GST-SIG4
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Local optimization of the convergence rate of implicit time advancements for Large-Eddy Simulation of complex flows

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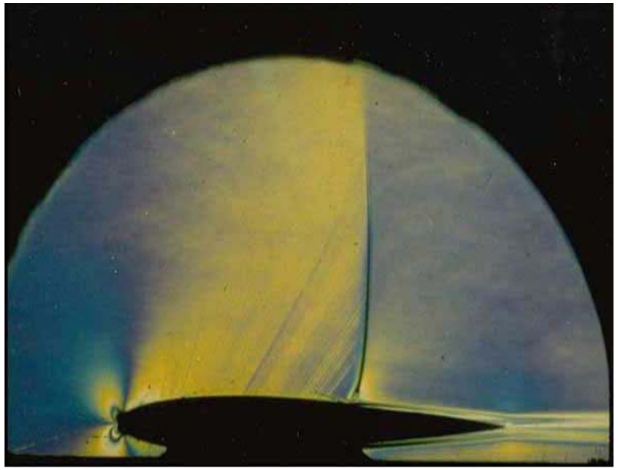
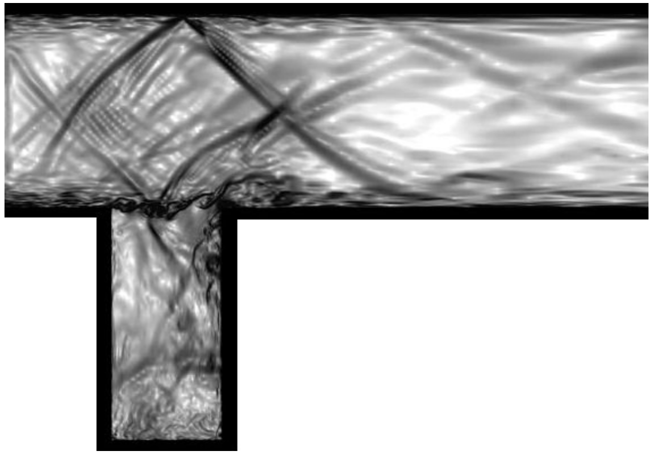
Context

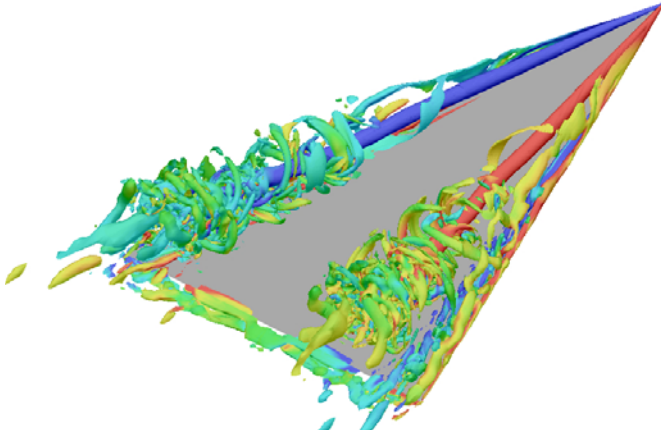
- **Need of unsteady data to describe finely the turbulence:**
    - prediction of sources for the aeroacoustics
    - comprehension of physical phenomena
    - data base for the development of turbulence models
- **Complementarity between experience and numerical simulation (LES or DNS)**
    - zone where measurements are difficult
    - confining
- **Some recent collaboration examples with experimental teams:**



Study of buffeting



Cavity flow



Vortex breakdown

Remarks for the use of DNS/LES in the aeronautical context

- **Physics dominated by the boundary layer dynamics (buffeting)**
  - 2D geometry
  - $\Delta t \approx 0.2\mu s$
  - 1h CPU ⇔ 0.0001s (1 proc. NEC SX5)
- **Physics dominated by the large scale vortices (cavity, delta wing)**
  - 3D geometry
  - $\Delta t \approx 10\mu s$
  - 1h CPU ⇔ 0.005s (1 proc. NEC SX5)
- **Need to reduce the CPU time to realise some studies:**
  - low-frequency phenomena (buffeting, flapping wing, ….)
  - « multi-scale » geometry: actuator for control

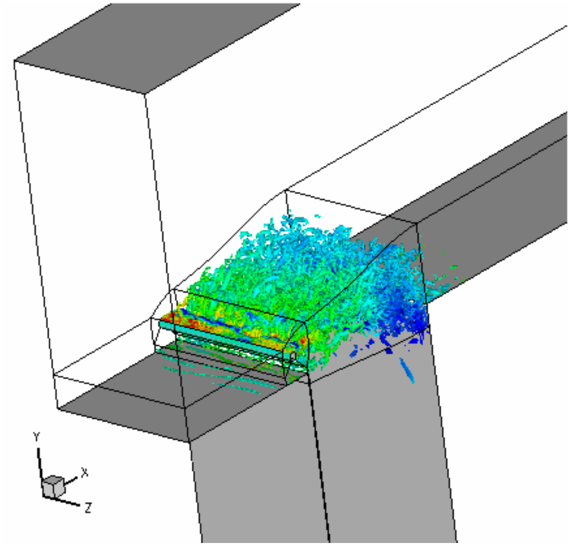
To increase the application field of the LES and the DNS

- **Improvement of the modelling**
  - subgrid scale model
  - RANS/LES coupling
- **Improvement of the numerical method**
  - space discretisation
  - **time integration**

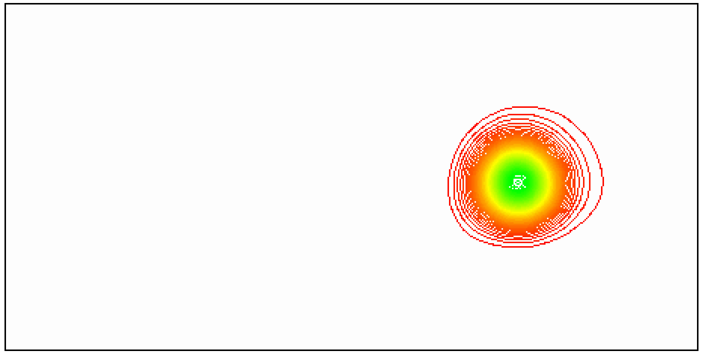
- **Explicit time integration:**
  - high accuracy
  - stability constraint (CFL) too restricting near the wall
- **Implicit Method:**
  - used in the DNS/LES context (Rai & Moin JCP 1993, ...)
  - progress are still needed to allow LES at a more affordable cost
  - transitional flows suffer from a lack of accuracy (Raverdy 2003)

Several test cases for the DNS/LES context

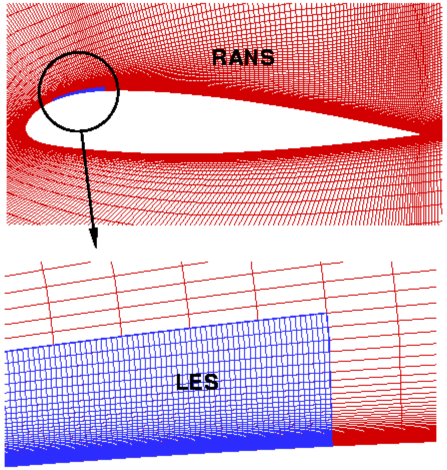
- **Controlled transonic cavity flow:**
  (very challenging objective)



- **Several configurations under consideration:**



Simple laminar flow



More relevant realistic test case

Numerical Method:
general context

- **« Cell-centered » finite volume method**
- **Structured multi-block meshes**
- **Spatial Discretization:**
  - convection: simplified formula of the AUSM+(P) scheme (Mary and Sagaut 2002)
  - diffusion: second-order accurate centered scheme
- **Time Integration:**
  - Gear scheme (second-order in time, A-stable) => $\Im\left(U^{n+1}\right) = 0$
  - Three-stage Runge-Kutta scheme (third order, explicit reference)

