High Fidelity Simulations of Combustion Turbine Systems, Niskayuna, NY, June 25th – 26th , 2012

CERFACS State-of-the-art and recent investigations for temperature predictions in Turbo-machineries

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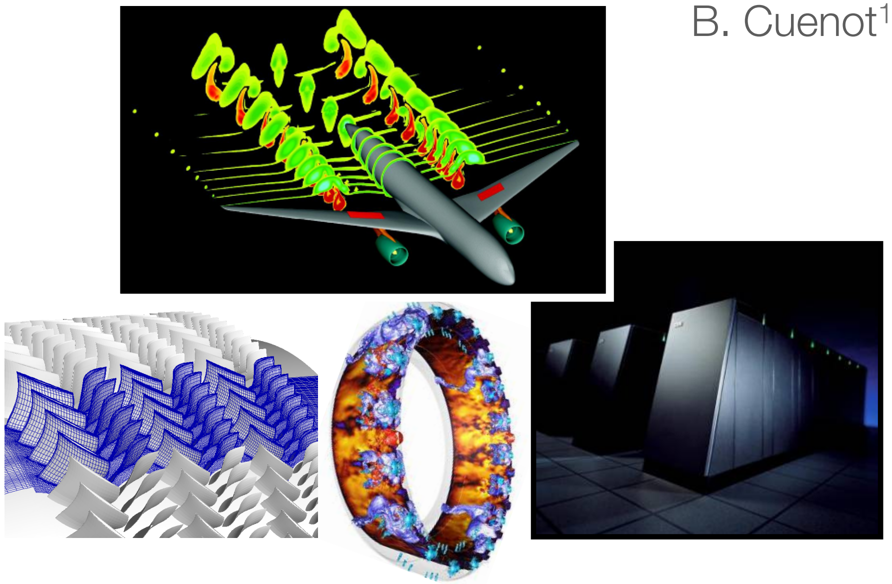
T. Poinsot[2]



[1] CERFACS - CFD Team, Toulouse
[2] IMFT, Toulouse

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Need to ensure scalability/portability and ‘*engineering*’ use of the tools:

AVBP – strong scaling

GUI of AVBP

Equivalent Performance

1
1
1
1

Produce state-of-the-art codes, methods and expertise for HPC while maintaining scientific excellence.

CFD team in 2011:

- 9 PhD dissertations – including 2 priced documents
- 35 Conference presentations – including invited conference talks
- 25 Journal publications

- Many EU research projects
- Many National research projects
- Many Bilateral research contract

Othe

- RIA)
- AVSP (acoustic), AVTP (heat transfer), PRISSMA (radiation)…

Where is CERFACS?

42 avenue G. Coriolis
31057 Toulouse Cedex 1, FRANCE

MUSAF II Colloquium – 18th-20th September 2013 – Toulouse (CIC)

Multiphysics, Unsteady Simulations, Control and Optimization Around aircraft and within engines

	Day 1	Day 2	Day 3
Morning	Acoustic & Noise Predictions	Reacting Flows	Optimization
Afternoon	Heat transfer, structures & loads	Rotating Flows	UQ-Control

I] State-of-the-art of unsteady simulations in combustors:

=> Massively parallel LES of combustors

=> Trends and potential orientations for LES in industrial burners

II] State-of-the-art massively parallel CFD for rotating and blade flows:

=> Massively parallel RANS/URANS of compressors

=> LES for turbine flows and aero thermal environment predictions

- High fidelity flow simulations (modeling issues)
- Wall heat transfer predictions and LES

III] Towards multi-physics CFD based on LES:

IV] Conclusions:

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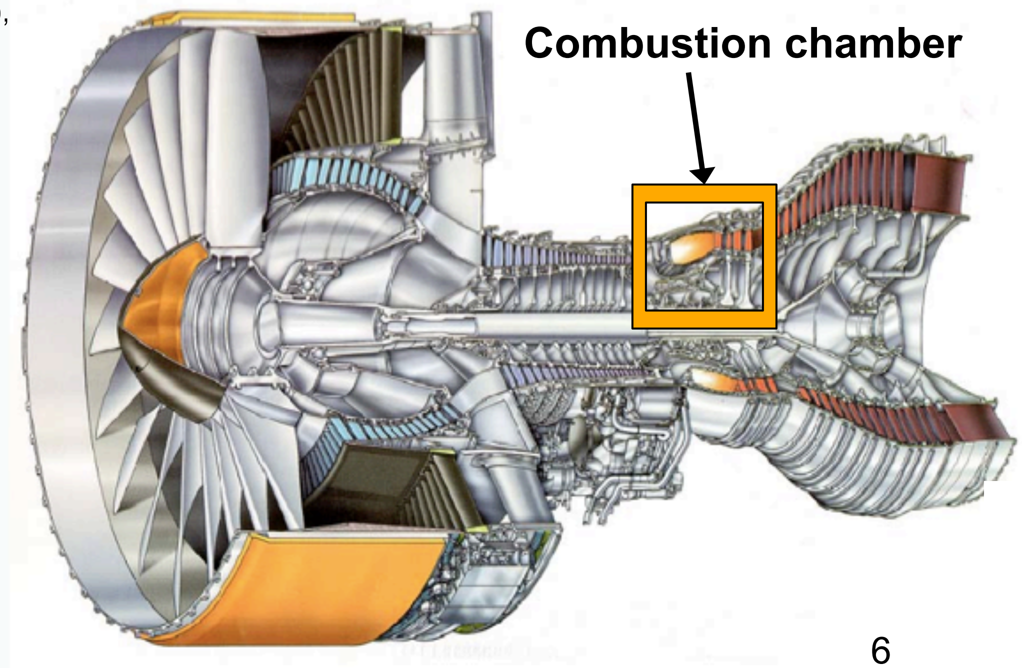
Flow acceleration due to gas expansion/combustion:

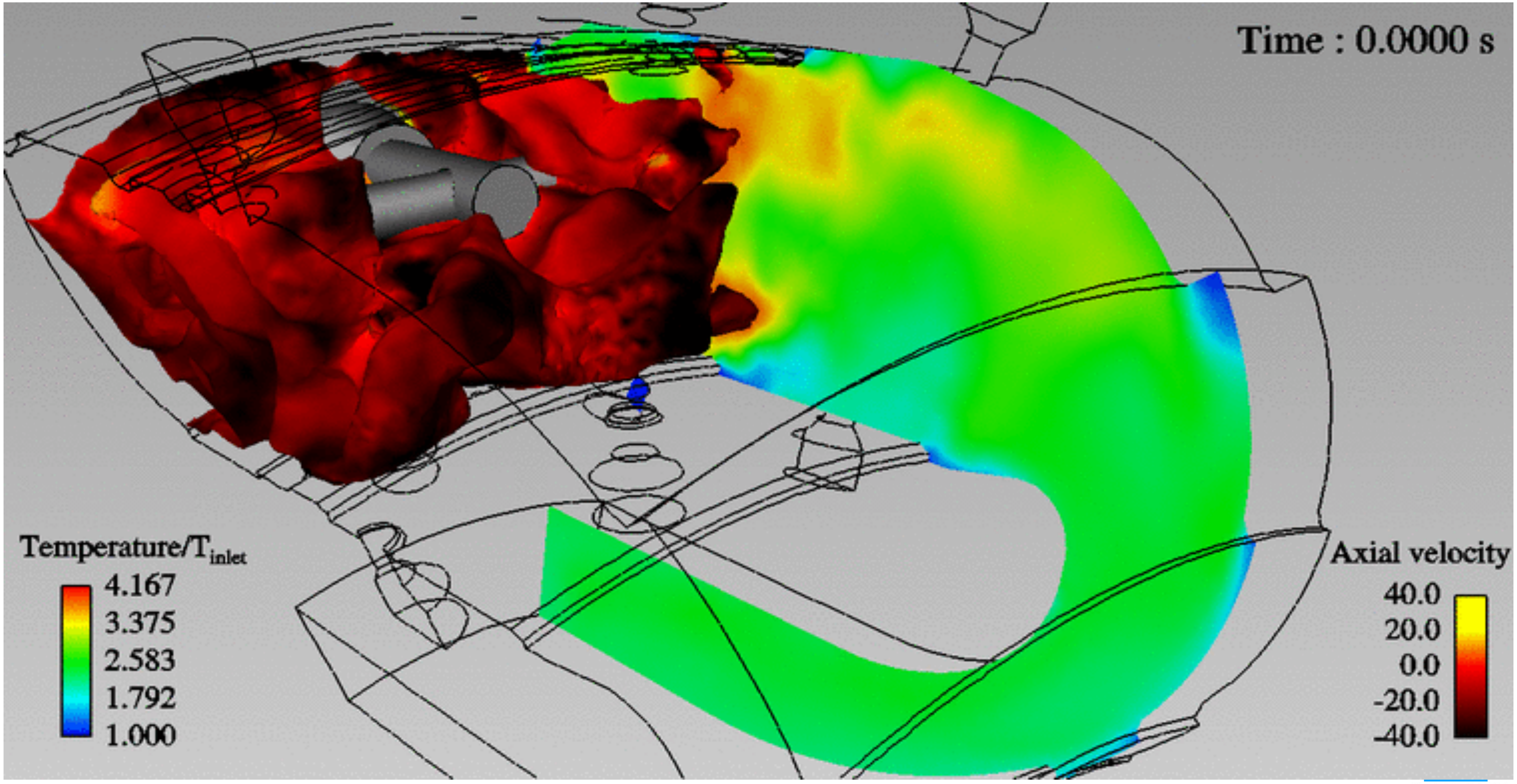
- Subject to thermo-acoustic oscillations (highly destructive and quasi unpredictable),
- Locus of pollutant formation,
- Strong thermal constraints…

=> Most recent publications demonstrate the superiority of LES [1]: i.e. captures the strong coupling between turbulence/mixing/combustion

[1] Gicquel, L.Y.M. et al., Large Eddy Simulations of gaseous flames in gas turbine combustion chambers, PECS (in press), 2012.



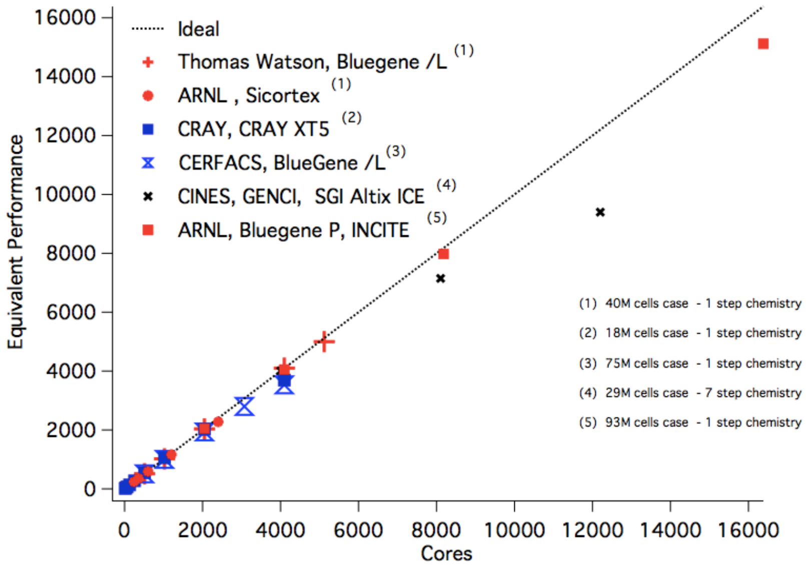
Target configuration: Single sector gaseous (partially premixed) LES [1]



[1] G. Boudier et al., Comb. Inst., 31(2):3057-3082, 2007.

Scalability/portability of LES codes open new perspectives:

AVBP – strong scaling



- **Full azimuthal chamber LES**

  => azimuthal thermo-acoustic instabilities [1]

- **Increase model accuracy of single-sector LES**

  => grid resolution sensitivity [2]

  => pseudo-detailed chemistry [3]

  => multi-phase flow models

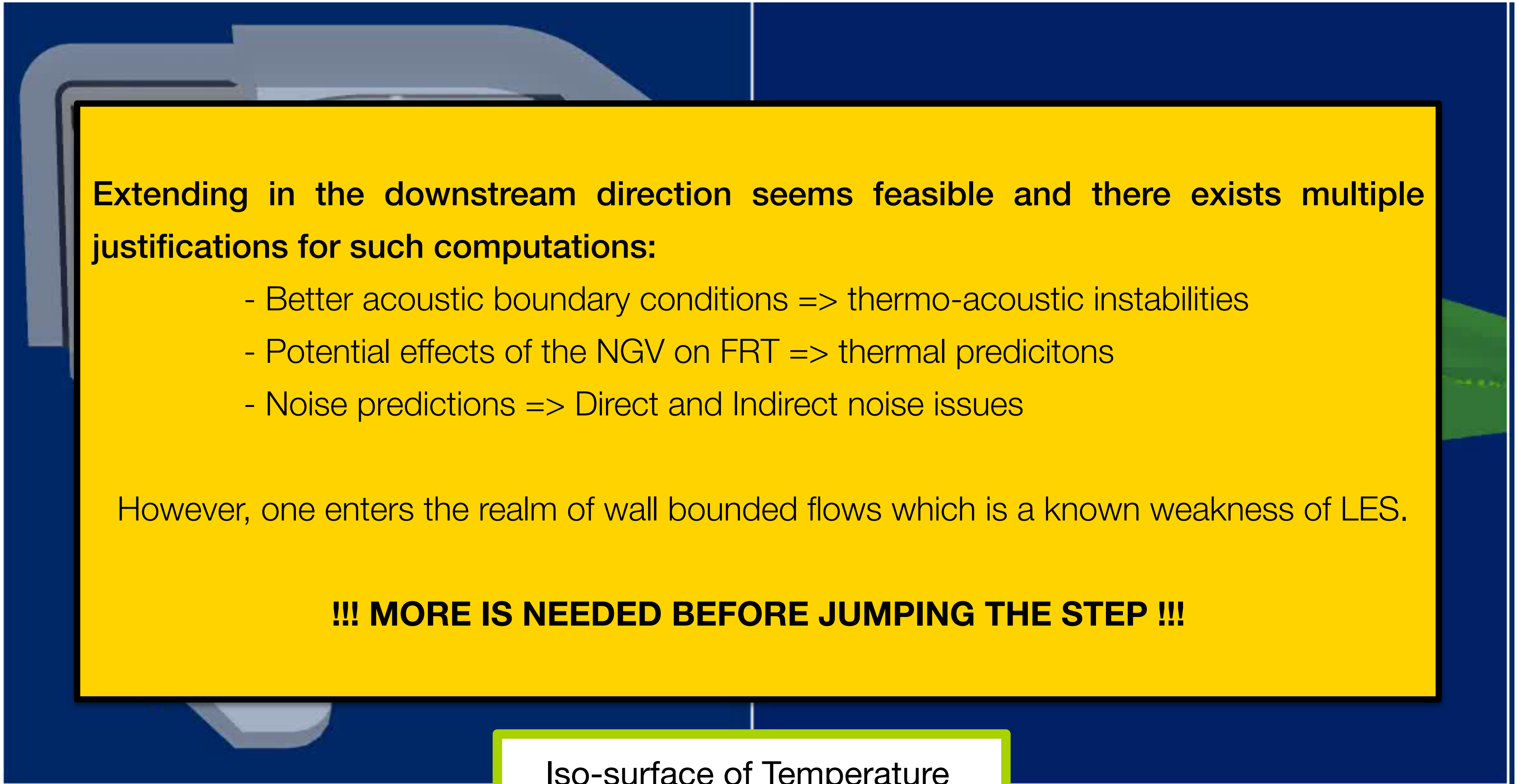
  - Euler / Euler approach
  - Euler / Lagrange approach

  => multi-physics: conduction, radiation [4]

[1] P. Wolf et al, CF (in press), 2012.
[2] G. Boudier et al, CF, 155:196-214, 2008.
[3] B. Frazelli et al, CF, 157(7):1364-1373, 2010.
[4] F. Duchaine et al, IJHFF, 30(6):1129-1141, 2009.

- **Extended single-sector LES (whenever possible)**

  => cover the elements after / before the combustor



Extending in the downstream direction seems feasible and there exists multiple justifications for such computations:

- Better acoustic boundary conditions => thermo-acoustic instabilities
- Potential effects of the NGV on FRT => thermal predicitons
- Noise predictions => Direct and Indirect noise issues

However, one enters the realm of wall bounded flows which is a known weakness of LES.

!!! MORE IS NEEDED BEFORE JUMPING THE STEP !!!

