Performance Comparison of Finite-Volume and Spectral/*hp* Methods for LES of Representative Gas Turbine Combustor Aerodynamics

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TURBO CDT
EPSRC Engineering and Physical Sciences Research Council
Rolls-Royce

Background

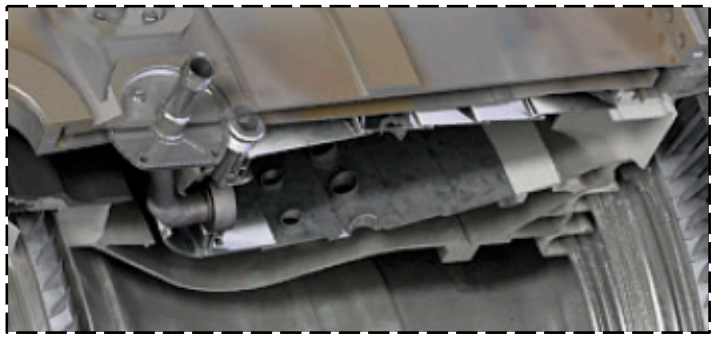
Loughborough University

National Centre for Combustion and Aerothermal Technology

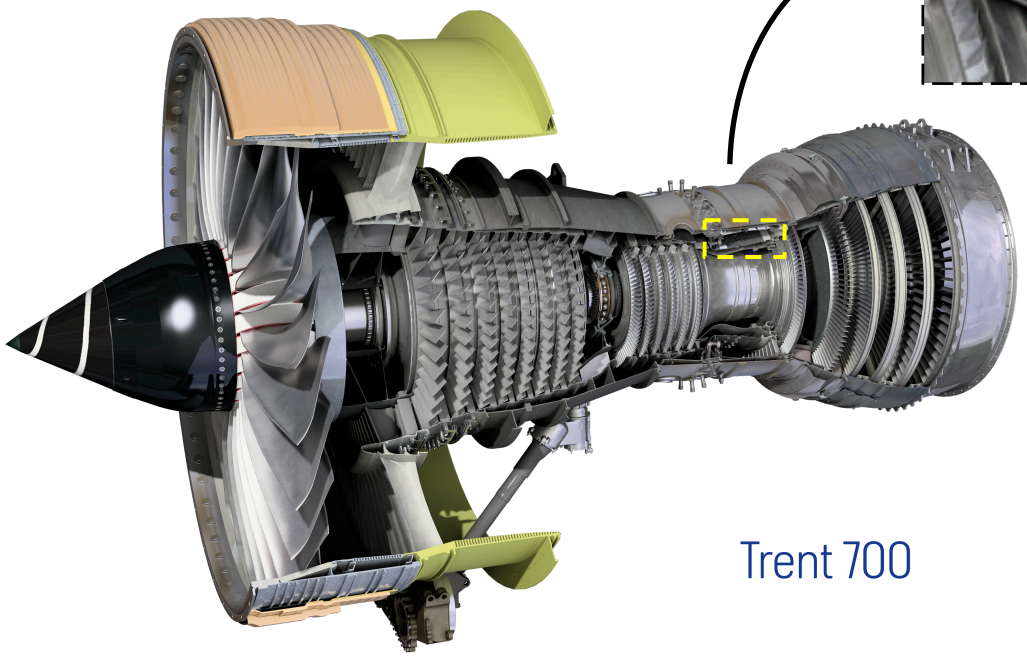
- Focus on low emission aircraft gas turbines
- Gas turbine combustion systems
- Aerodynamics underpin the combustion processes.

Introduction

~1% of engine-cost and weight



Combustor



https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-700.aspx

Introduction

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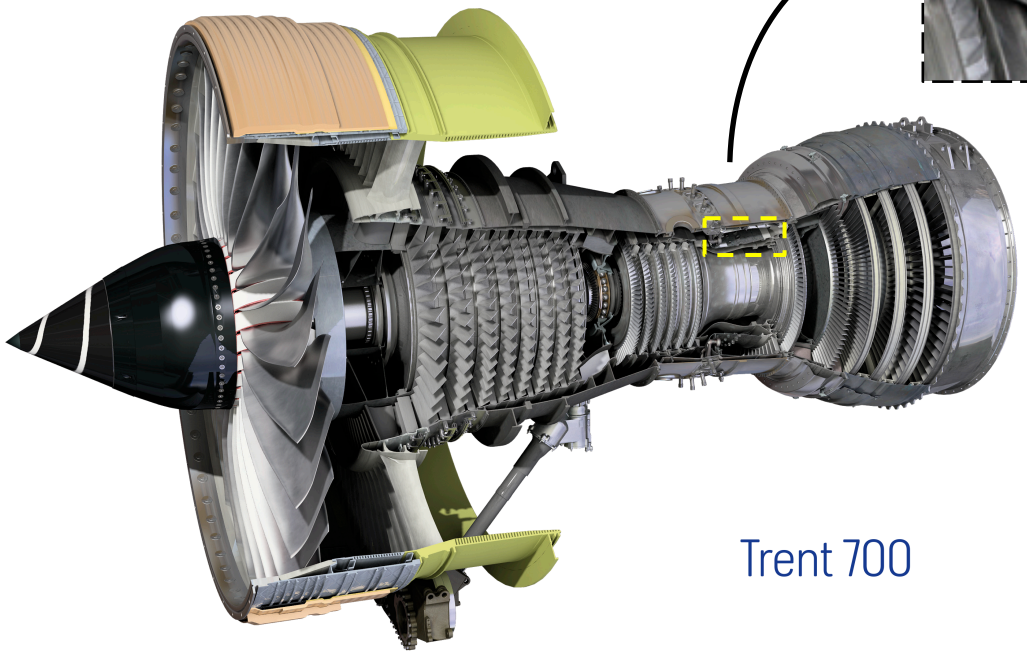

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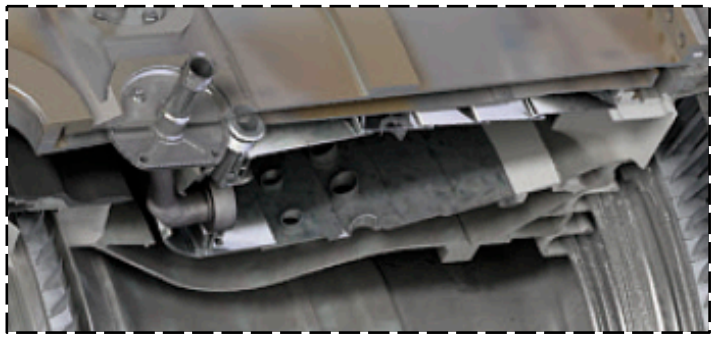

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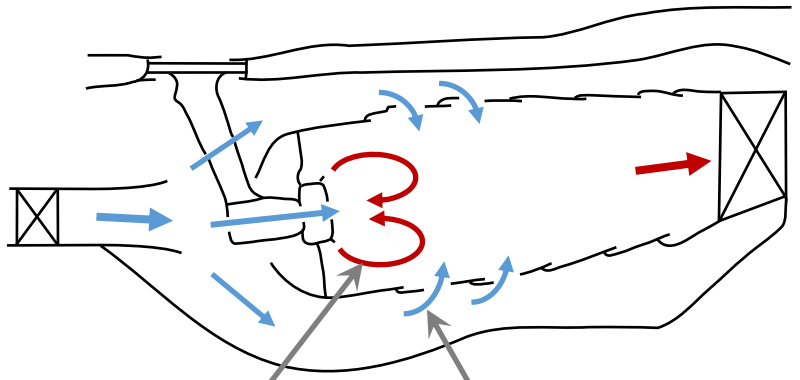


RCZ - swirling flow

Jets in cross-flow

$M < 0.3$

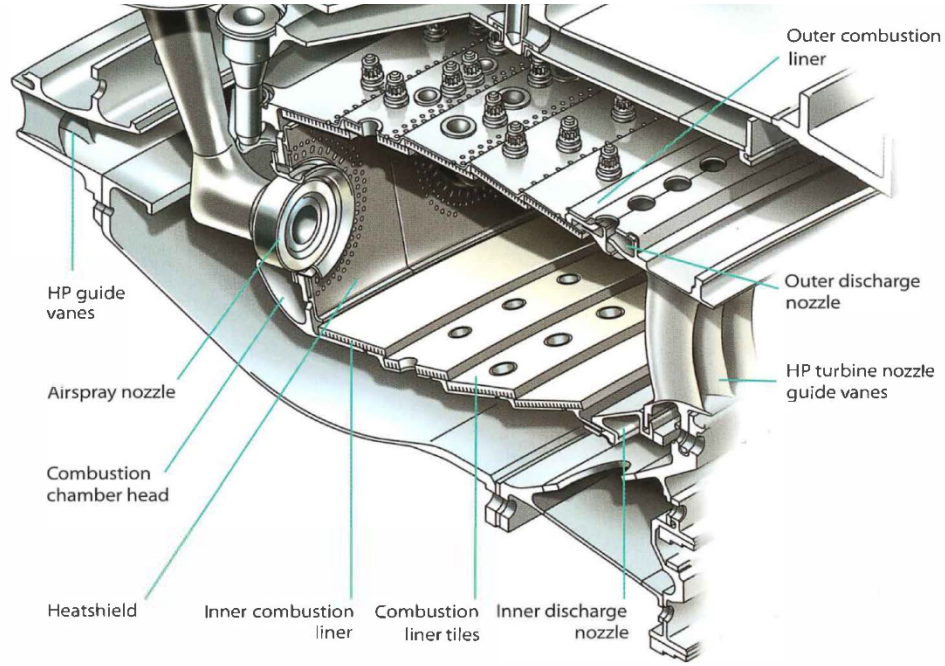
Combustor LES

Challenges:

- Complex geometry
  - Injector, Cooling holes
- Multi-physics

How is it done?

