Direct numerical simulation of shock wave/transitional boundary layer interaction

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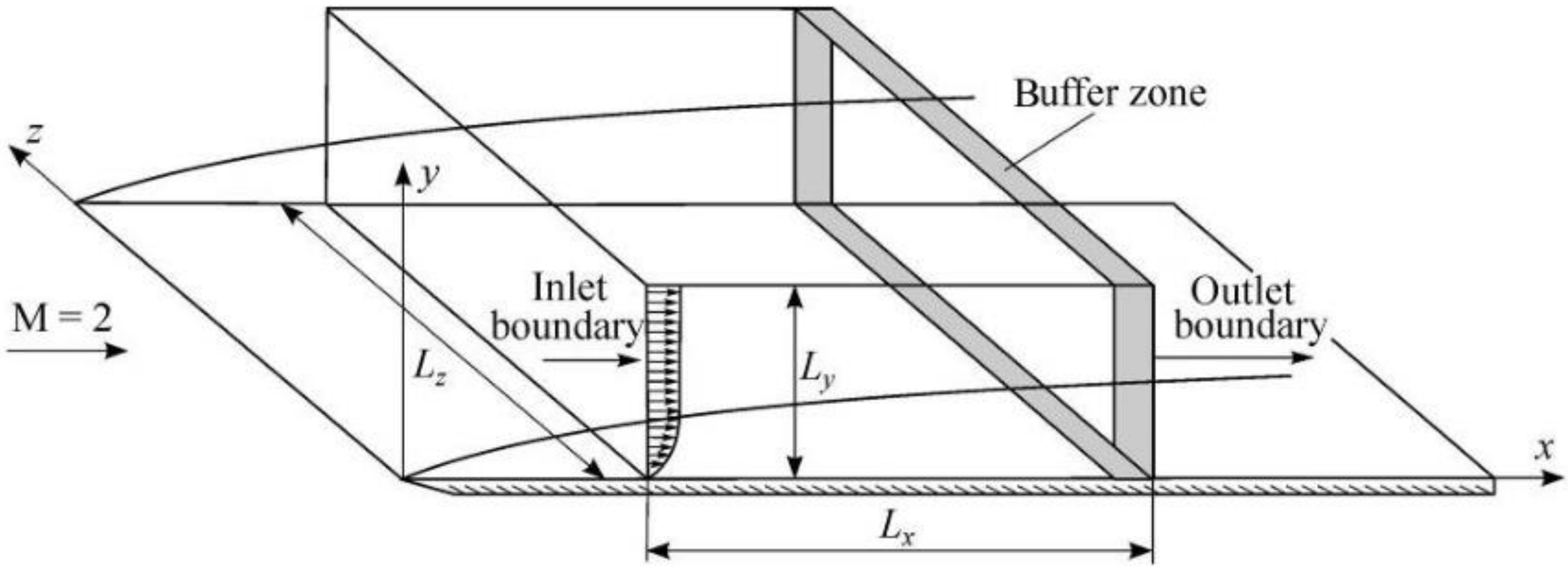
Outline

- Introduction and motivation
- Problem formulation
- Numerical approach
- DNS of the transitional boundary layer on a flat plate
- Shock wave / transitional boundary layer interaction
- Discussion and conclusions

Introduction & Motivation

- Shock wave / boundary layer interaction (SWBLI) is a complex flow phenomenon that is inherent in flows near various parts of transonic and supersonic aircraft, compressor blades and elements of air-breathing engine inlets.
- An interesting unsteady phenomenon arising in SWBLI is the low frequency oscillations of the separation region, which occur at frequencies much lower – typically two orders of magnitude below – than those that characterize the upstream boundary layer fluctuations.

Problem formulation



Schematic of the computational domain

Flow parameters

Flow parameters correspond to the experiments
Polivanov et al. Technical Physics Letters **36**, 104–107 (2010).

- Free stream Mach number M=2.
- The flow in the boundary layer is assumed laminar and self-similar in the range of coordinates $0 < x < x_0$.
- Reynolds number at x= x_0:

  $\mathrm{Re}_\delta = U\delta/\nu = 500$, where $\delta = \sqrt{\nu x/U}$

  $\mathrm{Re}_x = 250{,}000$.
- Wall temperature $T_w = 1.676\ T_e$ which corresponds to the case of the adiabatically isolated plate at the number M = 2.
- Boundary conditions at the inflow boundary specify the self-similar laminar boundary layer flow with the superimposed unsteady disturbance in the form of two most unstable Tollmien–Schlichting waves, which, in accordance with the linear stability theory, are symmetrical three-dimensional waves propagating at equal and opposite angles ±55° to the main flow

Numerical approach

- CFS3D code for solution of the compressible Navier–Stokes equations:
  - WENO-5 finite difference scheme for convective fluxes
  - Central 4th order approximation of the diffusive fluxes
  - 4th order time-accurate Runge–Kutta algorithm for time integration
  - MPI parallelization
- Now in testing HyCFS code — hybrid supercomputer version of the CFS3D
  - Nvidia CUDA for GPU parallelism
  - OpenMP threads within the computing node
  - MPI communications between the nodes

Numerical approach (cont'd)

- Boundary conditions:
  - Self-similar B.L. solution at inflow
  - Soft or non-reflecting boundary conditions at upper and outflow
  - Spanwise periodic conditions
  - Plate surface: no-slip velocity, zero-pressure gradient, fixed-temperature wall
  - Sponge buffer domain near the outflow

- Computational domain $L_x = 3000\ \delta$, $L_y = 100\ \delta$, $L_z = 2\pi/\beta$ (β is the wave number of the disturbance in the *z* direction).
- Surface-fitted structured mesh $N_x = 1024$, $N_y = 150$, $N_z = 64$.
- Computations are run at 64 CPU cores with CFS3D.