Iso-surface of Temperature
(representative of hot gases)

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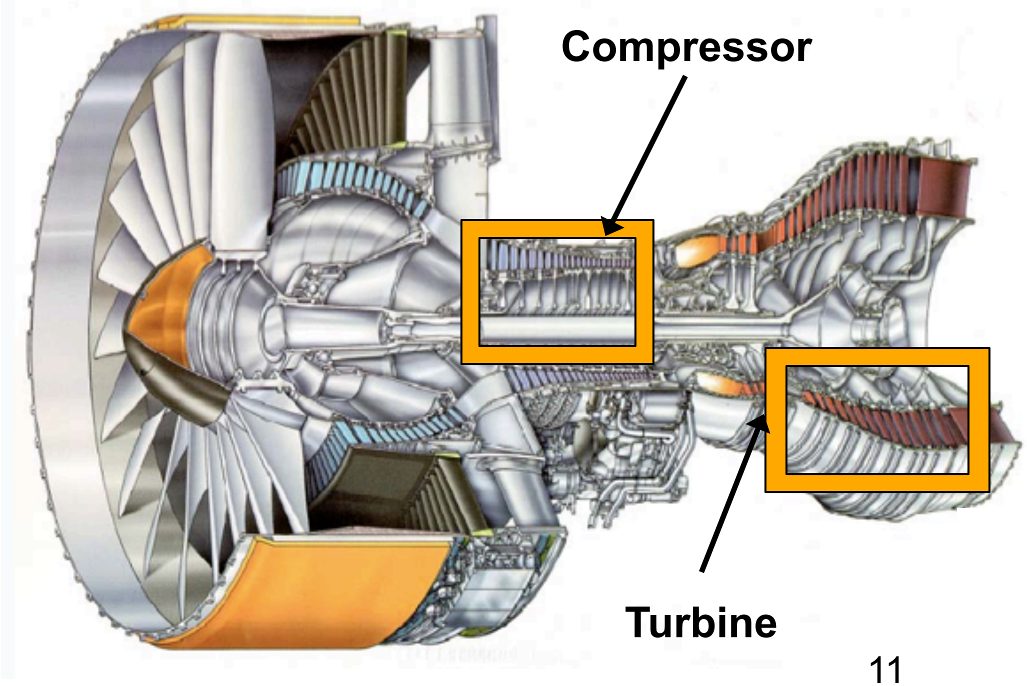
- Rotating machines are involved in most of the energy conversion processes,

- **<u>Unsteady flows</u>** are still not well understood, especially in multistage turbomachines,
  - ➢ aerodynamic instabilities are penalizing for efficiency (design margins).

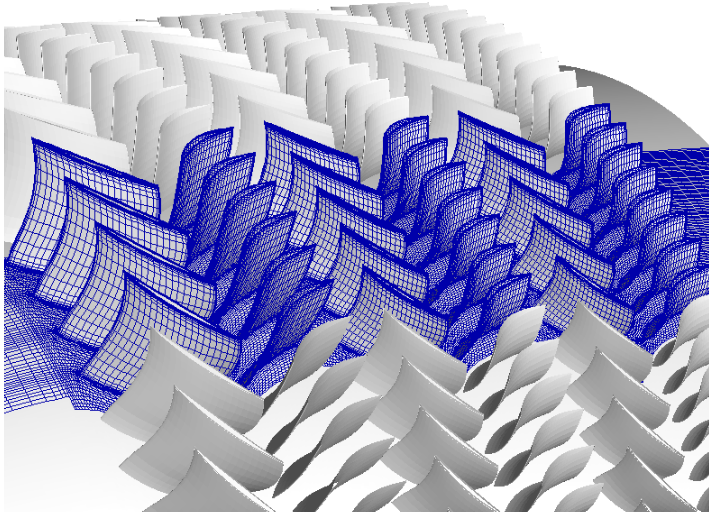
- Problems to simulate these devices are the **size**, the **complexity,** the **Re number** => **CPU costs**:
  - ➢ most of the industrial simulations focus on limited parts of the system (such as isolated blades) that are solved with a steady RANS approach.



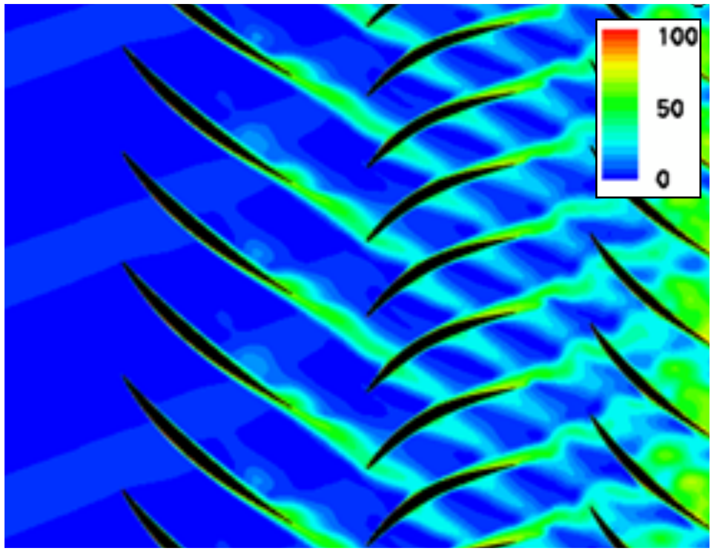
Research approach: unsteady whole configuration

Sliding mesh method (non-coincident interface):

- Unsteady RANS calculation considering the whole geometry,
- All unsteady interaction at interface are simulated,
- Whole mesh is around **100M – 1000M** cells for a 3 stage compressor [1].



- ➢ **unlimited number of rows,**
- ➢ **unsteady flow interactions,**
- ➢ **adapted to all configurations,**
- ➢ **important cost.**

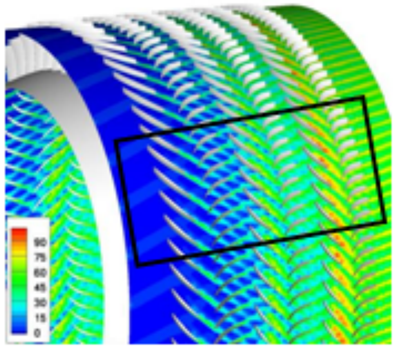


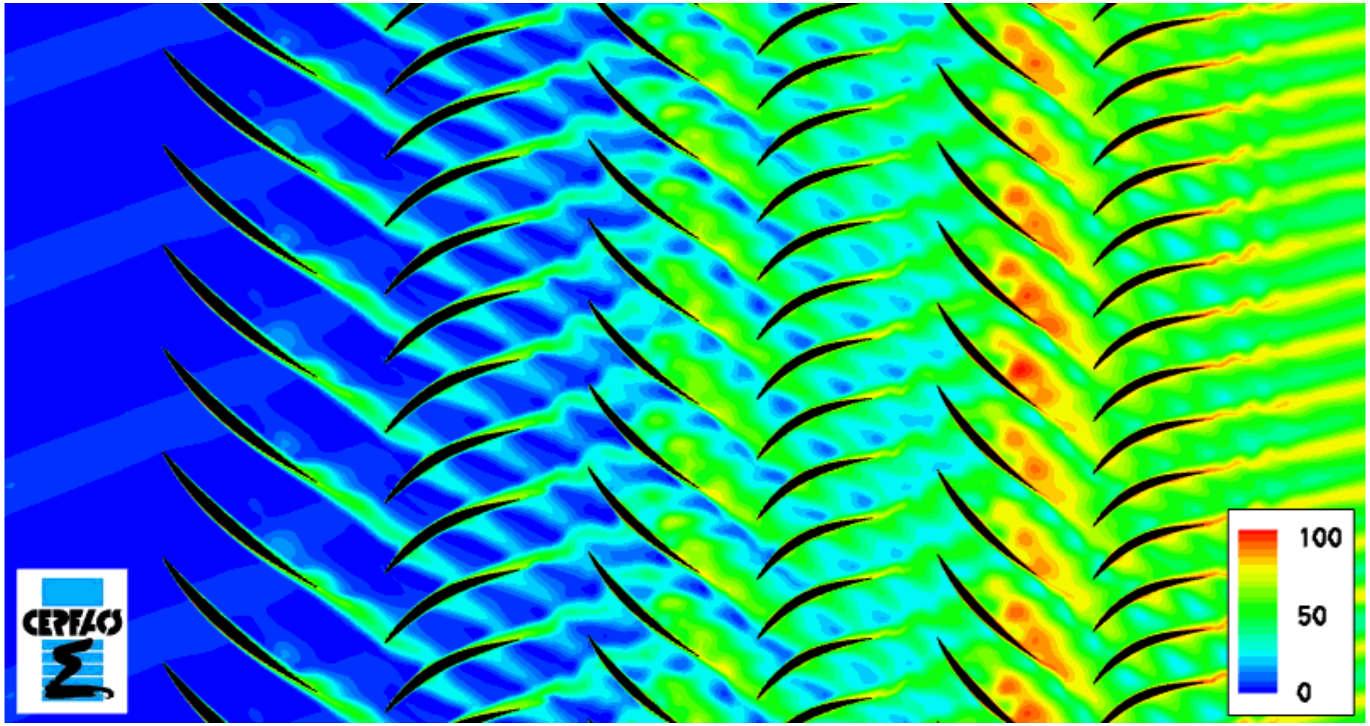
Unsteady whole configuration solution (entropy field)

[1] N. Gourdain et al, CSD, 2:015003, 2009.

Simulation at design operating point

- 512 processors (Blue Gene/L),
- 24 days of computation (one rotation), i.e. 300,000 CPU hours.





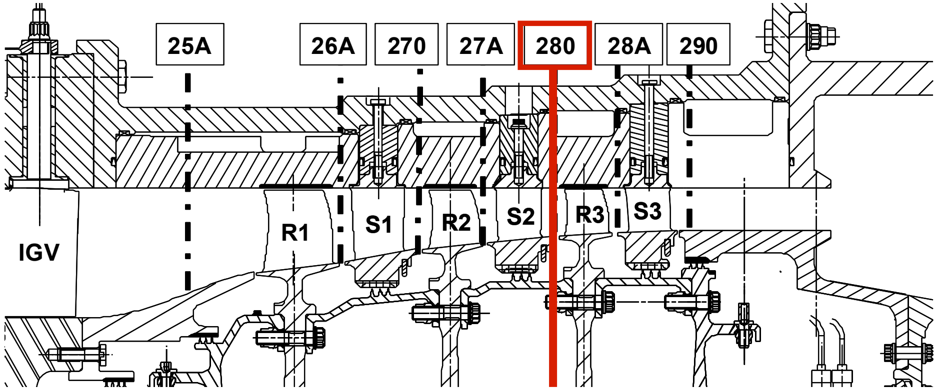
Entropy flow field (h/H=83%)

[1] N. Gourdain et al, CF: 39(9): 1644-1655, 2010.

Large multistage effects (blade rows interactions):

- flow in the 3rd rotor is partially driven by wakes of the 2nd stator.

Comparisons of experimental/research results

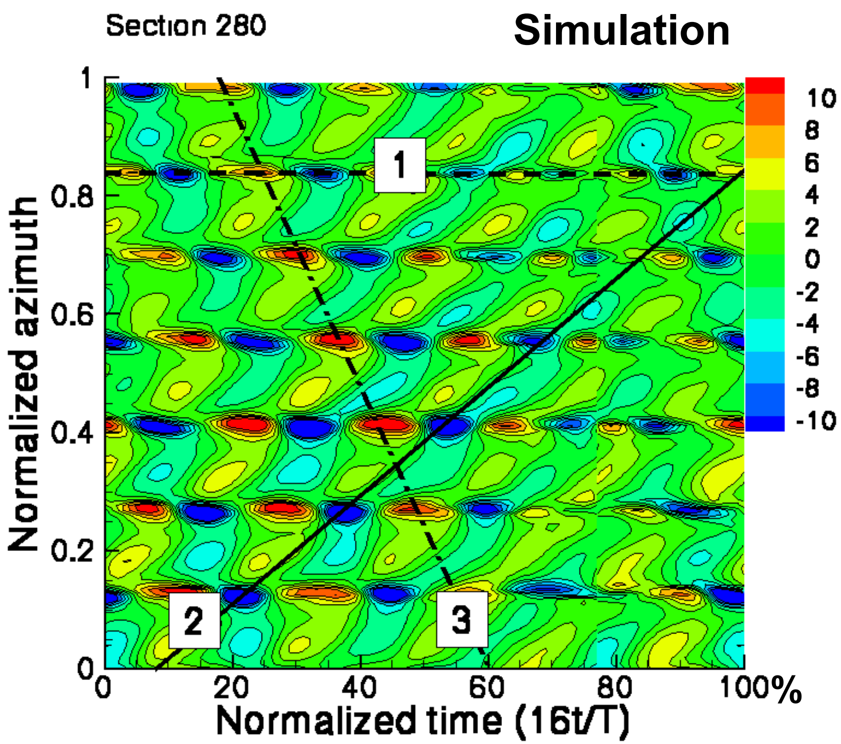


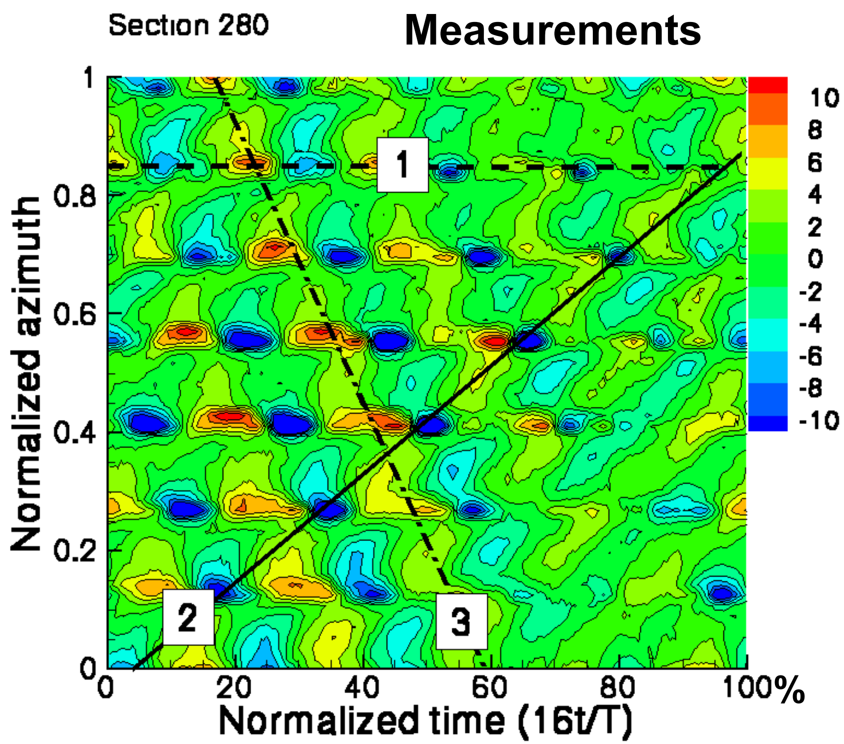
[1] N. Gourdain et al, CF: 39(9):1644-1655, 2010.

