Direct Numerical Simulation of Supersonic Flows Passing a Backward Step

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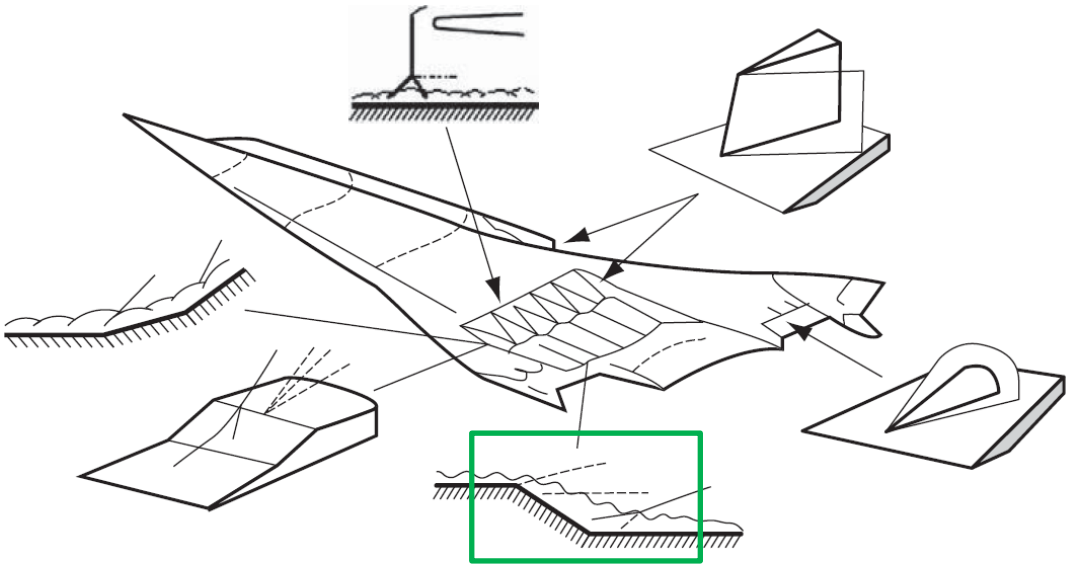
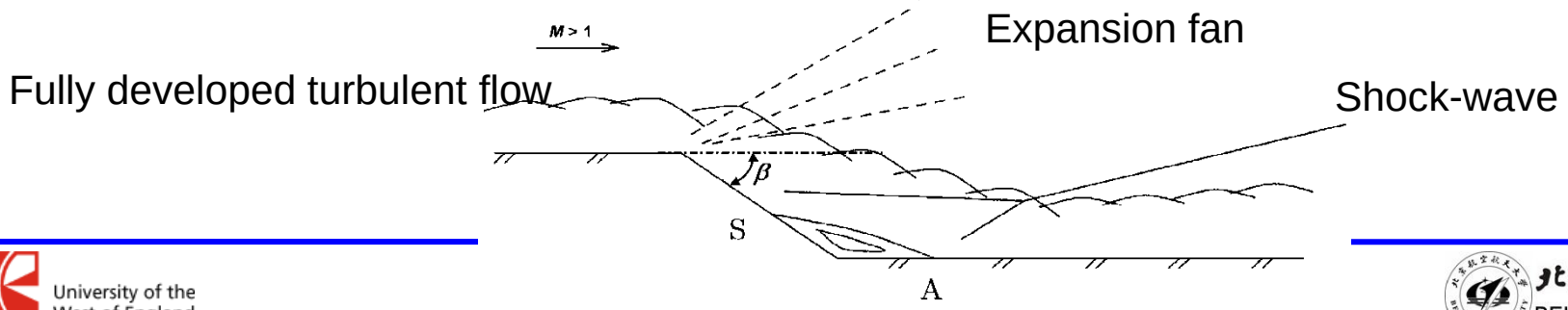
Problem Background

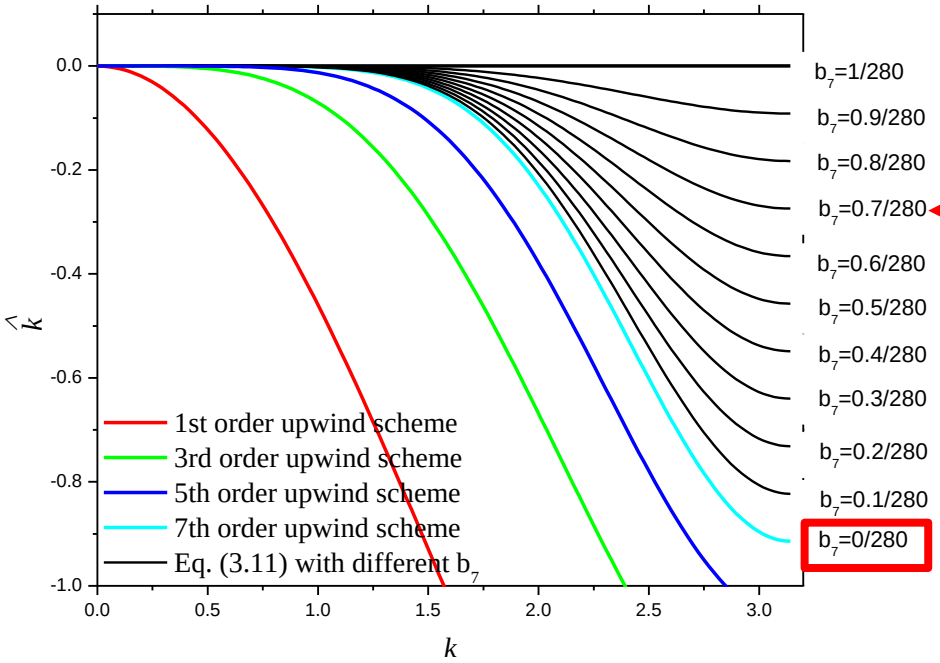
- **Supersonic flow passing a Backward step is one of key flow phenomena in high-speed vehicle and its propulsion systems**



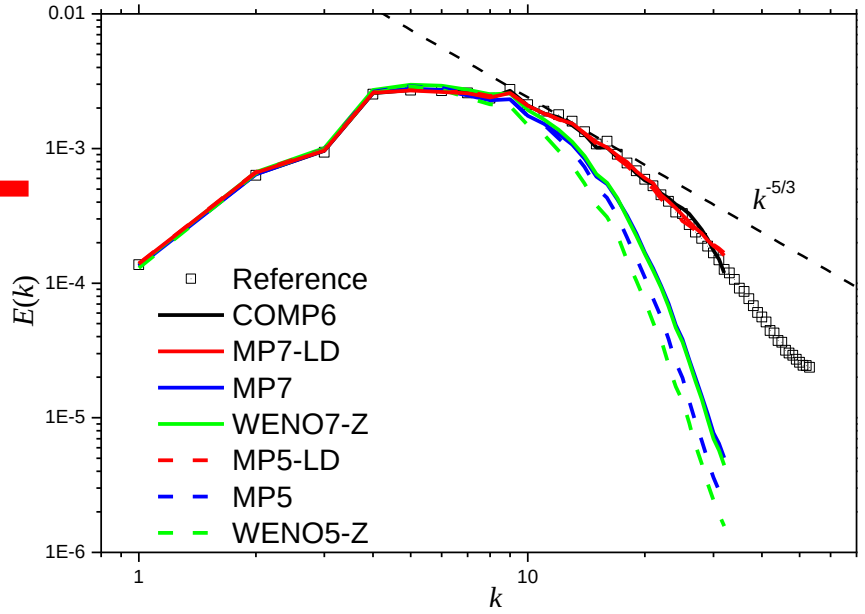


CFD code: Low-Dissipation Monotonicity-Preserving Scheme

- **Bandwidth dissipation optimization method（BDOM）is used to optimize the linear part of the MP scheme**
  1. *Fang, J., Li, Z. and Lu, L., Journal of Scientific Computing, 56:67-95, 2013.*
  2. *Fang, J., Yao, Y.F., Li, Z. and Lu, L., Computers and Fluids, 104: 55-72, 2014*