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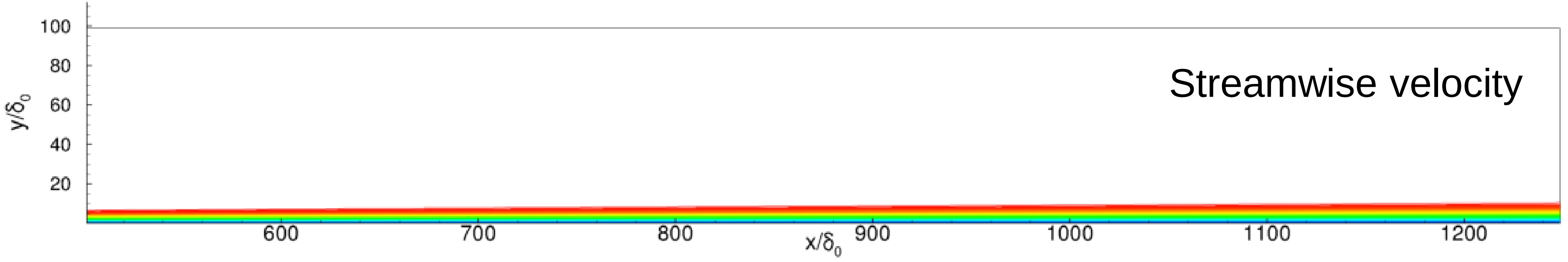
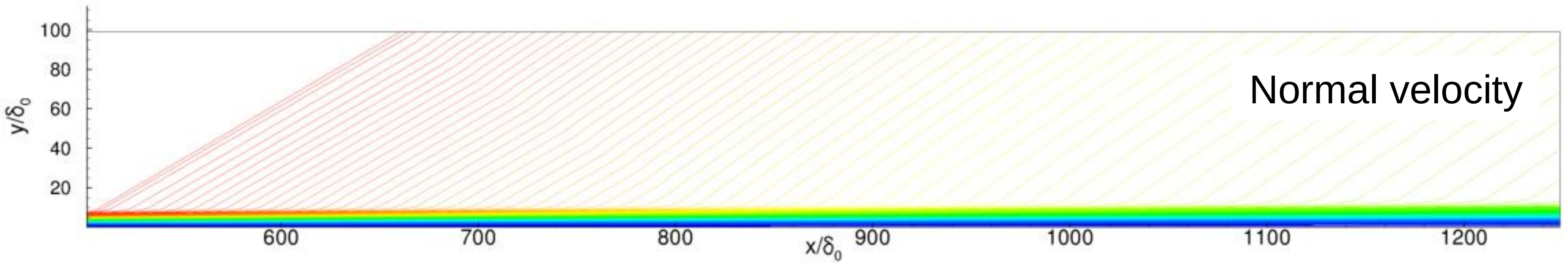
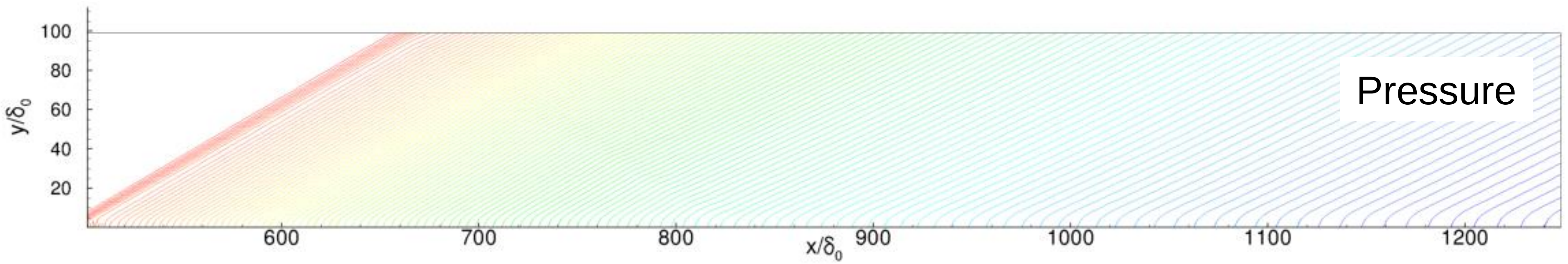
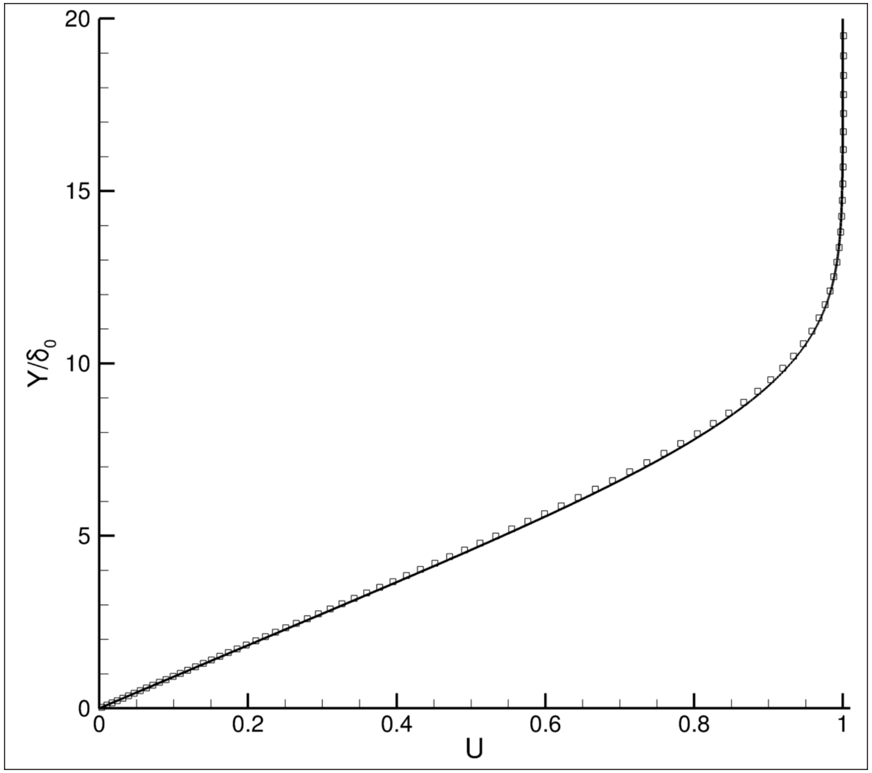
Code validation. Laminar boundary layer at M=2, $Re_{\delta 0}$=500



