Numerical study of shock wave-boundary layer interaction in cylinder-flare configuration

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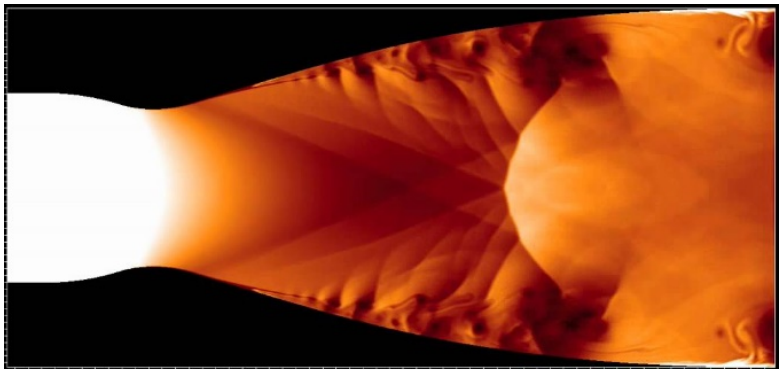
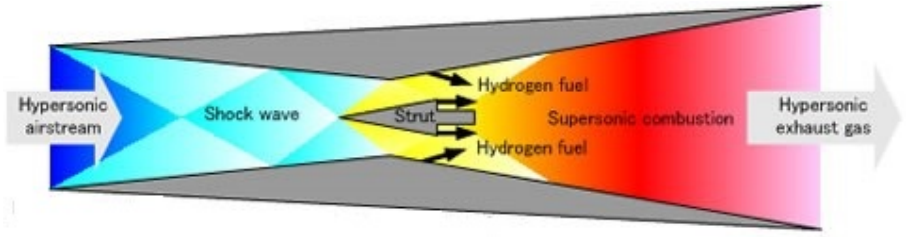
Introduction

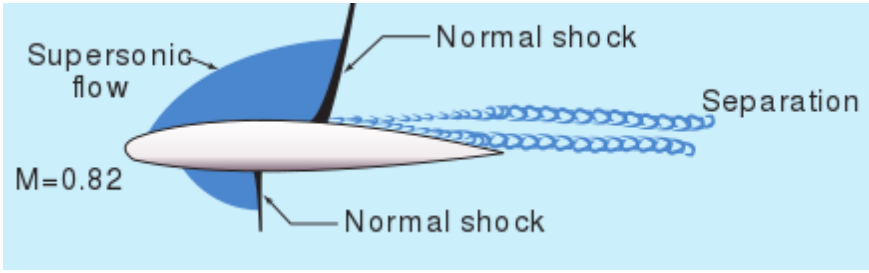
Air intake*3



Rocket nozzle*2



Scram jet*1

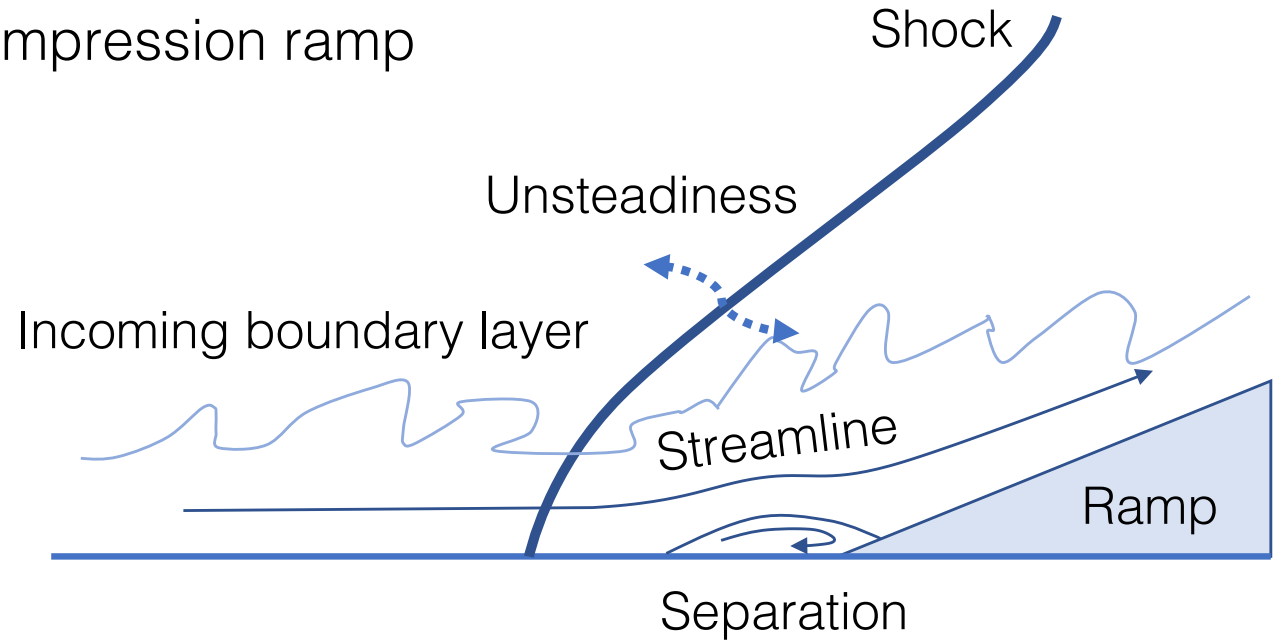


Transonic airfoil *4

*1. https://spaceflightnow.com/2016/08/30/india-tests-scramjet-demonstrator-over-bay-of-bengal/
*2. https://www.youtube.com/watch?v=iO1qvnFR3Wo
*3. https://www.flickr.com/photos/si558/1426458761
*4. https://en.wikipedia.org/wiki/Mach_tuck

Introduction

- Compression ramp, blunt fin, impinging shock, etc…
- Common features
  - Alteration of near-wall turbulence (Shahab et al, 2016)
  - Low frequency unsteadiness (Piponniau et al, 2009)
  - Oscillation in high-amplitude



