High-Speed Flow Dynamic Research Through High-Order Numerical Simulation on ARCHER

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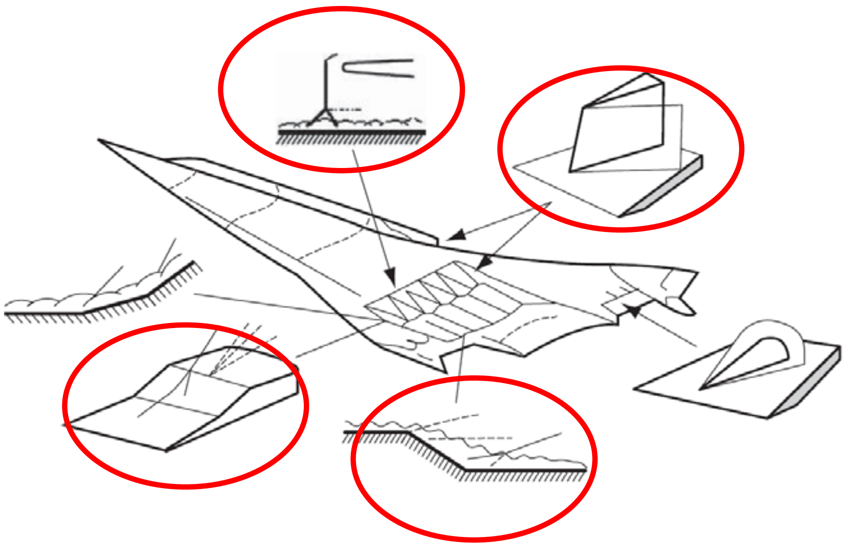
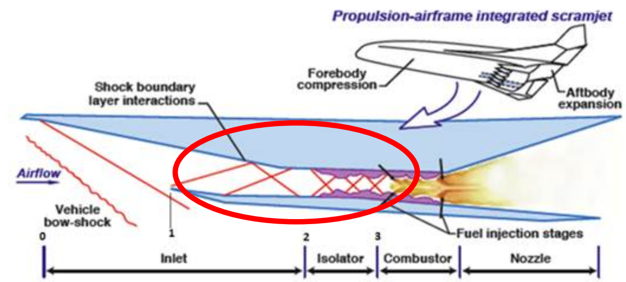
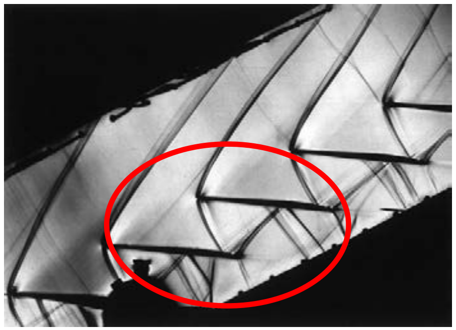
Outlines

- Background
- CFD Code
- Shock-wave/turbulent boundary layer interactions
- Flow Mechanisms
- Next-Gen Code for UKCTRF
- Conclusions
- Acknowledgements

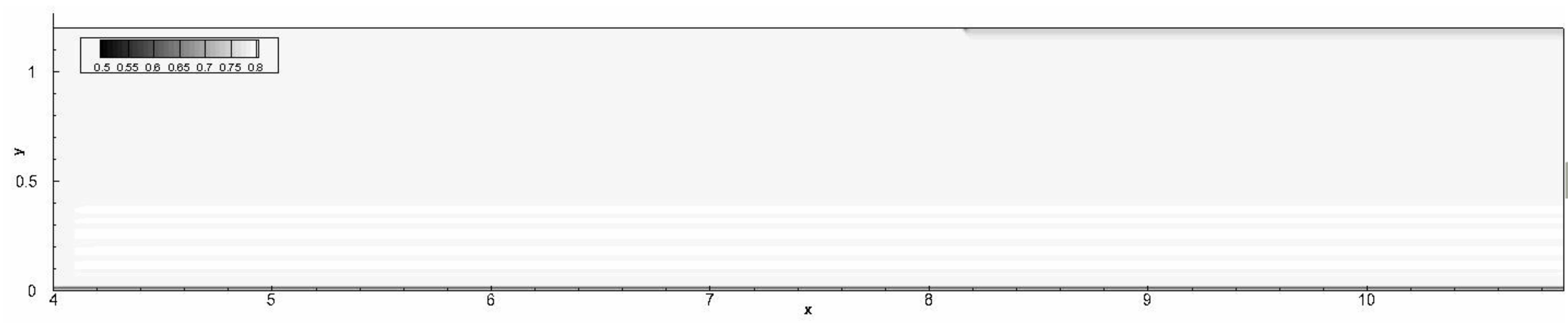
Background







Shock-Wave/Turbulent Boundary Layer Interaction



Background

- **Mean flow field, overall performance.**
- **Small amount of data, very efficient.**
- **Highly relied on turbulence model**

