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Large Eddy Simulations of a turbine cascade with strong non-ideal gas effects

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Outline

- Motivation and objectives
- Governing equations and models
- Case description
- LES validation for perfect gas
- Dense gas results
- Conclusions and future work

Motivation and objectives

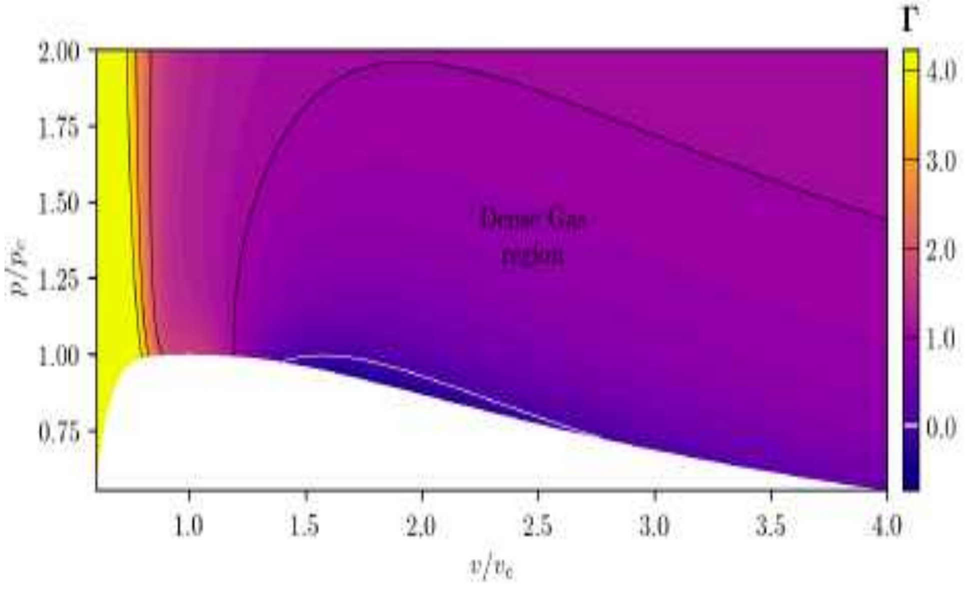
- Organic Rankine Cycles (ORC) are a promising technology for renewable energy generation and waste heat recovery
  - For medium to high power cycles (100 to 2000 KW), expansion is realized by means of a turbine → the working fluid is a dense gas
- Challenges:
  - Optimize the turboexpander using working fluids whose thermodynamic behavior strongly deviates from the perfect gas model.
  - Experimental benches providing fine-detail flow data not available yet
  - ORC design relies on Reynolds-Averaged Navier-Stokes (RANS) turbulence models, not well suited for laminar/turbulent transition, flow separation, shock/boundary layer interactions,…
- **Interest for performing high-fidelity simulations**
  - In this work we carry out wall-resolved Large-Eddy Simulations (LES) for:
    - Investigating the influence of strongly non-ideal effects on flow topology and boundary layer development
    - Assessing lower fidelity models relying on the solution of Euler or RANS equations

Dense-gas reminder

- Dense-gas effects governed by the Fundamental Derivative of Gas Dynamics (Thompson, 1971)

$$\Gamma := 1 + \frac{\rho}{c}\frac{\partial c}{\partial \rho}\bigg|_s$$

  - Measure of speed of sound variations in isentropic perturbations
  - Perfect polytropic gases: $\Gamma = \frac{\gamma + 1}{2} > 1$ → constant
  - Complex gases, Γ **variable**:
    - $\Gamma < 1$: dense gas region, reversed sound speed variation
    - $\Gamma < 0$: inversion region, nonclassical nonlinearities
    - Temperature- and density-dependent specific heats
    - Transport properties depend on both temperature and pressure (or density)
    - Highly variable Prandtl number
- In the present simulations we choose a **heavy fluorocarbon as working fluid (PP11)**:
  - Large inversion region
  - Used for previous studies (Sciacovelli et al.: THI, Channel flow, Boundary layer)



Iso-Γ for PP11 (MAH EoS)

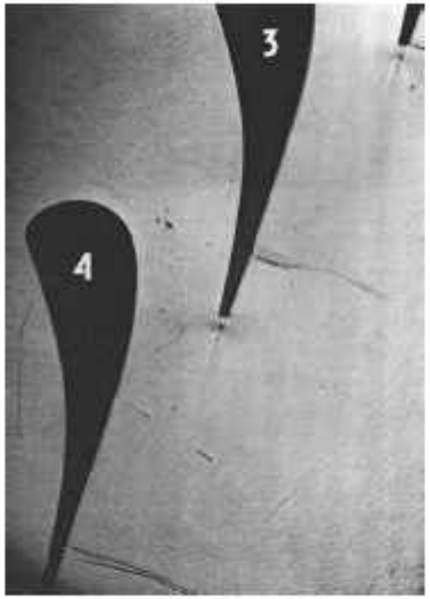
Governing equations and numerical methods