Motivation

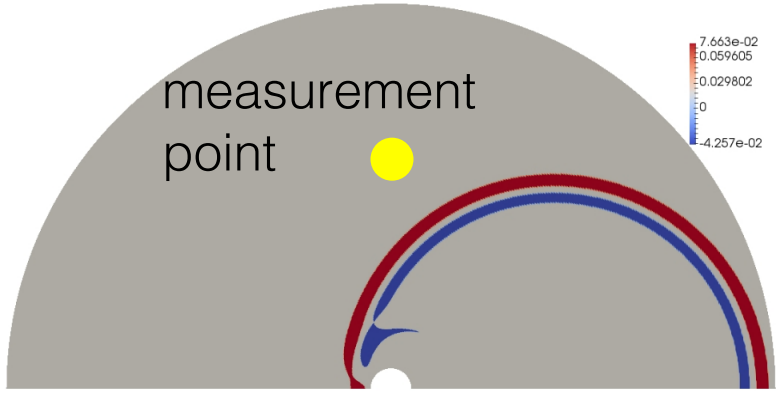
- Mainly studied on planar geometries or with simplified models (ex. RANS)
- In aerospace engineering, objects have often cylindrical or conical shapes
- Three-dimensional, azimuthal effects (difficult to capture by experiment)
- Perform numerical analysis on SWBLI in the cylinder/flare configuration to study this effect

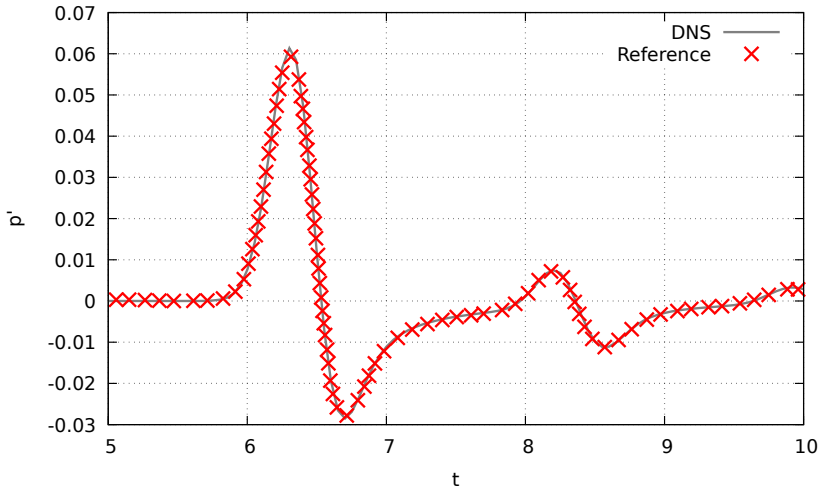
Numerical Method

- Compressible Navier-Stokes Equations
- Hybrid scheme
  - 6^{th} centered optimized finite difference + selective filter
  - 7^{th} WENO
  - dependent on a density gradient based shock sensor
- 4^{th} order Runge-Kutta
- Curvilinear transformation
  - errors needed to be characterized

