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INVESTIGATION OF UNSTEADY TIP CLEARANCE FLOW IN A LOW-SPEED ONE AND HALF STAGE AXIAL COMPRESSOR WITH LES AND PIV

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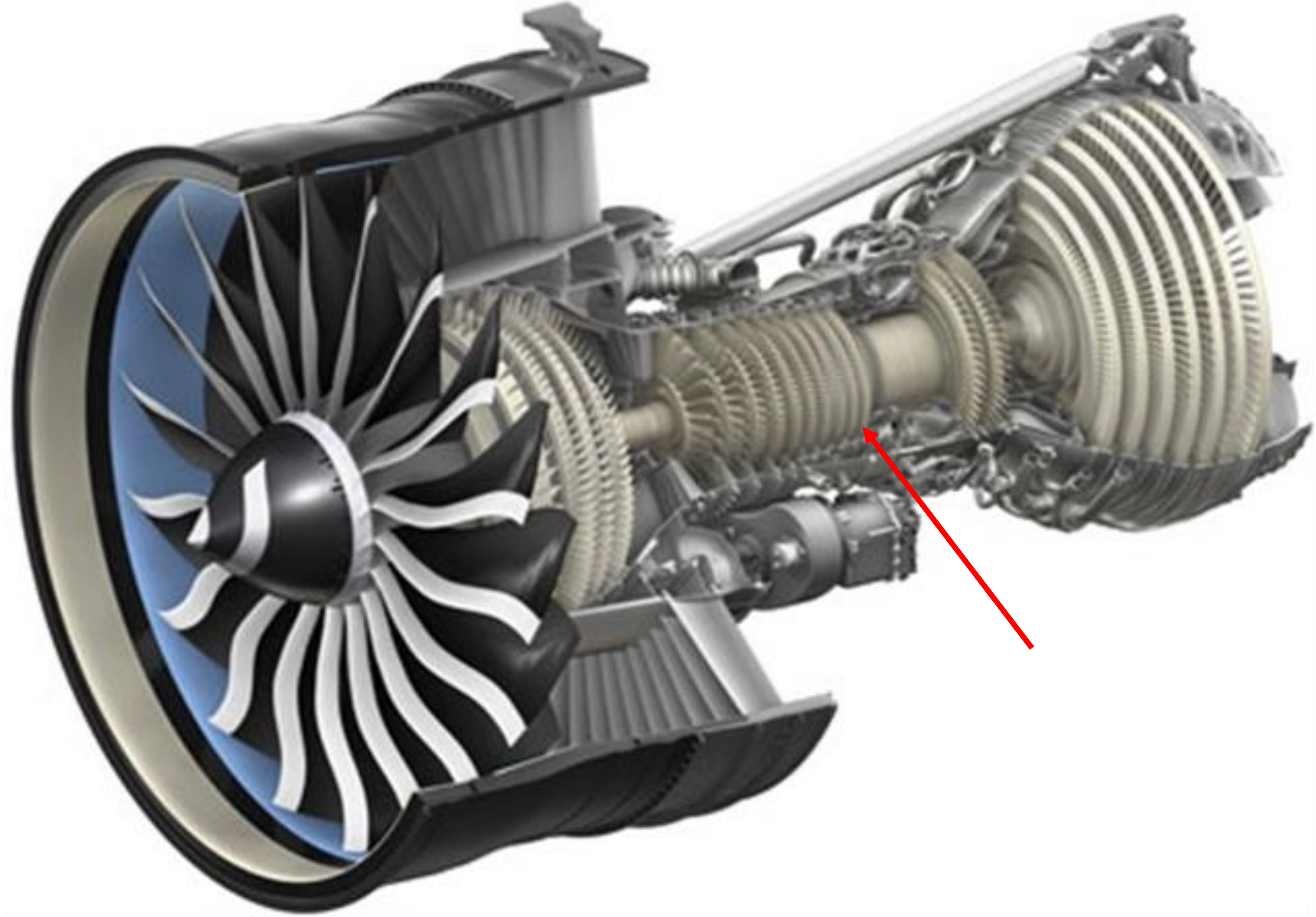


Background

- Large tip gap (3 – 5% of span) issue in rear stages of future small core engine.
  - Efficiency, flow range, possible blade vibration.
  - NASA NRA to study the flow and to develop strategies.

NASA's AATT NRA for compressor tip clearance flow (Johns Hopkins Univ.)

- Detailed unsteady PIV measurement of tip gap flow in the JHU's index matched facility (one and half stage).
- To understand effects of large tip gaps in small axial compressor rear stages.
- Numerical study with LES : NASA in-house effort.

Tip clearance flow in tubomachinery

- Traditionally handled as a steady flow; flow from pressure side of the blade to suction side of the blade across tip gap.
- Tip clearance flow is unsteady due to vortex shedding, tip vortex oscillation, blade interaction, etc. (sheet tip vortex is known as unstable).
- Unsteady characteristics are vital for flow instability, flow control, cavitation prediction.

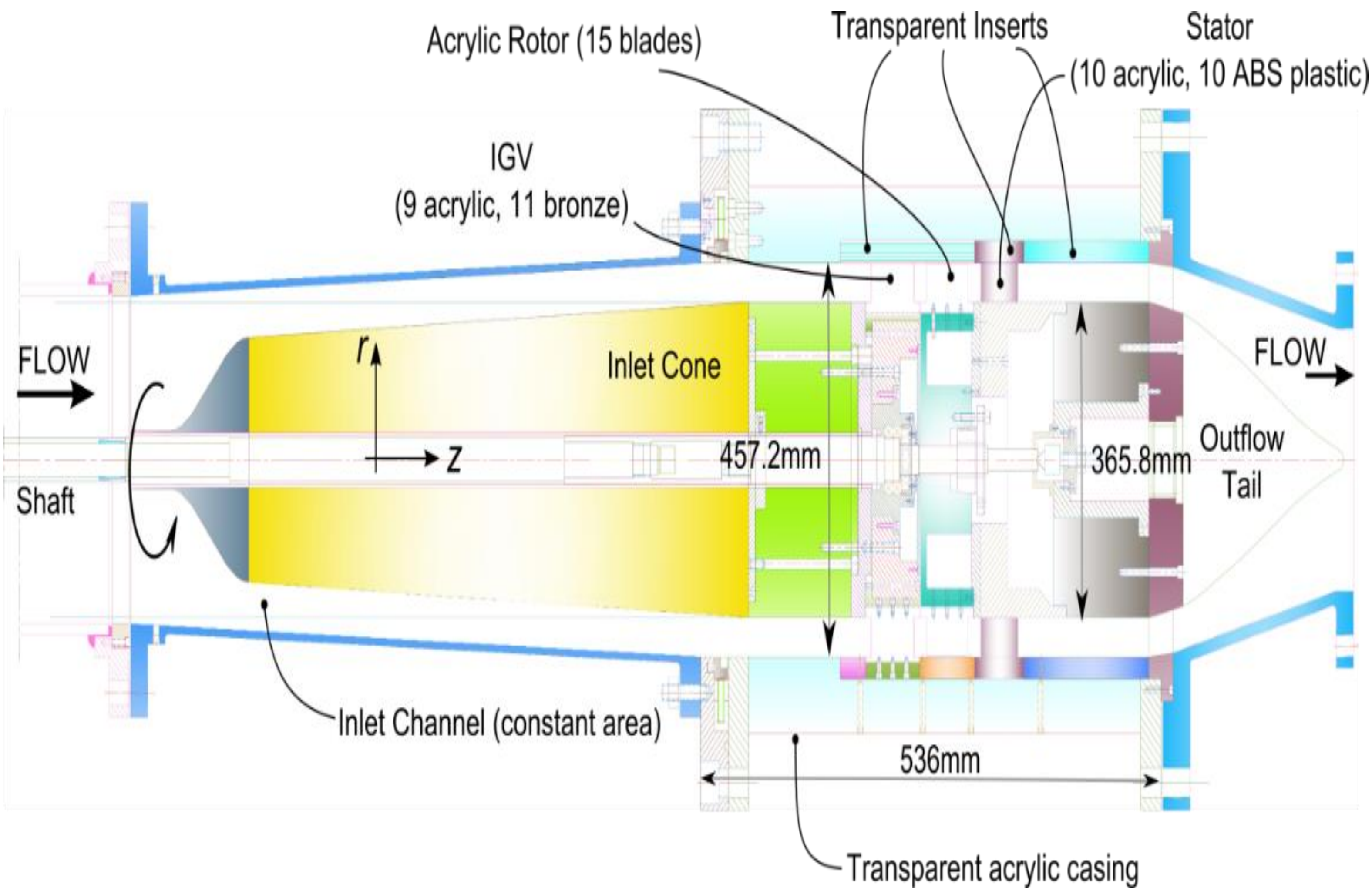
Objectives

1. Study of unsteady nature of tip clearance flow (tip vortex oscillation, instability vortex, vortex break down, non-synchronous blade vibration) with LES.
   - conducted in one and half stage low speed axial compressor with two tip gaps (0.5 & 2.3% tip chord)
   - 0.5 & 2.3% tip chord correspond 1.1 & 5.1 % span.
2. Comparison between PIV data and LES results.

Order of presentation

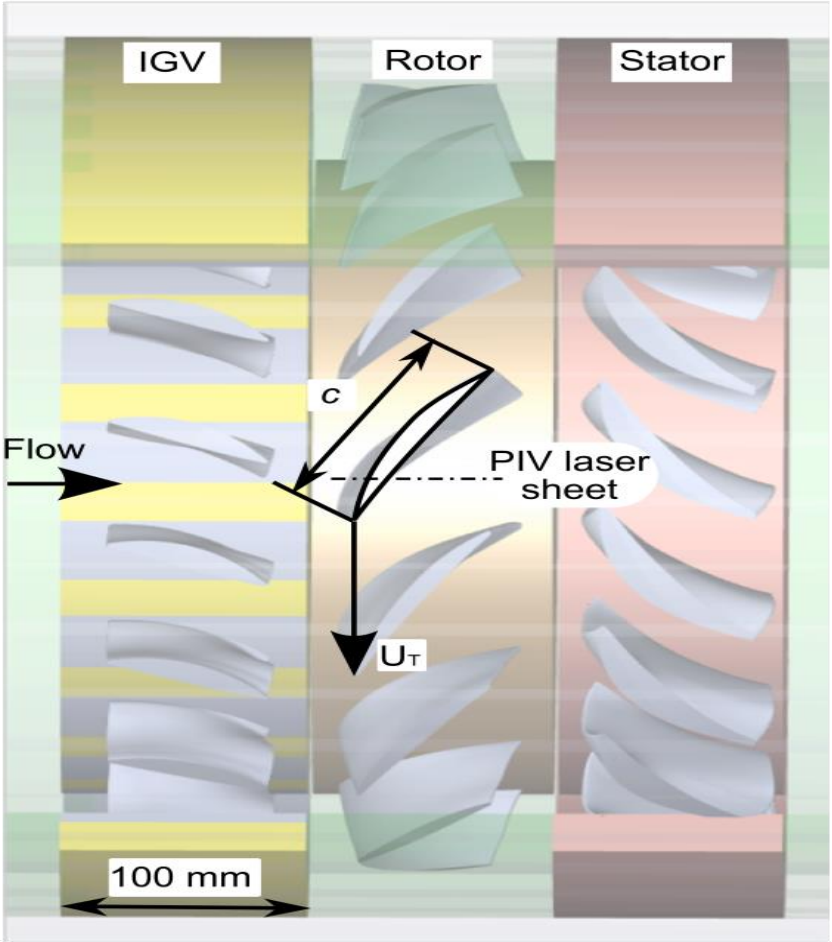
- One and half stage axial compressor test article scaled from the NASA research low speed axial compressor.
- Test rig and PIV setup at Johns Hopkins University.
- Detailed tip clearance flow investigation with PIV and LES.
- Observations and concluding remarks.