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Numerical Method:
Approximate Newton method

$$\Im\left(U^{n+1}\right) = 0$$

Non-linear fixed-point problem

$$\begin{cases} \partial_U \Im\big|_{U^{n+1,p}} \Delta U^{n+1,p} = -\Im\left(U^{n+1,p}\right) \\ U^{n+1,p+1} = U^{n+1,p} + \Delta U^{n+1,p} \end{cases}$$

Newton-Raphson Method

- ➢ Exact Newton method never used (too costly)
- ➢ Use of approximations :
  - ✓ Jacobian matrices (Jameson & Yoon, Coakley)
  - ✓ linear system (LU-SGS Factorisation)
  - ✓ boundary conditions

$$\begin{cases} (D+L)\Delta V^{n+1,p} = -\Im\left(U^{n+1,p}\right) \\ (D+E)\Delta U^{n+1,p} = D\Delta V^{n+1,p} \end{cases} \text{with } \Delta V^{n+1,p}\Big|_G = 0$$

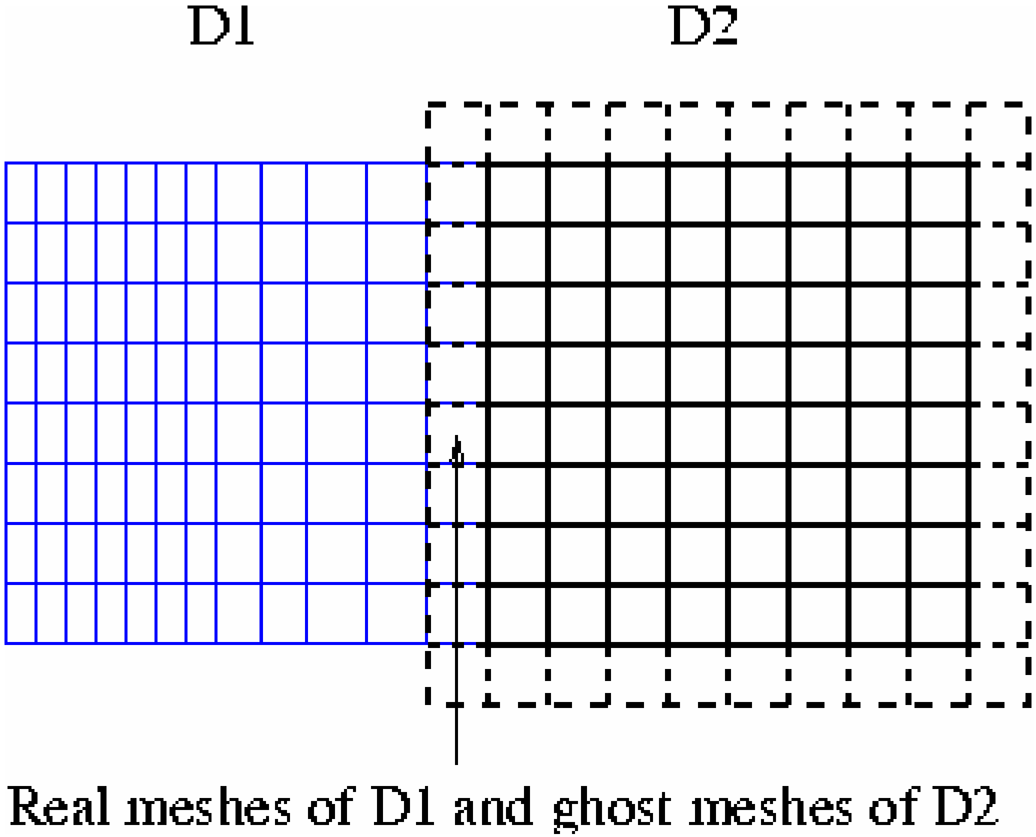
N = iterations number
in the inner process

Numerical Method:
Local optimization (LO) of convergence

The higher is the maximal CFL value, the higher is N

As the CFL number is inherently local (boundary layer : stretched meshes)

=> **local determination (per domain) of the iteration number N**



Real meshes of D1 and ghost meshes of D2

$$CFL_1 \geq CFL_2 \text{ so } N_1 \geq N_2$$

✓ We assume that $N_1 = mN_2$ with $m \in \mathbb{N}$

=> every m iterations,
D1 and D2 «communicate»

✓ We want to assure a transmission as well as possible between D1 and D2

=> **implicitation of BC between D1 and D2**

Numerical Method:
Implicitation of BC between D1 and D2

For one iteration where two domains are solved denoted p_{k+1}

LU-SGS Factorization for D1

$$\begin{cases} (D+L)\Delta V^{n+1,p_{k+1}}\Big|_{R_1} = -\Im\left(U^{n+1,p_{k+1}}\right)\Big|_{R_1} \\ (D+E)\Delta U^{n+1,p_{k+1}}\Big|_{R_1} = D\Delta V^{n+1,p_{k+1}}\Big|_{R_1} \end{cases}$$

$$\Delta V^{n+1,p_{k+1}}\Big|_{G_1} = 0$$

LU-SGS Factorization for D2

$$\begin{cases} (D+L)\Delta V^{n+1,p_{k+1}}\Big|_{R_2} = -\Im\left(U^{n+1,p_{k+1}}\right)\Big|_{R_2} \\ (D+E)\Delta U^{n+1,p_{k+1}}\Big|_{R_2} = D\Delta V^{n+1,p_{k+1}}\Big|_{R_2} \end{cases}$$

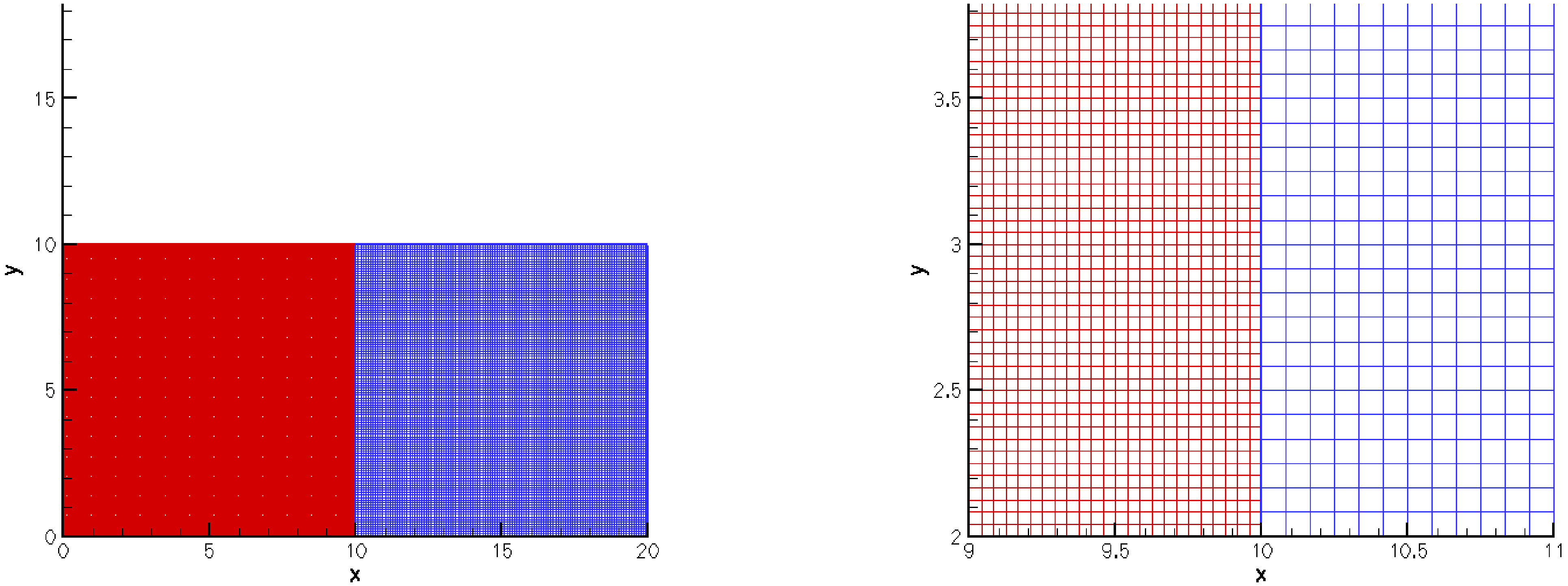
$$\Delta V^{n+1,p_{k+1}}\Big|_{G_2 \bigcap R_1} = \sum_{l=p_k+1}^{p_{k+1}} \Delta U^{n+1,l}\Big|_{R_1 \bigcap G_2}$$

p_k being the last iteration where the two domains are solved

$$p_{k+1} = p_k + m$$

Laminar 2D Vortex Advection (1/3)