Computational Fluid Dynamics

RANS

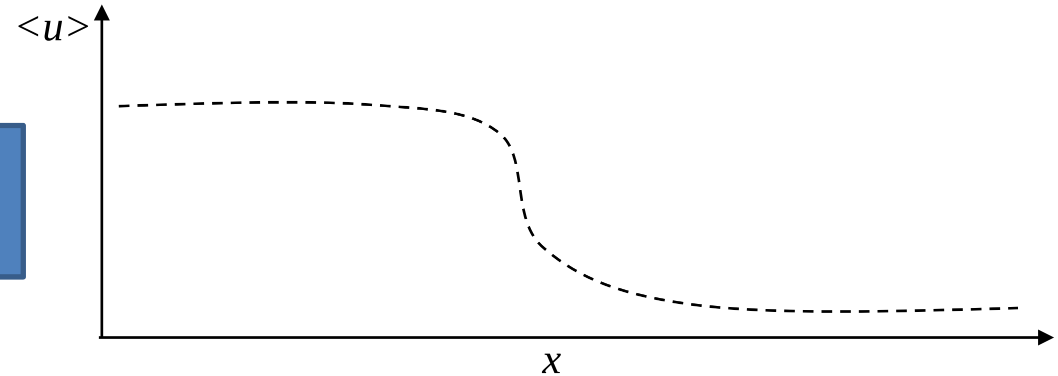
DDES

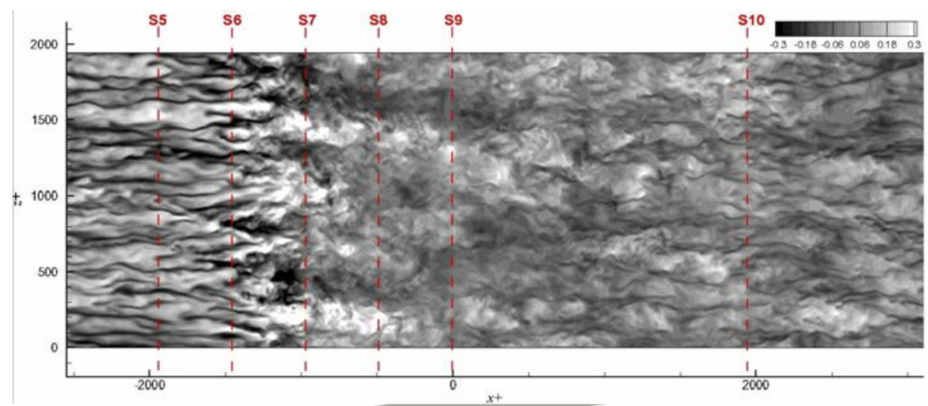
DES

LES

DNS

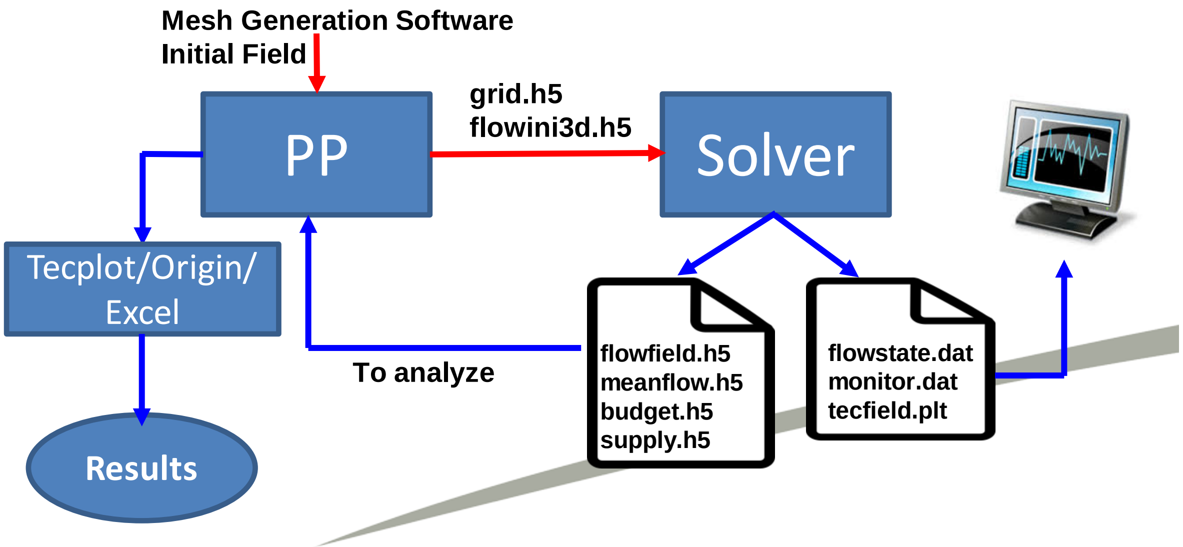
- **Fully temporal/spatial resolved flow field.**
- **High-accuracy, Lots of data.**
- **Very expensive, Not ready for industrial applications.**
- **Highly relied on HPC resource and CFD code.**