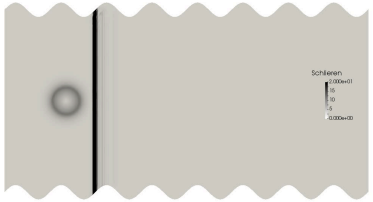
Validation & characterization

Acoustic pulse

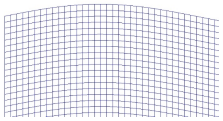




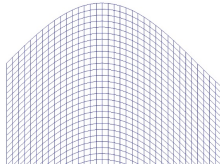
Shock/vortex interaction

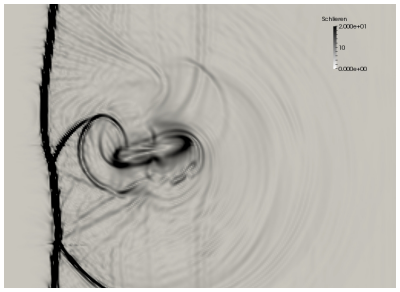


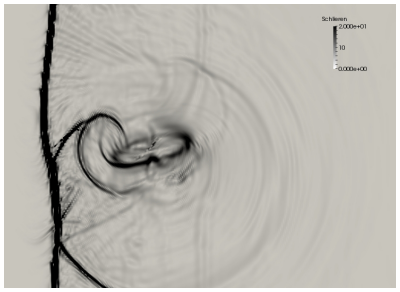
Mesh 1

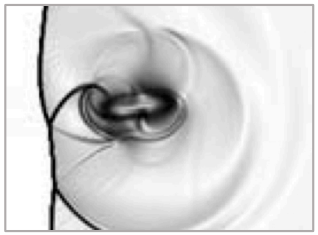


Mesh 2









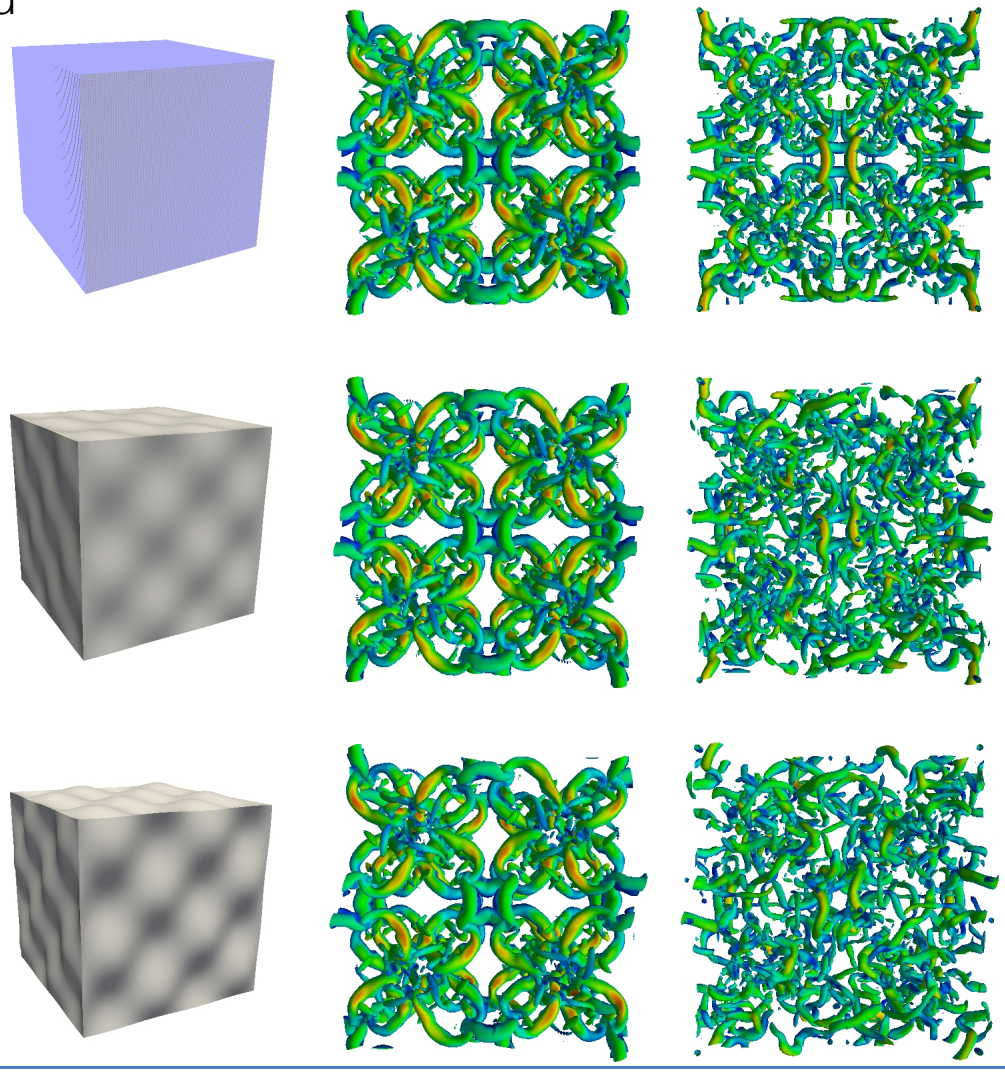
Reference case*1

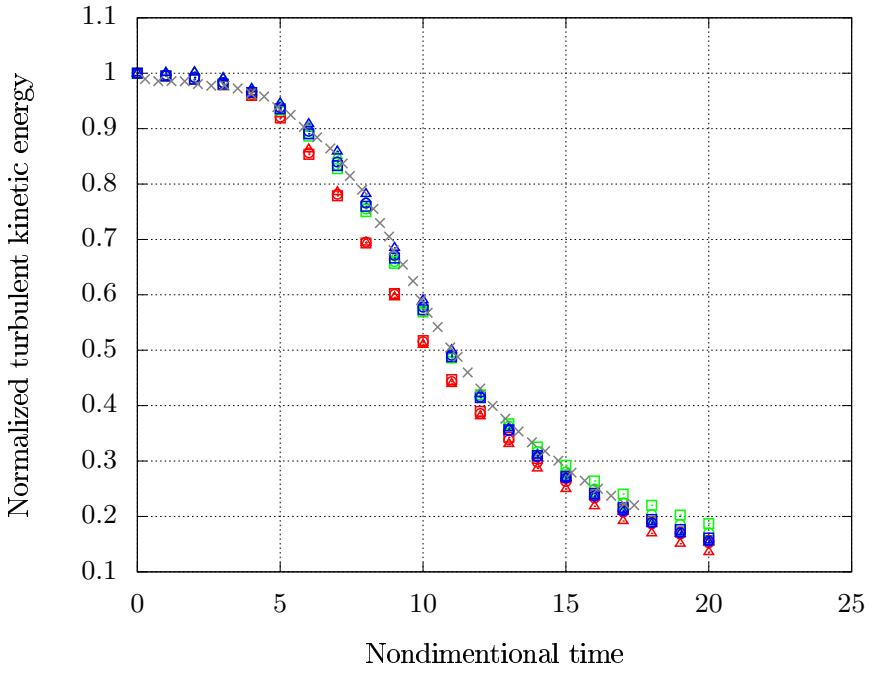
*1. A. Rault, G. Chiavassa and R. Donat, Shock-Vortex Interactions at High Mach Numbers , J. Flui. Mech., 420 (2000), 47–83.

Validation & characterization

Taylor green vortex t=5 t=12

Grid





Decay of turbulent kinetic energy

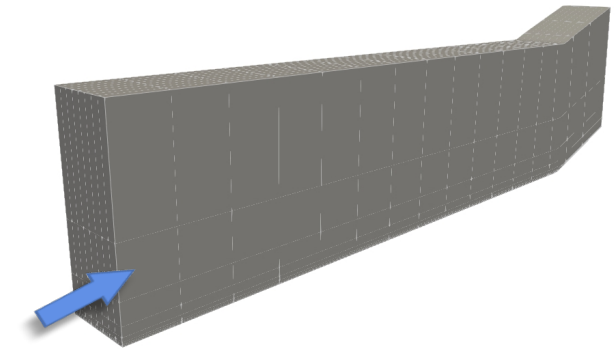
Cartesian(low)
Curvilinear-1(low)
Curvilinear-2(low)
Carte.(mid)
Curv.-1(mid)
Curv.-2(mid)
Carte.(high)
Curv.-1(high)
Curv.-2(high)

Numerical setup

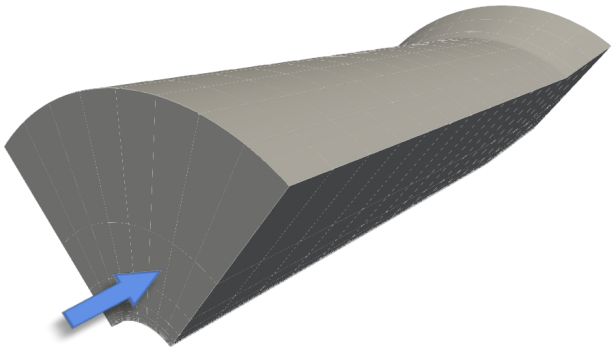
- Mach=3
- Ramp :18°
- $Re_\theta \approx 1200$
- 38 million points
- DNS resolution

  $(\Delta r^+ \approx 0.6, \Delta x^+ \approx 6.3, \Delta \theta^+ \approx 4.1)$
- Periodic condition on azimuth

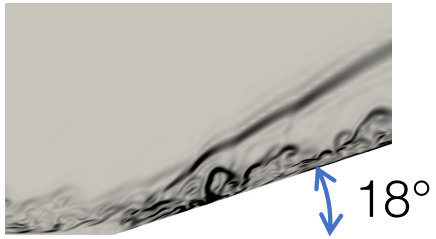
(Perturbations of harmonic span-wise mode on the inlet velocity)

