Application of structured and unstructured numerical algorithms based on enhanced DDES formulation accelerating the RANS-to-LES transition in shear layers for simulation of turbulent jet noise

A.P. Duben, T.K. Kozubskaya
KIAM RAS, Moscow, Russia
Computational AeroAcoustics Laboratory

M.L. Shur, M.Kh. Strelets
SPbPU, Saint-Petersburg, Russia

- Gradual development and enhancement of DES approach (DES97 → DDES → IDDES → new enhanced DES) has significantly expanded the frames of its application
- The most resent DES formulation [Shur et. al, 2015] has strongly advanced in solving so-called "grey-area" problem: delay of "numerical" transition from steady RANS to unsteady LES solution in shear layers
- DES has been extended to simulation of a wide range of problems where the delay of developed 3D turbulence generation in shear layers causes unacceptably poor accuracy in prediction of most important ("principal") properties
- Jets are a typical demonstrative example of such flows
- The simulations of **immersed unheated subsonic round jet** (Re_D=1.1·10^6, M_{jet}=0.9) considered

  Reference data:
  - Turbulence: [Lau, 1981], [Arakeri et al., 2003], [Simonich et al., 2001]
  - Aeroacoustics: [Viswanathan, 2004]
- Computational setup (meshes and nozzle exit precomputed profiles using RANS) is provided by M. Shur and M. Strelets from SPbPU
- Computations using **structured** and **unstructured** algorithms on a sequence of refining meshes are considered
  - **"structured" results are used as reference** (as providing maximum accuracy of jet simulation on considered meshes) for "unstructured" results

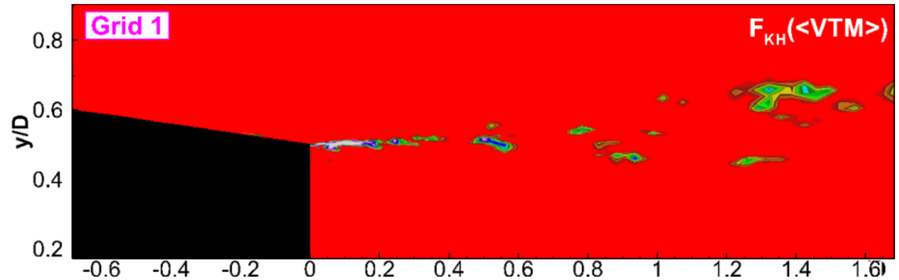
- New enhanced DES modification, proposed in [Shur et. al, 2015] considered new subgrid LES length scale (SLA – Shear Layer Adapted):

$$\Delta_{SLA} = \tilde{\Delta}_{\omega} F_{KH}(<VTM>)$$

$\tilde{\Delta}_{\omega}$ grid-dependent SGS that takes into account peculiarities of typical grids used in early shear layers (anisotropic cells). It is like a photo of the cell from vorticity direction and applying Δ_{max} from this photo

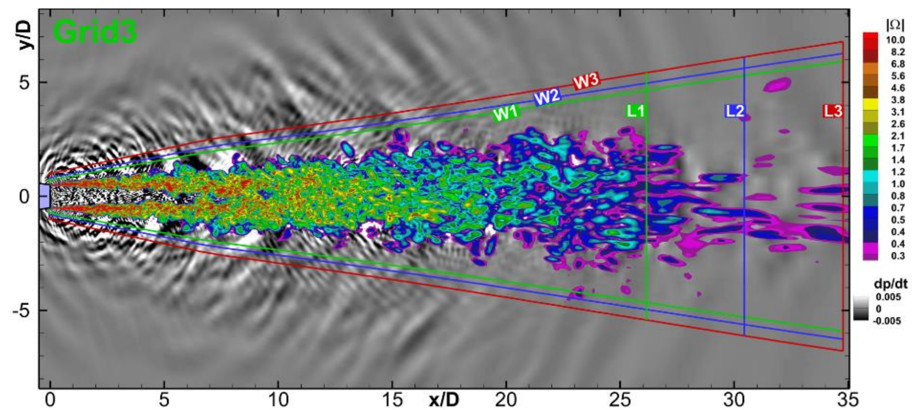
Was formulated for structured cell-centered algorithm. **Generalized for arbitrary unstructured meshes and vertex-centered method.**

$F_{KH}(<VTM>)$ kinematic quantity for identification of quasi-2D flow regions



- Δ_{SLA} provides automatic identification of the initial regions of shear layers and corresponding reduction of subgrid viscosity in these areas
  - switches to the classical (for LES branch of DES) SGS definition Δ_{max} in the regions of developed turbulent flow

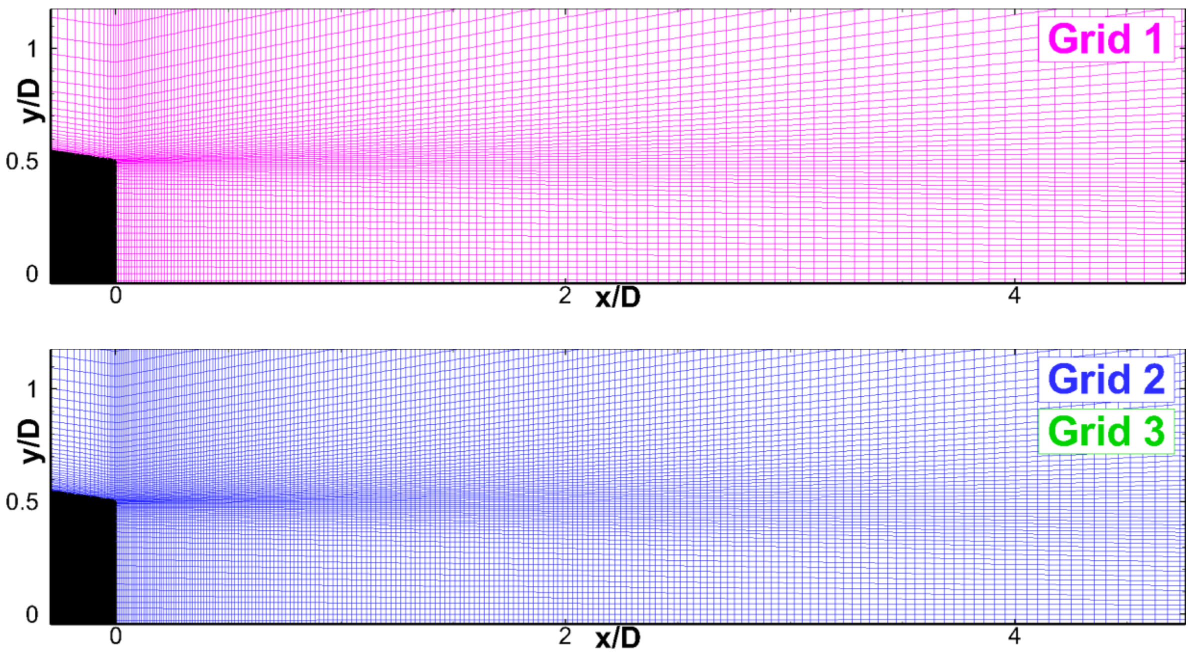
<table>
<tr><th>NTS</th><th>NOISEtte</th></tr>
<tr><td>Structured</td><td>Unstructured</td></tr>
<tr><td colspan="2">Finite volume</td></tr>
<tr><td>Cell-centered
Multi-block overset meshes (Chimera type)</td><td>Vertex-centered
Tetras, Pyramids, Prisms and Hexas</td></tr>
<tr><td colspan="2">Convective fluxes: weighted 4^{th} (6^{th}) order centered / 5^{th} order upwind based scheme
Based on MUSCL approach and Roe Riemann solver</td></tr>
<tr><td>2^{nd} order implicit three-layer scheme</td><td>2^{nd} order Newton iterations
with BiCGStab solver</td></tr>
<tr><td colspan="2">Farfield: Ffowcs-Williams-Hawking method</td></tr>
<tr><td colspan="2">Sponge layer is used to dump disturbances and avoid reflections from boundaries</td></tr>
</table>