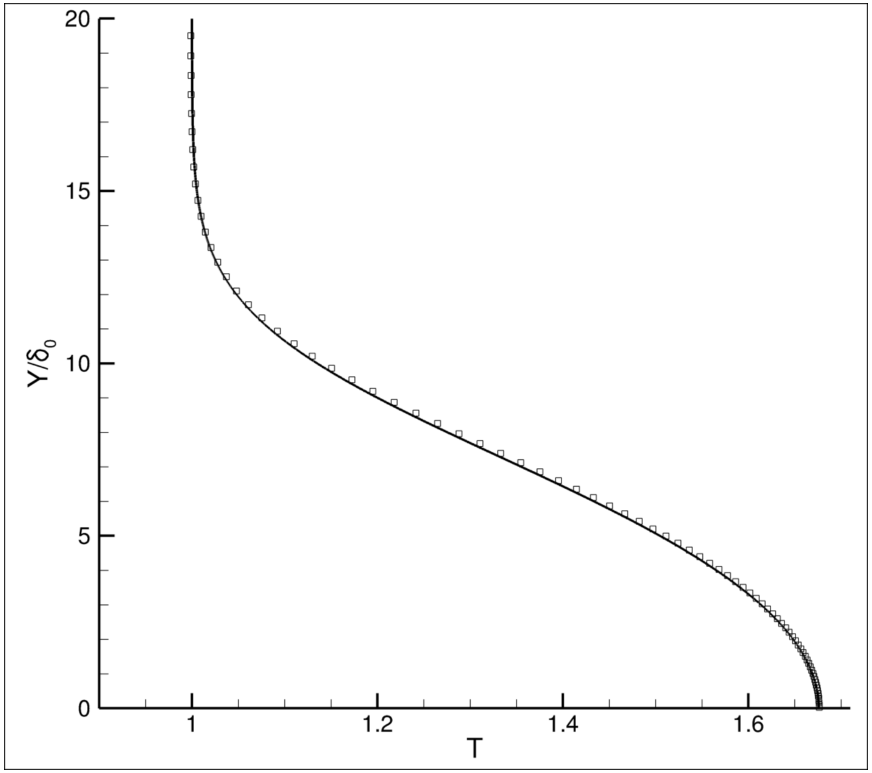




Laminar boundary layer profiles. M=2, $Re_{\delta 0}$=500.



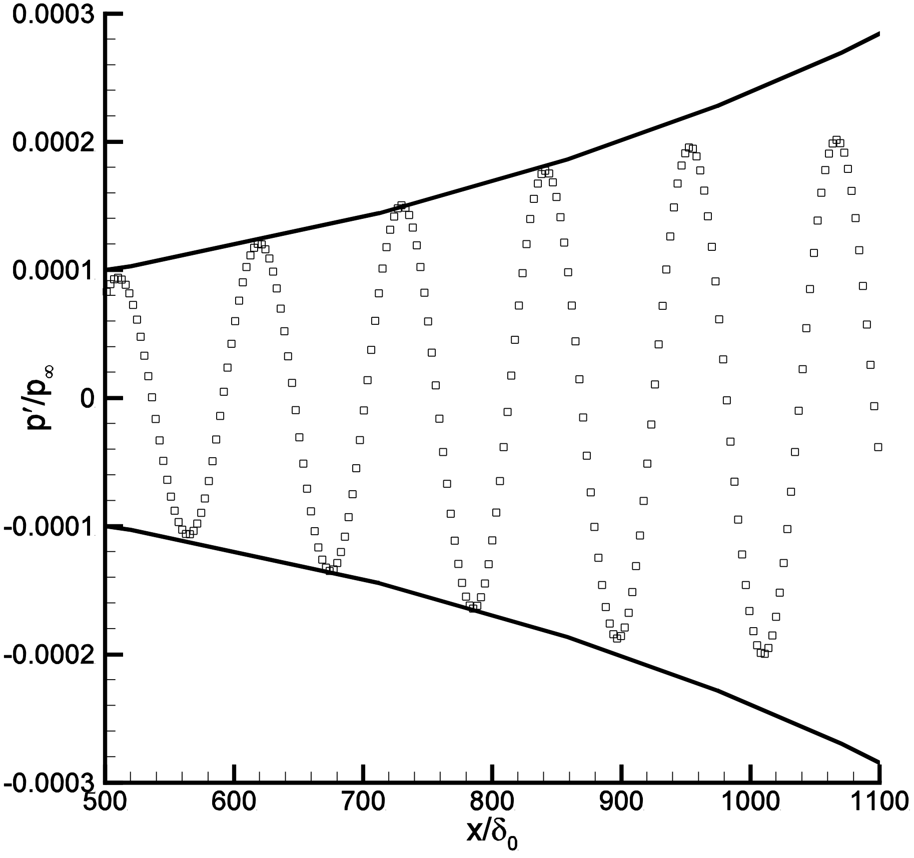
Streamwise velocity



Temperature

Solid curves correspond to self-similar solution

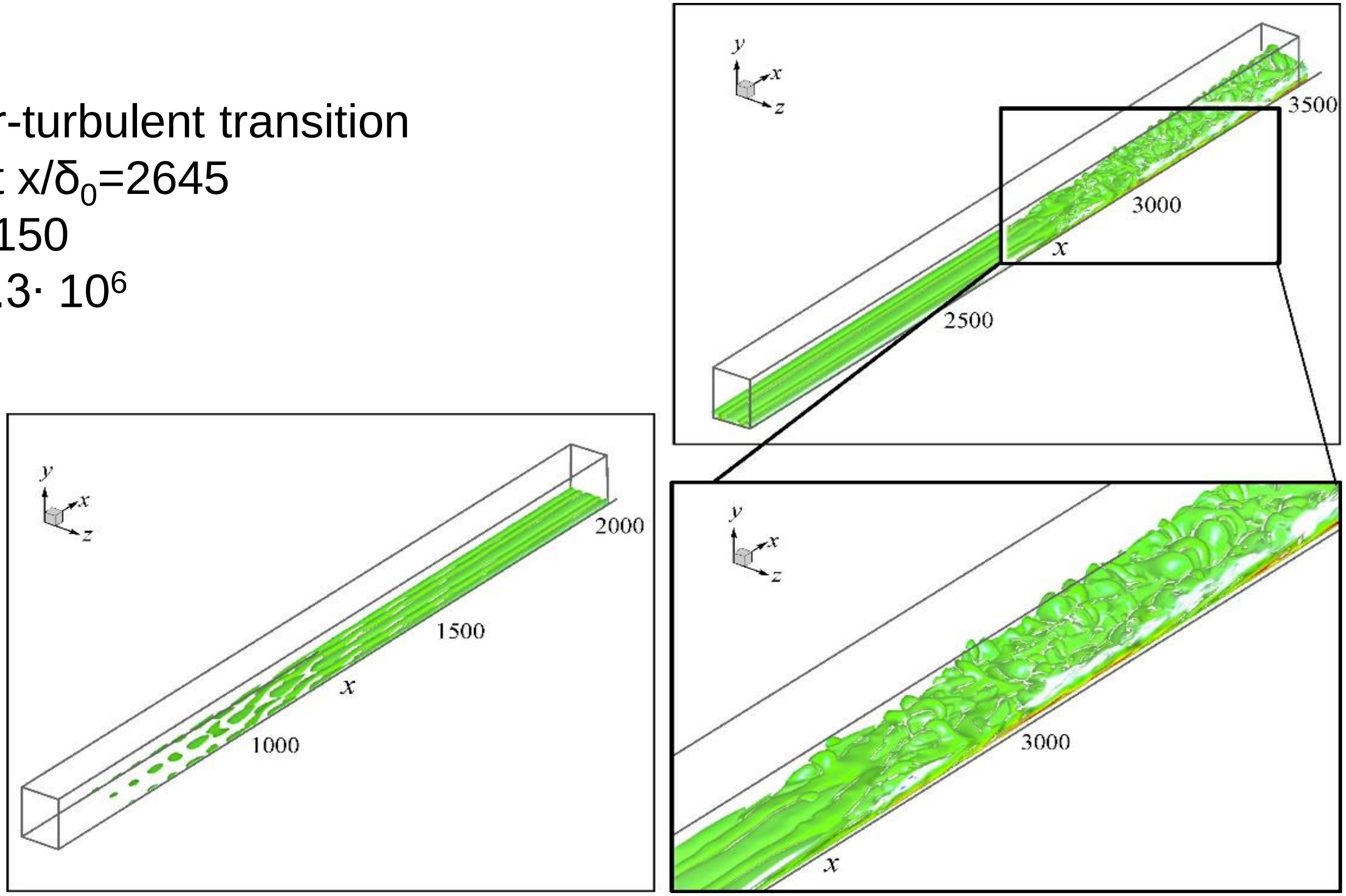
Comparison with linear stability theory, M = 2