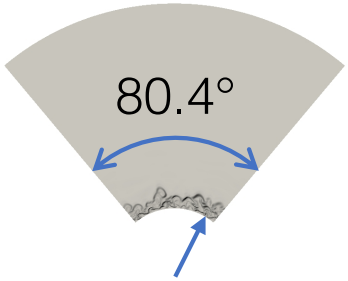


Flat case



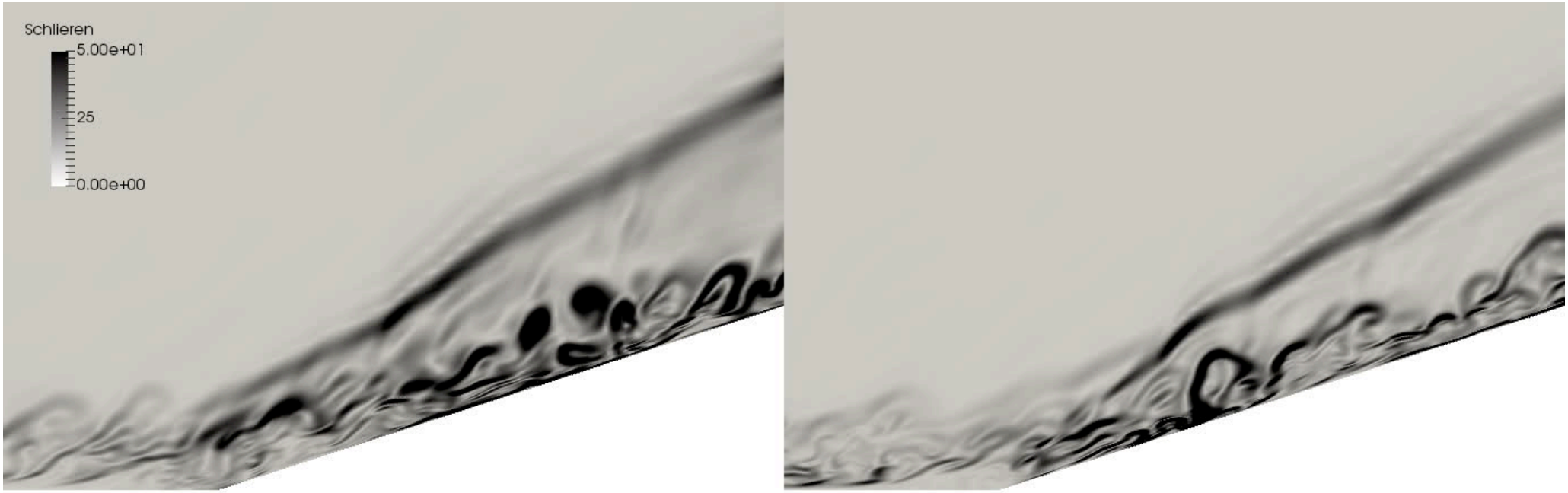
Cylindrical case





$\delta/R \approx 0.19$

Flow field (Schlieren)

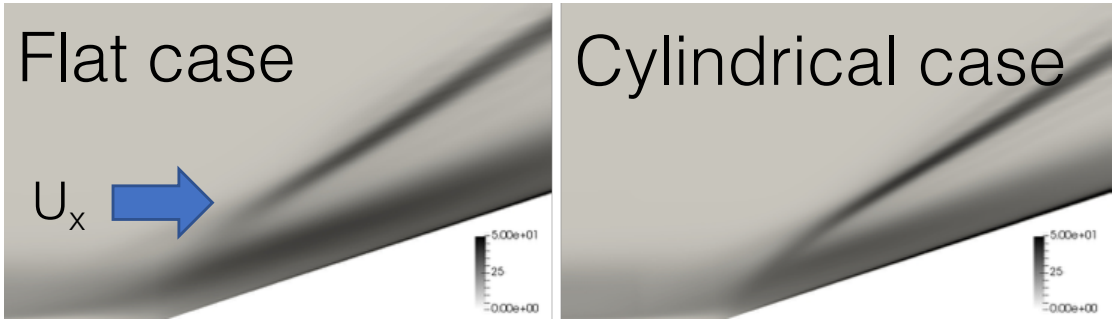


Flat case

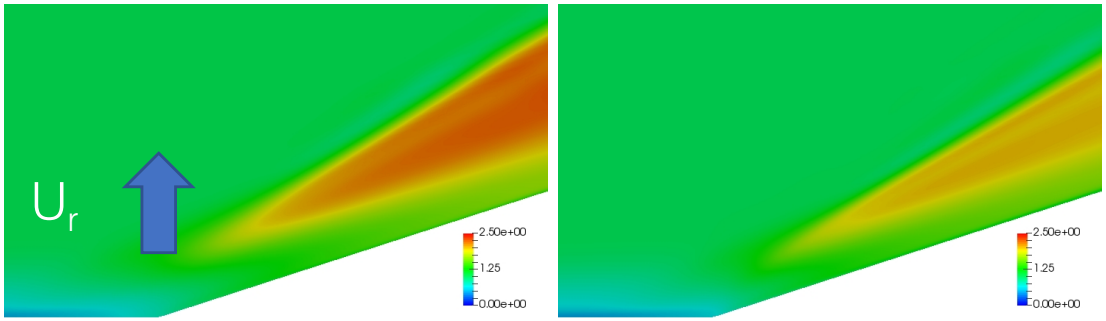
Cylindrical case

- Weaker shock by the geometrical difference
- Upstream : no big difference
- Downstream : More turbulent in the flat case

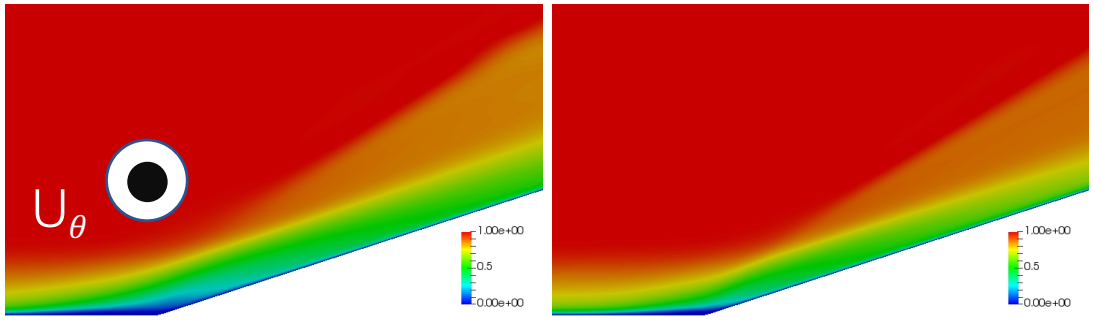
Average field



Schlieren



Density(ρ /ρ_∞)