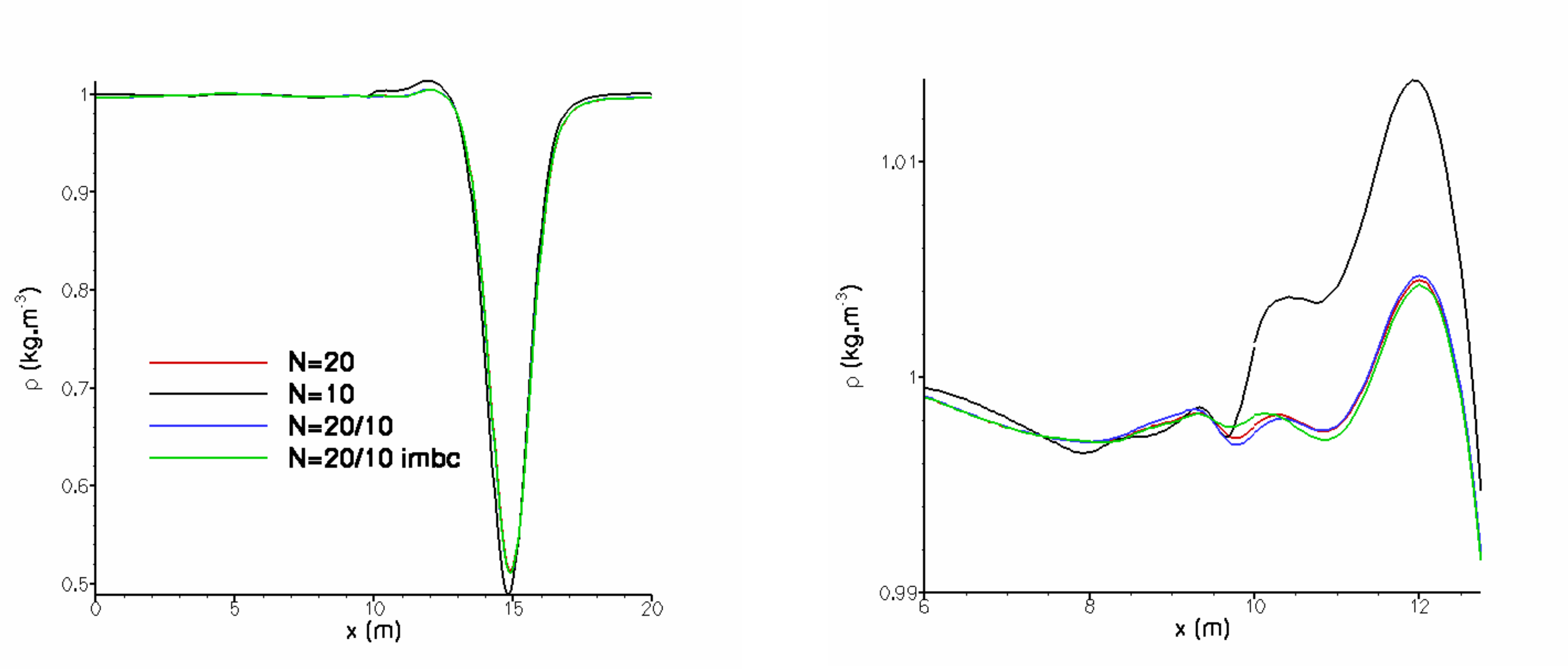
To check the potential of the proposed method



- ➢ Computational domain divided into two parts
- ➢ Time step is identical, only the resolution differs

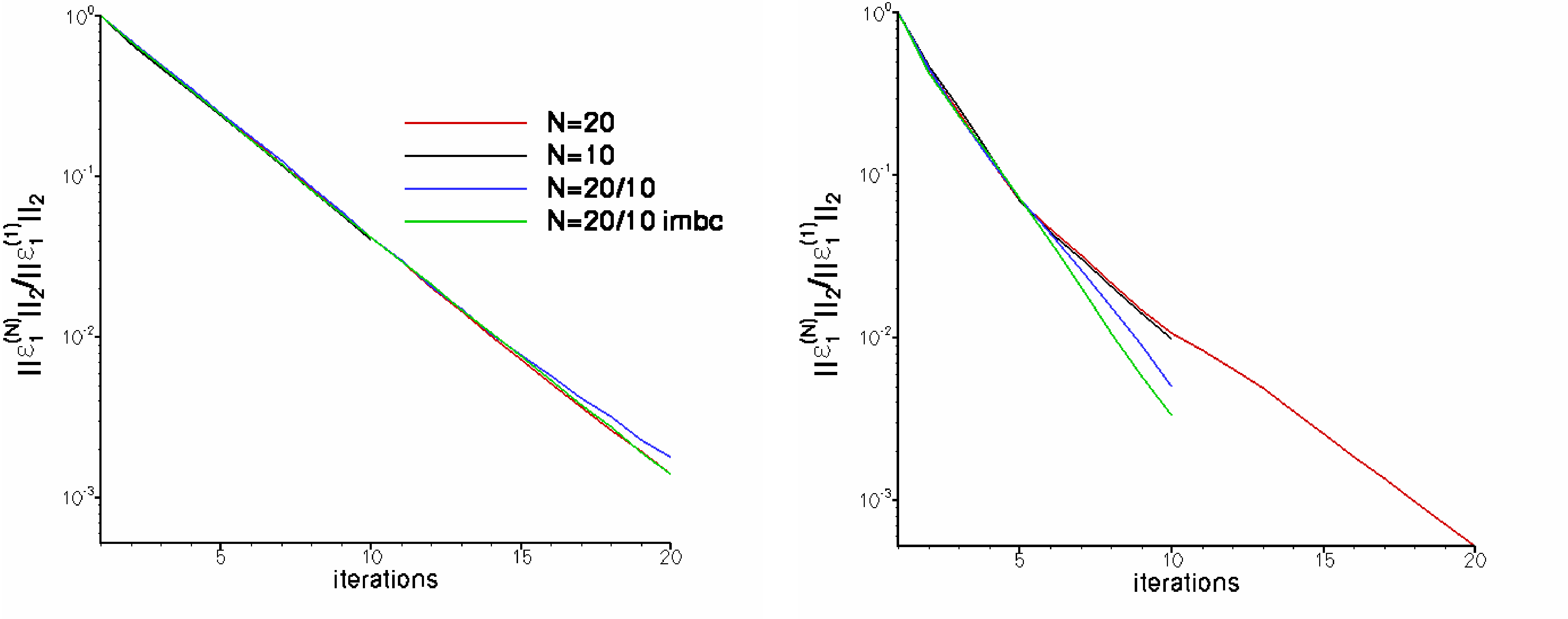
Laminar 2D Vortex Advection (2/3)

Assessment on the mean flow



Good agreement between LO method and “converged” implicit method

Laminar 2D Vortex Advection (3/3)



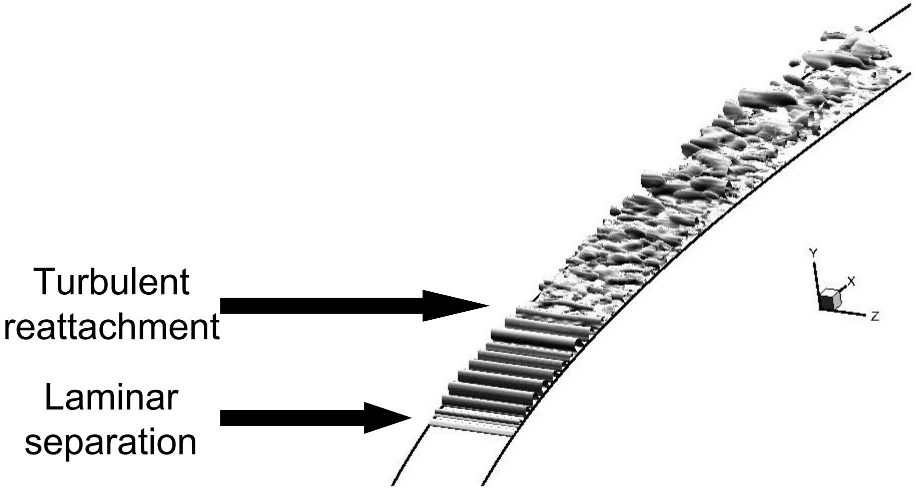
Residual Newton for continuity equation for Domain 1 and Domain 2