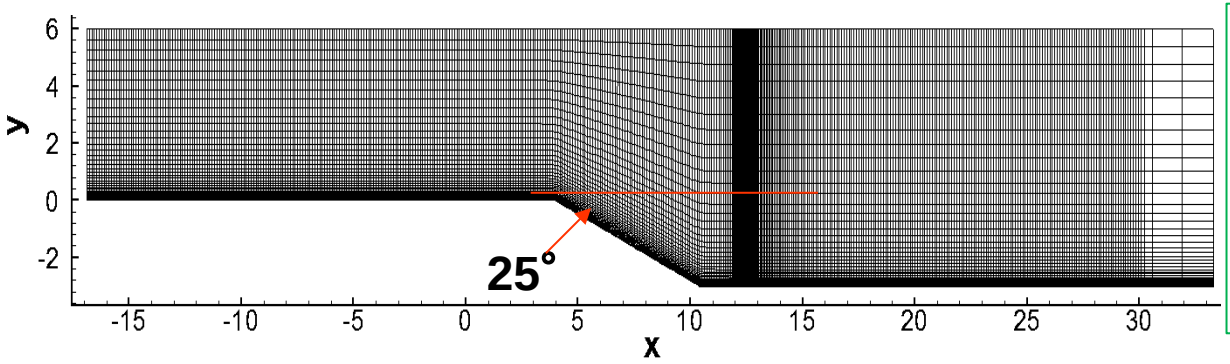


Bandwidth property of MP7-LD scheme



DNS of isotropic turbulence

Supersonic flow passing a backward step

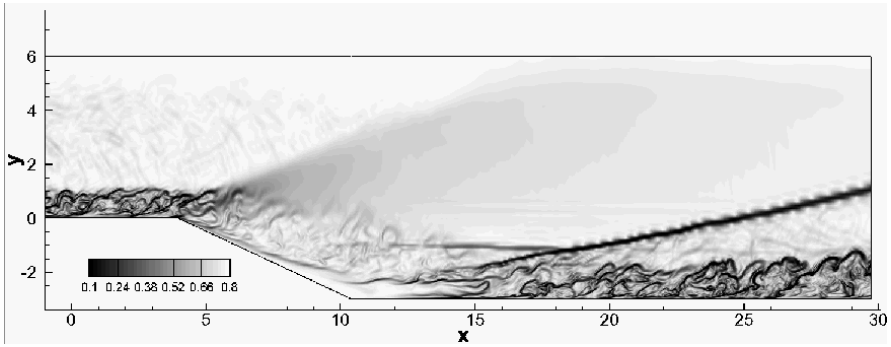


Mach=2.9

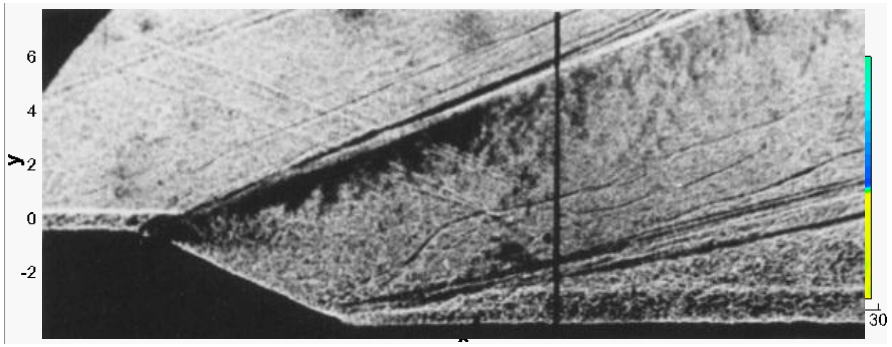
Case 1: Re_δ=20000

Case 2: Re_δ=40000

Case 3: Re_δ=80000



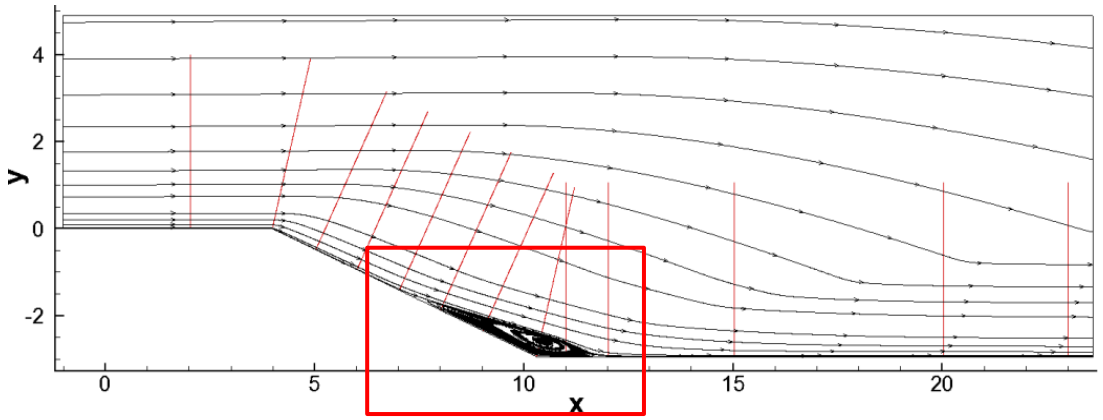
Density Schlieren



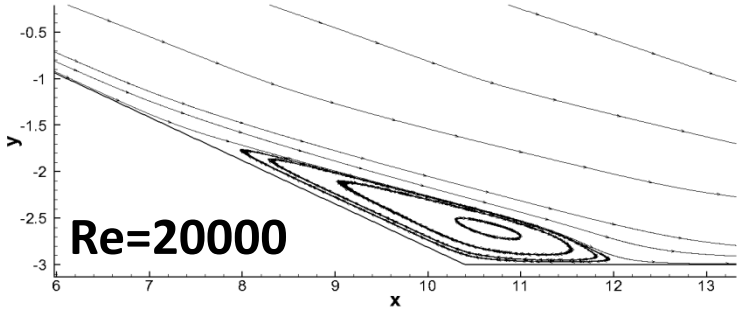
Pressure Field

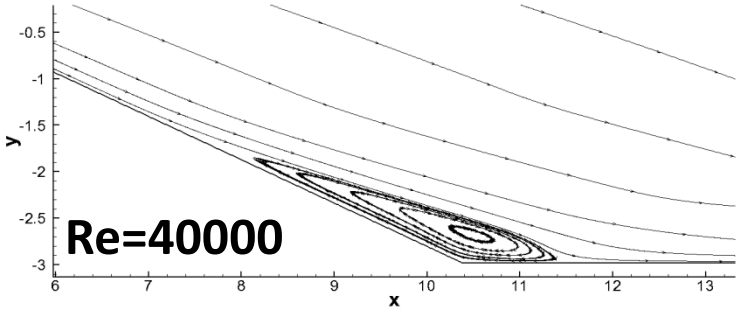
Ref: Zheltovodov, A., et al. (1990). An Experimental Documentation of Supersonic Turbulent Flows in the Vicinity of Forward and Backward-Facing Ramps.