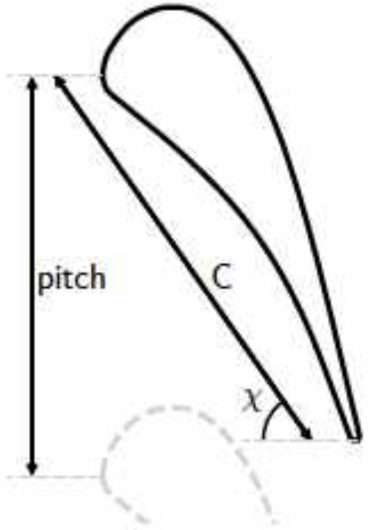
- Compressible Navier-Stokes equations supplemented by
  - Equation of state of Martin-Hou (reasonably accurate model for fluorocarbons)
  - Chung-Lee-Stirling models for the transport properties
  - Wall-resolved implicit LES:
    - No wall functions, y+ = O(1)
    - Energy drain at subgrid scales insured by the scheme's numerical dissipation
- Finite volume spatial discretization
  - Convective fluxes:
    - Fourth-order centered approximation
    - 3rd-order Jameson-like adaptive nonlinear artificial dissipation + Ducros sensor
  - Viscous fluxes: 2nd-order standard finite-differences
- Time integration
  - Explicit six-step low-storage Runge-Kutta scheme +
  - High-order Implicit Residual Smoothing (IRS, Cinnella and Content, 2016)
    - Relaxes strong time-step constraints due to mesh clustering close to the walls
- Calculations based on our in-house code DynHOLab
  - Very good MPI scalability verified up to 32768 cores

Case description

- Choice of a configuration with compressibility effects and well documented for perfect gas (PFG)

  →**Linear turbine cascade LS89**
  - High loaded stator blade designed for transonic flow of PFG
  - Experimental data available: Arts et al.
  - Numerical LES data available: Gourdain et al., Pichler et al. …
  - **Characteristics**:
    - Chord : C = 67.647mm
    - Pitch-to-Chord ratio : 0.85
    - Stagger angle : = 55°

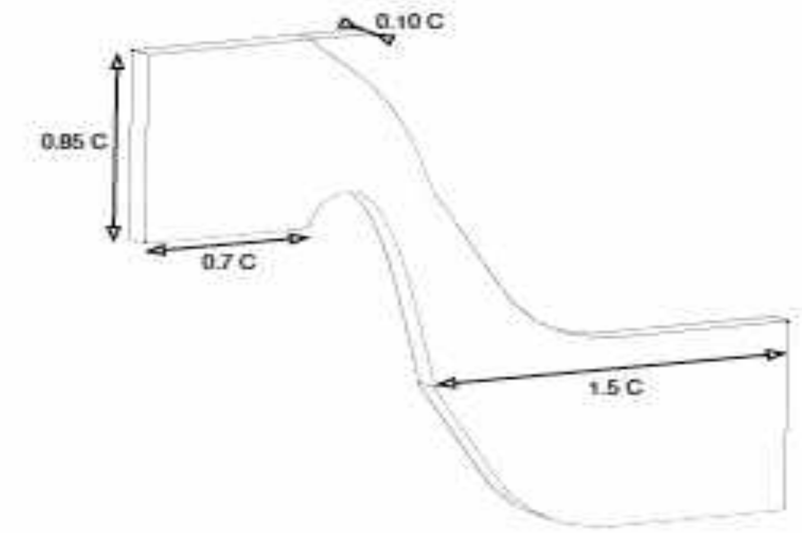


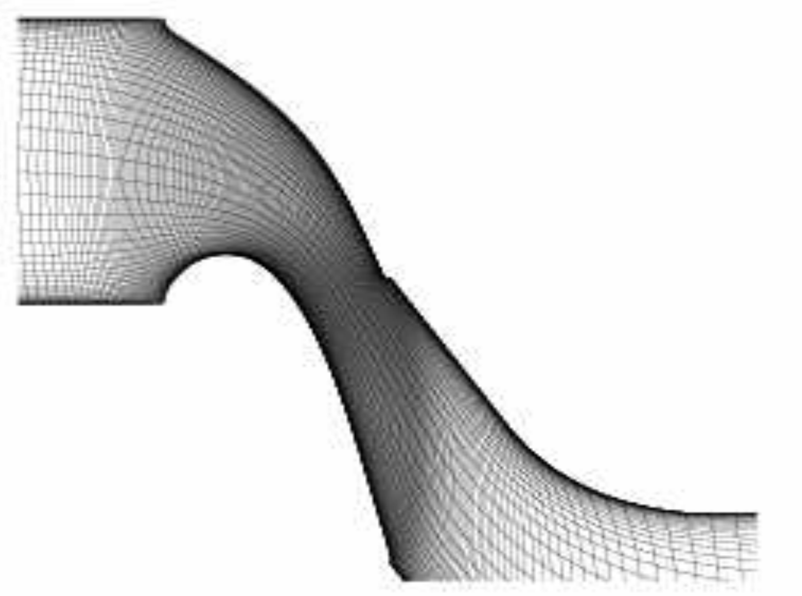


Case description

- Computational grid
  - H-type, ≈30 million points
  - Clustered at solid walls
  - Blade geometry discretised by 1100 points
  - Spanwise width: 10% of the chord