1: stator wakes

2: rotor potential effects

3: rotor-stator interaction modes





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- Challenges today for turbine designers is the prediction of heat transfer:
  - a **15 K difference** on the temperature prediction leads to a **reduction of the engine life duration by a factor 2**,
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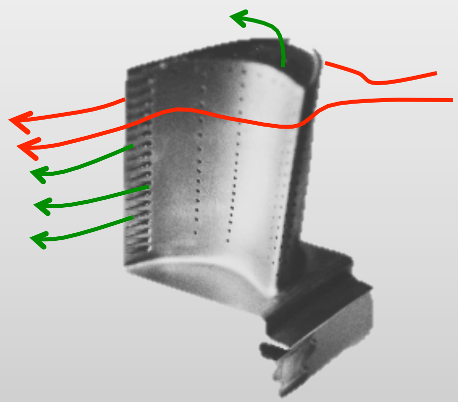
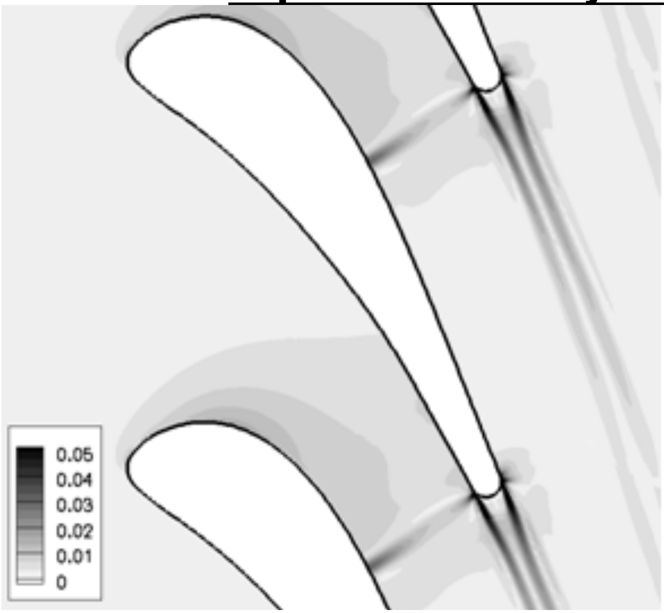
Two leverages to release or anticipate better the aero thermal constraints of this device

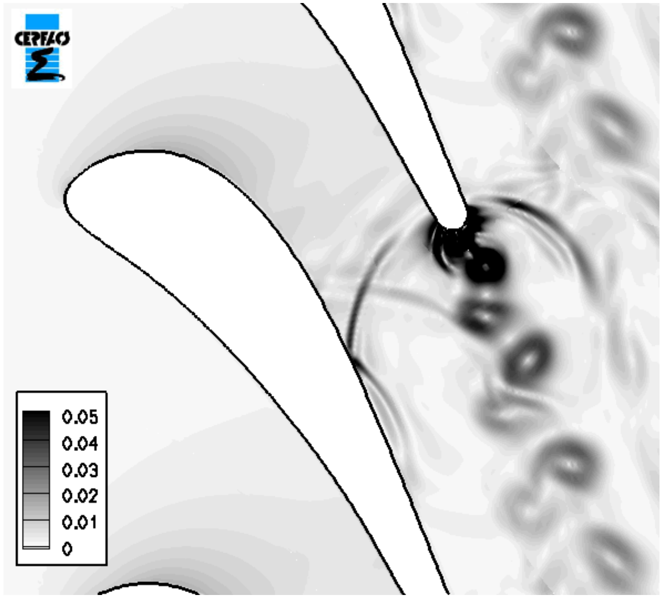
Flow around the blade



Improved cooling systems

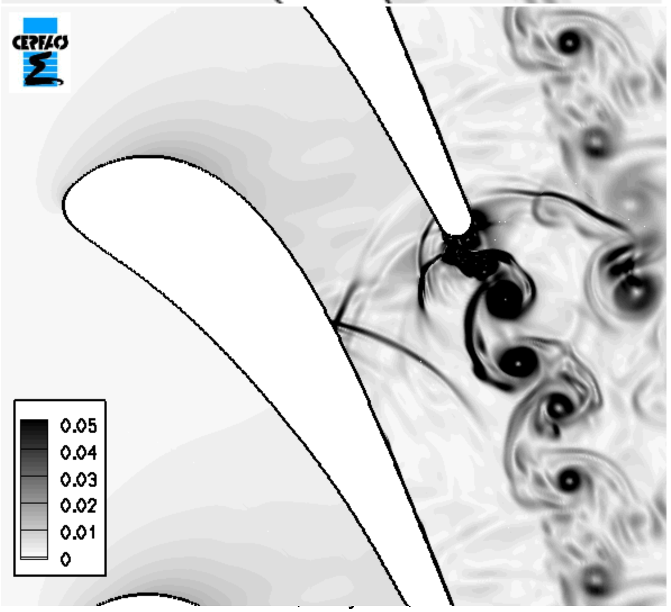
Impact on unsteady aerodynamic performance





T. Léonard et al., in ASME Turbo-Expo, Glasgow, 2010.

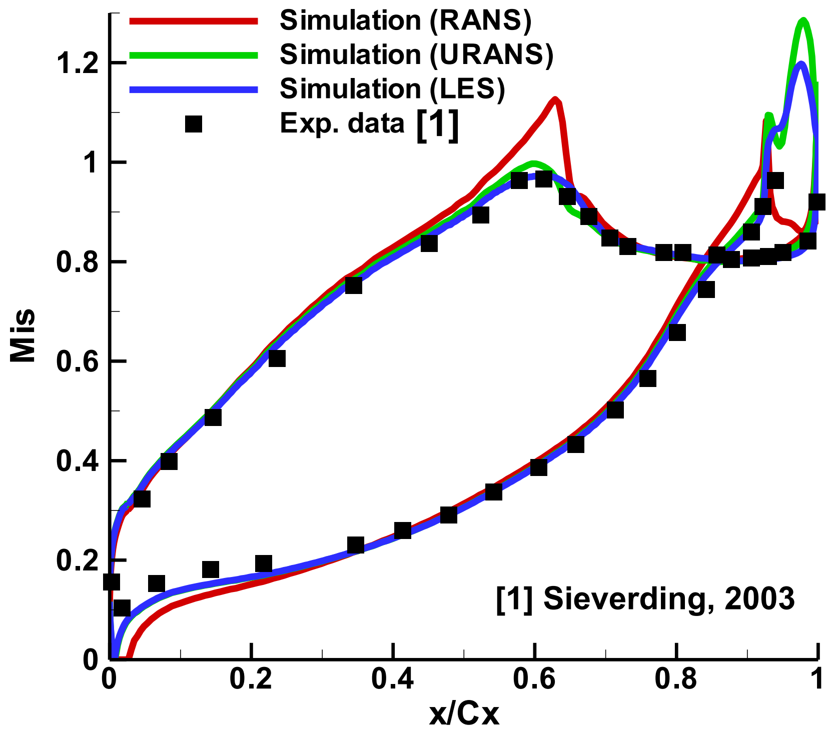
N. Gourdain et al., in ASME Turbo-Expo, Vancouver, 2011.



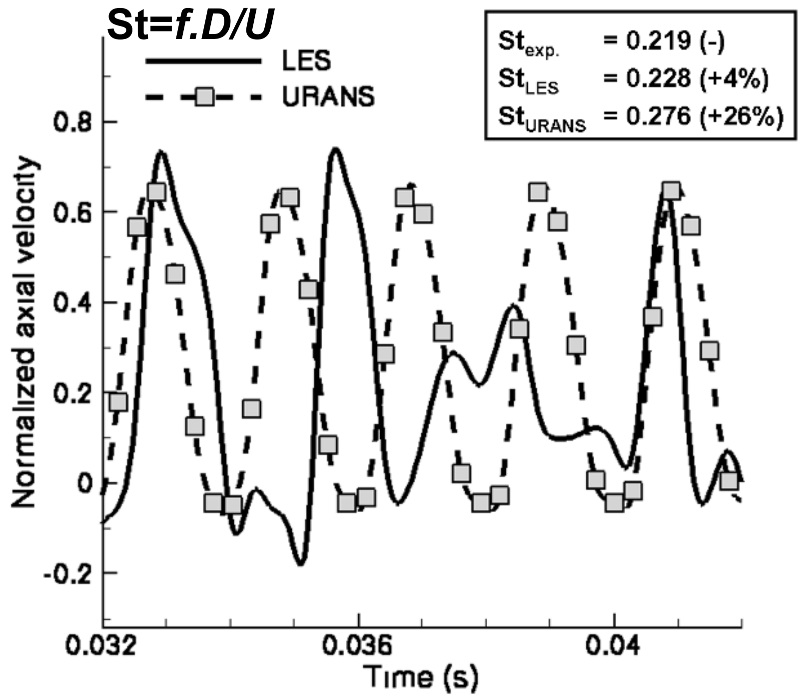
Instantaneous grad ρ flow field (*elsA*)

- RANS predicts a non-physical shock-wave,
- URANS predicts the vortex shedding but flow features are damped by artificial viscosity,
- LES demonstrates its capacity to transport flow vortices and acoustic waves.

Comparisons with experiments



Axial velocity registered behind the trailing edge



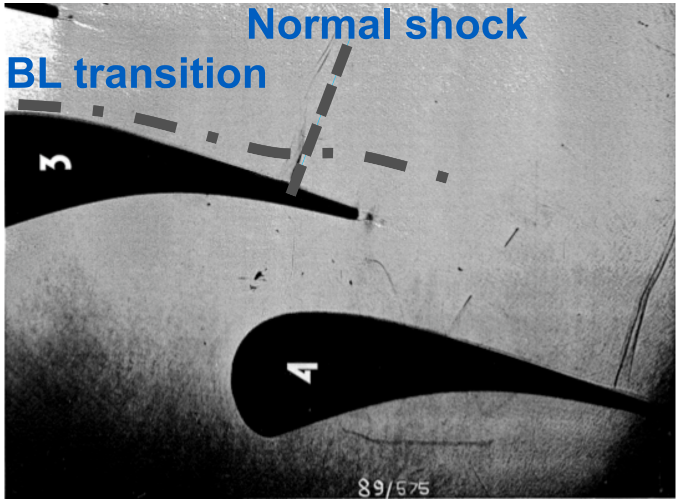
- RANS predicts a non-physical shock on suction-side,
- URANS/LES correctly predict global values,
- **LES estimates correctly the experimental Strouhal number.**

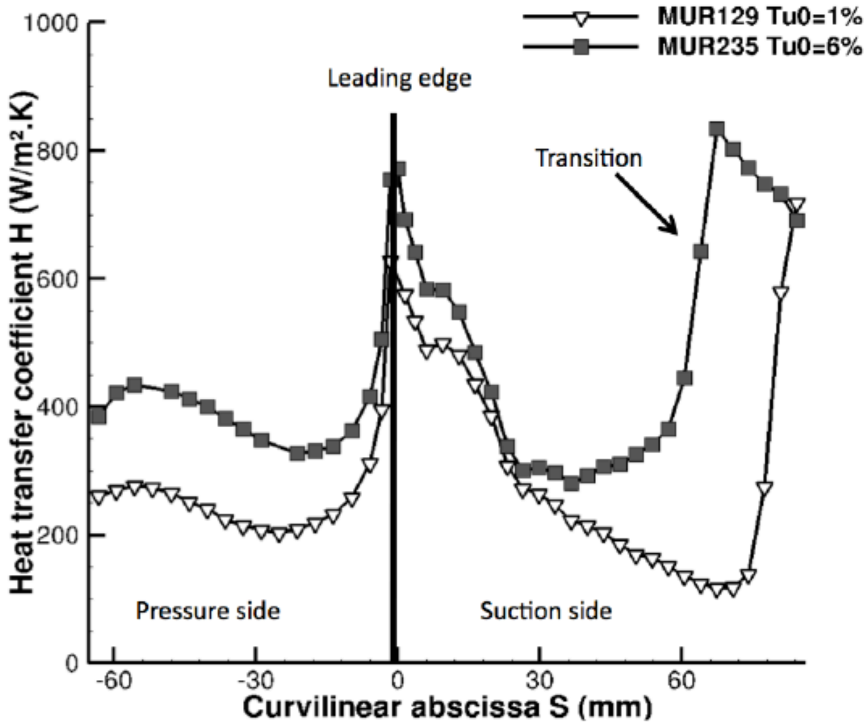
LS89 blade

The heat transfer coefficient is defined as (ΔH~5%):

$$H = \frac{Q_{wall}}{T_\infty - T_{wall}}$$

Test case	Re_2	$M_{is,2}$	$P_{i,0}$	$T_{s,wall}$	Tu_0
MUR129	$1.13\ 10^6$	0.840	$1.87\ 10^5\ Pa$	298 K	1.0%
MUR235	$1.15\ 10^6$	0.927	$1.85\ 10^5\ Pa$	301 K	6.0%





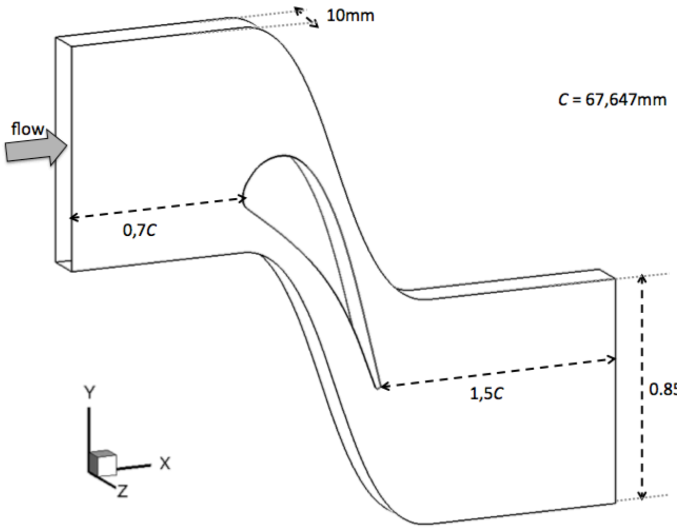
[1] Arts et al., J. Turbomachinery, 1992

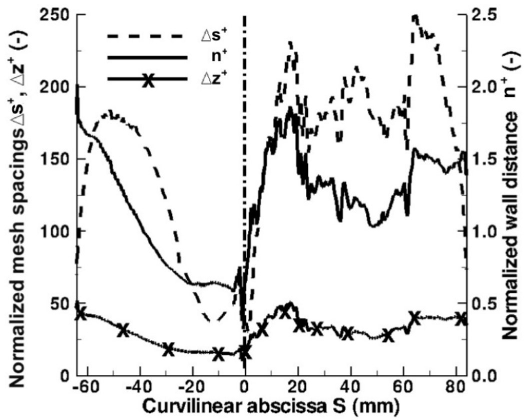
Heat transfer is driven by the *freestream turbulent* intensity (i.e. the turbulence at the inlet)

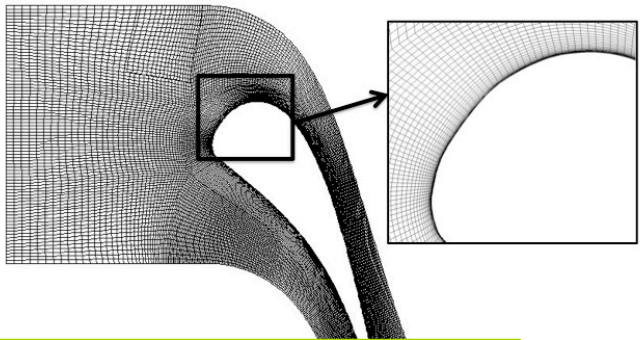
Basic questions about LES around blades:

- what numerical scheme (explicit vs implicit), what mesh topology / resolution
- what SGS model (wall model or wall resolved)
- what computational domain extent