JHU test compressor cross section



New Facility - Images

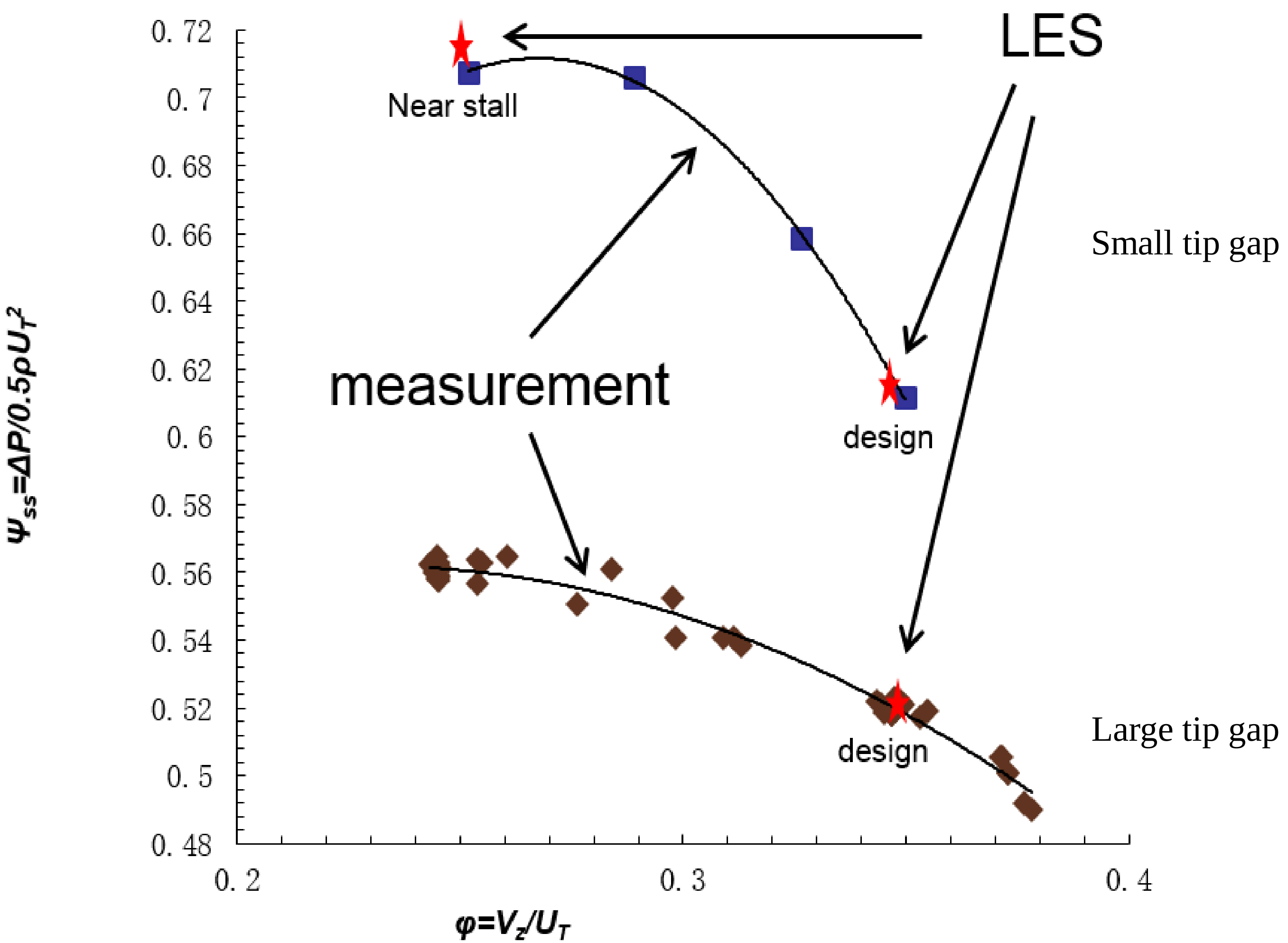
One and half stage axial compressor



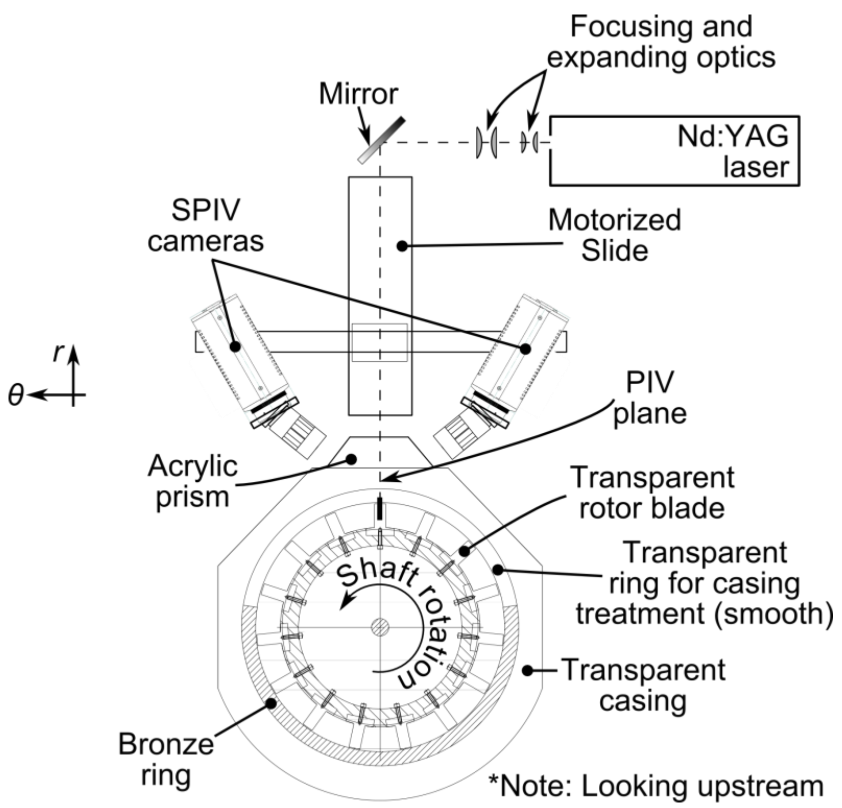
20 15 20

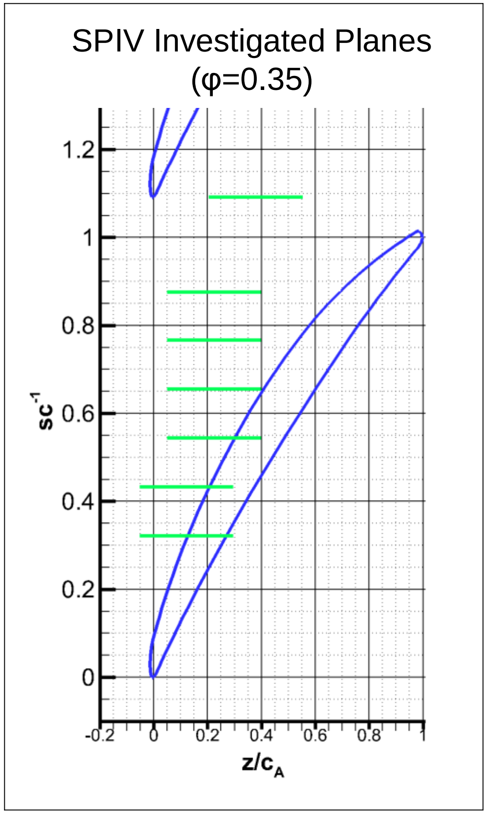
Number of blades

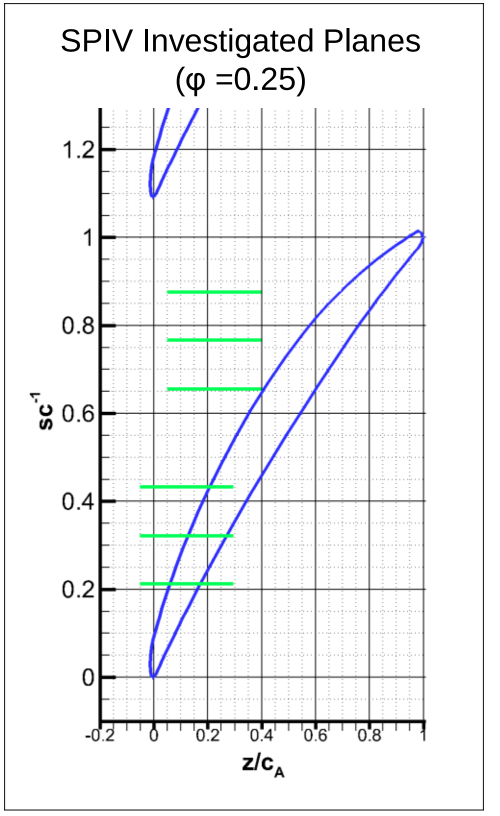
Pressure rise characteristics



Stereoscopic, Higher Resolution SPIV Measurements(GT2014-27195)







Stereoscopic PIV (2D-3C)

- Camera resolution: 2048 x 2048 pixels
- 532 nm Nd:YAG laser double pulsed at 20μs interval
- Field of view: 10.06×17.64 mm^2
- Vector map spatial resolution: 0.084mm
- 2500 realizations averaged at each location
- Meridional plane (*r-z* plane, *z* aligned with shaft axis)
- Calibration performed by positioning a transparent acrylic box containing the same index matched fluid on top of the machine, and translating a target aligned with the laser sheet in it