Implicitation of the BC between the 2 domains increases the convergence

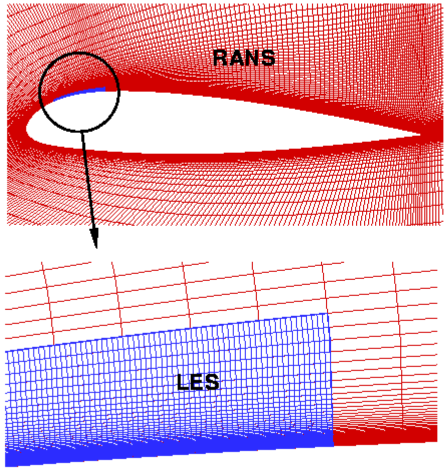
Transitional boundary layer around an airfoil (1/10)

complex physics

discriminating for the time integration technique



Pressure fluctuation isosurface in the transitional zone

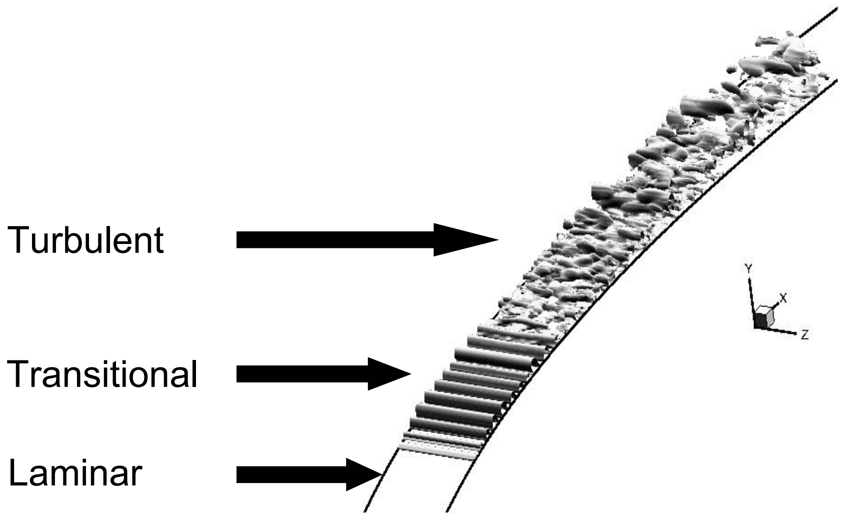


View of meshes of the RANS and LES zones

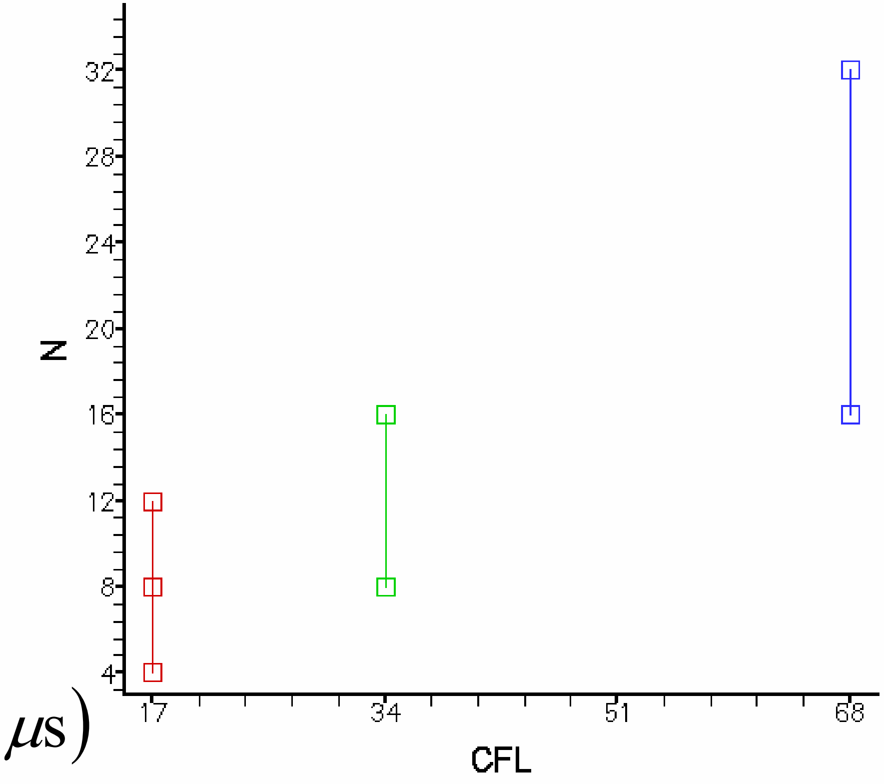
- ➢ Use of coupled RANS/LES (Nolin *et al.* 2005)
- ➢ LES zone 7%-20% of the chord, 600 000 points

Transitional boundary layer around an airfoil (2/10)

- **Assessment of the implicit method:**
  mean-flow, rms fluctuations, wall pressure spectra in different regions



Pressure fluctuation isosurface in the transitional zone

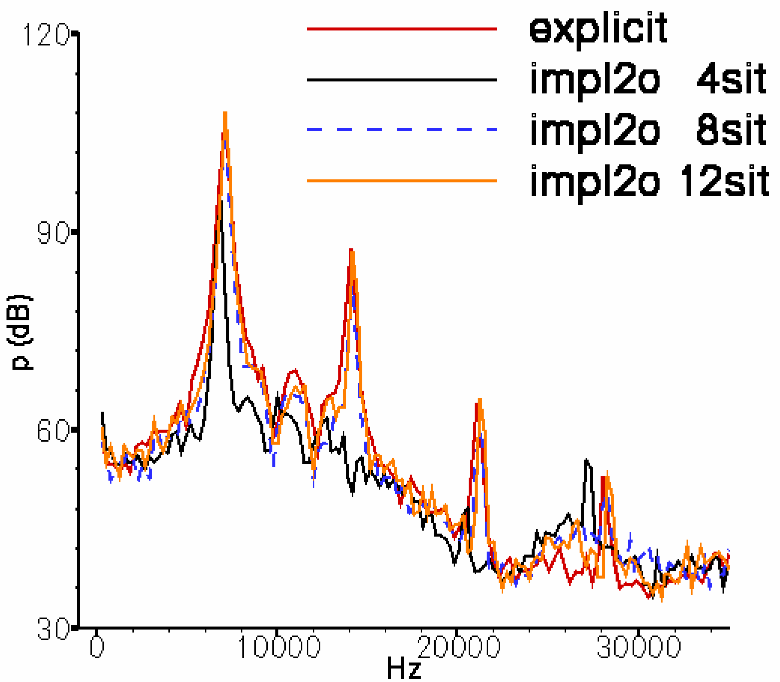


CFL number versus iterations number

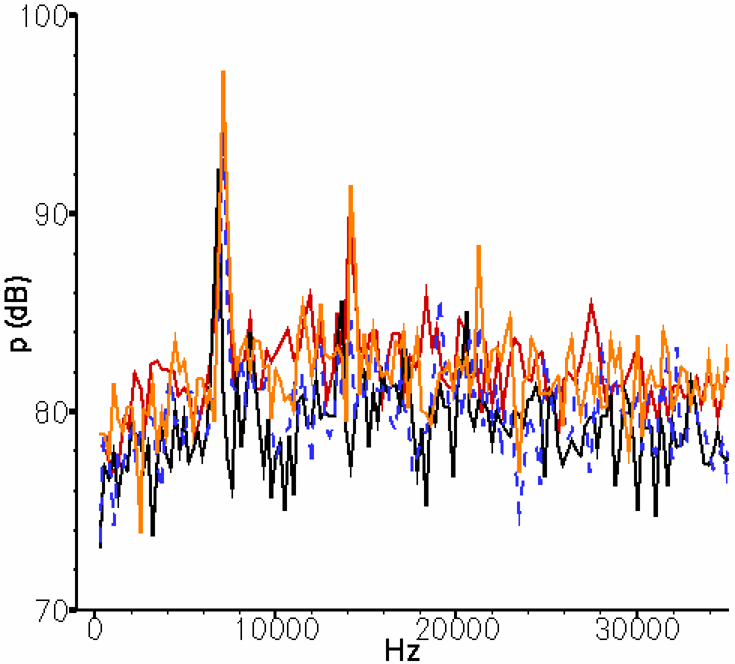
- **Influence of N at fixed CFL = 17** $\left(\Delta t = 0.25\,\mu s\right)$
- **Simulations repeated at larger CFL**
- **Effect of the LO on the accuracy**