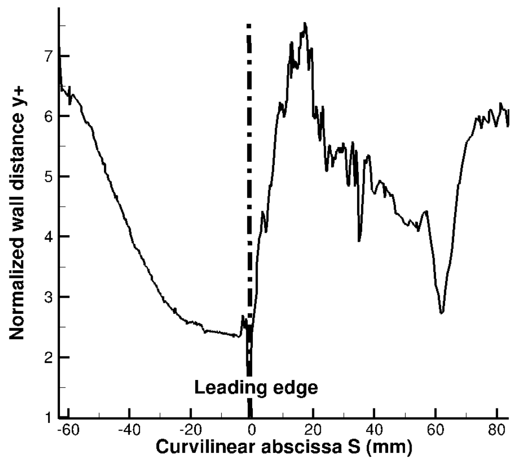
Computational domain

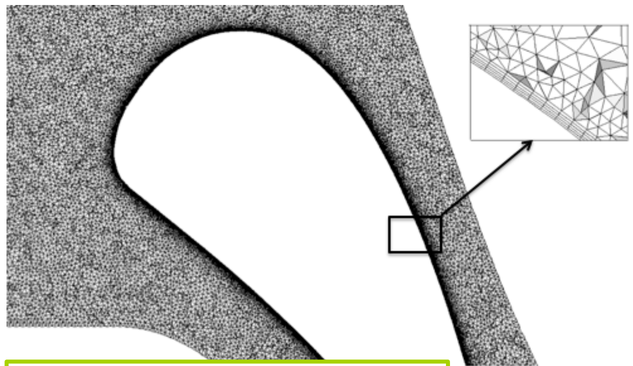






Structured mesh - elsA

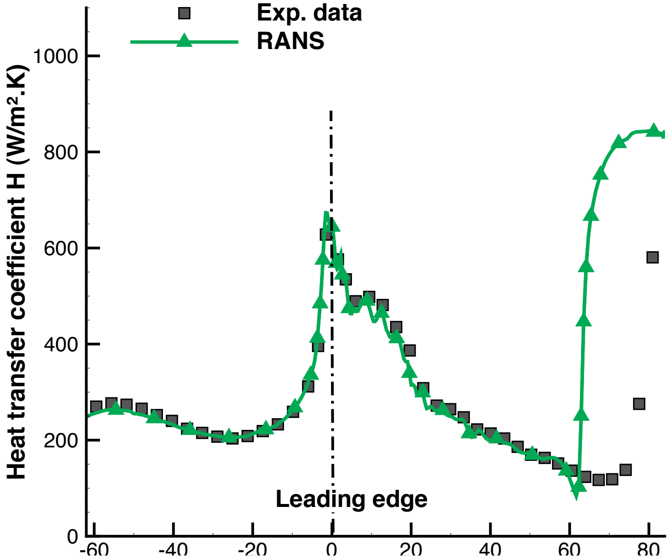


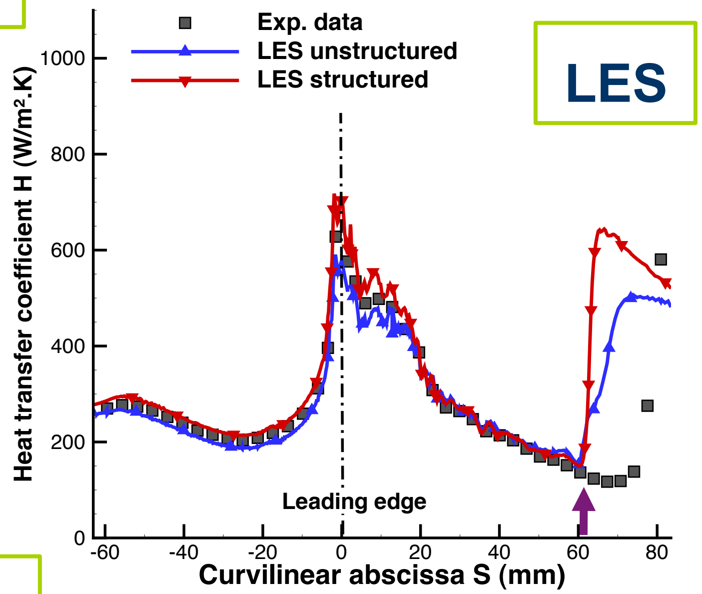


Hybrid mesh - AVBP

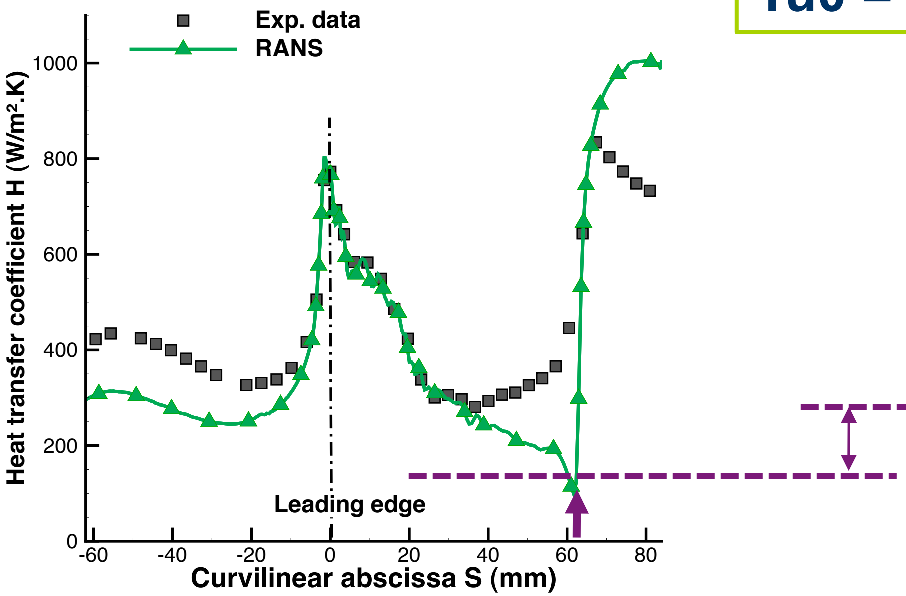
Turbines: LES vs RANS

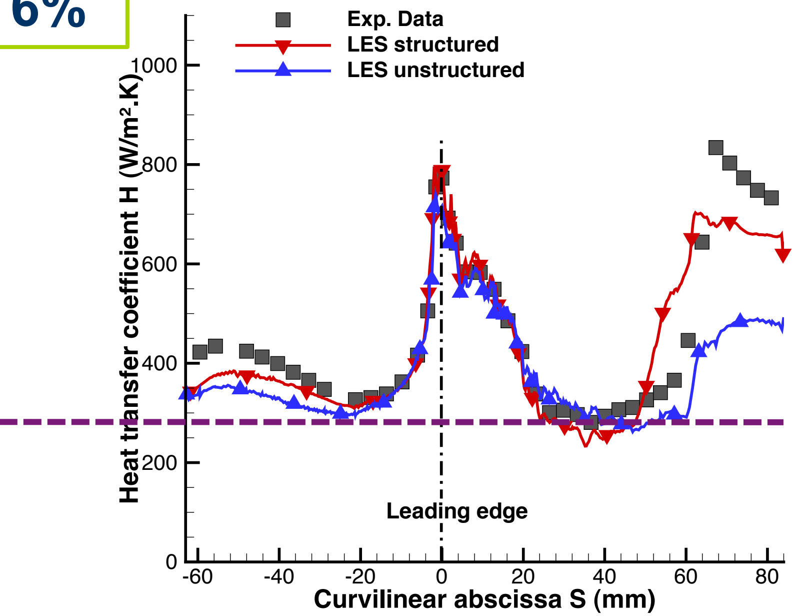
Tu0 = 0%



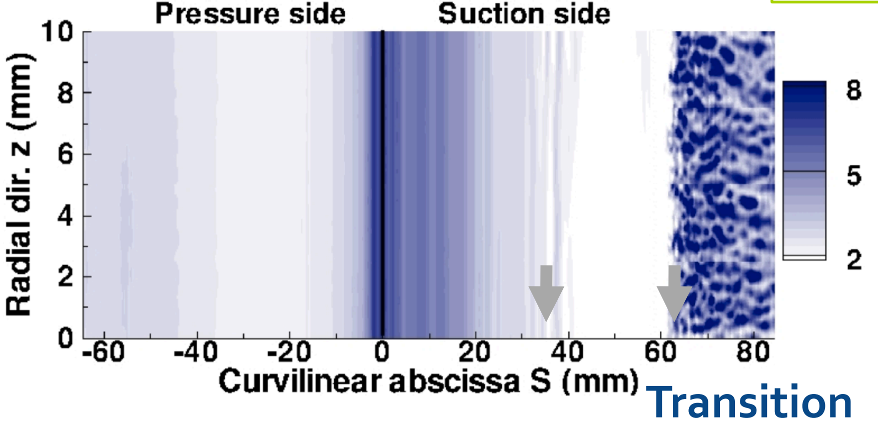


Tu0 = 6%

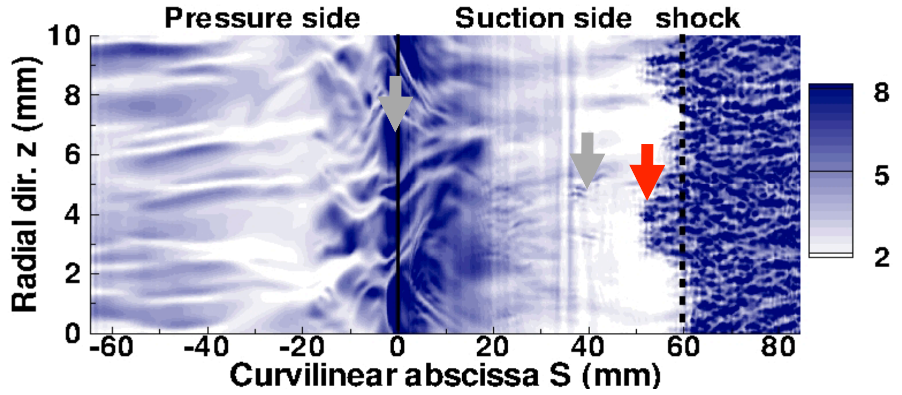




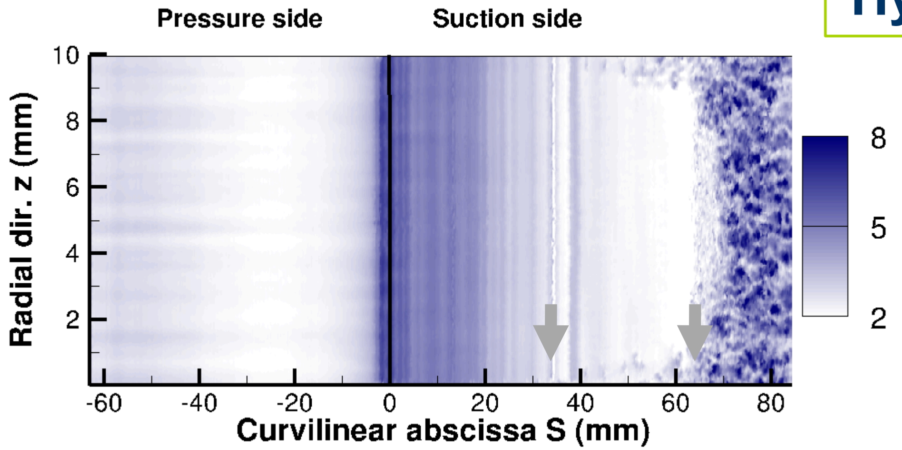
Tu0=0% **Structured** **Tu0=6%**

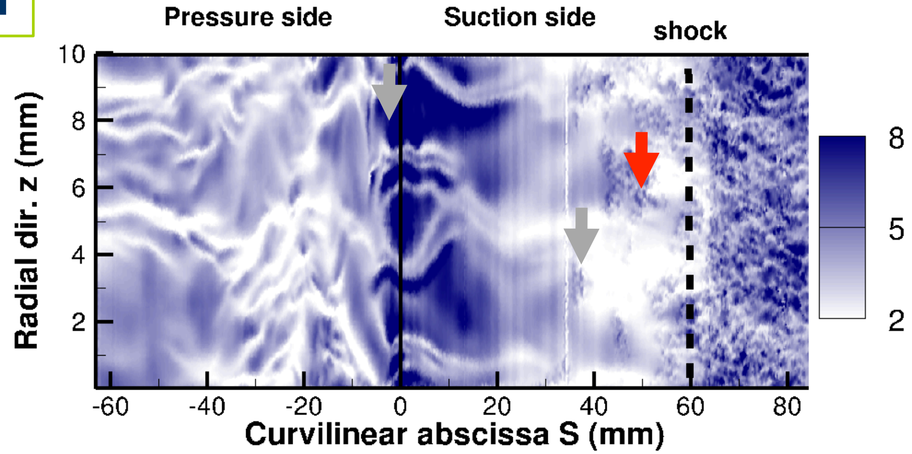


Transition



Hybrid





[1] E. Collado Morata, N. Gourdain and L.Y.M. Gicquel. Structured vs. Unstructured LES for the Prediction of Free-Stream Turbulence Effects on the Heat Transfer of a High Pressure Turbine Profile, IJHMT (in press), 2012.

One key element for LES to reproduce such behaviors is the introduction of an unsteady turbulent field at the inlet of the vane [1, 2]

Wall-resolved LES of the flow in the vane *seems possible* and *does improve reliability* of the thermal predictions (aerodynamic response of the flow).

HOWEVER:

- Very large grids (structured or unstructured)
- Massively parallel machines and code scalability are pre-requisite

- **Alternatives** => wall models (DES, DDES, wall laws…)
  => need for reliability studies of such solutions

!!! What is really needed in terms of design for these flows !!!

Turbines

- As for compressors, unsteady flows are still not well understood,
- Problems are the **size**, the **<u>complexity</u>,** the **Re number** (although lower than for compressors)

  => **CPU costs**

- Challenges today for turbine designers is the prediction of heat transfer:
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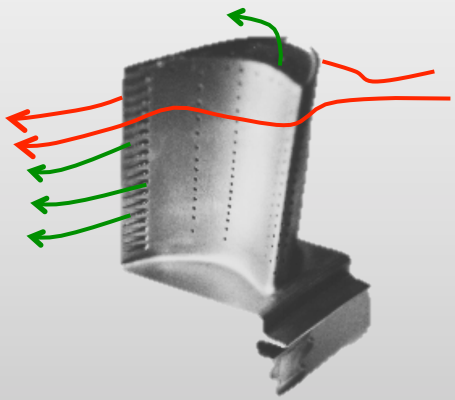
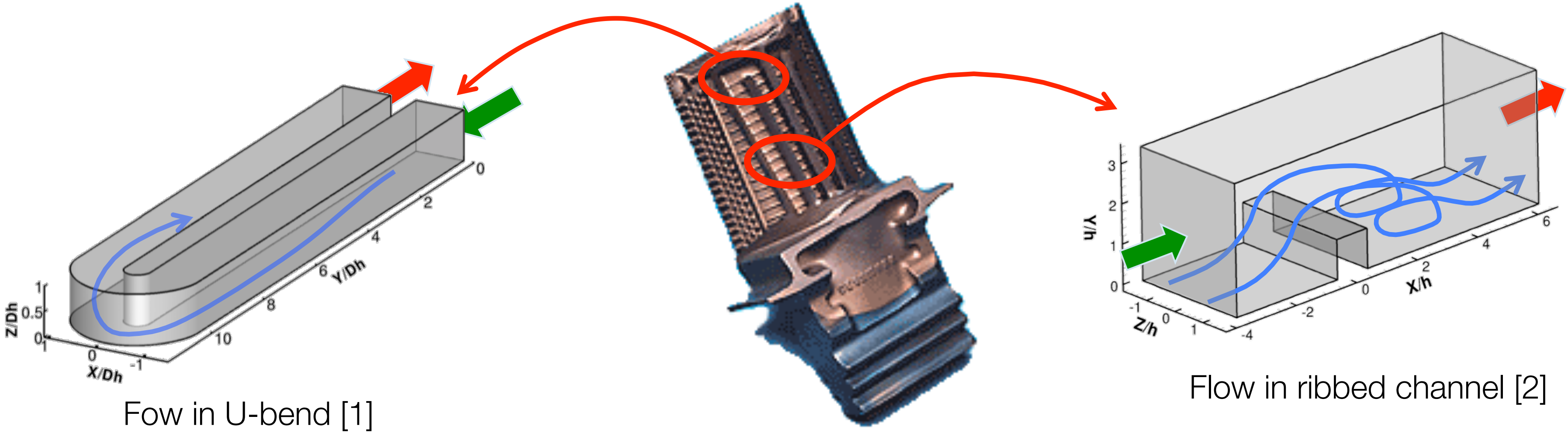
Flow around the blade



Improved cooling systems

Comparison of CFD methods to predict blade internal cooling channel flow:



Fow in U-bend [1]

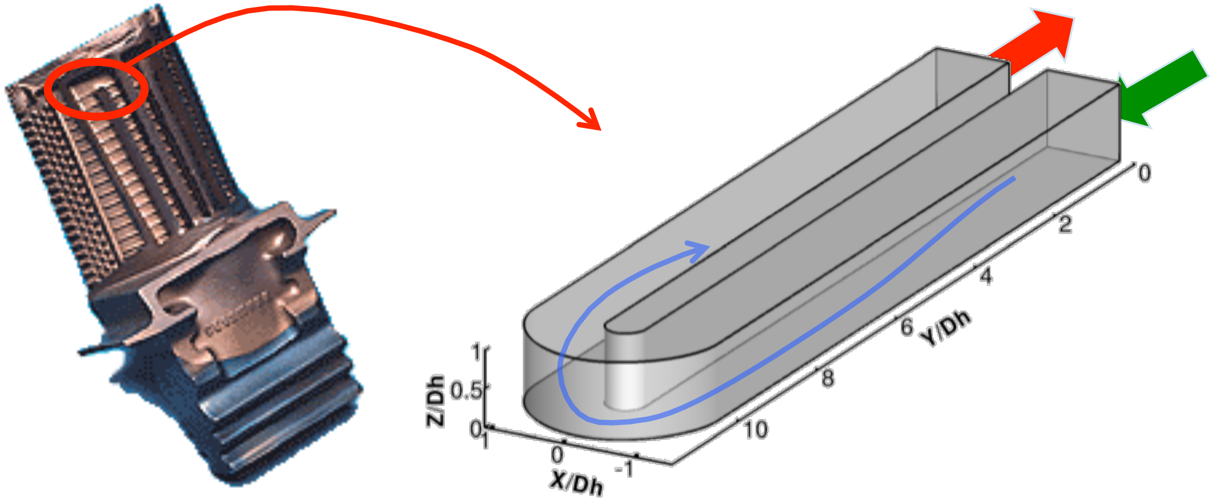
Flow in ribbed channel [2]

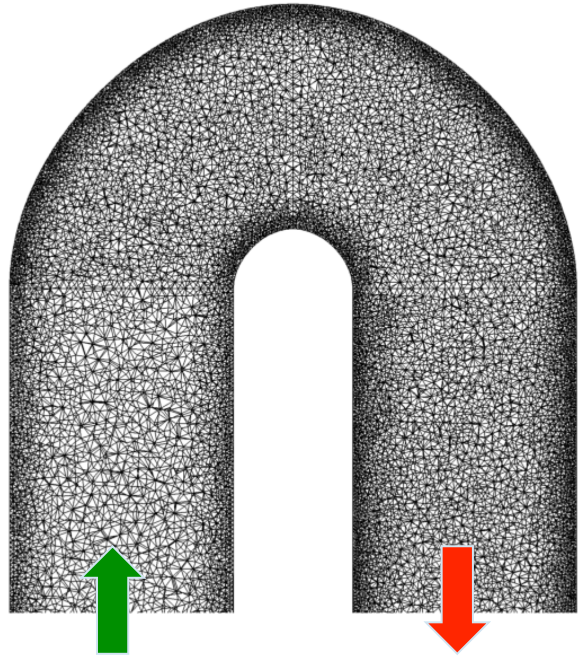
[1] Gourdain, N., Gicquel, L. Y. M., Fransen, R., Collado, E. & Arts, T. Application of RANS and LES to the Prediction of Flows in High Pressure Turbines Components. ASME Turbo Expo 2011 (2011).
[2] Fransen, R., Gourdain, N., Gicquel, L.Y.M., Steady and unsteady modeling for heat transfer predictions of high pressure turbine blade internal cooling, ASME Turbo Expo 2012 (2012).