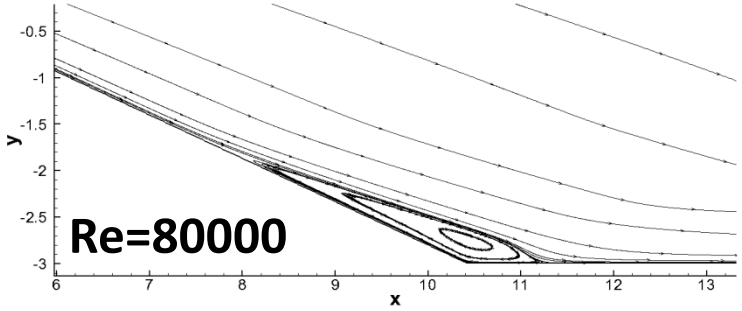
Separation bubble reduces with Reynolds number



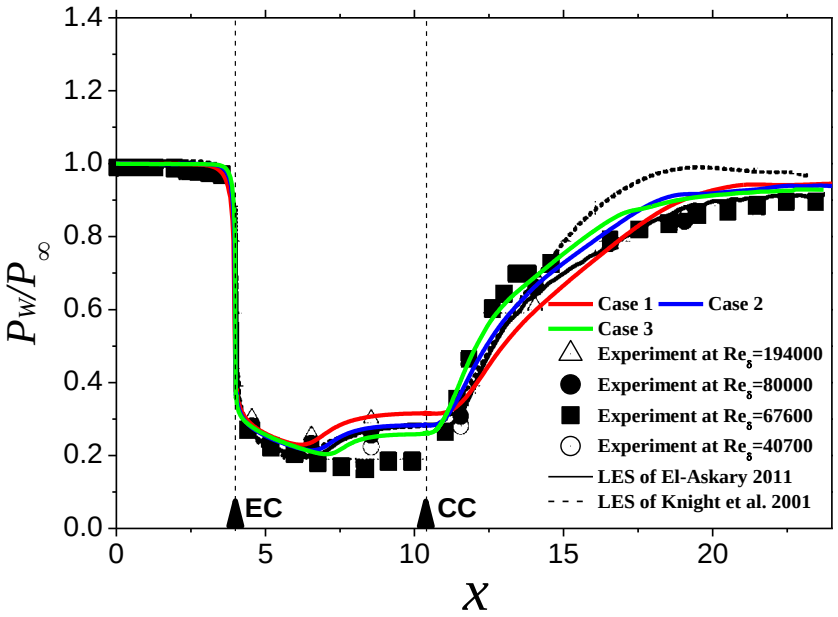
Mean Streamlines



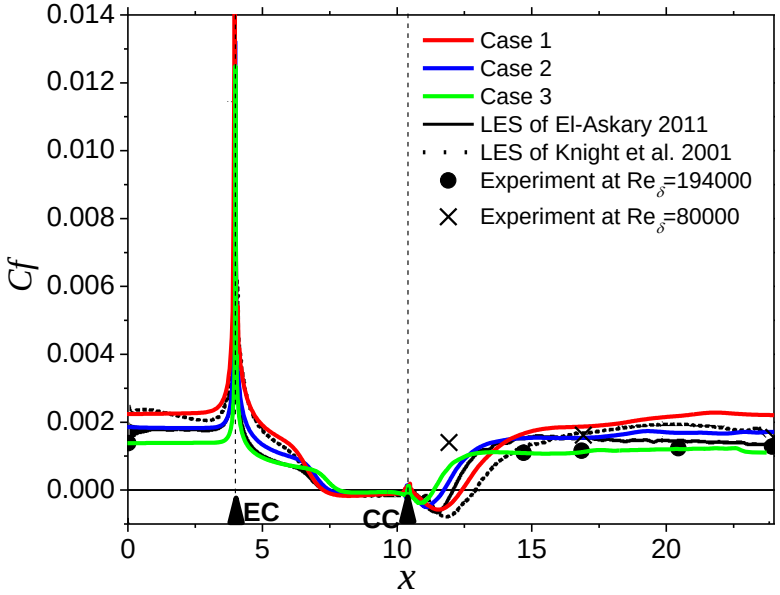




Surface pressure and skin friction



Wall Pressure

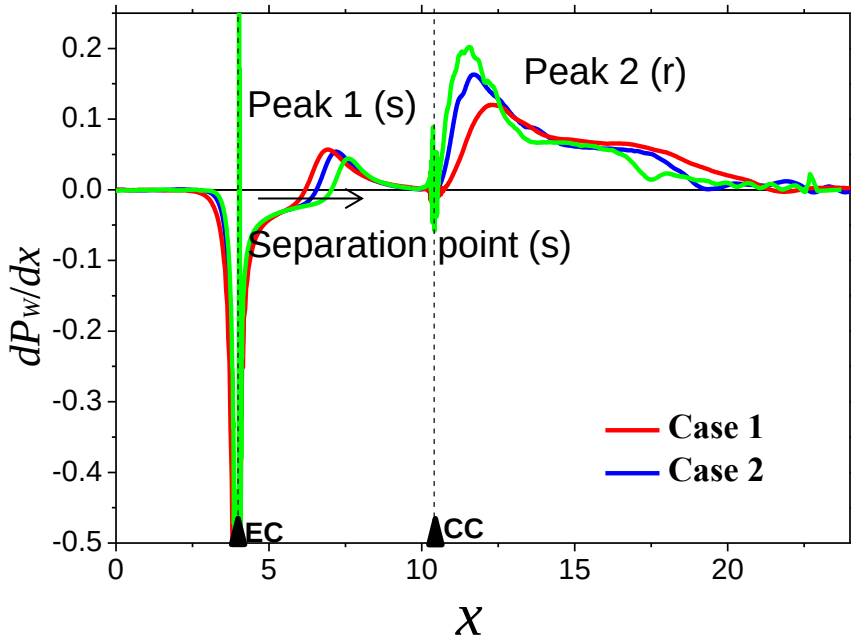


Skin friction

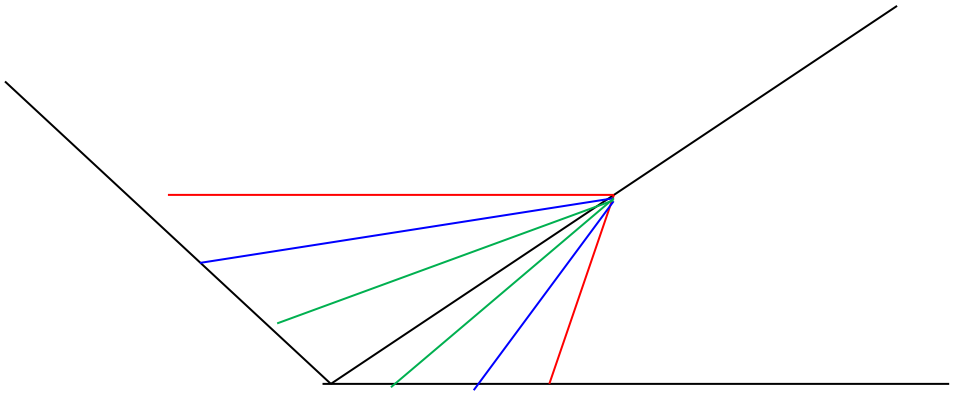
EC: expansion corner; CC: compression corner

Ref : Zheltovodov, A., et al. (1990). An Experimental Documentation of Supersonic Turbulent Flows in the Vicinity of Forward and Backward-Facing Ramps.

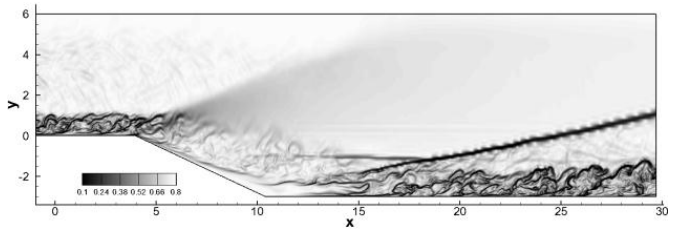
Pressure gradient and numerical Schlieren