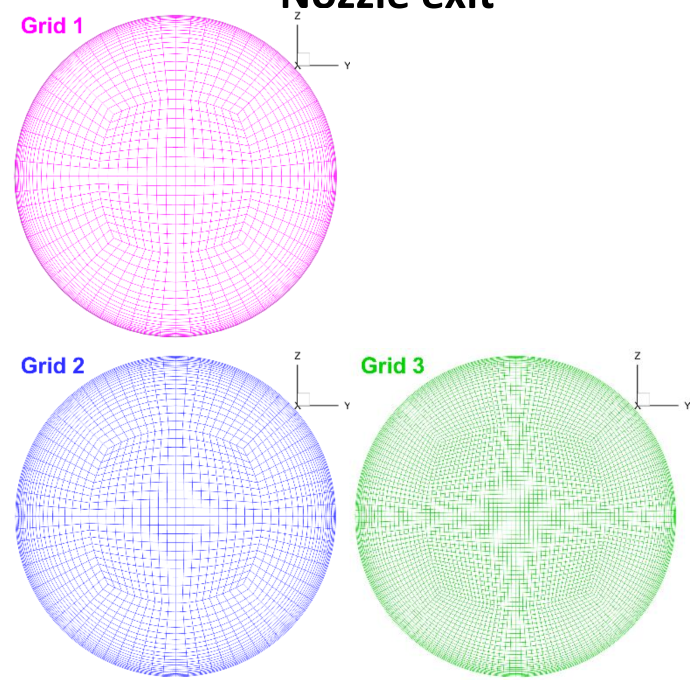
Computational meshes

Mesh parameters	Grid 1	Grid 2	Grid 2	Grid 4
Number of nodes	1.52M	4.13M	8.87M	23M
N_{ϕ} (azimuthal)	64	80	160	240
Δx/D an nozzle exit	0.011	0.008	0.008	0.005
Average Δx/D for 0<x/D<4	0.033	0.022	0.022	0.016
Min Δr/D in shear layer	0.003	0.0025	0.0025	0.0018

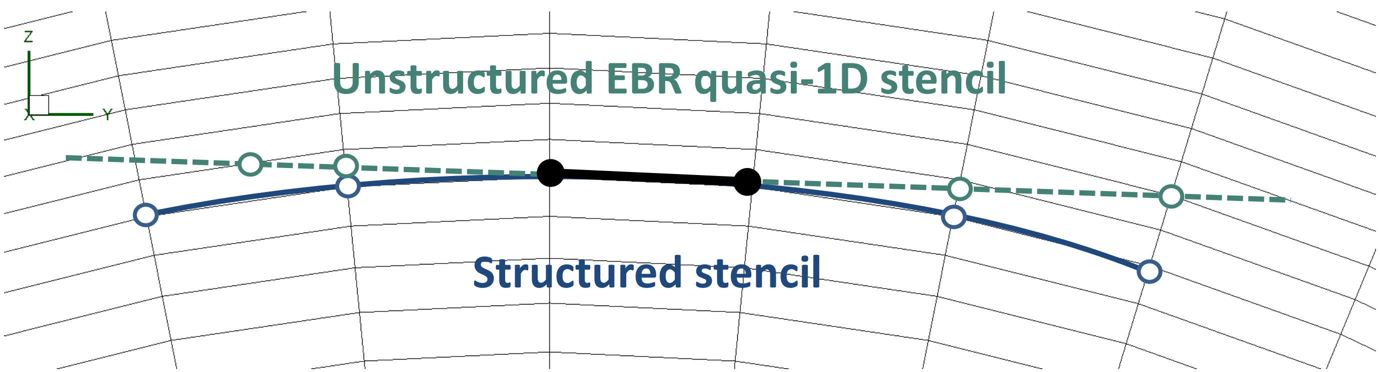
Slice z/D=0

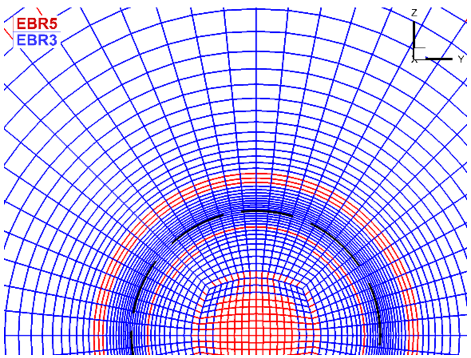


Nozzle exit

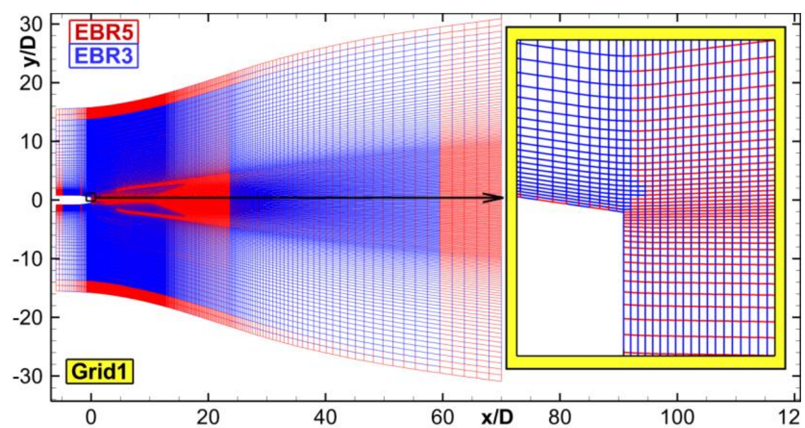


- Structured meshes (built for structured algorithm) are used for computations
  - they have anisotropic cells, especially in initial shear layer regions
  - best quality parameters of mesh are in this region (stretching coefficients)
- Initial shear layer is essential for accurate jet simulation
  - any additional dissipation delays the RANS-to-LES transition
  - numerical scheme should provide high accuracy