- RR's in-house code PRECISE (at most 2nd order accurate)
- Need to improve computational efficiency of the LES



Rolls-Royce. The Jet Engine.
Wiley 2015.

Present Project

Gap: Benefit of high-order schemes for LES on complex geometries.

Aim: **Objectively** evaluate the accuracy and cost of **high-order LES** on gas turbine combustor **relevant geometries.**

Challenges:

- "**Objectively**": evaluation of fair measures of cost and accuracy,
- "**high-order LES**": LES methodology for high-order methods,
- "**relevant geometries**": generating a high-order mesh.

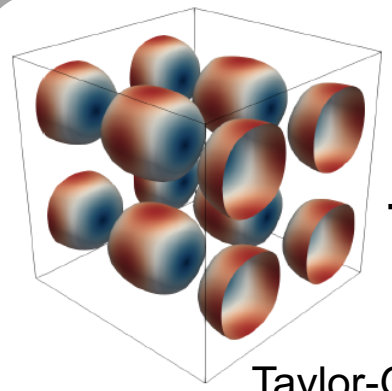
Method: Evaluate the accuracy benefit for given cost and cost benefit for given accuracy using available packages.

Research Path

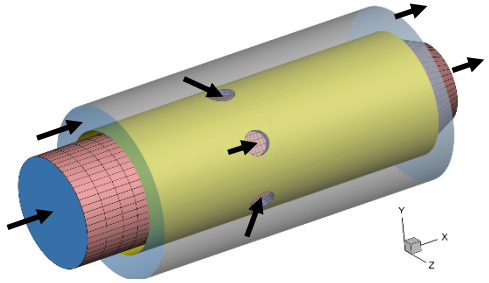
Literature Review

Canonical case

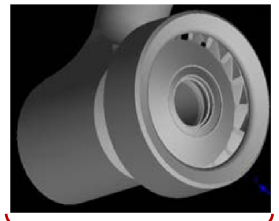
Advanced cases



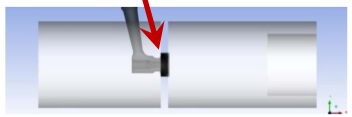
Taylor-Green Vortex



Radial Jets in Cross Flows



M. Dianat et al. (ERCOFTAC 2014)



Injector Swirling Flow

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Taylor-Green Vortex (TGV)

- Standard test case for evaluating numerical schemes for DNS/LES
- Complex 3D transient flow in a periodic box
- *Re*=1600, *M*=0.1

Solvers:

- PimpleFoam, OpenFoam - Central 2nd order
- IncNSSolver, Nektar++ - P4

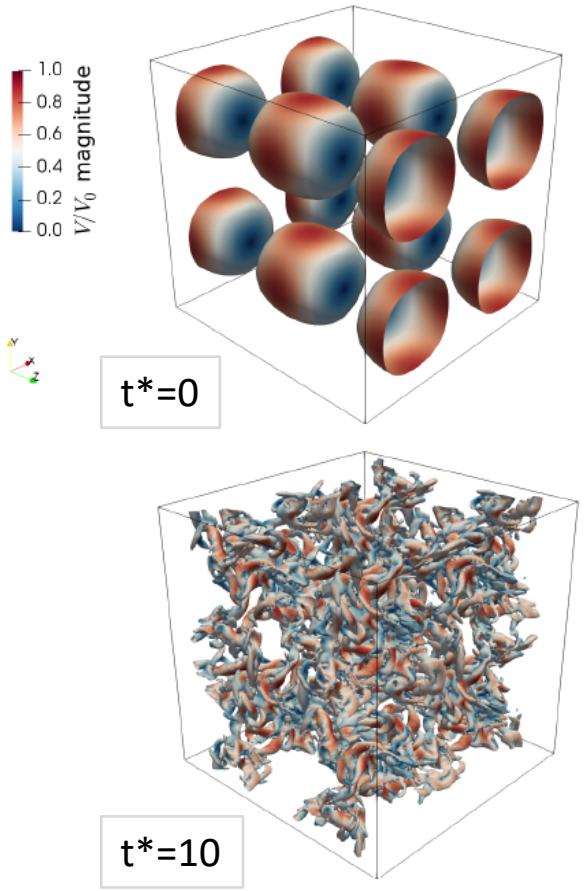


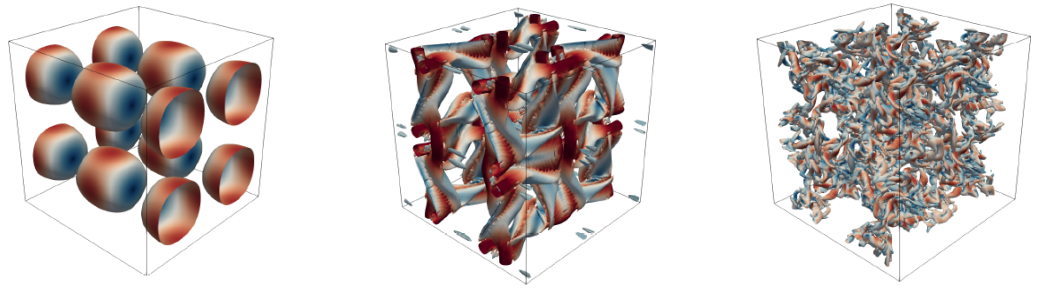
Fig: Iso-surfaces of vorticity magnitude coloured by velocity magnitude.

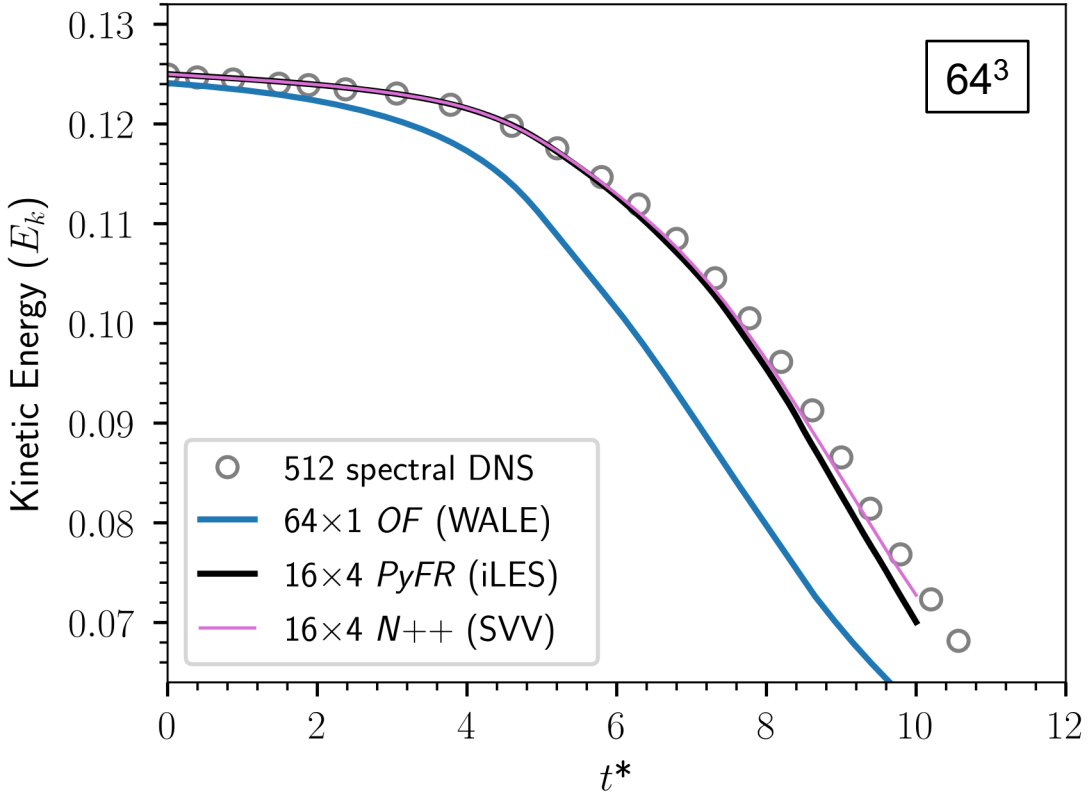
TGV

- HO LES: iLES, SVV.
- Hexahedral mesh:
  - 64^3 - “low” resolution
  - 32^3 - “very-low” resolution

A general point: Use the right preconditioners.

Observed **2-5x** speed-up by replacing “Diagonal” with “LowEnergyBlock”.