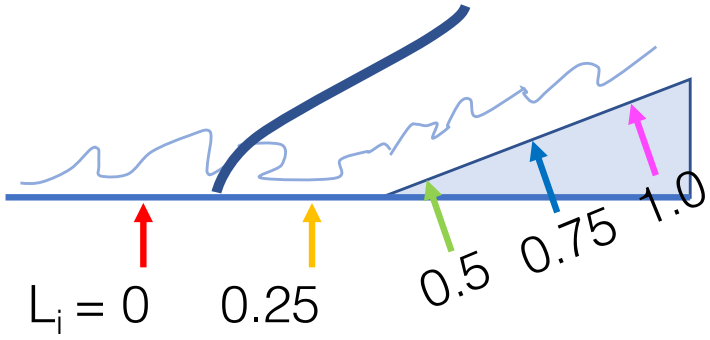


Stream-wise velocity(u/u $_\infty$)

- stronger shock and a thicker boundary later in the flat case
- Separation zone
  - about 2.0 times longer in the flat case
  - Bigger interaction region in the flat case

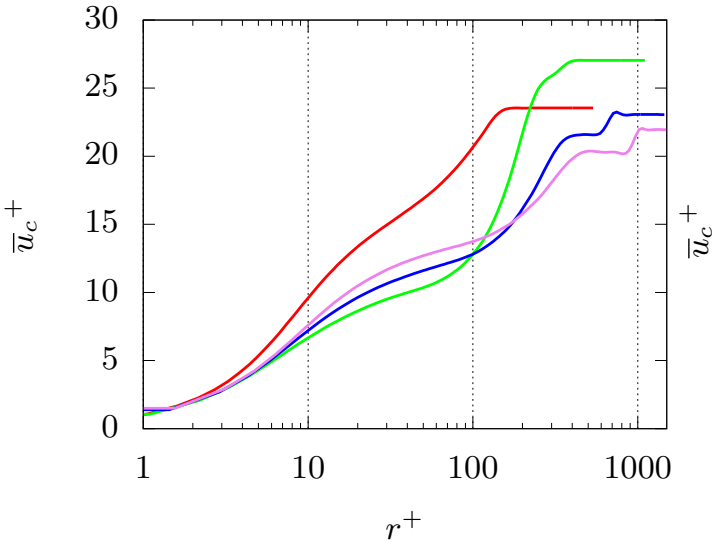
Average field

Different interaction length
=> Cannot compare the evolution of the flow on the stream-wise
=> Define a relative length to the interaction length

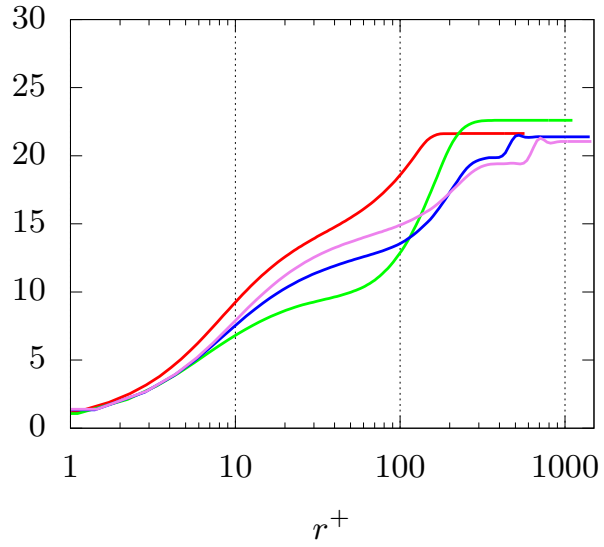


$L_i=(X_i-X_0)/L_{interaction}$

Flat case



Cylindrical case

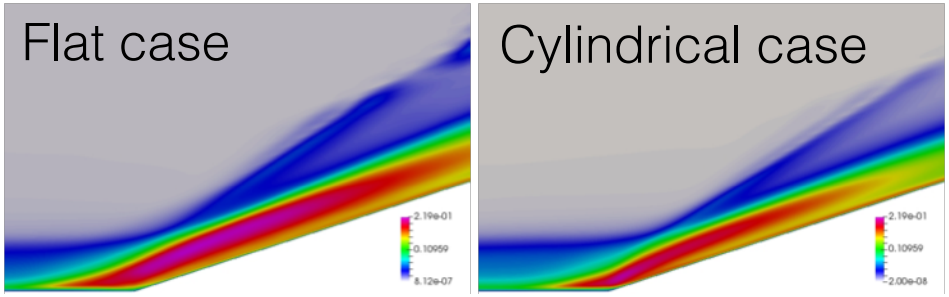


In the two cases,
- No big difference upstream
- Shifted through the interaction region

In the cylindrical case,
- Rapid relaxation, return to the red line (by the weaker shock)

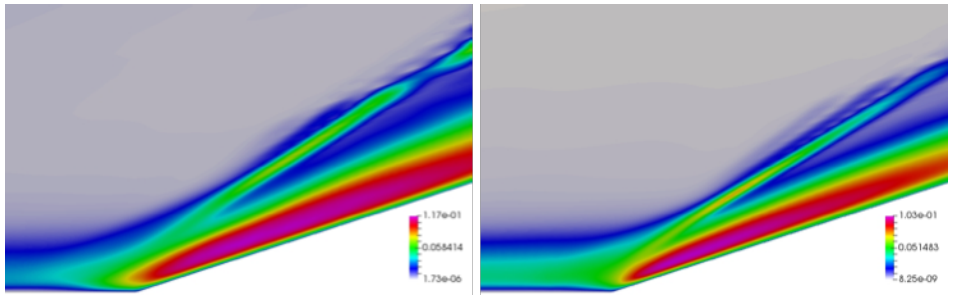
Wall-normal profiles of stream-wise velocity (van Driest)