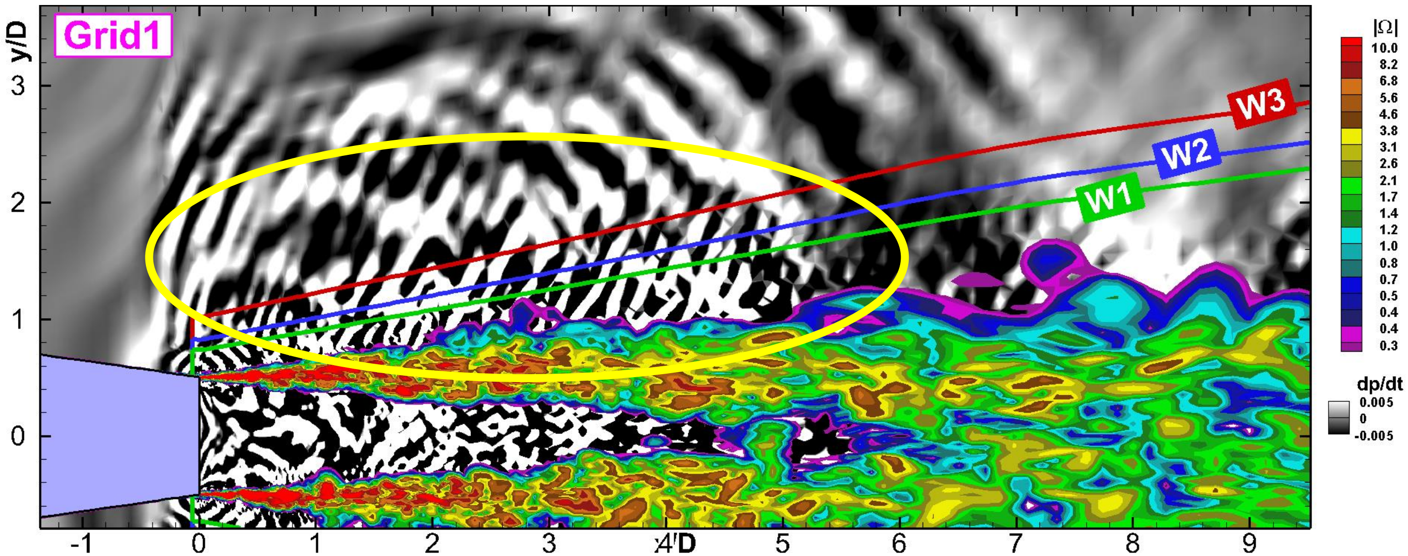




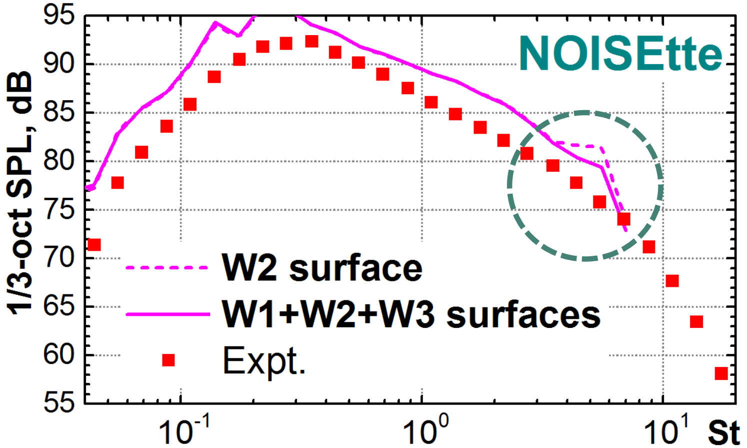
- Due to quasi-1D property unstructured EBR scheme could be unstable while involving wide numerical stencil and low numerical dissipation
- Some modification of the EBR scheme was developed to cure this issue:
  - switching to compact stencil based on analysing its local steps and interpolaton coefficients



- Despite the modification of EBR algorithm scheme generates “numerical” standing waves which cross FWH surfaces → it results spurious noise in farfield at high frequencies

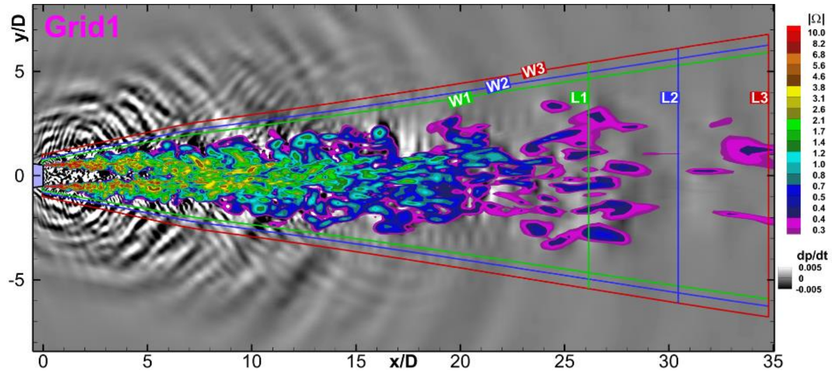


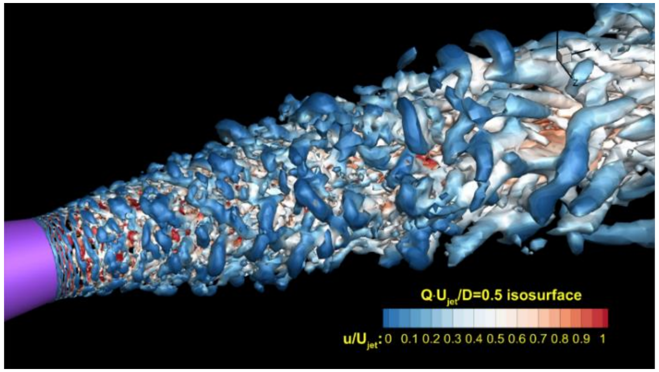
- In [Nichols et. al, AIAA, 2010] averaging of signals obtained from wide cone FWH surfaces was done to suppress spurious noise generated by “numerical” oscillations
    - the idea of this technique is phase averaging of non acoustic waves
- The same technique was applied for considered “unstructured” results



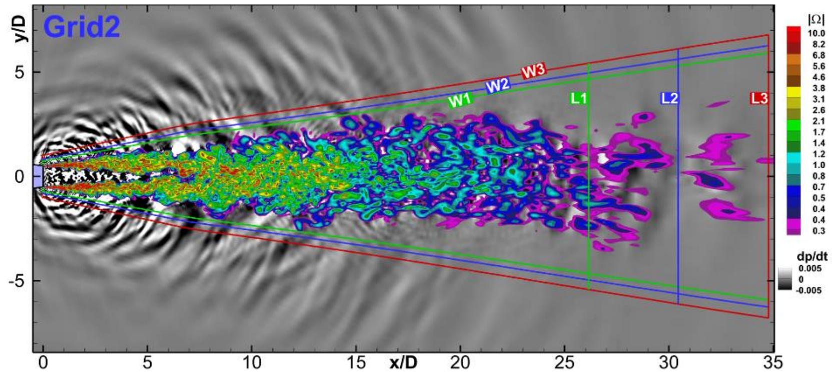
Slice z/D=0 | **3D vortices visualization**

