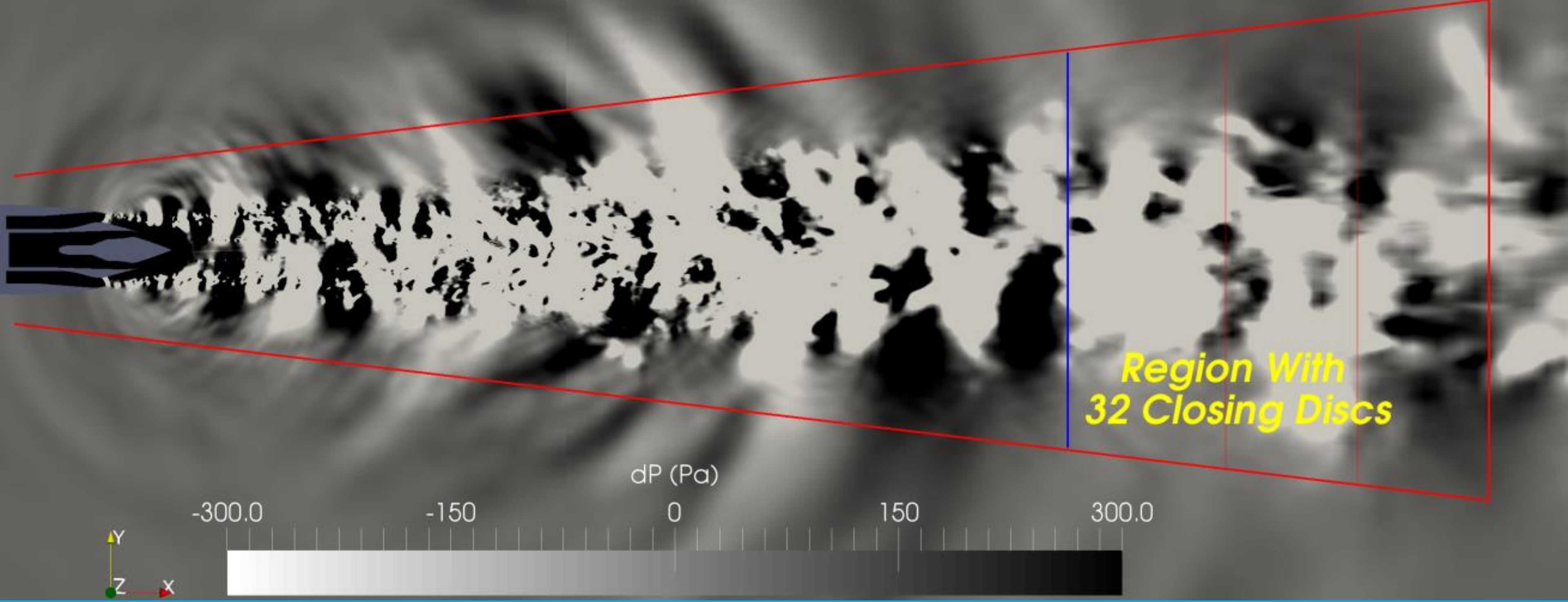

GPU CABARET Solutions for the CoJen Jet Noise Experiment

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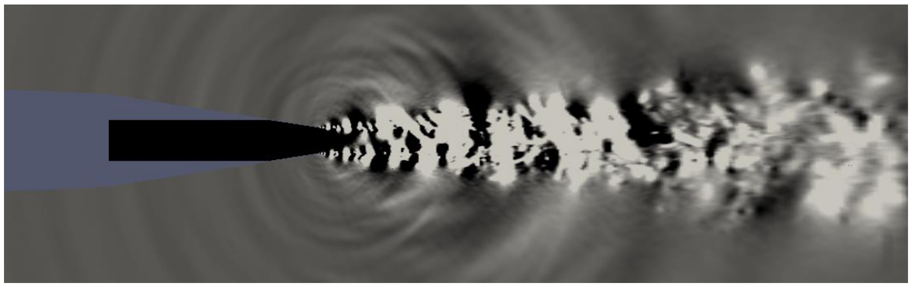
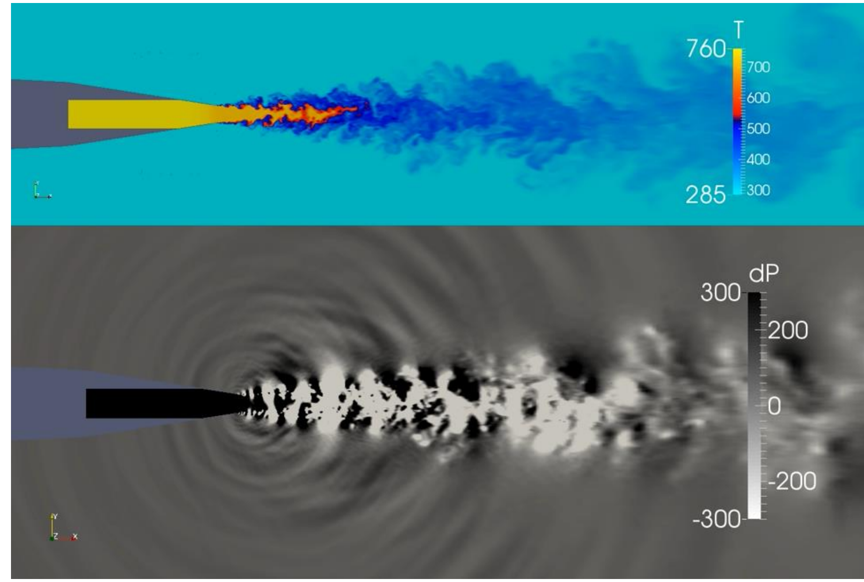
* *GPU-prime Ltd., Cambridge, UK*

Some previous work (GPU-CABARET LES)

SILOET Ma=0.9 Cold & Hot Jet, 20-80 mln cells

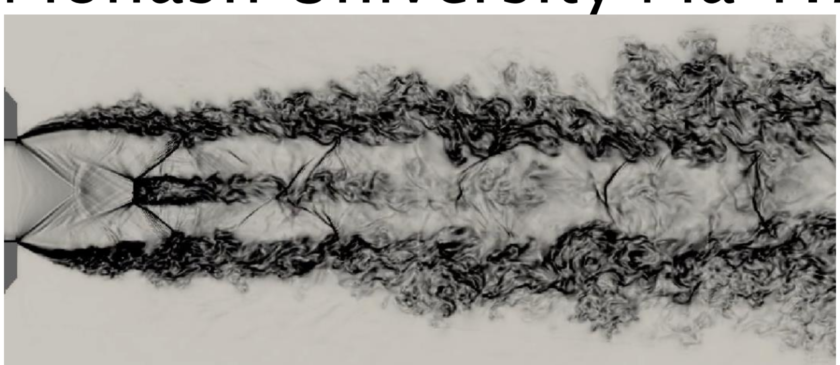


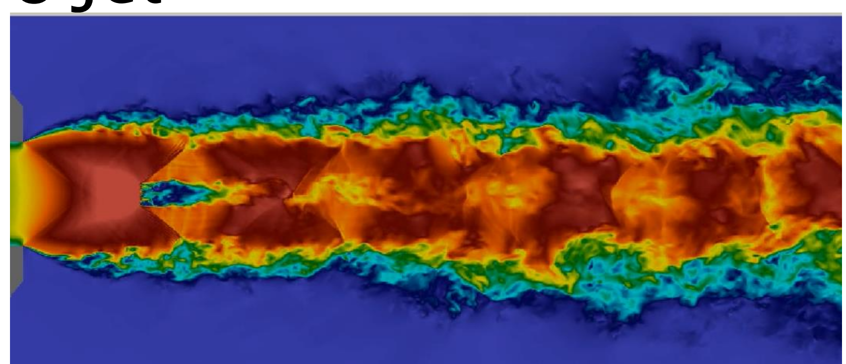


NASA SMC000 SP7

Ma=0.9, 50-80 mln cells

Monash University Ma 1.78 Jet



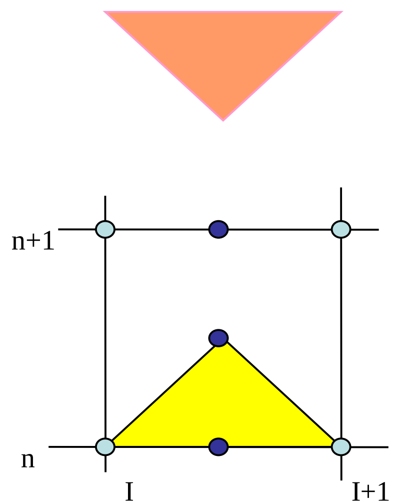


GPU CABARET LES Solver

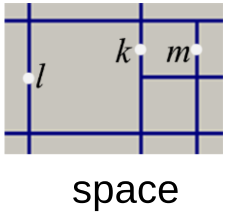
- GPU CABARET:
  - CABARET method, 2nd order, low dissipative, low dispersion
  - LES code coupled to FW-H acoustic solver
  - Computations are performed on GPUs 100%
  - Low memory-footprint implementation including optimised for single precision computations
  - Asynchronous timestepping (partly avoid CFL bottleneck)
  - Industrially relevant acoustic sensitive LES calculations (50-100 mln cells), with total computation time of several days to a week for initialisation flow and statistics gathering, on a **standard workstation computer**

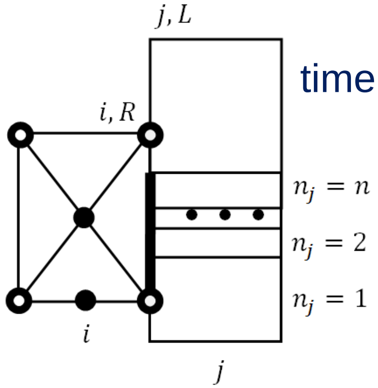
GPU CABARET

- 100 mln cells LES on a home computer?
- Is this possible? How do the numbers add up?
  - (TFLOPS potential) 1 GPU compared to 1 core CPU **~80x**
  - (Scalability) Four high performance GPUs per workstation **~4x**
  - (Method) Using asynchronous time stepping **~5x–20x**
  - (Total) 1 workstation = 1600–6400 equivalent cores!



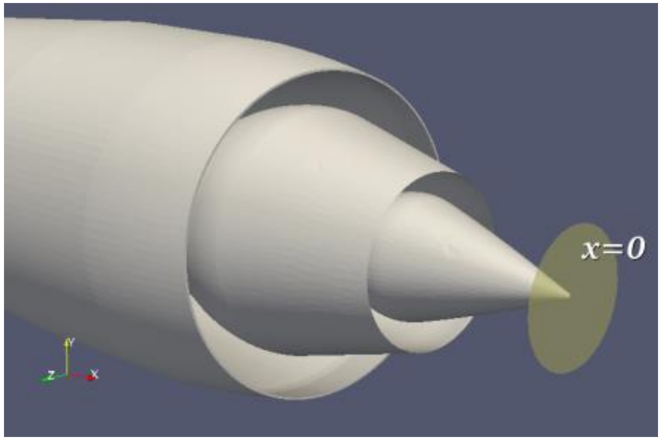
Unstructured hanging-node type grids and asynchrono stepping

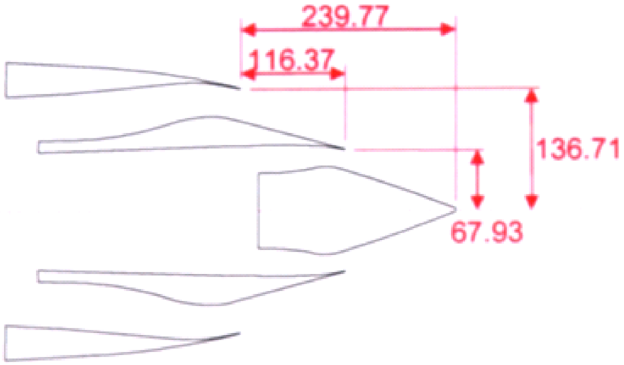




This work

- GPU CABARET LES solver applied to 3 different operation points corresponding to the heated dual-stream jet conditions from the **EU CoJen experiment**
  - Locally refined 65 million cells and optimised 80mln cells LES grid generated using snappyHexMesh (OpenFOAM)
  - Grid sensitivity of the flow solution is tested
  - Flow solutions compared with the experiment and reference LES solutions published in the literature.
  - Noise predictions compared with experiment for a wide range of frequencies and far-field microphone angles (FW-H)





CoJen Experiment

Figure 1. The anechoic chamber of the QinetiQ Noise Test Facility.

Figure 9. Source-location array.

Computation of **Co**axial **Je**t **N**oise, aimed at accelerating the development of computational tools capable of accurately predicting generation of noise

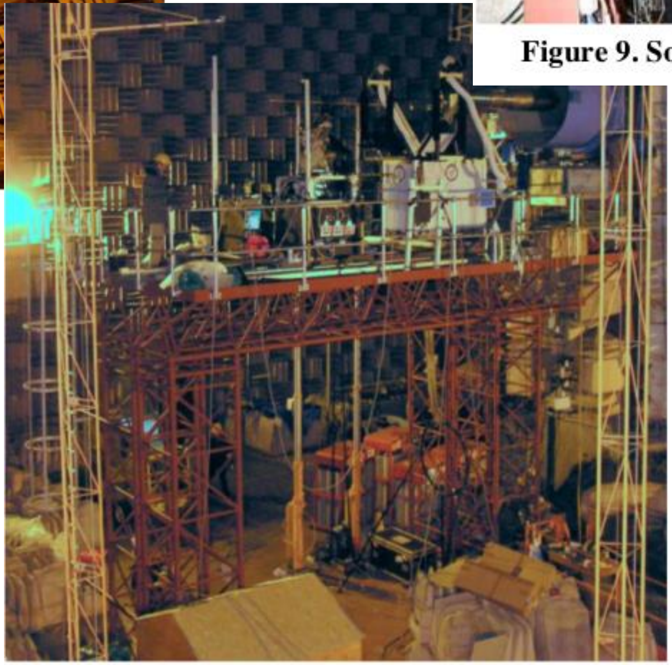


Figure 6. Gantry, traverse and PIV systems installed in the NTF chamber.