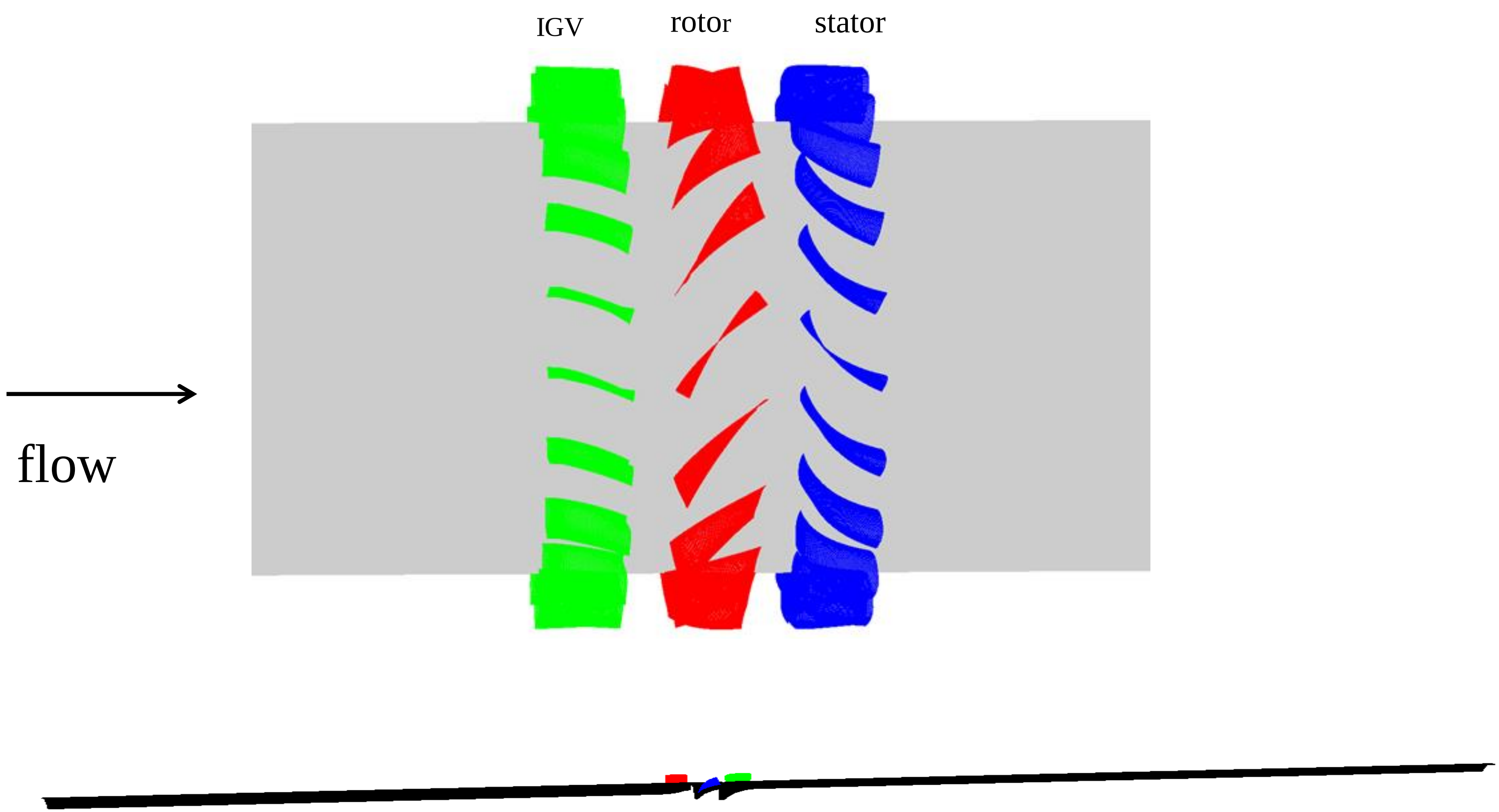
LES for unsteady tip clearance flow in compressors

- URANS : Effects due to entire turbulence scales are modeled. Solution depends on turbulence model. Difficult for separated flow, flow transition, Reynolds number effects.
- LES : Significant increase in computing cost. Requires large computational grid. Needs further development/validation for high speed flow.

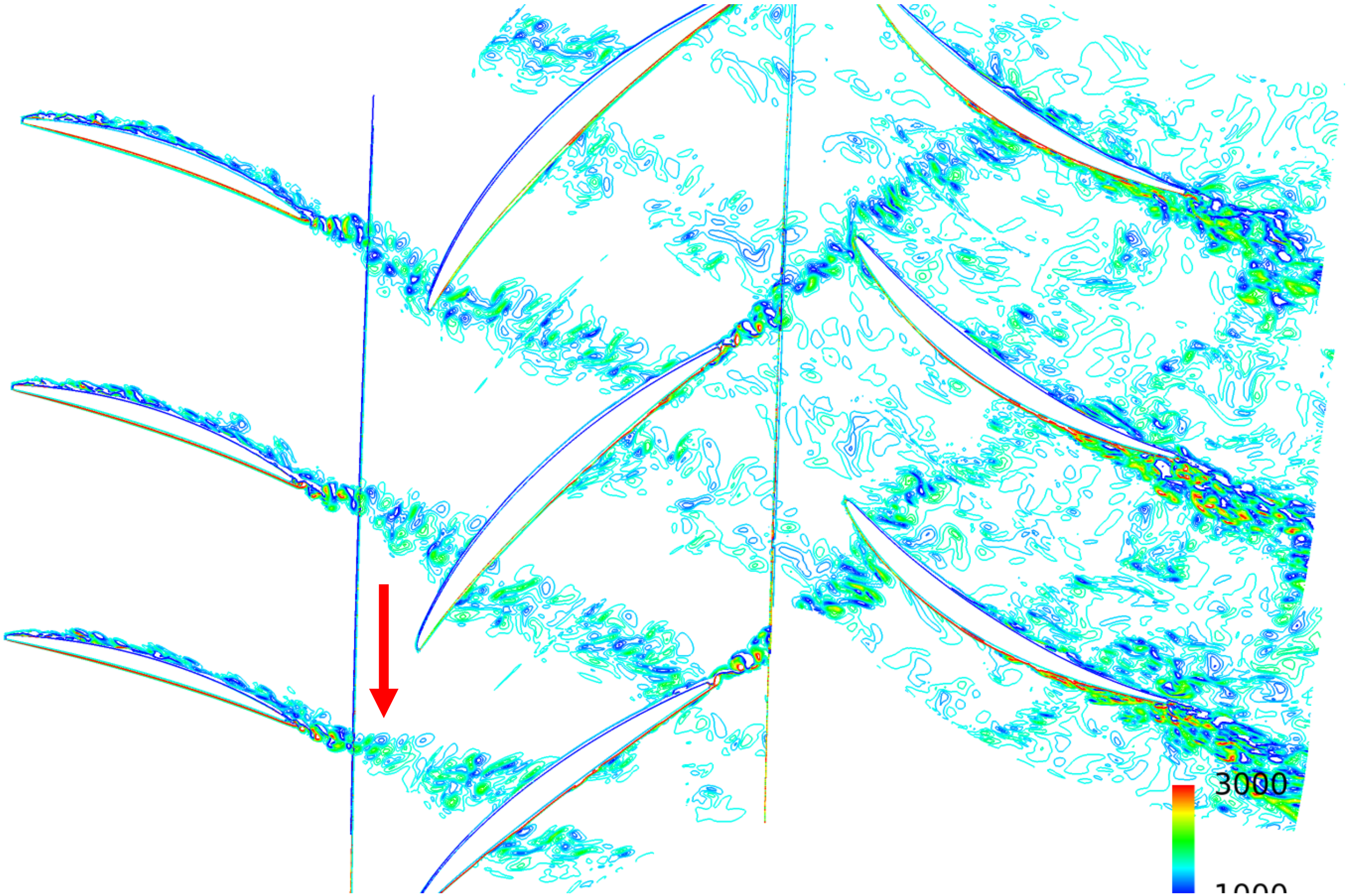
Applied LES procedure

- 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.
- Multi-block I-grid, 980 million nodes for all blade passages with 74 radial nodes inside tip gap.
- Incompressible flow simulation.

