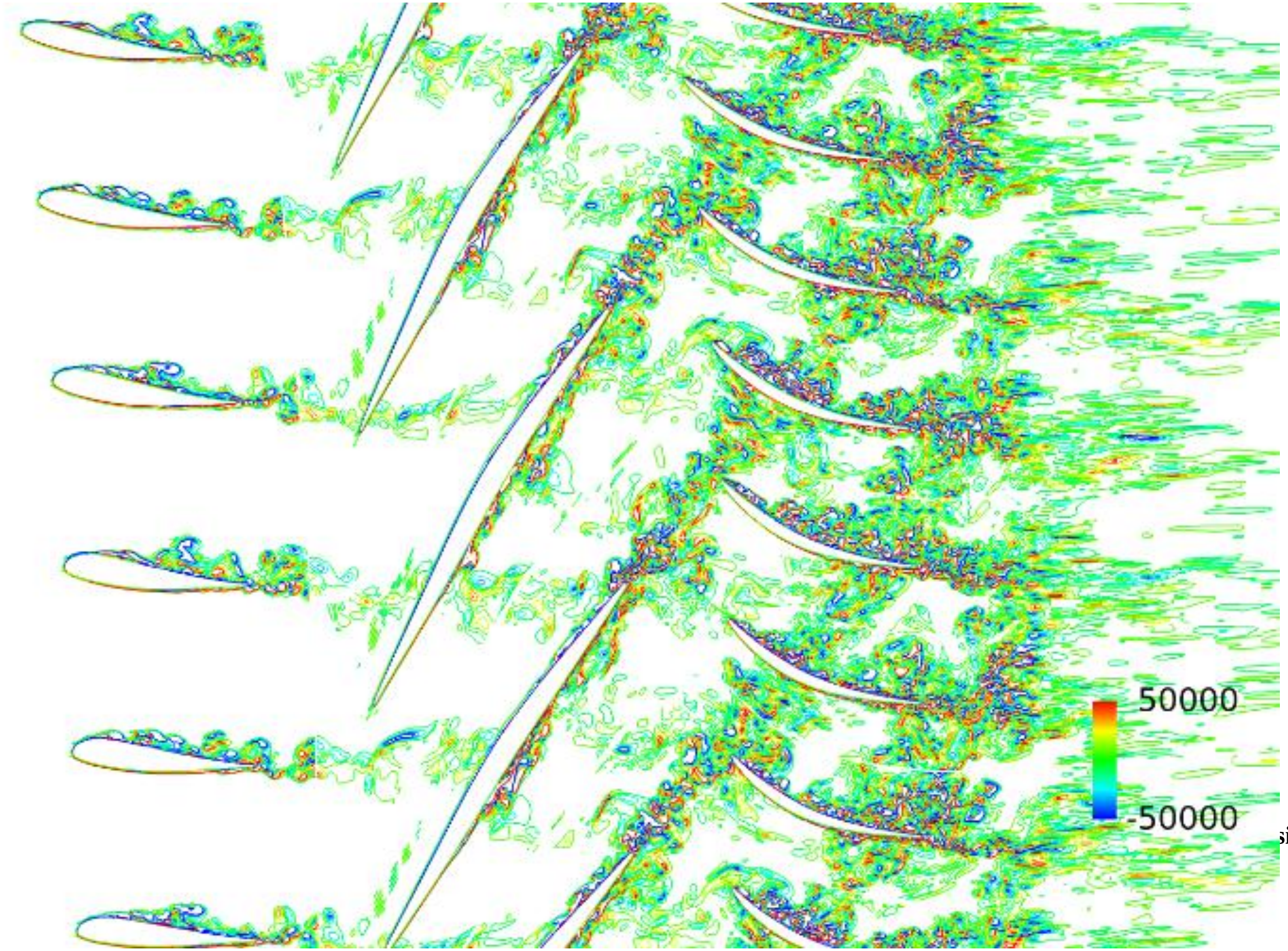


Overall compressor flow field from LES

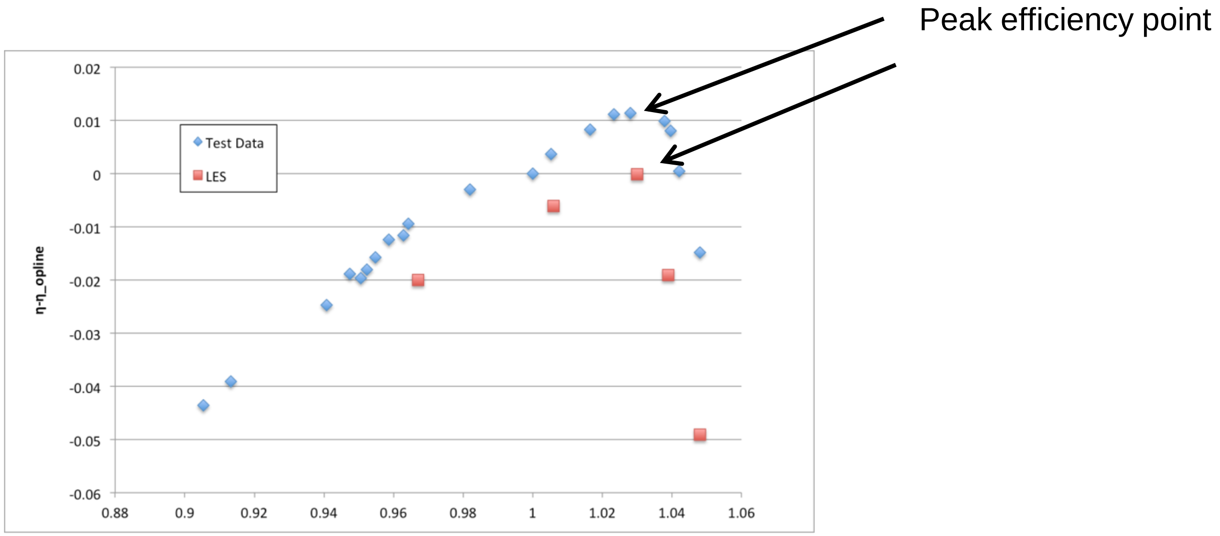
Instantaneous pressure distribution at mid-span