Spatially growing disturbance.
Pressure fluctuations.
$M=2$, $Re_{\delta 0}=500$, $A=10^{-4}$

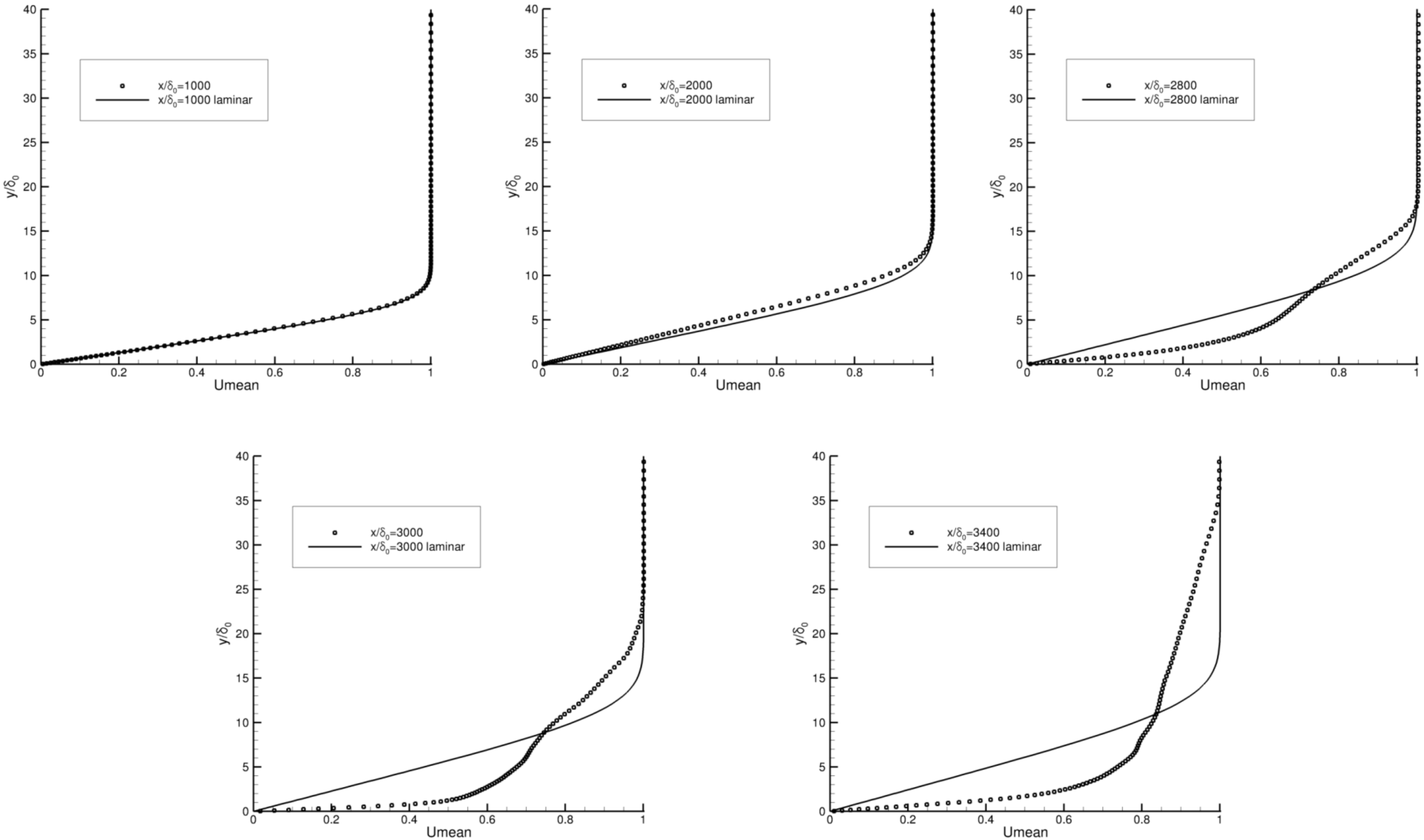
Transition to turbulence in a flat-plate boundary layer