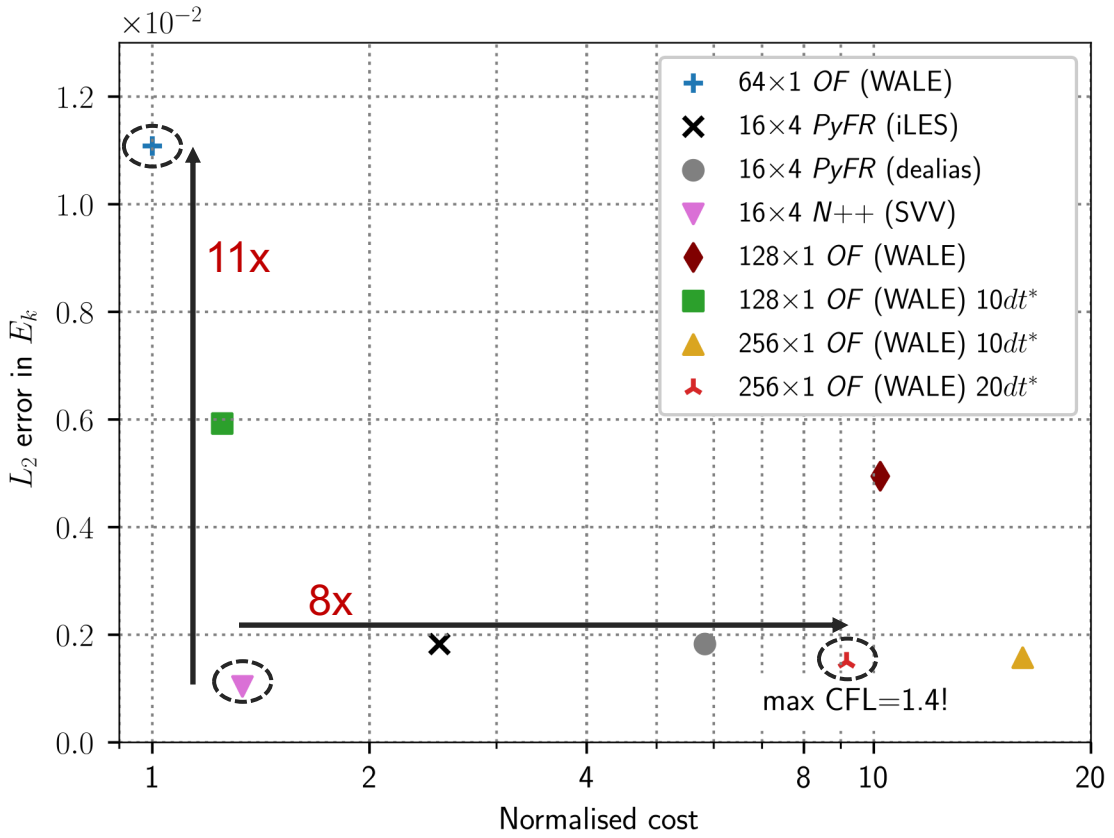
TGV: Cost vs. Error

64^3 High-order vs. varying 2nd order

- Similar accuracy achieved by 4x coarser mesh using P4
- For similar accuracy, *N*++ ~8-9x faster
- For given cost, *N*++ ~11x low in error

32^3 High-order vs. varying 2nd order

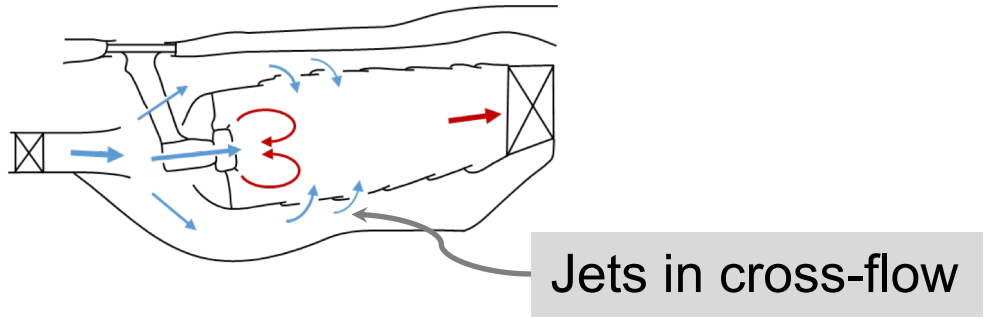
- For similar accuracy, *N*++ ~8-9x faster
- For given cost, *N*++ ~2.5x low in error



Radial Jets in Cross Flow (R-JICF)

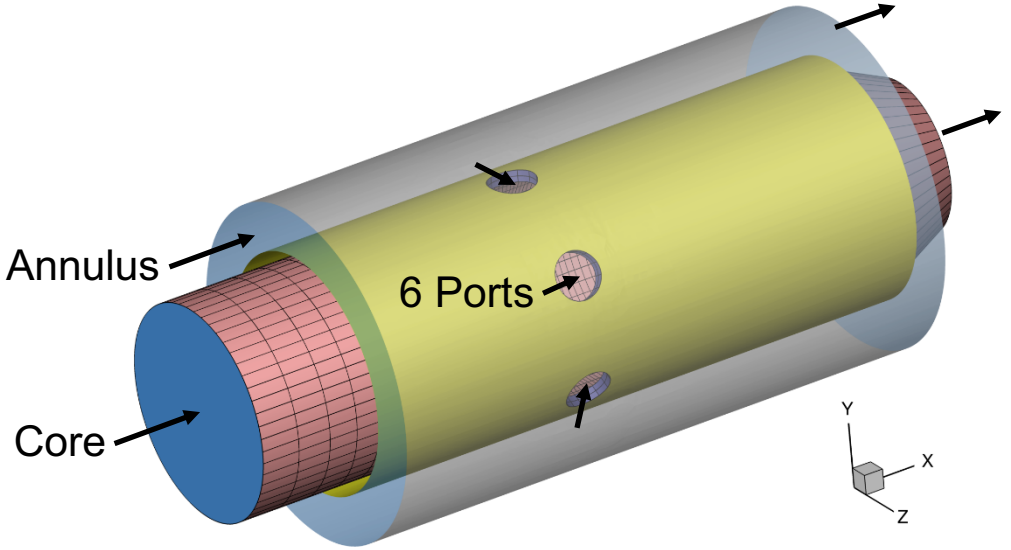
TGV caveats:

- Simple Geometry
- Lacks turbulence equilibrium



R-JICF:

- More realistic/relevant flow features
  - boundary layers, jet shear layers,
  - vortex shedding, high levels of mixing.
- Studied by A. Spencer (LDA) and D. Hollis (PIV) at L'boro on a water-based rig.



R-JICF

Simulation parameters:

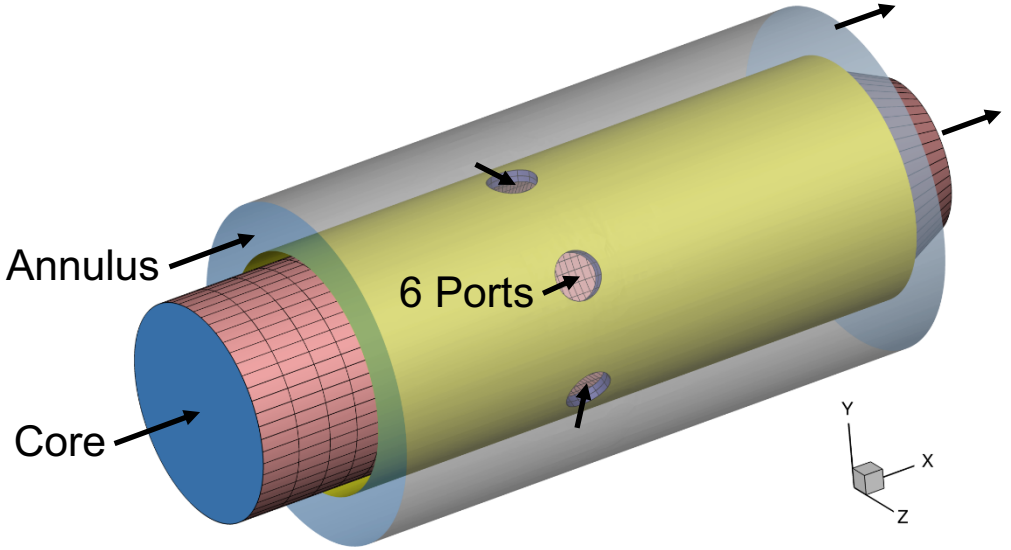
- Velocity Ratio, V_p / V_c = 5,
- Bleed Ratio, $\dot{m}_p$ / $\dot{m}_a$ = 0.5,
- Jet *Re*, Re_p ~ 2.2×10^4

Solvers:

- PimpleFoam - Blended 2nd upwind & 2nd central (40:60), WALE
- Nektar++ (IncNSSolver) - P4, SVV (Power Kernel)

Other:

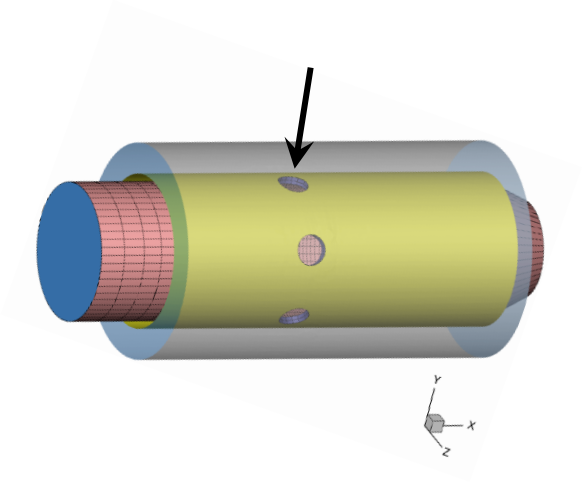
Time step 5e-6s, Linear solver tolerances 1e-7 for u, 1e-6 for p.