Transitional boundary layer around an airfoil (3/10)

Influence of N on pressure spectra



transitional region (x/c=0.09)



turbulent zone (x/c=0.17)

➢ **transitional region:**

- ✓ 4 iterations not enough (residual divided by 5.5)
- ✓ good agreement between explicit and 8 iterations

➢ **turbulent region:**

weak influence of convergence level

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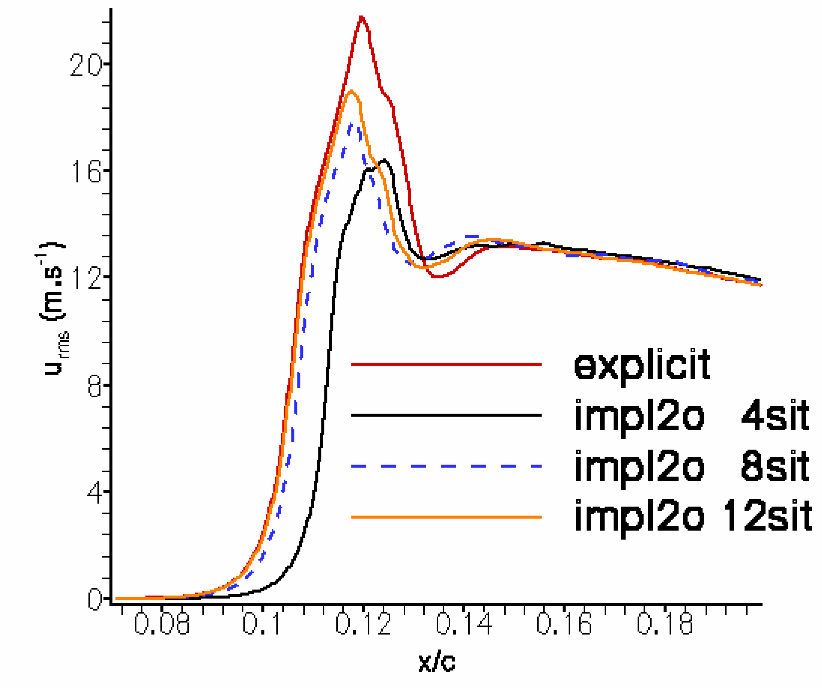
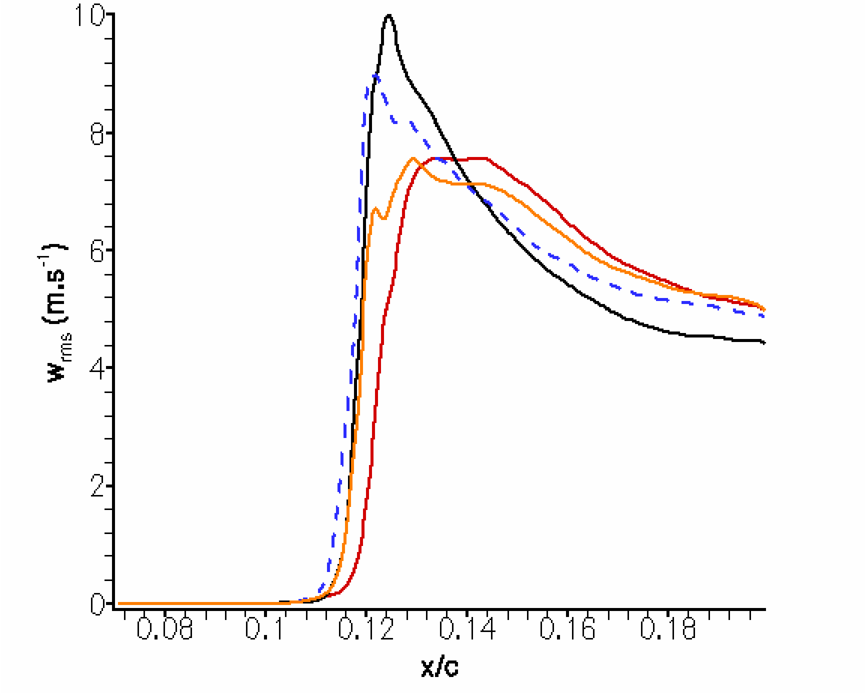
Transitional boundary layer around an airfoil (4/10)

Influence of N on rms flow along longitudinal direction



Streamwise velocity fluctuations at $y^+ \approx 30$



Spanwise velocity fluctuations at $y^+ \approx 30$

- ➢ Reynolds-stress affected in the transition zone
- ➢ Out of the transition zone, behaviours are similar

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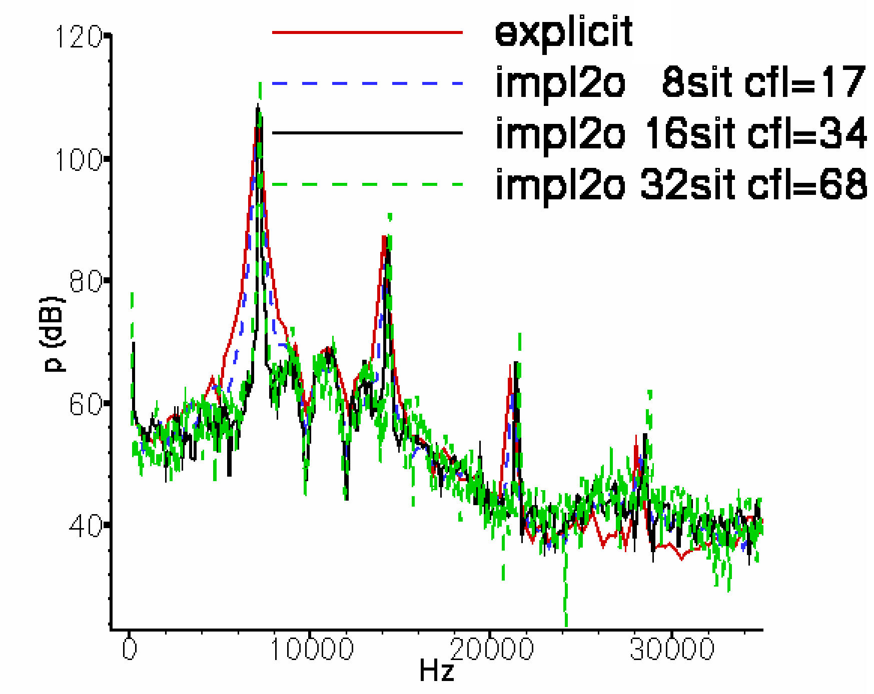
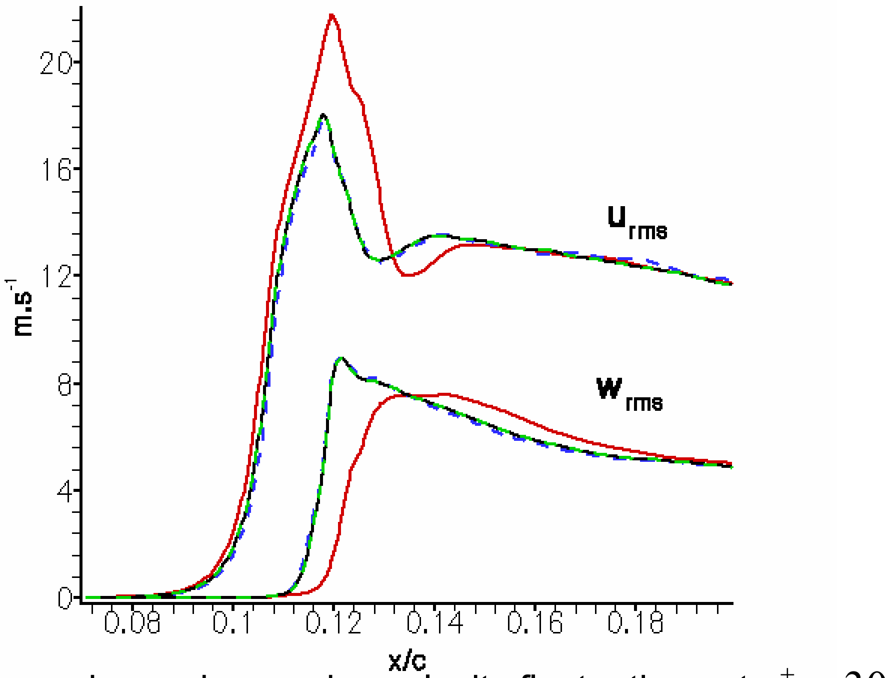
Transitional boundary layer around an airfoil (5/10)