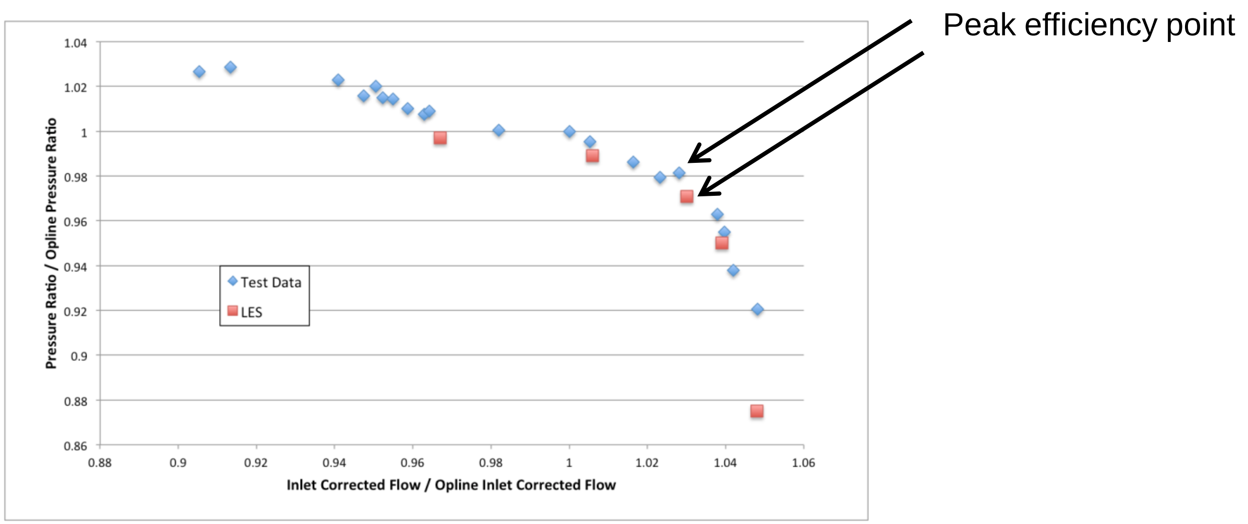


Instantaneous vorticity distribution at mid-span

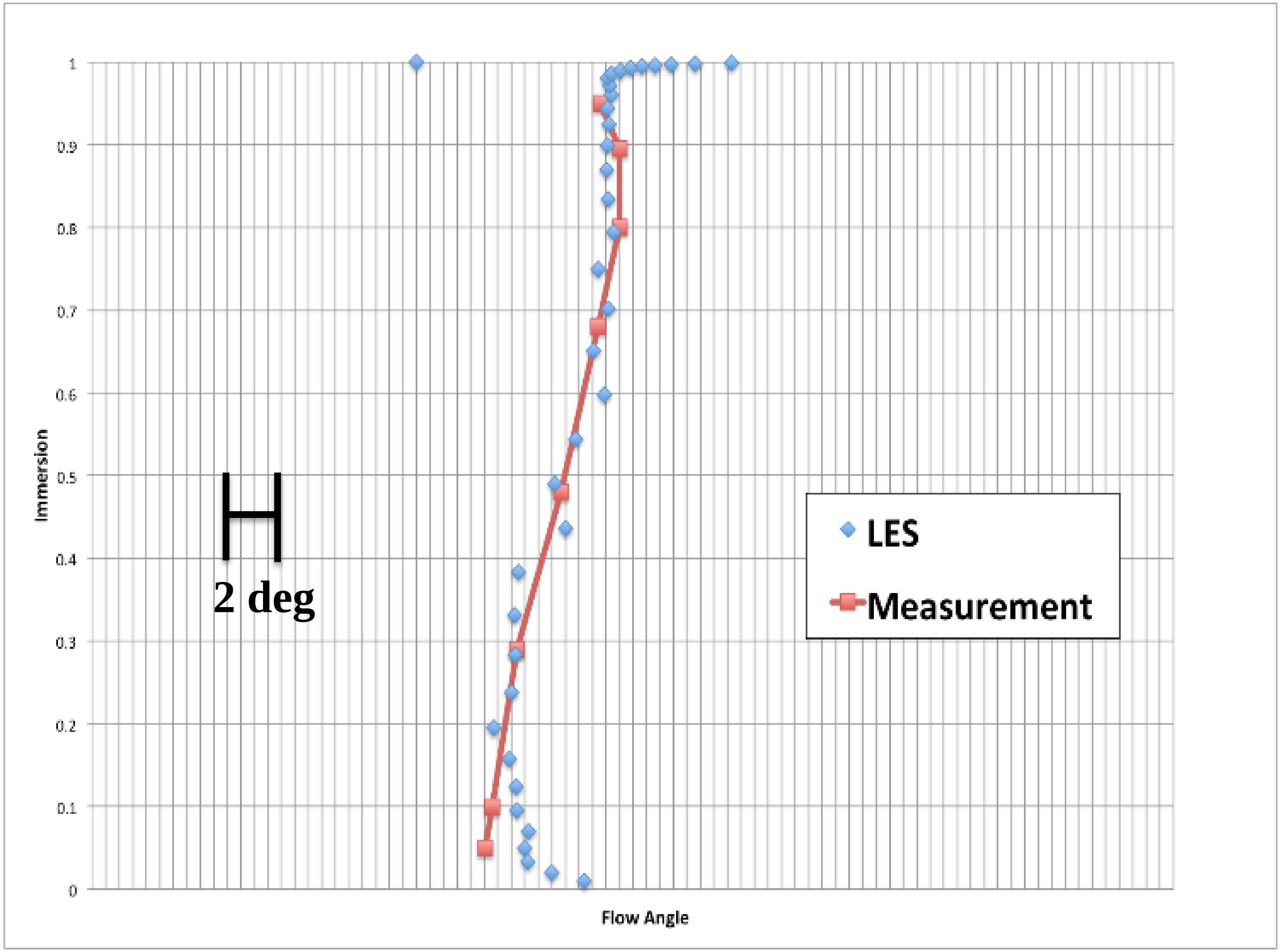


Comparison of corrected speedline relative to multi-stage compressor opline

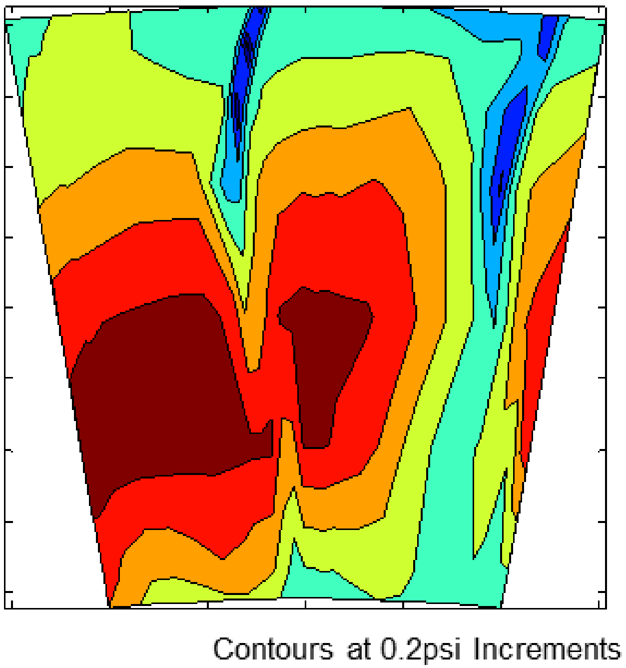




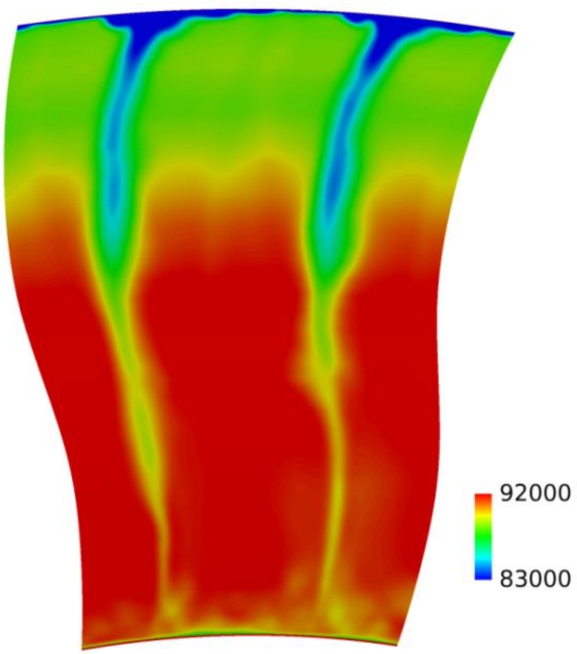
Comparison of IGV exit swirl angle



Comparison of total pressure at IGV exit



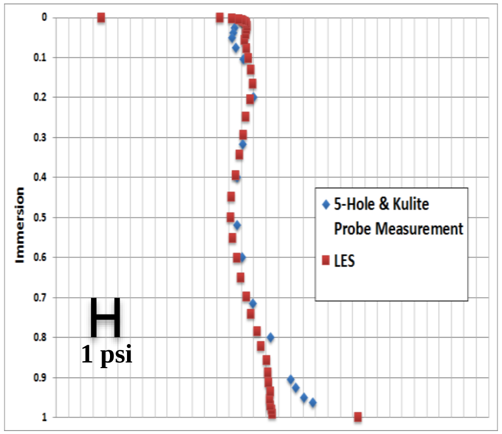
5-hole traverse



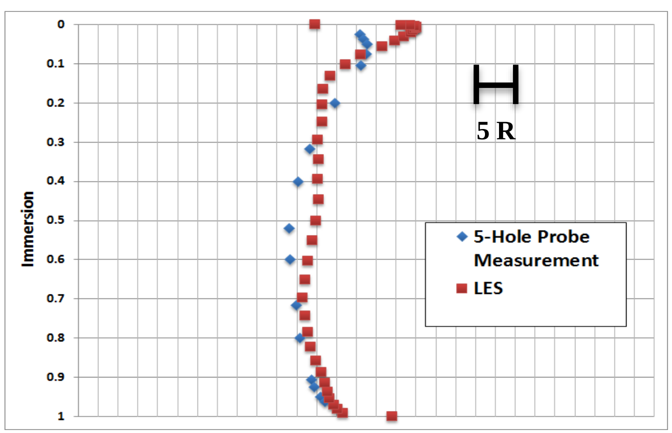
LES

Comparison of Pt and Tt at exit of R1 and S1

Pt

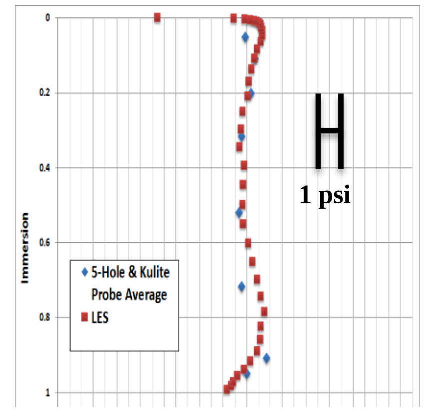


Tt

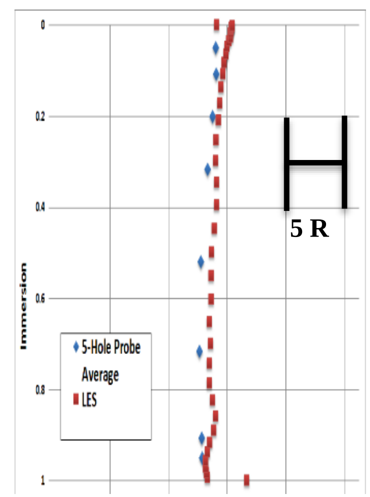


R1 exit

Pt



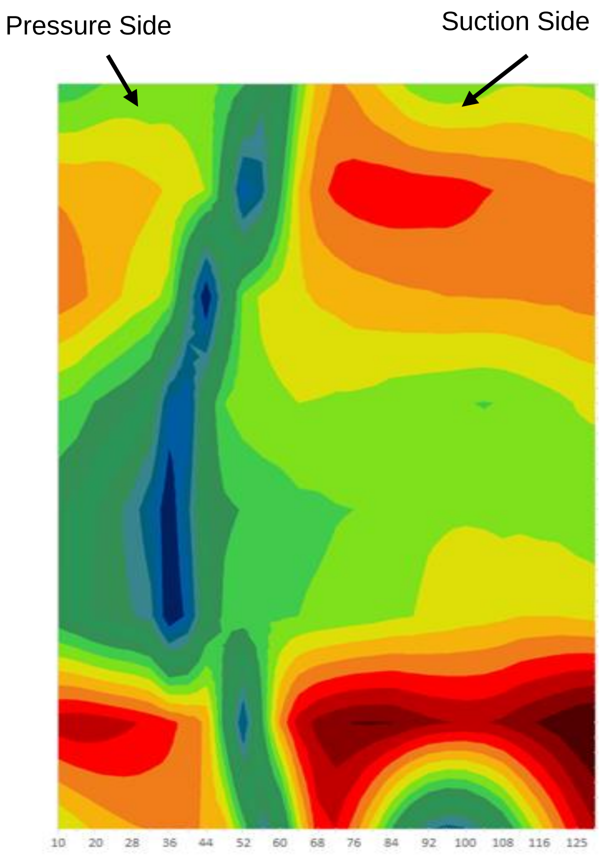
Tt



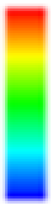
S1 exit

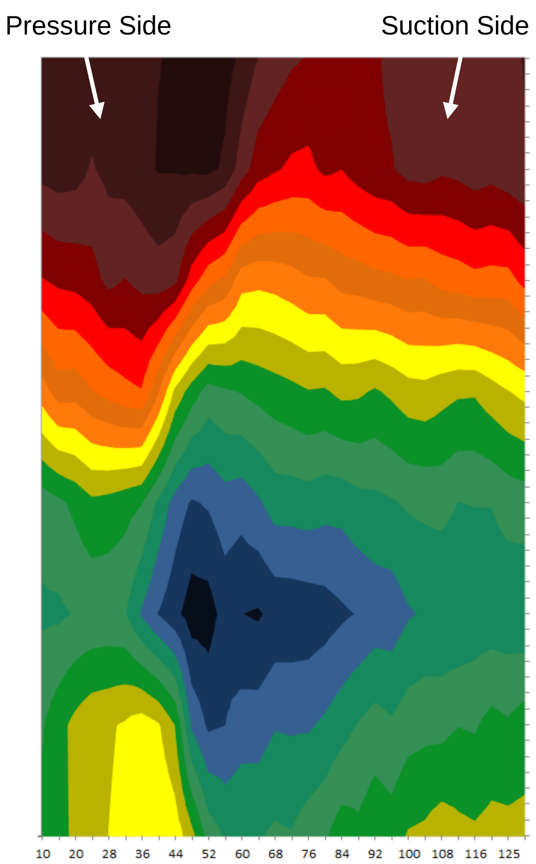
Unsteady loss generation in the stator due to incoming rotor wake