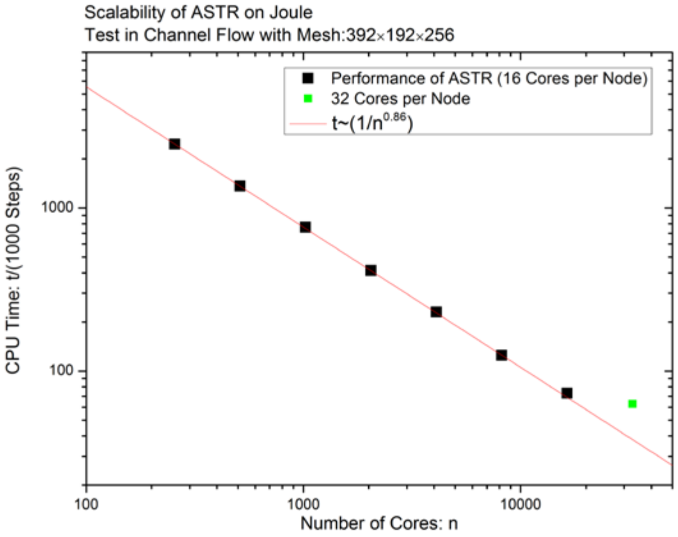




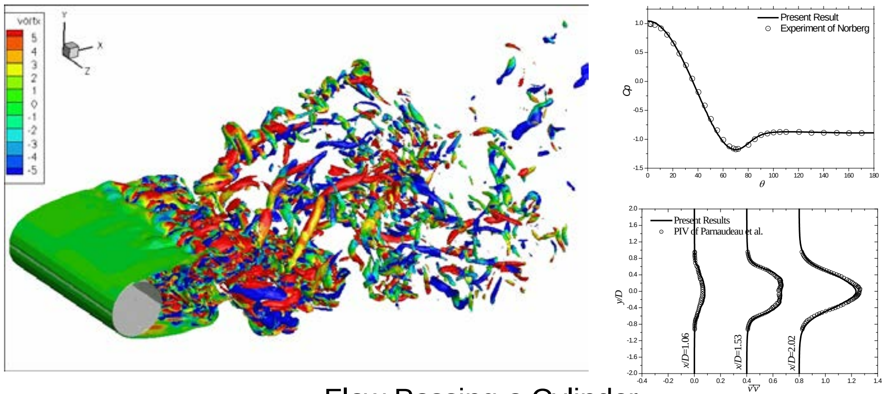
CFD Code

- **ASTR (Advanced flow Simulator for Turbulence Research)**
  - High-order FDM on generalized mesh
    - High-order Dealiasing Compact Central scheme
    - High-order Low-Dissipative Shock-Capturing Scheme
    - 3rd-order Runge-Kutta time scheme
  - Modern Fortran 90
  - Parallelized by using MPI and Hybrid MPI-OpenMP
  - Collective HDF5 I/O
  - Tested in ARCHER, Tianhe, Hector, Blue Genes…

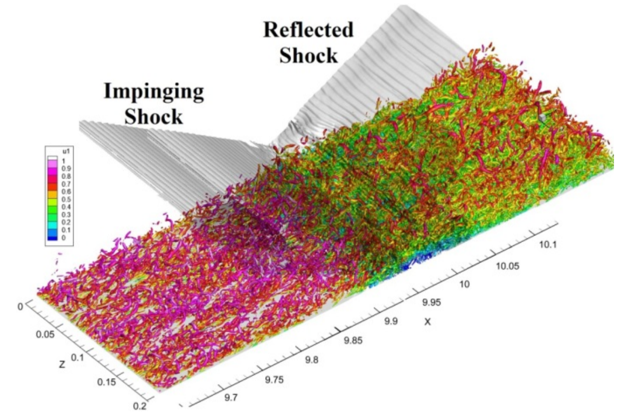




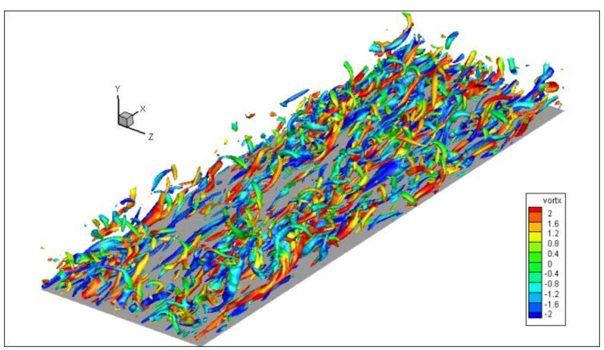
Benchmarks



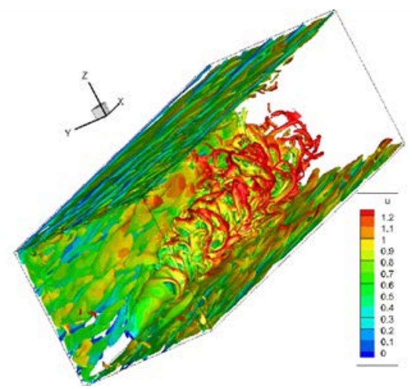
Flow Passing a Cylinder



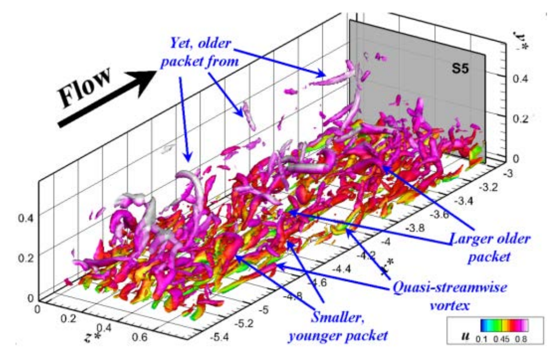
Impinging Shock-Wave/Flat-Plate Boundary Layer Interaction