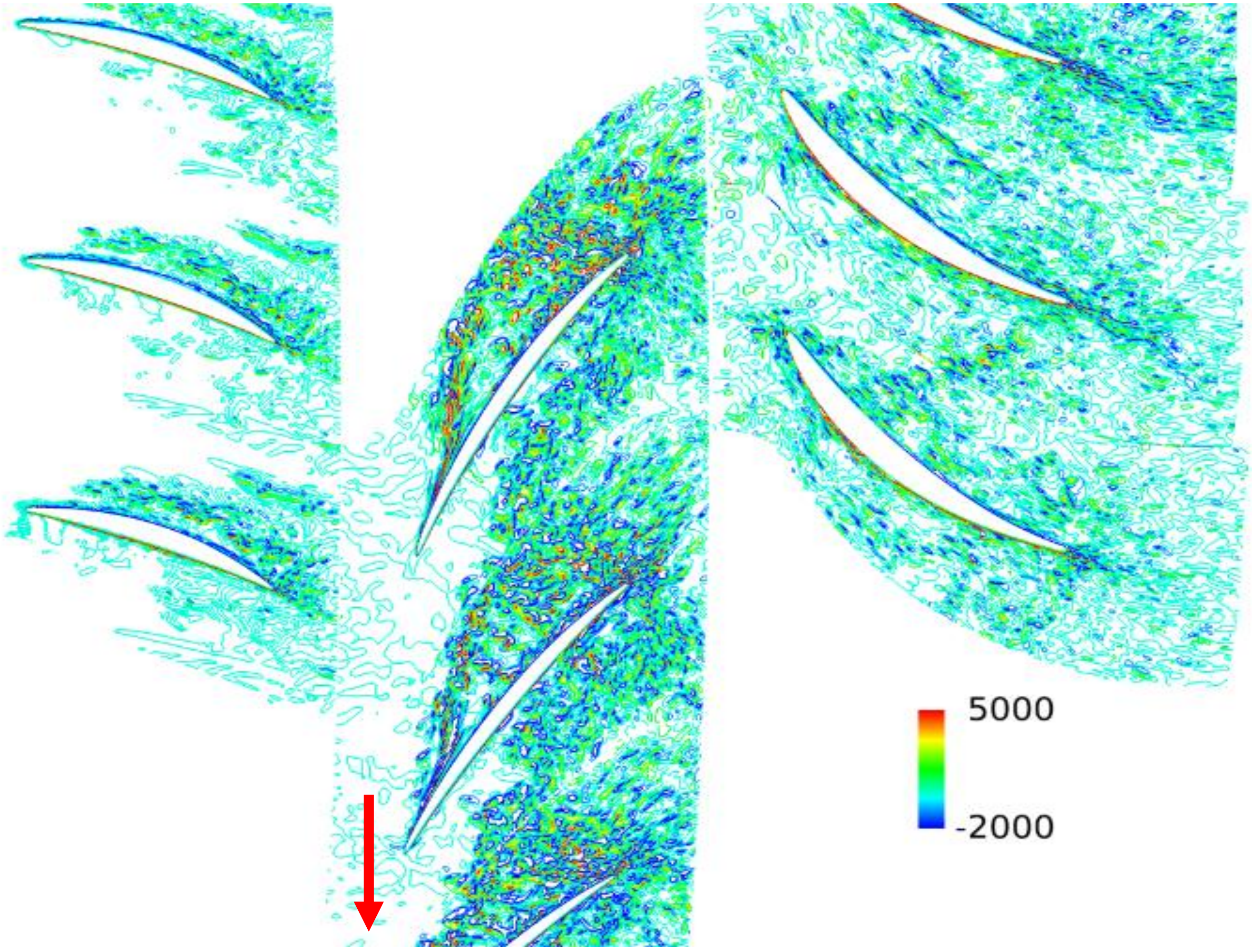
Computational grid and domain



Instantaneous vorticity contours at 20% span

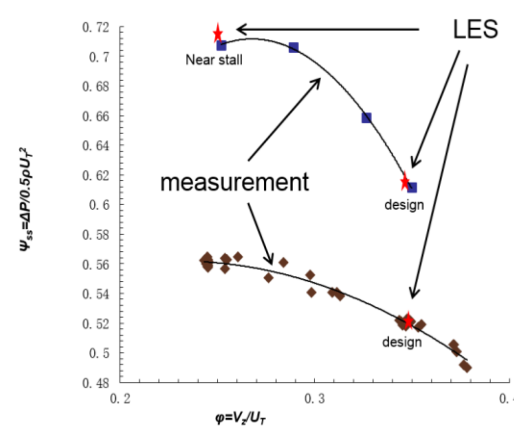


Instantaneous vorticity contours at rotor tip

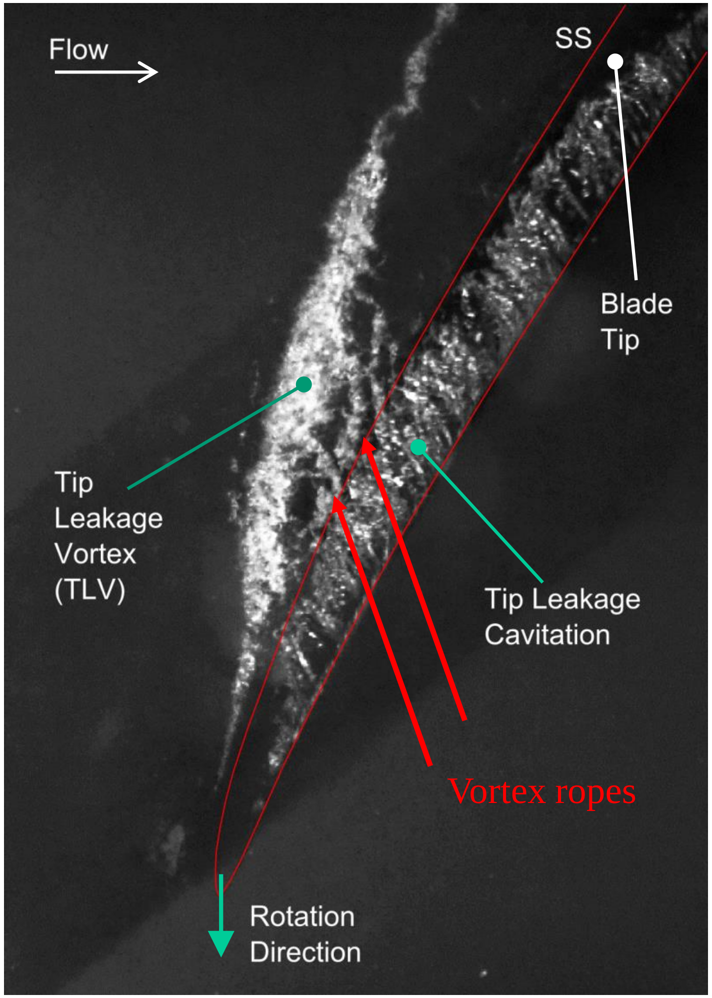


Tip clearance vortex structure at three flow conditions

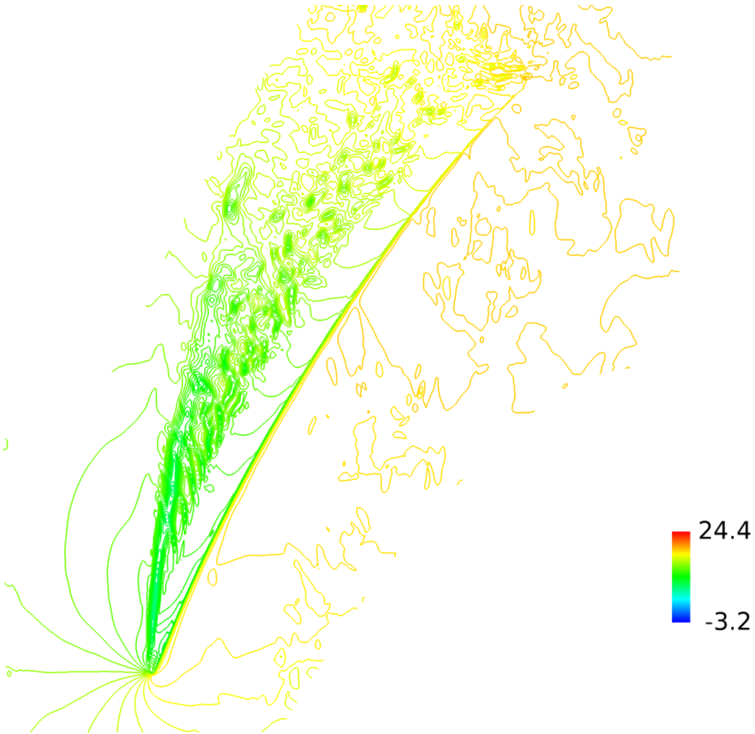
- Comparison between flow visualization with cavitation and LES.
- 0.5mm tip gap : peak efficiency and near stall.
- 2.4mm tip gap : peak efficiency.