Turbulent field

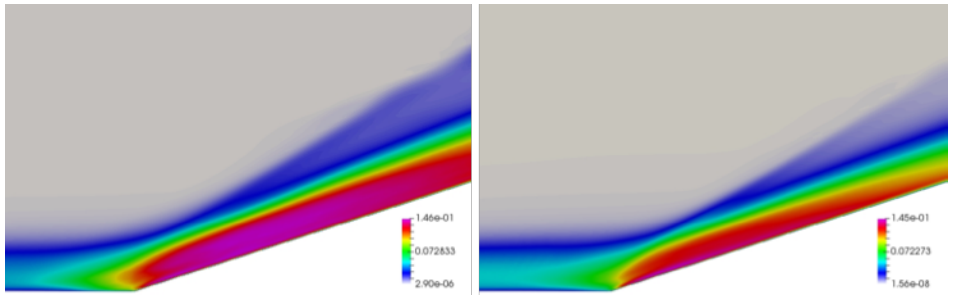


Stream-wise turbulent stress components

$$\sqrt{\overline{\rho u\prime_x u\prime_x}/\rho_\infty U_\infty U_\infty}$$



Radial $\sqrt{\overline{\rho u\prime_r u\prime_r}/\rho_\infty U_\infty U_\infty}$



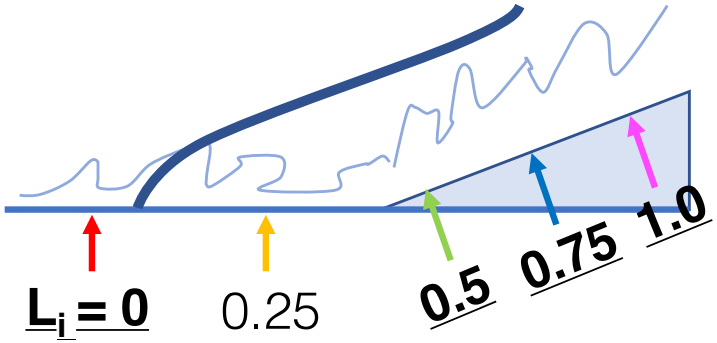
Azimuthal $\sqrt{\overline{\rho u\prime_\theta u\prime_\theta}/\rho_\infty U_\infty U_\infty}$

In cylindrical case,

- The increase of turbulent stress (red) is shifted downstream
- It decreases earlier than in the flat case

(expected by the intensity of the shock)

Turbulent field

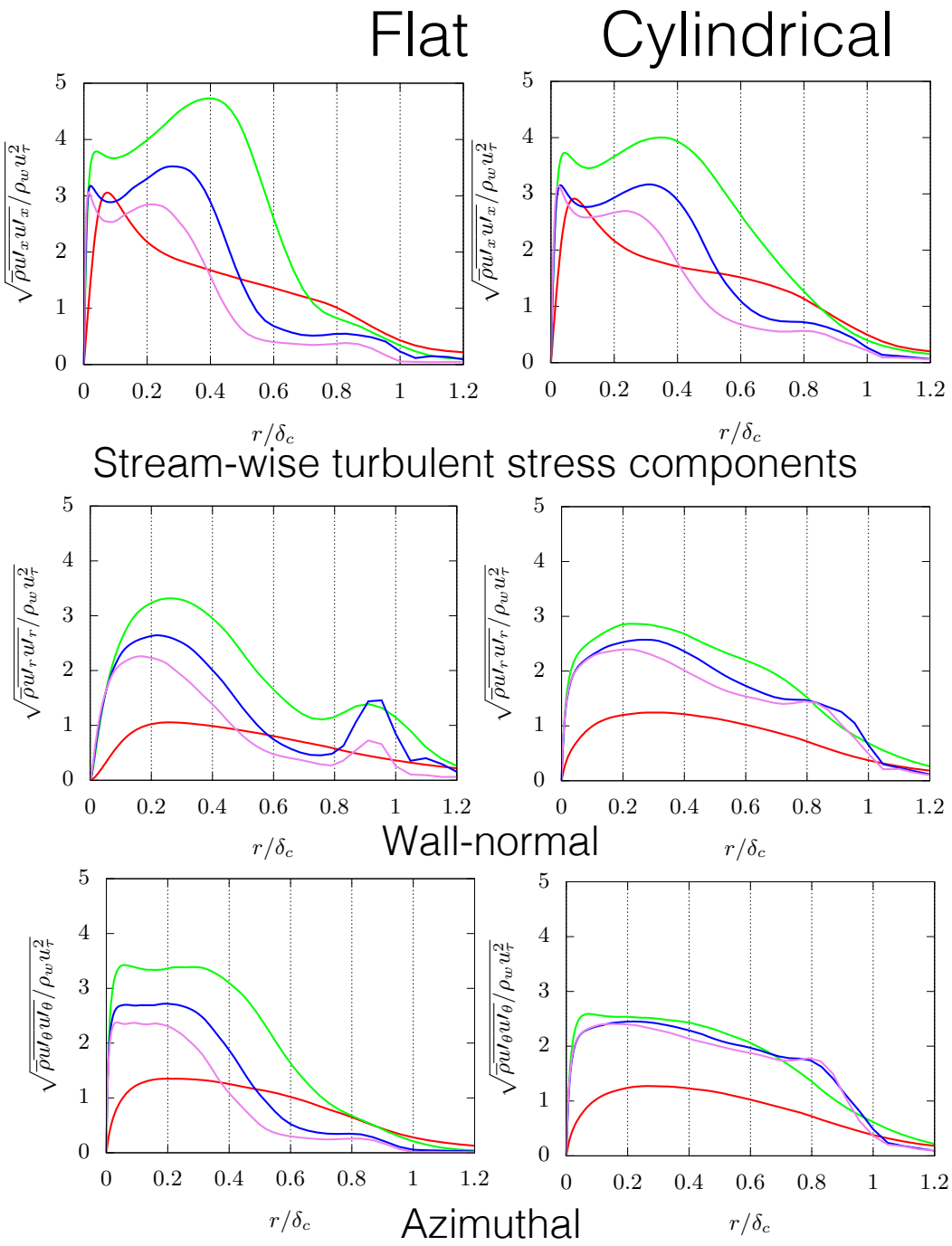


- The boundary layer is perturbed at the interaction and subsides.