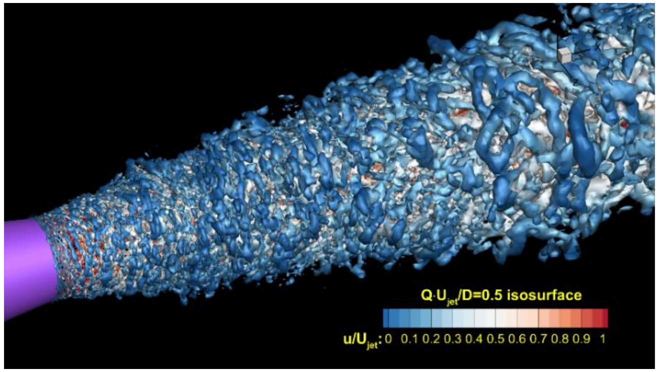
Grid 1



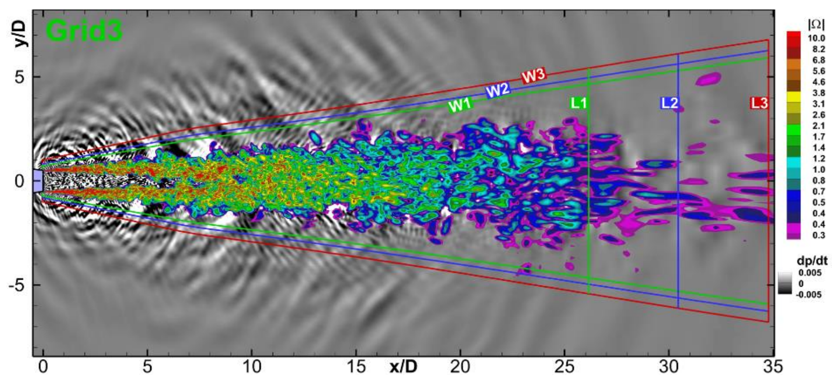


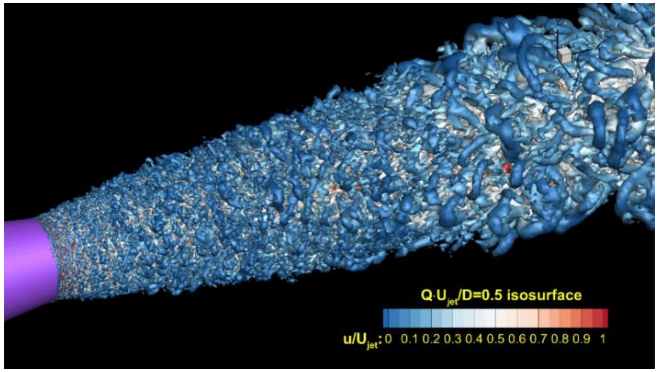
Grid 2





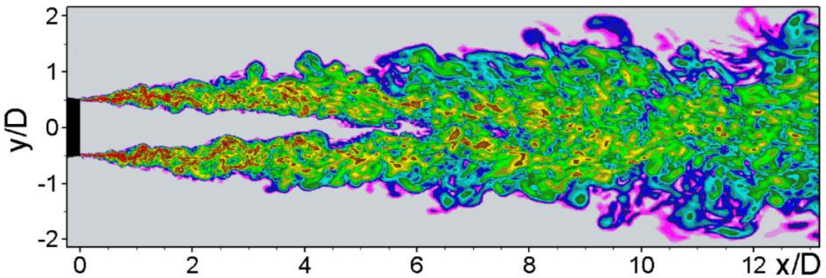
Grid 3

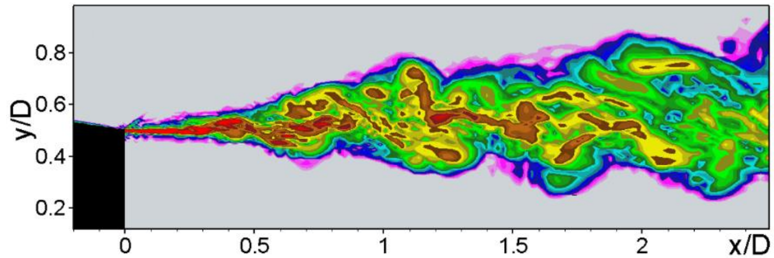


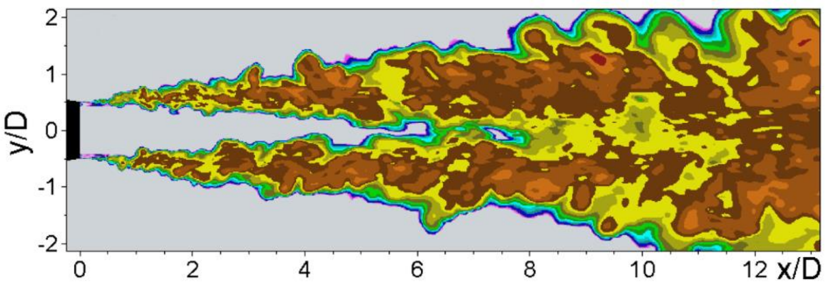


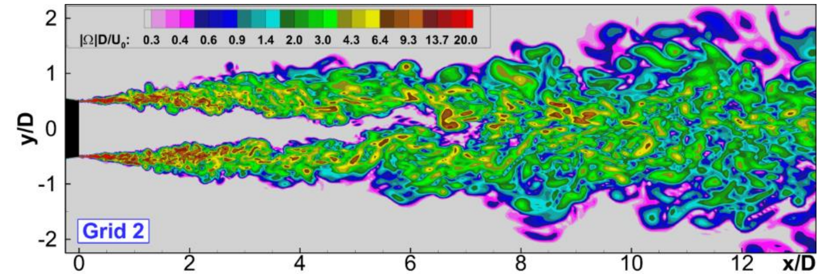
Results: instantaneous flow fields (NTS and NOISEtte)