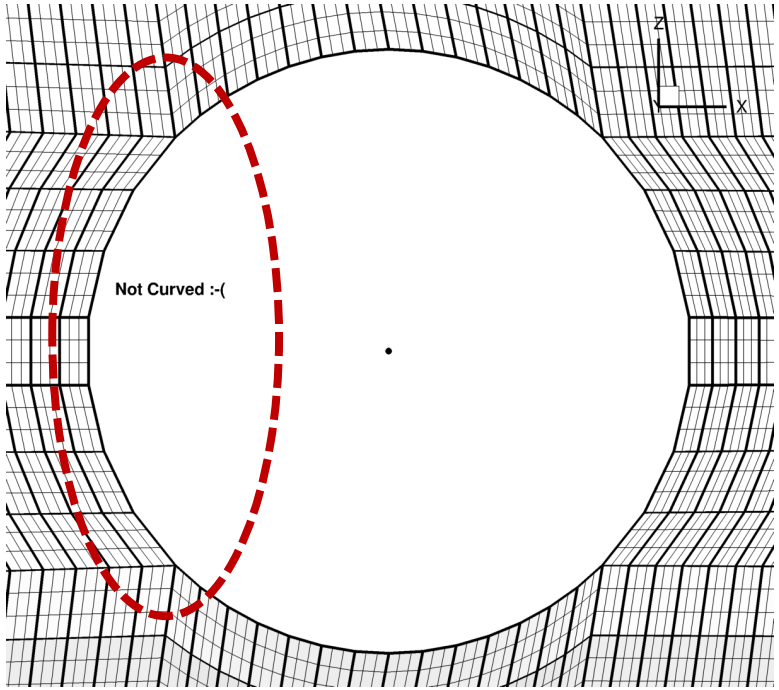


R-JICF meshing

High-order mesh:

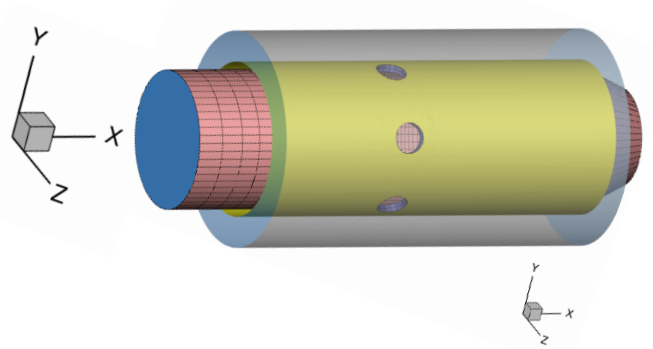
- Prepared the coarse mesh
  - Pointwise
- Elevate the information to high-order
  - Spherigons in NekMesh

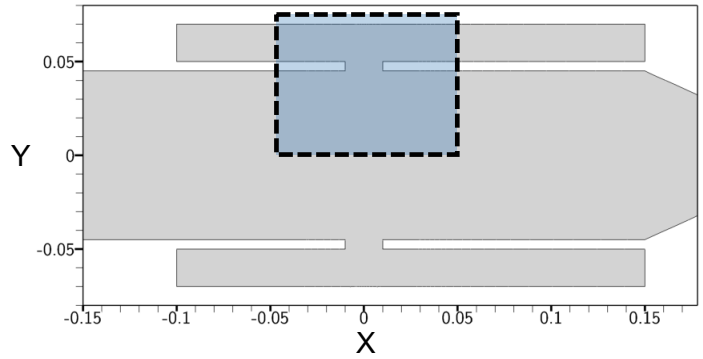


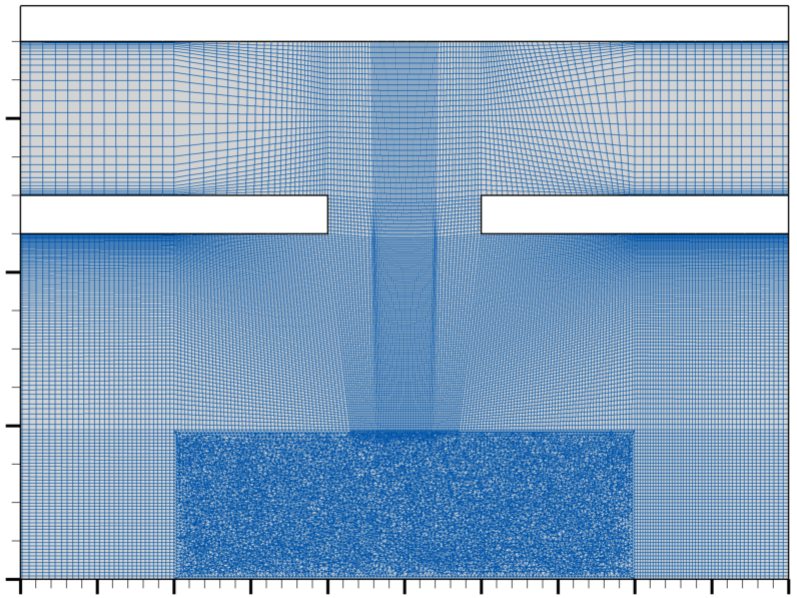


R-JICF mesh

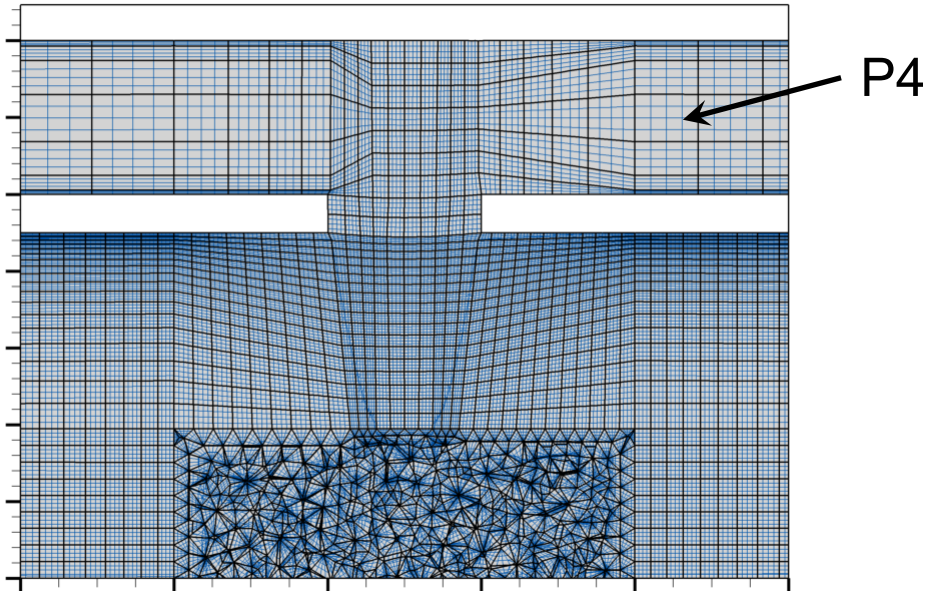
- Similar simulation cost
- Similar distribution
- Mixed: Hexs, Tets, Pyramids