Effect of the couple (CFL,N) on pressure spectra and rms flow



Pressure spectra at x/c=0.09



Streamwise and spanwise velocity fluctuations at $y^+ \approx 30$

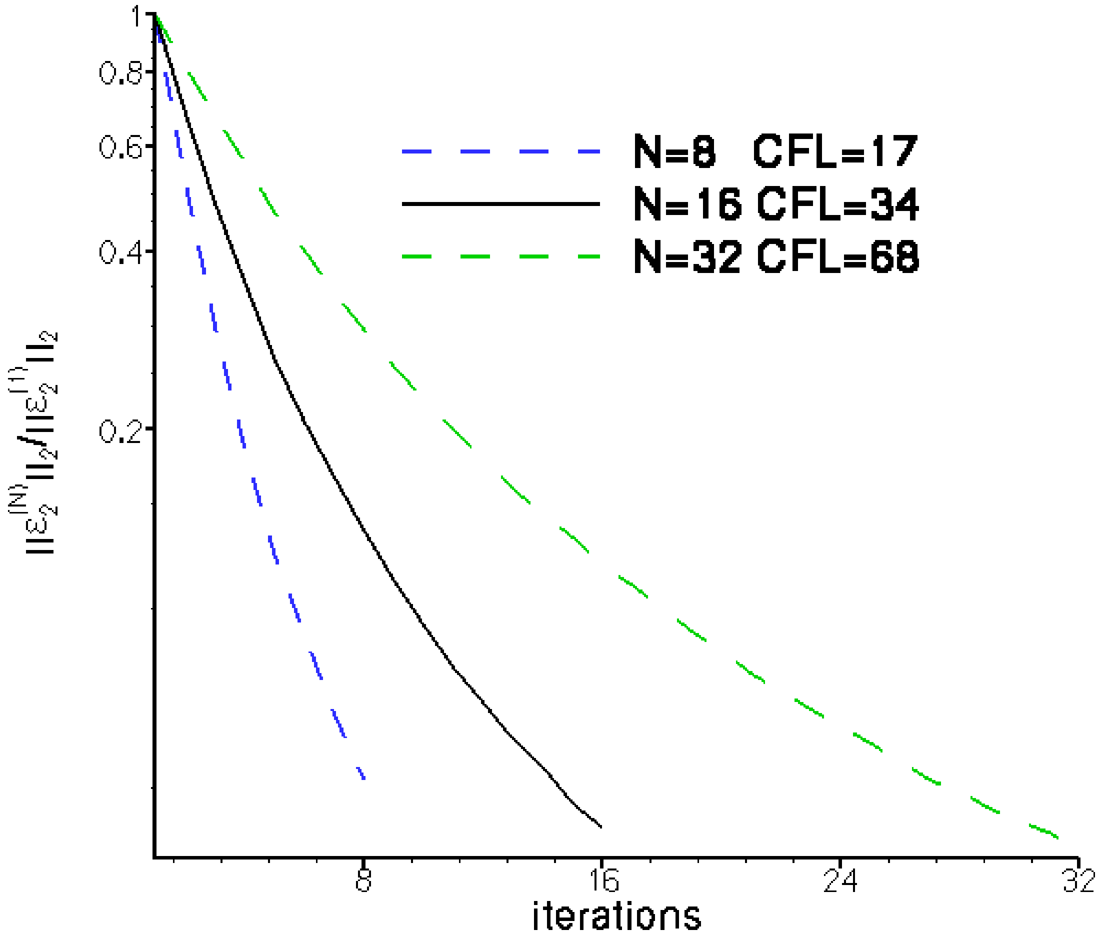
- Good agreement between (CFL,N)=(17,8), (34,16) and (68,32)

- $\Delta t \nearrow$ if N suitable
  => no improvement of efficiency

	explicit	implicit			implicit		
CFL	1,30	17	34	68	17	34	68
N	/	8	16	32	4	8	16
CFL/N	/	≈2			≈4		
CPU time (%)	100	50			25		

Transitional boundary layer around an airfoil (6/10)

Effect of the couple (CFL,N) on the convergence rate



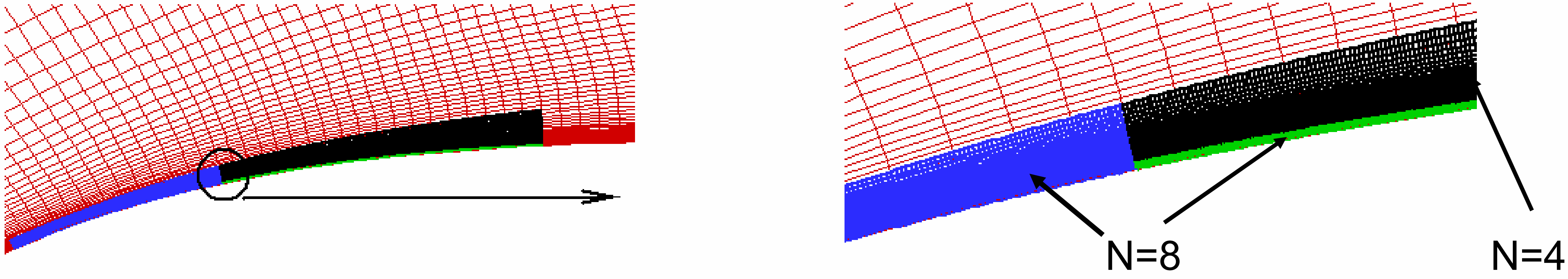
Newton residual for the first momentum equation in the LES domain

- ➢ The maximal CFL value drives the convergence

Transitional boundary layer around an airfoil (7/10)