Turbulent Channel Flow



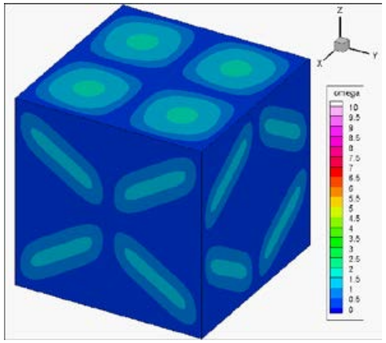
Tip-Leakage Vortex



Well resolved wall-turbulence

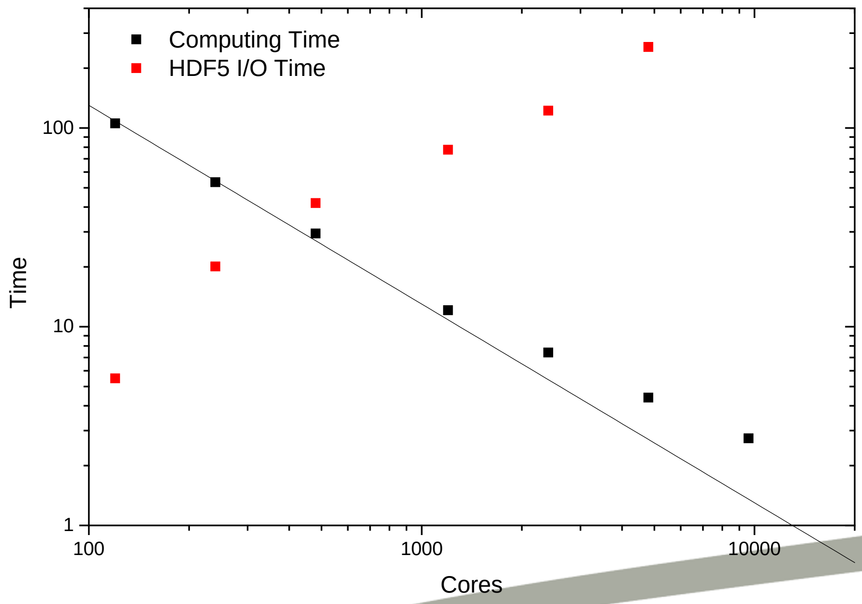
Performance on ARCHER

Test Case: 3D Taylor-Green Vortex
Mach:0.1, Re=1600
Mesh size: 16.8M=256×256×256



ARCHER Nodes

Cores	CPU Time	I/O Time
120	105.41	5.49
240	53.36	20.08
480	29.44	41.87
1200	12.1	77.74
2400	7.41	122.27
4800	4.39	255.47
9600	2.74	-



Performance on ARCHER

Test Case: DNS of Turbulent Boundary Layer

Mach:0.2, Re_δ=7500

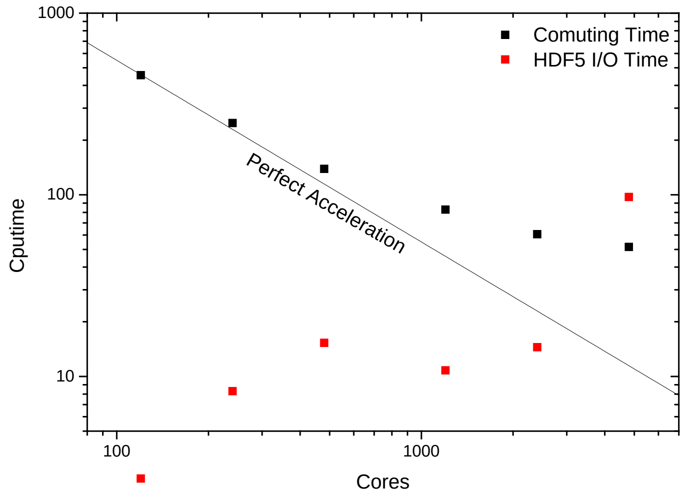
Mesh size: 71.2M=1980 × 120 × 300

ARCHER Nodes

Cores	CPU Time	I/O Time
120	455.64	2.74
240	248.36	8.29
480	138.96	15.3
1200	82.81	10.80
2400	60.65	14.48
4800	51.63	97.22

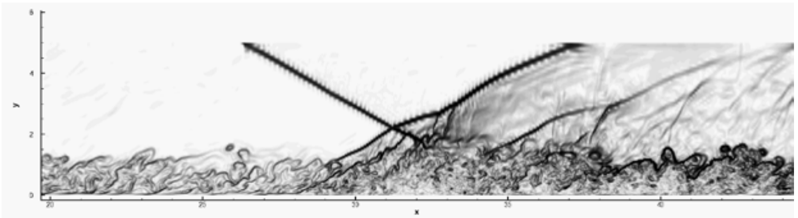
KNL Nodes

Cores	HyperThread	MPI	OpenMP	CPU Time
256	4	256	4	523.05
256	4	8	128	1629.69
8	-	8	-	17076.09
256	-	256	-	513.281

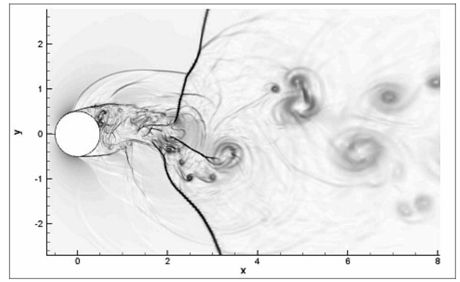


Shock-wave/turbulent boundary layer interactions

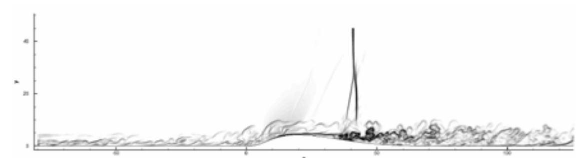
- **Cases studied**



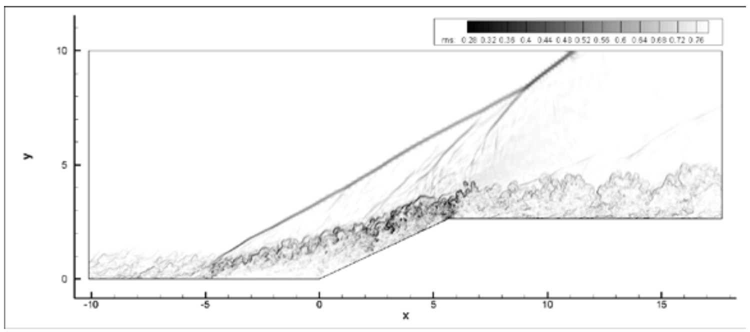
Impinging Shock-Wave/Flat-Plate Boundary Layer Interaction