Pictures from: Mead, C.J., Wrighton, C., Britchford, K., AIAA 2015-3122

CoJen Experiment

- Operating Points
  - Designed to be representative for takeoff (8 in total)
  - The three considered here have constant bypass conditions and a heated core with increasing core velocity
  - Can the LES solver capture the difference?

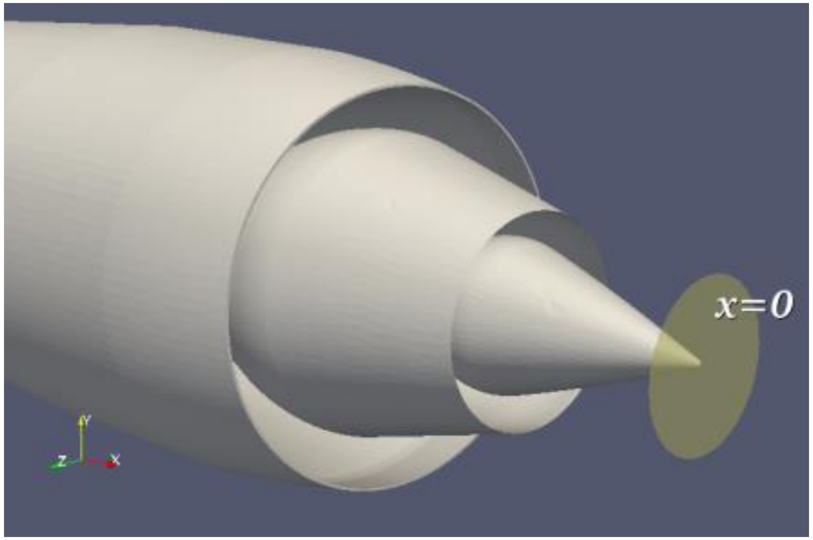
Table 1 – Operation points of the CoJen experiment (Skeen, 2006)

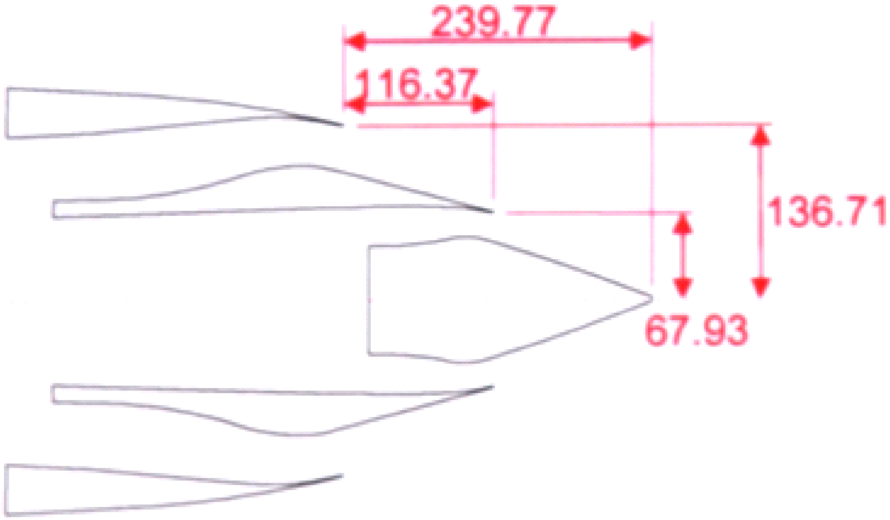
Operation Point:		1.1	1.2	1.3
Core	U_j (m/s)	340.3	404.5	480.7
	M_j	0.621	0.738	0.877
	T_{sj} (K)	775.6		
	T_{tj} (K)	827.9	849.5	879.9
Bypass	U_b (m/s)	306.8		
	M_b	0.902		
	T_{sb} (K)	288.14		
	T_{tb} (K)	335.0		
U_b/U_j		0.902	0.759	0.638

CoJen Experiment

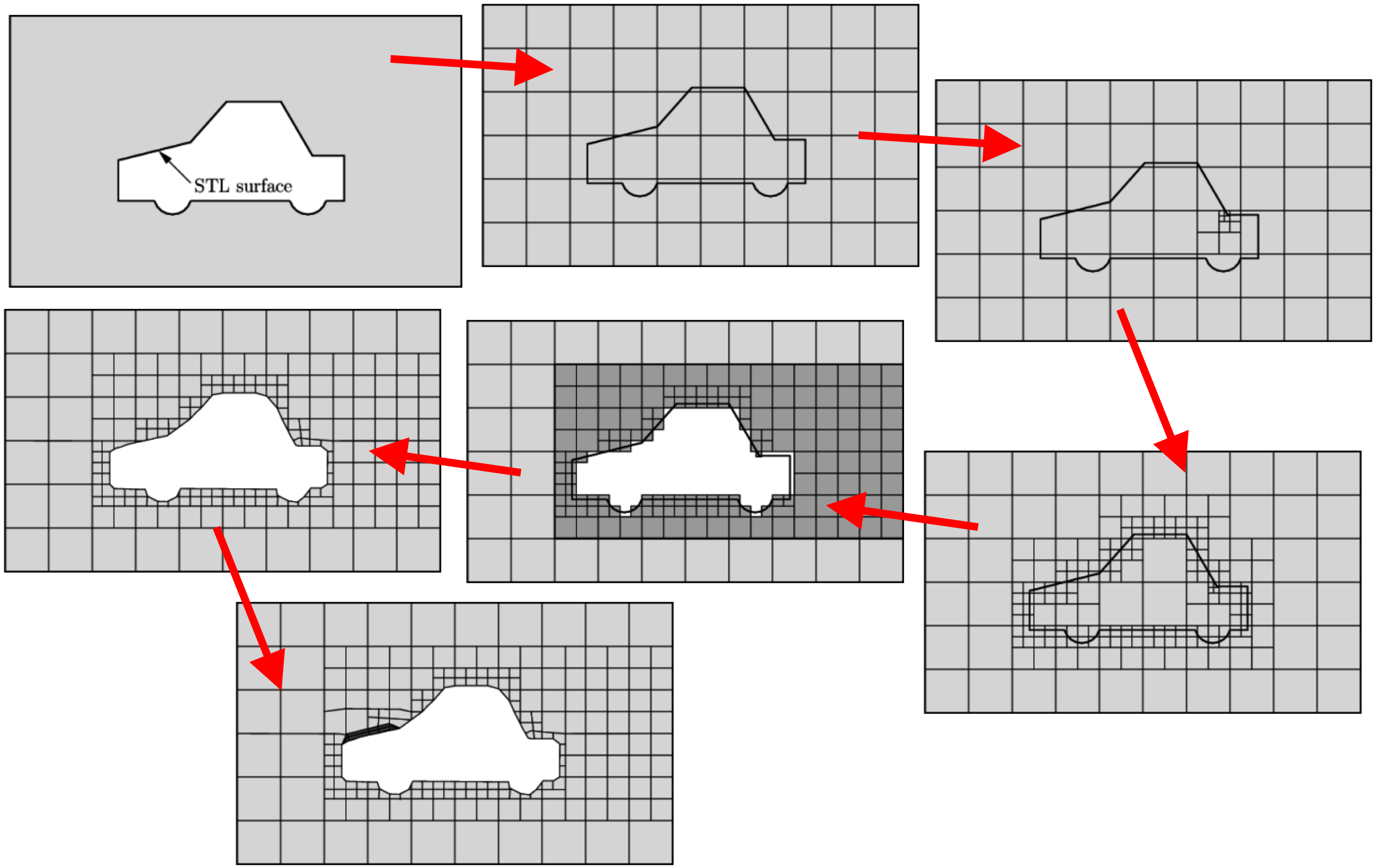
- Nozzle
  - CoJen Experiment considers three (coplanar, plain short cowl, and serrated short cowl)

  - Nozzle investigated here: <u>plain short cowl</u>
  - CAD geometry used for (automatic) grid generation



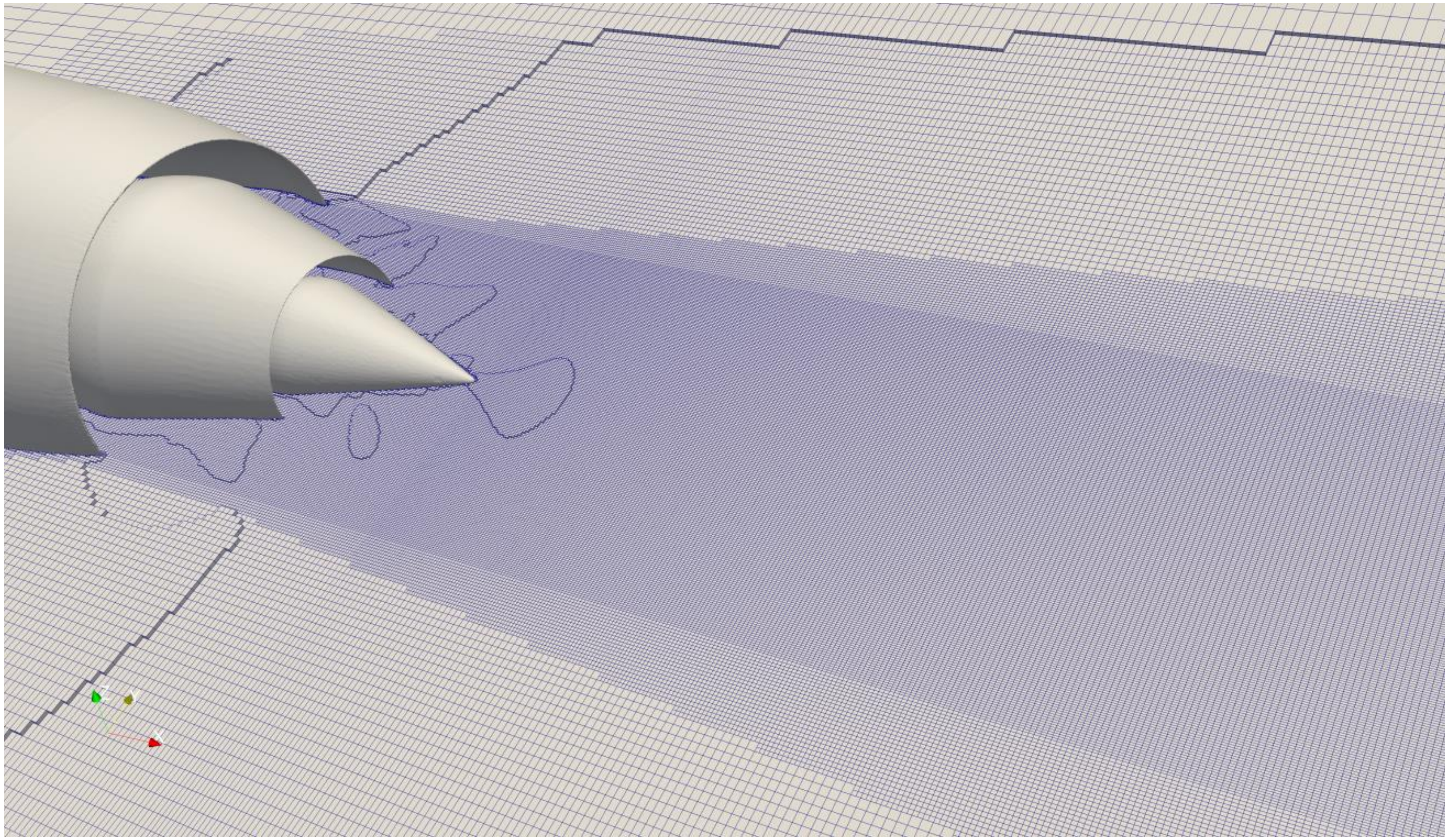


Grid Decomposition: Snappy Hex Meshing (OpenFOAM)

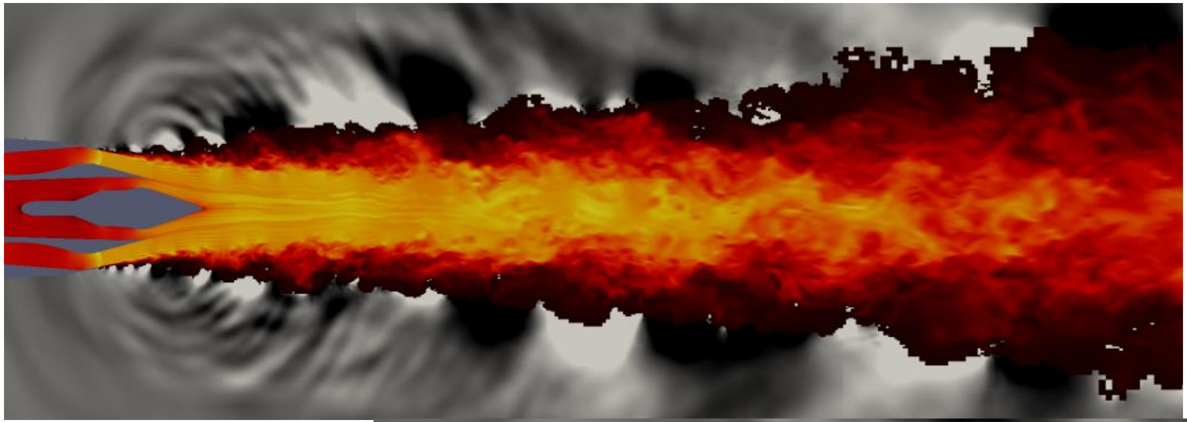


Mesh Details

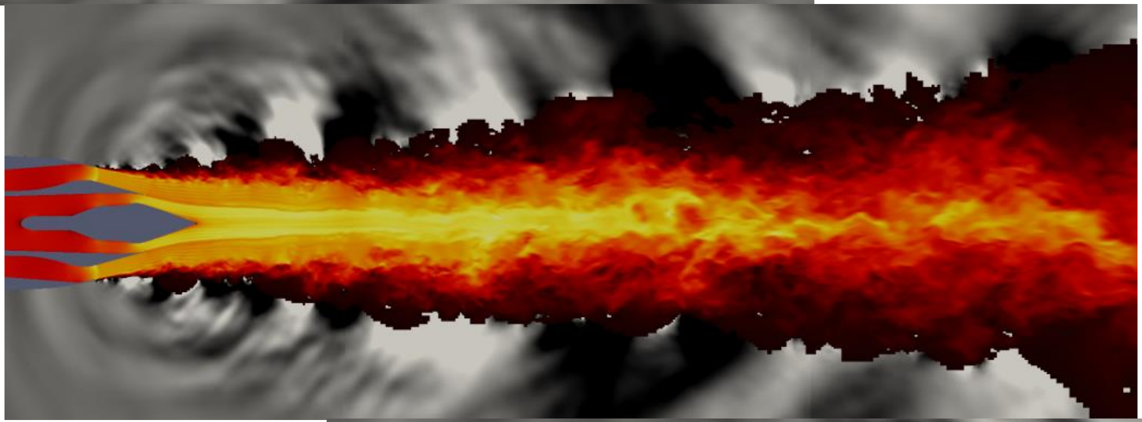
- snappyHexMesh is OpenFOAM utility to generate hexa-dominant meshes using CAD geometry as an input
- Typical LES grid generated (65 mln)
- Separate study in sensitivity of shear layer development