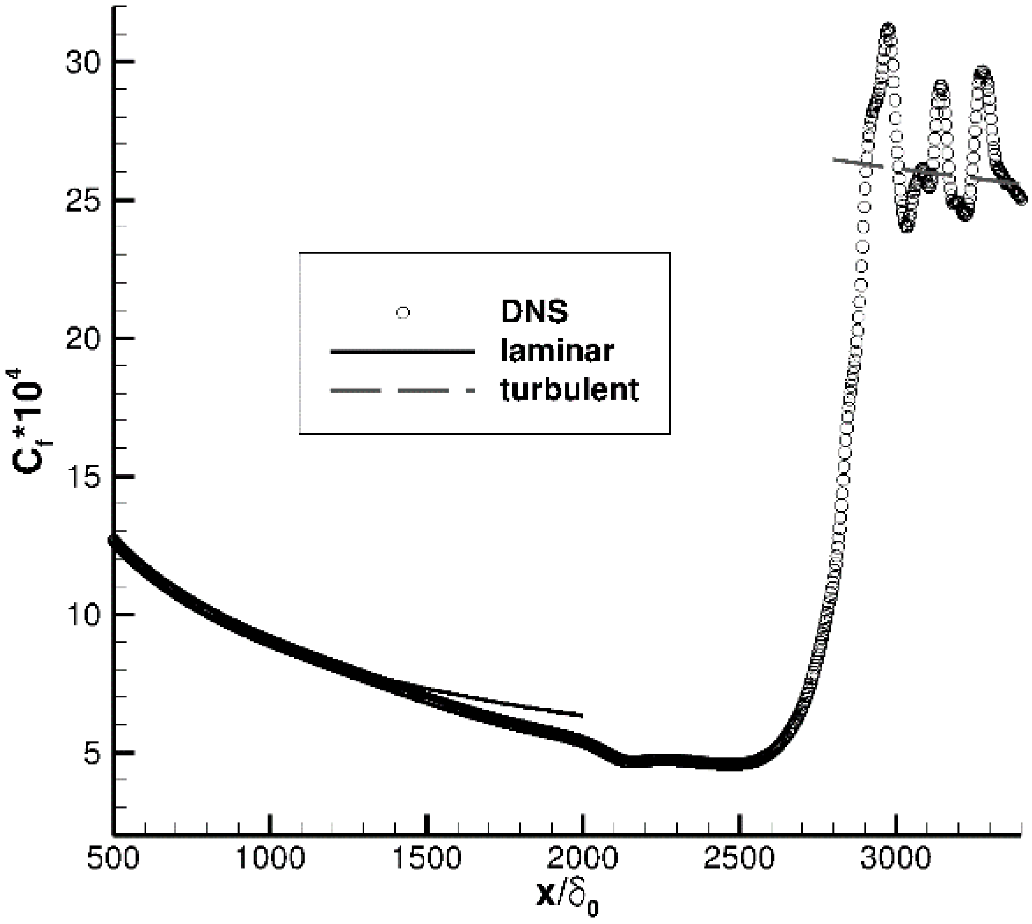
Laminar-turbulent transition
starts at x/δ_0=2645
Re_δ = 1150
$Re_x = 1.3 \cdot 10^6$



Isosurfaces of streamwise velocity component

Mean velocity profiles in several cross-sections along the plate.
Solid curves correspond to laminar basic flow.



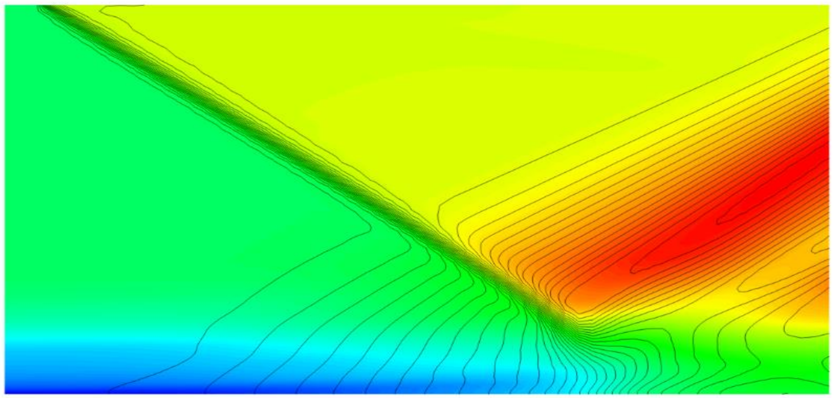


Skin friction coefficent distribution along the plate

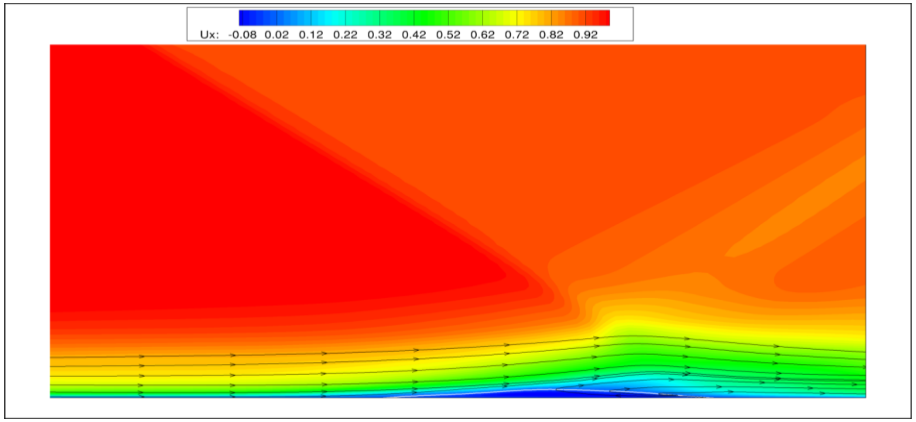
Shock wave / boundary layer interaction

- The SWBLI is initiated by the incident shock impinging on the transitional boundary layer from the external flow.
- In the experiments the incident shock wave was generated by a wedge located at some distance above the plate.
- In our computations, the incident shock is set up as a jump in the boundary conditions on the upper boundary of the computational domain. The shock wave angle is 36.2°, which corresponds to the wedge angle 7°.
- The location of the shock wave on the upper boundary of the computational domain is x_s = 3260 which corresponds to the conditions just downstream the boundary layer laminar-turbulent transition point.
- Corresponding $Re_x = 1.5 \cdot 10^6$, $Re_{\delta\,(0.99)} \approx 12000$.