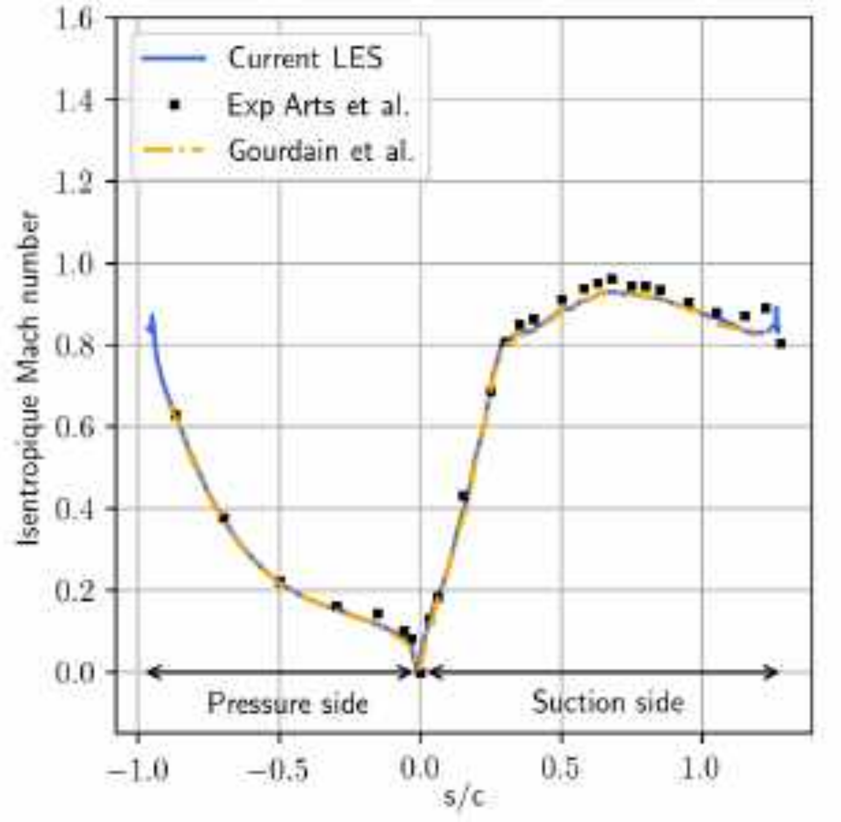
- Boundary conditions :
  - Characteristic conditions based on 1D Riemann invariants
    - Total pressure and density at inlet
    - Static pressure at outlet (subsonic normal velocity), extrapolation otherwise
  - Quasi-adiabatic isothermal condition at walls
  - <u>No inlet turbulence</u>

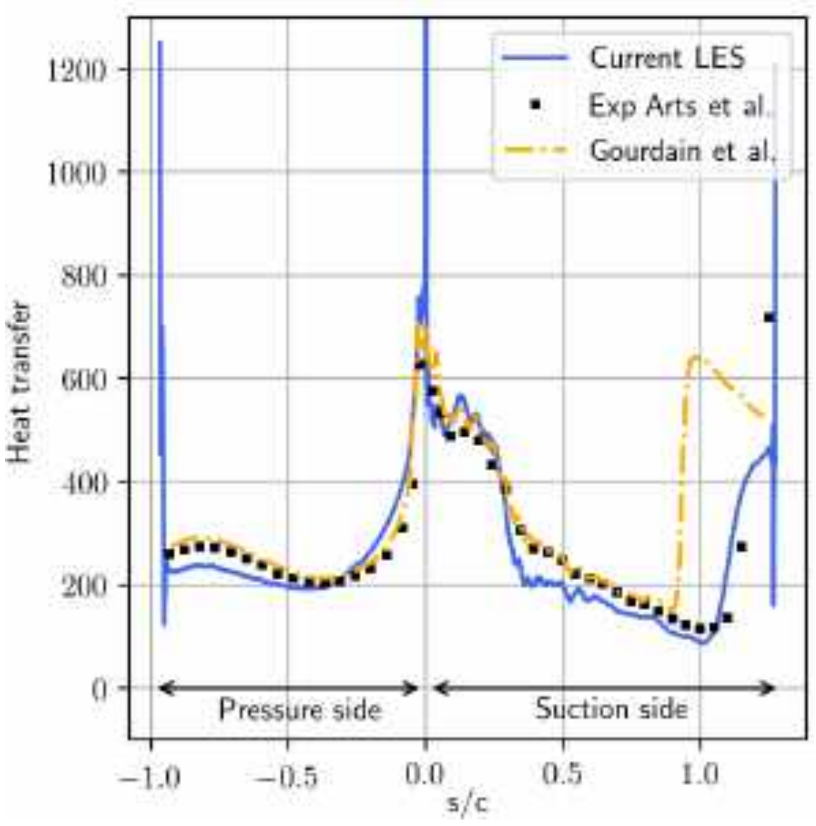




LES validation for PFG

- From Hoarau, Cinnella & Gloerfelt, Comp Fluids, 2019
- PFG calculations carried out for case MUR129:
  - $Re_{out} \approx 10^6$, $M_{is,out}$= 0. 84 (i.e. p^0_1 / p_2 = 1.58) and Tu_{in} = 0%
  - Average mesh resolution in wall units y+≈1.5, x+≈100, z+≈25 (coarse wall-resolved LES)
  - Δt = 3x10^{-8} s → CFL≈7
- Wall distribution of the isentropic Mach number and heat transfer coefficient: comparison with experiments by Arts et al. and simulations by Gourdain et al.