Results: Instantaneous Velocity

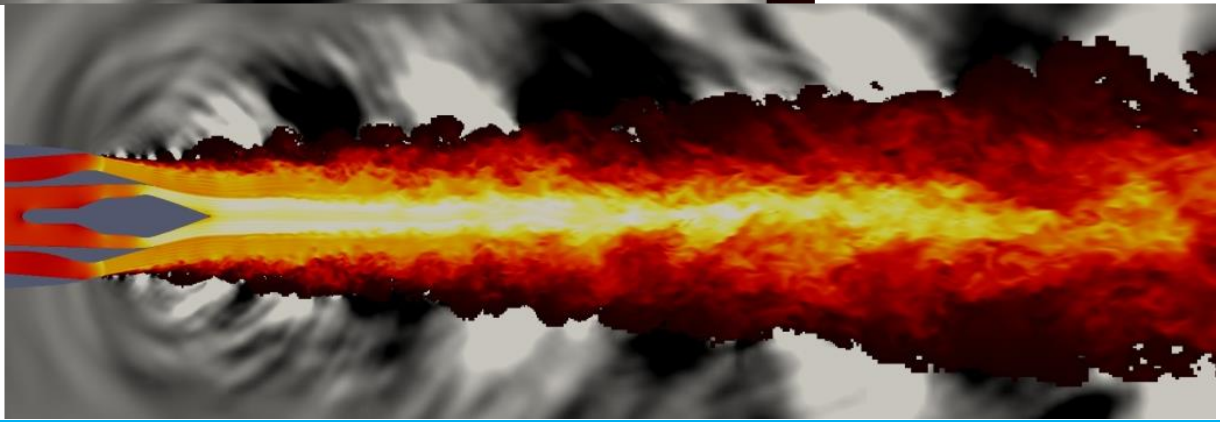


OP 1.1



OP 1.2

OP 1.3

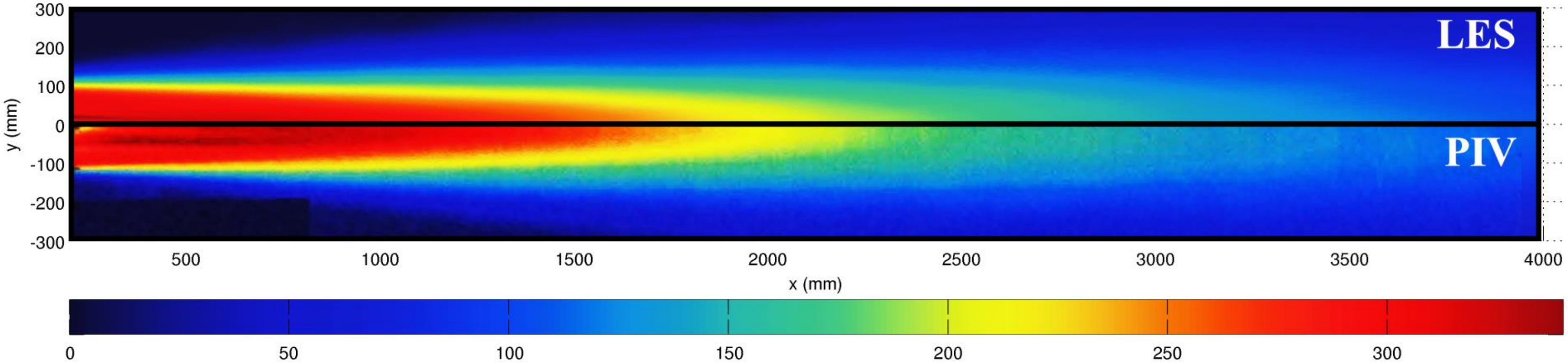


Results: Verification with Experiment

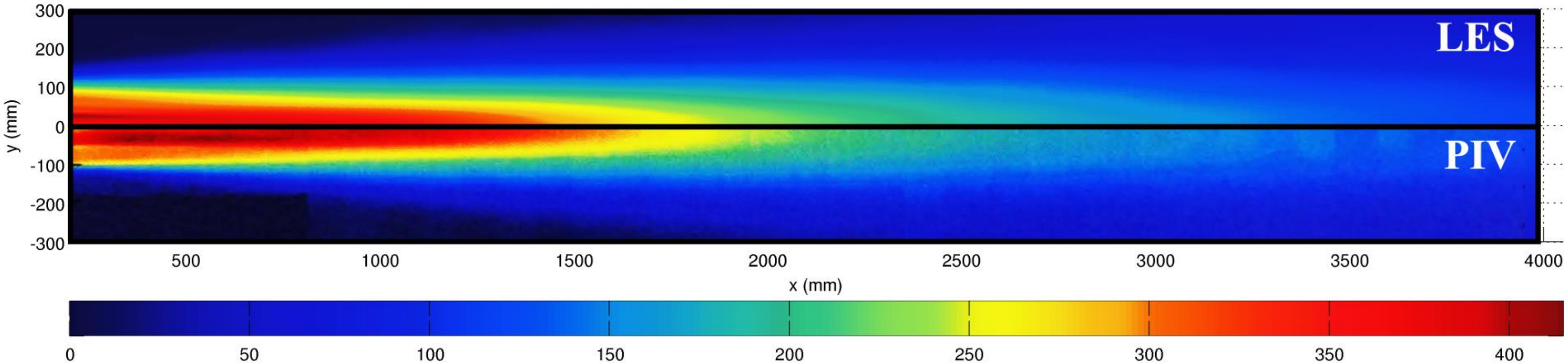
- Verification details:
  - The CoJen Noise data has kindly been provided by Dr Craig Mead
  - Near-field data had to be obtained from the literature
    - PhD Thesis of Andrew Skeen (Warwick 2006) which provides PIV result (badly scanned) pictures* (but not data)
    - A handful of articles comparing to operating point 1.3 at the centreline and several disc locations

*In order to compare, pictures were carefully digitised and cleaned-up for colour