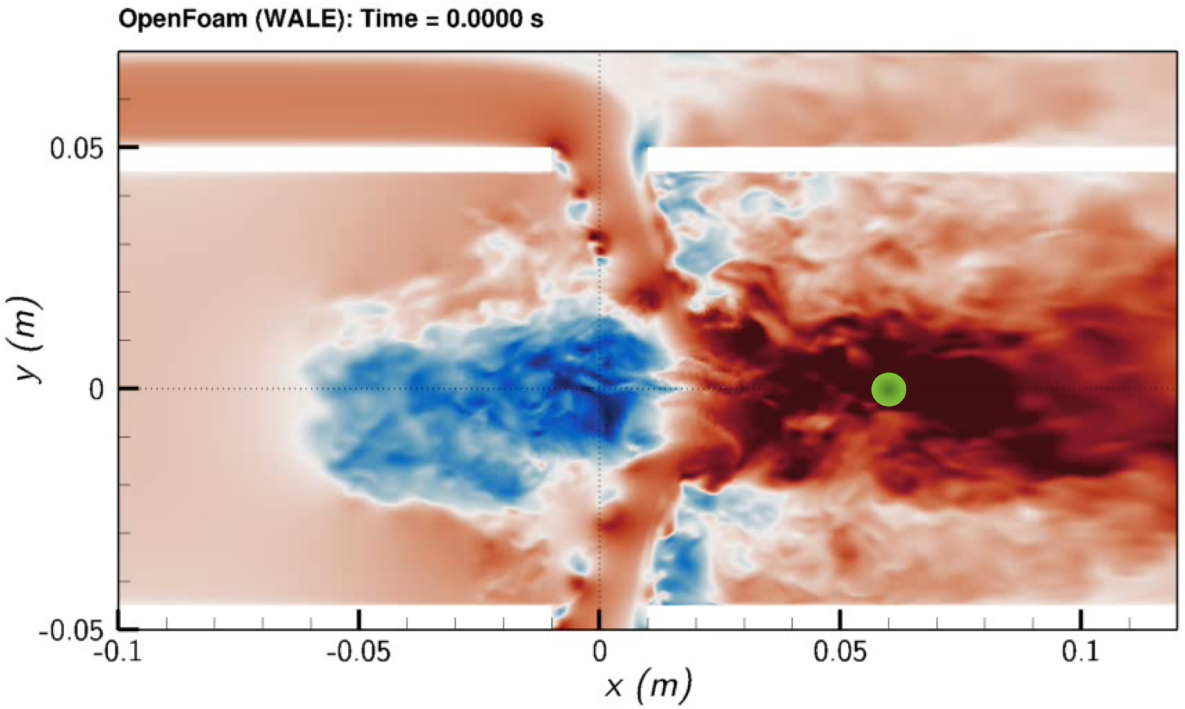
OF: 16M cells

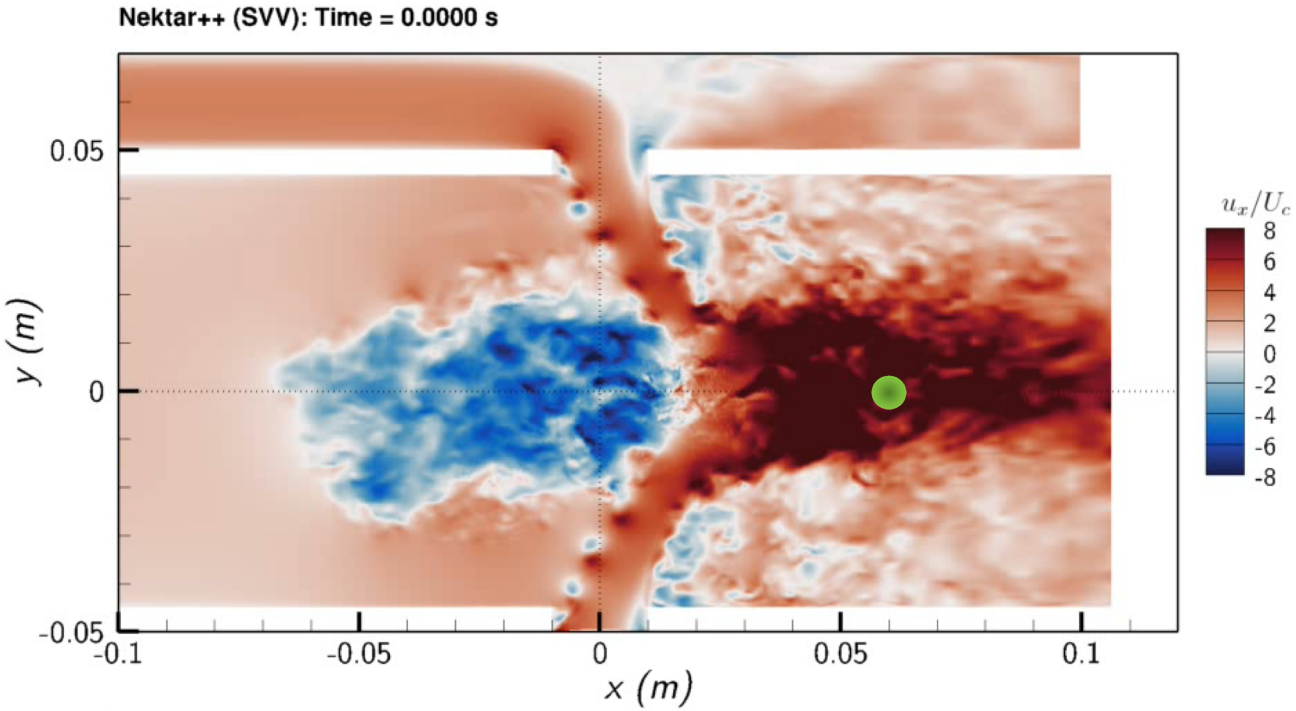


N++: 130k Ele. (~8.5M sol. points)