Mean flowfield visualization of the SWBLI

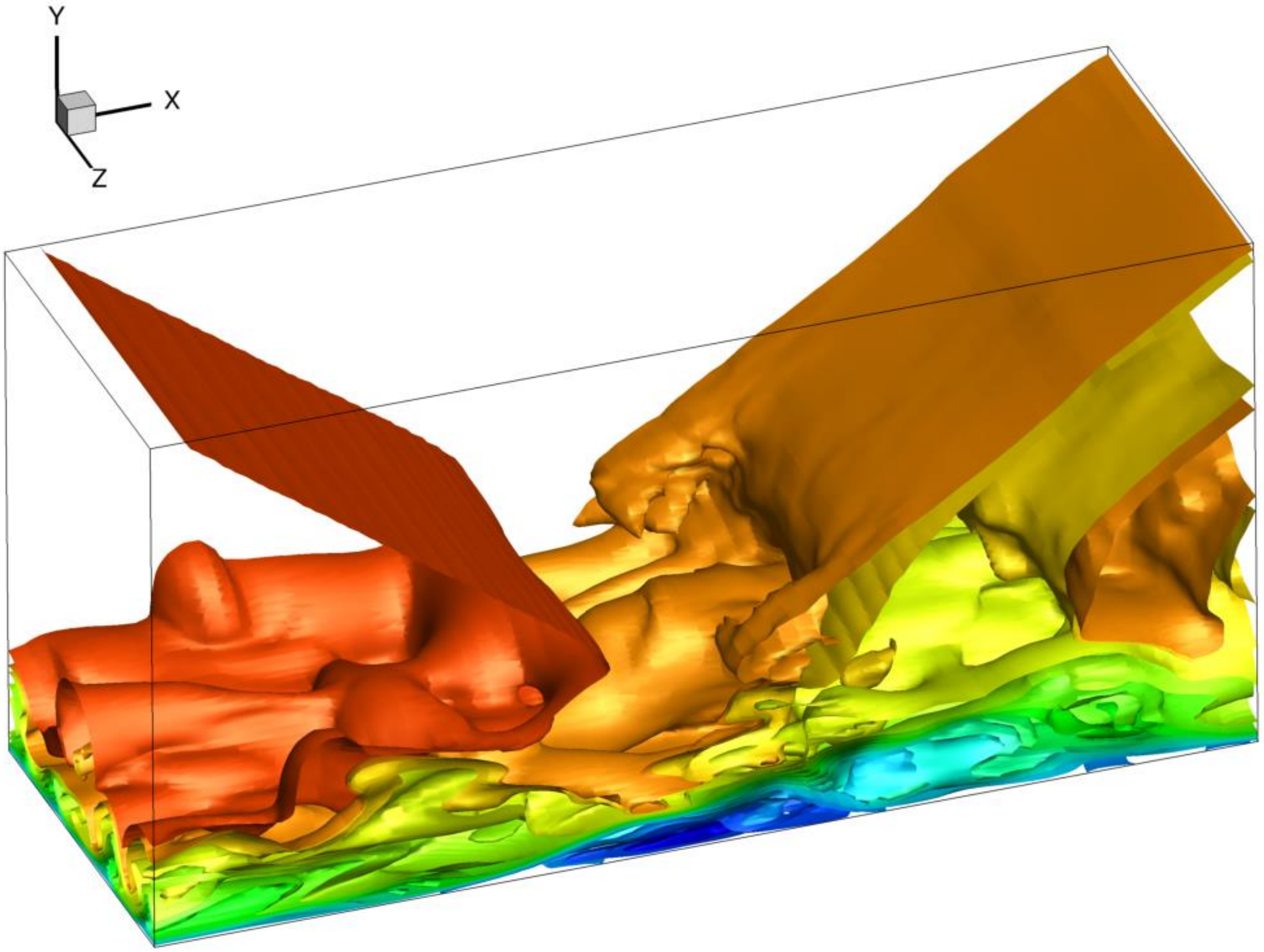


Density flowfield and isobars

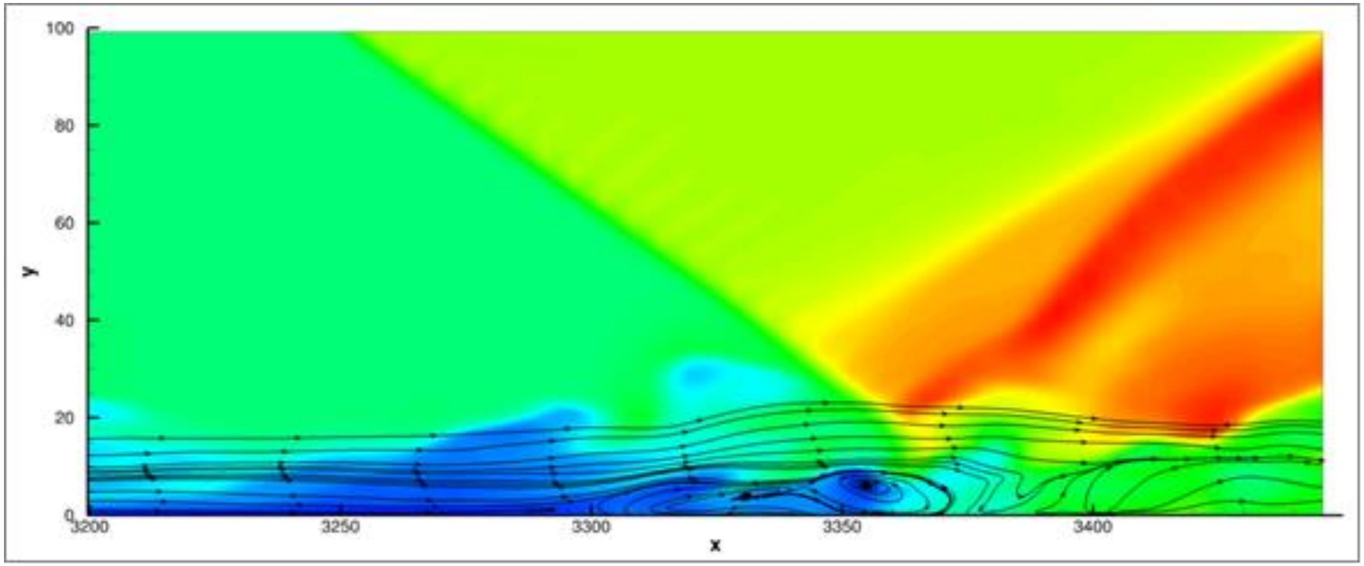


Streamwise component of the velocity and selected streamlines