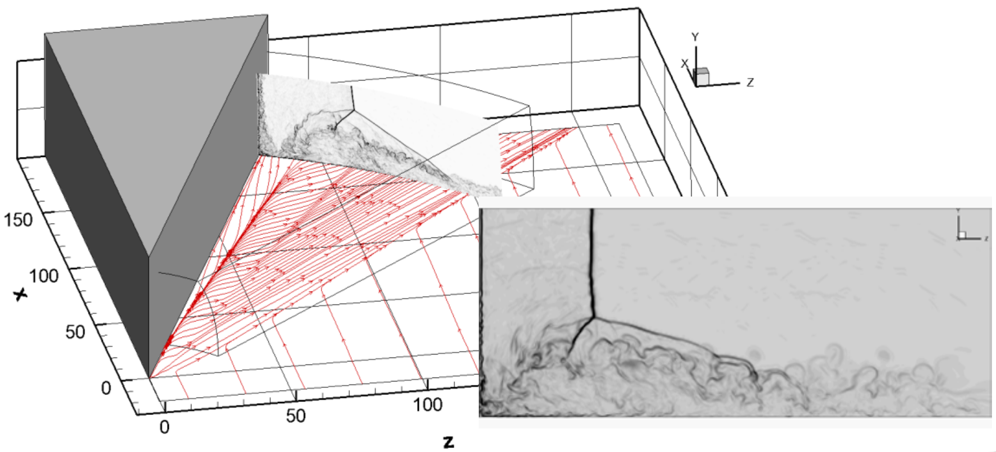
Transonic Flow Passing a Cylinder



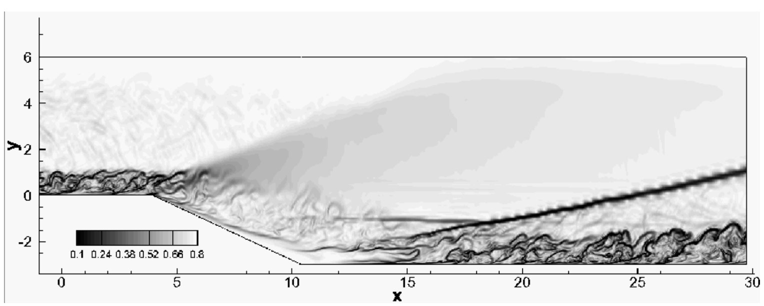
Transonic Airfoil



Compression Corner



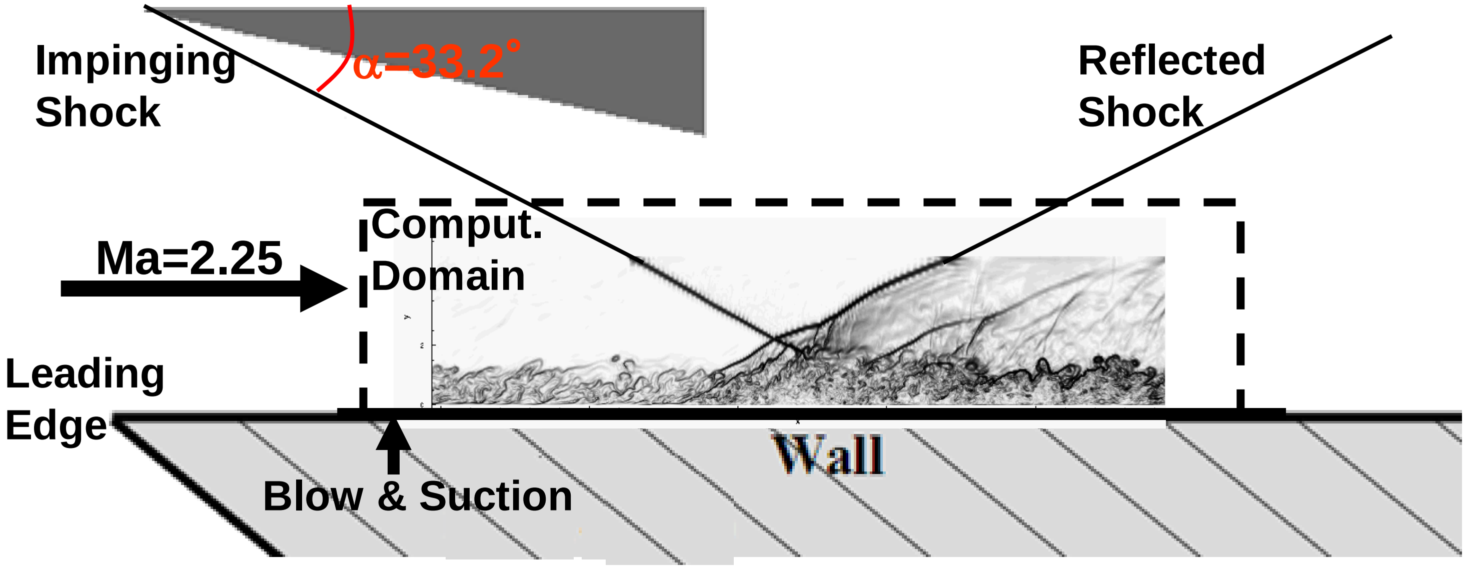
3D Single-Fin Flow

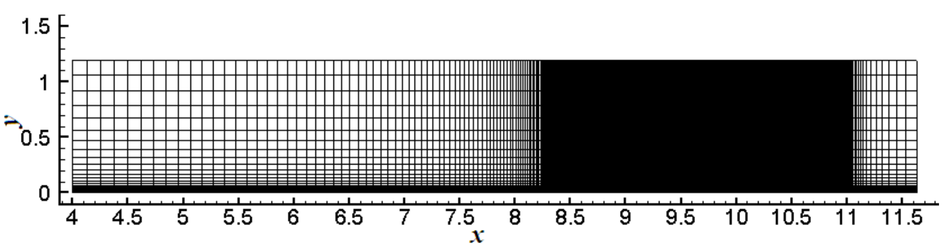


Supersonic Backward Step

Impinging Shock-wave/flat plate boundary layer interaction

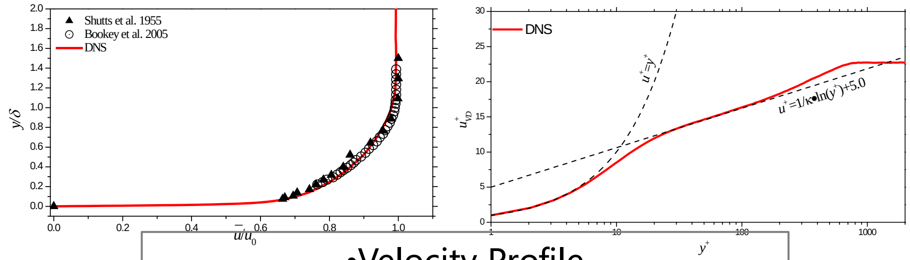