➔ **Context of this study :**

U-bend, Ribbed channel → Thermal study / Rotating study → Industrial configuration with conjugated heat transfer

U-bend

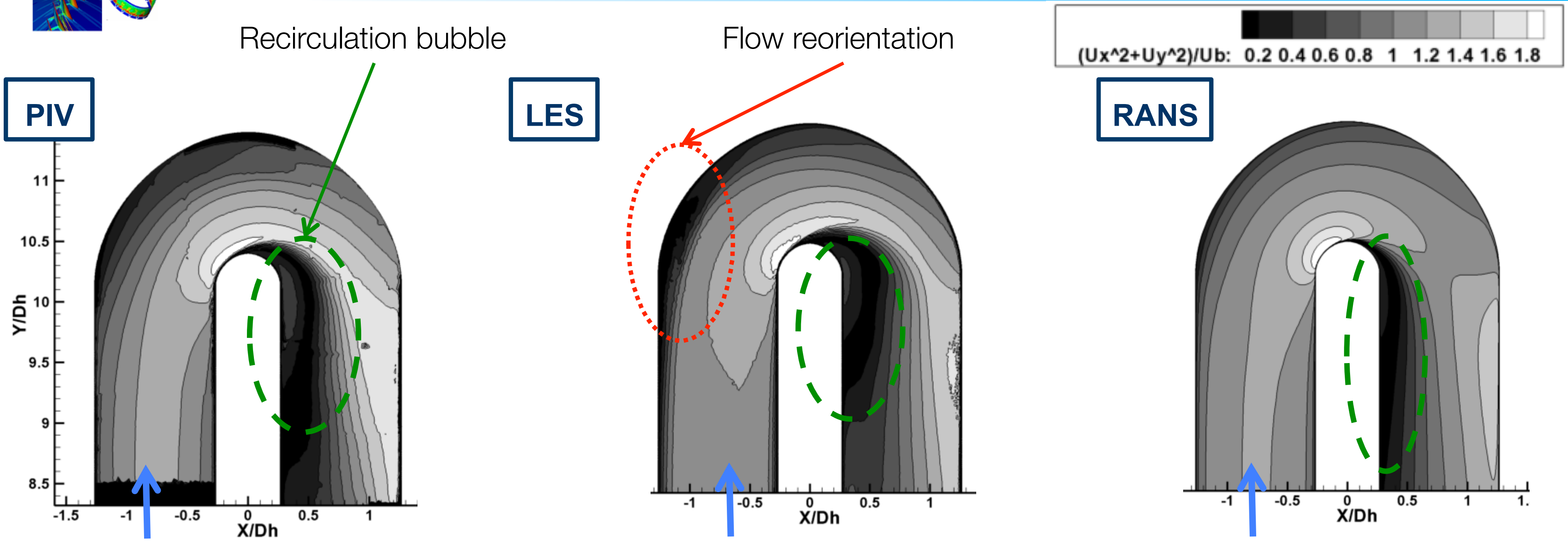




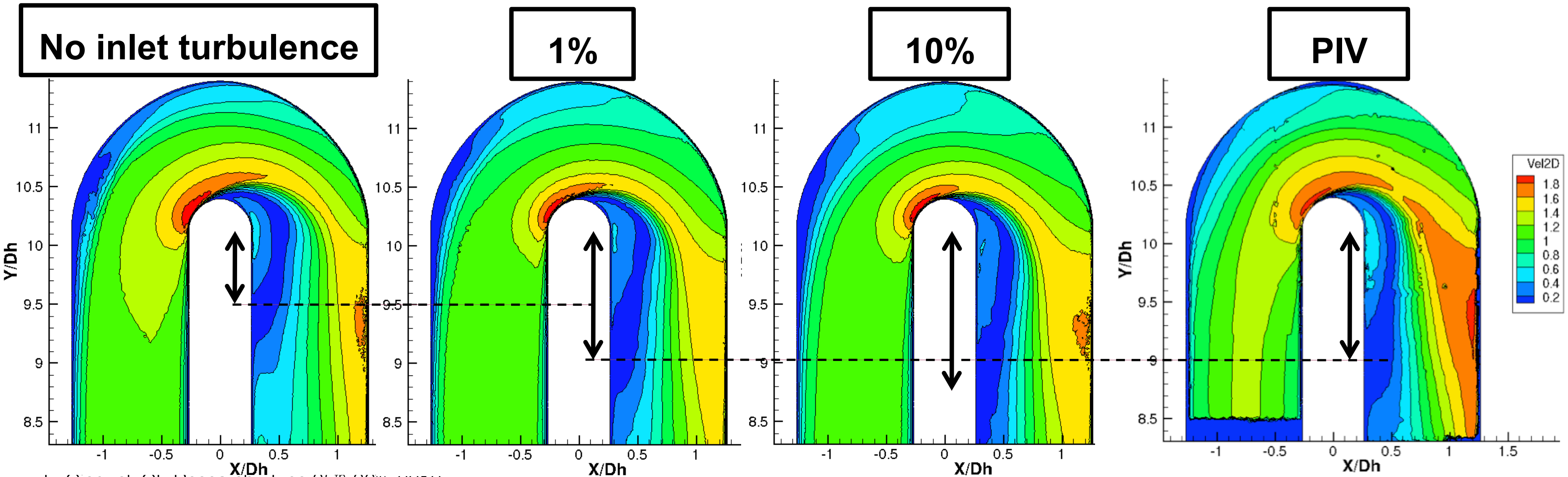
- Geometrical parameters
  - Hydraulic Dh= 0.075 m
  - External radius= 1.26 Dh
- Re = 40000

- Grid: full-tetra 6M cells
- Inlet profile obtained from RANS predictions
- Pressure outlet BC
- No-slip adiabatic walls – (wall-resolved LES)

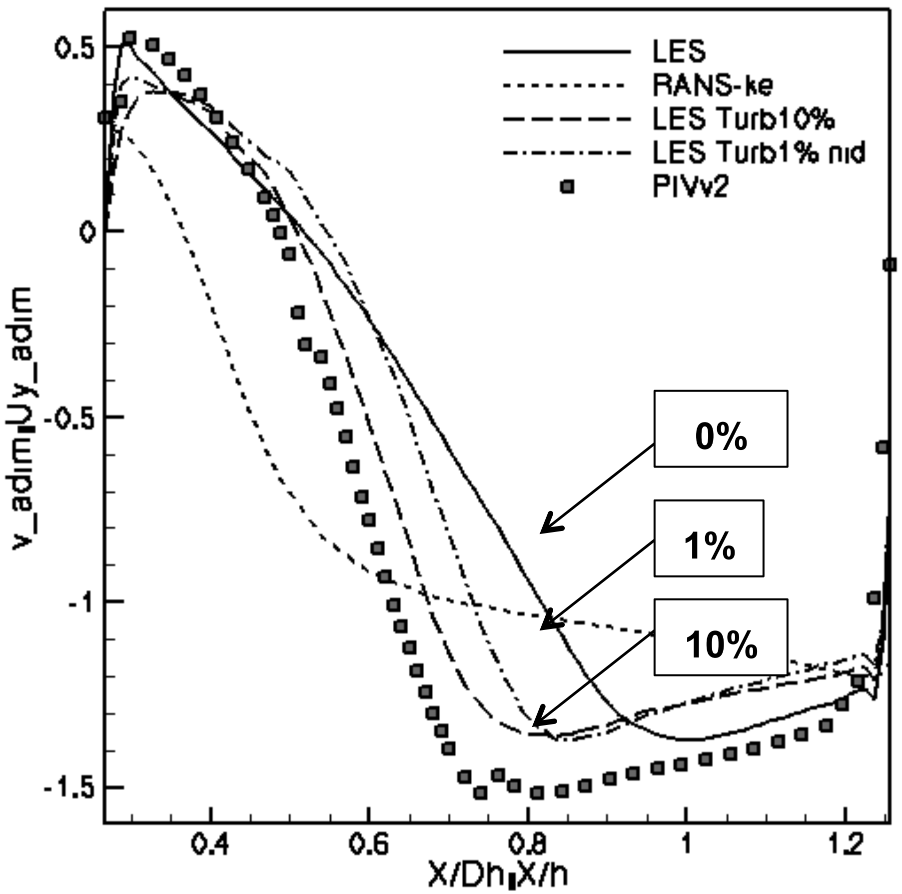
U-bend

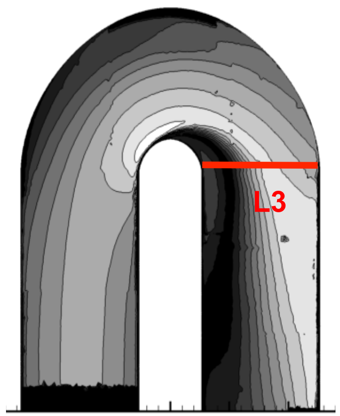


Recirculation bubble
Flow reorientation
(Ux^2+Uy^2)/Ub: 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
PIV
LES
RANS
Y/Dh
X/Dh

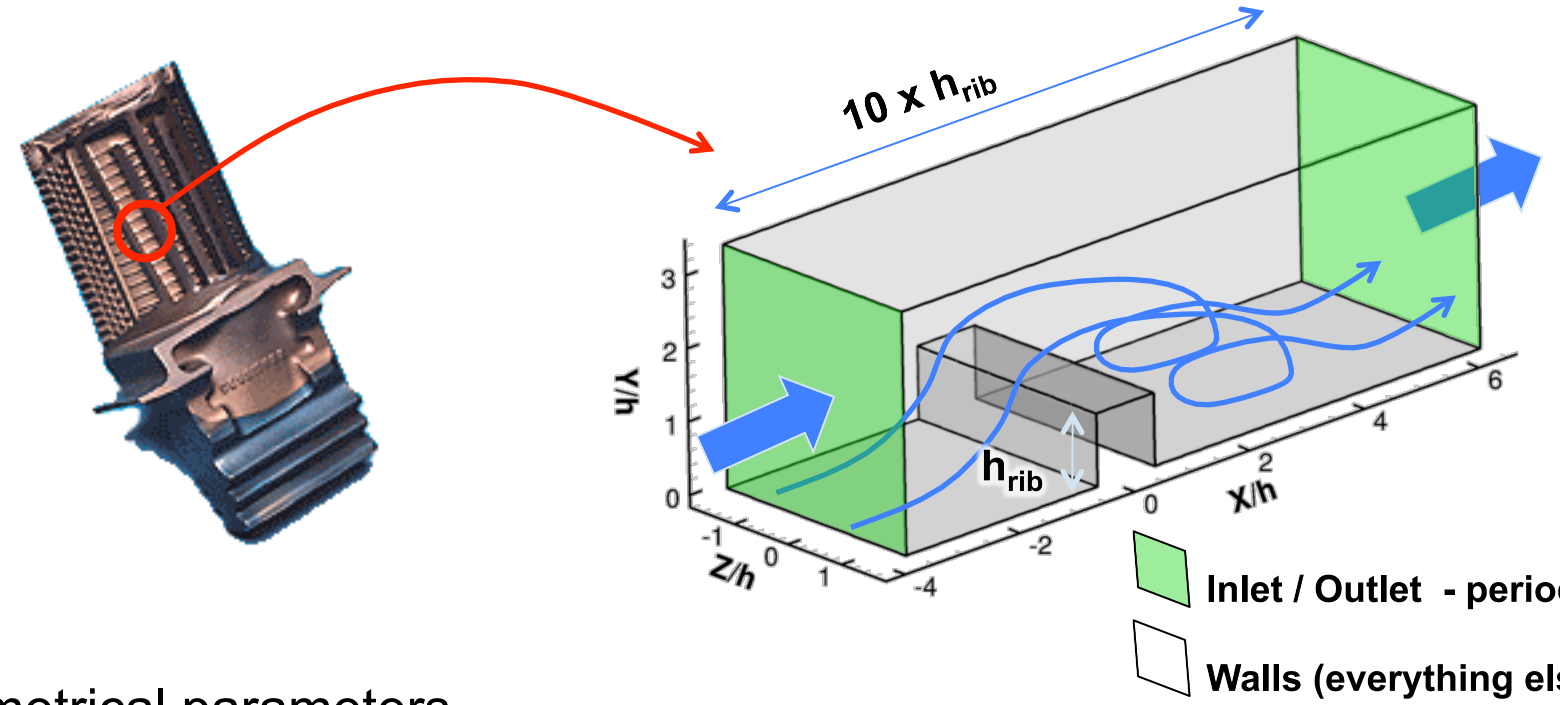


No inlet turbulence
1%
10%
PIV
Vel2D
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Y/Dh
X/Dh





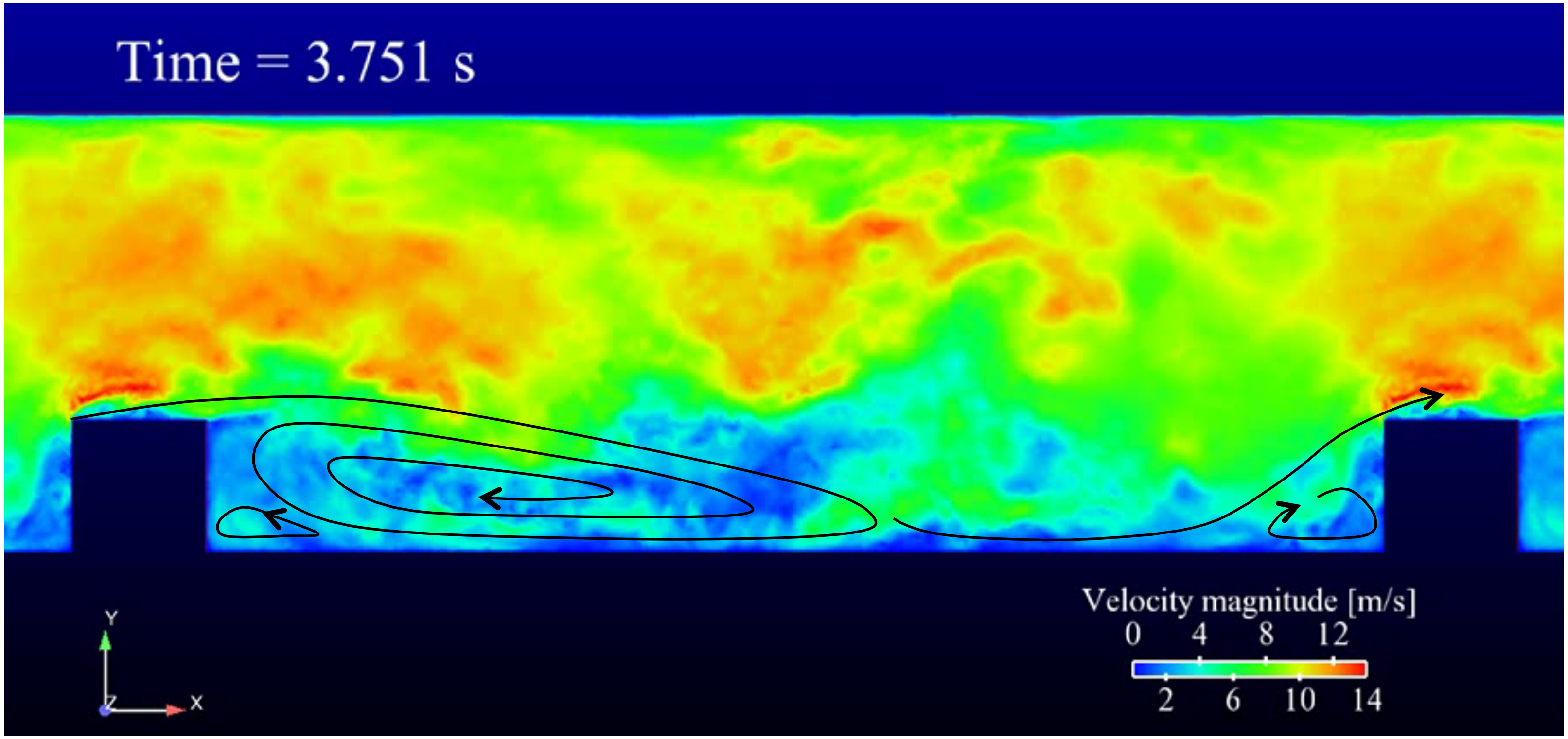
Interactions between turbulence and the recirculation bubble flow strongly impact the minimum velocity peak value and its positionning within the veine