Comparison of tip gap flow structure, 0.5mm gap, design condition

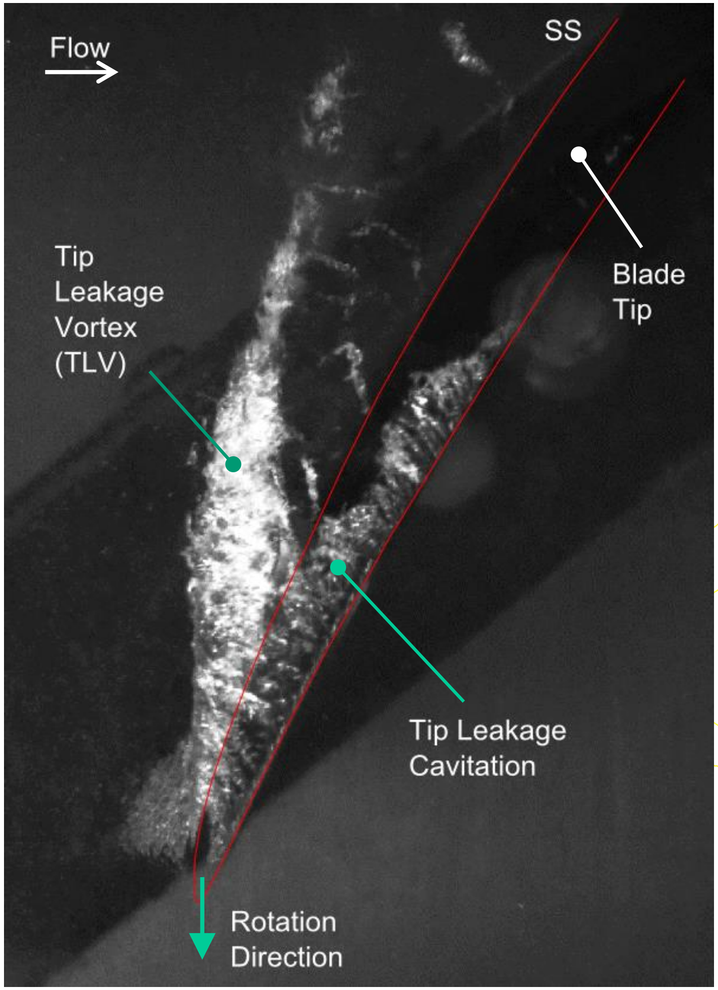


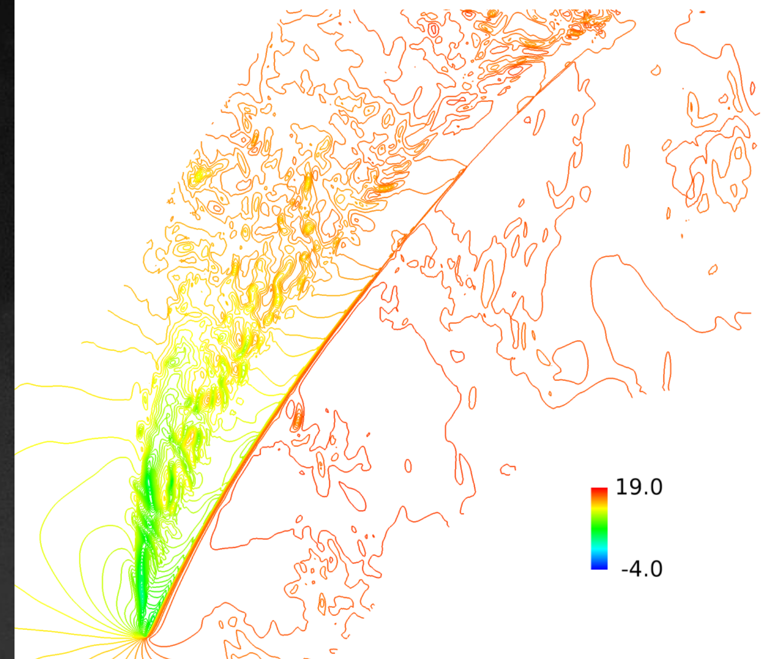
Cavitation visualization



Static pressure from LES

Comparison of tip gap flow structure, 0.5mm gap, near stall condition

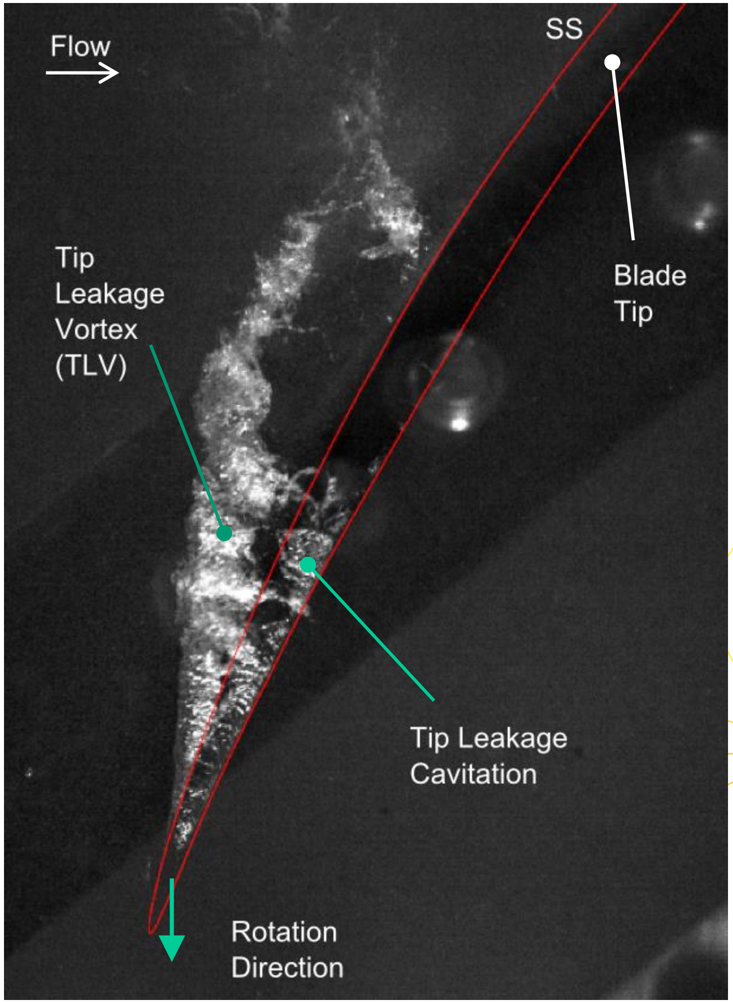


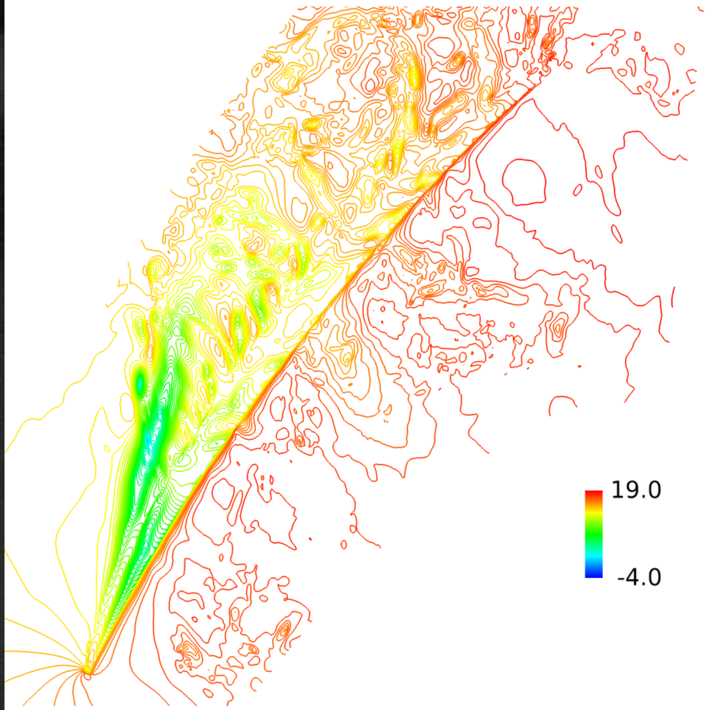


Cavitation visualization

Static pressure from LES

Comparison of tip gap flow structure, 2.4 mm gap, design condition

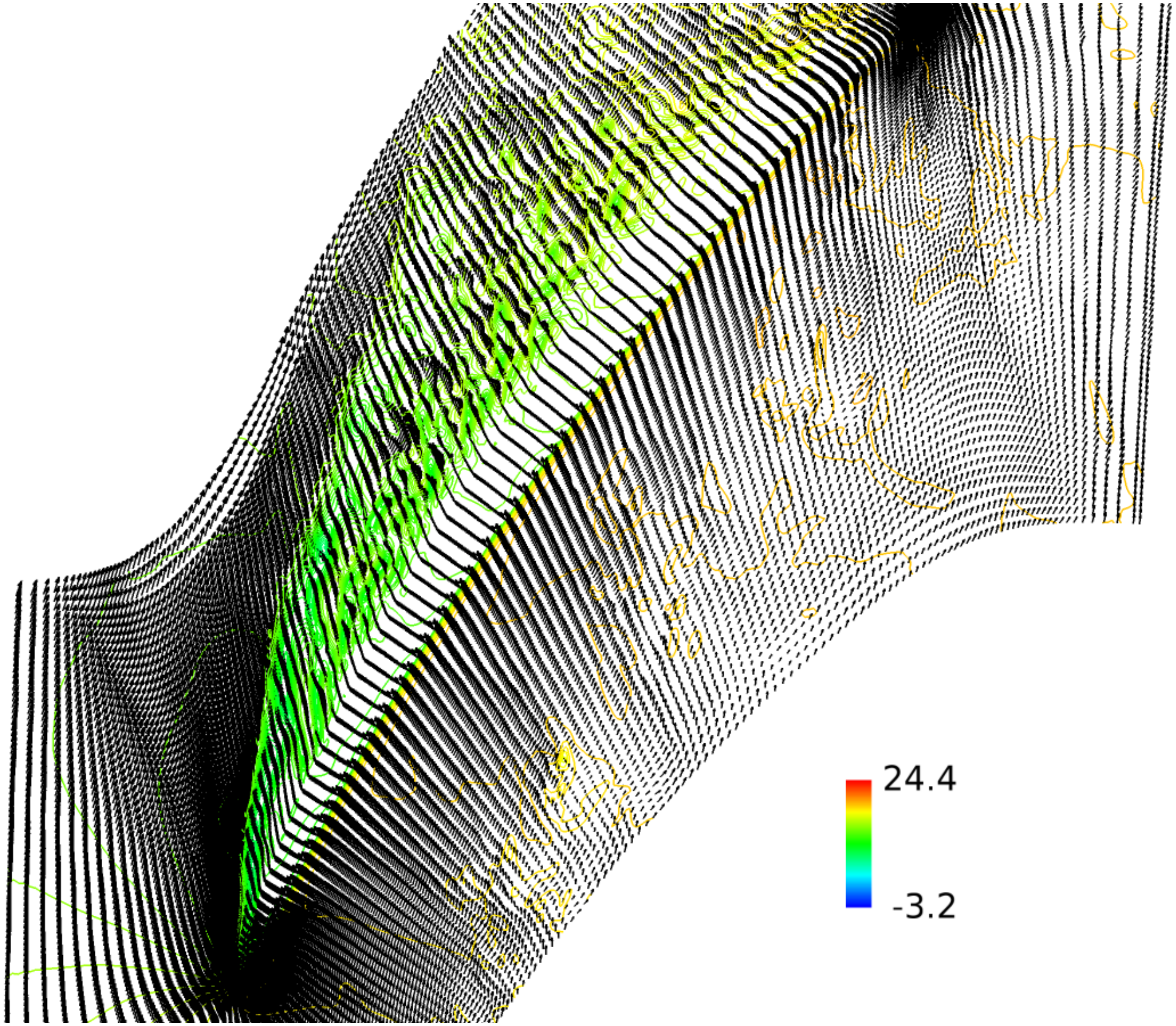




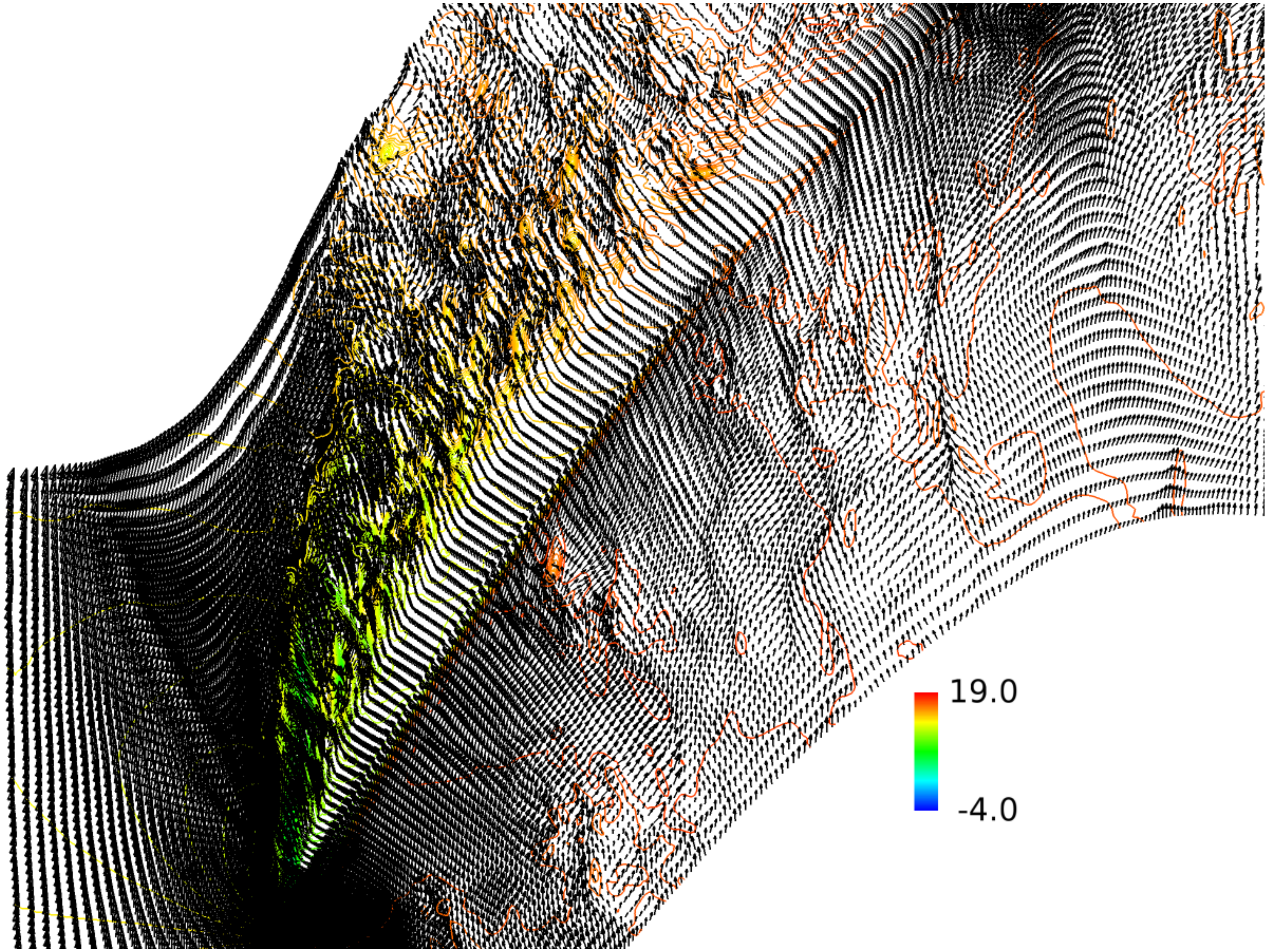
Cavitation visualization

Static pressure from LES

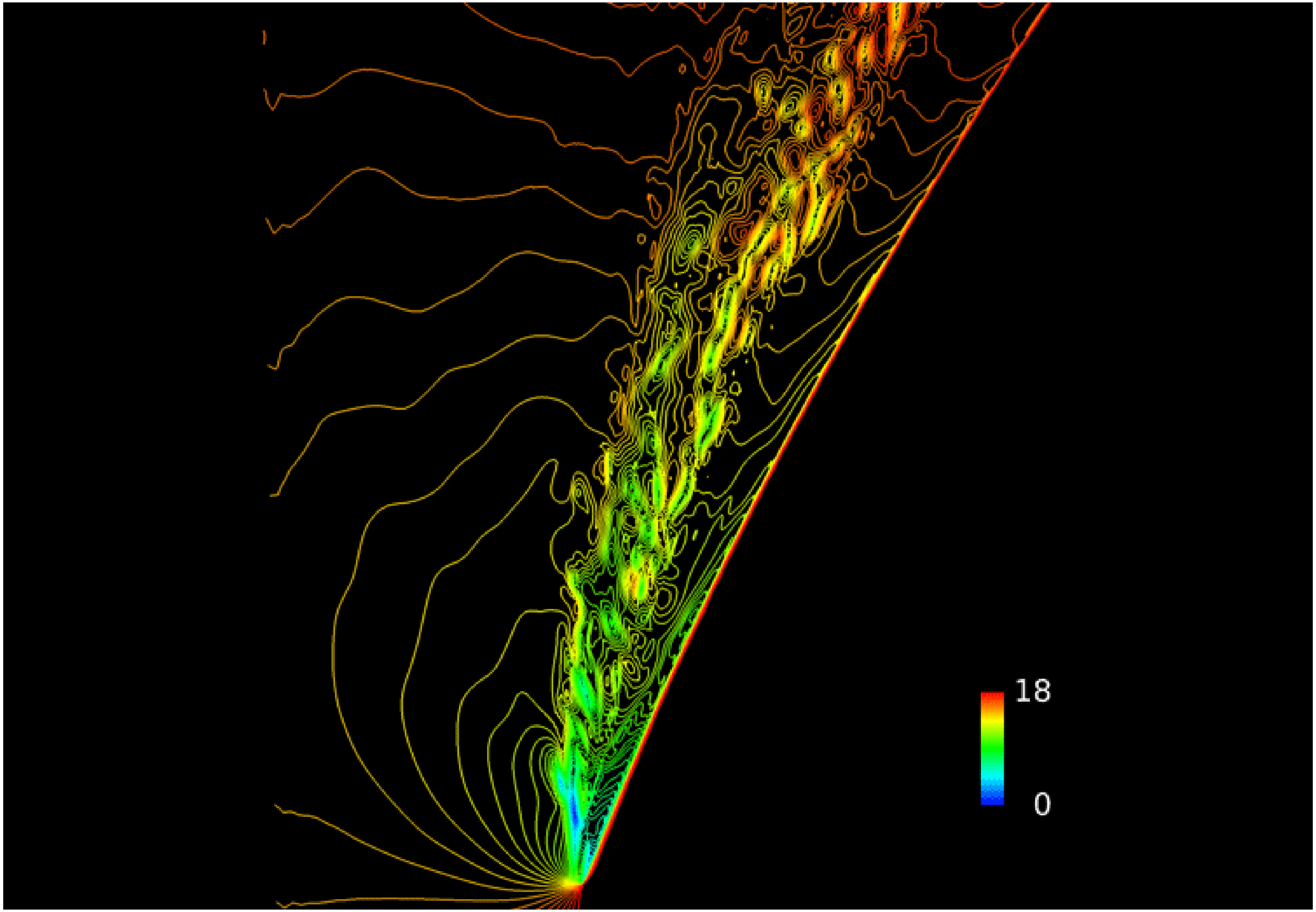
Instantaneous velocity vectors, 0.5 mm gap, design condition, 0.02 mm above tip