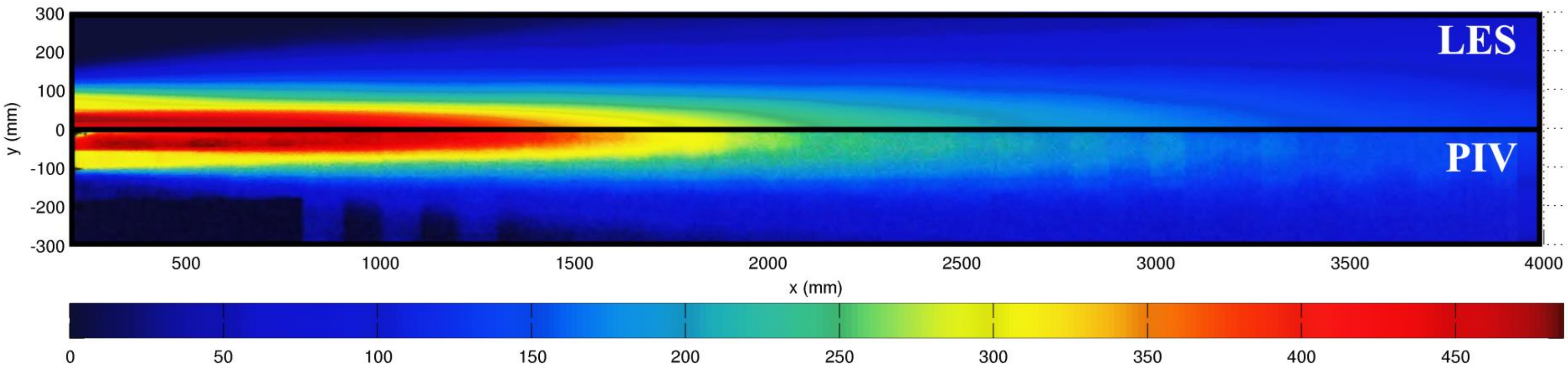
Results: LES Mean compared to PIV



OP 1.1



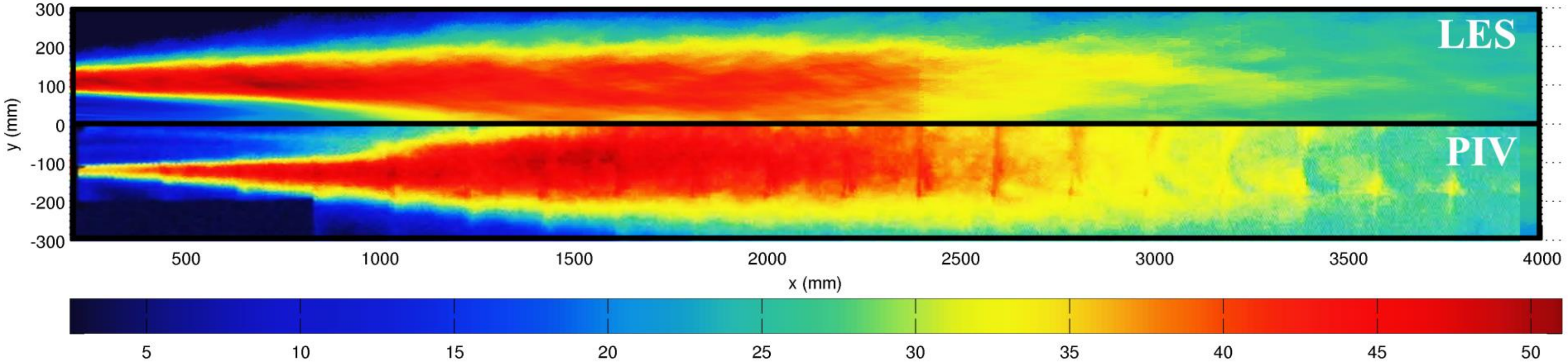
OP 1.2



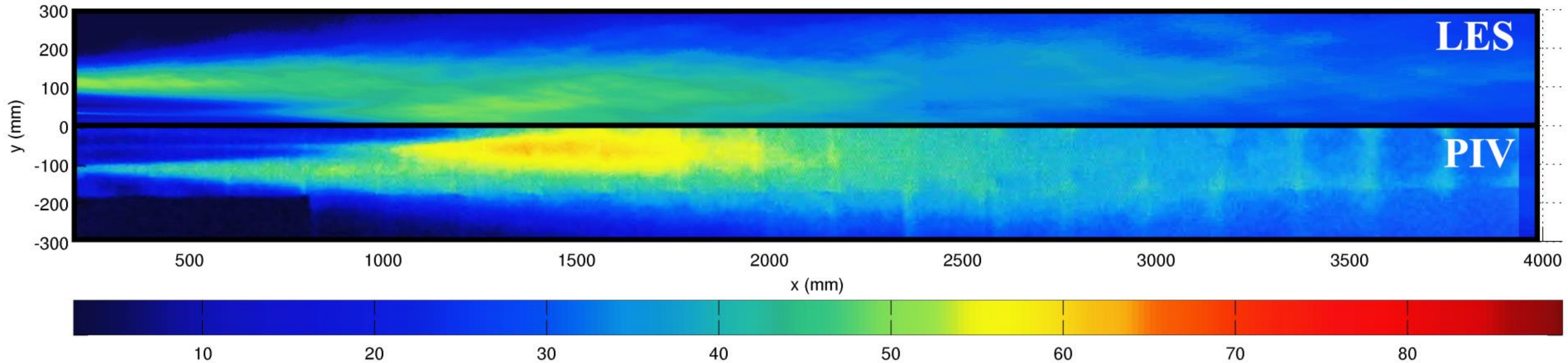
OP 1.3

PIV pictures from: PhD Thesis, Andrew Skeen, 2006, Warwick University

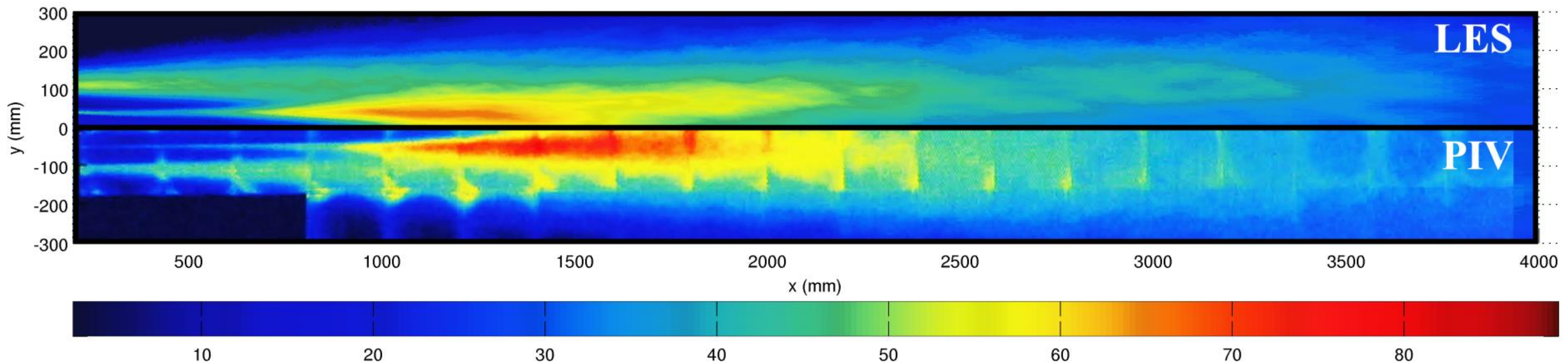
Results: u'_x compared to PIV



OP 1.1



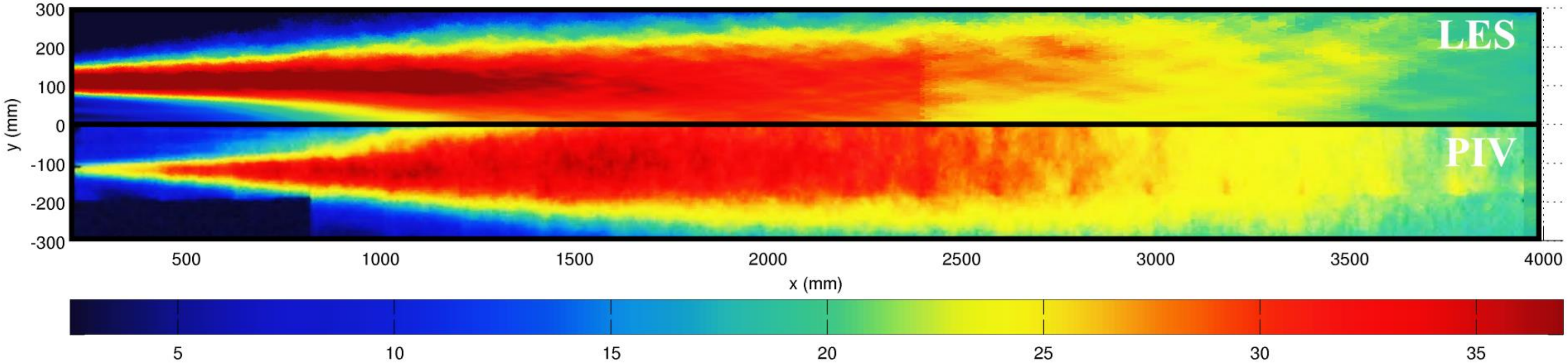
OP 1.2



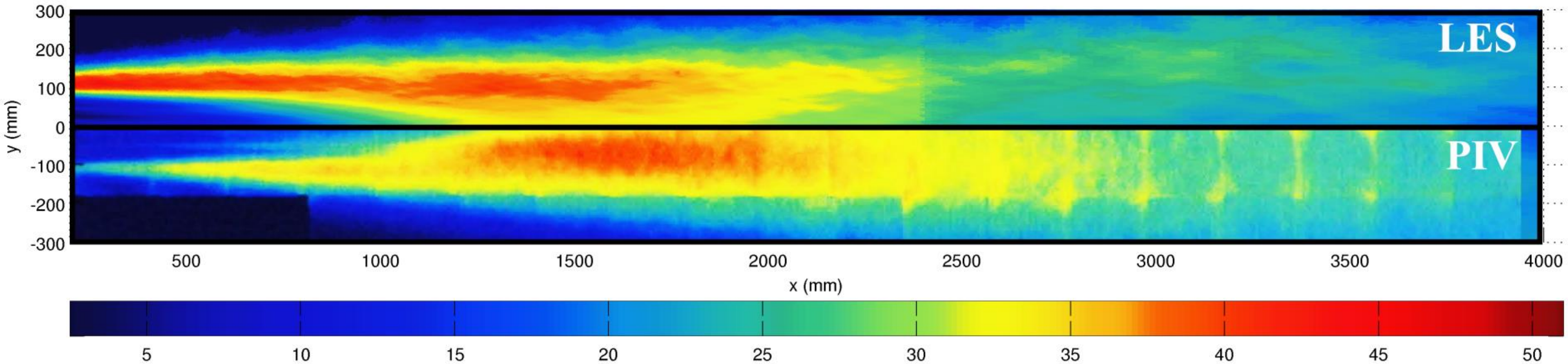
OP 1.3

PIV pictures from: PhD Thesis, Andrew Skeen, 2006, Warwick University

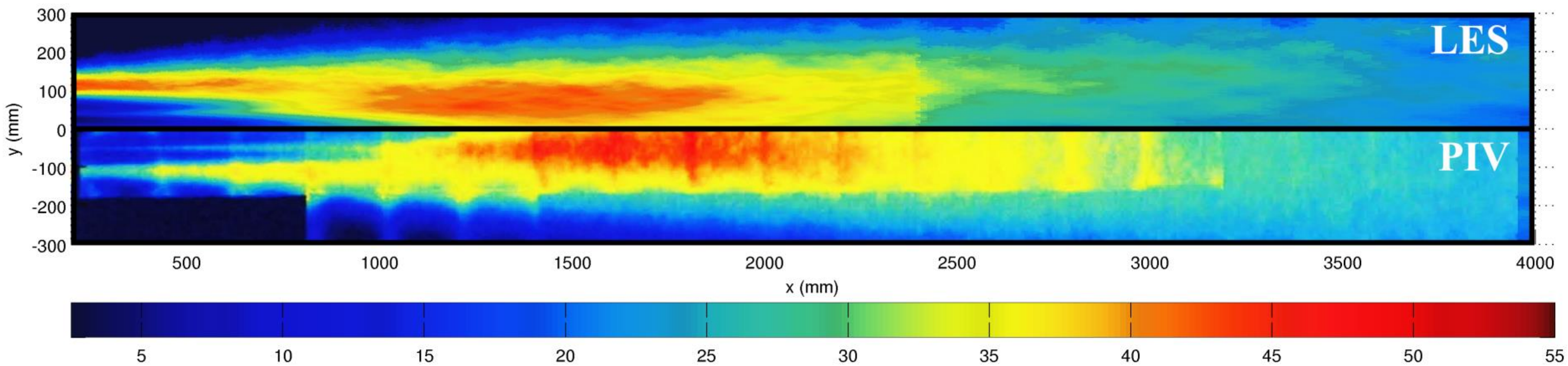
Results: u'_r compared to PIV



OP 1.1



OP 1.2

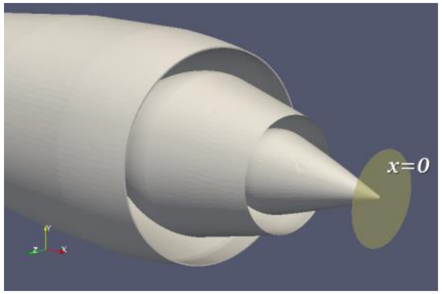


OP 1.3

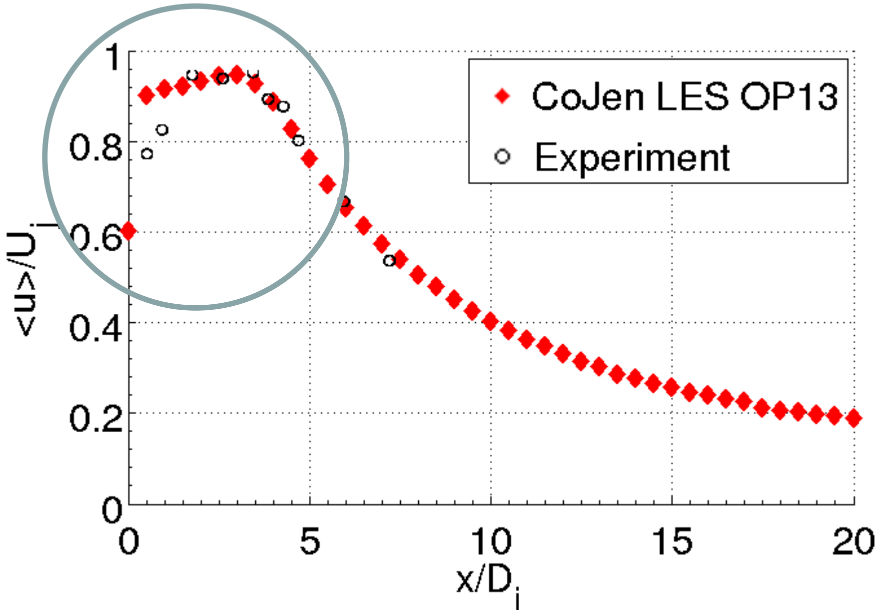
PIV pictures from: PhD Thesis, Andrew Skeen, 2006, Warwick University

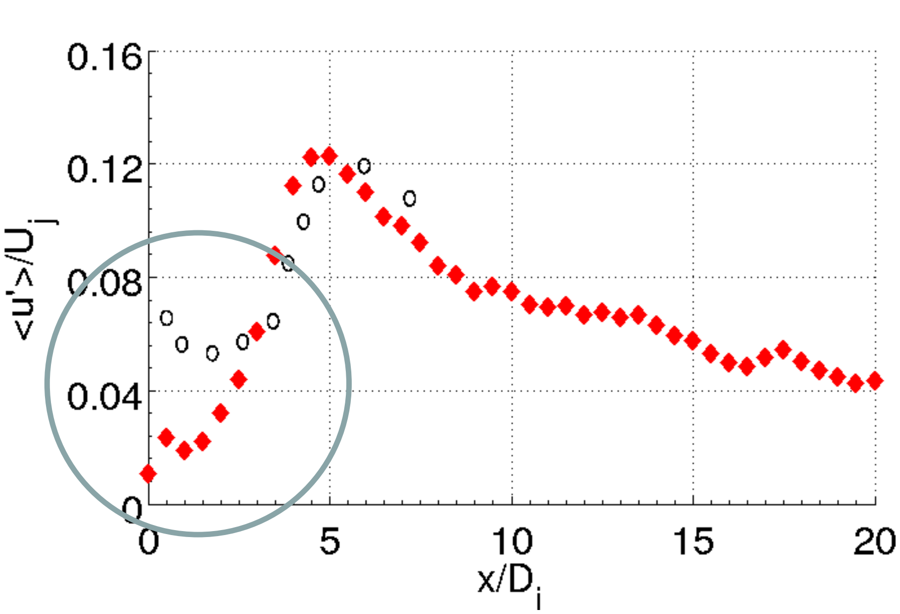
Results: Centreline

- Centreline
  - Normalised Mean Axial Velocity and Velocity Fluctuations (U_j=480 m/s)



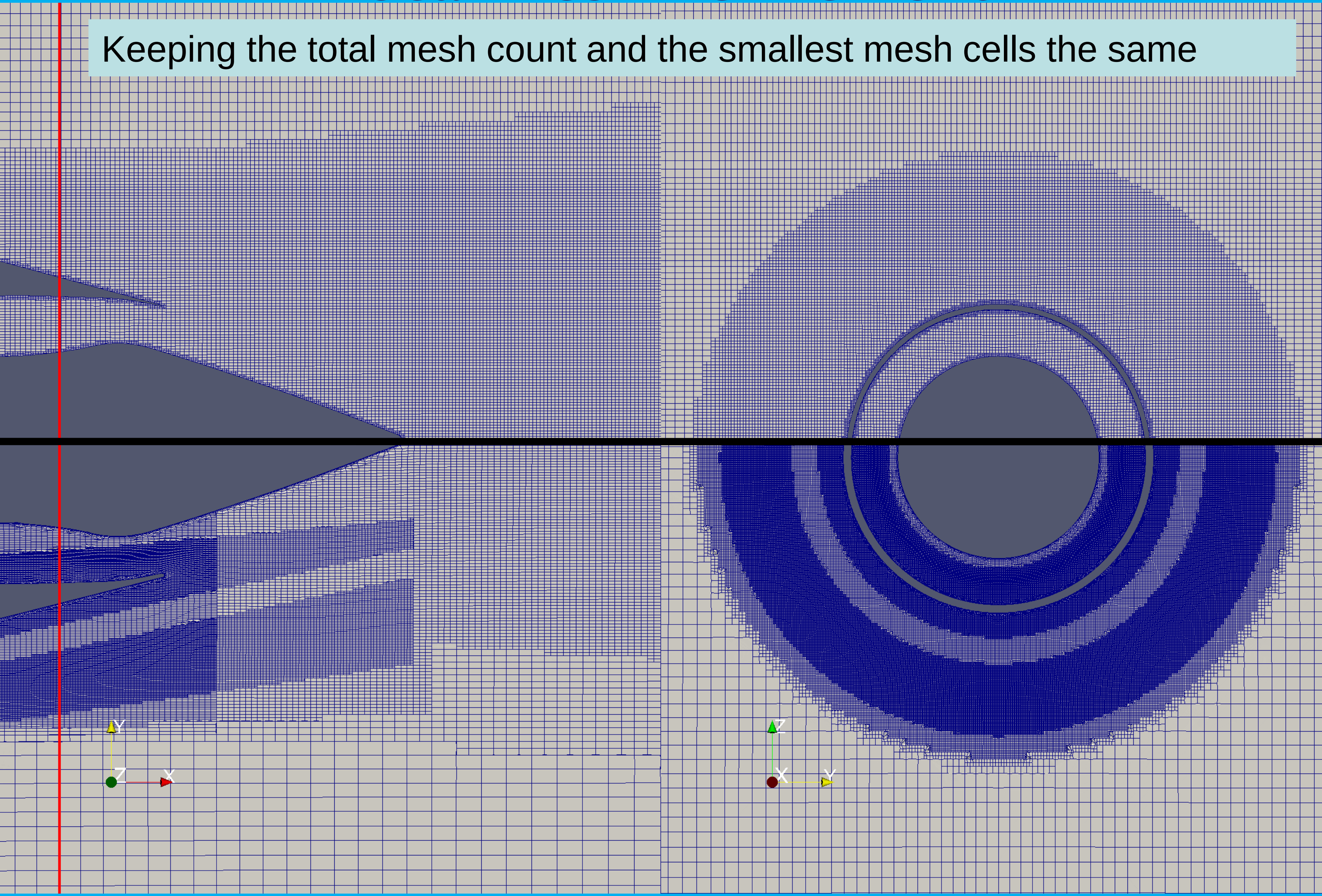
Differences after central body are due to mesh density? → refining the mesh