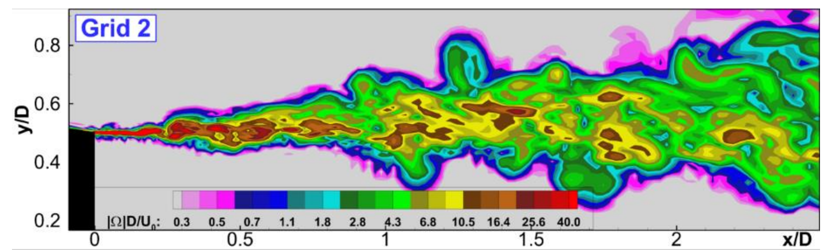
NTS	Grid 2	NOISEtte

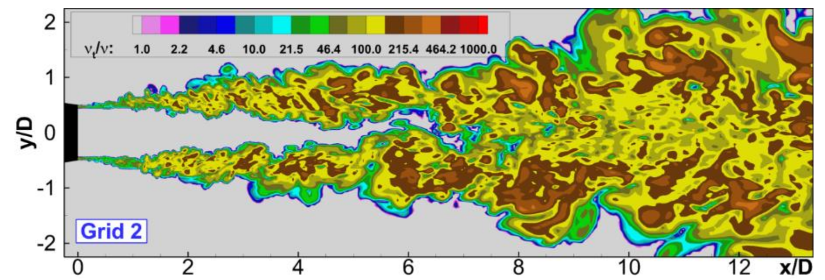






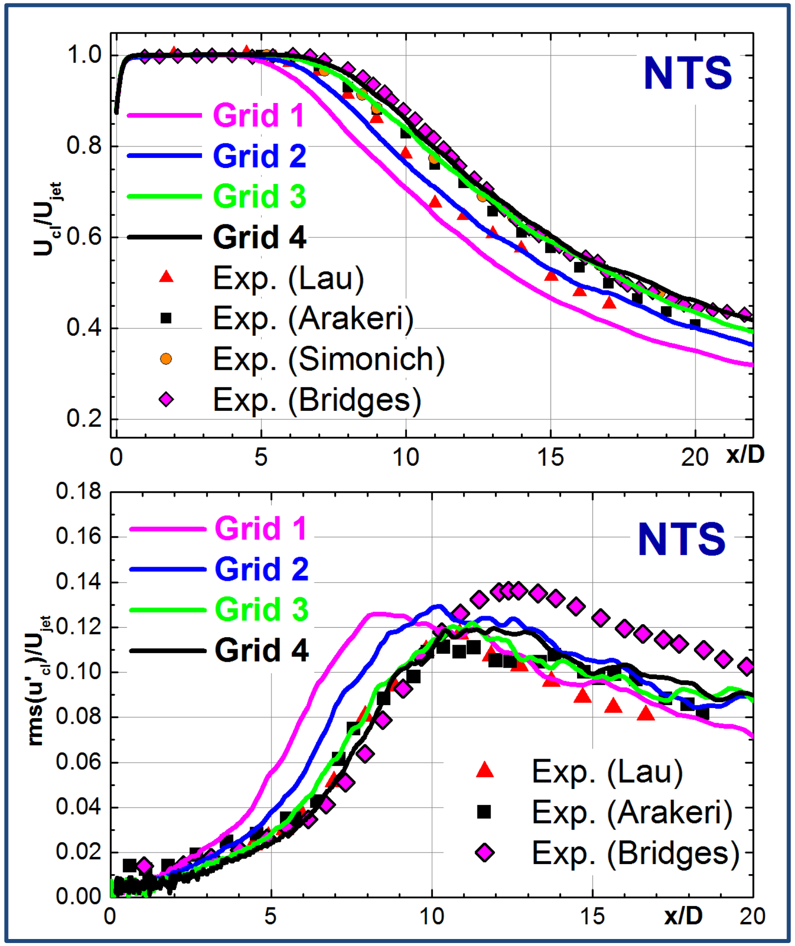


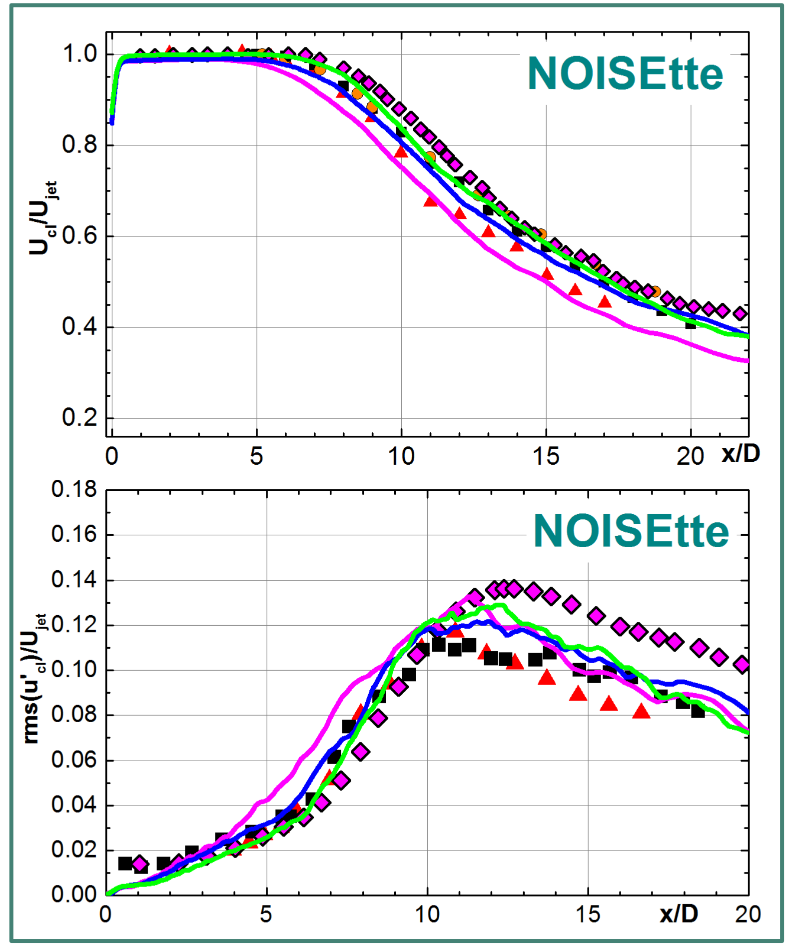


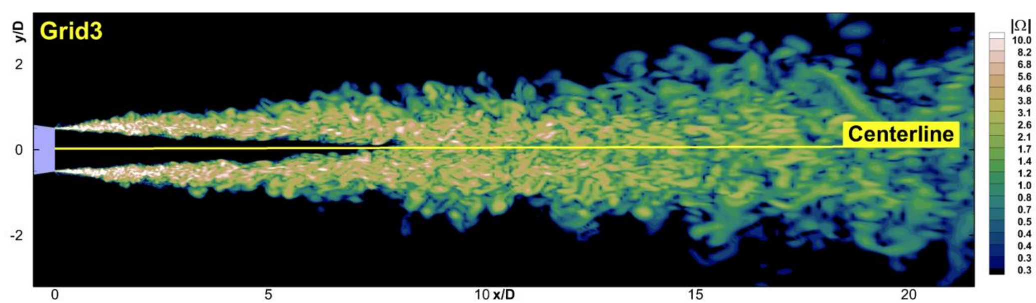


- **NTS** computation is characterized by smaller scales of resolved turbulent structures
- But shear layers develop similarly in both computations

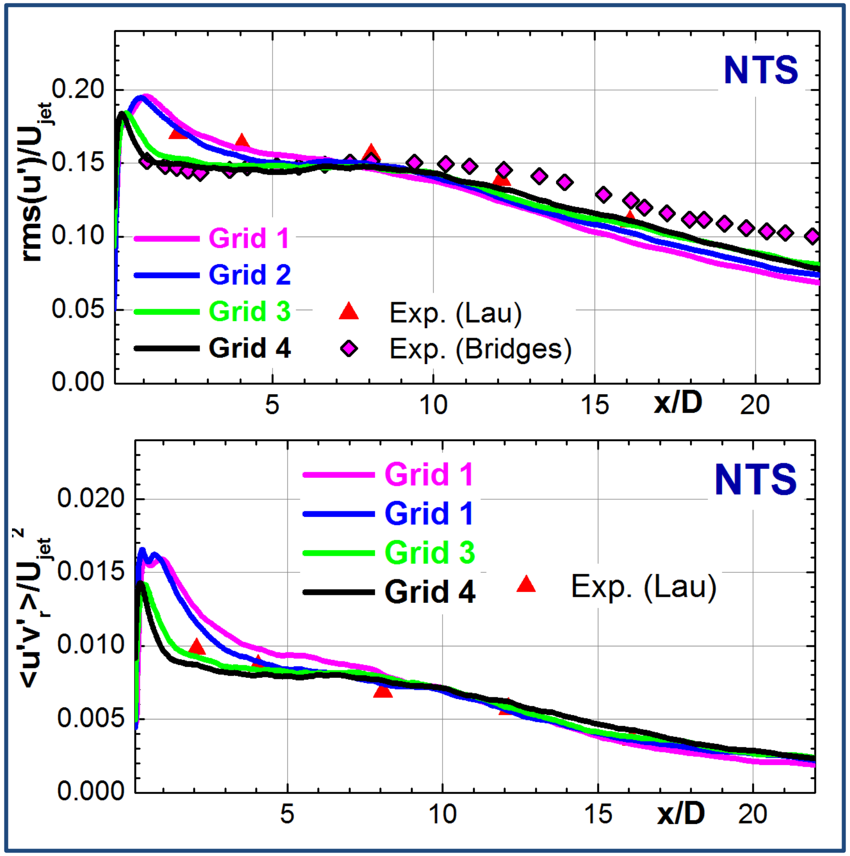
Results: averaged (NTS and NOISEtte) 1/4