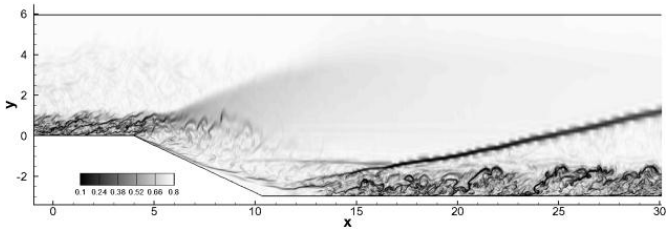
Wall Pressure Gradient



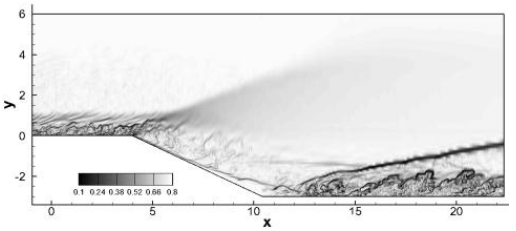
Schematic draw of separation length



Re=20000

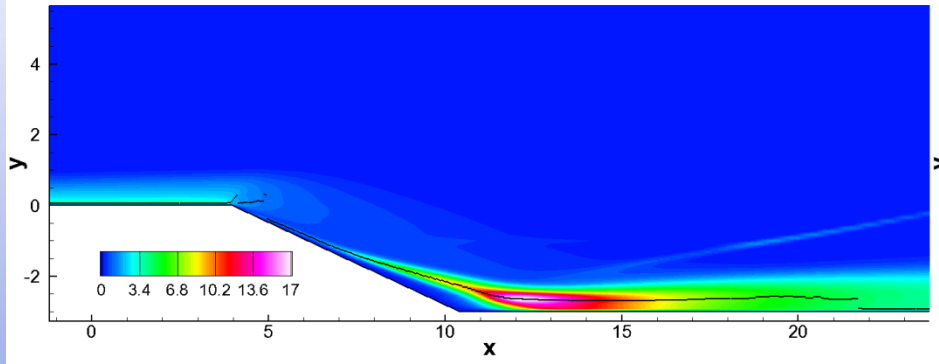


Re=40000

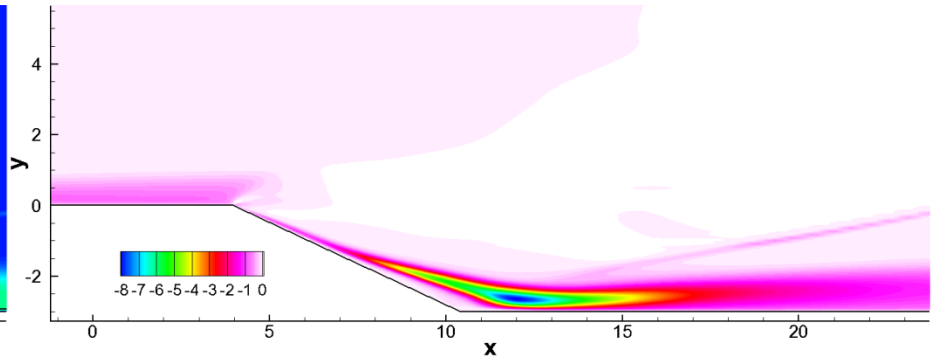


Re=80000

Turbulent flow properties and its variation

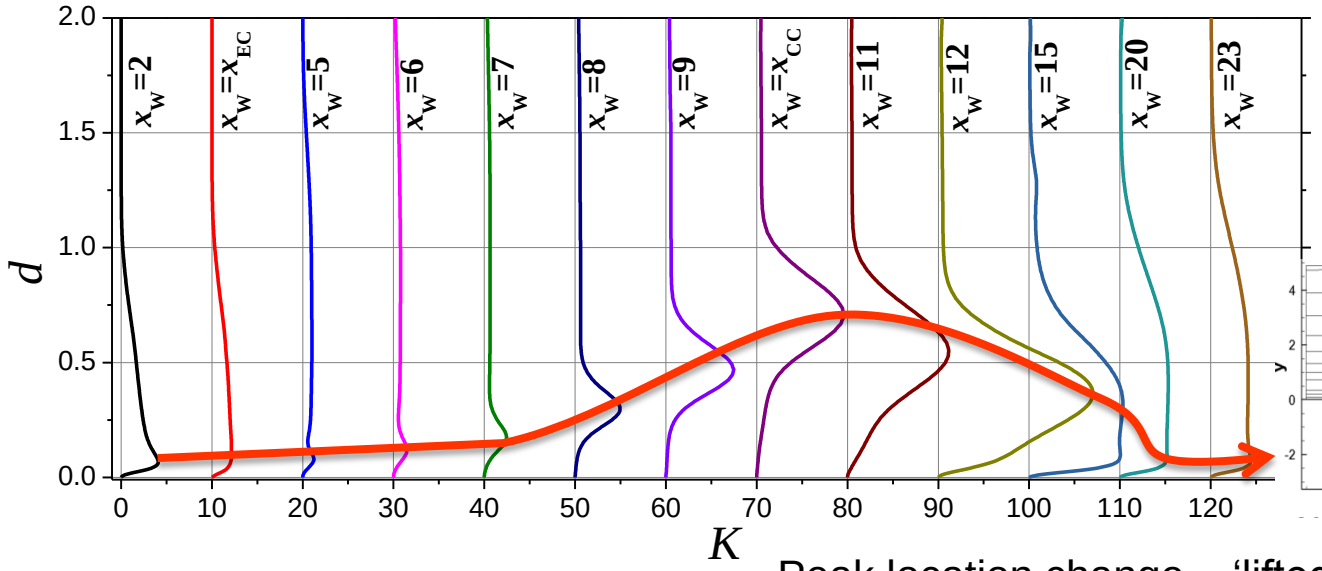


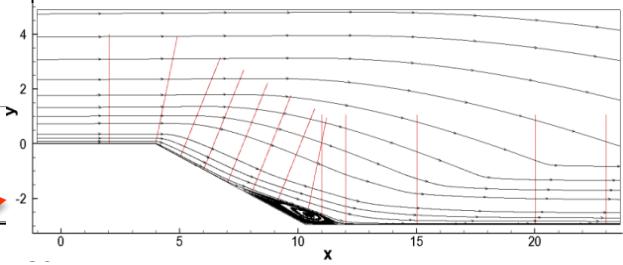
Turbulence Kinetic Energy



Reynolds Shear Stress

$< u'v' >$

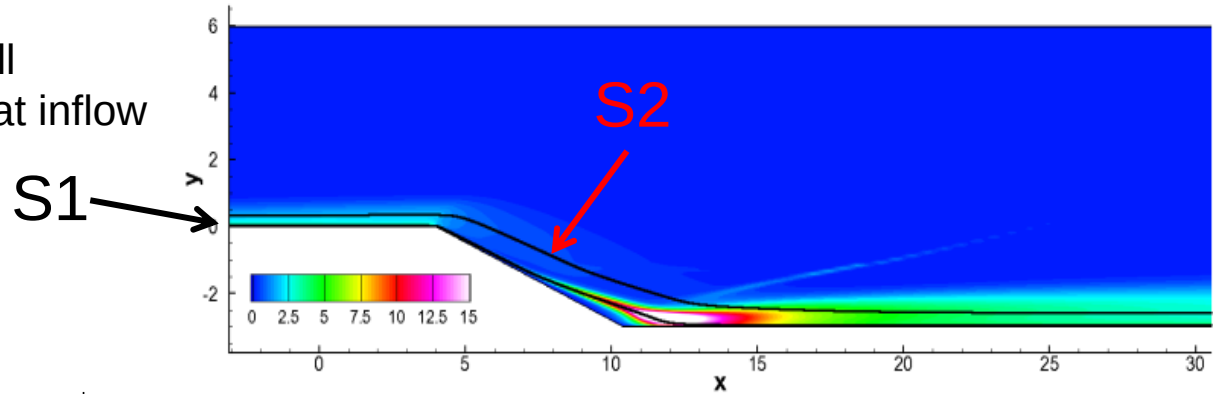


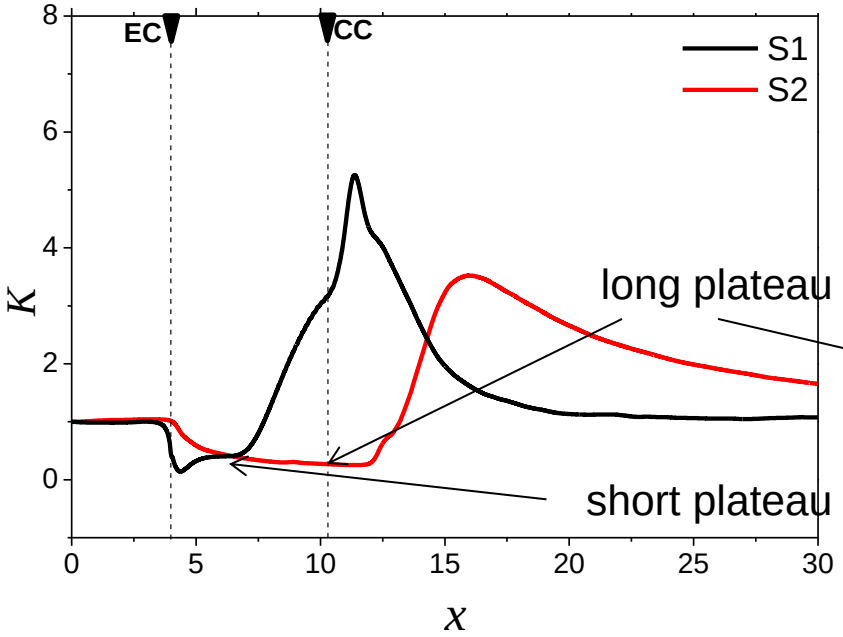


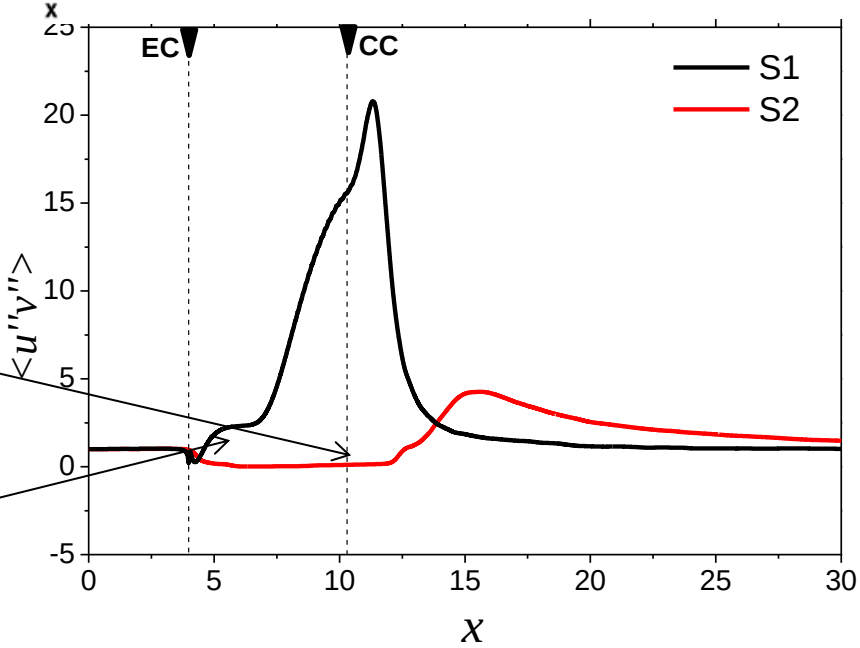
Peak location change – ‘lifted’ during separation