Measured Pt and Tt at stator exit



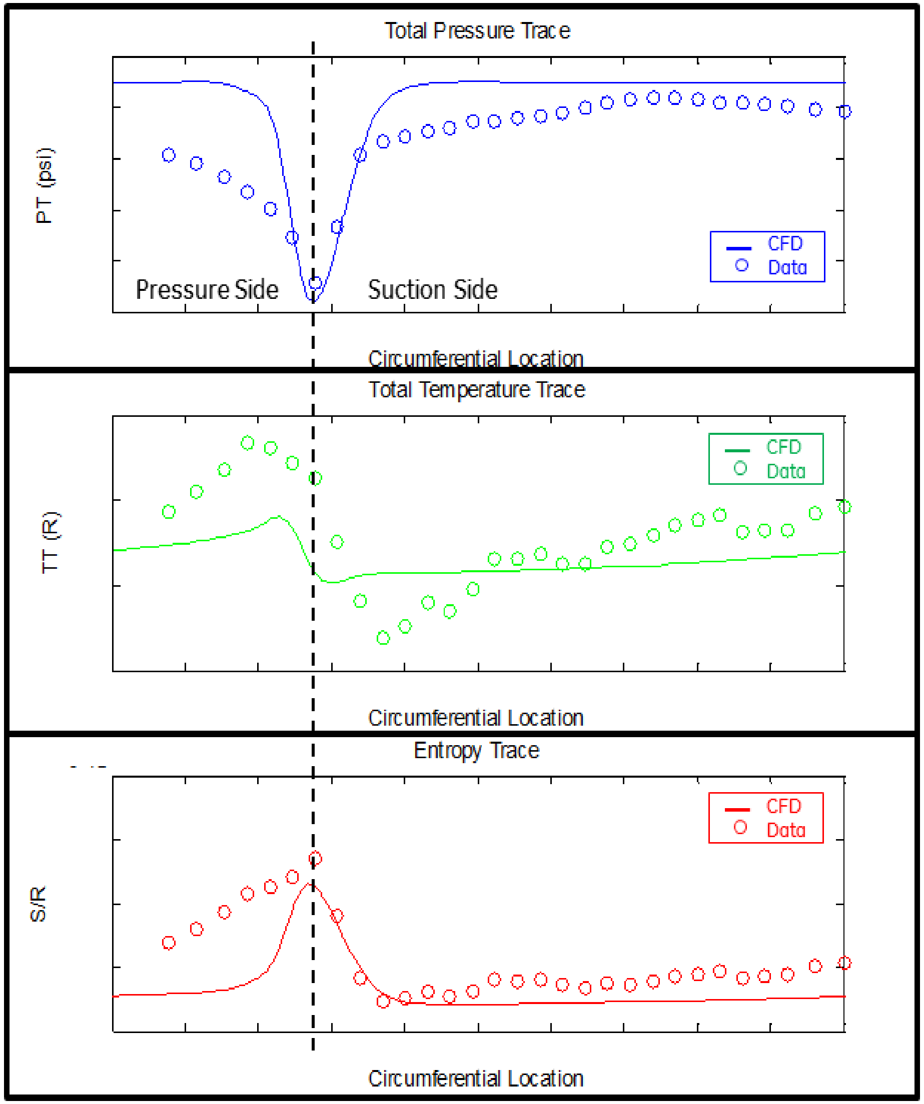
Pt



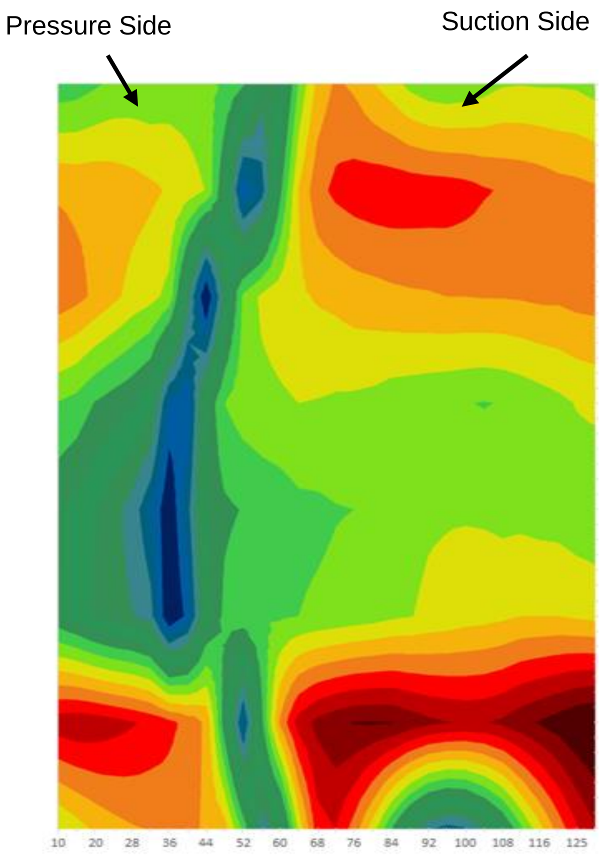


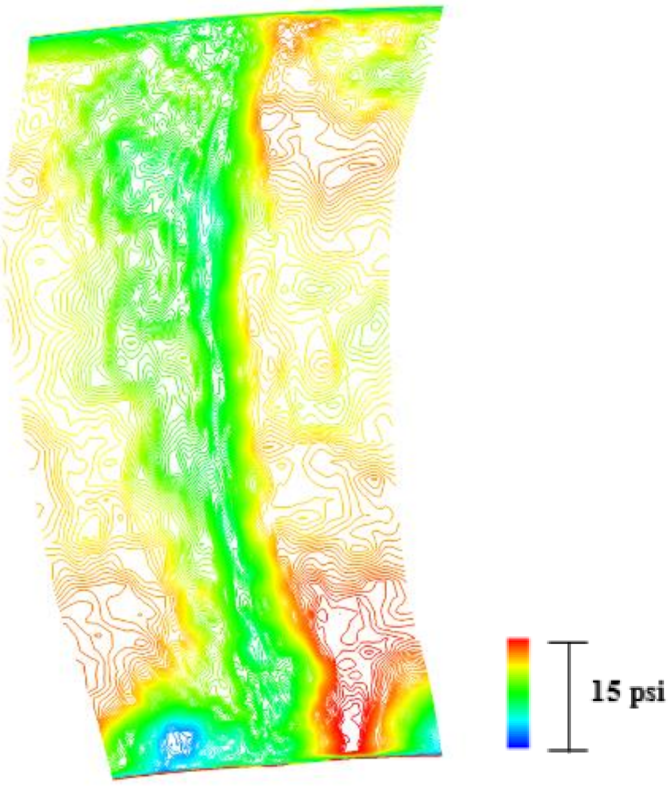
Tt

Measured Pt, Tt, and entropy at 48.1 % span (Lurie and Breeze-Stringfellow[GT2015-42526])