In the cylindrical case,

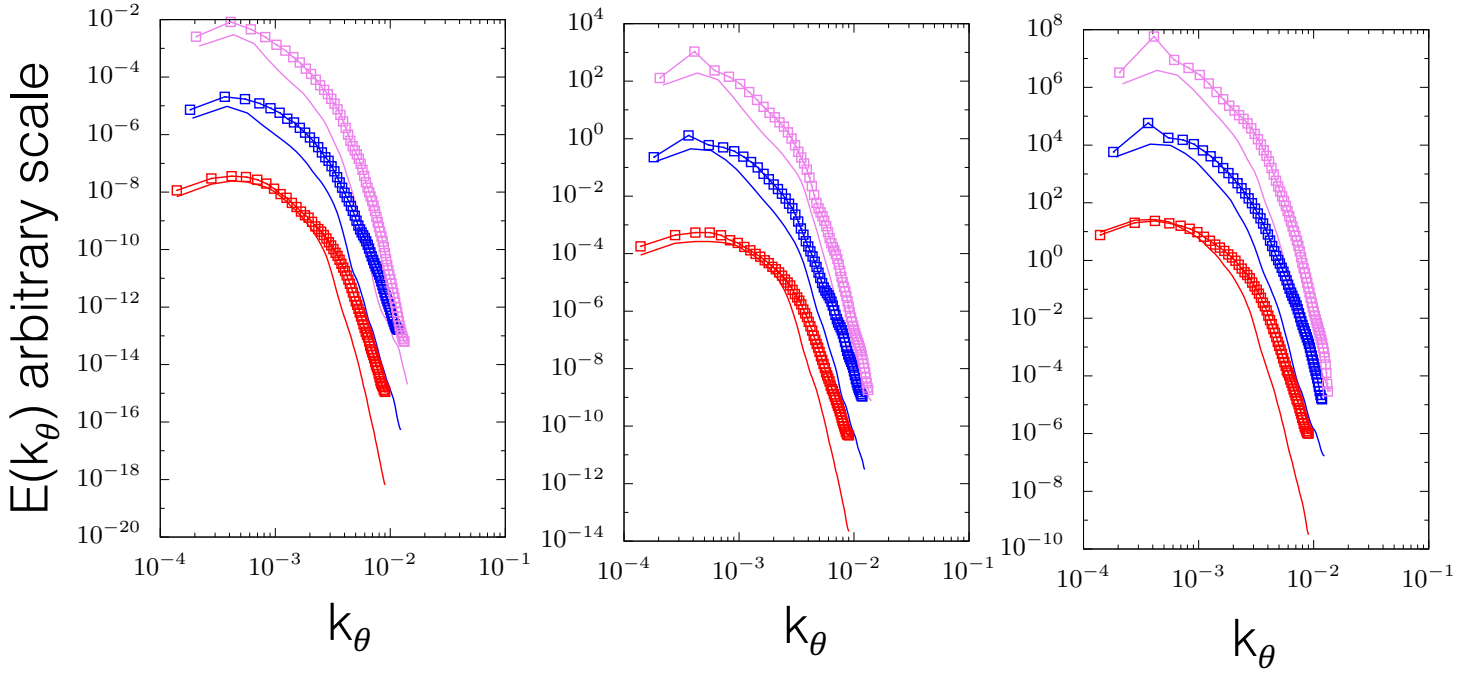
- The relaxation of turbulent intensity slows down
- The perturbation is maintained until the upper part

=> wall-normal, azimuthal direction
=> 3-dimensinal evolution



Spatial spectra on the azimuthal direction at r/δ=0.6

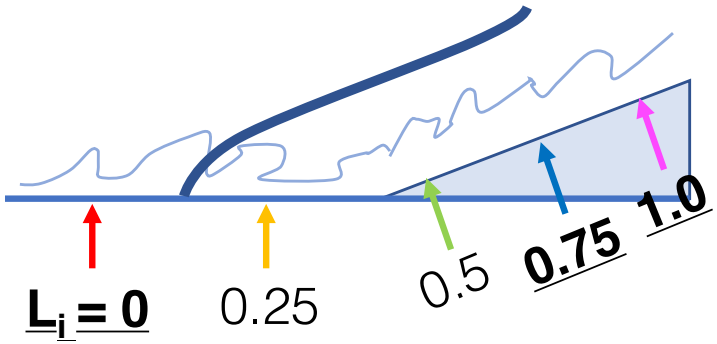
Solid line :
flat case
Symbols :
cylindrical case



$E(k_3)$ of stream-wise fluctuation velocity

$E(k_3)$ of wall-normal

$E(k_3)$ of azimuthal



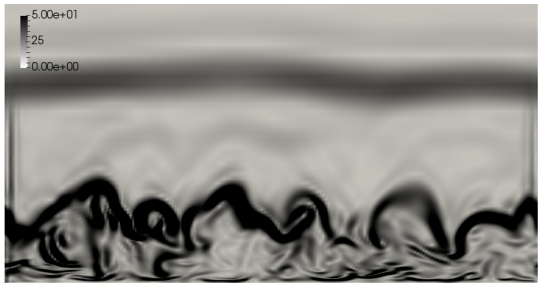
In the cylindrical case,

- Global increase
- Peaks in the azimuthal and radial direction which can be associated with the 3-dimensional evolution
- Further investigations are needed.