Variation along two streamlines

S1: near wall
S2: mid-BL at inflow

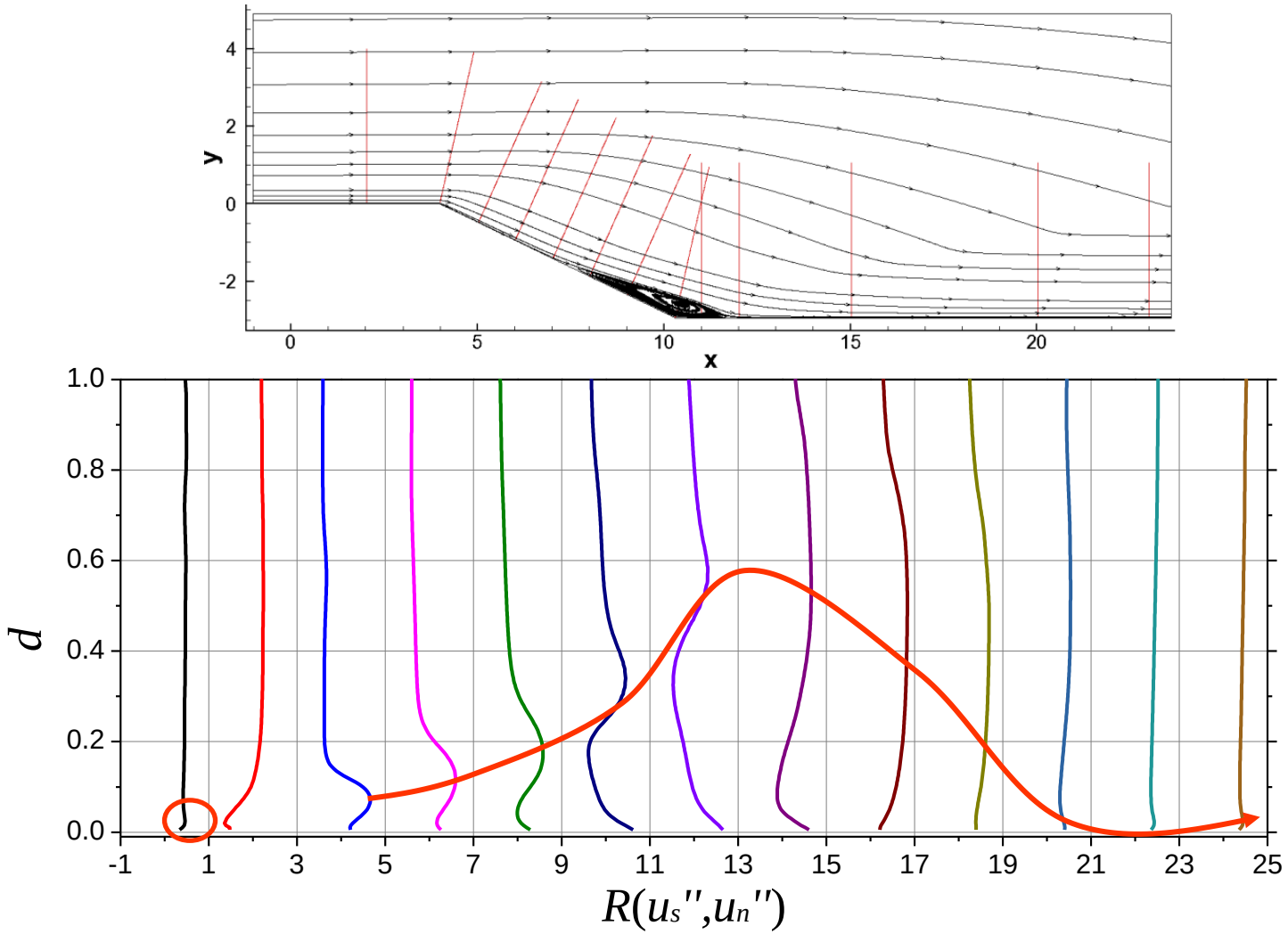






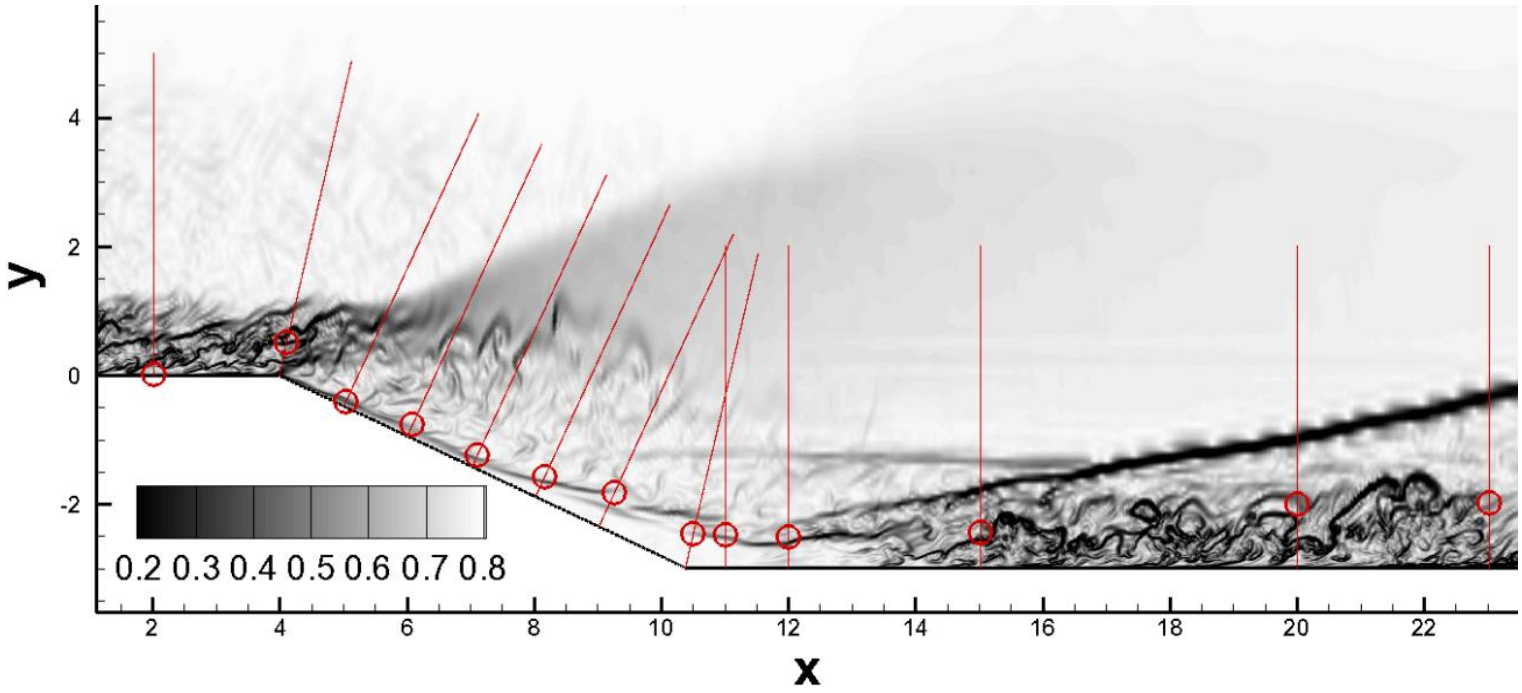
Different evolution process of TKE and Reynolds shear stress along two streamlines

Variation of cross correlation



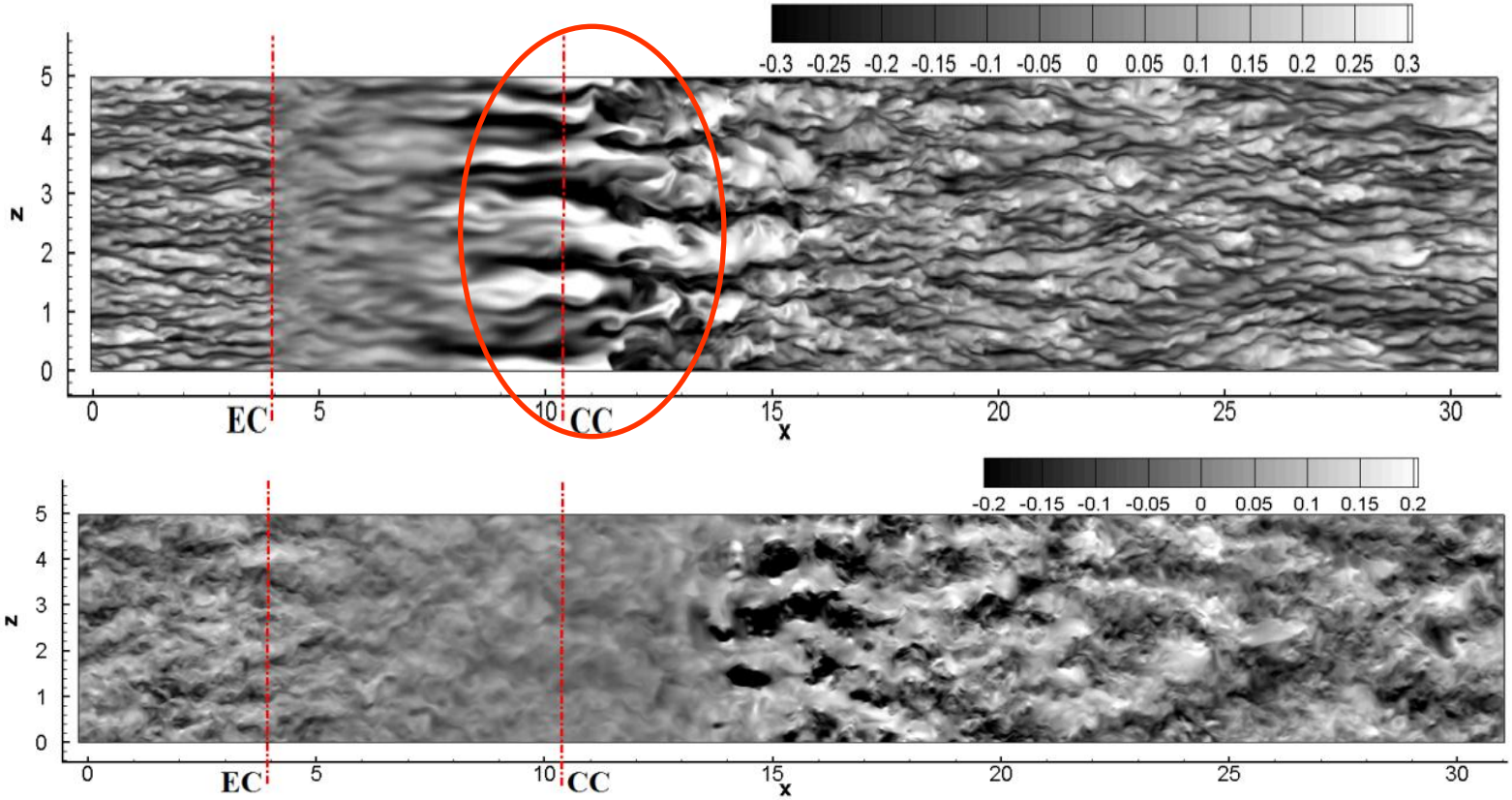