Comparison of Pt from LES, S1 exit

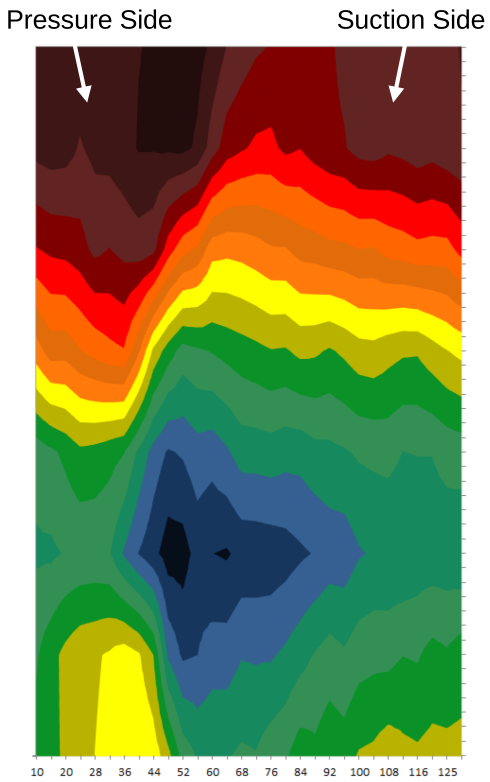


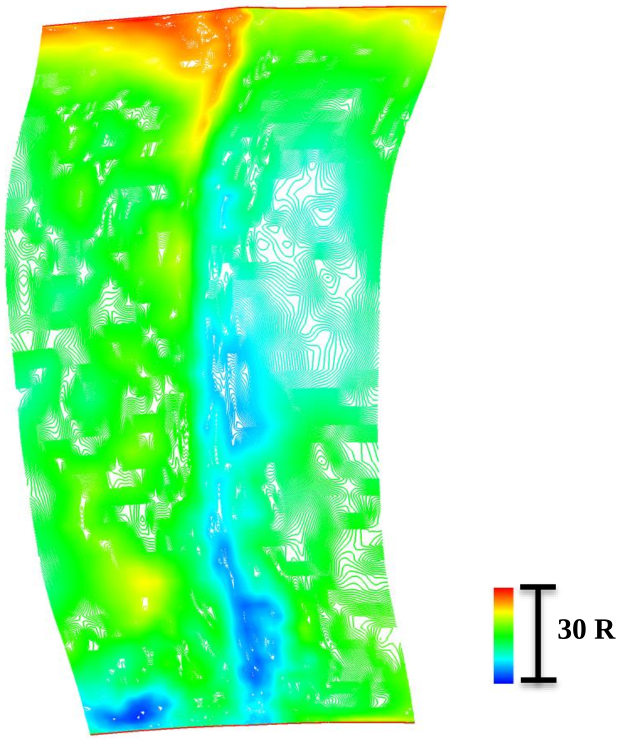


Five hole probe

LES

Comparison of Tt from LES, S1 exit

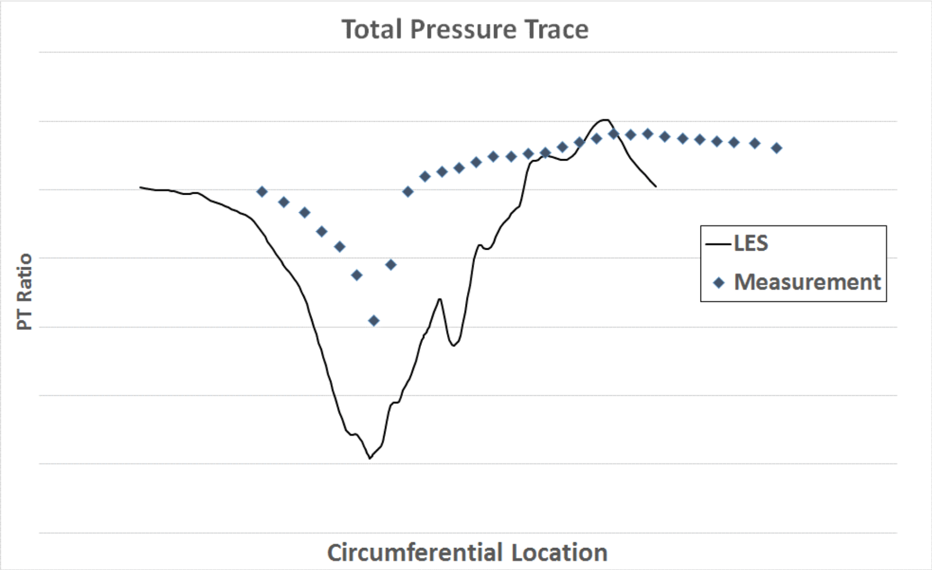


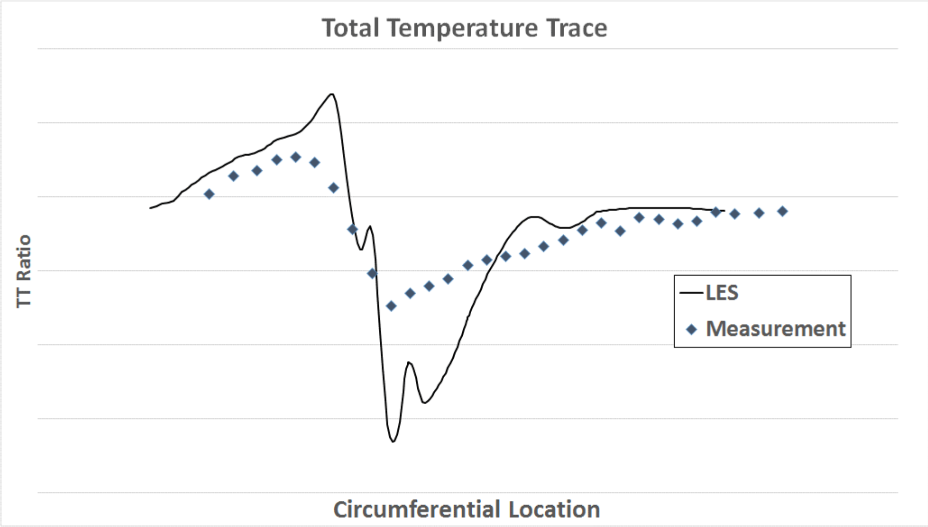


Measurement

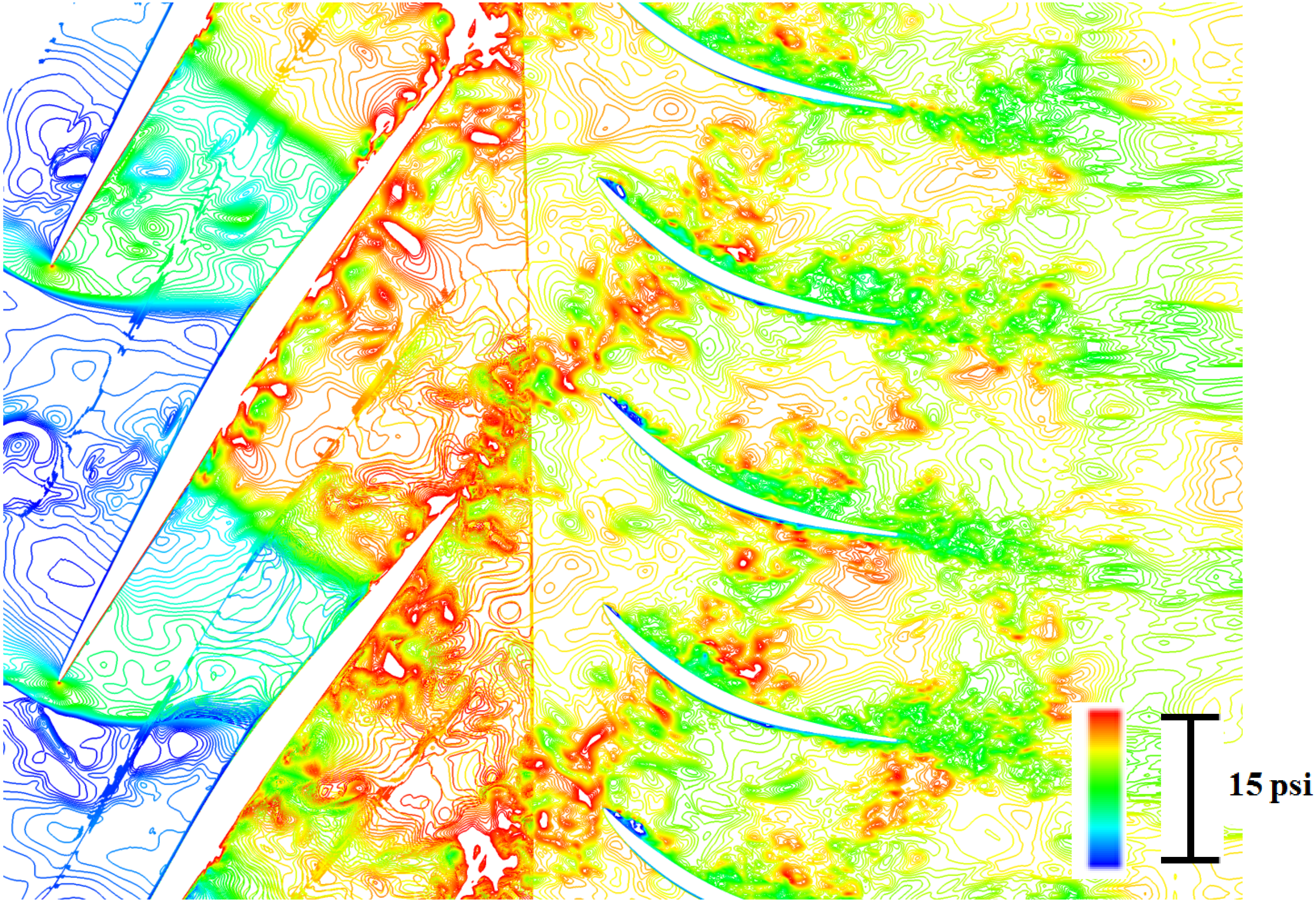
LES

Comparison of Pt and Tt at mid-span

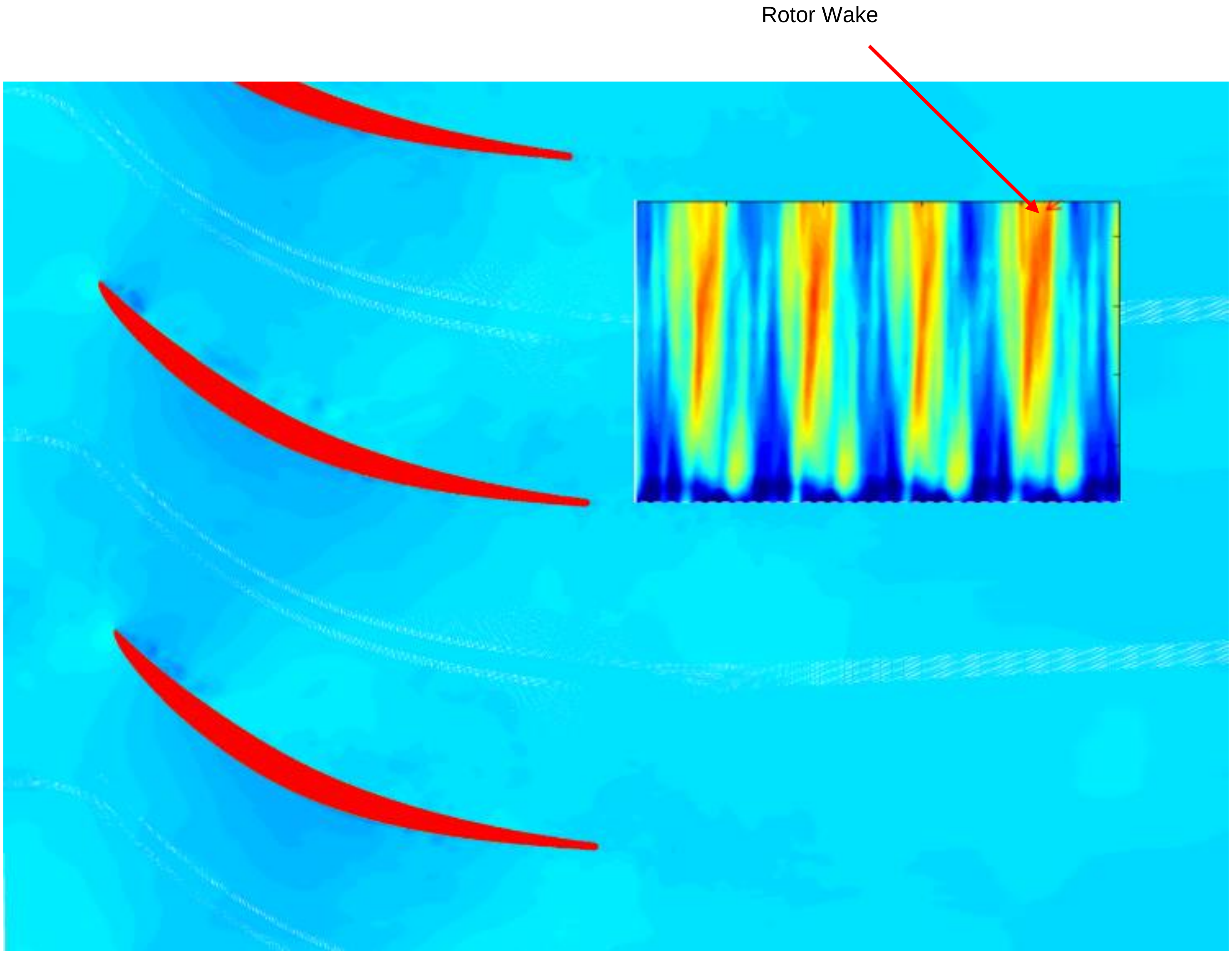




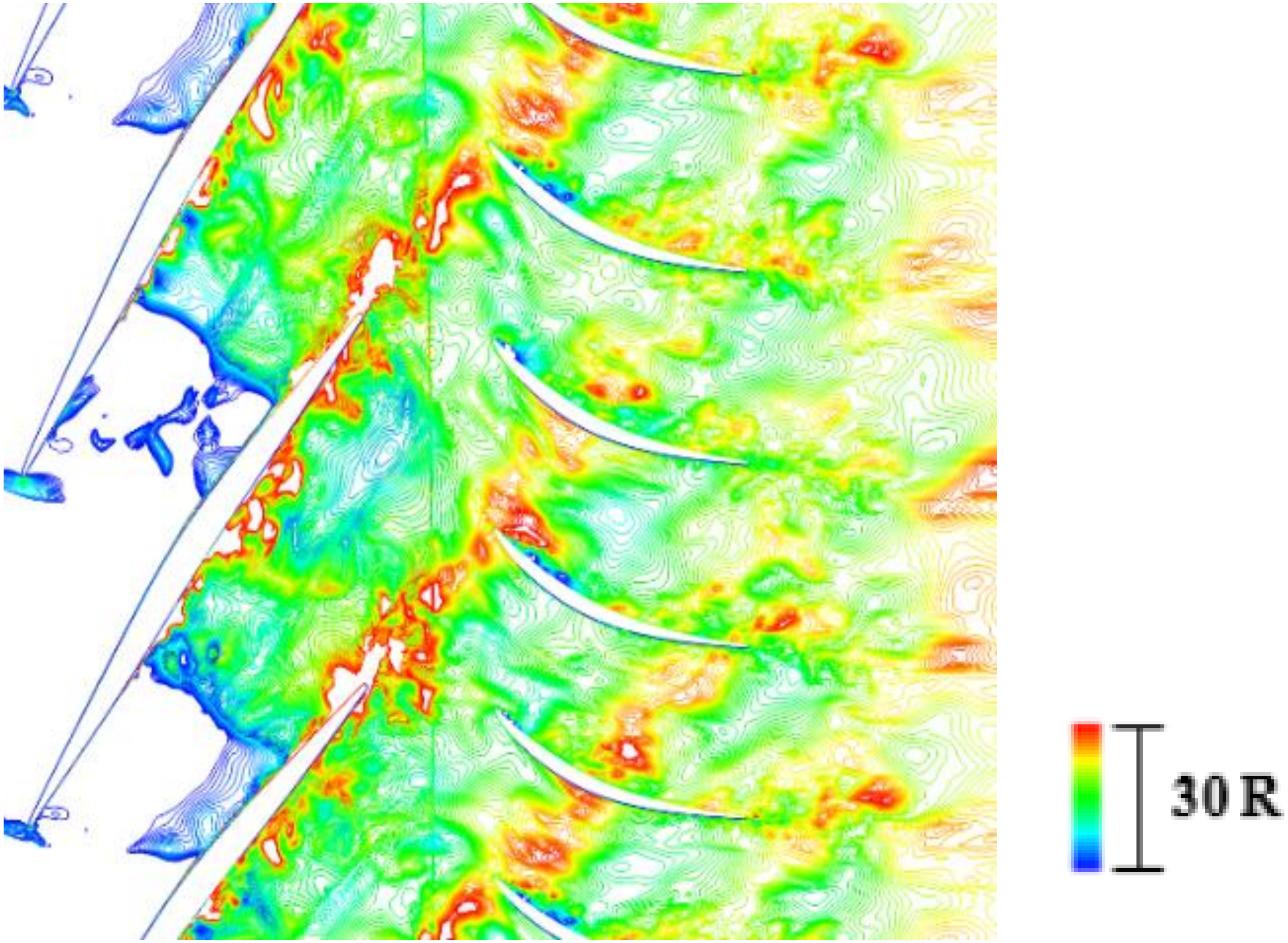
Instantaneous distribution of Pt from LES