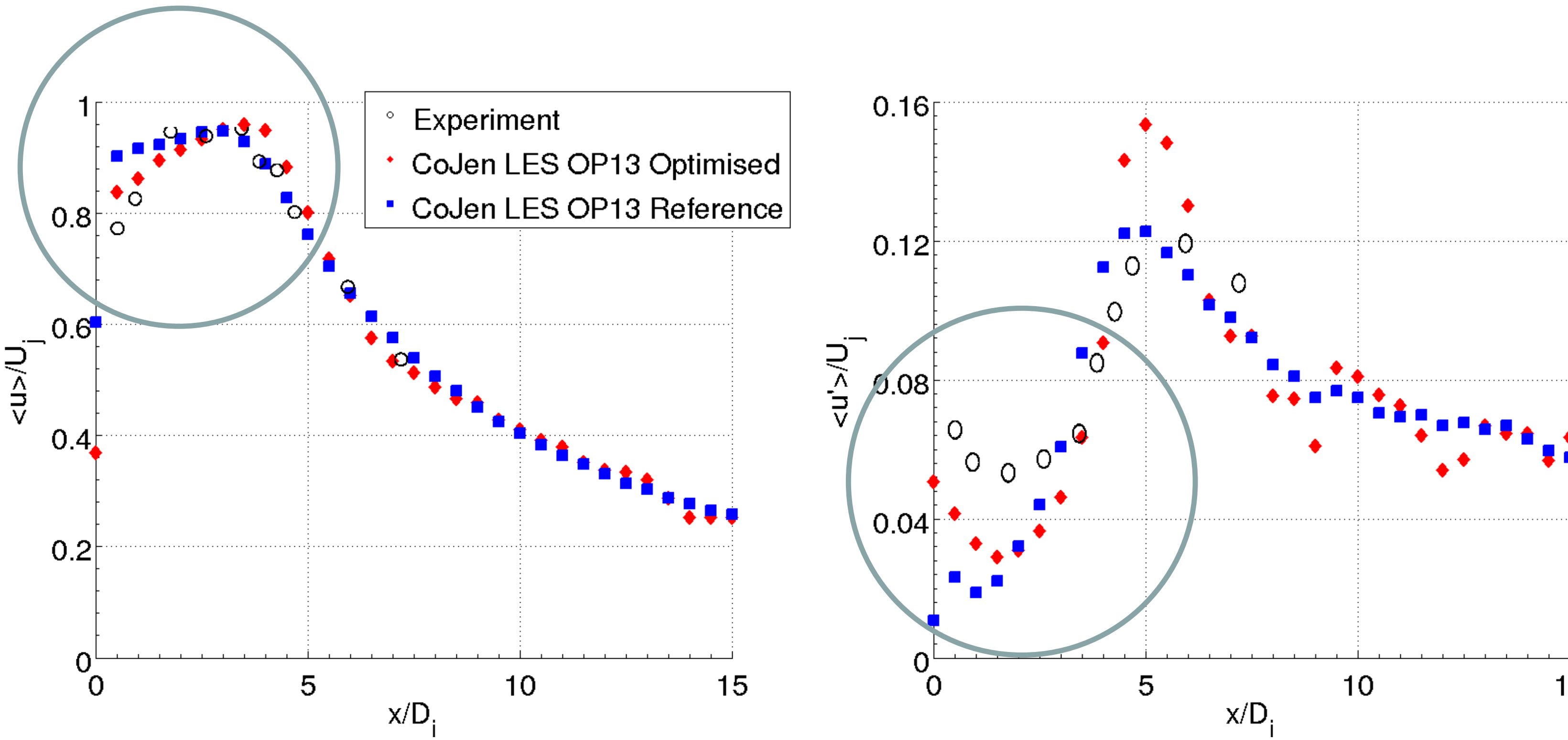


Local Mesh Refinement

Keeping the total mesh count and the smallest mesh cells the same

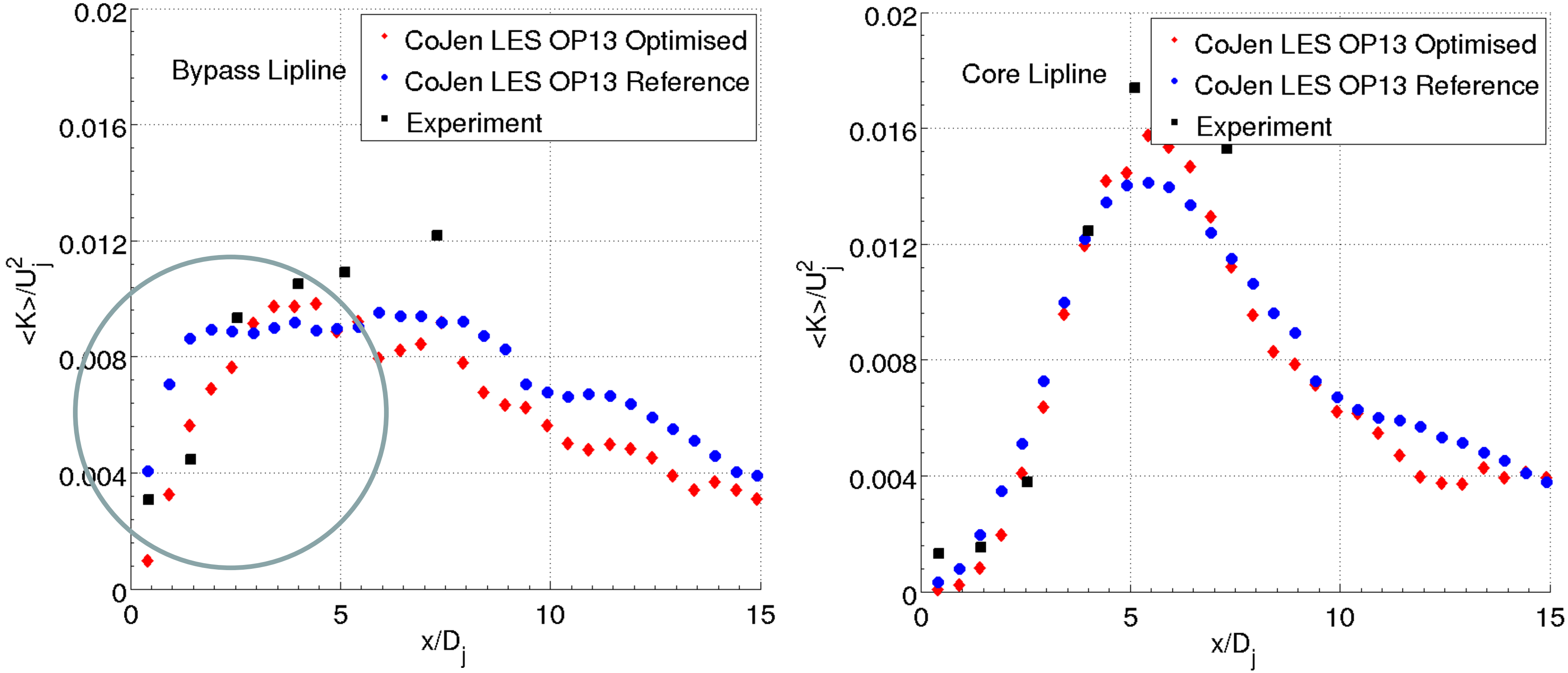


Results: Centreline Mean



The agreement with the experiment for x/D< 2.5 is improved

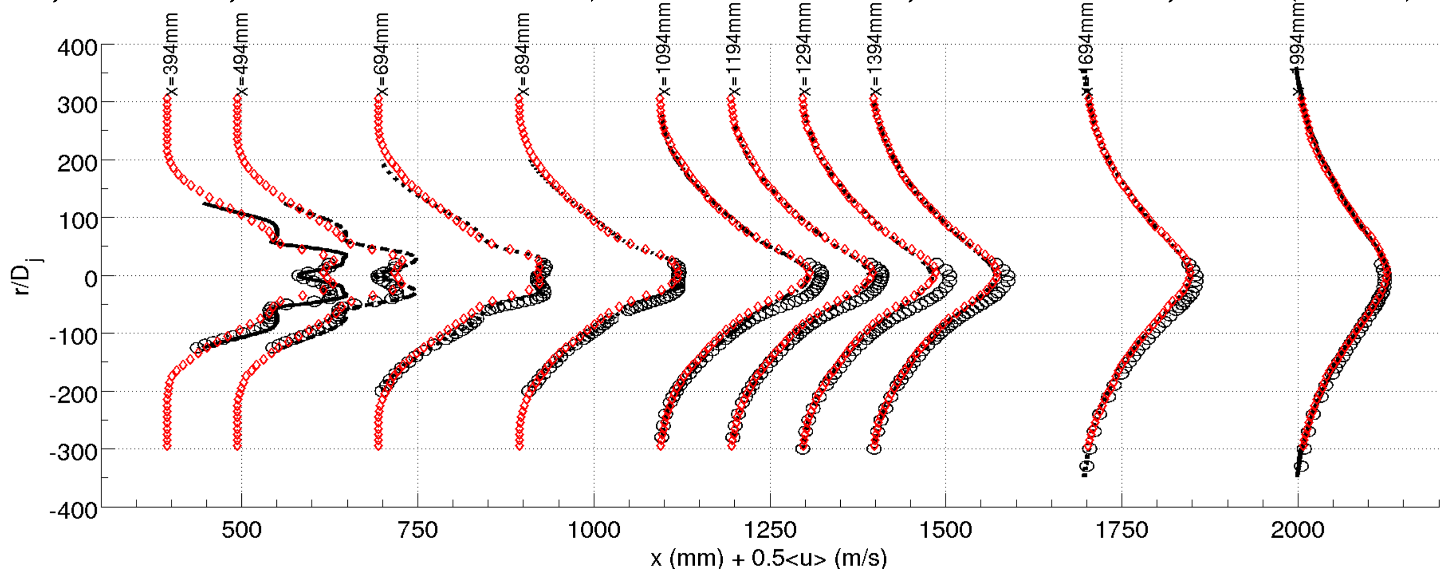
Results: Lipline Core and Bypass



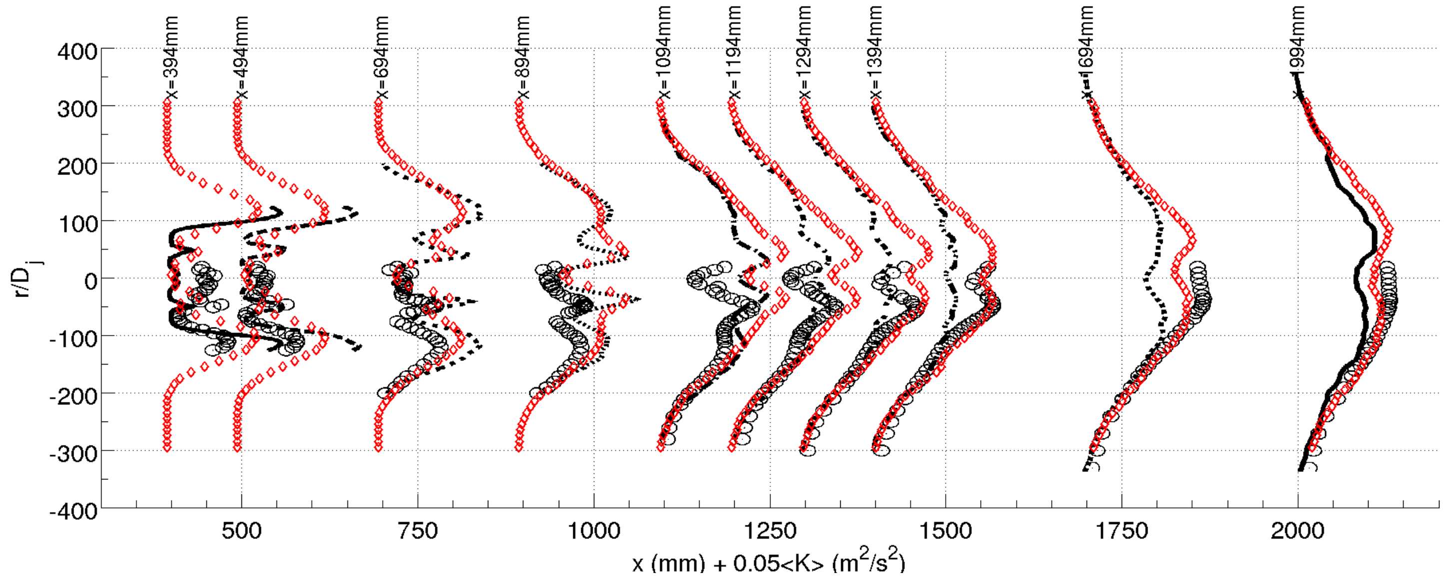
The agreement with the experiment for x/D< 5 is improved
But the flow solution > 2.5D is not affected much

Results: Several cross sections OP1.3

Our LES results (red diamonds) compared to experimental (circles) and numerical results (solid, dashed, and dotted lines) from Casalino, D. and Lele, S.K. (2014)