Correlation of streamwise and normal velocity fluctuation

Locations for comparison



Location of correlation peaks

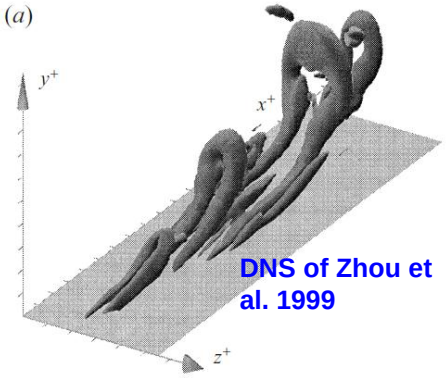
Instantaneous streamwise u’



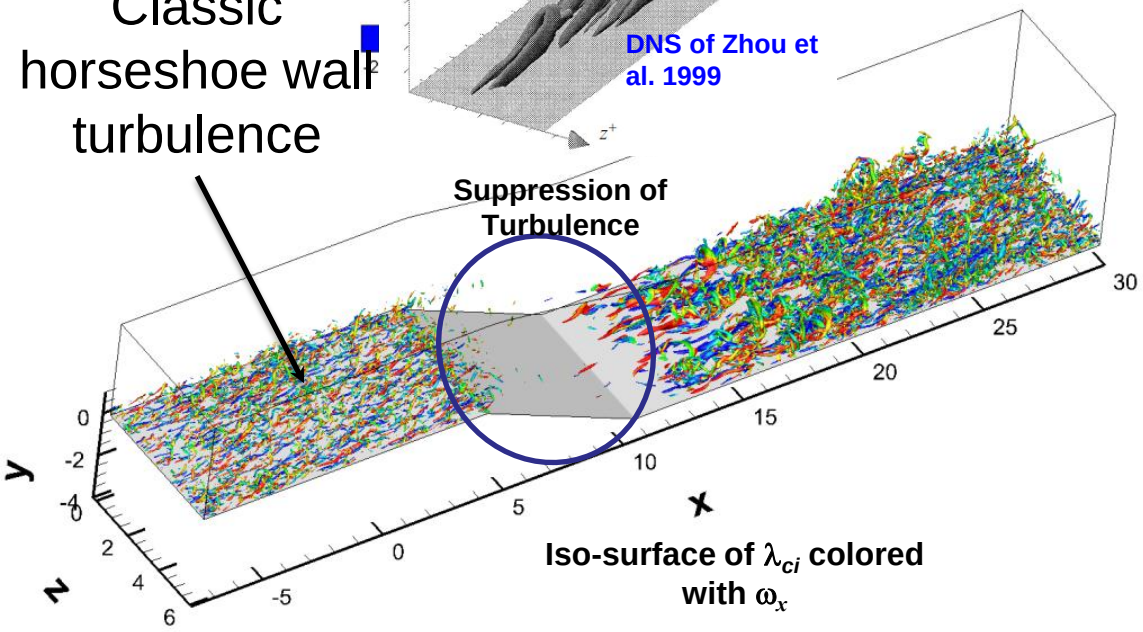
Streamwise velocity fluctuation along the streamlines S1 and S2