- Mach=2.25； Impinging Angle: α=33.2°
- Re_δ=41167, Re_θ=3148



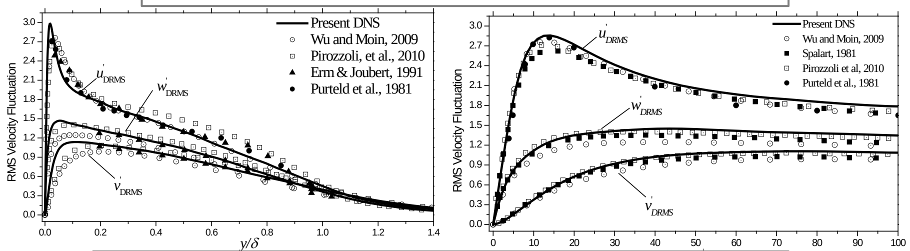


IM×JM×KM	$\Delta x \cdot \Delta y \cdot \Delta z\ (10^{-4})$
2800×150×256	4.0×1.00×7.81
$\Delta x_{min}^{+} \times \Delta y_1^{+} \times \Delta z^{+}$	Lz^{+}
3.9×0.97×7.6	1950

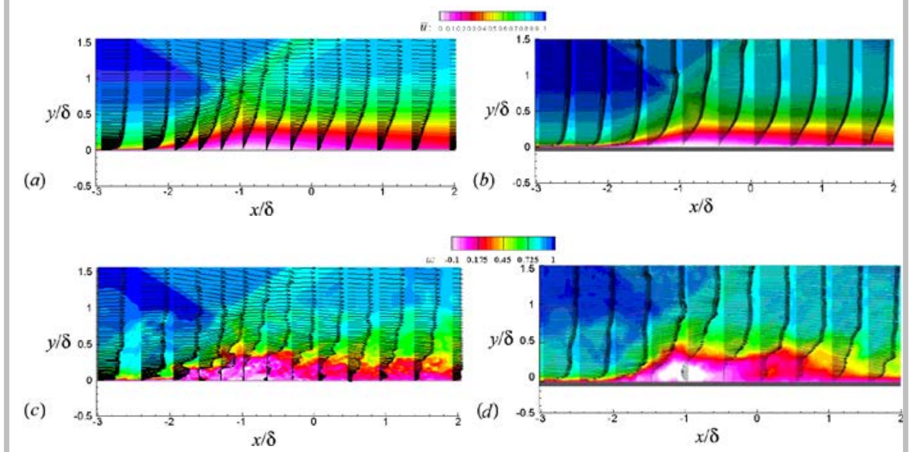
Impinging Shock-wave/flat plate boundary layer interaction