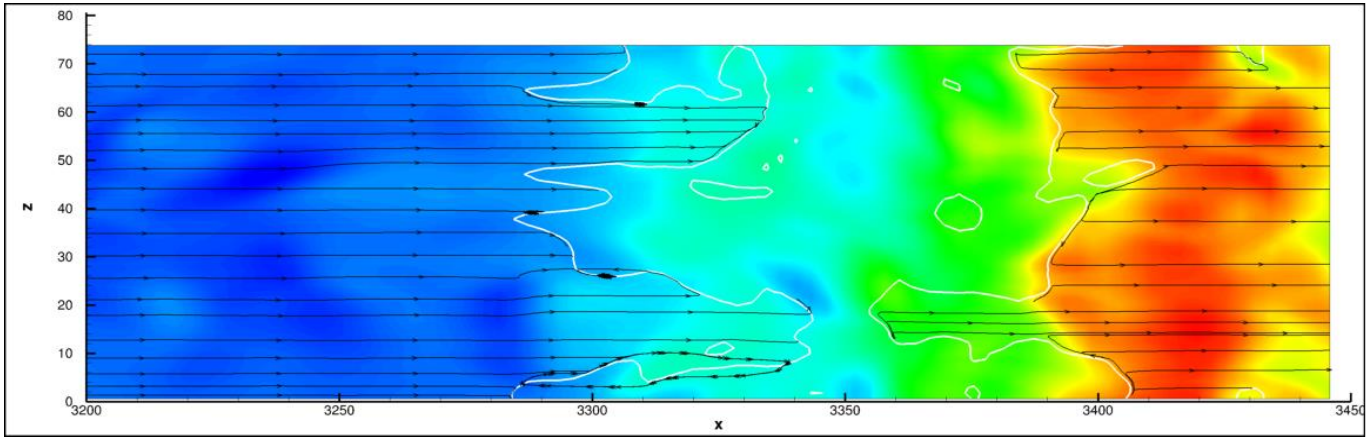
Xs = 3340, Xr = 3410



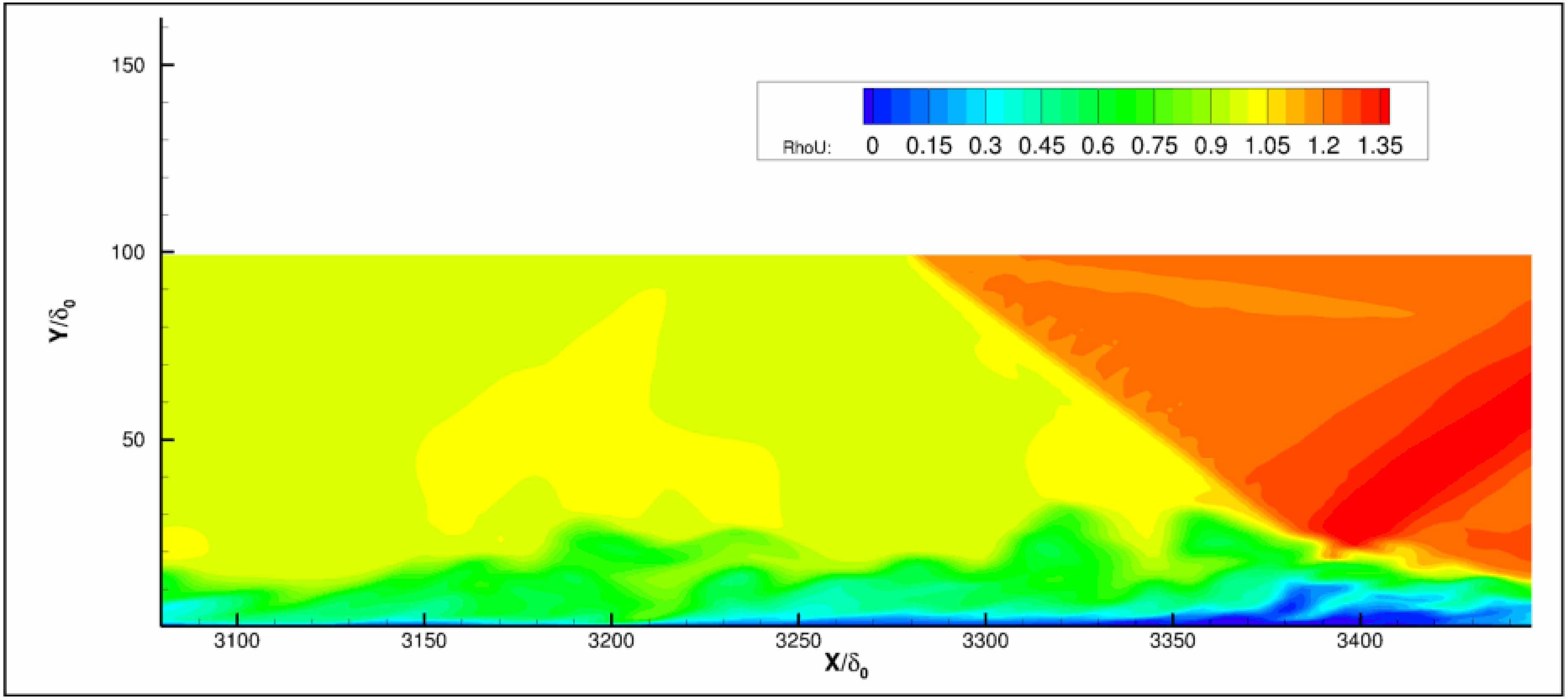
Instantaneous isosurfaces of the streamwise velocity in SWBLI region