Pt time-space plot at S1 exit



Instantaneous distribution of Tt from LES



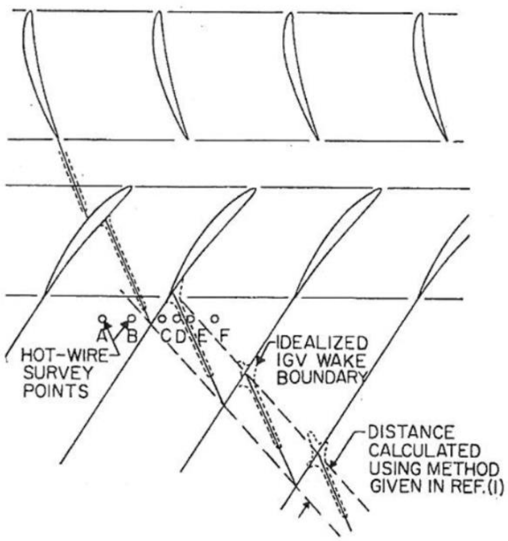
Why higher Tt and lower Pt on the pressure side of the stator ?

Why URANS does not pick up this trend ?
Why LES shows the correct trend ?

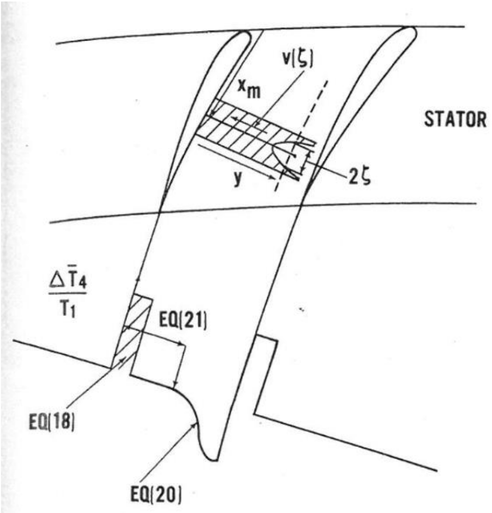
Flow mechanism for unsteady loss generation

Loss generation in multi-stage compressors

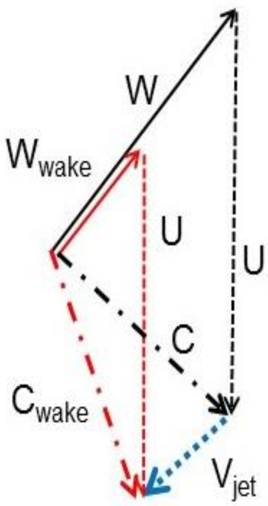
Smith, L.H. Jr. : Wake Dispersion, 1966.