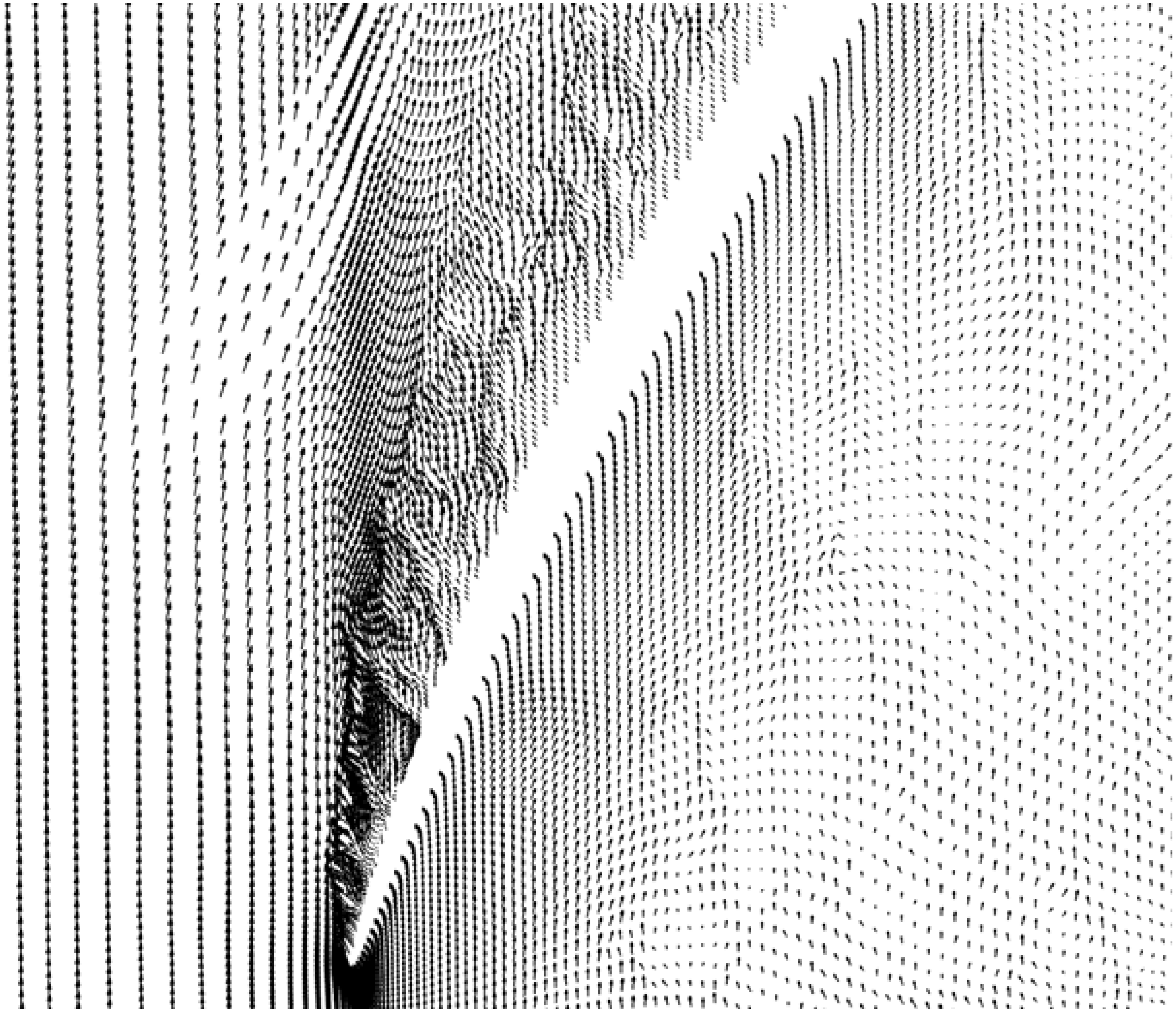
Instantaneous velocity vectors, 0.5 mm gap, near stall condition, 0.02 mm above tip



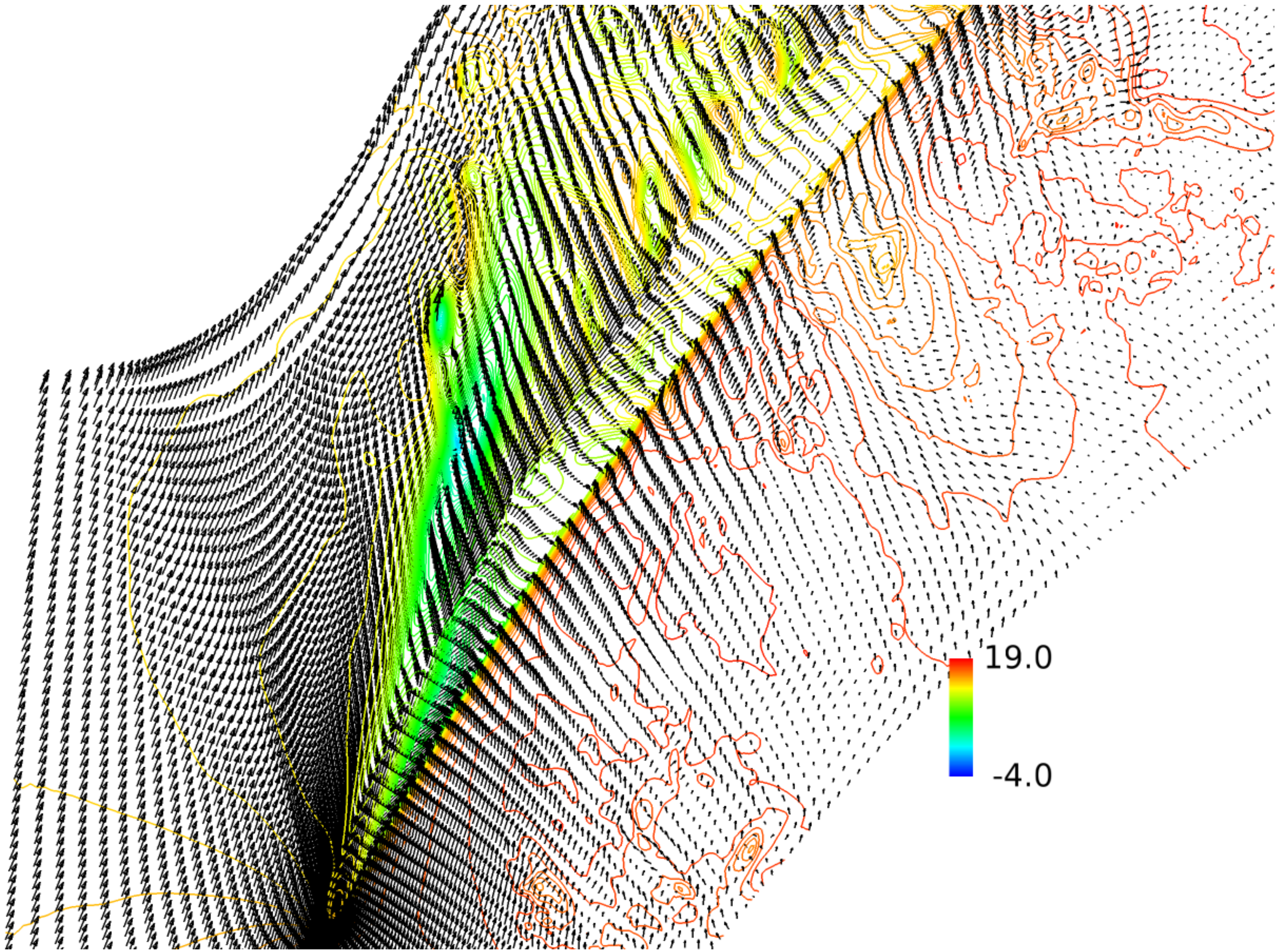
Change in pressure field, 0.5 mm gap, near stall



Change in velocity field, 0.5 mm gap, near stall



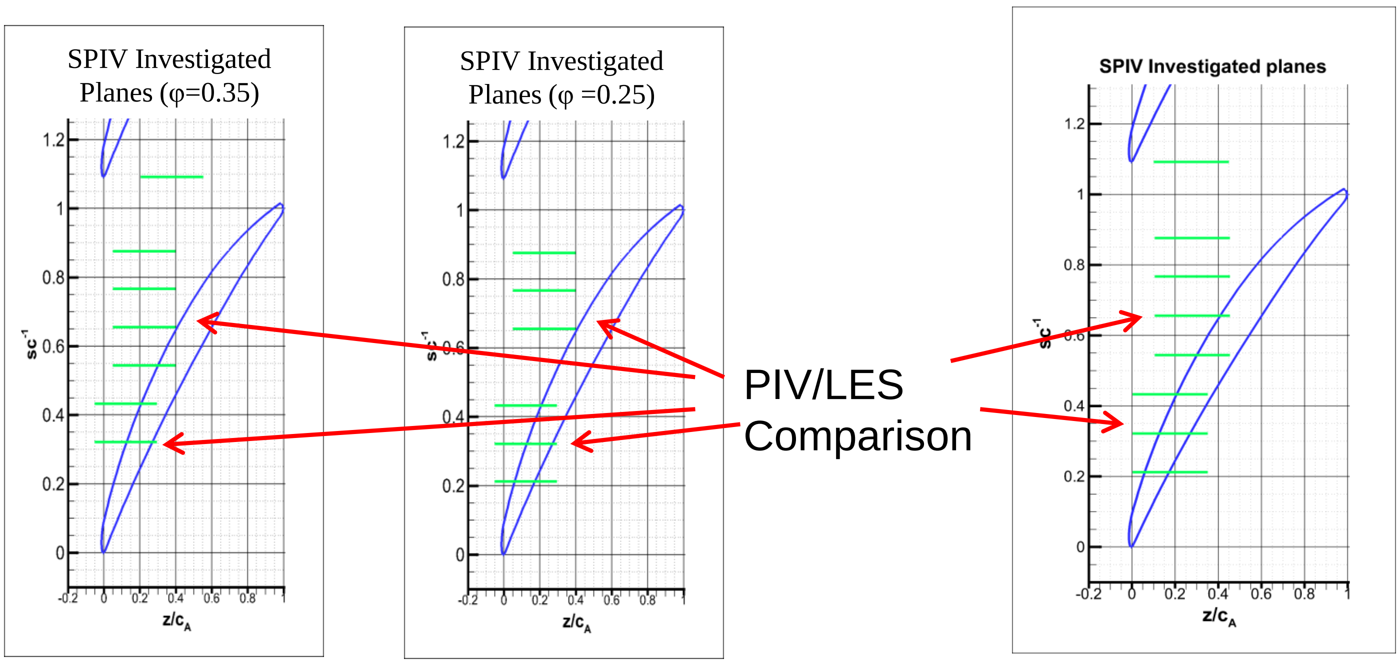
Instantaneous velocity vectors, 2.4 mm gap, near stall condition, 0.02 mm above tip



Tip vortex structure from visualization and LES

- Tip vortex structures from LES agree well with the visualization.
- Tip flow is unsteady at all flow conditions.
- The role of vortex ropes ?