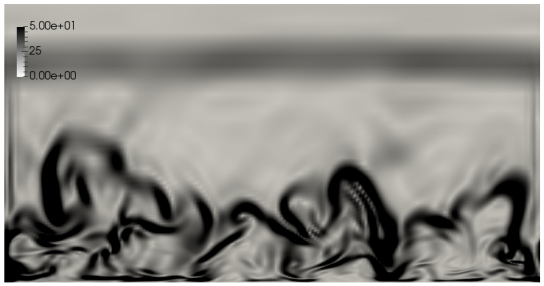
Azimuthal Flow

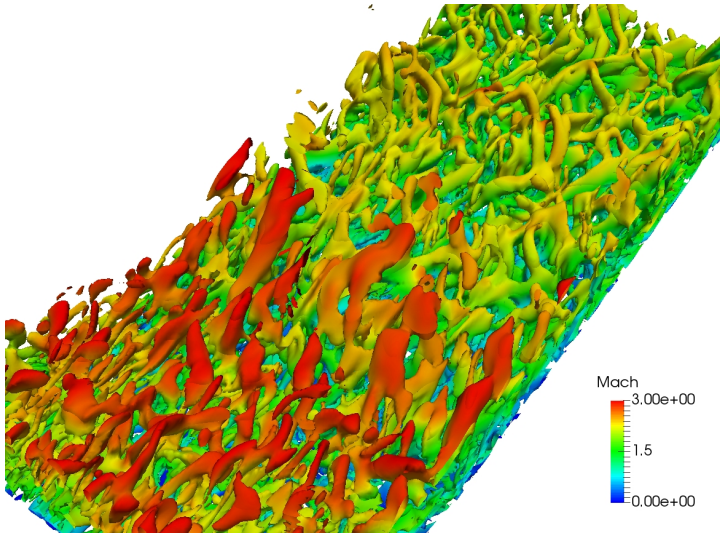
Flat case

Time A

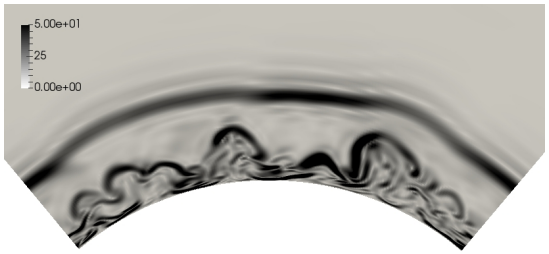


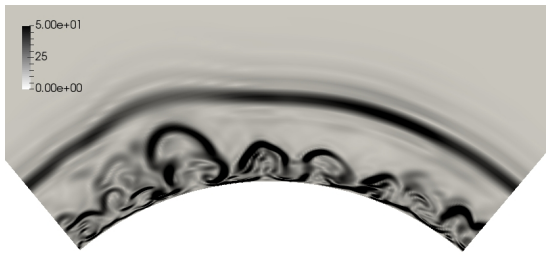
Time B



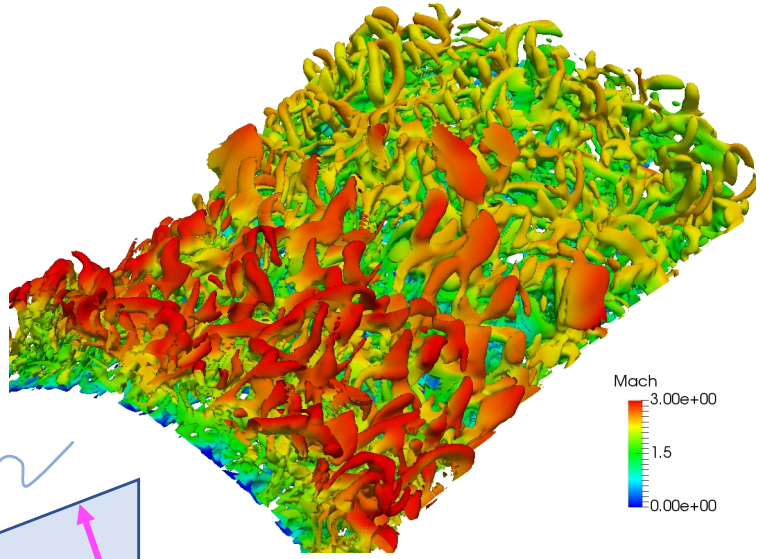


Cylindrical case





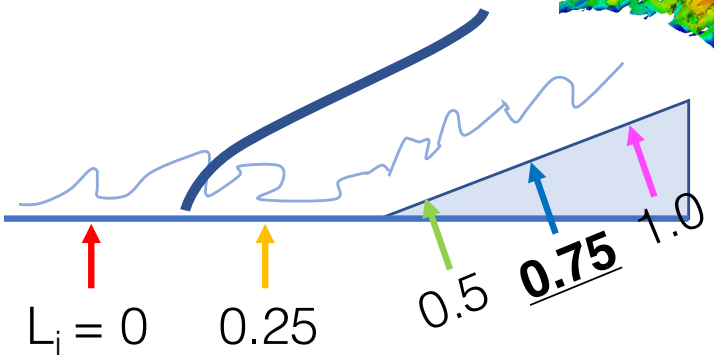
Cross-section view on azimuth



Iso-Qcritatia
(Q=0.0005Qmax)

In the cylindrical case,

- More organized structures
- Extended hairpin-like structures in the azimuthal direction



Conclusion

- Validation of the high fidelity schemes to deal with turbulent structures
- Characterization of the turbulence structures in the boundary layer near the interaction

For the cylindrical case,

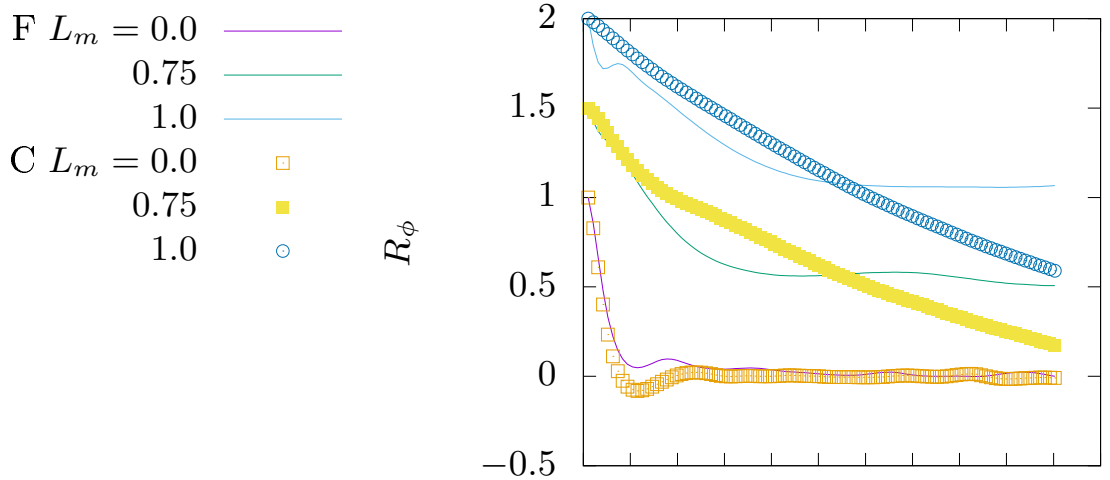
- A 3-dimensional characteristic evolution of vortex structures after the interaction is suggested by the multiple analysis.
- Further investigations are needed to determine its origin.

Perspective

- Determine the origin of the 3-dimensional evolution by more detailed analysis in the cylindrical case
- Various curvature
- Geometrical effect on the low-frequency unsteadiness

Correlation at r/δ_c=0.6

- Flat case converges to zero at those three stream-wise position
- Cylinder case doesn't converge but decreases quasi-linearly
- Downstream of the interaction, 3-dimensinonal flow structures are generated



Two point correlation of u_r