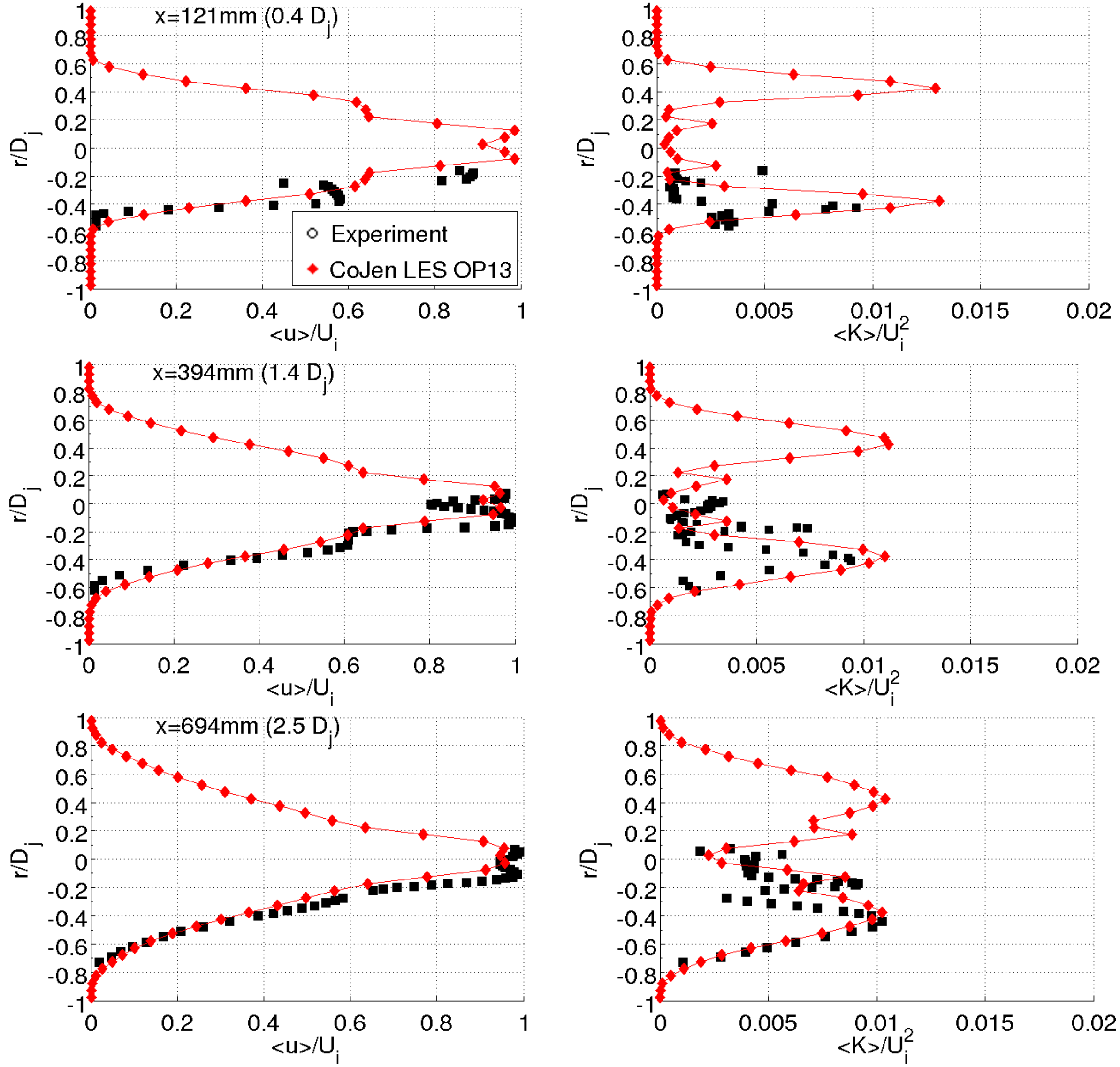
Mean axial velocity



Mean turbulent kinetic energy

Results: Several cross sections OP1.3

Our LES results (red diamonds) compared to Vuillot, F. et al, 46th AIAA Aerospace Sciences Meeting and Exhibit 7 - 10 January 2008, Reno, Nevada



Results: Several cross sections OP1.3

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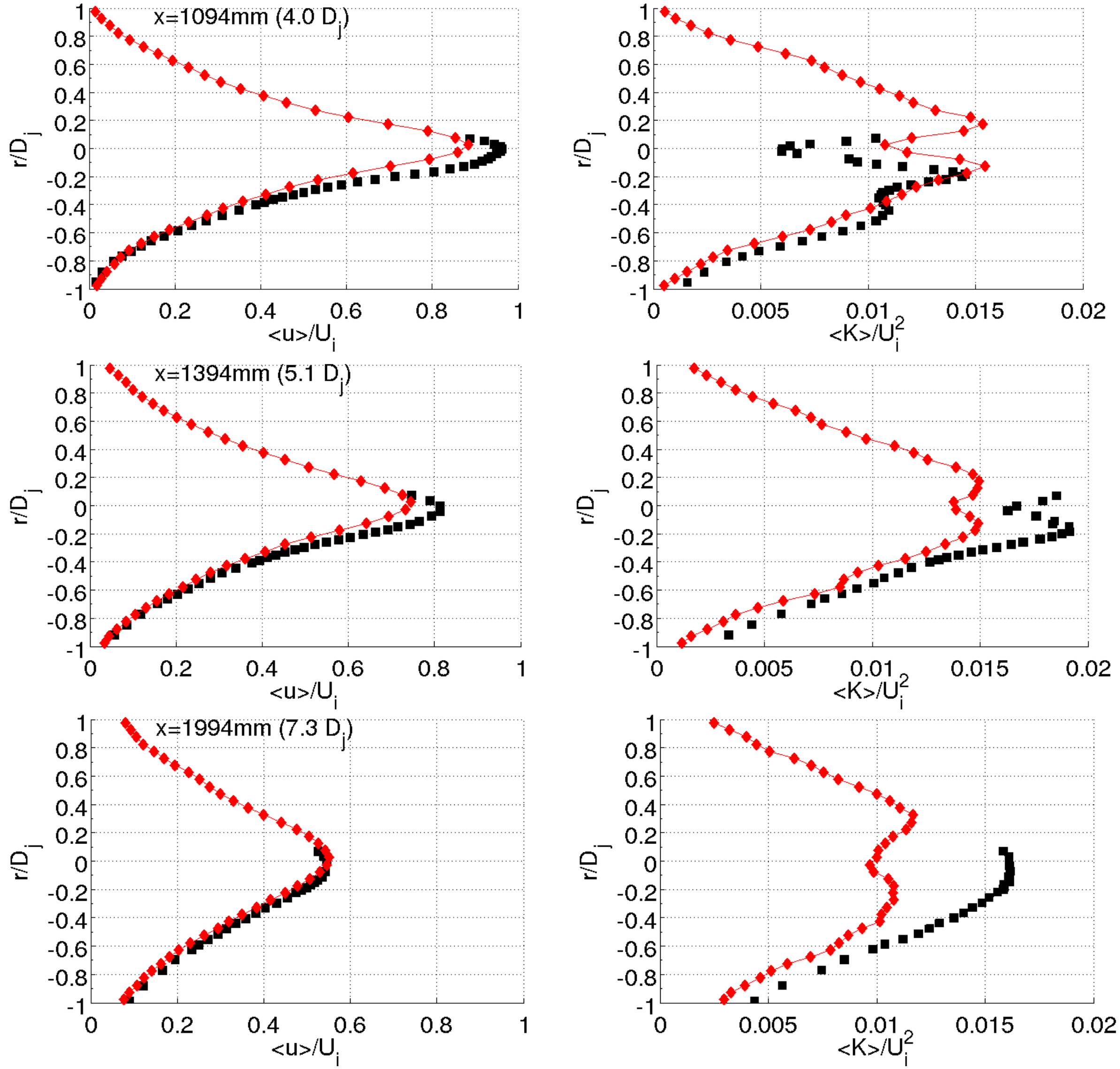
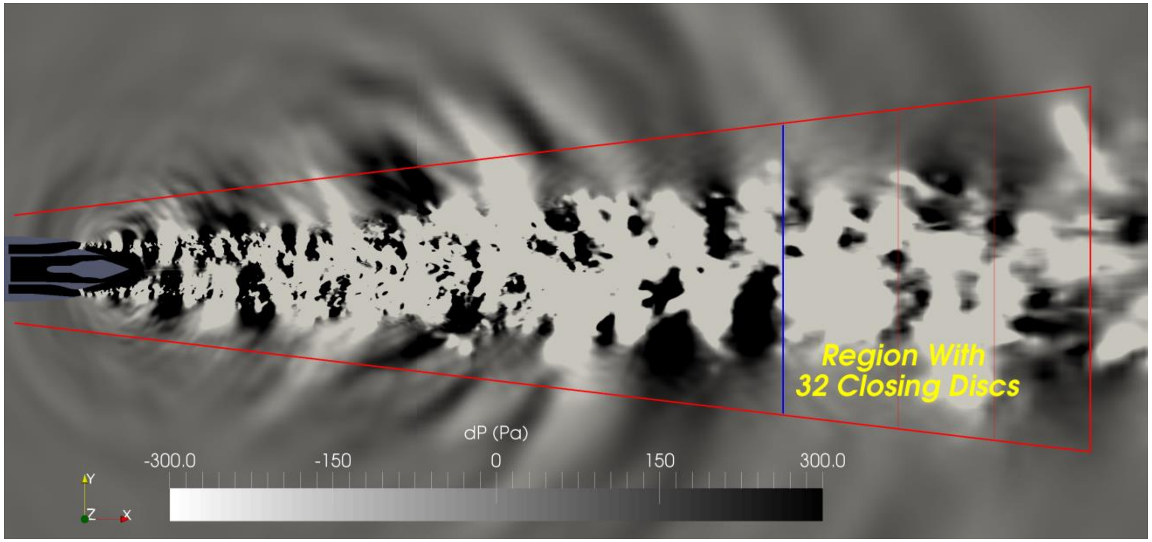


Losing the grid resolution for x/D>5

FW-H Acoustic Predictions

- GPU LES solver collects acoustics “on-the-fly”



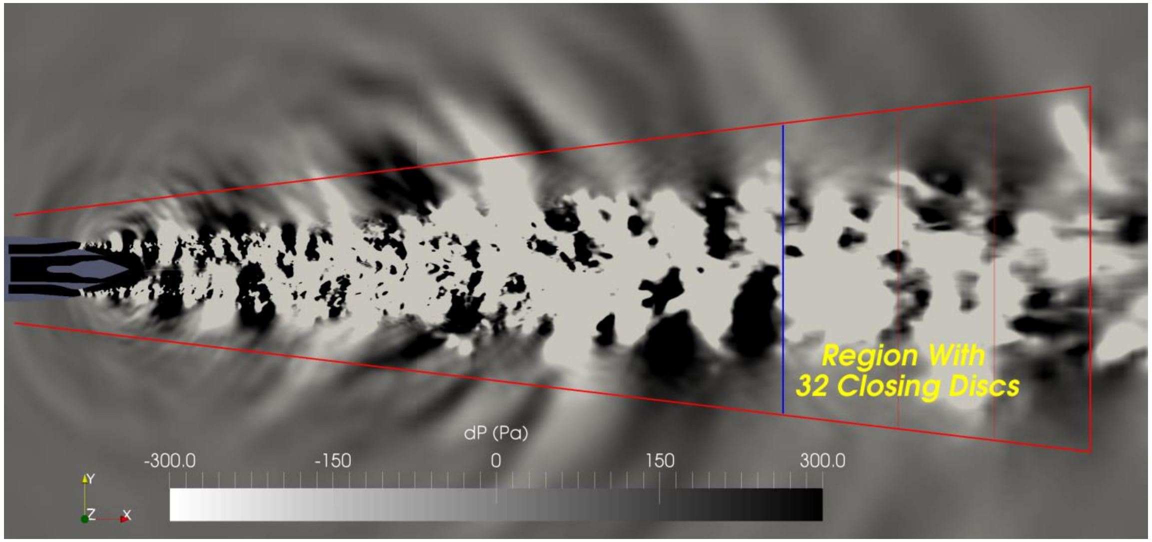
On-the-fly post-processing means many surface “sets” and several “closing discs” can be investigated
This case: 32 closing discs used

Off-line post-processing would have required TBs of data (although option remains in code to output this data of course)

FW-H signal sampled for 200 ms for all operation points (240,300, and 360 TUs)

FW-H Acoustic Predictions

- GPU LES solver collects acoustics "on-the-fly"

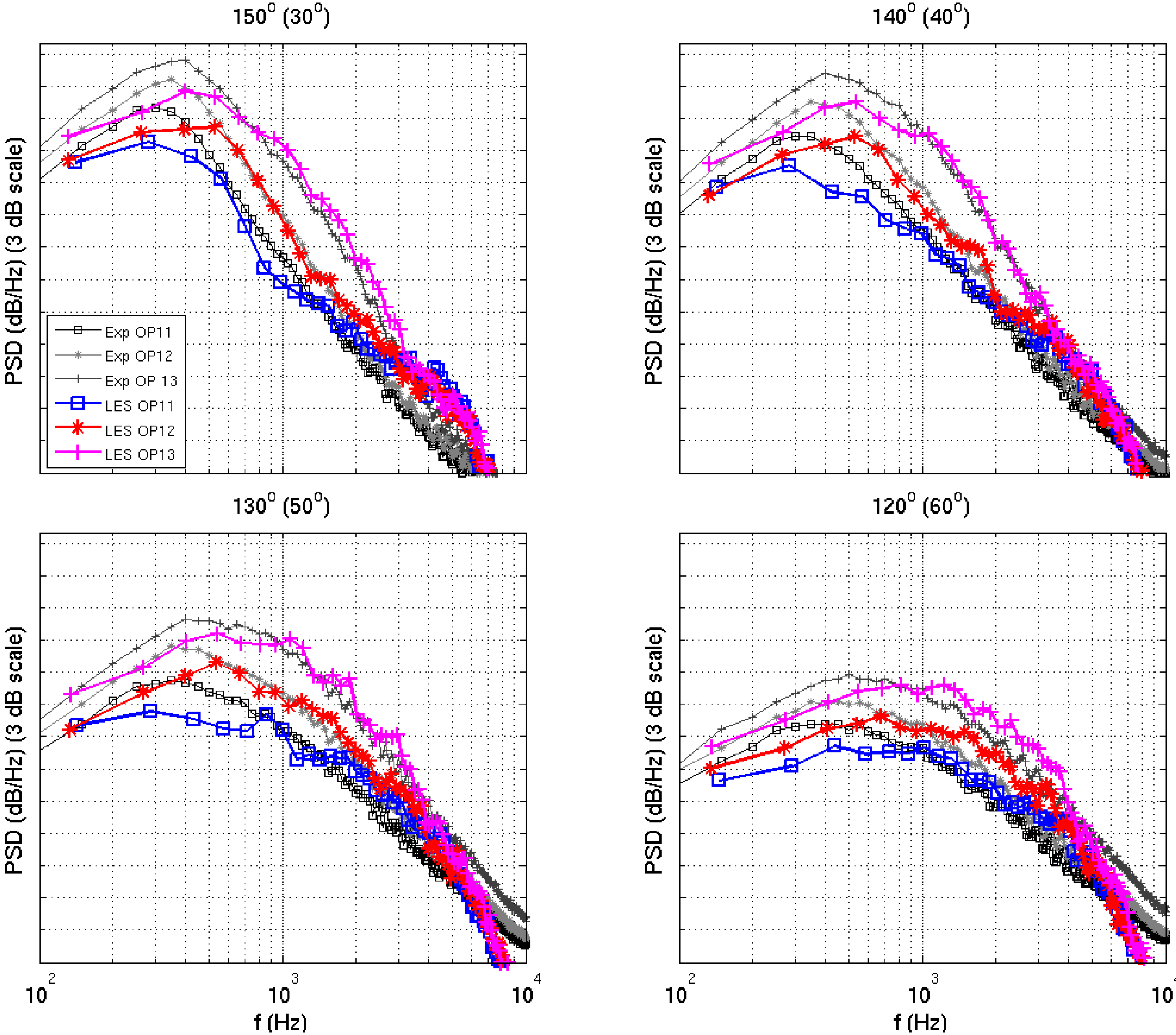


On-the-fly post-processing means many surface "sets" and several "closing discs" can be investigated
This case: 32 closing discs used