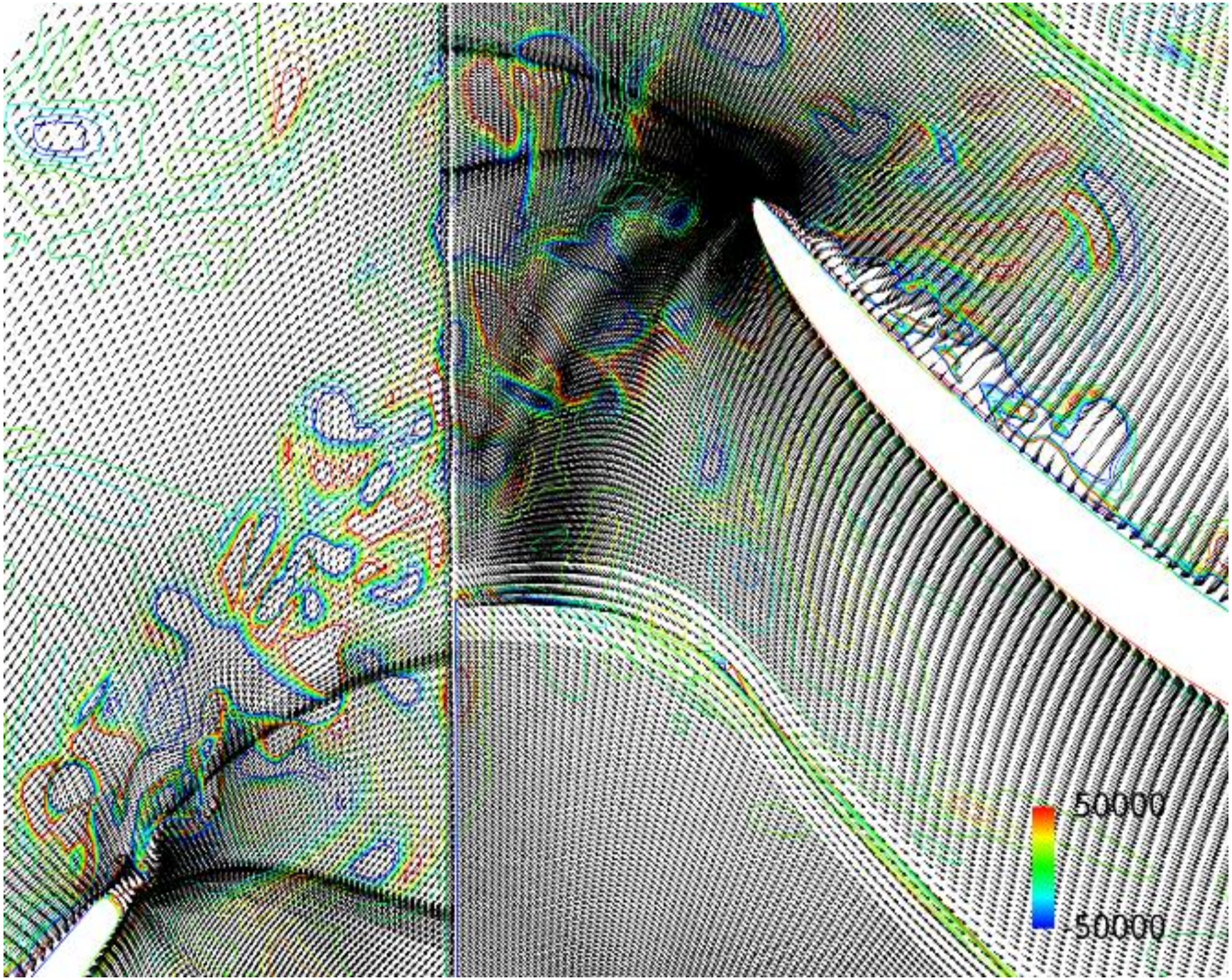


Kerrebrock, J.L. and Mikolajczk, A.A. :
Intra-Stator transport of rotor wakes, 1970