R-JICF instantaneous

Animations





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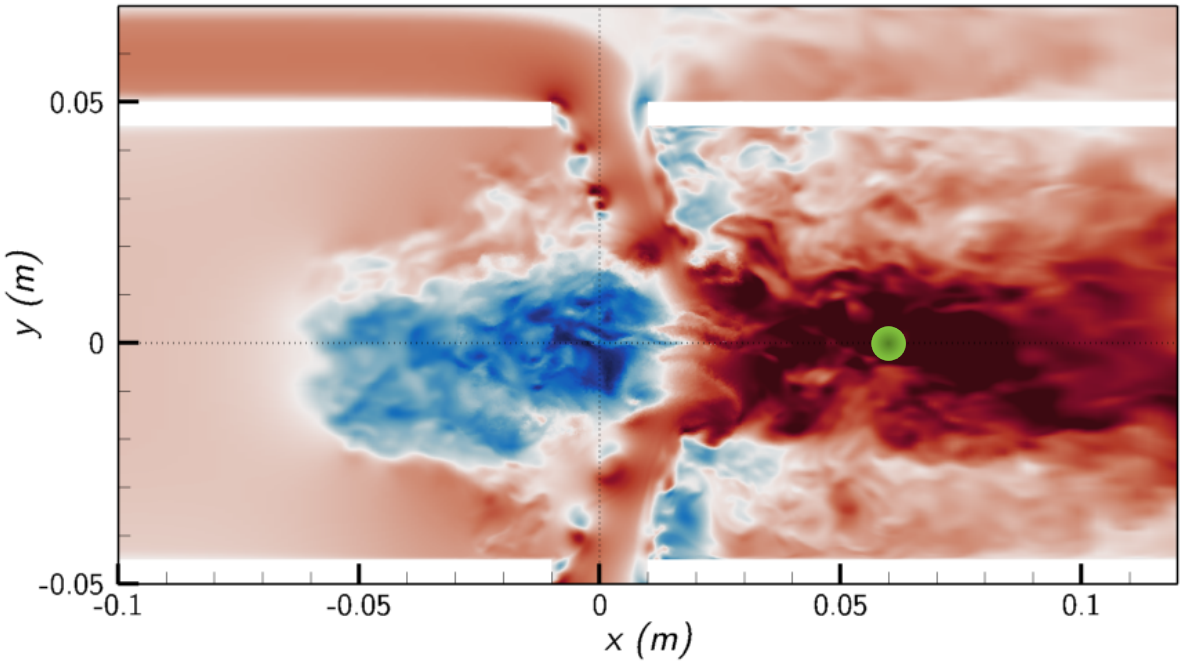
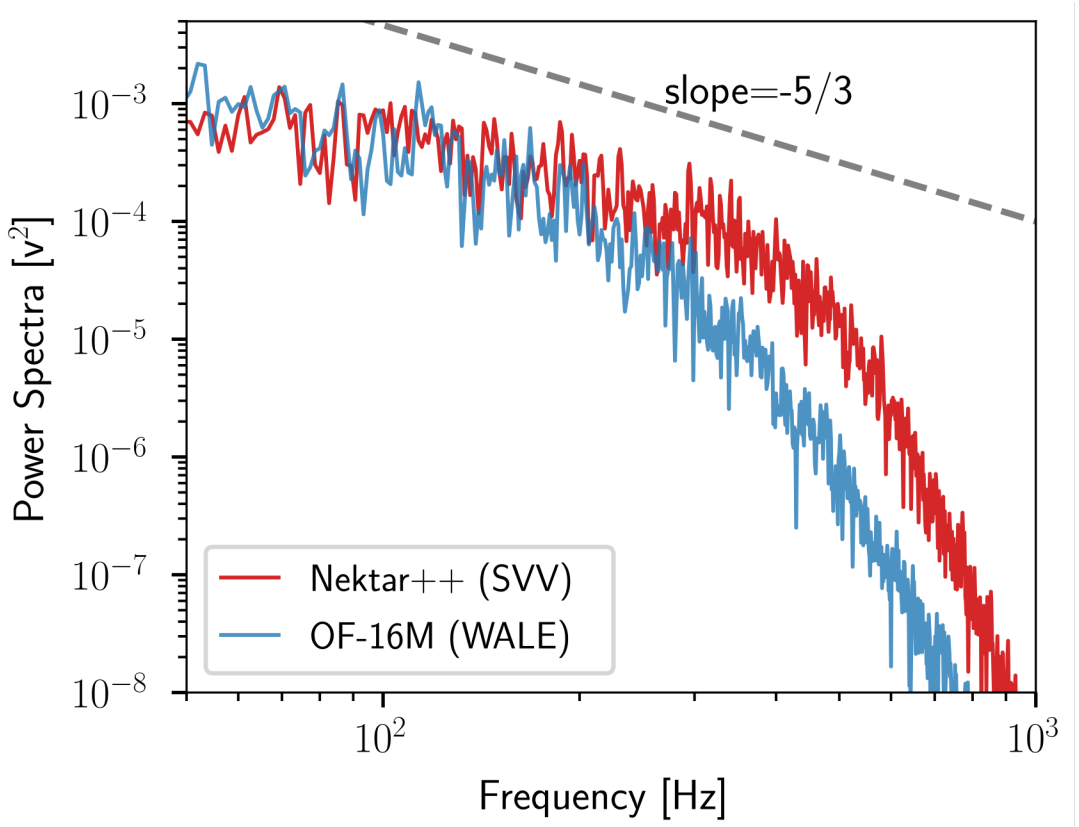
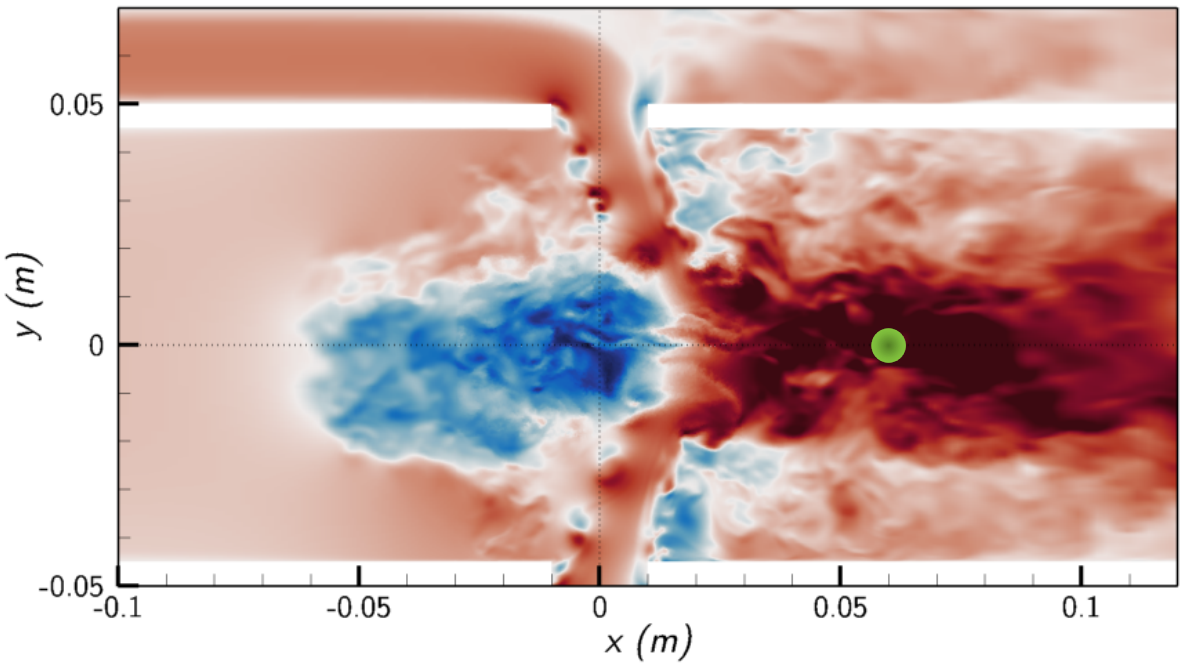
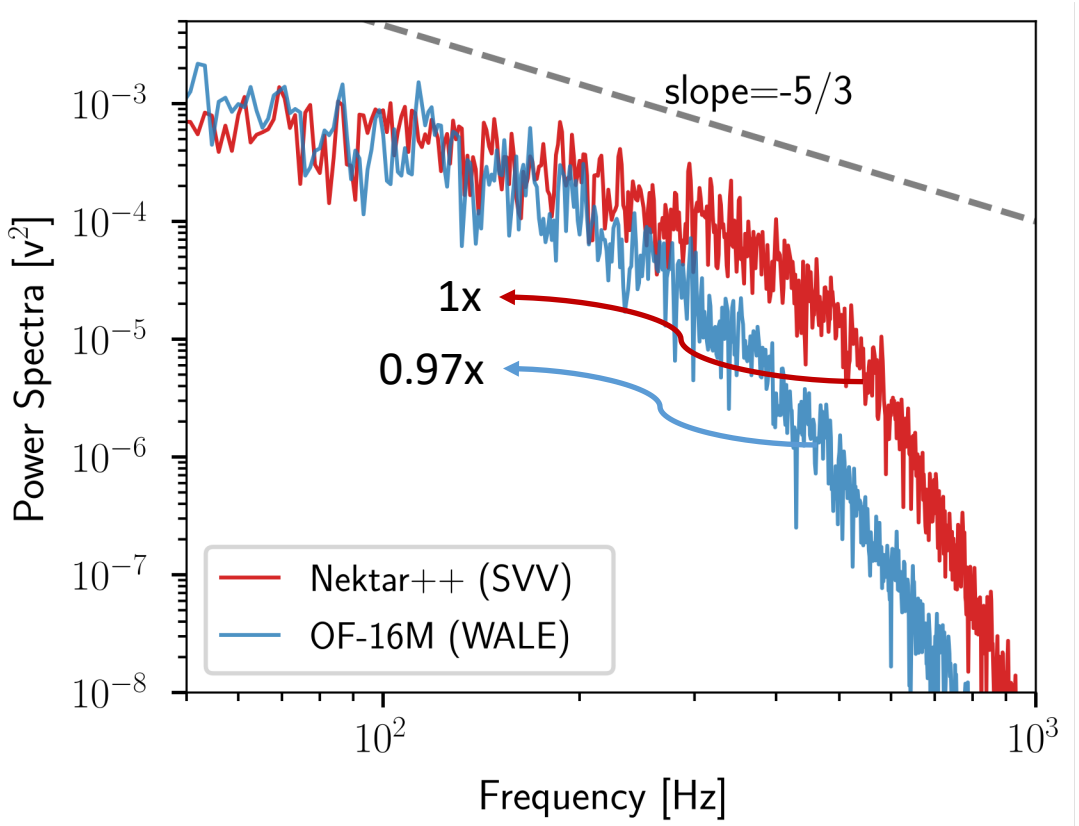
R-JICF spectra