Every Operating Point LES (65 mln cells) computations took ~8 days (initialisation + noise predictions) using 3 GPUs

Reminder: No super-computer facilities were used, but just a high-end home PC with relatively cheap "gaming" GPUs
(NVidia GTX1070 (8GB) GPUs, costing roughly $450 each + electricity bills – compare with ~ $60k cost of running the same on a supercomputer)

FW-H Acoustic Predictions (PSD)



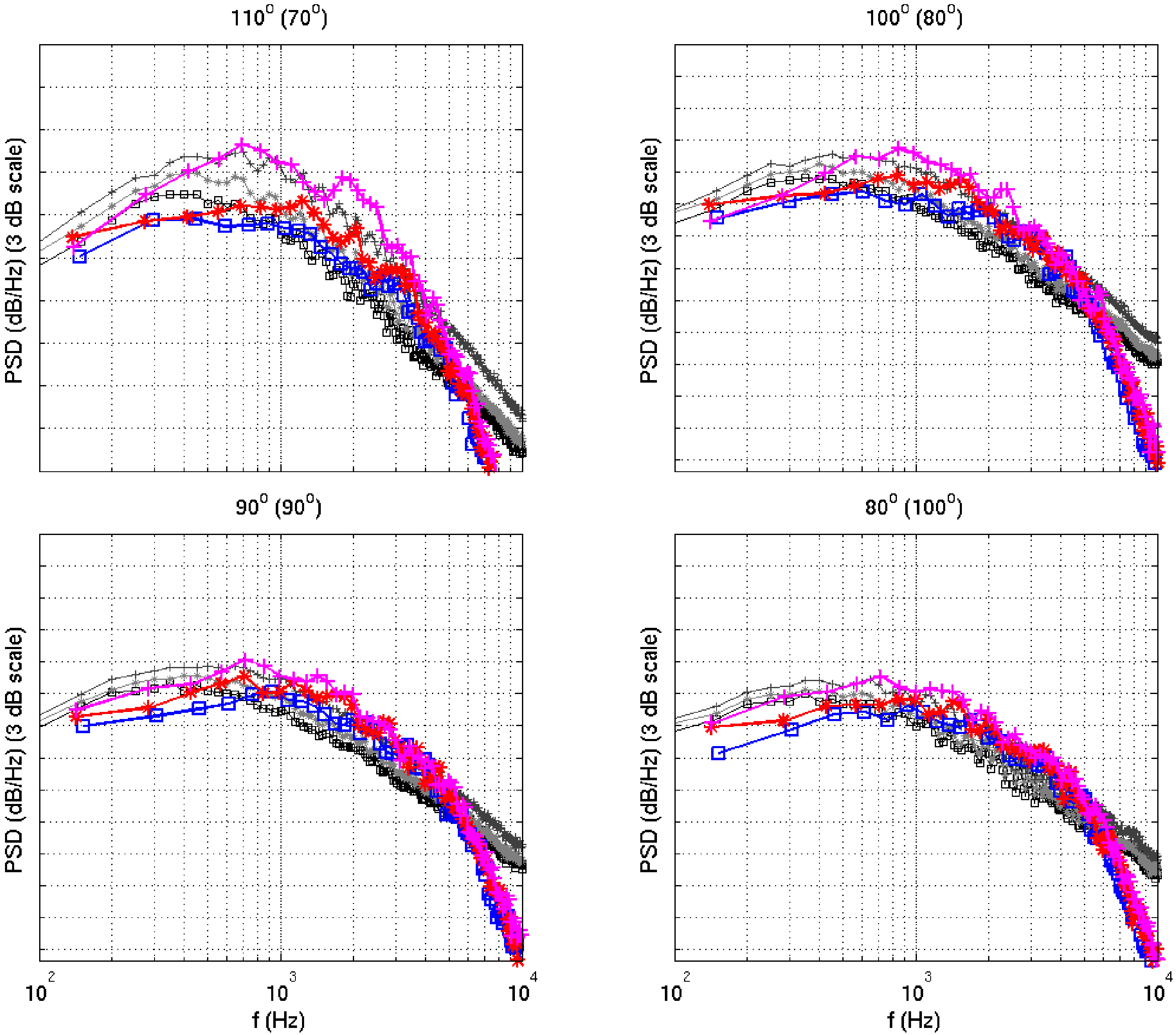
Axis show frequency

In terms of Strouhal number the pictures are from St =0.06-6

The sudden fall-off of SPL is at St~2.0 for OP1.3, while it is at St~2.5 and St~3.0, for OP1.1 and 1.2 respectively

Spectra predictions capture same trend as experiment: noise increases with increase of the core velocity of the jet

FW-H Acoustic Predictions (PSD)



Current spectra predictions are within 2-3dB from the experiment for most angles and frequencies.

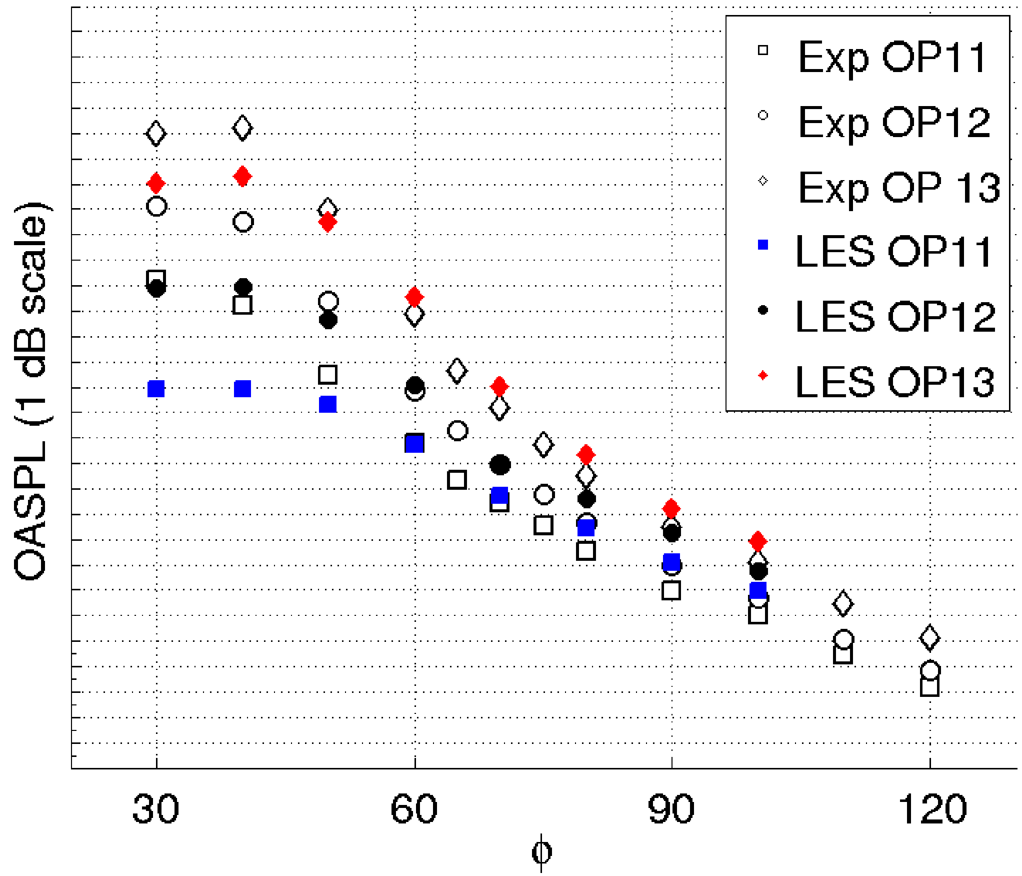
The under prediction at low frequencies likely to be associated with insufficient mesh resolution downstream from the nozzle exit

FW-H Acoustic Predictions (OASPL)

Band-Limited OASPL for the three cases (Strouhal number 0.1 to 3.0)

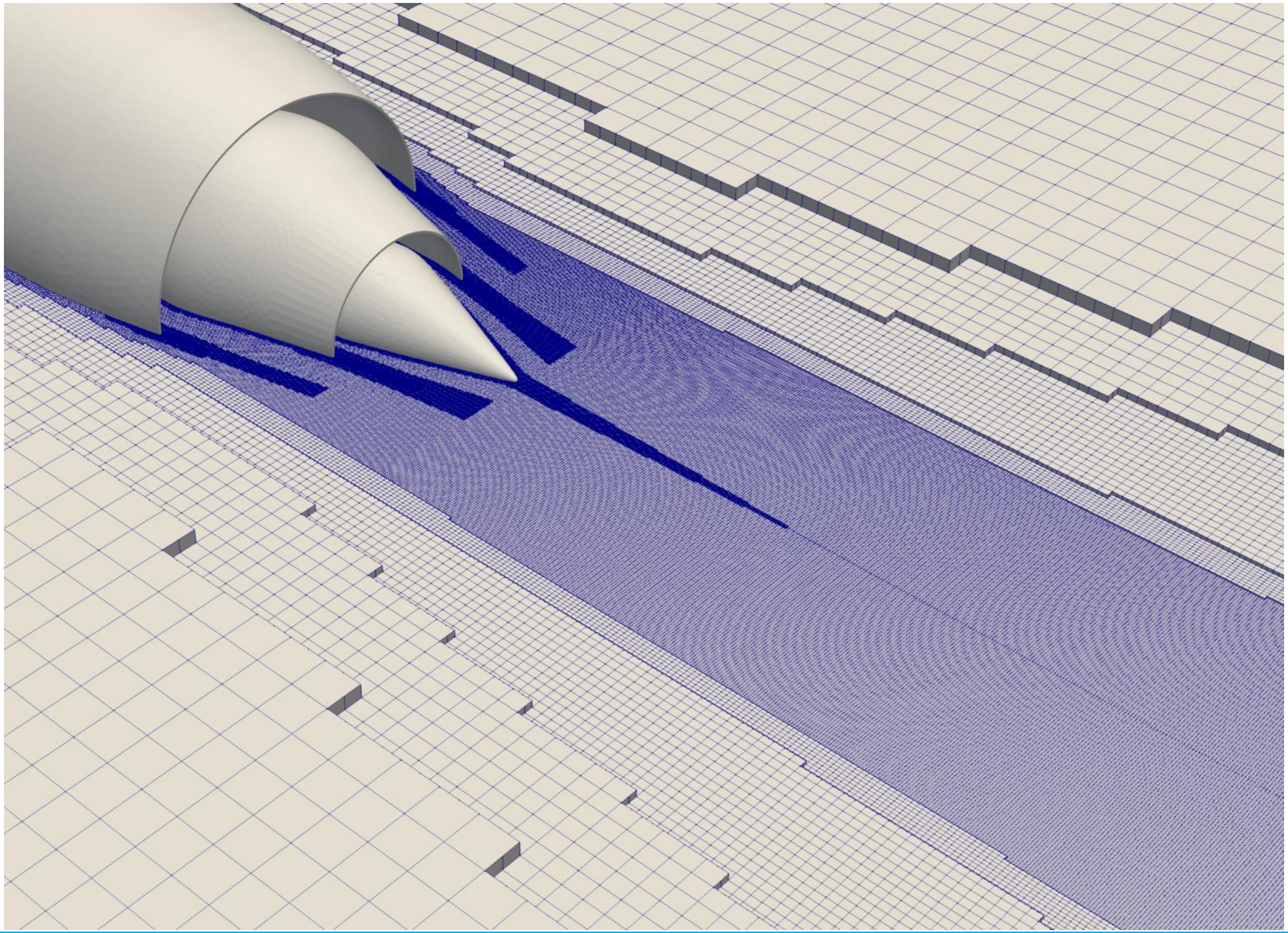
OP1.3: Current predictions are within **0.5-1dB** from the experiment for high polar angles and within **1-2dB** for 30º and 40º angles to the jet flow

OP1.2 and OP1.1: Agreement with the experiment for polar angles higher than 40º is also within 1dB The noise at peak noise angles, 30º and 40º is under resolved for these cases: by 2-3dB in the OP1.2 case and 3-4dB in the OP1.1 case



Current

- 80 mln refined mesh is generated, calculation on 4 GPUs, ~80 TUs per day (1 case per week)
- Initial flow and acoustic results look very encouraging



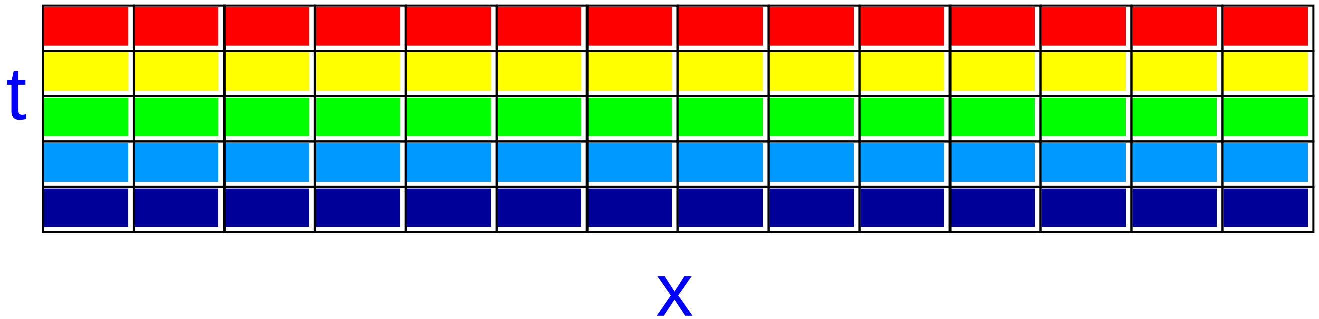
Conclusions

- Flow solutions obtained with GPU-CABARET are in encouraging agreement with the experiment and reference LES solutions
- Initial mesh refinement study shows reasonable improvement in results compared to experiment in the upstream part of the jet
- Noise spectra predictions capture the relative trend between the three operation conditions and are within **2-3dB** from the experiment for most angles and frequencies upto **St=2-3**.
- The peak noise for the operation condition corresponding to the fastest mixing, i.e. the jet with the biggest difference between the bypass and the core velocity, is captured within **2dB**
- For the two slower jets, the low-frequency noise at small angles is attenuated due to the decay of current LES grid resolution away from the jet