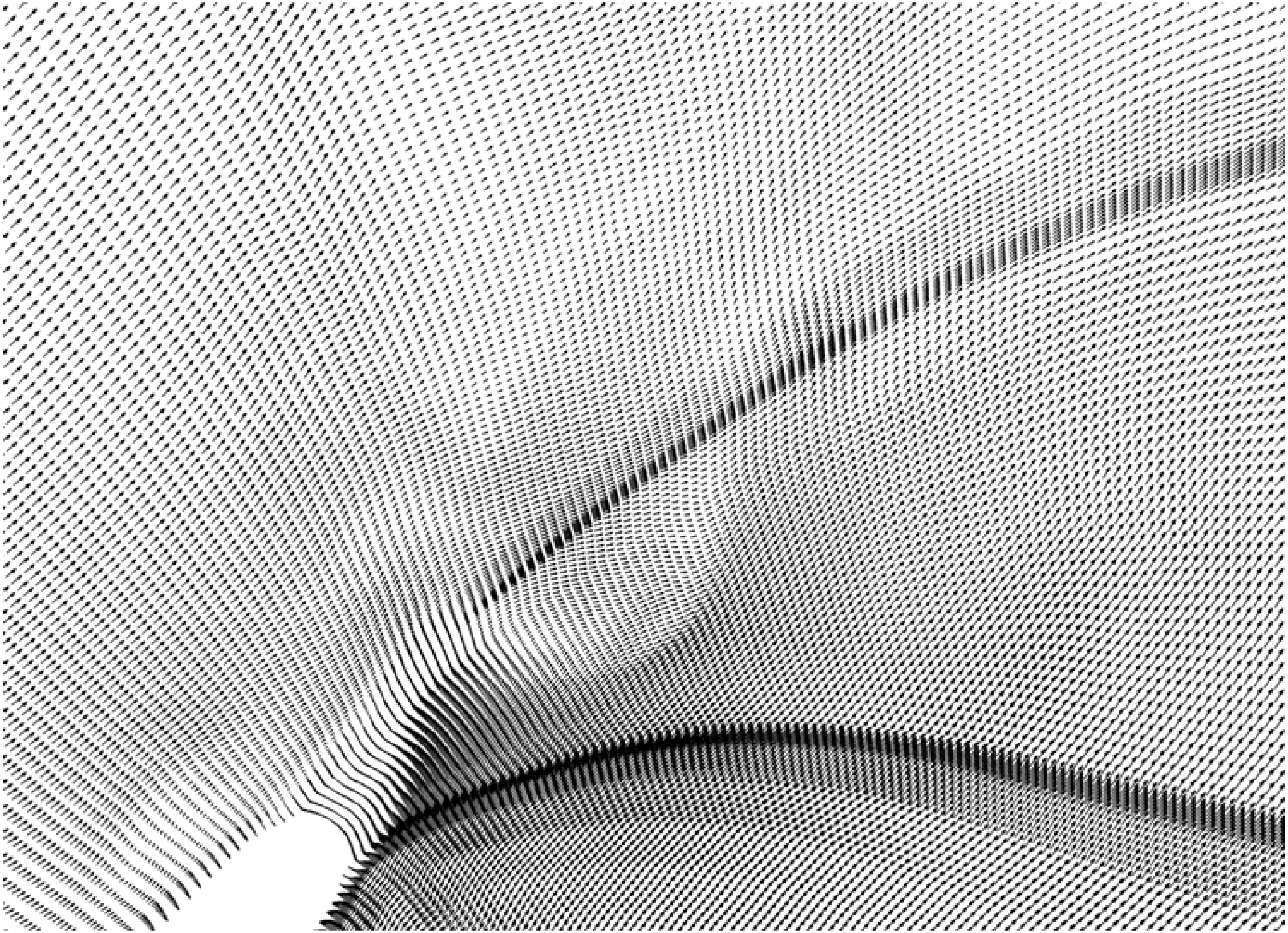


Instantaneous velocity vectors at mid-span

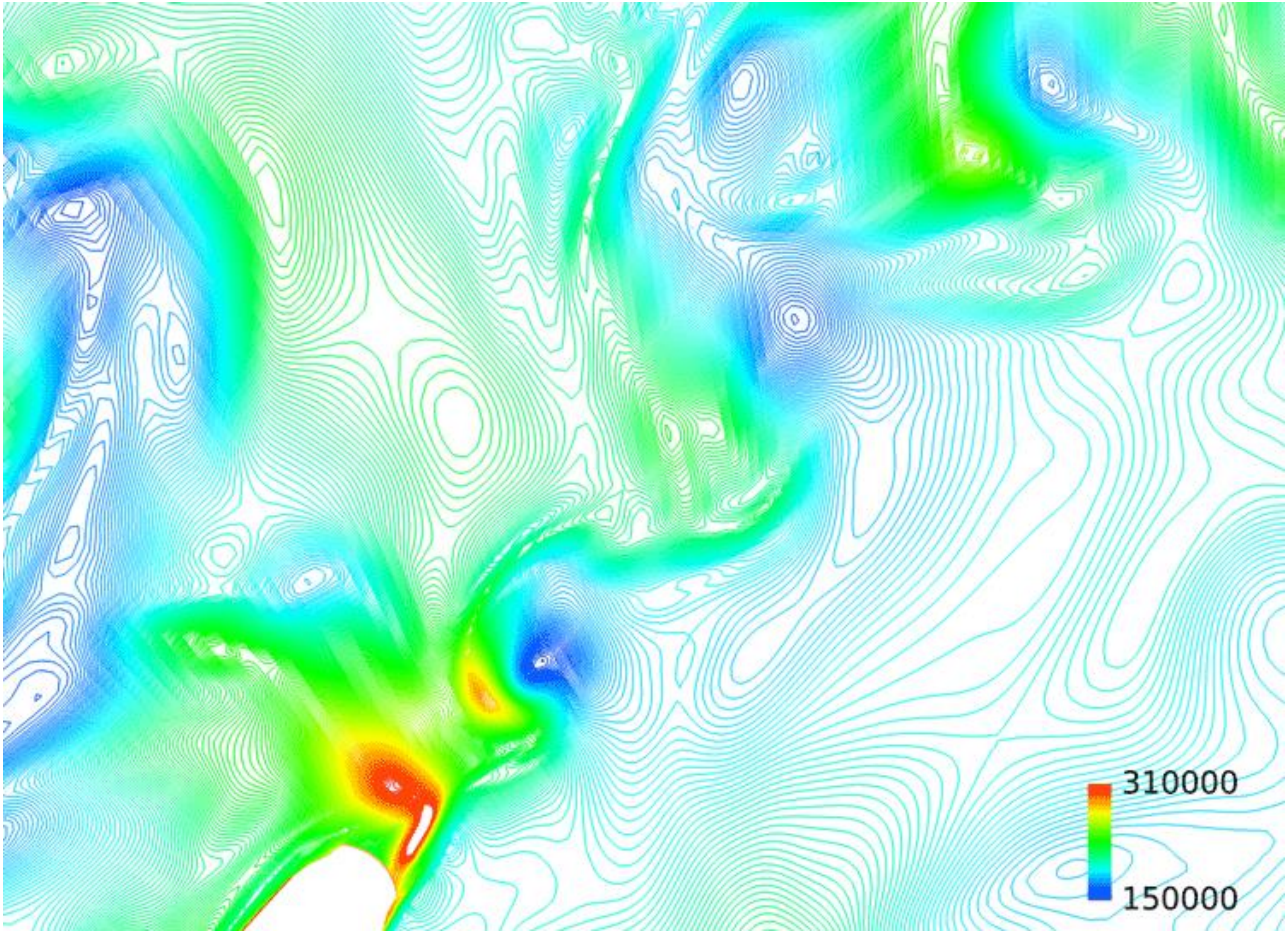




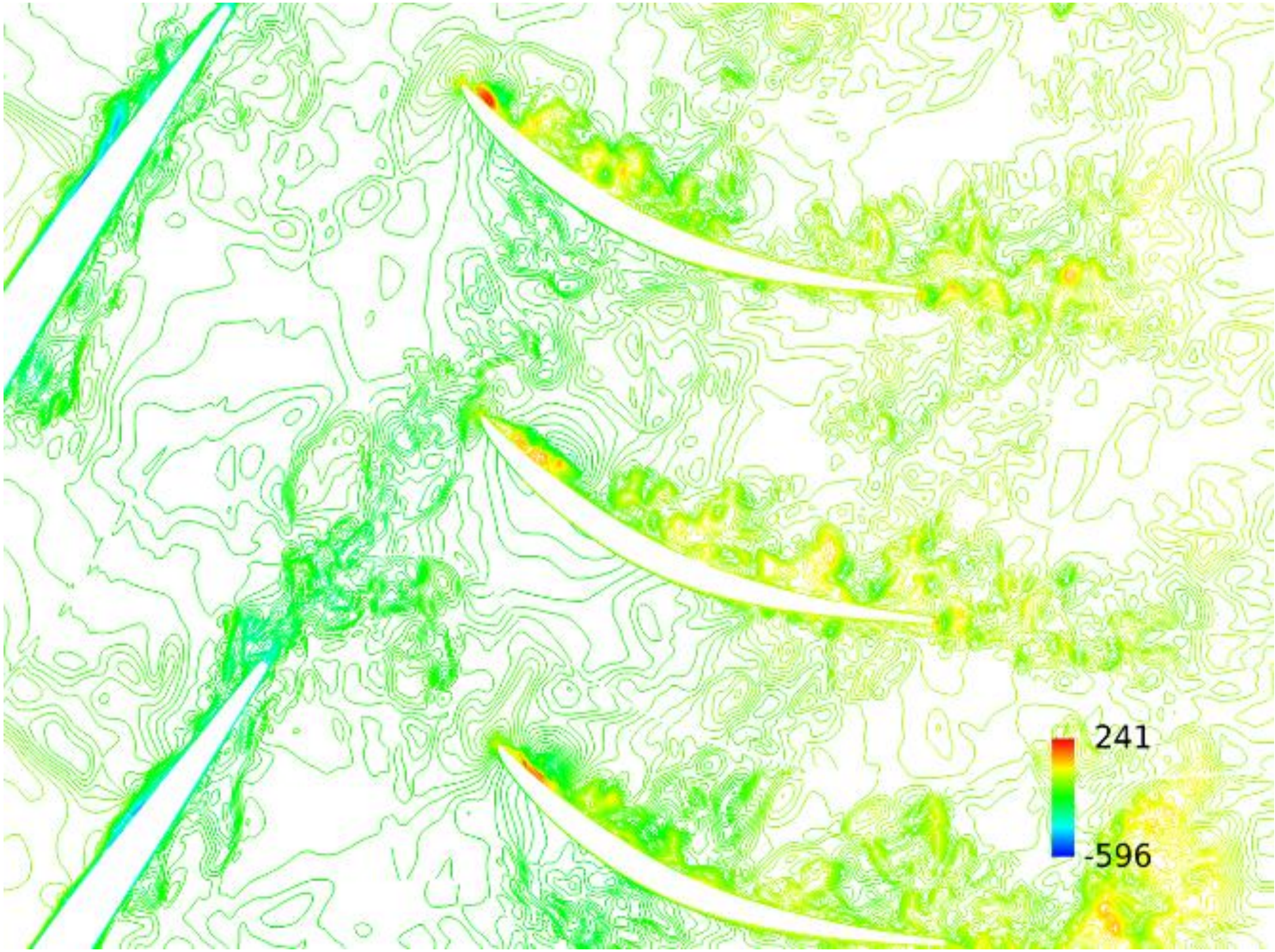
Velocity vectors in rotor wake



Absolute Pt in the rotor wake



Instantaneous tangential velocity component in stator frame



Intra-stator transport of rotor wake for high Tt on PS

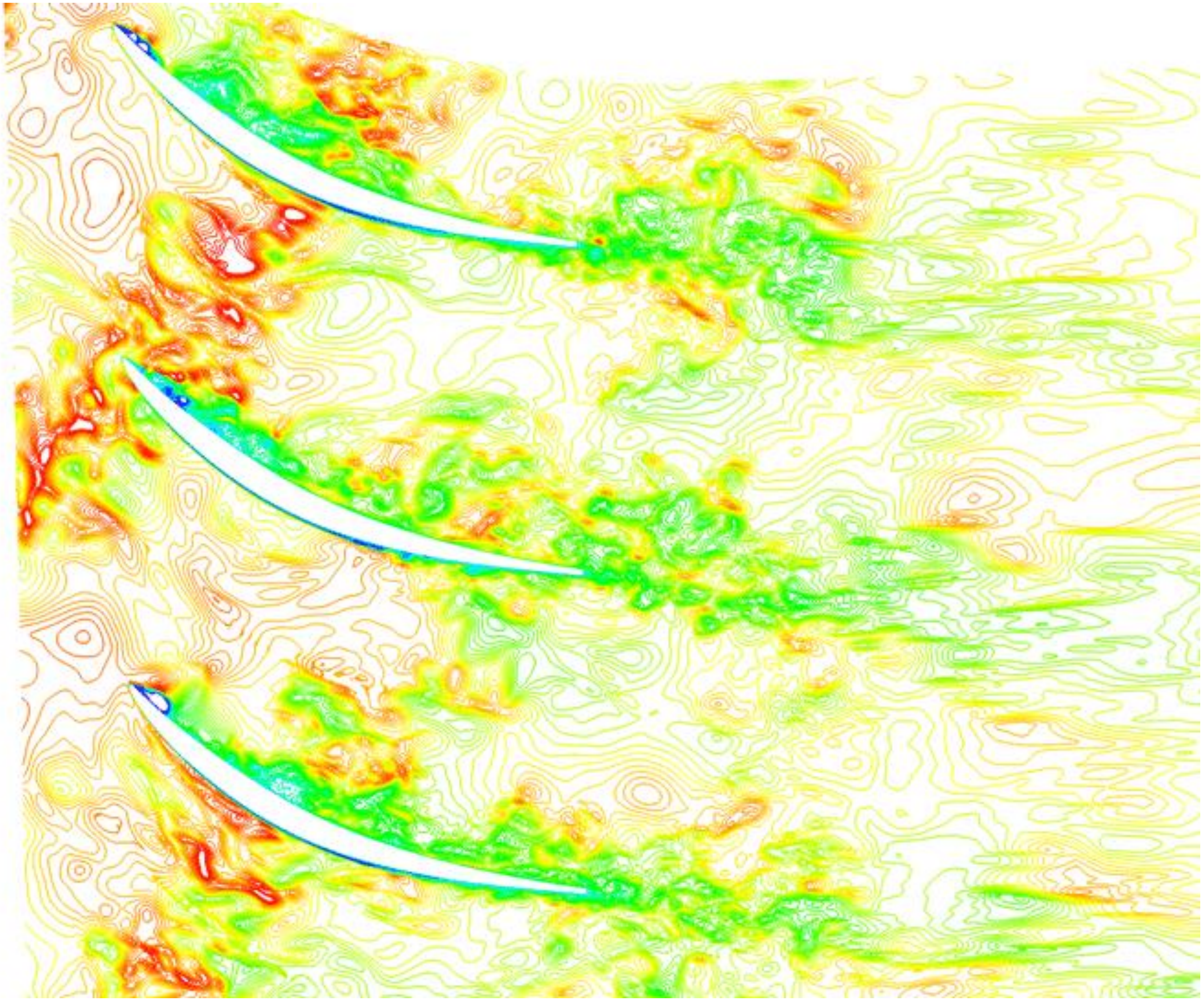
Both Tt and Pt are higher in rotor wake for the current compressor.

Jet velocity in the rotor wake decays very fast and The rotor wake is not like 2-D inviscid wake.