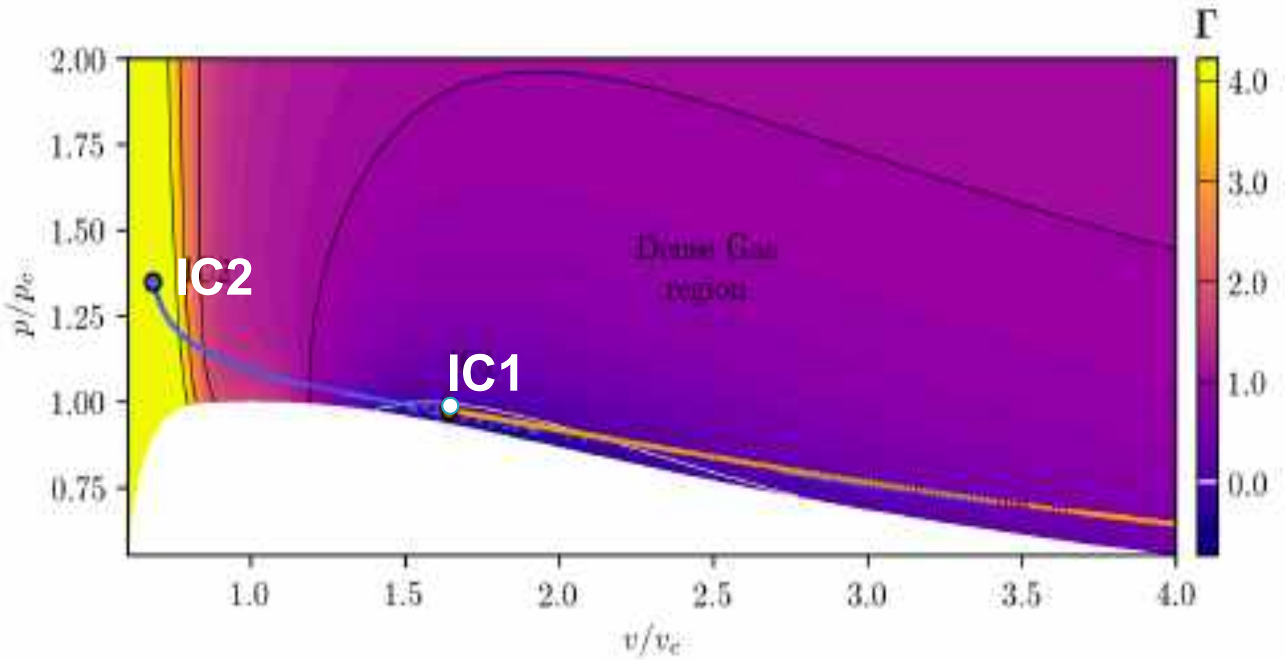
Dense-gas results

- Similar space and time resolution as in PFG calculations
- Outlet Reynolds number and pressure ratio similar to those considered for PFG.
  - Blade geometry rescaled by a factor 20, to match the PFG Reynolds number and ensure similar wall resolution
  - Low pressure ratio case (LPR): $p^0_1 / p_2 = 1.58$ as in MUR129
  - High pressure ratio case (HPR): $p^0_1 / p_2 = 2.10$
- Two thermodynamic inlet conditions (IC):
- Subcritical (IC1):

$\hookrightarrow$ $p_1^\circ = 0.98 \times p_c$
$\hookrightarrow$ $\rho_1^\circ = 0.62 \times \rho_c$
$\hookrightarrow$ $\Gamma_1 = -0.093$

- Supercritical (IC2):

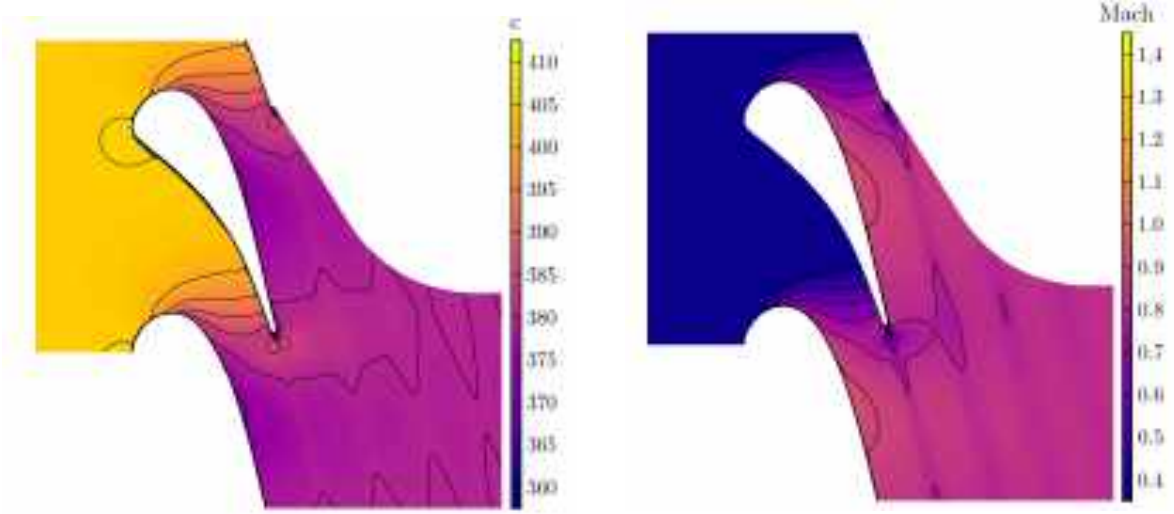
$\hookrightarrow$ $p_1^\circ = 1.47 \times p_c$
$\hookrightarrow$ $\rho_1^\circ = 1.35 \times \rho_c$
$\hookrightarrow$ $\Gamma_1 = 6.65$