Local optimization of the convergence rate

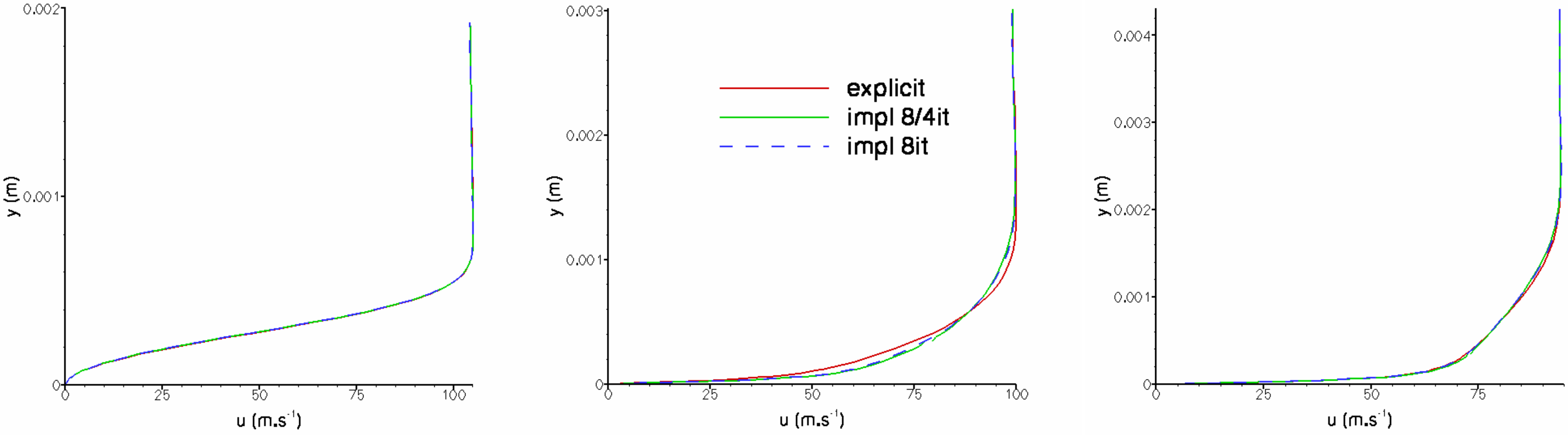
- Local determination (per domain) of iterations number N
- Time step fixed at 0,25 μs => CFL max = 17
- Partitioning of the LES domain:
  - ✓ partitioning retained follows the position of the transition region
  - ✓ 17 % CPU time reduction expected



- Implicitation of BC to assure a better «connection»

Transitional boundary layer around an airfoil (8/10)

Local optimization of the convergence rate

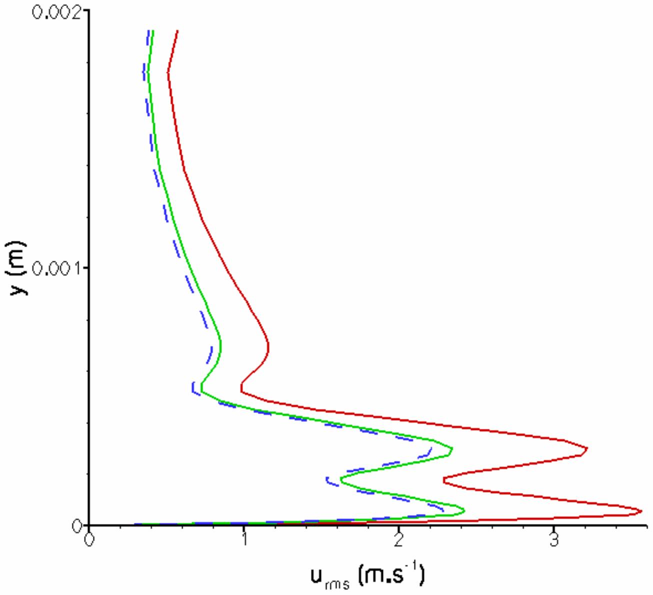


x/c=0.09 x/c=0.13 x/c=0.17

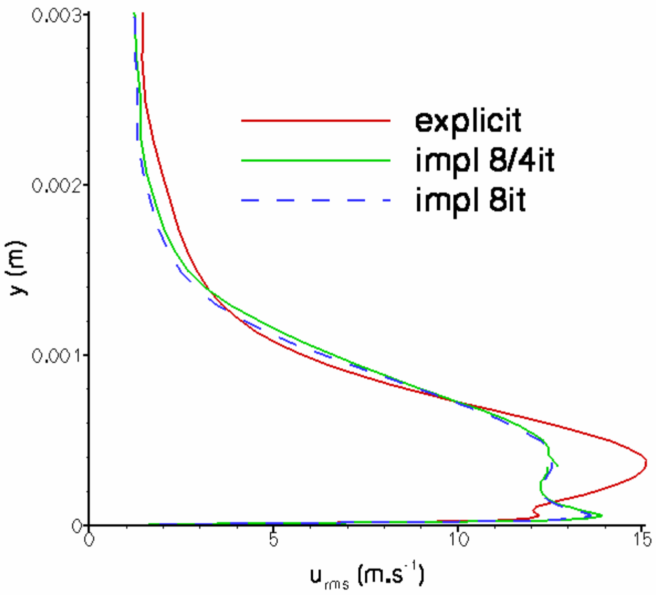
➢ Very good agreement between (CFL,N)=(17,8) and the LO (CFL,N)=(17,8/4) on the streamwise mean velocity in the different regions of the boundary layer

Transitional boundary layer around an airfoil (9/10)

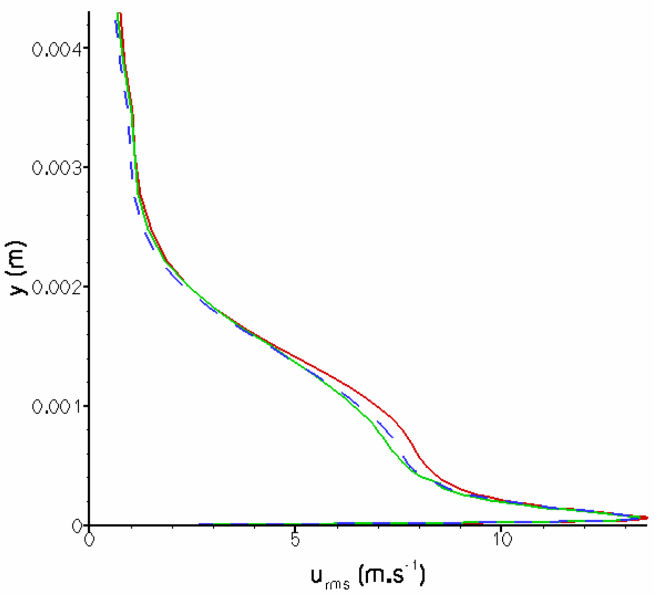
Local optimization of the convergence rate