•Velocity Profile

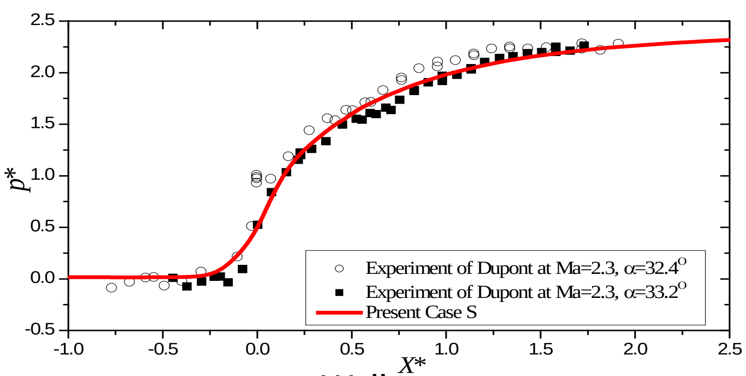


•RMS Velocity Fluctuation Intensity Profile



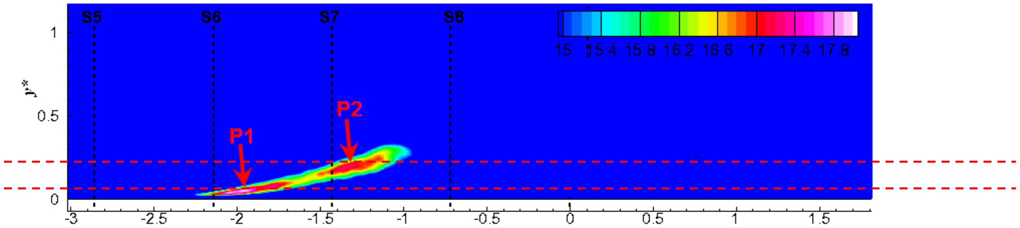
•DNS .vs. PIV

Humble, R.A., et al., Exp. Fluids, 2007, 43:173-183

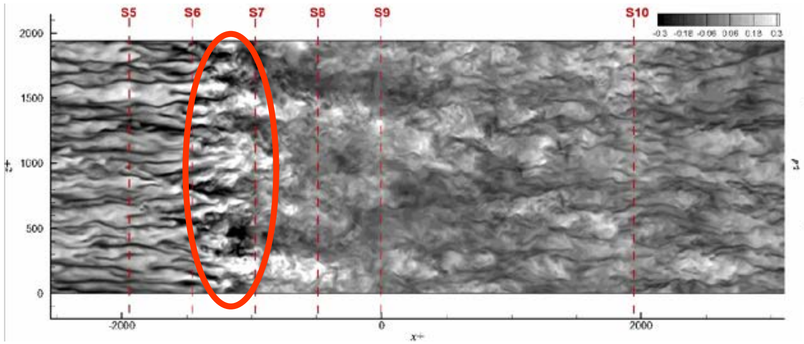


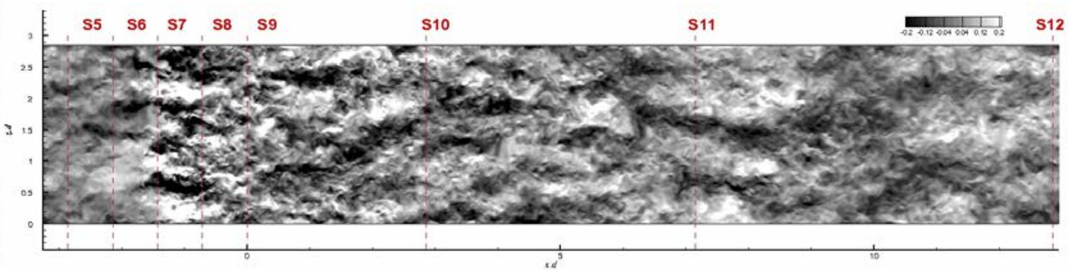
•Wall pressure

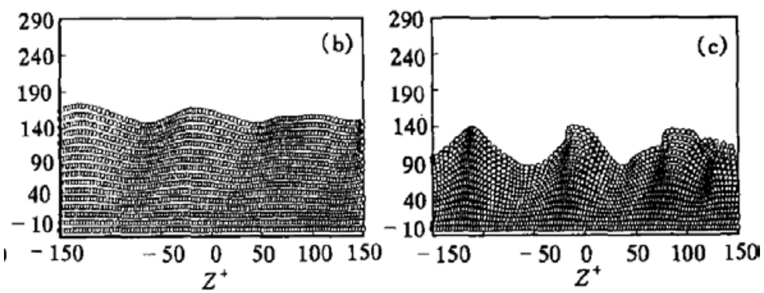
Flow Mechanisms



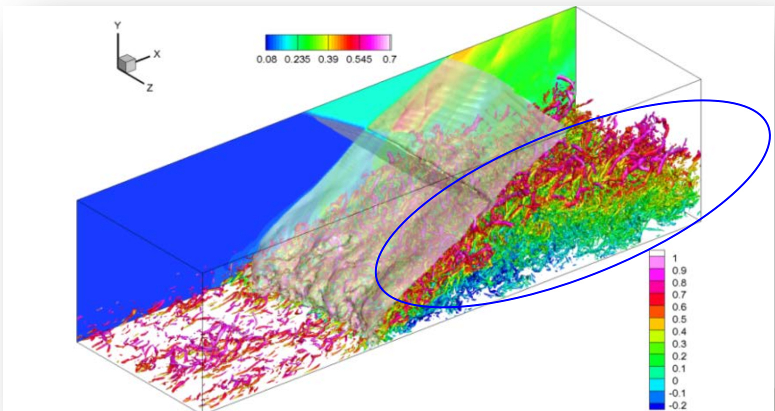
Turbulent Kinetic Energy







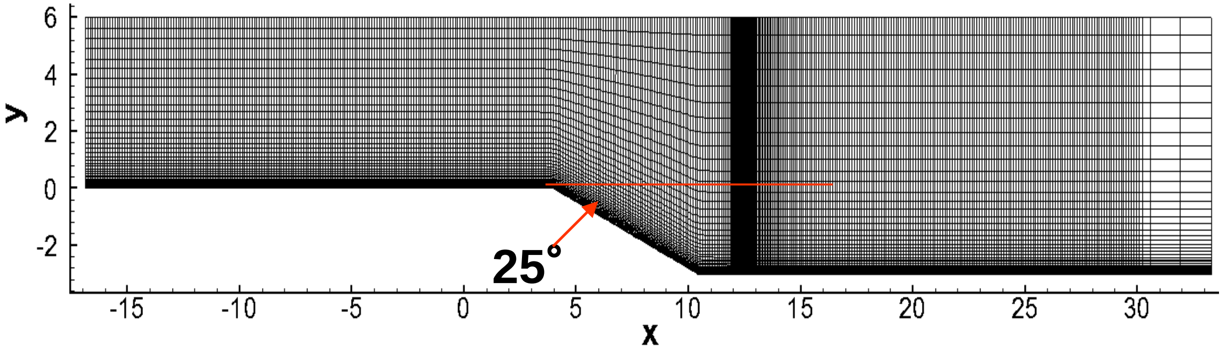
Turbulent structures under zero and adverse pressure gradient

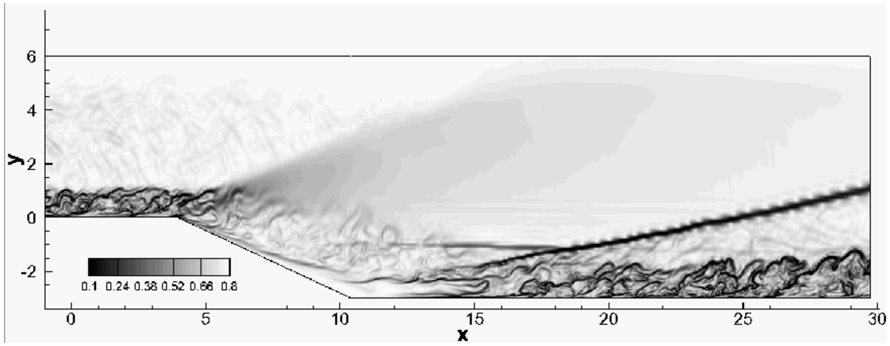