- Geometrical parameters
  - Hydraulic diameter= 0.1 m
  - Rib spacing = 10 x h_{rib}
  - Blockage ratio = 30%
- Re = 40000

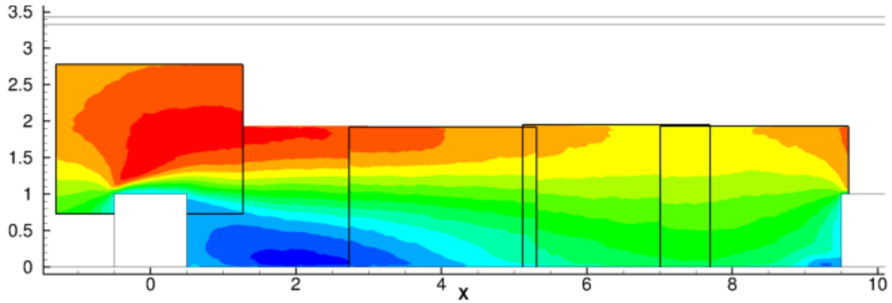
- <u>Ref. data :</u>

Casarsa, L. (2003). Aerodynamic performance investigation of a fixed rib-roughened internal cooling Passage. PhD Thesis, Universita degli Studi di Udine, Von Karman Institute for Fluid Dynamics



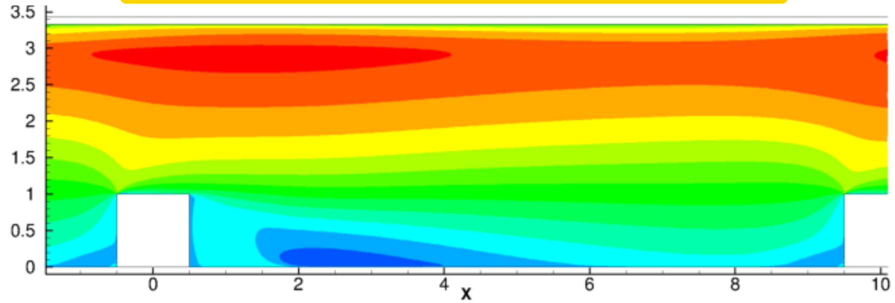
Complex unsteady separated flow between the ribs

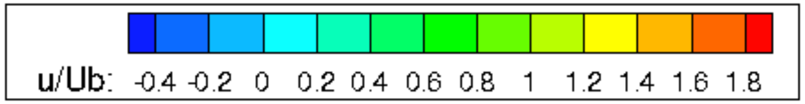
PIV



RANS (EARSM)

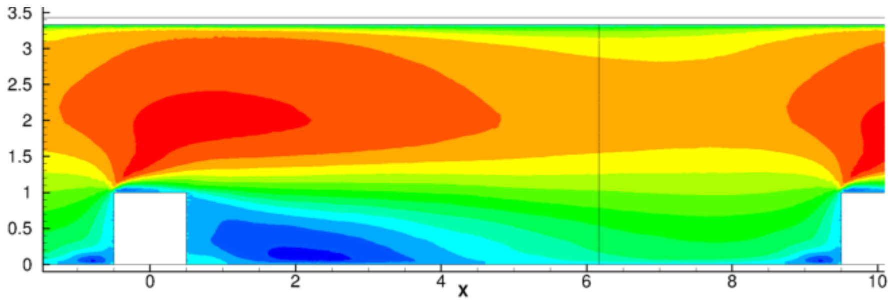
Struct. mesh / 4.5M cel. / $y^+ \sim 1$





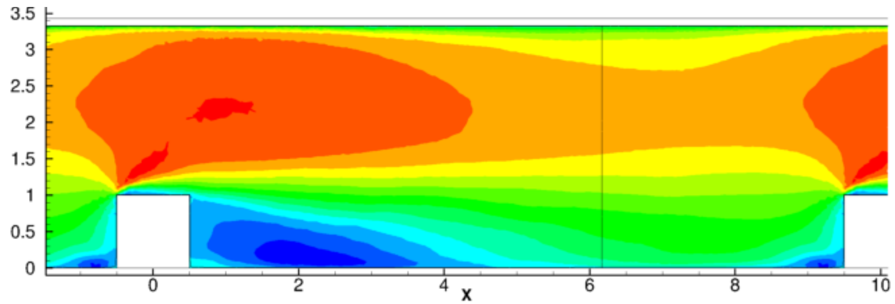
LES

full tetra / 7M cel. / $y^+ \sim [5, 10]$



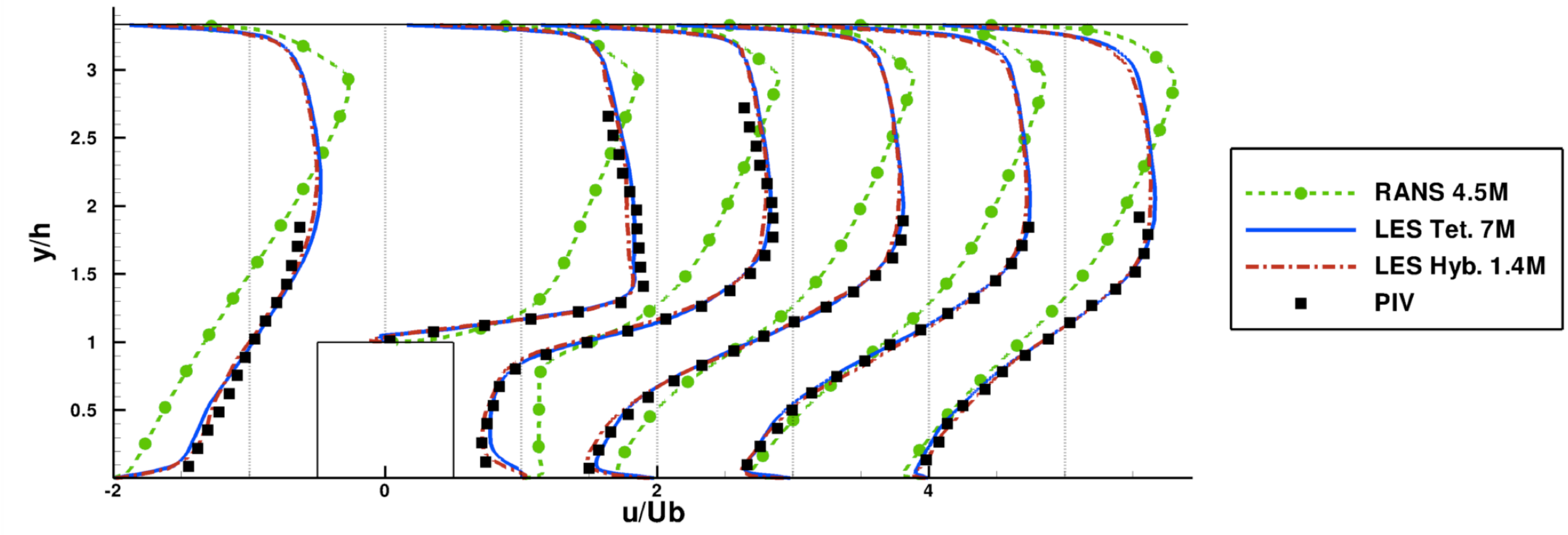
LES

tetra+prisms / 1.4M cel. / $y^+ \sim [2.5, 5]$



Same difficulties – same conclusions…

Axial velocity mean profiles in the symmetry plane

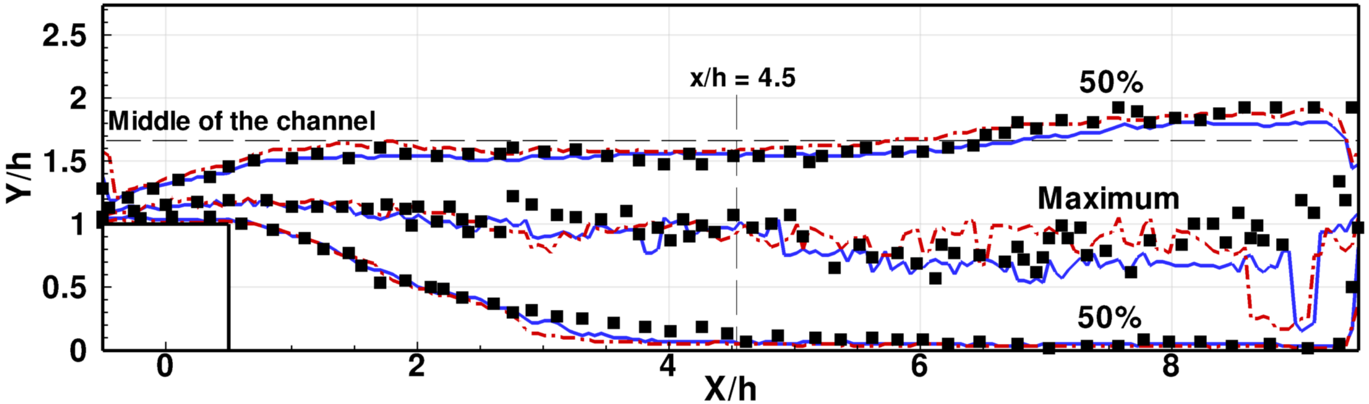


Whatever grid topology (provided that you can do a wall-resolved LES)

=> you will capture the first moments

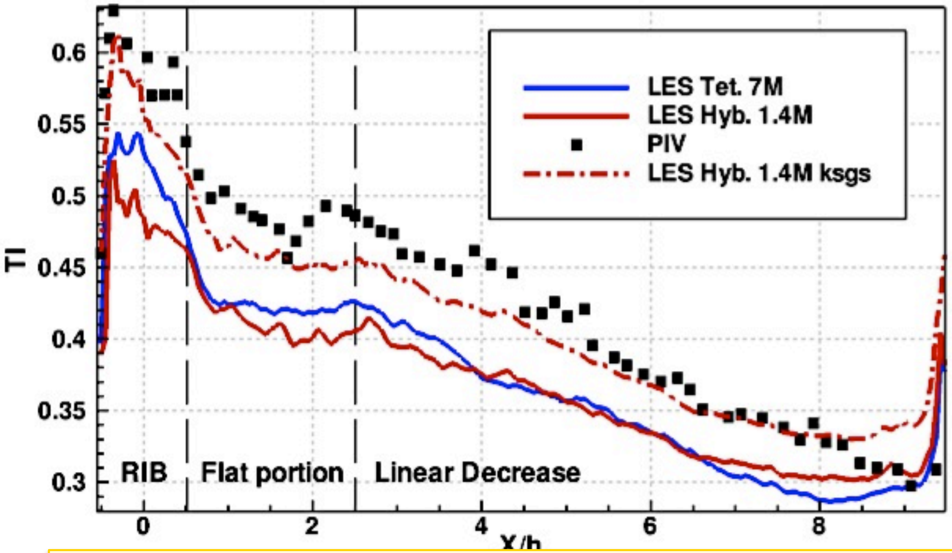
Higher order moments (tubulence)

$$\mathbf{TI} = \sqrt{\frac{1}{3}(u^2_{x,rms} + u^2_{y,rms} + u^2_{z,rms})}/U_b$$



High Turbulence Intensity zone after the rib

(maximum and 50% of maximum lines)

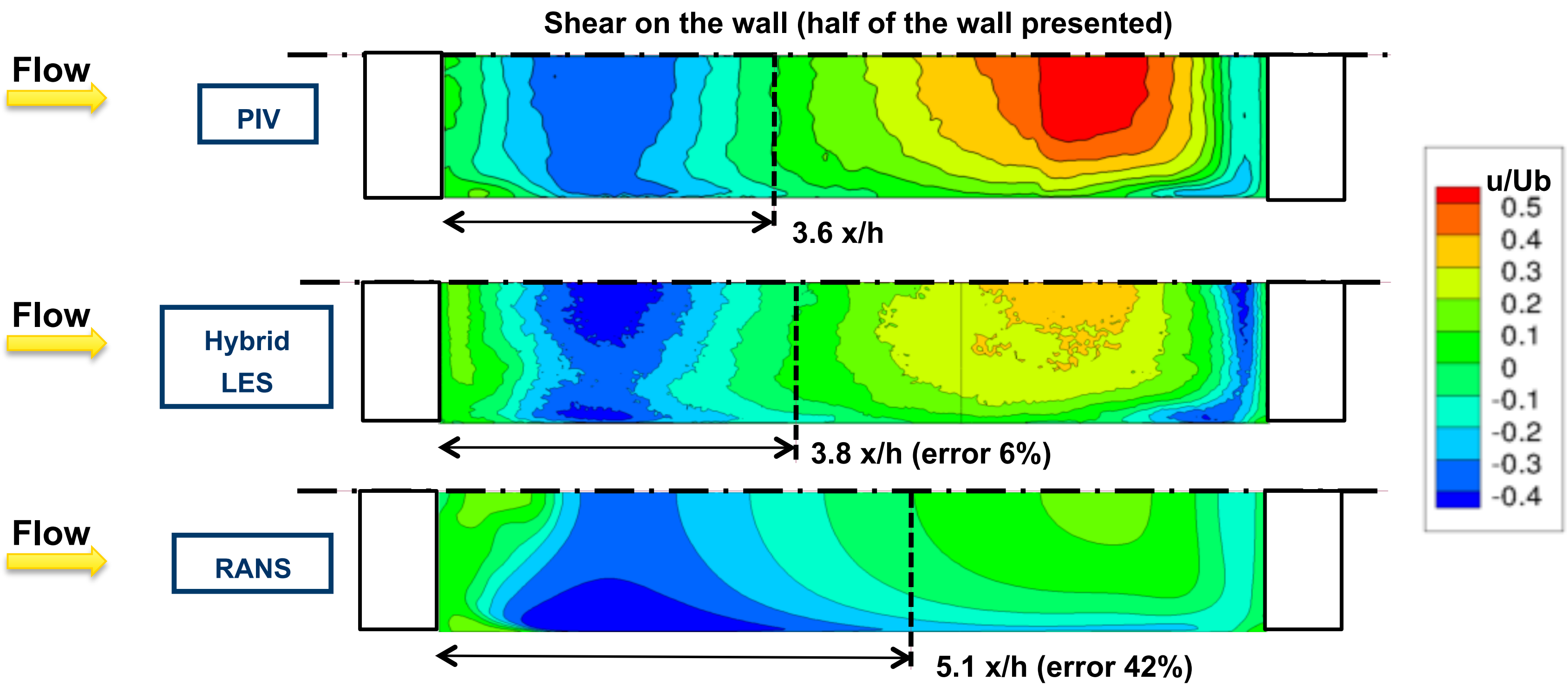


Value of Turbulence Intensity on the maximum line

[1] Yoshizawa, A. Statistical theory for compressible turbulent shear flows, with the application to subgrid modeling. Phy. of Fluids 29, 2152-2164 (1986).