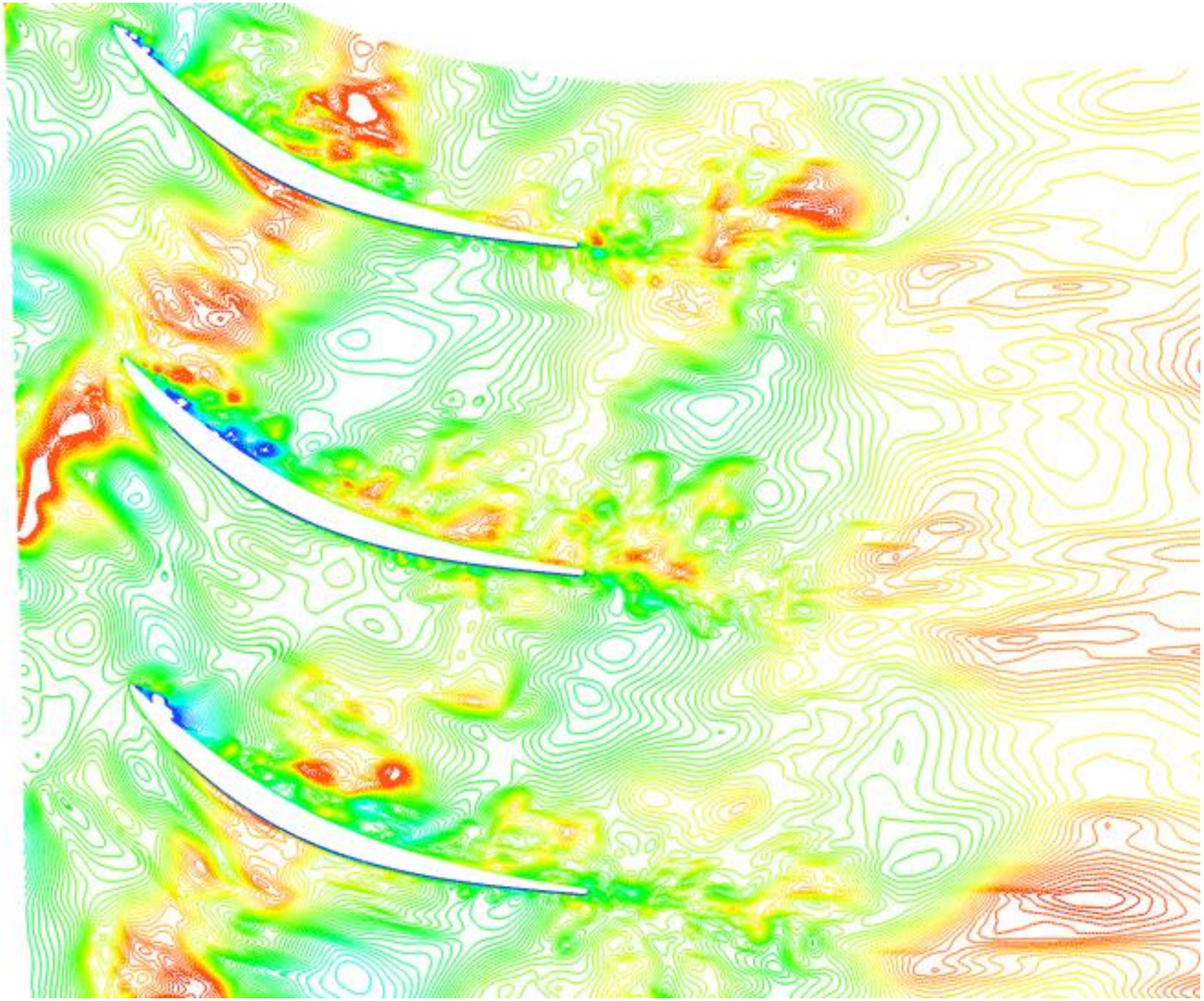
What makes Tt higher on pressure side of S1 ?

Why Pt is lower on pressure side of S1 ?

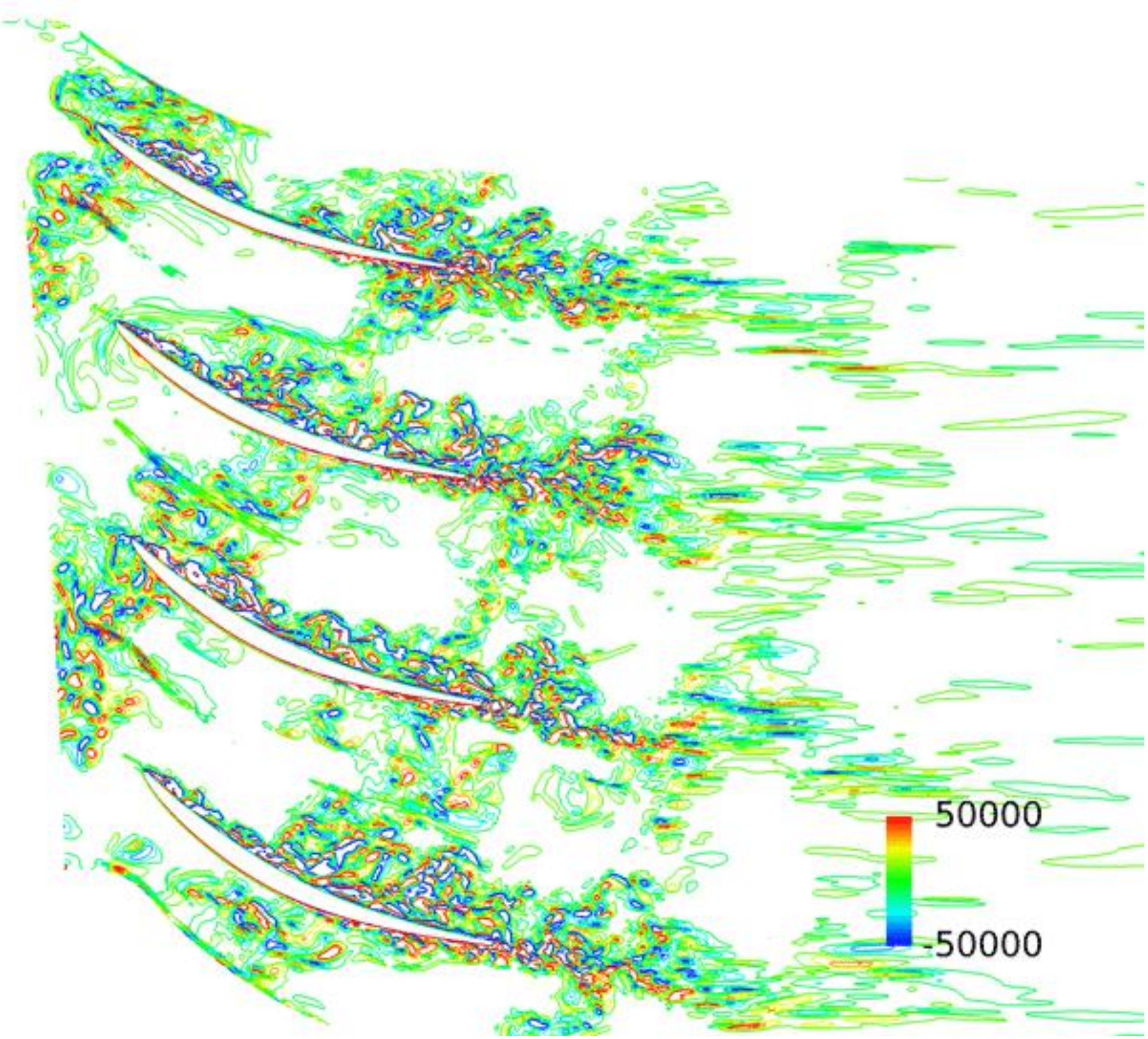
Changes of Pt inside the S1



Changes of Tt inside the S1



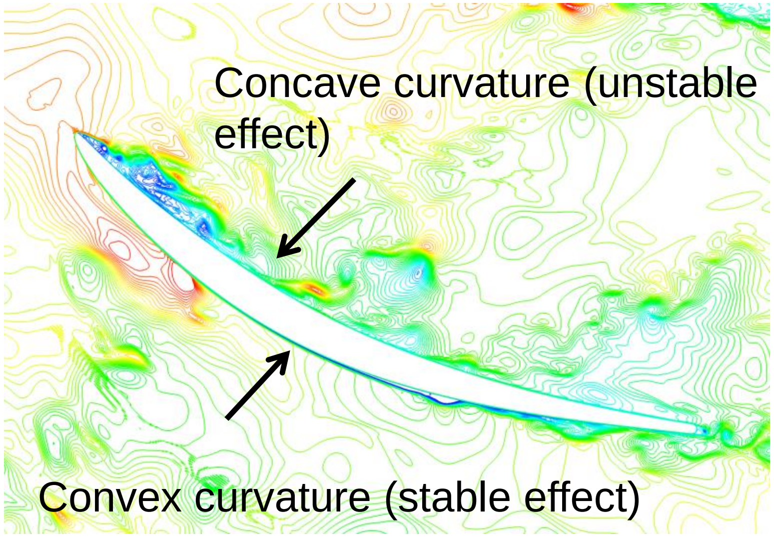
Changes of Vorticity inside the S1

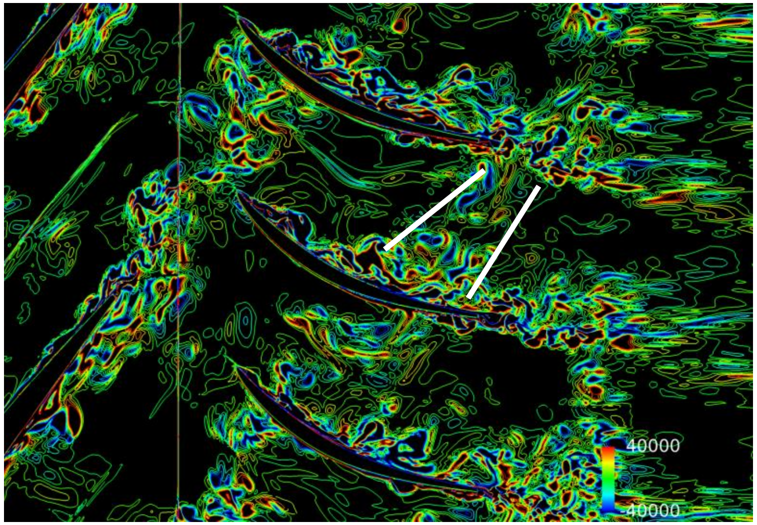


Possible mechanism of high Tt and low Pt (higher loss) on pressure side of S1

- Higher measured Tt at S1 exit might not be due to inviscid intra-stator transport of rotor wake for this compressor. (jet velocity decays fast, URANS does not calculate Higher Tt on PS).
- Different 3-D unsteady vortex interactions near SS and PS due to curvature effects.
- Wake stretching contributes wider rotor wake near the PS (higher Tt at S1 exit).

Mechanisms of unsteady loss generation





Curvature effects

Wake stretching

Concluding remarks

- Investigated unsteady loss generation in the stator passage due to incoming rotor wake.
- Three-dimensional unsteady vortex interaction seems to be the main reason for the high loss near the pressure side of the stator.
- Further focused experimental/analytical studies will lead to advanced designs.