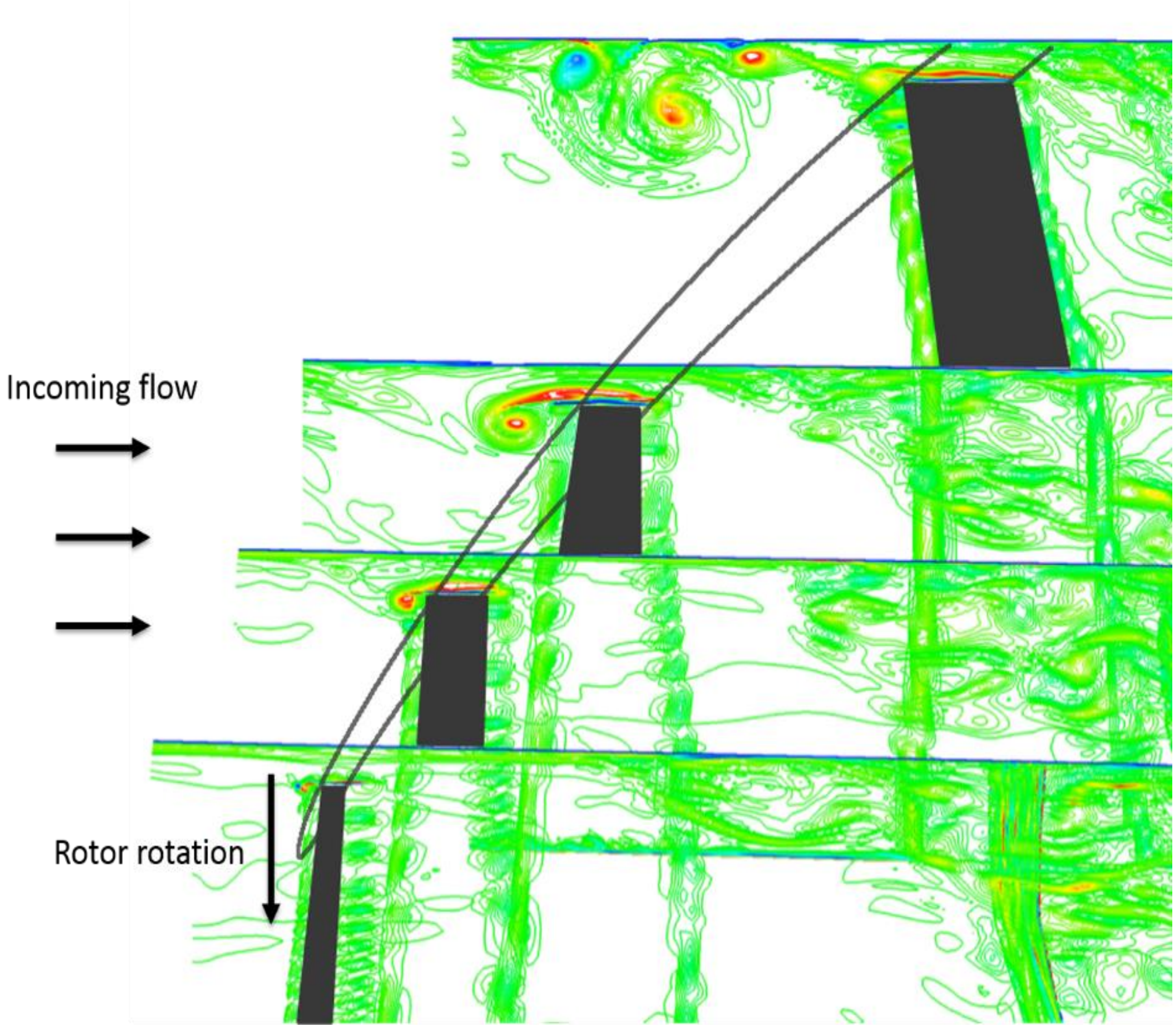
Meridional planes of PIV measurements



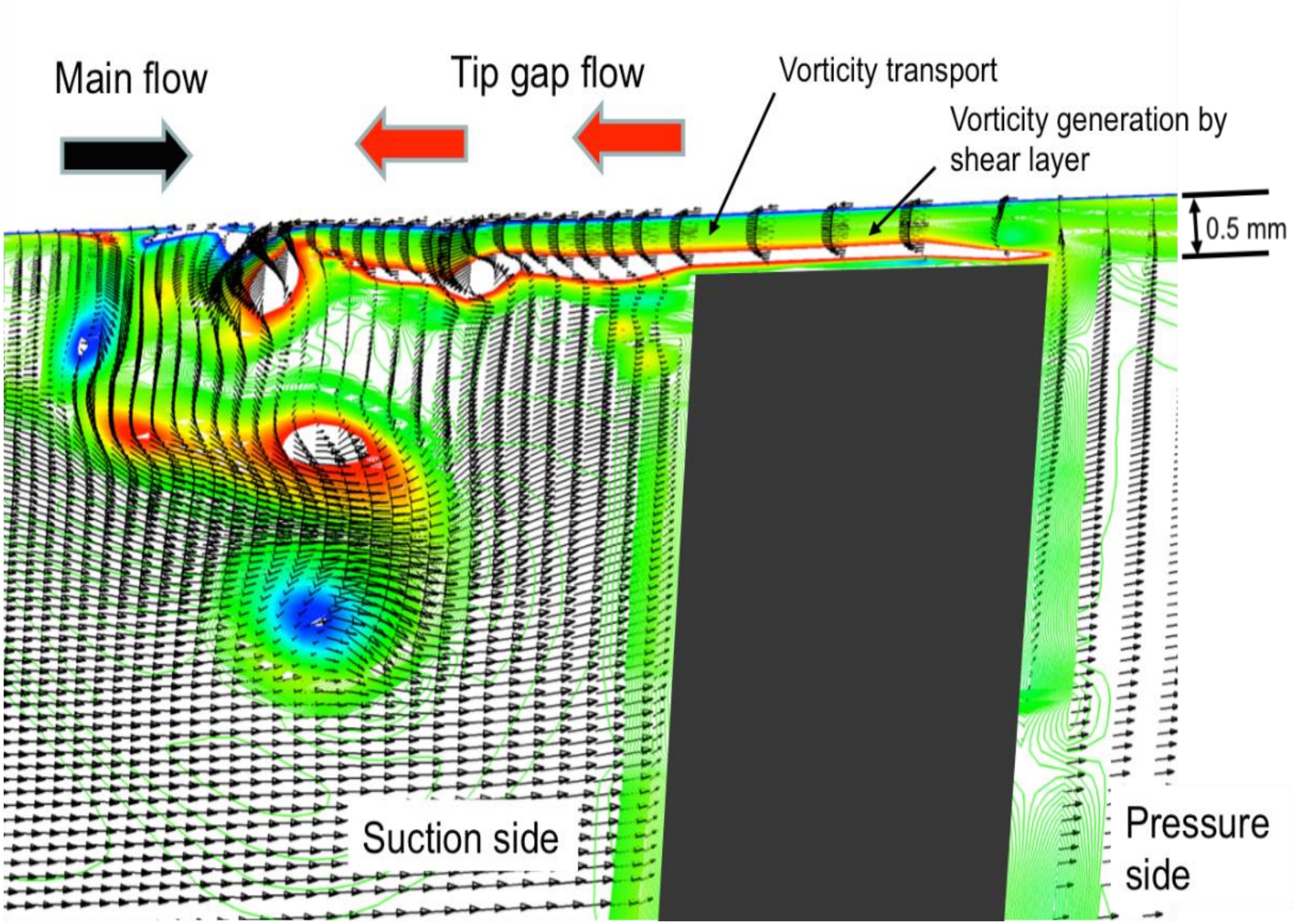
0.5 mm tip gap

2.3 mm tip gap

Instantaneous vorticity distribution around tip vortex from LES



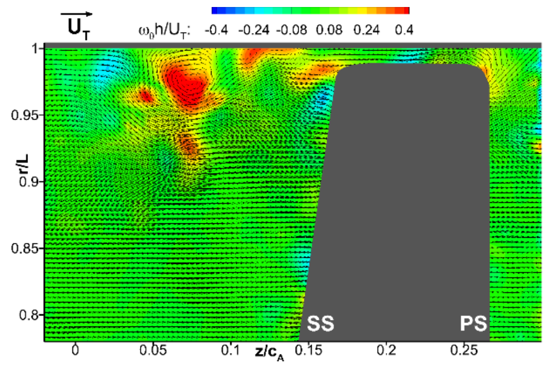
Mechanism of tip clearance vortex generation from LES



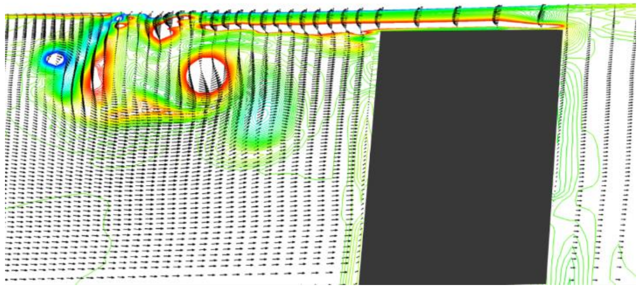
Mechanism of tip clearance vortex generation

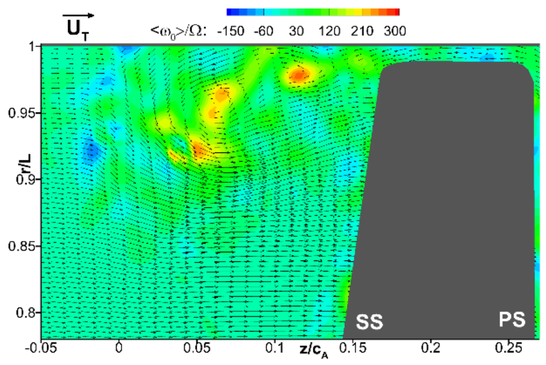
- Tip clearance vortex is generated by the shear layers on the blade tip and casing wall, not from the collision of main tip flow and the incoming main passage flow.
- This understanding will help in developing future strategy to control the tip clearance flow at near stall operation.