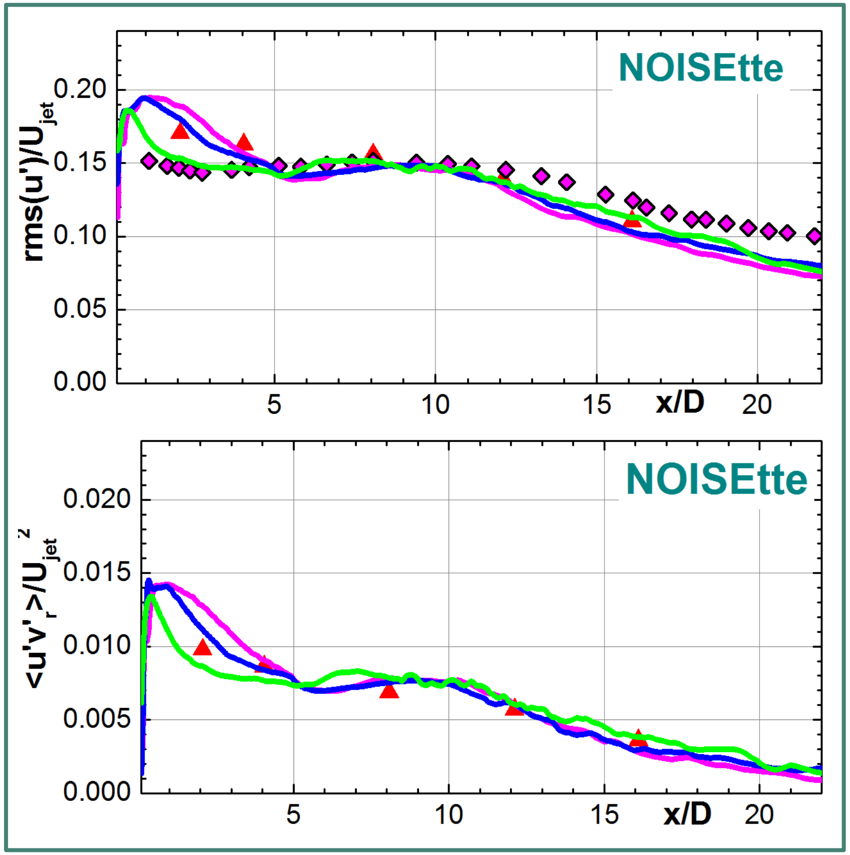


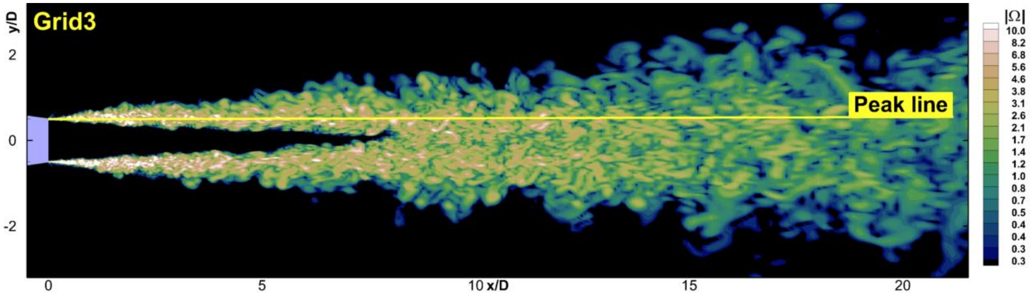




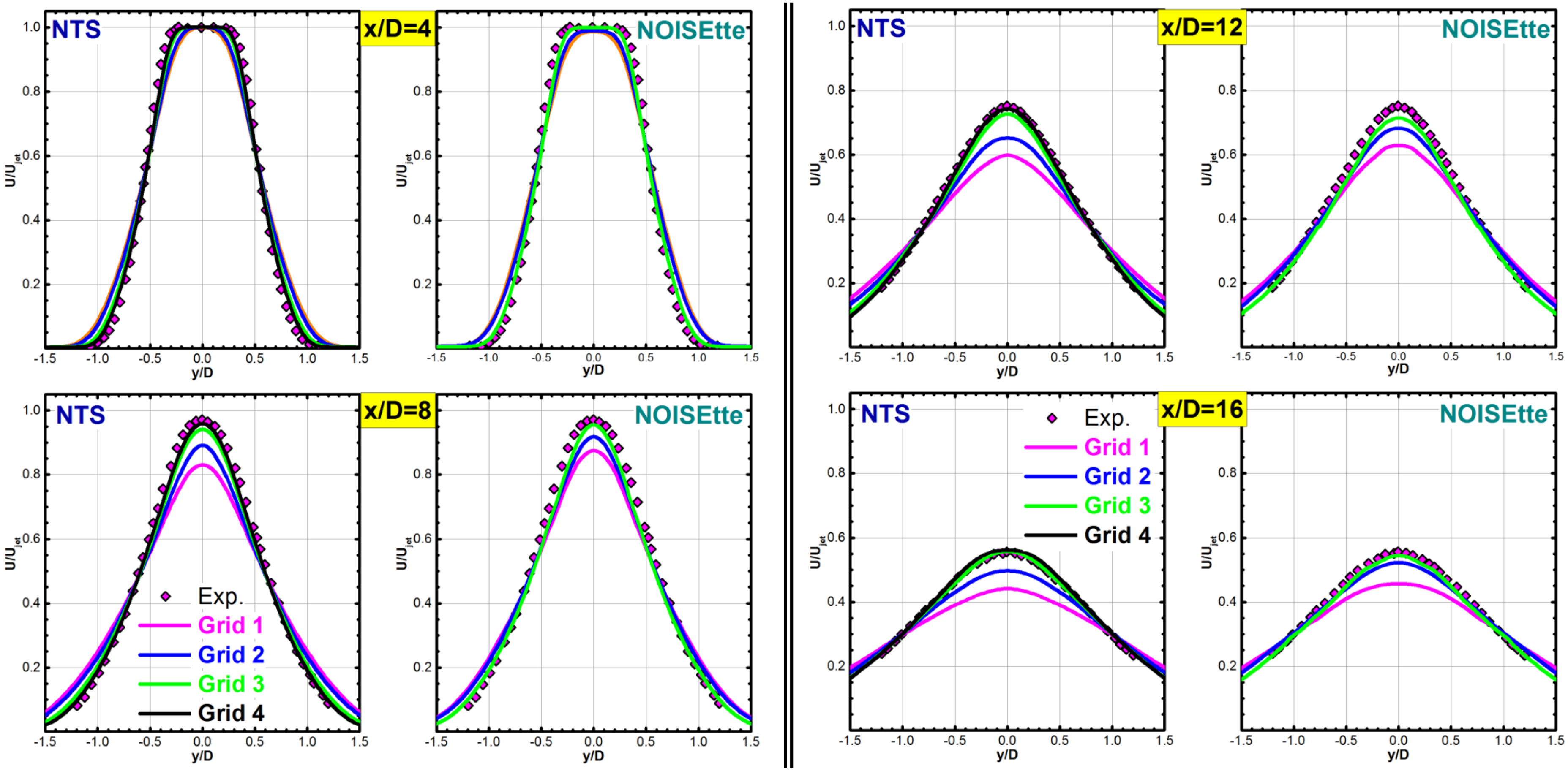
Results: averaged (NTS and NOISEtte) 2/4