R-JICF spectra





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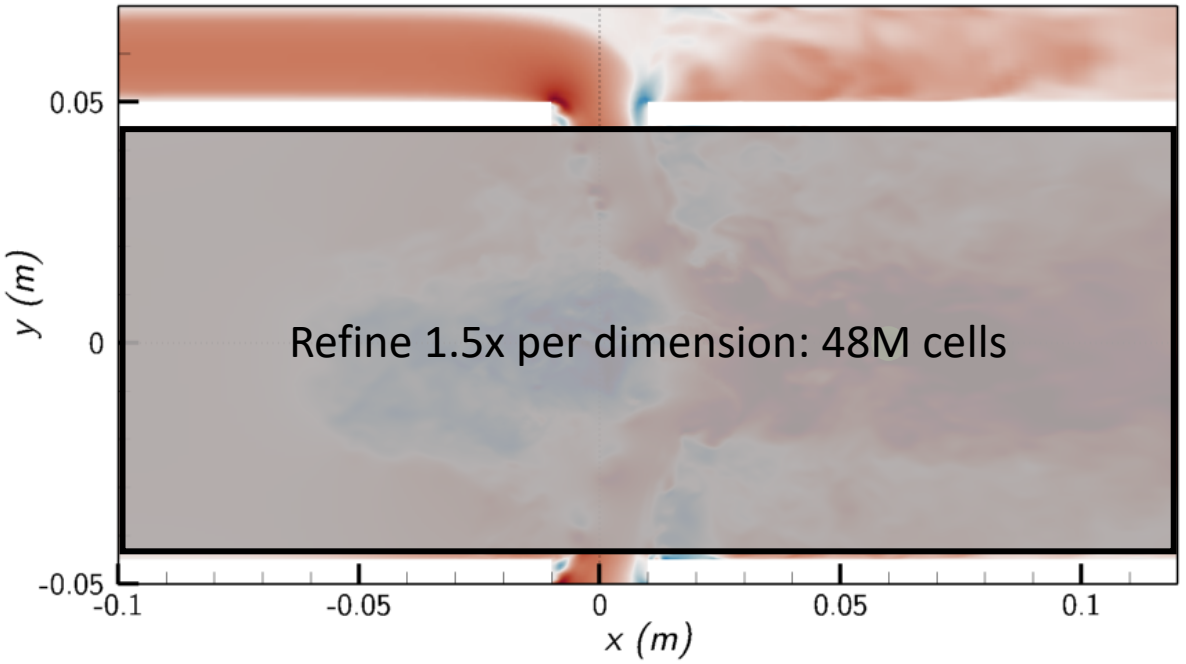
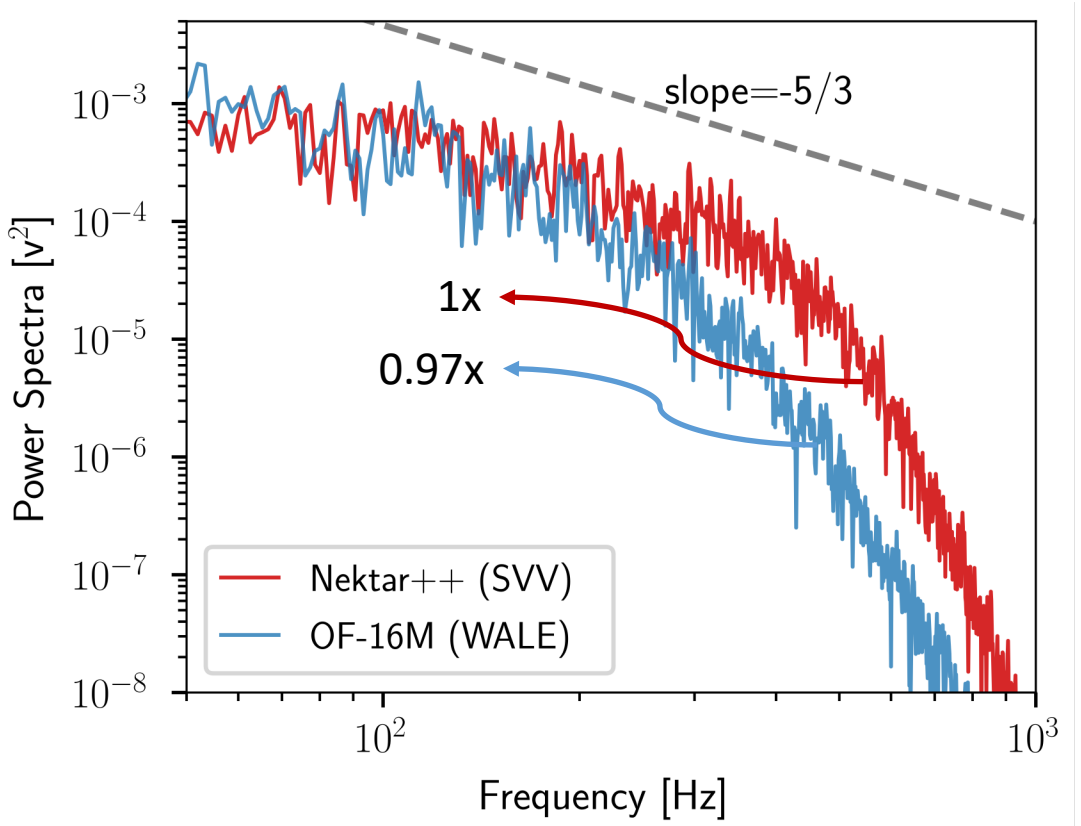
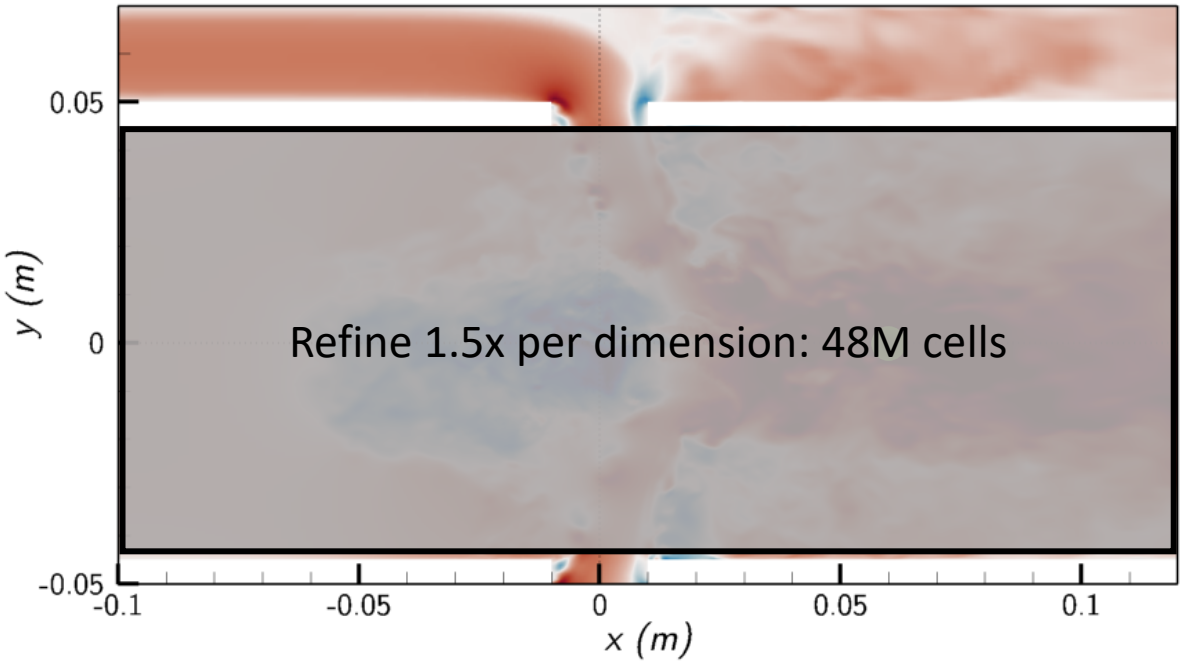
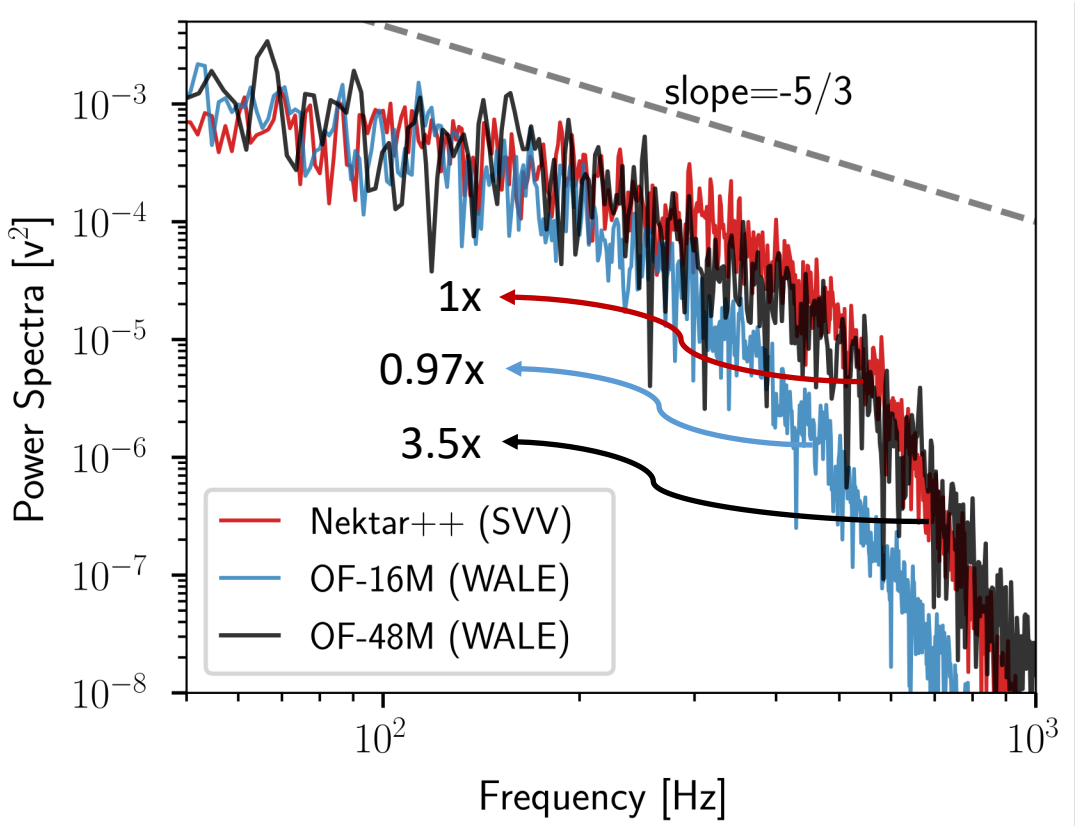