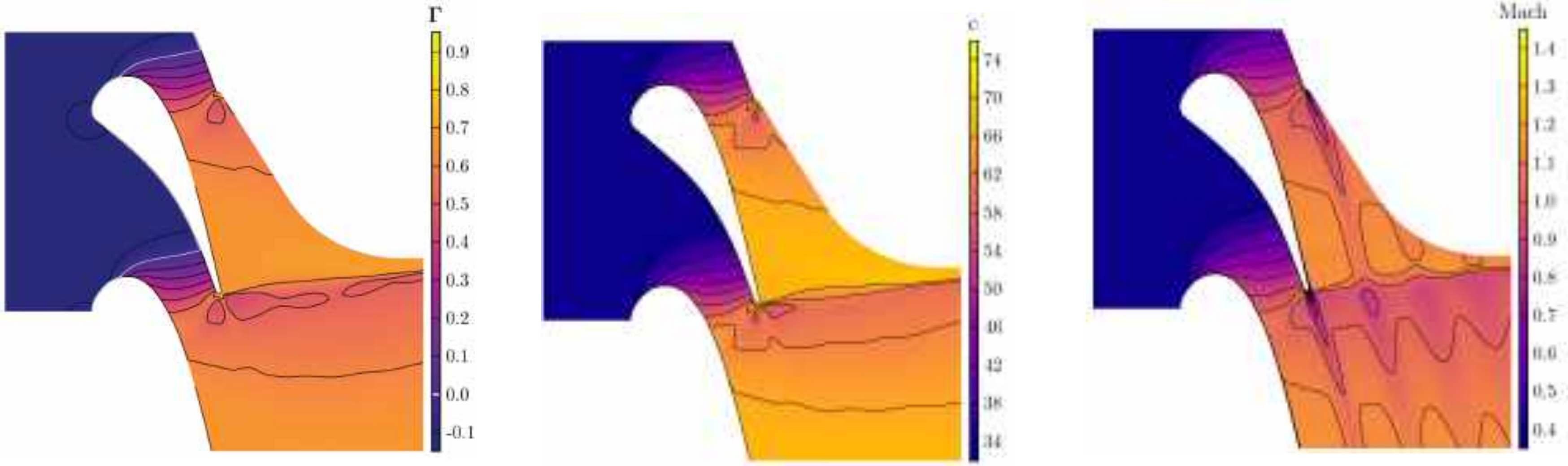
Location of the IC in the Clapeyron diagram of PP11

Comparison with perfect gas

- LPR case, IC1-LPR: comparison with the perfect gas case MUR129 (average fields)
  - DG: **Γ<1** thoughout the flow
  - Speed of sound **increases** in DG expansion but is **much lower** than in PFG → **higher compressibility**



PFG, MUR129: speed of sound and Mach number

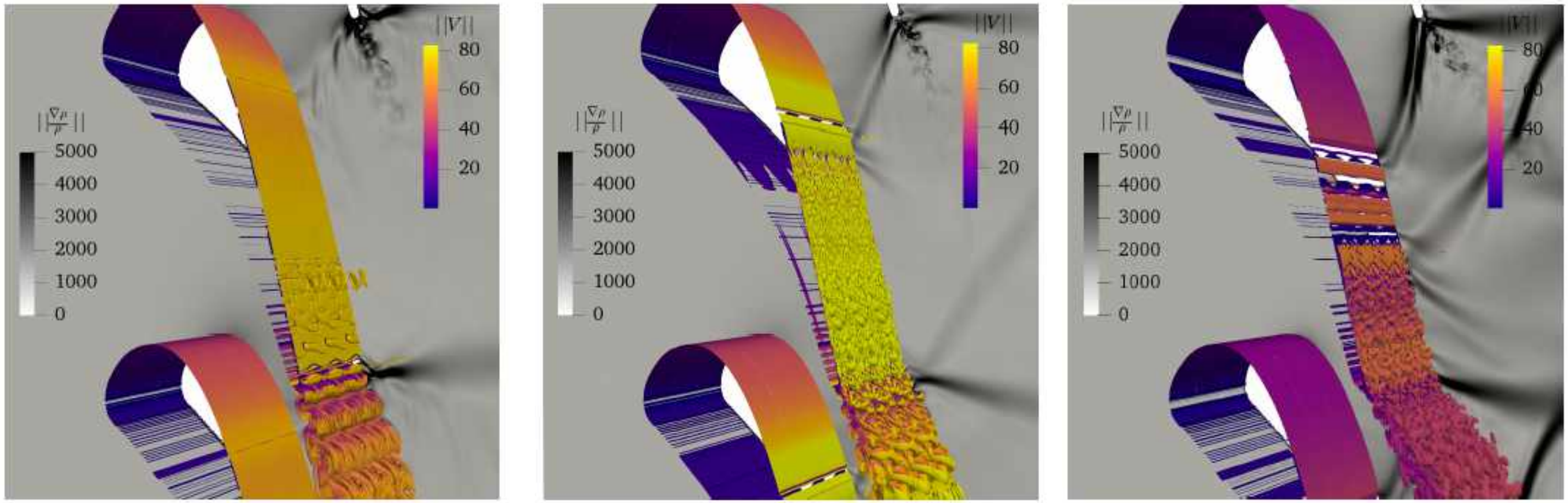


DG, LPR, IC1: Γ, sound speed and Mach number

Overview of flow topology

- Influence of the pressure ratio and thermodynamic working point:
  - IC2 exhibits non-classical waves. Specifically, a non-classical expansion (NCE) wave is generated at the pressure side of the trailing edge