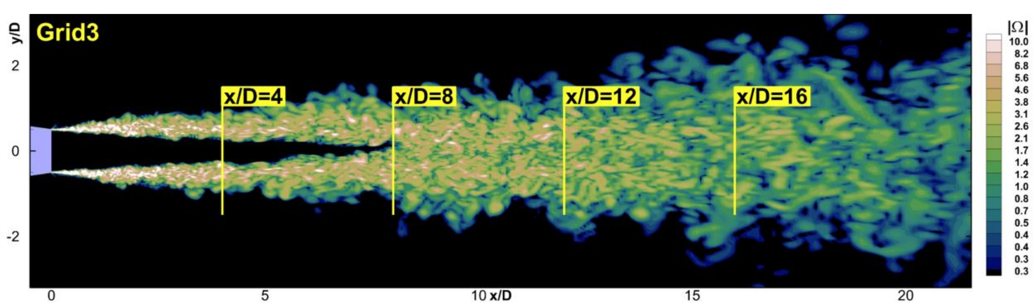




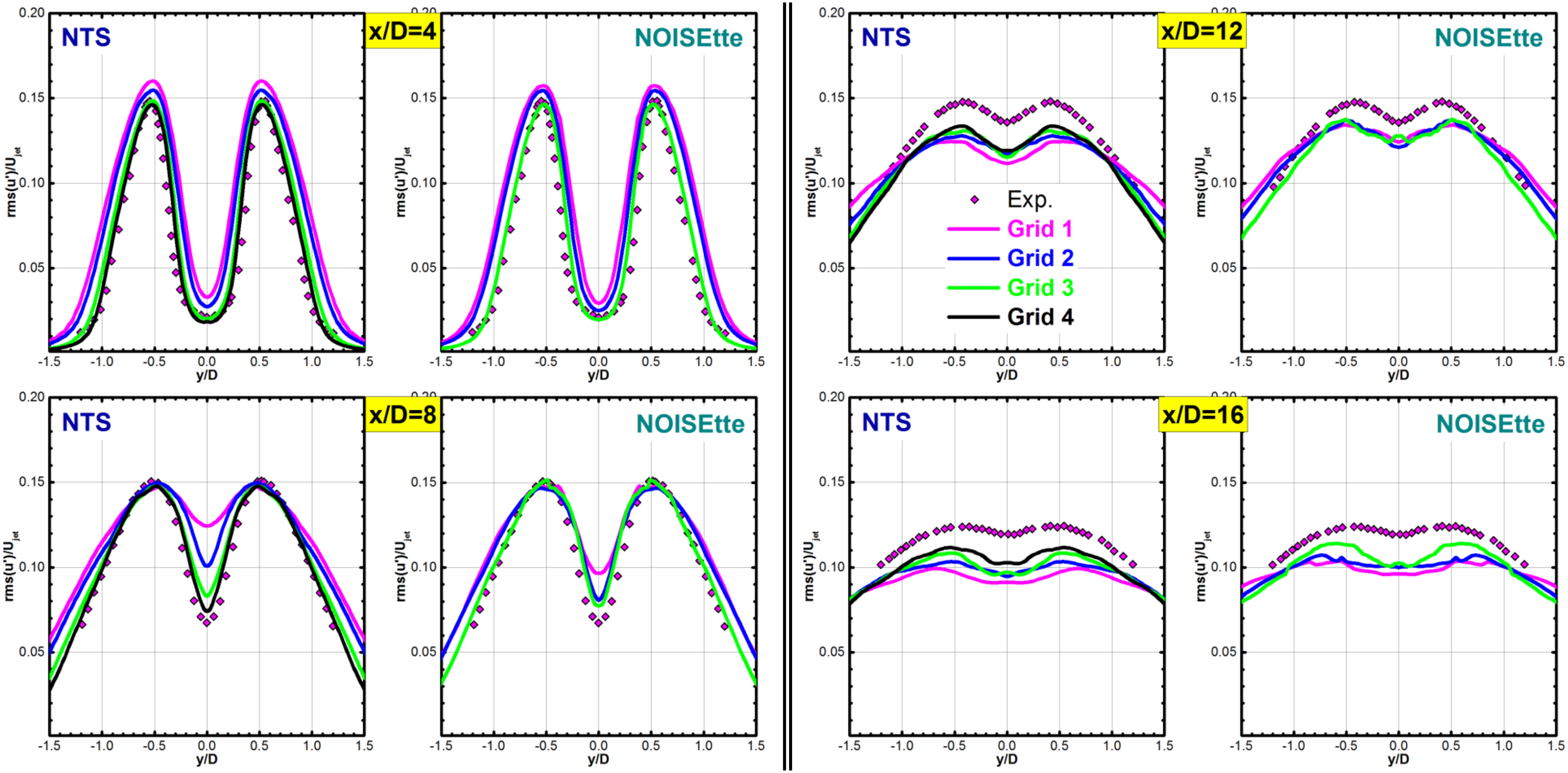


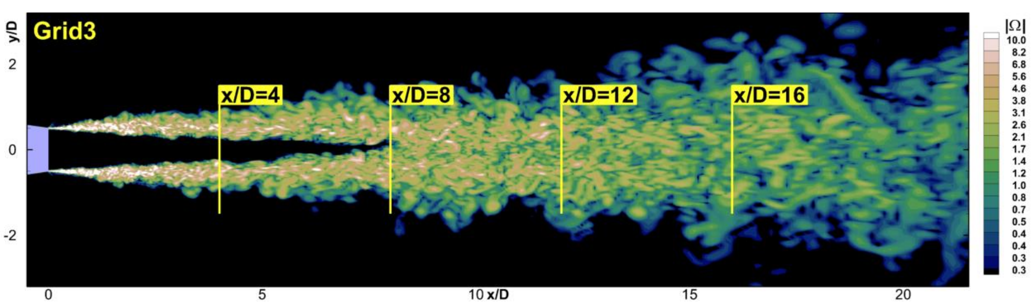
Results: averaged (NTS and NOISEtte) 3/4