Finer flow structures

Classic horseshoe wall turbulence

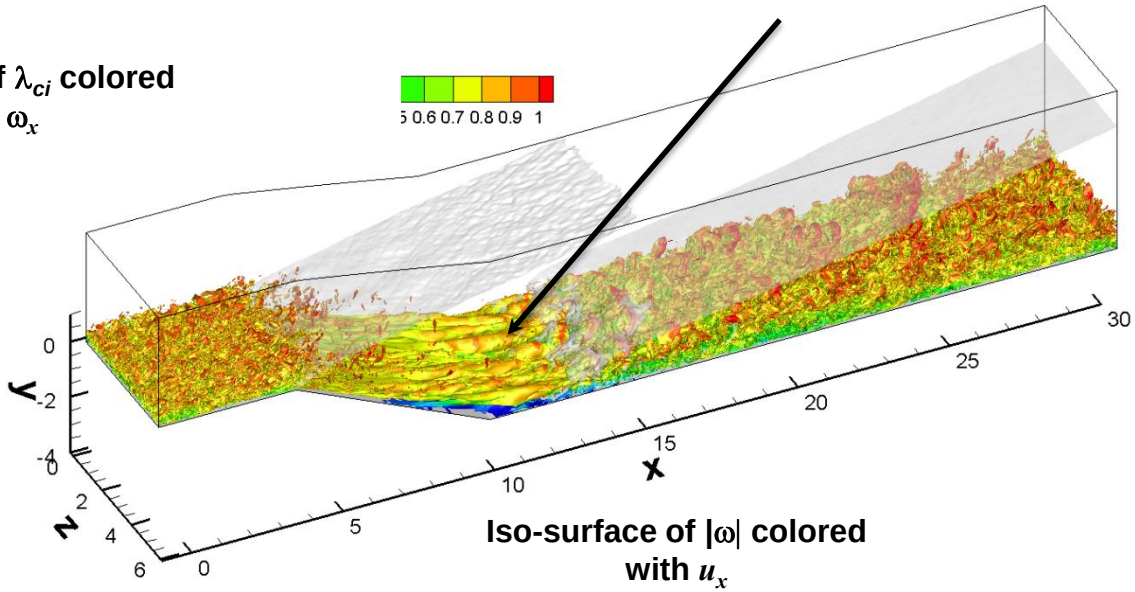


DNS of Zhou et al. 1999



Iso-surface of λ_{ci} colored with ω_x

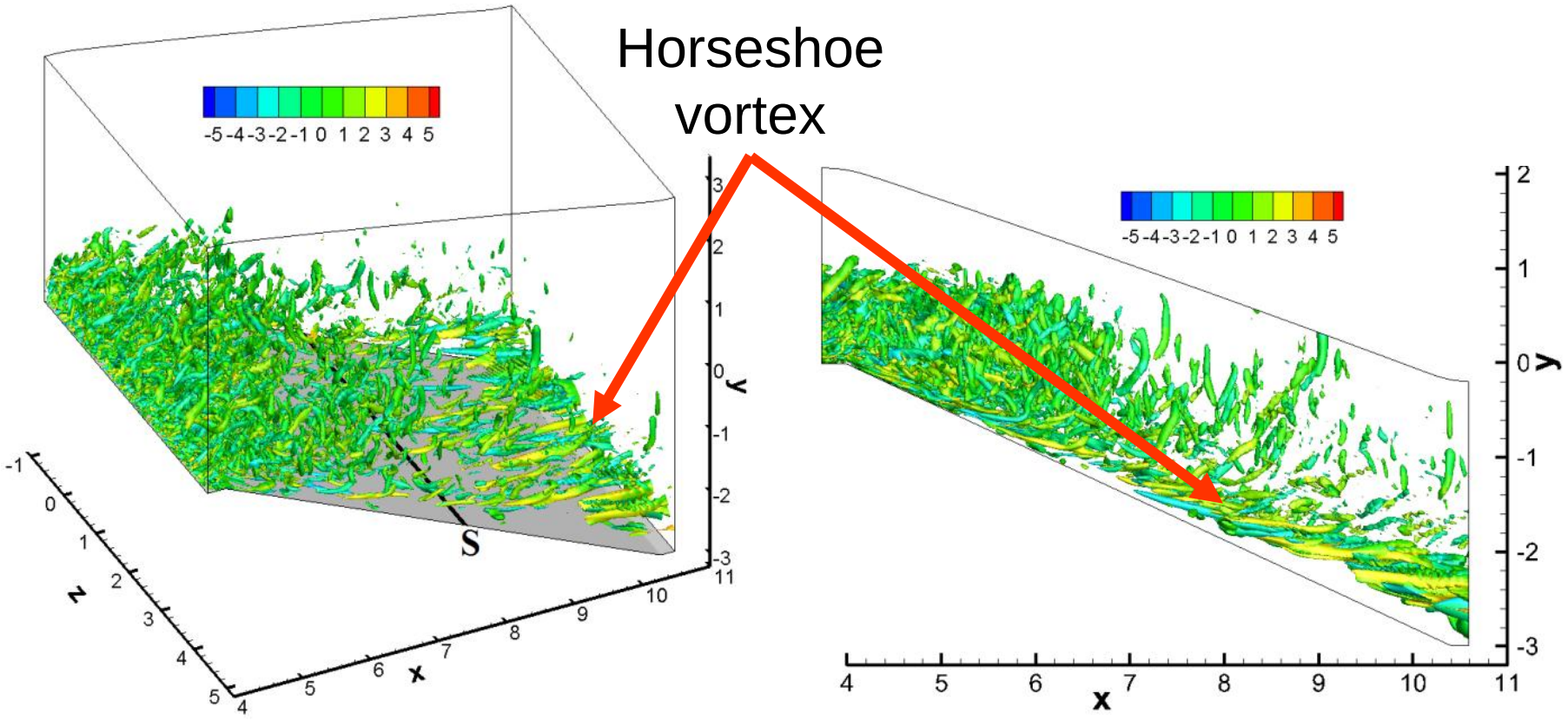
Large-scale Görtler Vortex



Iso-surface of $|\omega|$ colored with u_x

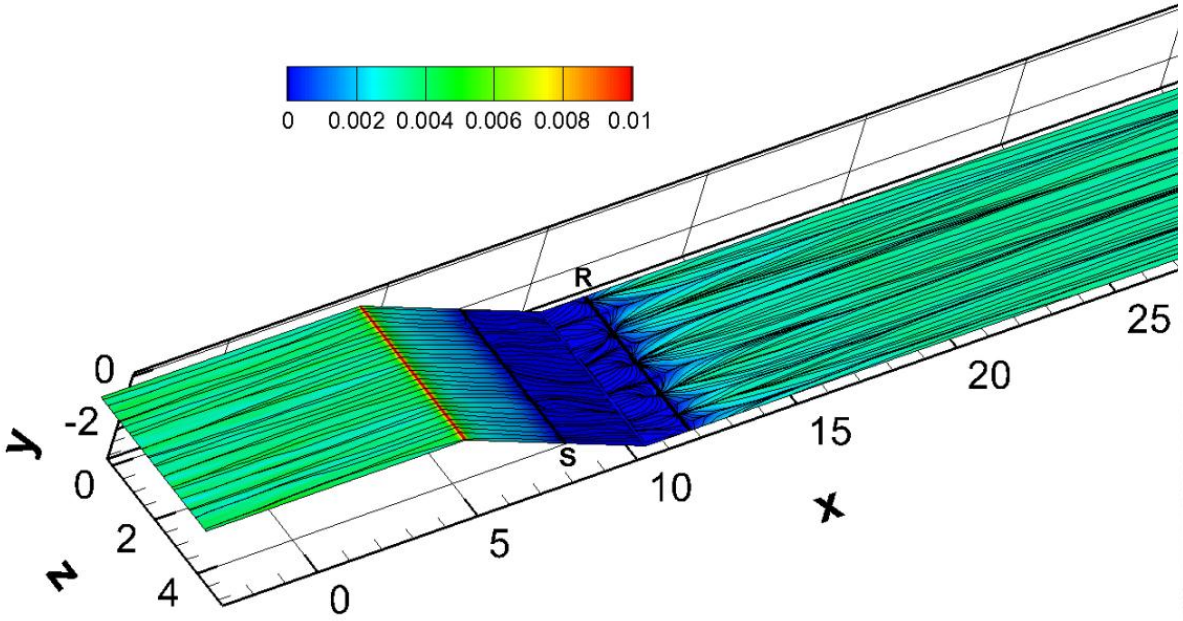
Turbulent Coherent Structure

Close view of flow structures

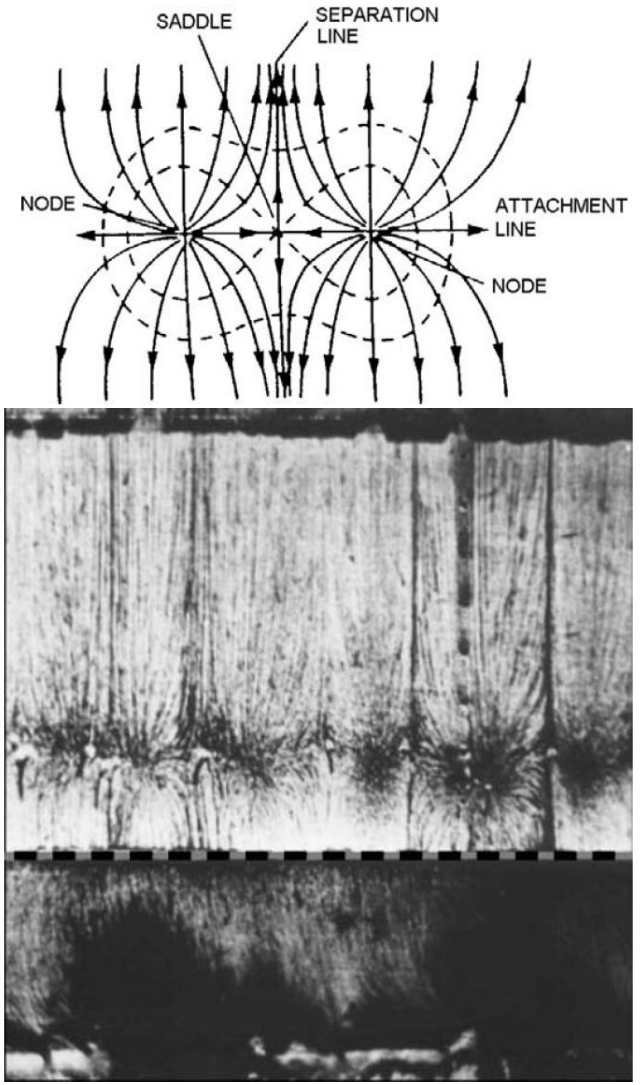


Turbulent coherent structures in the ramp region

Flow topology compared to Oil-flow test

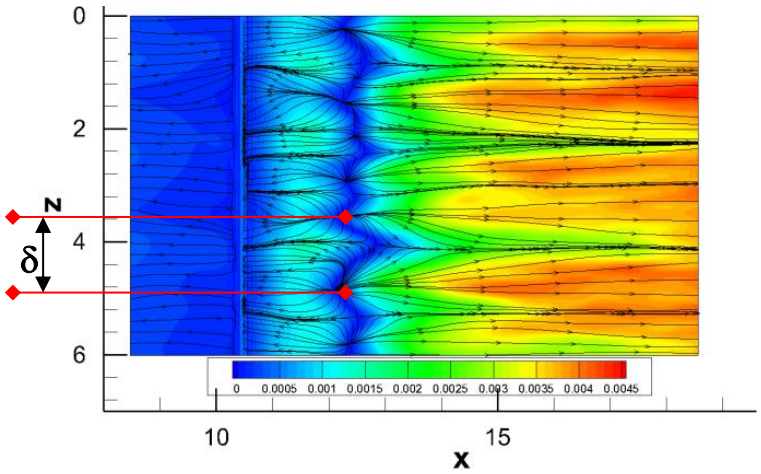


Time mean wall streamline and skin friction

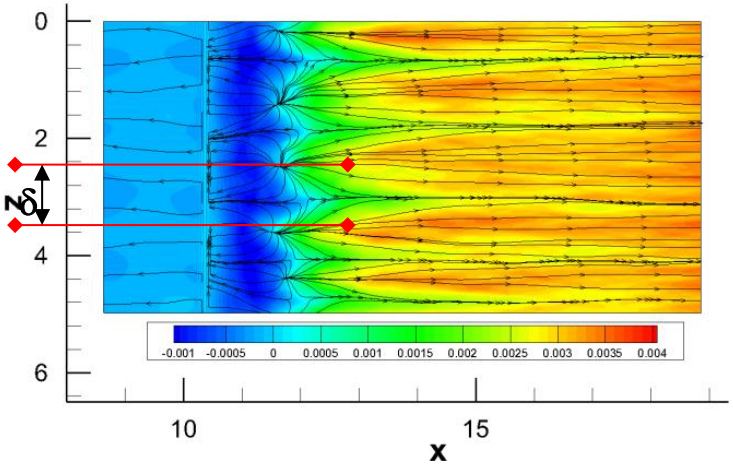


Oil-flow visualization (Zheltovodov et al., 1983)

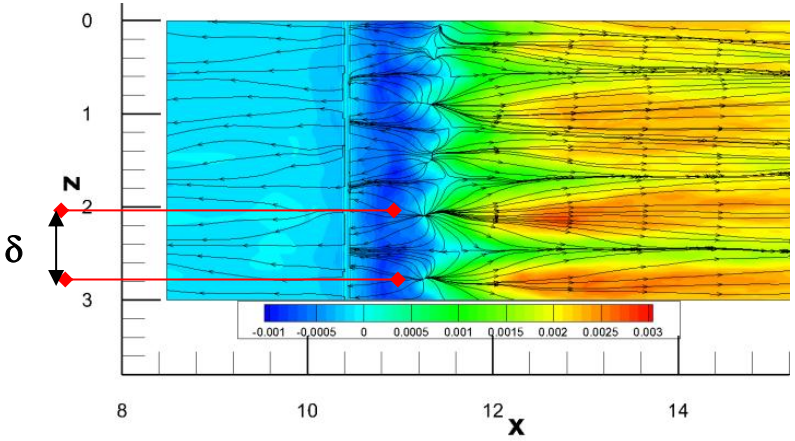
Surface flow topology



Re=20000



Re=40000



Re=80000

Distance between neighbour nodes = BL thickness δ

Concluding Remarks

- **Supersonic Expansion/Compression Corner is investigated by using DNS**
  - **Turbulence is suppressed during expansion but enhanced in compression;**
  - **Two different characteristics of turbulent structures was found in the ramp region as**
    - **In the outer layer, turbulence is consistently suppressed;**
    - **In the inner layer, (1) turbulence is largely suppressed only in the corner region, then gradually redevelops; (2) coherence structure of fluctuations is preserved and it increases during the compression**
  - **Large-scale Görtler vortices are clearly captured, indicating its connection to upstream wall turbulence;**
  - **Reynolds number effect is observed**
    - **Separation bubble shrinks with the increase of Re, but**
    - **Scale of Görtler vortices is independent of Re (distance between nodes)**

Thank You!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