Istantaneous iso-surface of the Q-criterion. Background: density gradient



Left: IC1-LPR; Middle: IC1-HPR; Right: IC2-LPR

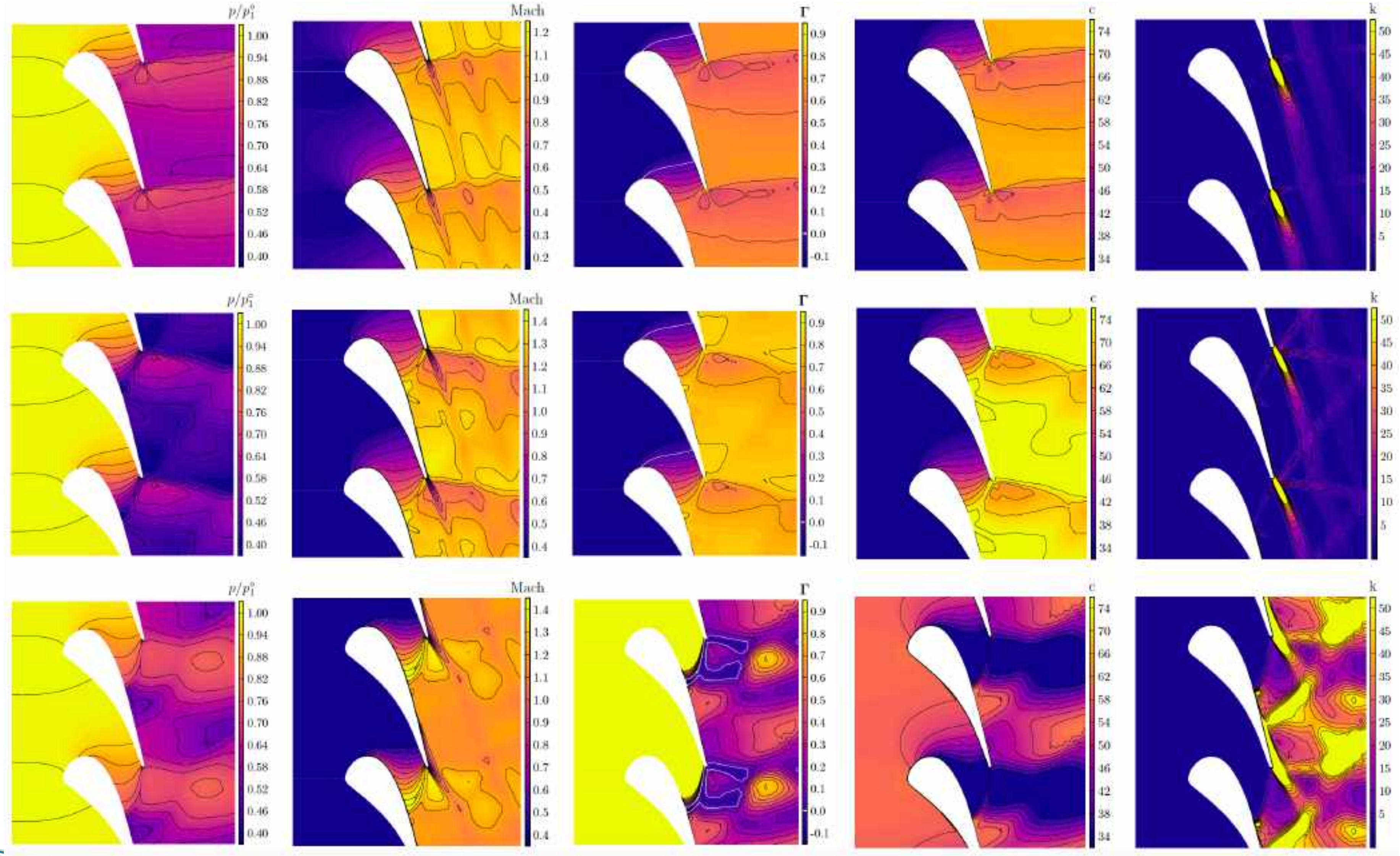
Effects of the operating conditions

- Influence of the pressure ratio and thermodynamic working point: average fields and kinetic energy of velocity fluctuations