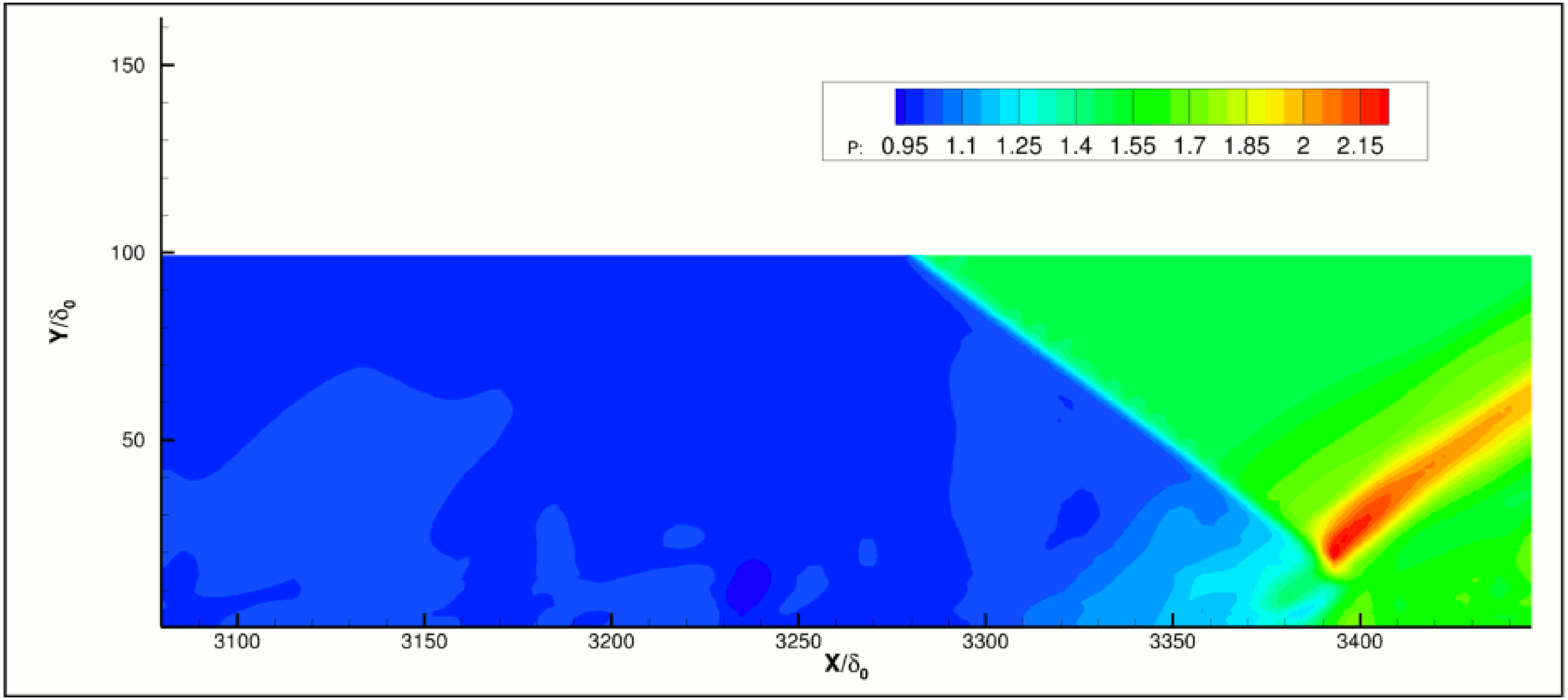
Density flowfield and selected streamlines



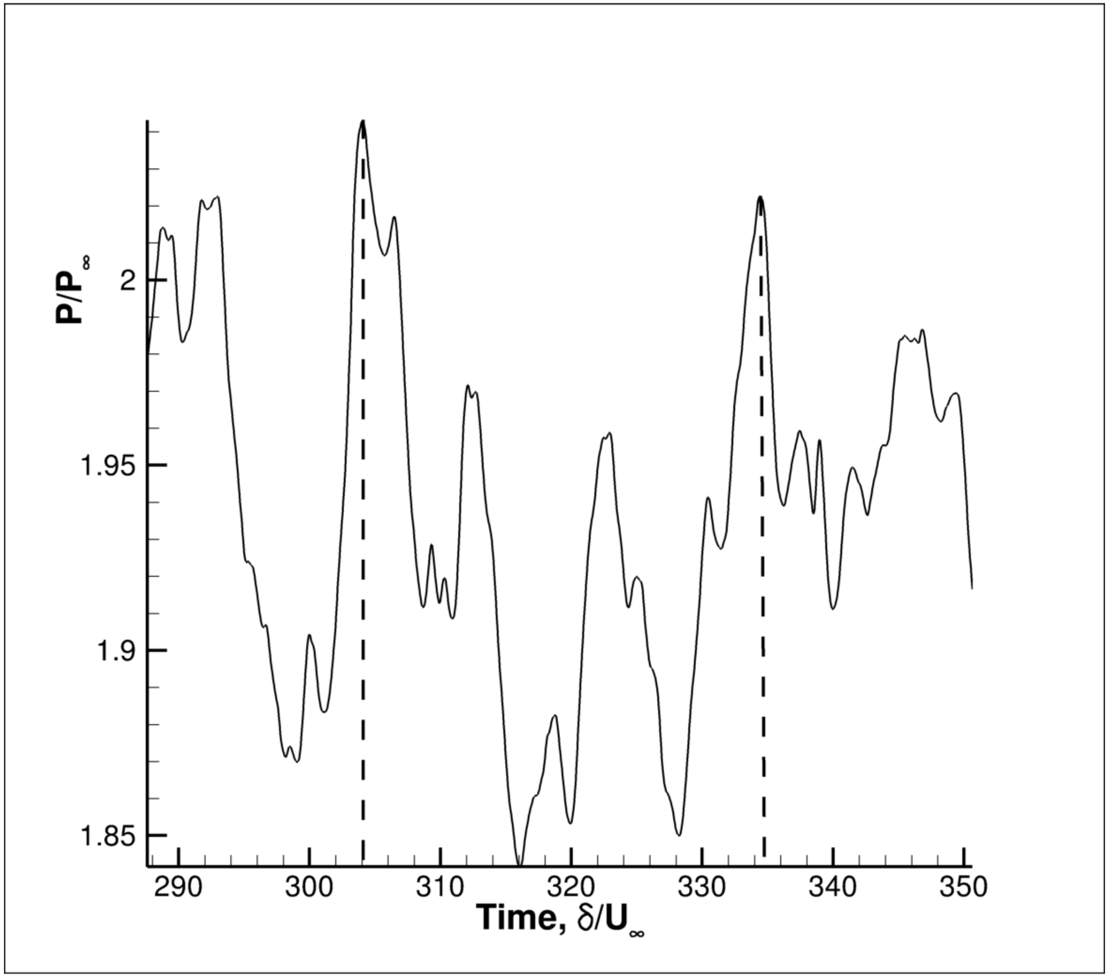
Density distribution and limit streamlines on the plate surface



Instantaneous mass flow rate flowfield in SWBLI region



Instantaneous pressure flowfield in SWBLI region



Pressure fluctuation history downstream of the SWBLI region

Characteristic period of pressure fluctuations is 10-12 $\delta_{0.99}/U_\infty$.
Maximum observed period is 30 $\delta_{0.99}/U_\infty$ corresponding to Sh=0.033.

Conclusions

- The numerical simulation of the unsteady effects in the interaction of an incident shock wave with the transitional flat-plate supersonic boundary layer has been performed.
- The Mach 2 supersonic boundary layer excited by unstable disturbances in the form of linear stability waves undergoes laminar-turbulent transition.
- An incident oblique shock wave impinges on the transitional boundary layer thus causing boundary layer separation.
- Large-scale turbulence structures evolving in the transitional boundary layer cause significant flow oscillations in the shock wave / boundary layer interaction region which manifests in fluctuations of the position and shape of the separation and reattachment lines, and also in staggering of the reflected shock wave.

Thank you
for your attention !