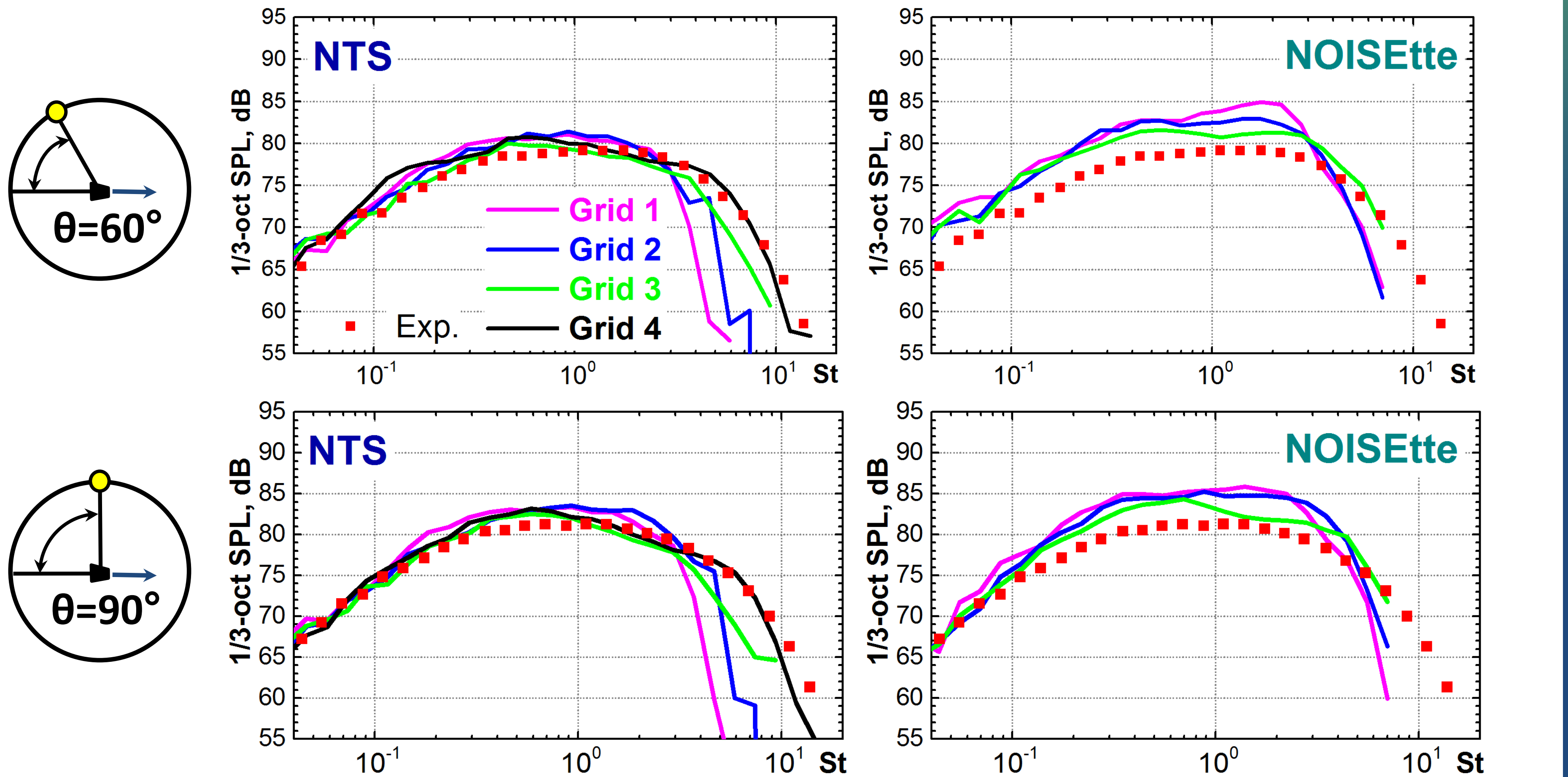


Results: averaged (NTS and NOISEtte) 4/4



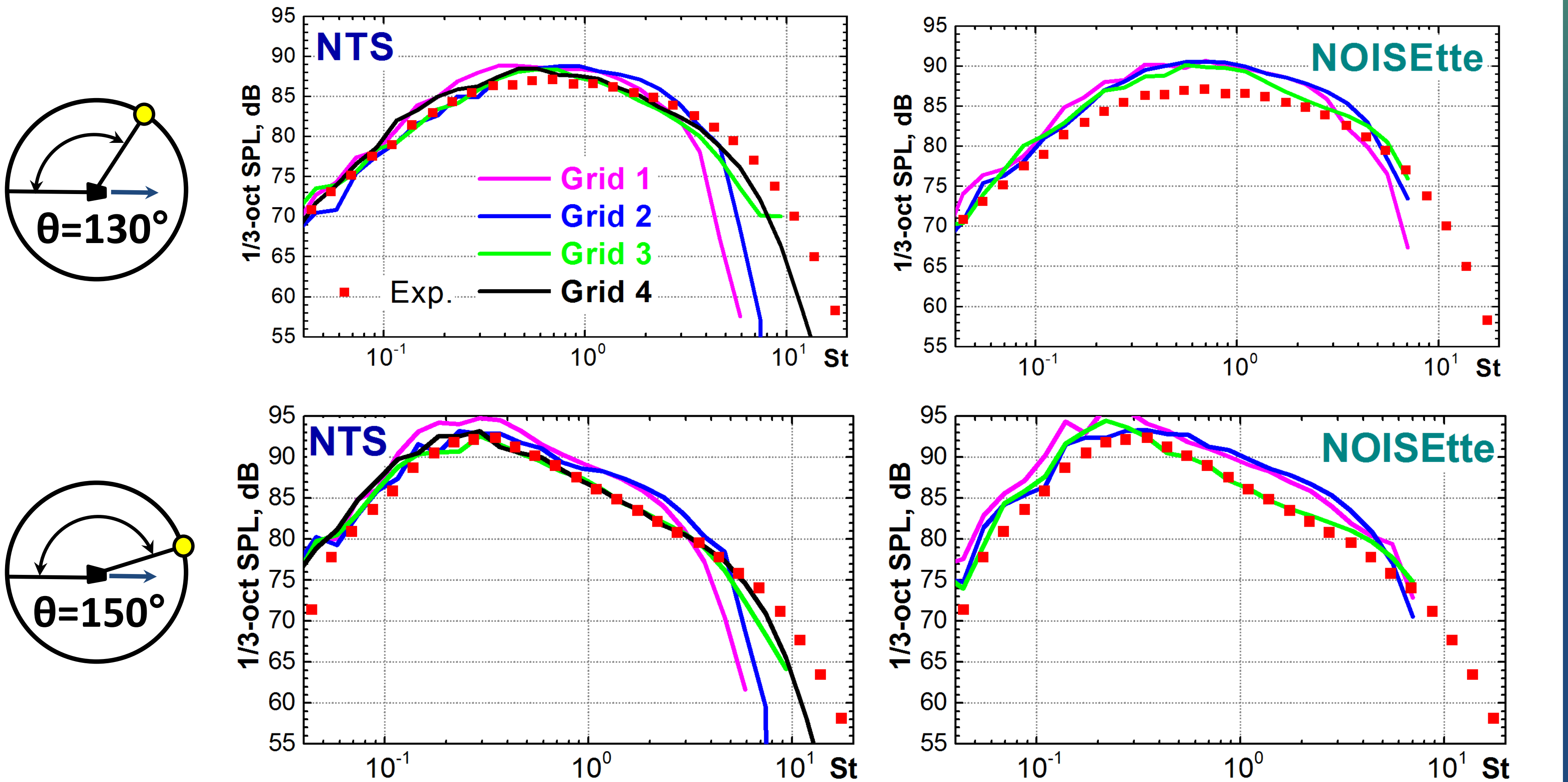


- Both NTS and NOISEtte results are similar with negligible discrepancies
- Mesh refinement leads to the convergence of both structured and unstructured results



- Both structured and unstructured results confirm the common trend that mesh refinement leads to its convergence and better agreement with the experiment
- A slight discrepancy between the algorithms could be observed: NOISEtte noise spectra are overestimated

Results: farfield (1/3 octave band spectrums) 2/2



- Better agreement of unstructured results with the experiment is seen for high observation angle (θ =130°)
- The reasons of spectra overestimation is not clear and is being investigating

Conclusions

- The results obtained using both structured and unstructured algorithms are well correlated
- This fact and the convergence of results confirms a correctness of the considered formulation of new subgrid scale () for unstructured meshes
- Furthermore the results prove that the developed methodology of solving the Navier-Stokes equations with the use of higher order numerical schemes on unstructured meshes provides the accuracy well compared with that obtained by low dissipative numerical algorithms for structured meshes
- Further development and improvement of unstructured numerical algorithm is required. Adaptation of the scheme for solution and mesh peculiarities is on demand to make it robust and to apply it for industrial problems

- The research is supported by Russian Science Foundation, project № 14-11-00060
- Unstructured computations were carried out using «Lomonosov» (MSU) and 10P (JSCC RAS) supercomputers

Thanks for attention!