x/c=0.09



x/c=0.13

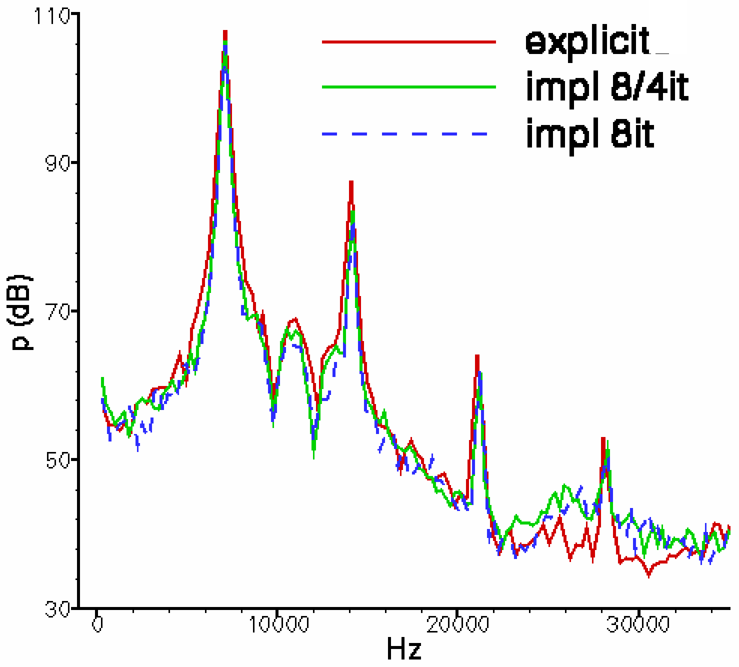


x/c=0.17

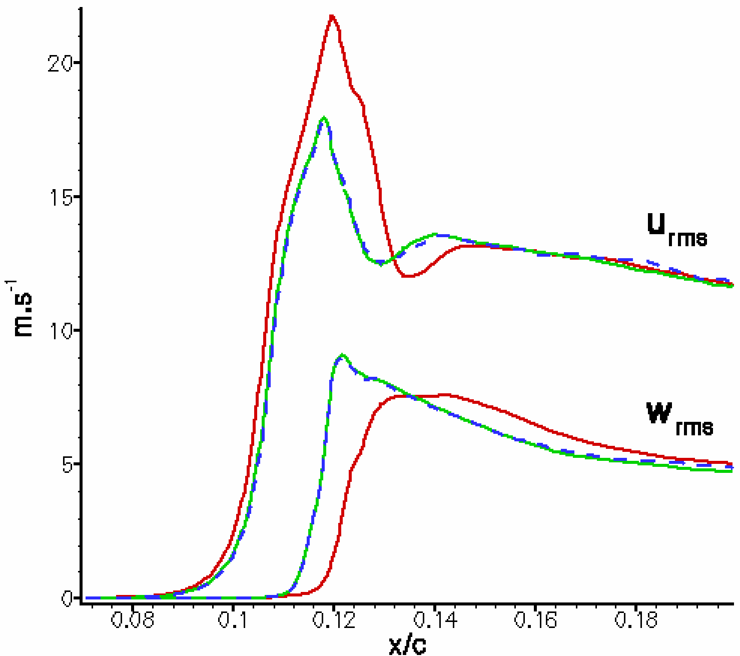
- ➢ Satisfactory collapse for the profiles of velocity fluctuations between the implicit reference and the LO

Transitional boundary layer around an airfoil (10/10)

Local optimization of the convergence rate



Pressure spectra at x/c=0.09



Streamwise and spanwise velocity fluctuations at $y^+ \approx 30$

- Good agreement between (CFL,N)=(17,8) and the hybrid method (CFL,N)=(17,8/4)
  => **Validation of the local optimisation of the convergence**

Conclusion and futures plans

Conclusions

- Presentation of an improvement of the slover's efficiency

  Local optimization of the convergence rate and IMBC

- Validation on two test cases (vortex advection and boundary layer)

- In particular on transitional boundary layer around an airfoil

  Necessity of an important convergence rate in the transition zone which prejudices the CPU time benefit

- Gain expected can be very promising

Futures plans

- Controlled cavity flow by means a spanwise cylinder

Controlled cavity flow simulation

- Large pressure fluctuations produced by high-speed flows past open cavities

  => this flow control is essential

- LES a reliable tool to predict cavity flow (Larchevêque *etal.* JFM 2004)

  dynamics of the flow governed by large detached vortices

- A cylinder put in front of the cavity = efficient purview to avoid the production of high pressure fluctuations

- Two different fluid dynamics problems = cavity flow + TBL around a cylinder

  => computation more complex than the one without cylinder
  (boundary layer dynamics stronger impact on the global flow dynamics)

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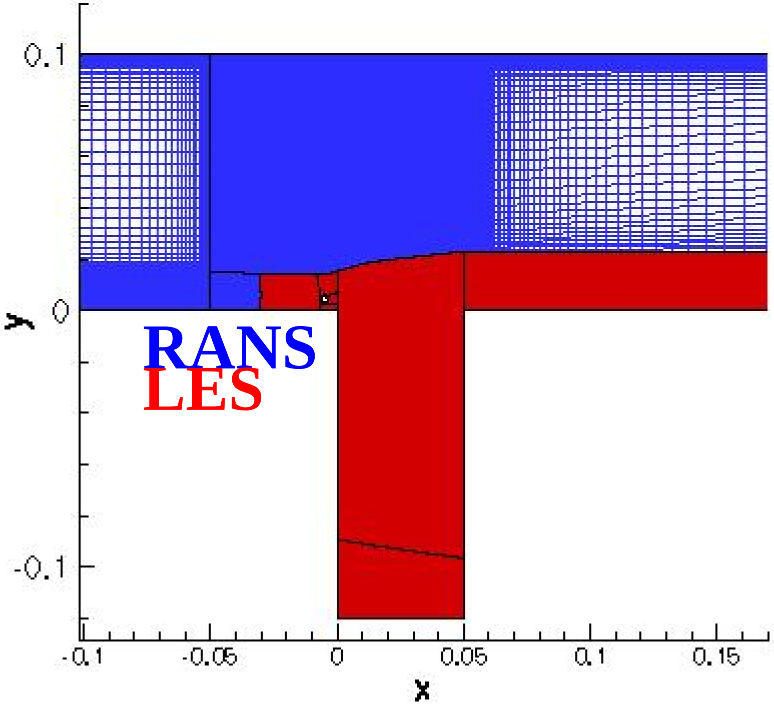
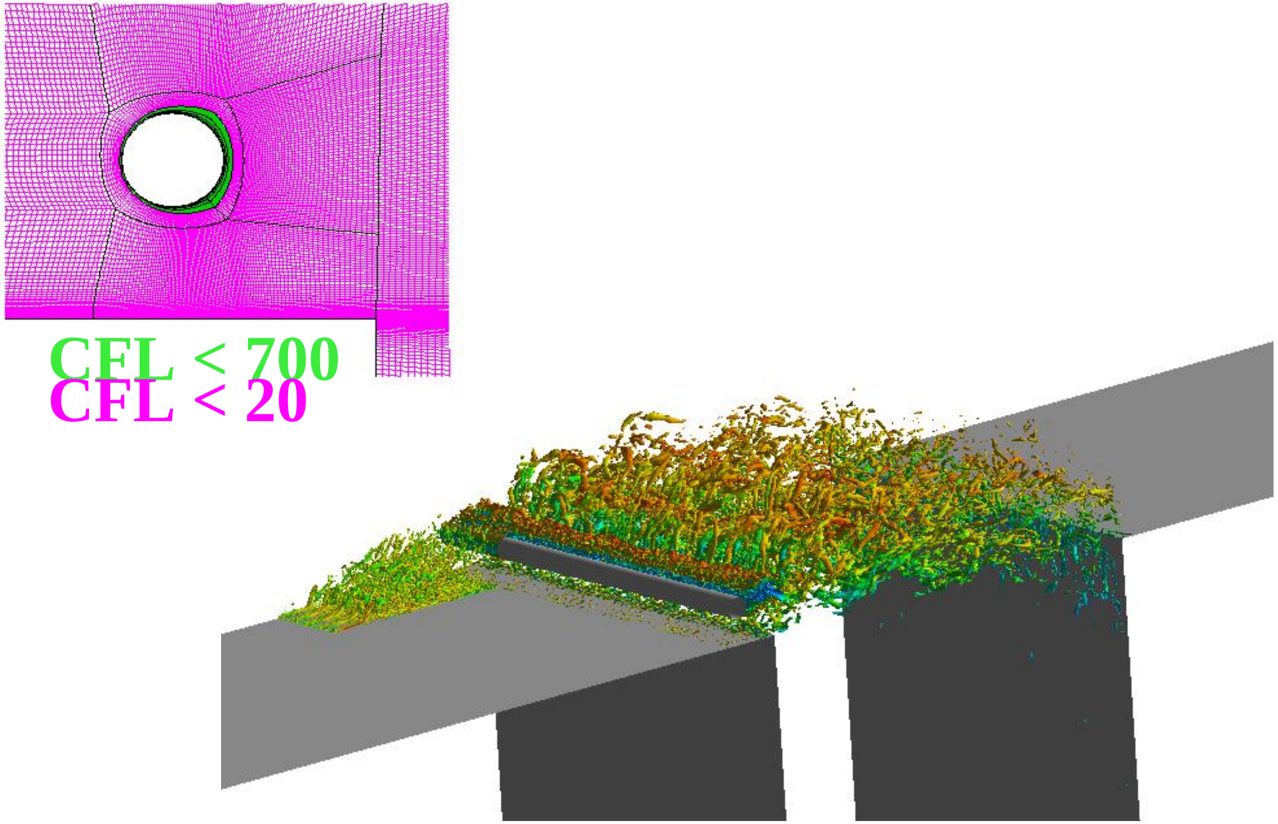
Controlled cavity flow simulation





	Cells Number (10^6)			N		CPU time (%)
	CFL≤16	16<CFL≤700	total	CFL≤16	16<CFL≤700	
Fixed N	20	0.5	20.5	**80**	**80**	**100**
Local N	20	0.5	20.5	**4**	**80**	**10**