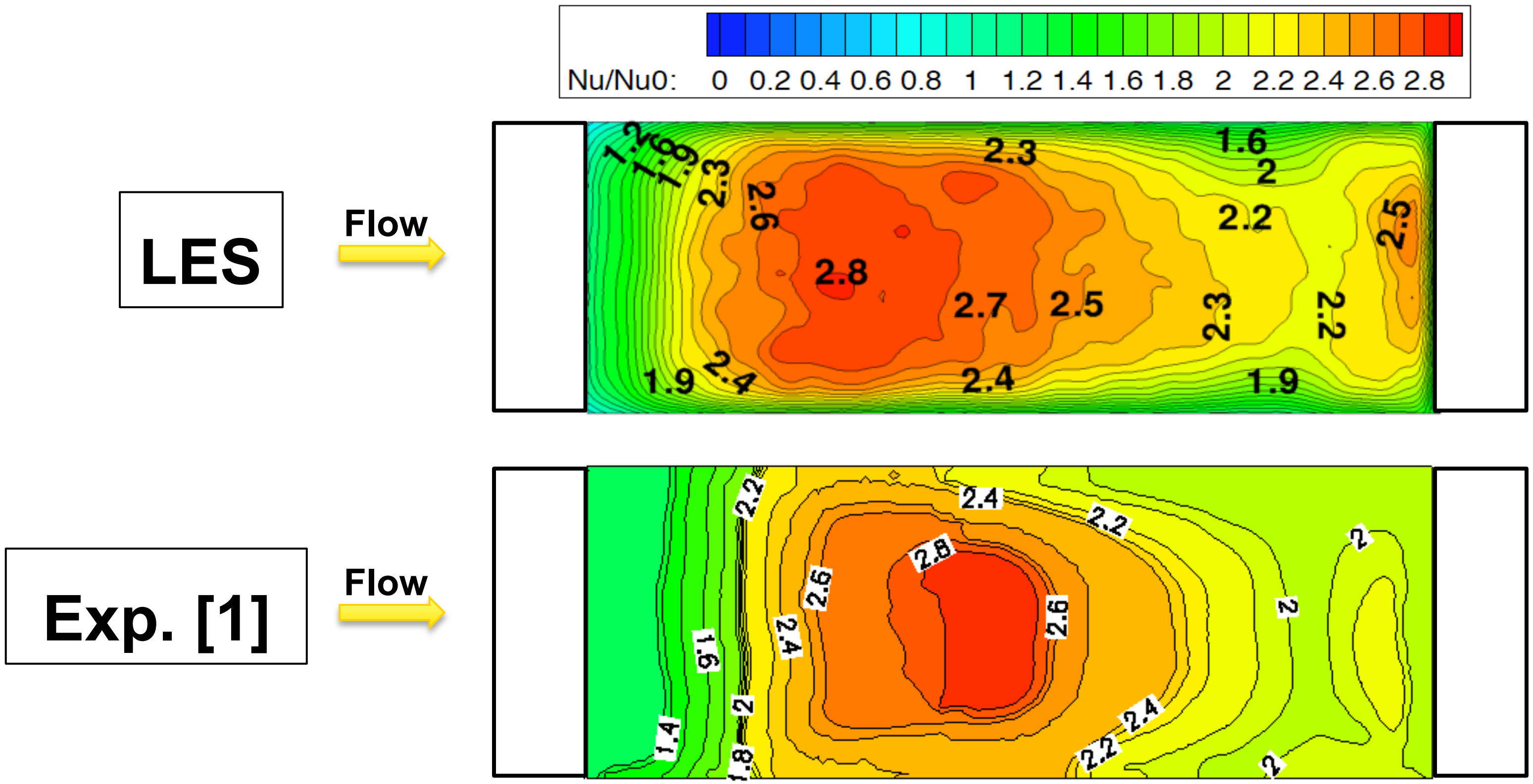
LES predicts correctly the unsteady features (intensity and extend)
(lack of 10/20% being in modeled kinetic energy [1])

- The main outcome is a better estimation of the wall shear stress map:



- One has to keep in mind that LES cost is still much higher than RANS…

As well as the wall heat flux: here expressed in terms of an Enhancement Factor [1]



[1] Cakan, M. Aero-thermal Investigation of Fixed Rib-roughened Internal Cooling Passages. (2000).

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LES in the vane & the cooling channels: conjugate heat transfer problem…

Multiple difficulties appear covering physical and HPC issues:

1/ All-in-one or *multiple dedicated* solvers

2/ How to *couple efficiently two partitioned non coincident domains*?

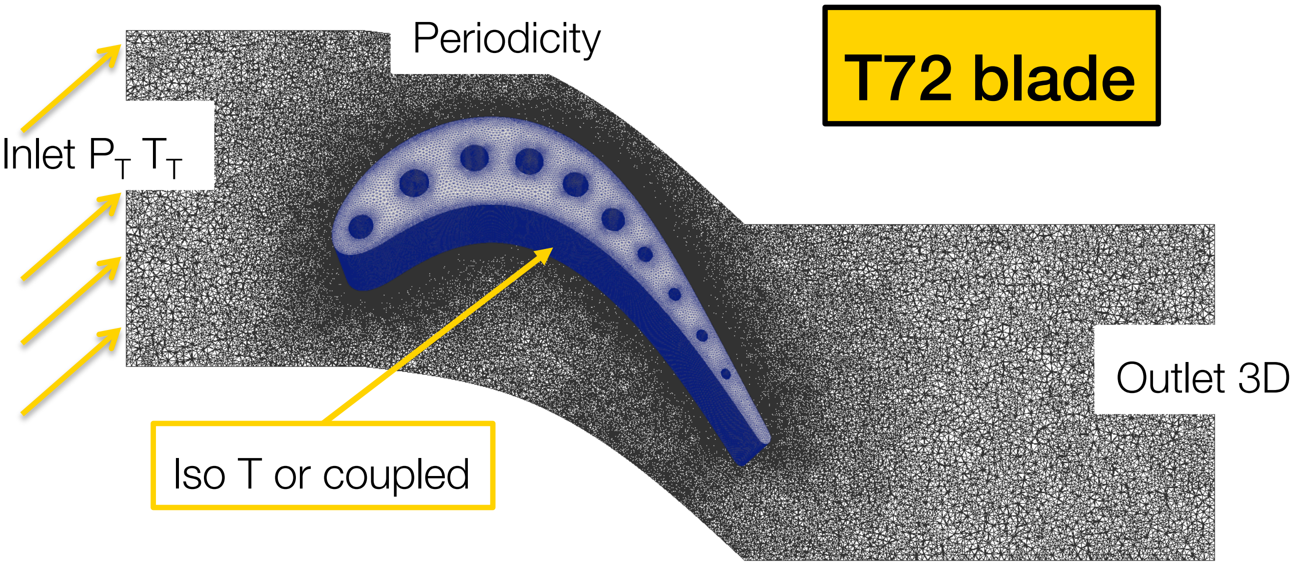
- data distribution versus centralization
- interpolation, conservation

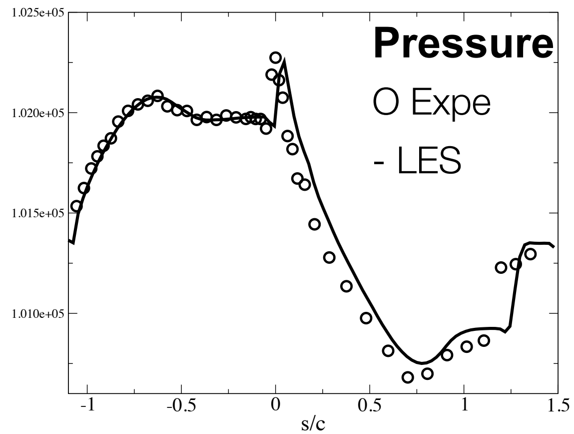
3/ What *quantities / fields* to exchange and at *what rate*?

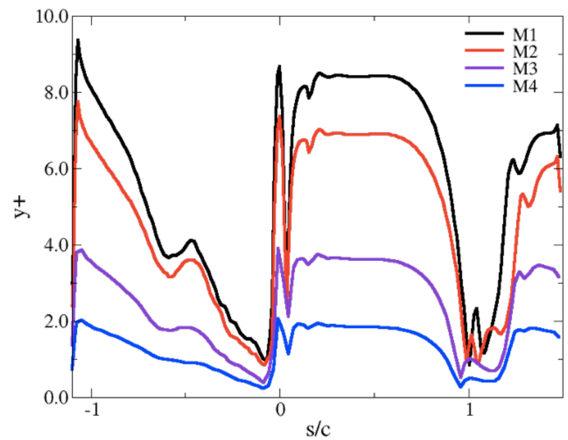
4/ How to converge two fields dictated by very *different time scales*?

5/ Whatever the method retained is the *aggregated numerical solver stable*?

Typical investigation for couple LES / conduction: courtesy of F. Duchaine



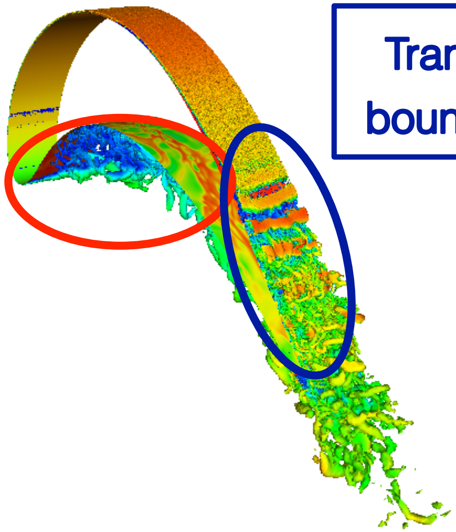




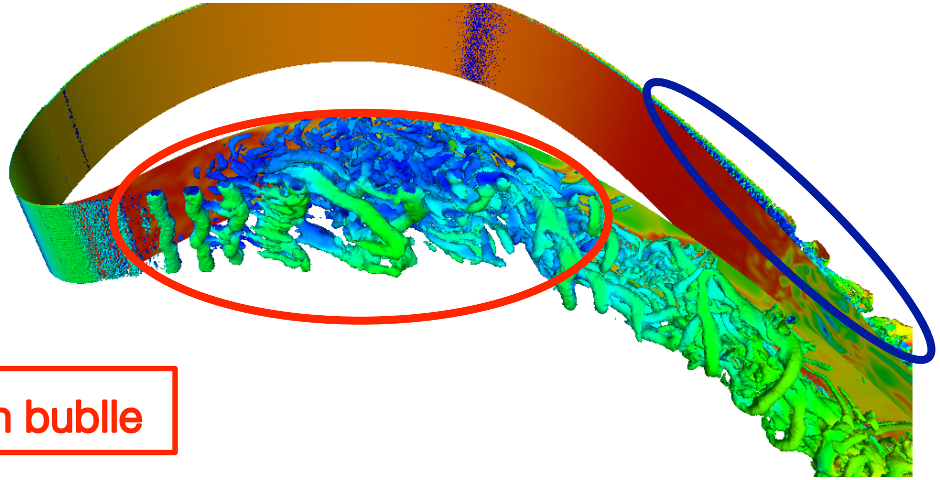
- ✓ Size of the span = 10 mm
- ✓ 5 prim layers in the fluid boundary layer
- ✓ Convergence of fluid to track heat transfer coefficient with iso-thermal wall
- ✓ Influence of turbulence injection (not done)
- ✓ Coupled aero thermal simulation

——	9.3 M cells	=> dt = 67.6 ns
——	13.2 M cells	=> dt = 54.6 ns
——	37.4 M cells	=> dt = 26.7 ns
——	54.8 M cells	=> dt = 20.0 ns

Instantaneous flow field: Iso Q-criterion colored by velocity



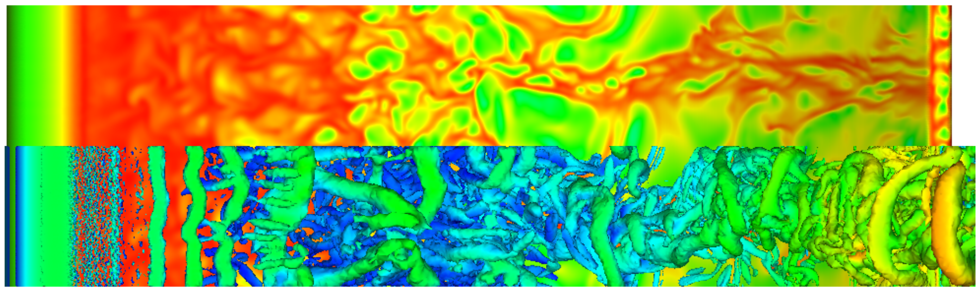
Transitioning boundary layer



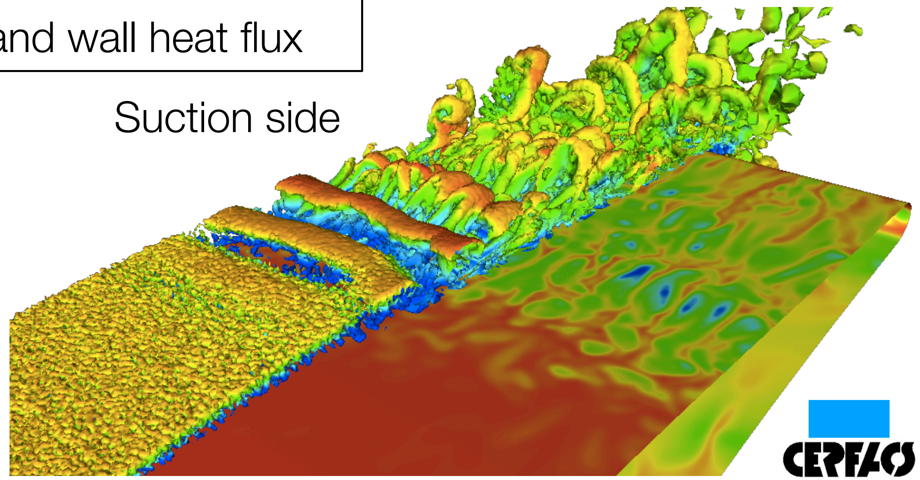
Recirculation bublle

Instantaneous view on heat transfer: Q-criterion and wall heat flux

Pressure side



Suction side



Conjugate heat transfer problem based on LES:

=> the tools exist although the most efficient way to use them is not yet clear

=> the potential is clearly present

- LES capacity to represent fine scale / transitions / bifurcations of the flow to upstream and near wall event
- Brute force and HPC seem a pre-requisite at least for the scientific context (produce understanding and modeling databases)

Alternatives for industrial use of such solutions:

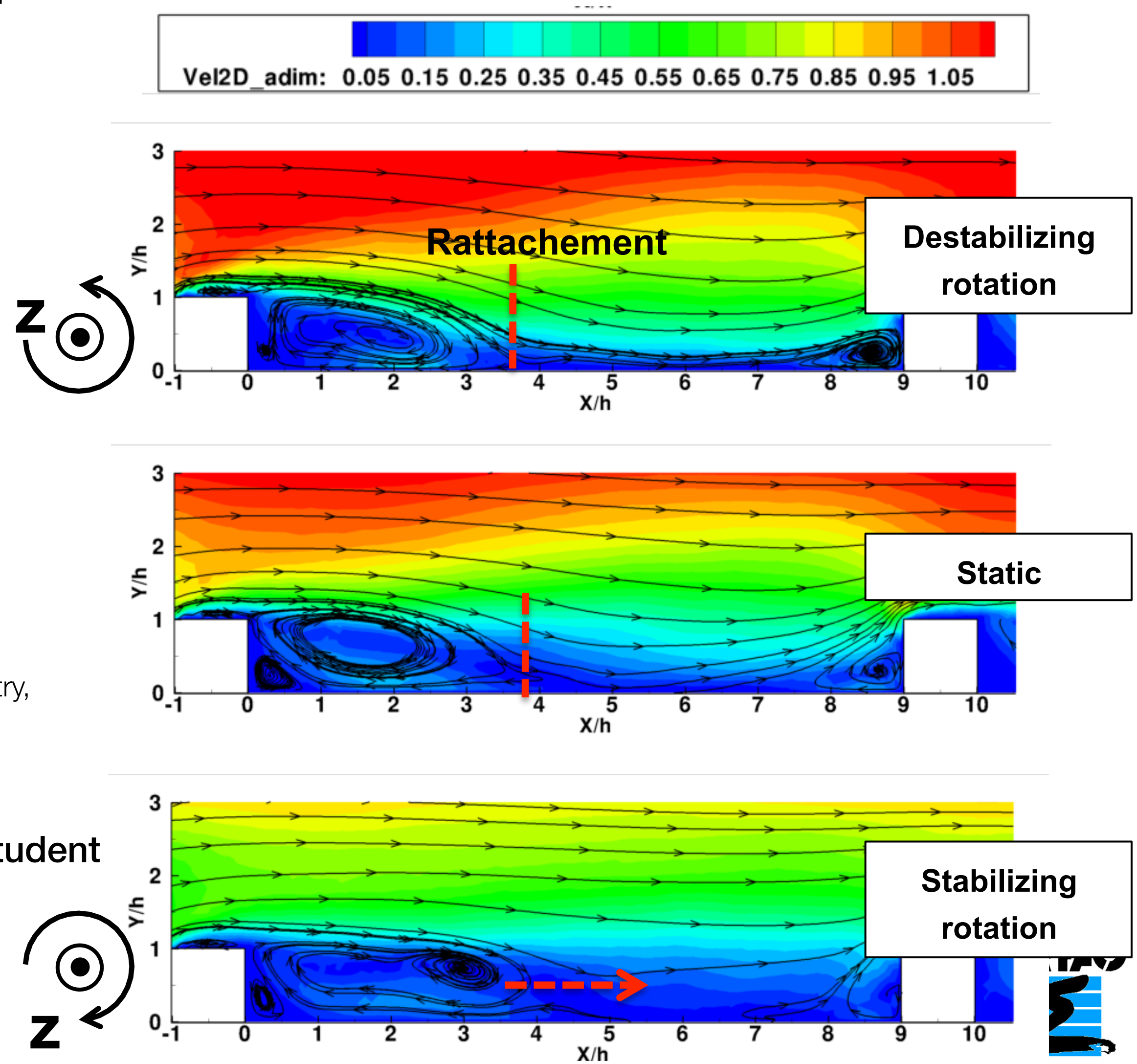
=> wall models (DES, DDES, wall laws…) versus brute force wall resolved LES

!!! You also need to consider other aspects !!!

Overview of LES computation with ALE method :
(rotation of all the channel in absolut frame)

- **LES in rotating channels is needed:**
  - Wall normal rotation
  - LES simulations of stabilizing and destabilizing effect of Coriolis and centrifugal forces.