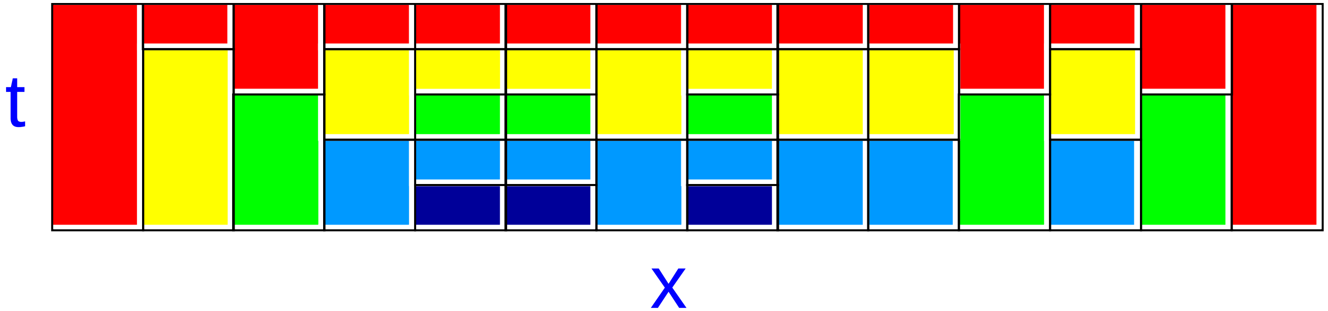
Conclusions

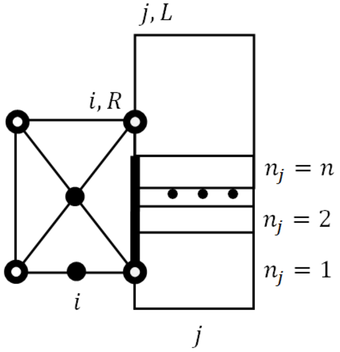
- Band-Limited Over All Sound Pressure Level (OASPL) predictions are obtained which are within **1dB** from the experiment for high polar angles
- For small polar angles, 30^o and 40^o polar angles to the jet flow, larger discrepancies with the experiment are observed depending on the jet case
- Overall, the best OASPL accuracy of the current calculations (OP1.3) corresponds to **1-2dB**
- Current work involves the grid refinement study to improve the LES grid resolution away from the nozzle exit to capture the low frequency noise in all cases

Homogeneous



Asynchronous time-stepping

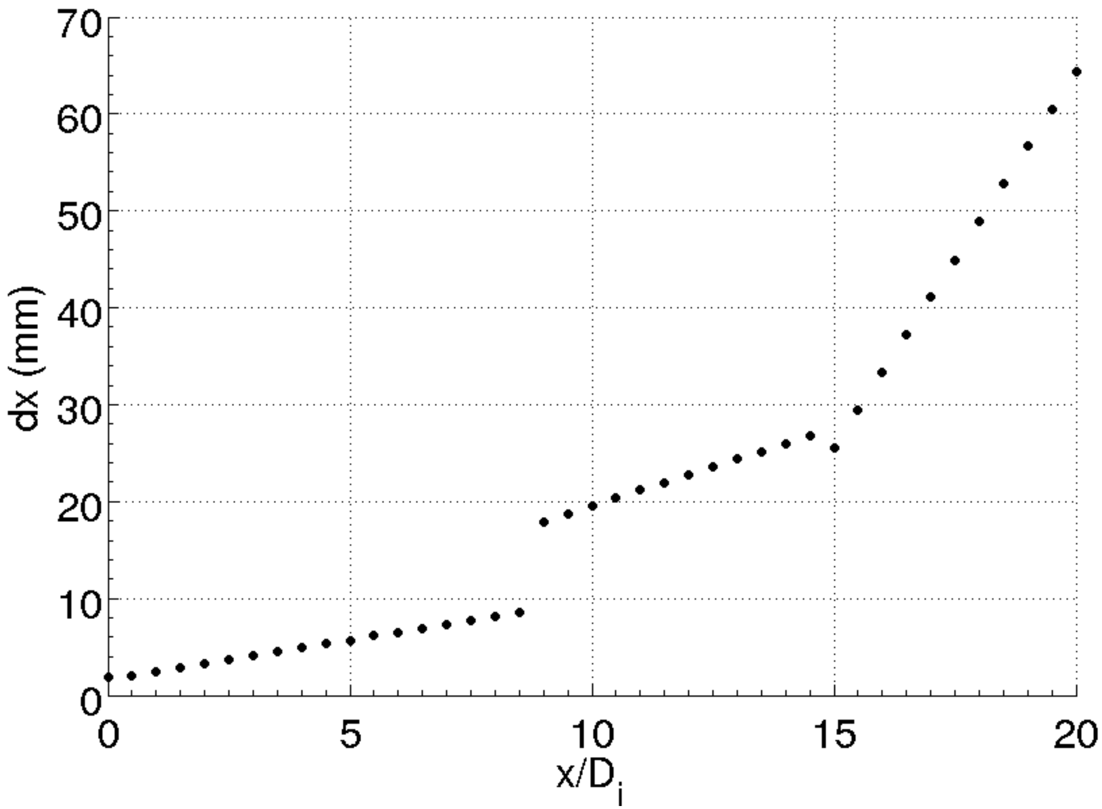




1st 2nd 3rd 4th step

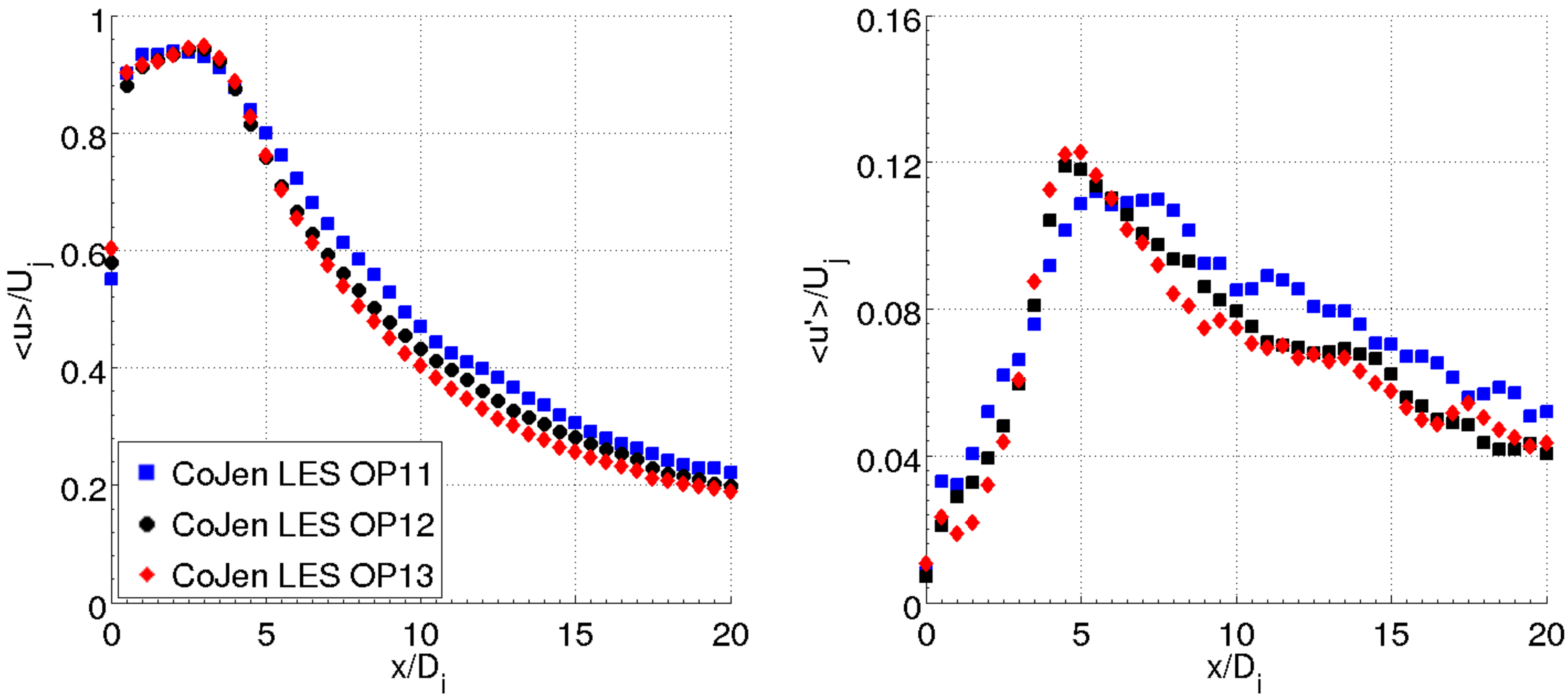
Mesh Details (65 mln)

- Non-optimised grid relatively coarse
- Resolution near boundary layer and initial shear layer: dx=1.8mm, dy=dz=1.4mm (nearly uniform grid cells with the size of **0.5%** of the bypass nozzle diameter)
- Mesh size (mm) in axial direction (jet axis)

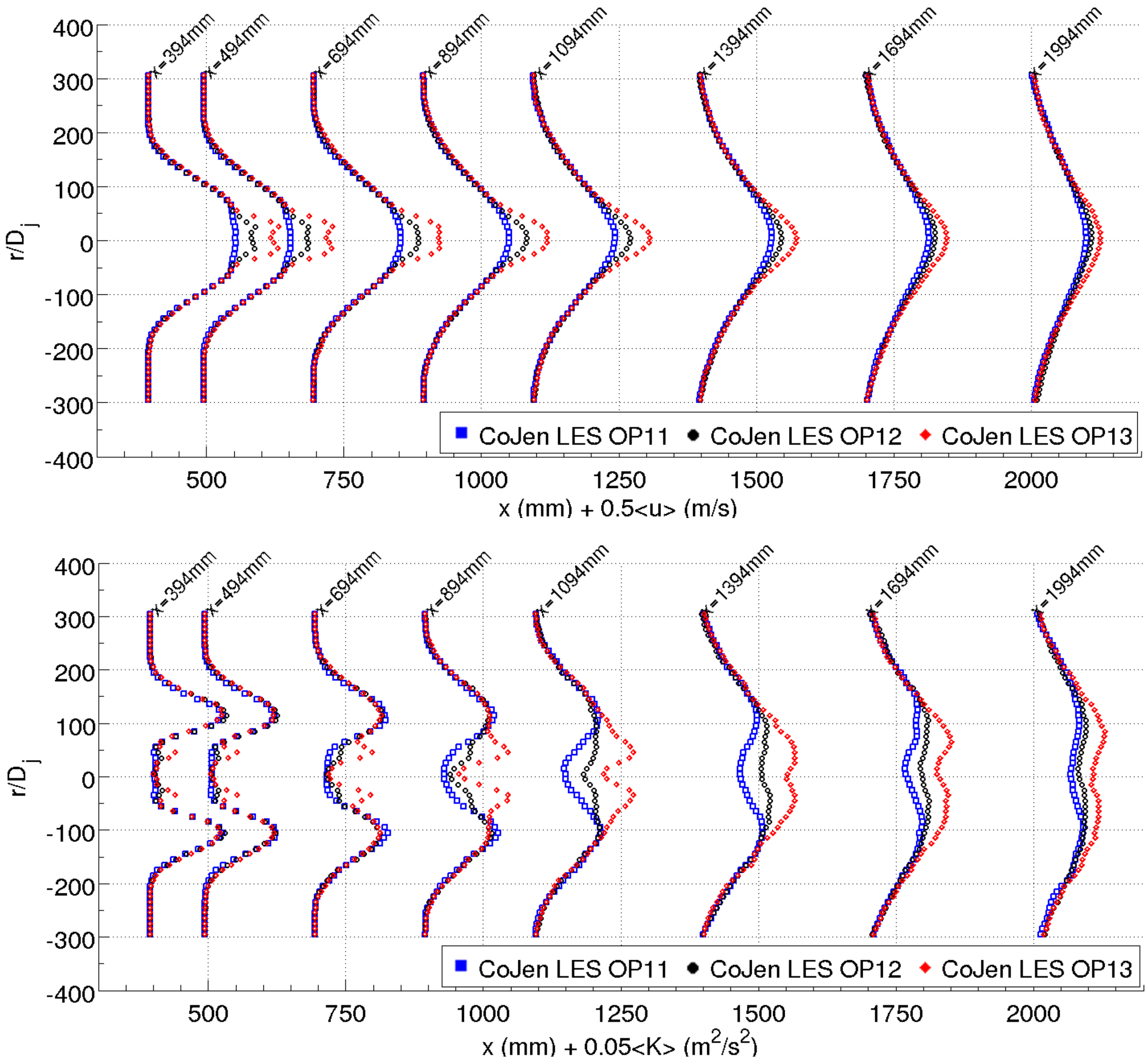


Results: Differences in Operating Points

- Increasing core velocity (340.3, 404.5, 480.7 m/s)
  - OP1.2 and 1.3 very similar, OP1.1 large difference behaviour of axial velocity fluctuations, predicting longer potential core
  - Probable reason: OP1.1 similar to a single stream jet (bypass velocity=306.8 m/s)



Results: Differences in Operating Points



Besides the fact the increased core velocity for OP1.1 to OP1.3 and the increased energy at the inner shear layer location is clearly visible, the curves are very similar