Comparisons of tip vortex at design condition and near stall, 0.5 mm gap, s/C=0.328

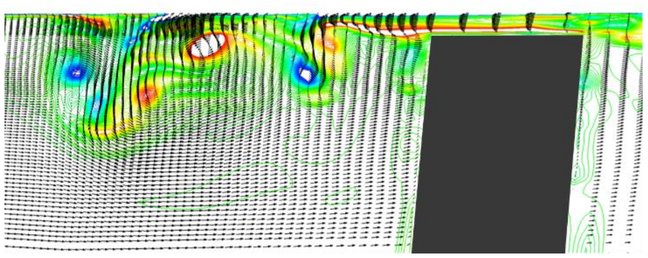


design





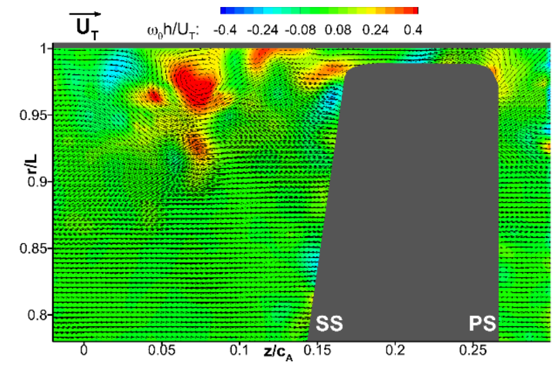
Near stall



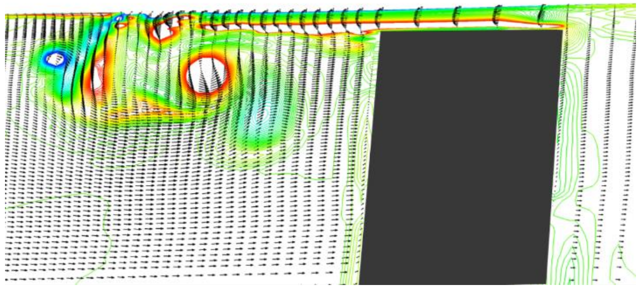
PIV

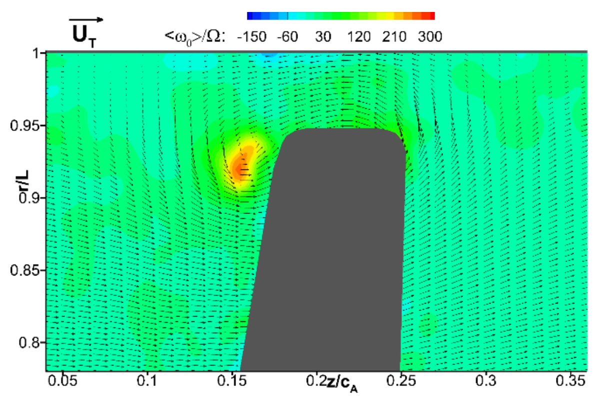
LES

Comparisons of tip vortex with two tip gaps (0.5 mm and 2,4 mm at design condition, s/C=0.328

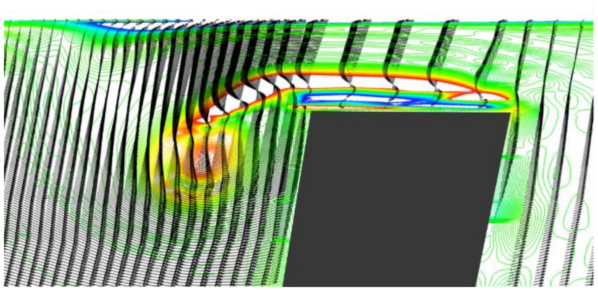


0.5 mm





2.4 mm



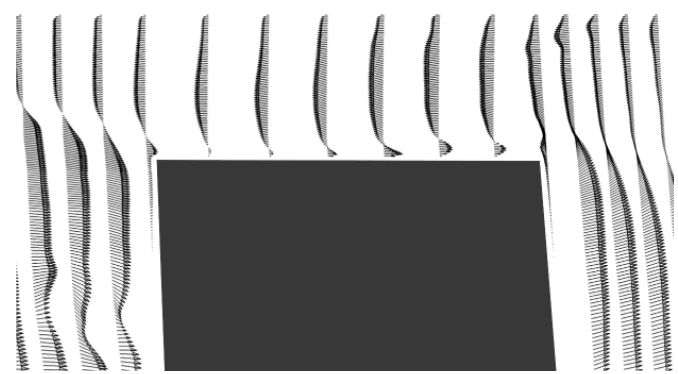
PIV

LES

Changes of velocity vectors near tip gap at s/c=0.328

0.5mm gap, design condition

0.5mm gap, near stall

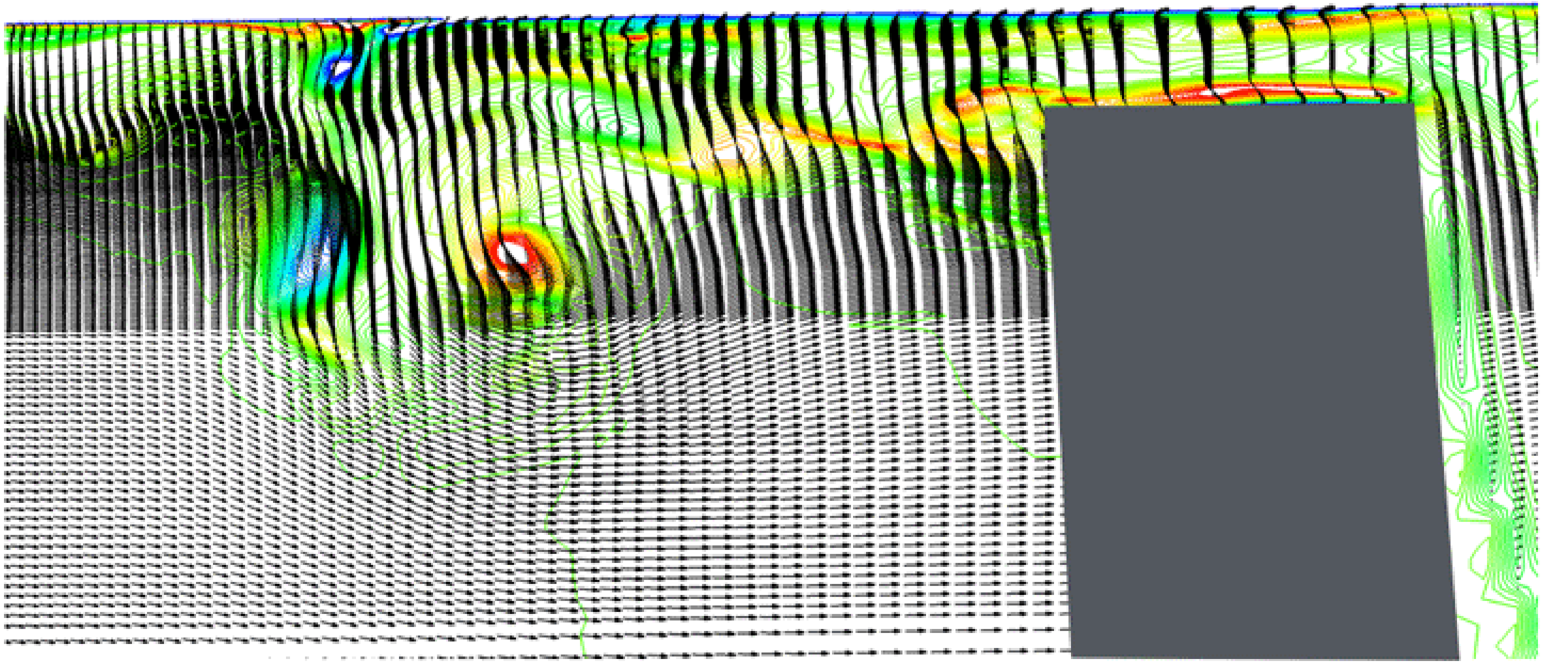


2.4 mm gap, design condition

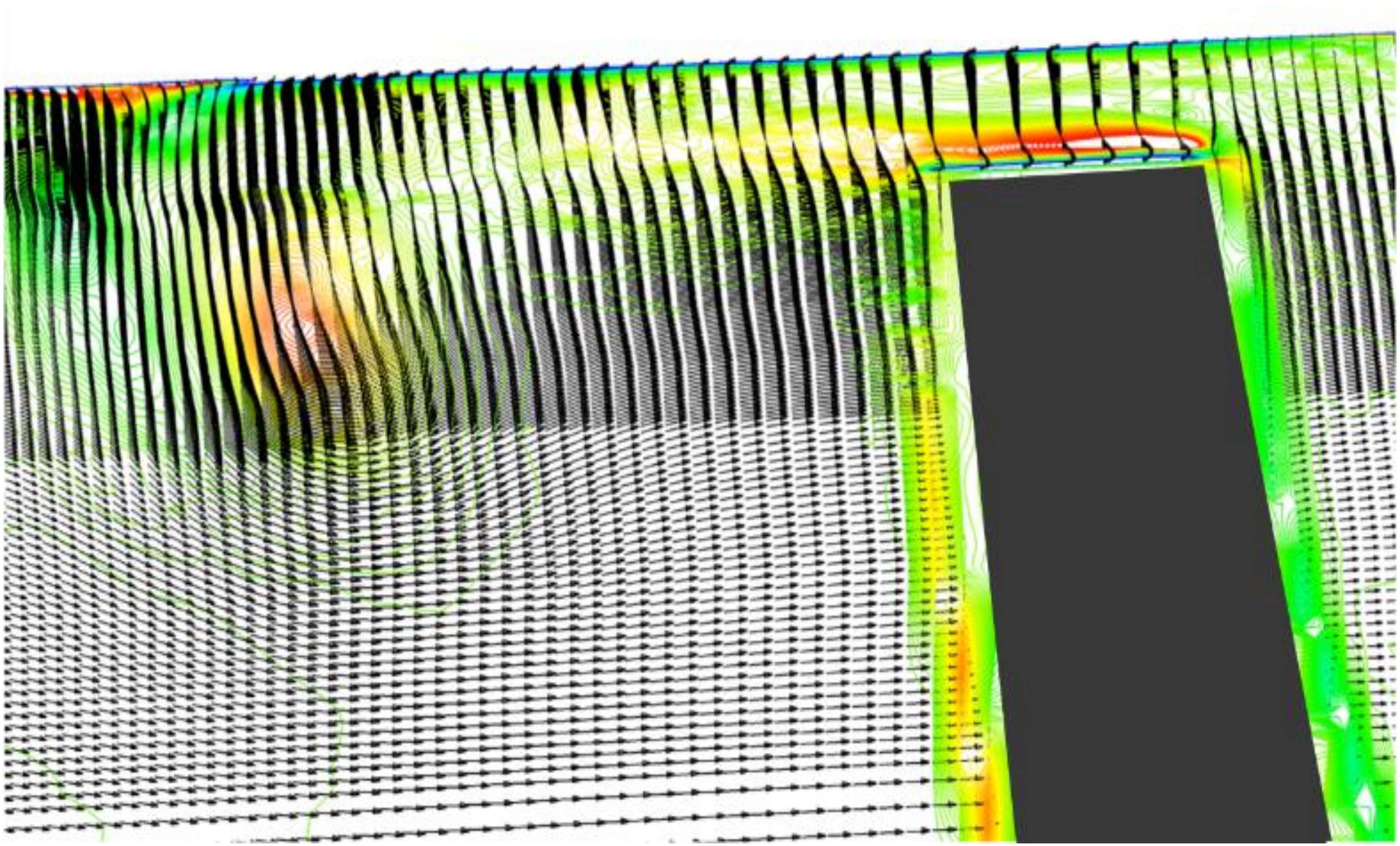
Effects of tip gap size and flow rate on tip vortex structure

- Tip vortex starts early, move away from the blade further, and radially mover further inward when mass flow rate is decreased (0.5 mm tip gap).
- Tip vortex stays closer to blade tip when tip gaps is increased at design condition.

Changes in tip vortex structure, 2.4mm and s/c=0.655



Time-averaged tip vortex structure, 2.4 mm and s/C=0.655



Unsteady behavior of tip clearance vortex

- Tip clearance vortex is transitional and never converges to the time-averaged structure.
- Flow control strategy should be based on the unsteady structure of the tip clearance flow.

Concluding remarks

- Tip clearance flow is highly transitional at all flow conditions.
- Vortex ropes are observed at all operating conditions and play important roles in unsteady nature of tip vortex.
- Any flow control strategy should be based on the detailed unsteady tip flow structure.