IC1-LPR

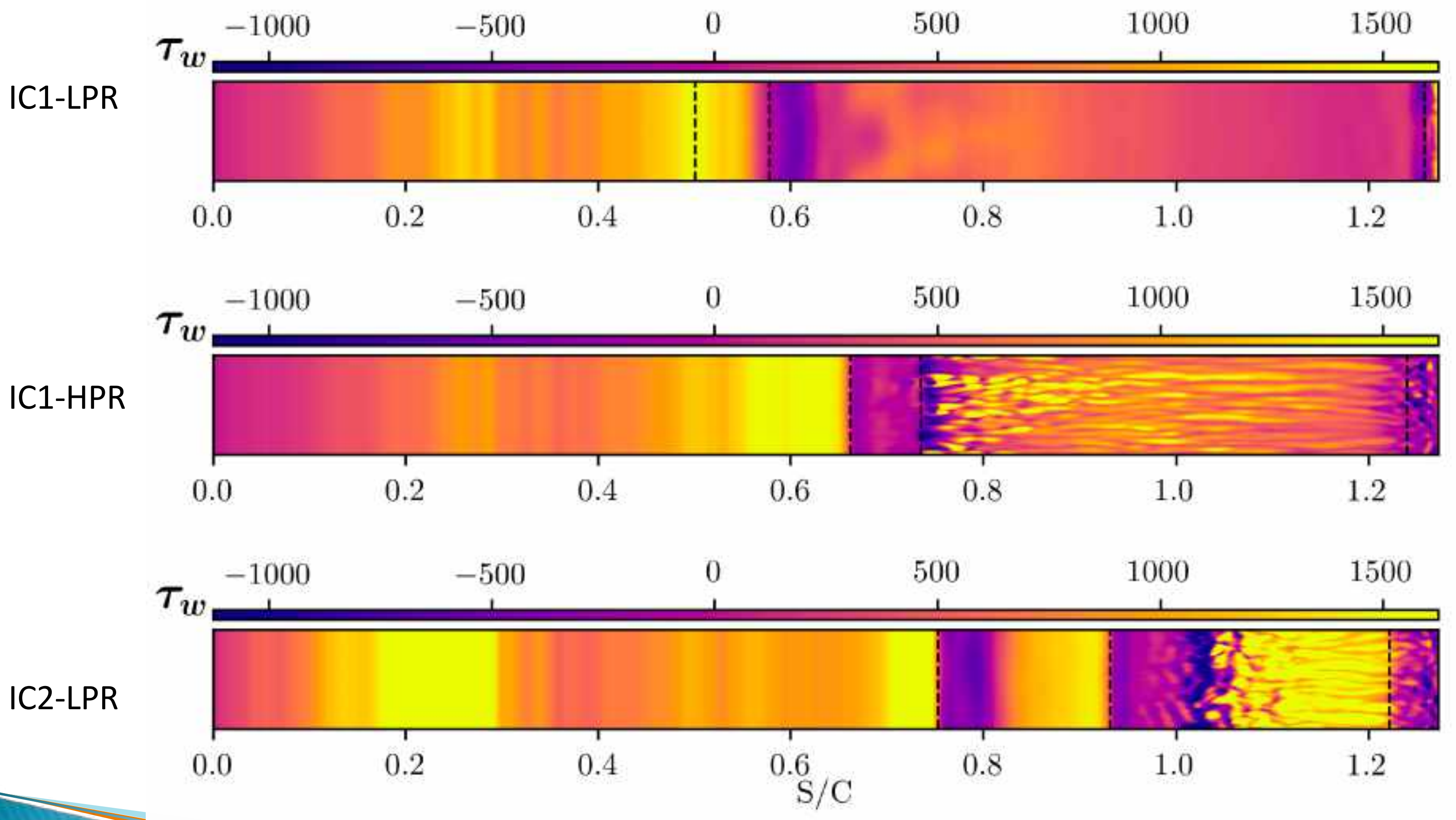
IC1-HPR

IC2-LPR



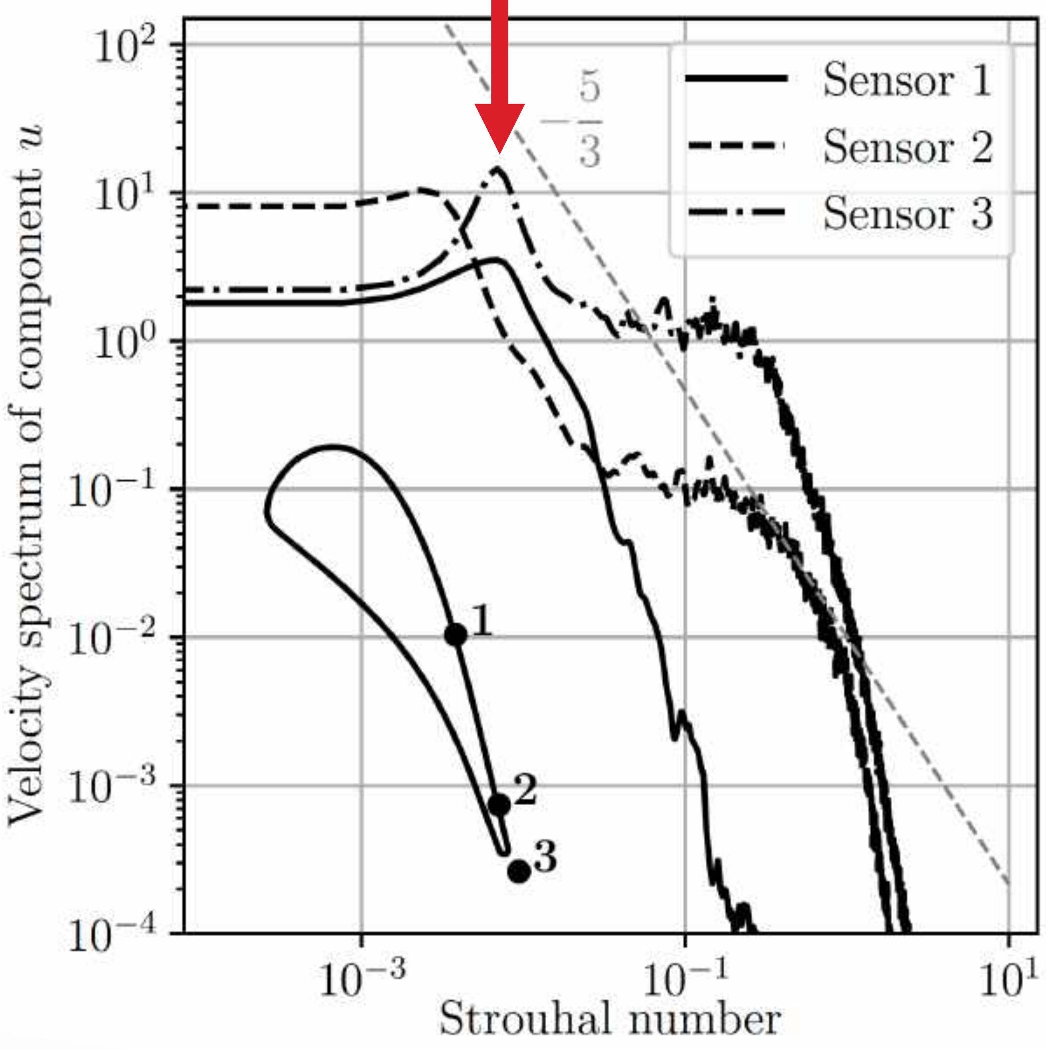
Boundary layer evolution

- Influence of the pressure ratio and thermodynamic working point, instantaneous wall friction:
  - IC1-LPR: laminar boundary layer, transition in the wake
  - IC1-HPR: transition due to shock/boundary layer interaction
  - IC2-LPR: transition triggered by unsteady motions of the impinging mixed expansion wave