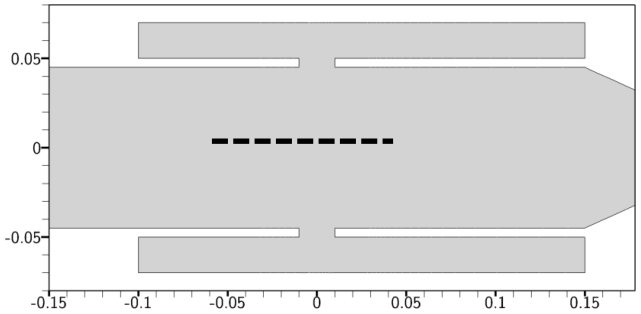


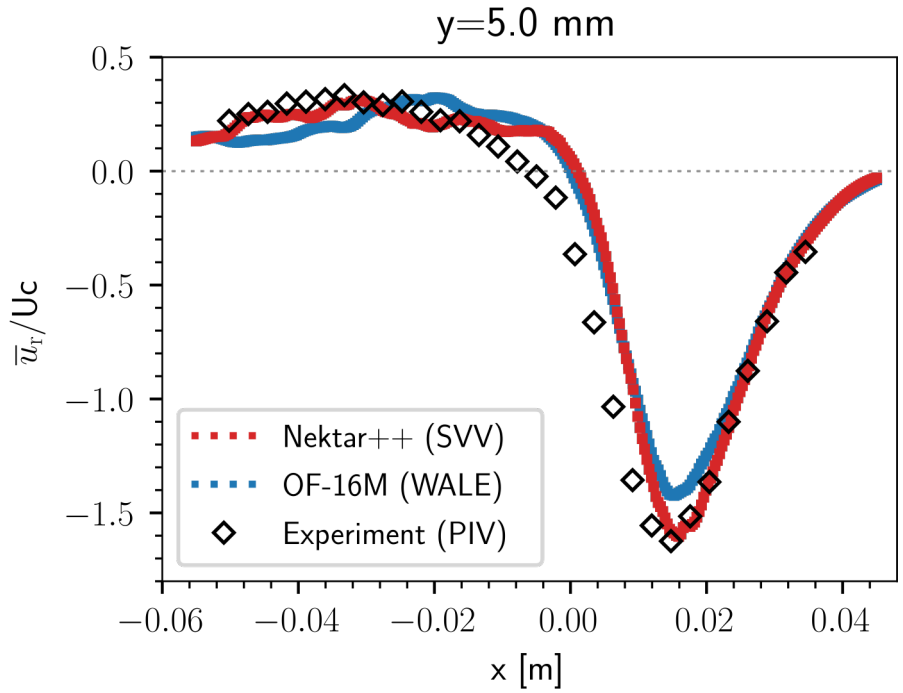
R-JICF spectra

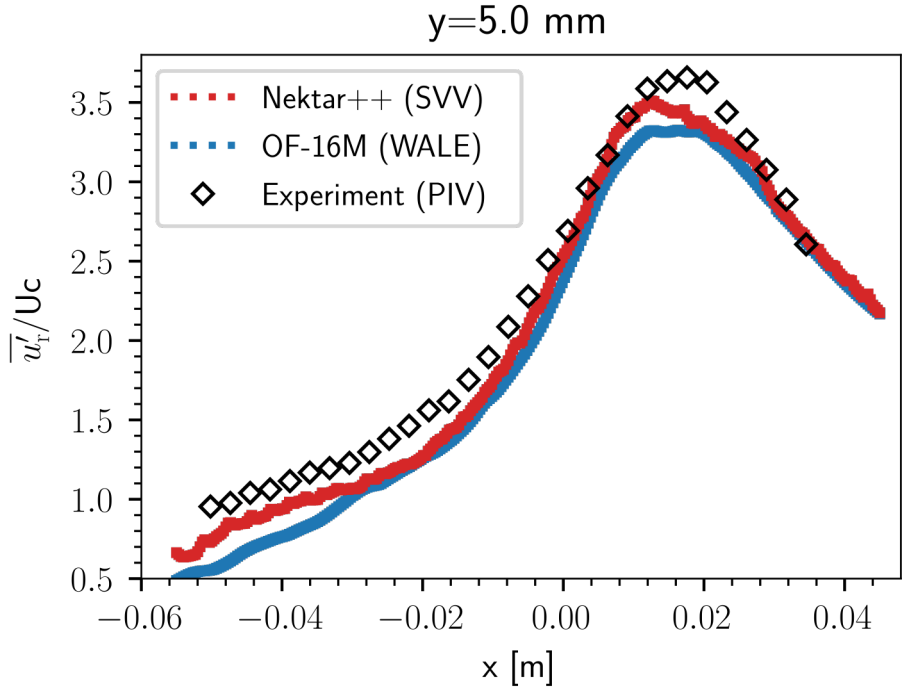




R-JICF mean quantities

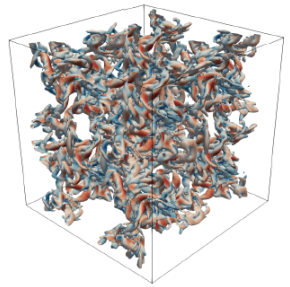


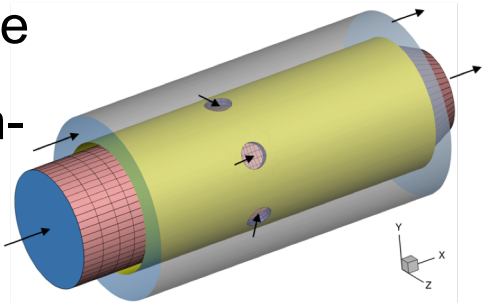




Conclusions

- Present project aims to quantify the benefits (if any) of the High-Order LES on combustor relevant geometries.
- For TGV case, P4 LES were found to be 8x cheaper for given accuracy and 2.5-10x more accurate for a given cost.
- For R-JICF case, P4 LES resolved broader turbulent scales at a key location for a given cost. Equivalent spectrum was obtained by a 3.5x more expensive 2nd order simulation. Mean quantities are less distinctive but in favour of high-order. Further investigation on R-JICF case is ongoing.





Thank you for the attention.
Questions?

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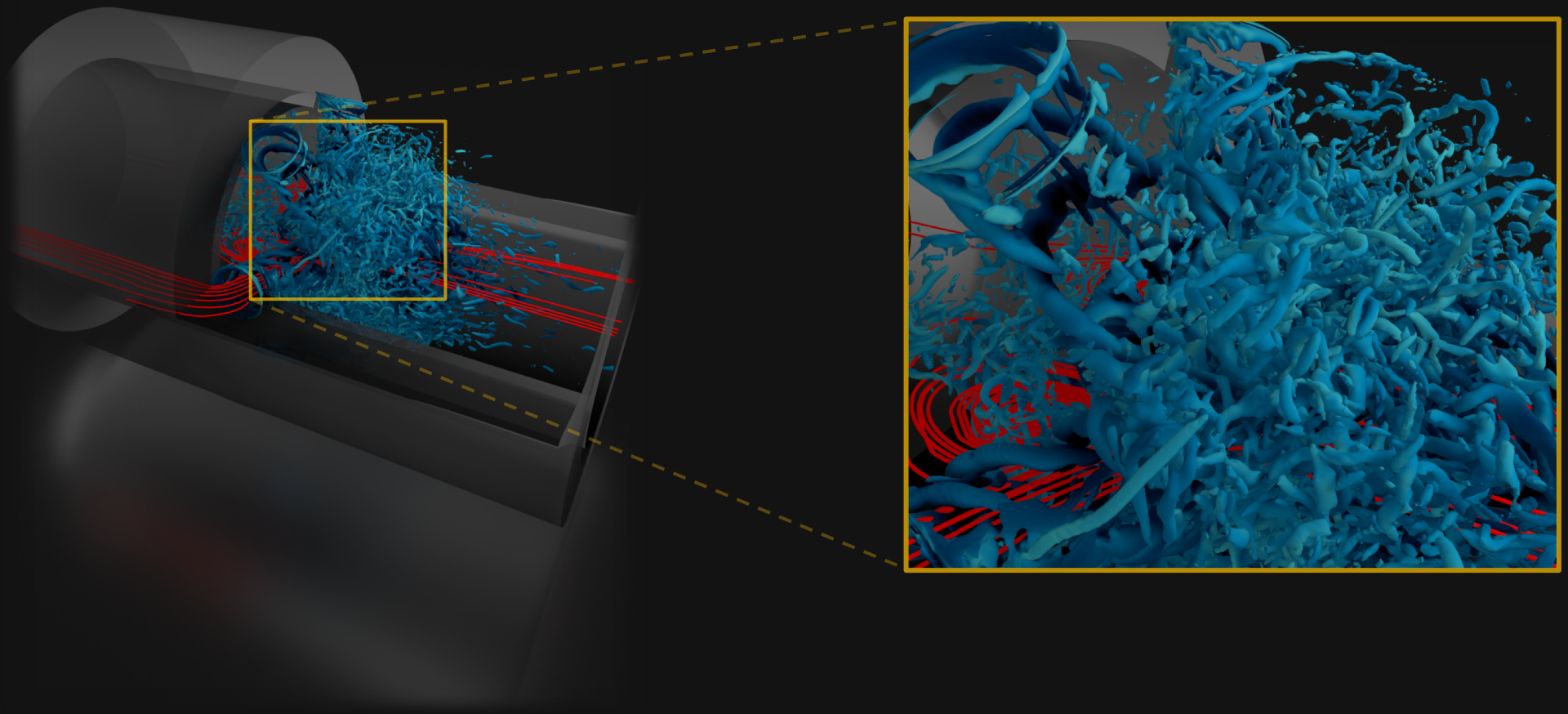

Acknowledgements

- Centre for Doctoral Training in Gas Turbine Aerodynamics
- EPSRC
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- HPC Midlands+
- Nektar++ team