- **Experimental data from VKI [1]:**
  - full rotating test bench
  - time resolved PIV



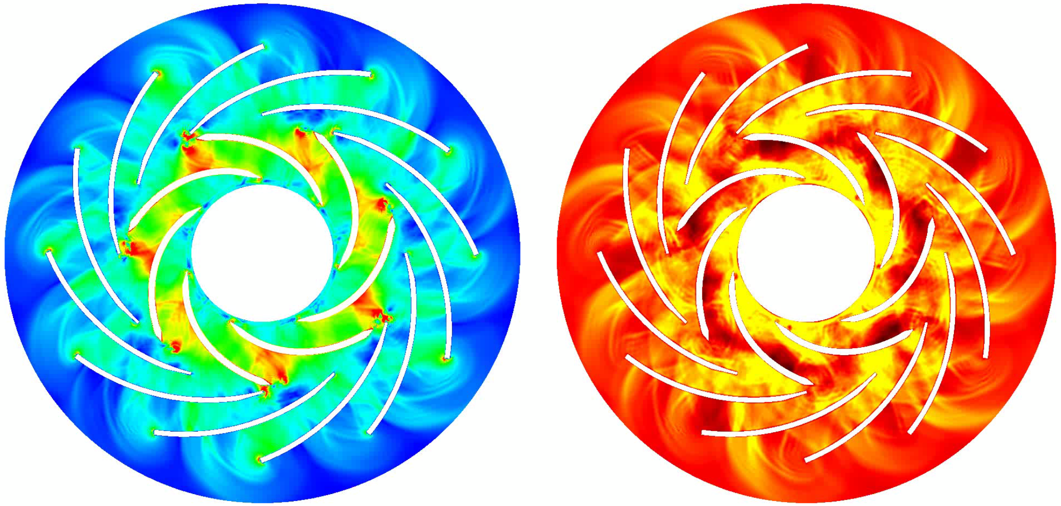
[1] Coletti et al., Flow field investigation in rotating rib-roughened channel by means of particle image velocimetry, Exp. in Fluids (2011)

Courtesy of R. Fransen: CERFACS PhD student

- **LES in rotating vanes is also needed:**
    - Strategies need to be evaluated
        - Single passage
        - Multiple passages
        - Interface treatment
    - Gain in flow physics needs to be confirmed
    - **CPU cost of such tools ???**
- **Experimental data??**

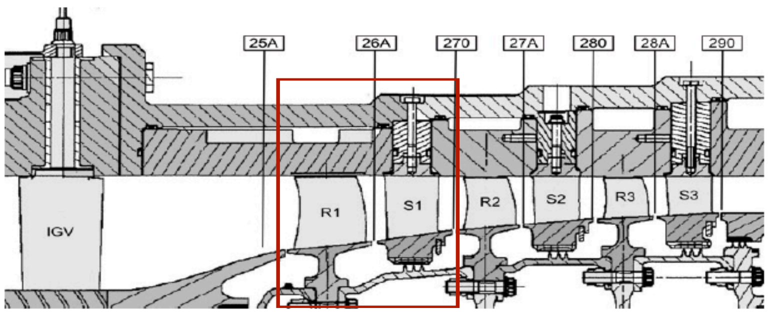
2D Pump

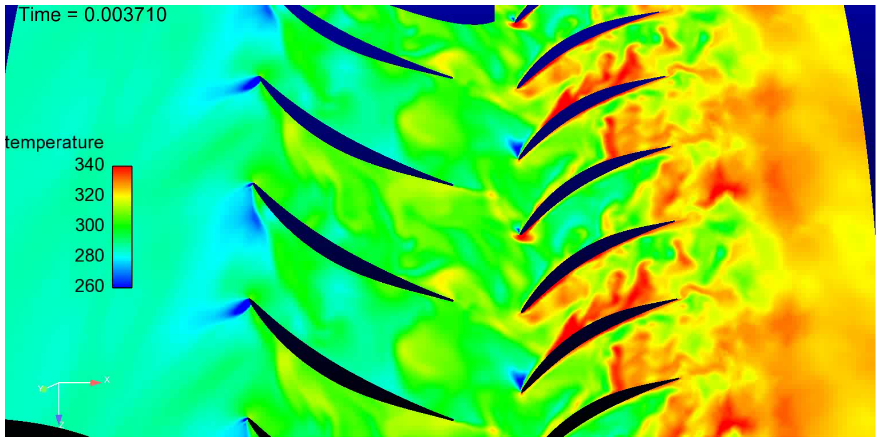
velocity — t = 0.00100 | temperature — t = 0.00100



Courtesy of G. Wang: CERFACS Post-Doc fellow

CREATE Compressor





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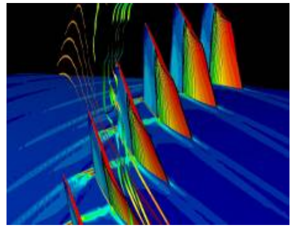
LES for combustion chamber is quasi-acknowledged as being a mandatory tool:

=> Can serve as multiple purpose tool: design, advance diagnostics…

=> How to use it as an efficient complement to RANS

LES around blades:

=> There is a need for such a tool: especially if aero thermal quantities are to be accurately estimated

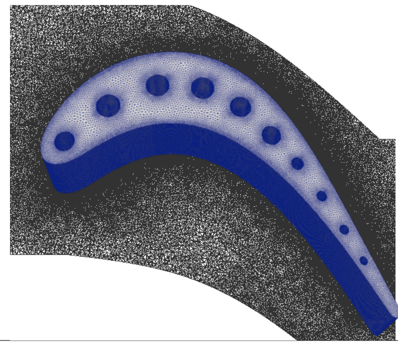


=> Wall-resolved LES will be expensive (other alternatives?)

LES in the cooling channels of the NGV or blades:

=> Clearly accessible today provided that you have CPU time and a massively parallel code

Future: fully coupled LES and conduction solver…

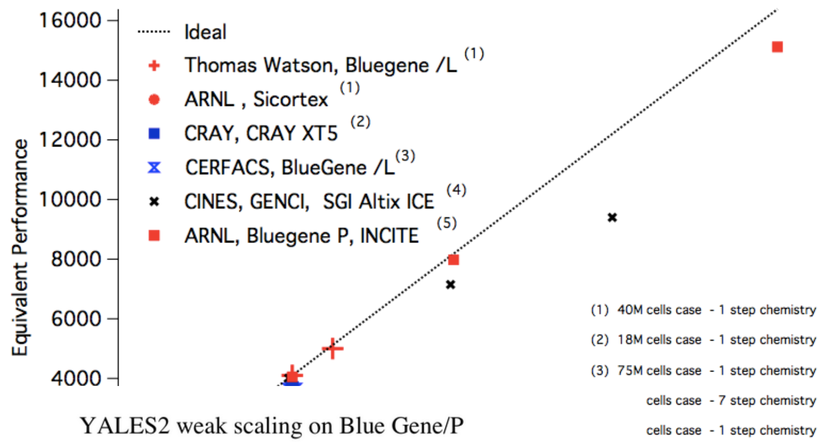


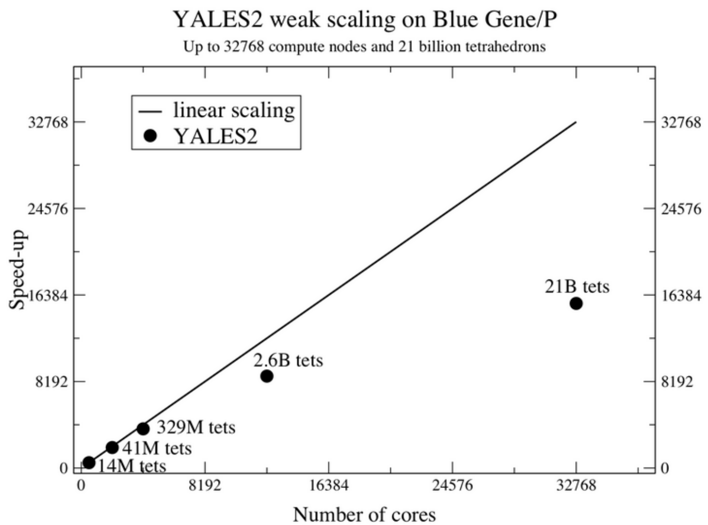
Gas turbine flows have a very high Reynolds number:

$$\mathrm{Re} = \frac{\rho U L}{\mu} \quad \Rightarrow \quad \mathrm{N} \propto (0{,}1\,\mathrm{Re})^{9/4}$$

- Compressor at operating conditions:
  Re ~ 5 10^6 => N ~ 37 $10^{11.25}$
- Combustor at operating conditions:
  Re ~ 5 10^5 => N ~ 37 10^9
- Turbine at operating conditions:
  Re ~ 1 10^6 => N ~ 1 $10^{11.25}$

PROPER HPC DESIGN OF CODES AND MACHINES WILL MAKE THE DIFFERENCE IF LES IS TO BE USED BY INDUSTRY

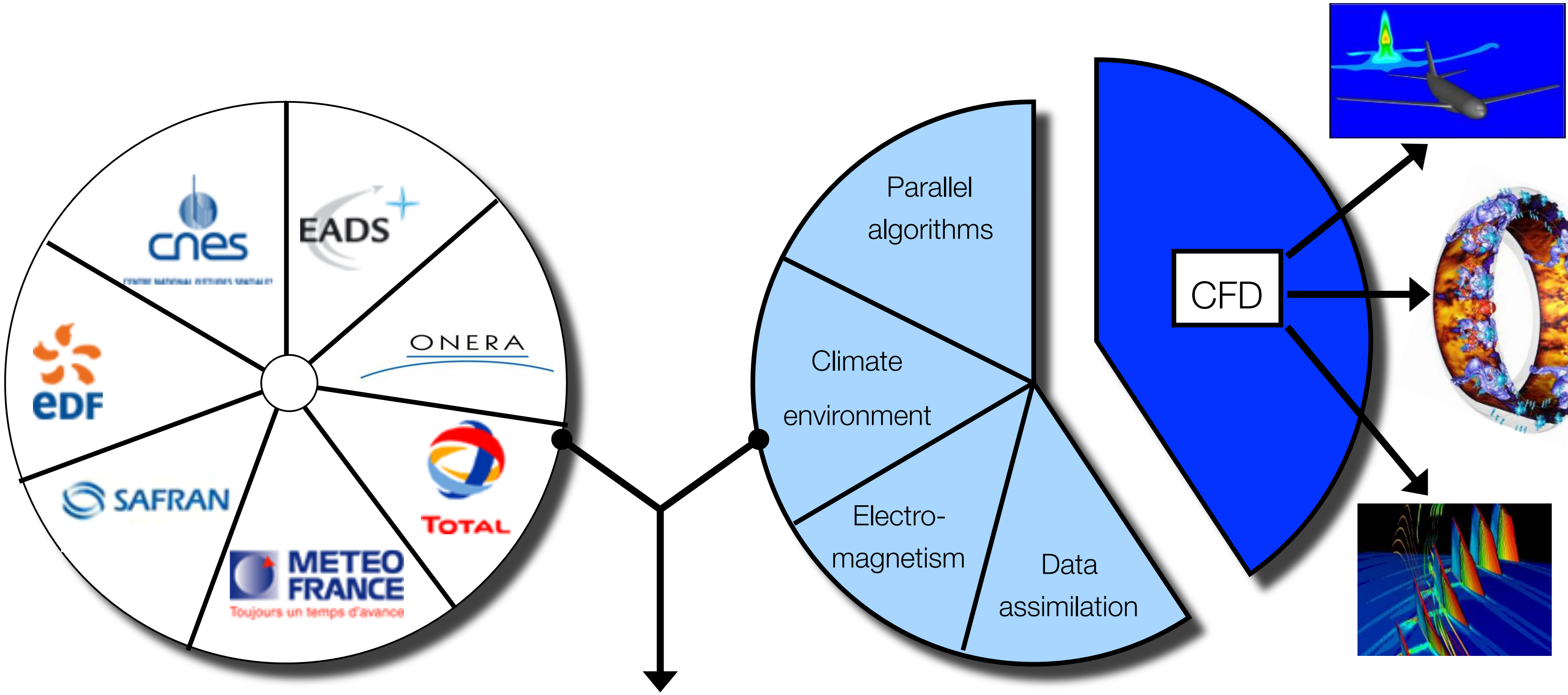




What's CERFACS?

CERFACS has seven shareholders

One hundred permanent people in 5 teams



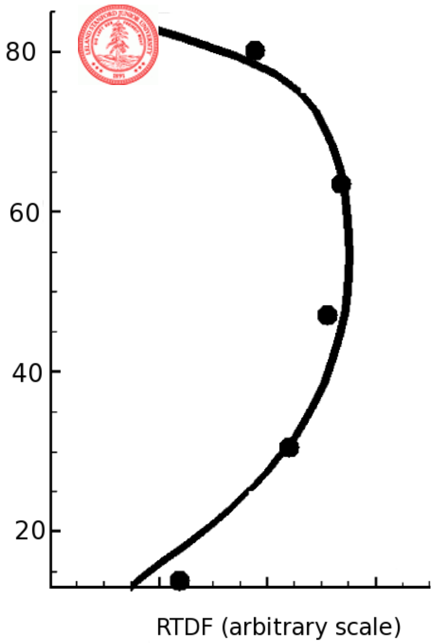
- **Expertise in scientific computation**
- **Access to large computational resources**

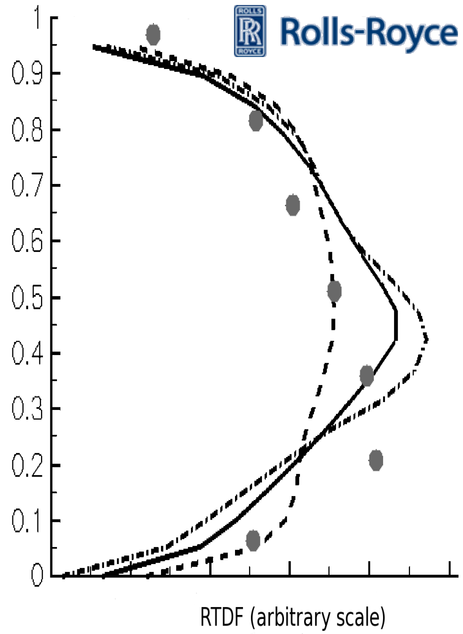
http://www.cerfacs.fr

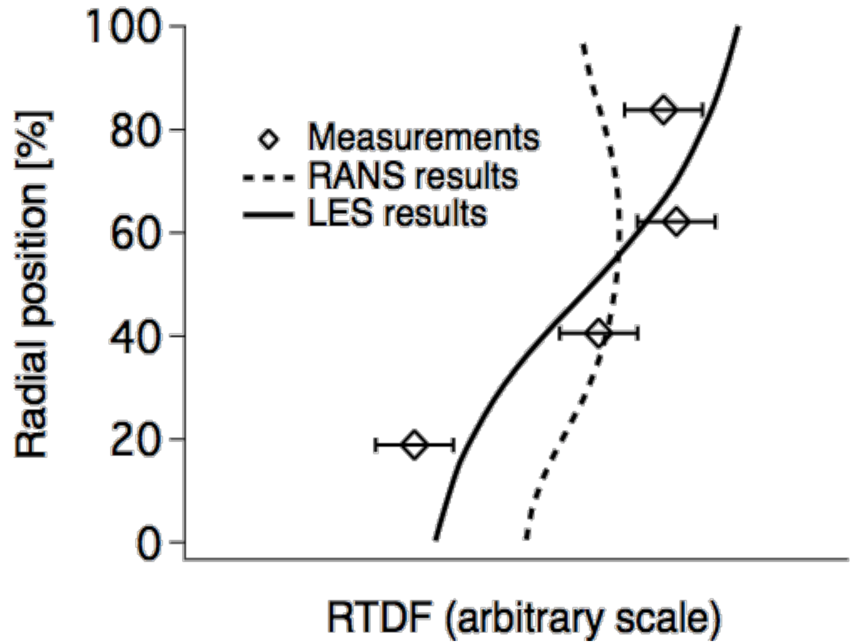
<u>RANS versus LES :</u> Impact on a design criterion (i.e. RDTF) [1-4]

$$RTDF(r) = \frac{\left\langle \overline{T}(r,\theta) \right\rangle_{\theta} - \left\langle \overline{T}(r,\theta) \right\rangle_{\theta r}}{\left\langle \overline{T}(r,\theta) \right\rangle_{\theta r} - \overline{T}_{inlet}}$$

RTDF(r) profile measures the radial temperature heterogeneities through the exit plane of the chamber ⇒ controls the turbine lifetime !!







[1] G. Boudier et al., Comb. Inst., 31(2):3057-3082, 2007.
[2] G. Boudier et al., INCA workshop, 2005.
[3] S. James et al., AIAAJ, 44(4):674-686, 2006.
[4] P. Moin et al, AIAAJ, 44(4):698-708, 2006.