Flow unsteadiness

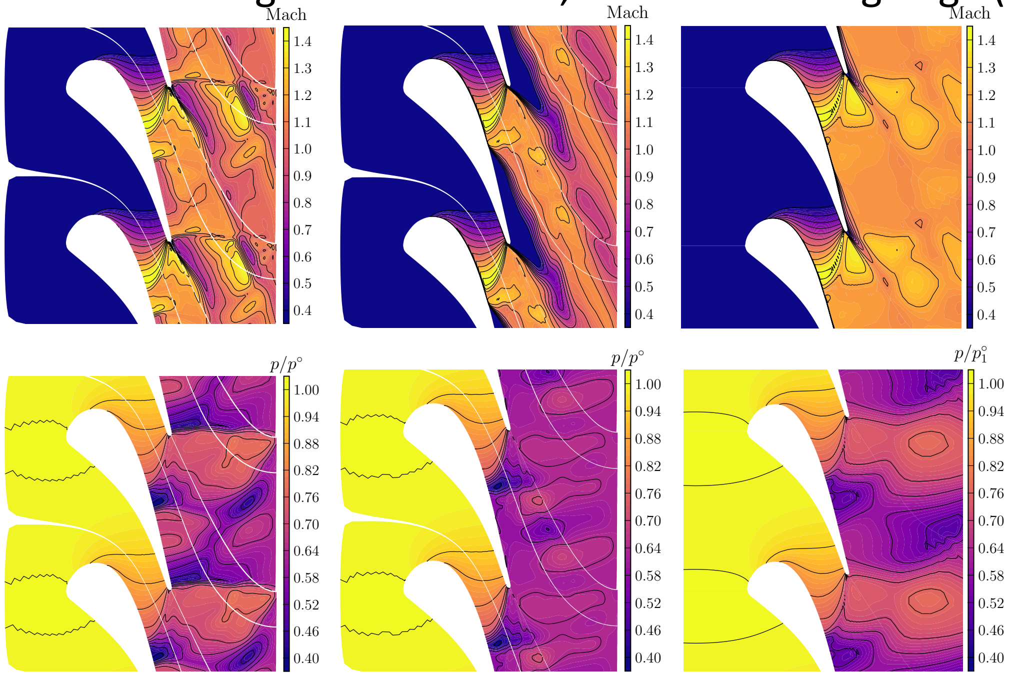
- Analysis of flow unsteadiness: spectral power density of axial velocity



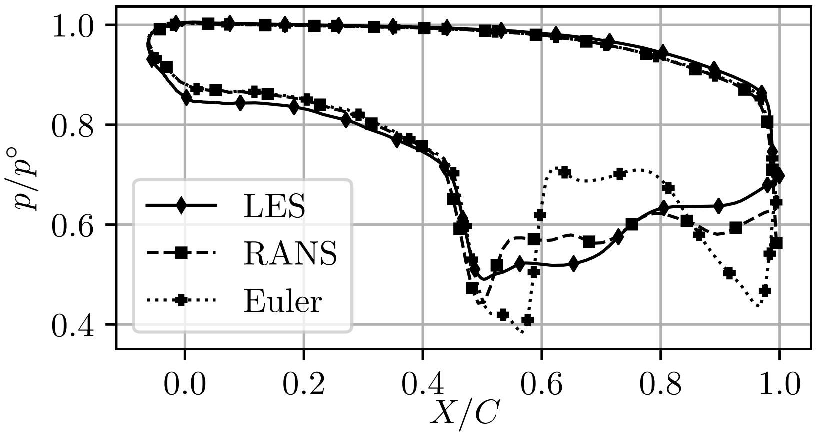
Low-frequency shock movement

Effect of the flow model

- Highly non-ideal case IC2-LPR
  - (U)RANS: Spalart-Allmaras model, C-grid 384x64 cells, $y^+ \approx 1$, 2nd-order backward time scheme
  - Euler: C-grid 384x32 cells, modified trailing edge (wedge)



Euler RANS LES



Pressure distribution at the blade wall

- Region up to the NCE insensitive to the flow model: mostly potential flow
- Trailing edge wave system highly dependent on boundary layer status and its coupling with outer flow
  - (U)RANS: large separation bubble appears due to abrupt recompression downstream of the NCE
  - Euler: reflected wave/contact discontinuity interactions downstream of the trailing edge
- Impact on loss coefficient:

	LES	**RANS**	**Euler**
$\zeta = \dfrac{T_{2,is}\Delta s}{h_1^0 - h_{2,is}}$	0.53x10^{-1}	0.37x10^{0}	0.45x10^{-1}

Conclusions and future work

- First wall-resolved LES of highly non-ideal flow in a turbine cascade presented
- Supercritical flow conditions
  - Complex non-classical shock system attached to the trailing edge observed
- At the present (moderate) Reynolds number, boundary layer transition plays a fundamental role
  - Weak sensitivity to the flow model upstream of the throat
  - RANS in poor agreement with LES, due to incorrect boundary layer transition and thickness
- Future work:
  - Carry out finer grid simulations at higher Reynolds numbers
  - Validate against experimental results: REGAL-ORC project
    (Arts et Métiers/Sorbonne Université/FH Muenster/TU Illmenau)
  - LES of supersonic ORC turbine geometries