Jian Fang, Zhaorui Li, and Lipeng Lu, An Optimized Low-Dissipation Monotonicity- Preserving Scheme for Numerical Simulations of High-Speed Turbulent Flows, Journal of Scientific Computing, 2013, Vol. 56, pp. 67–95.

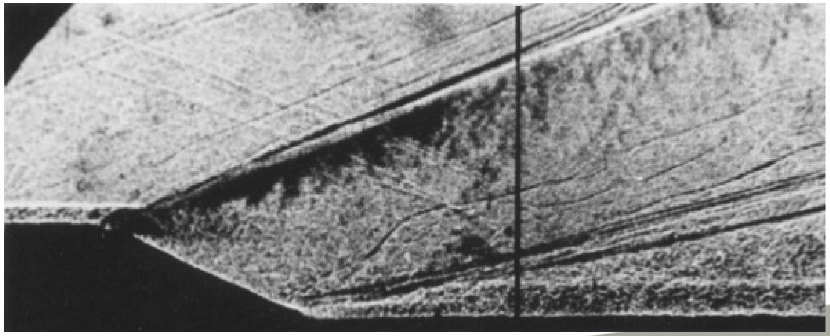
Expansion-Compression Corner

- Expansion-Compression Corner
  - Mach=2.9； Deflection Angle: β=25°
  - Re_{δ}=20000/40000/80000
  - Mesh size: 1420×120×256/2020×120×300/2620×200×400



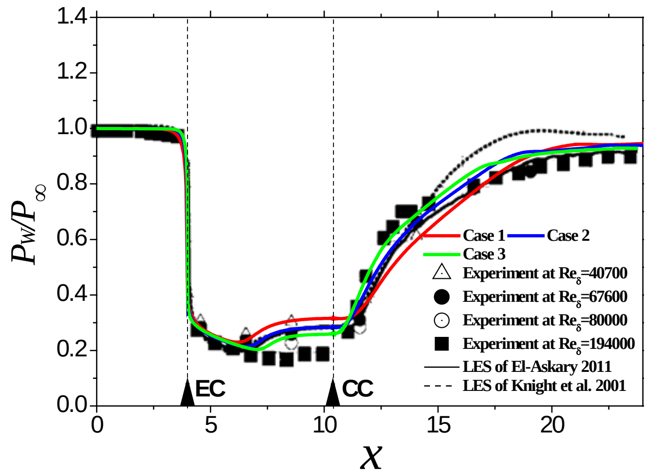


Density Schlieren

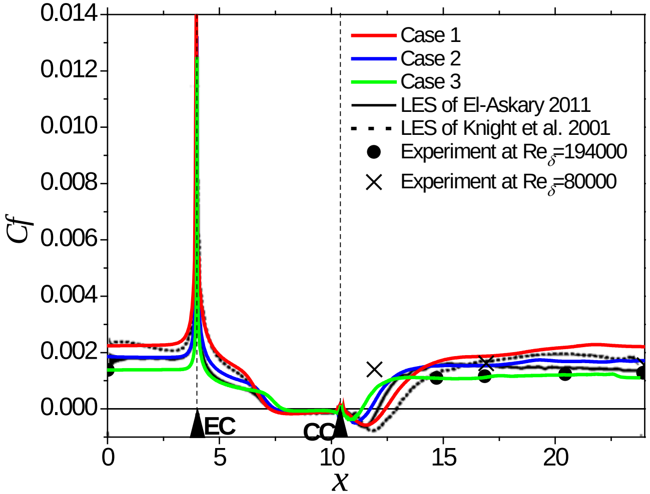


Pressure Field

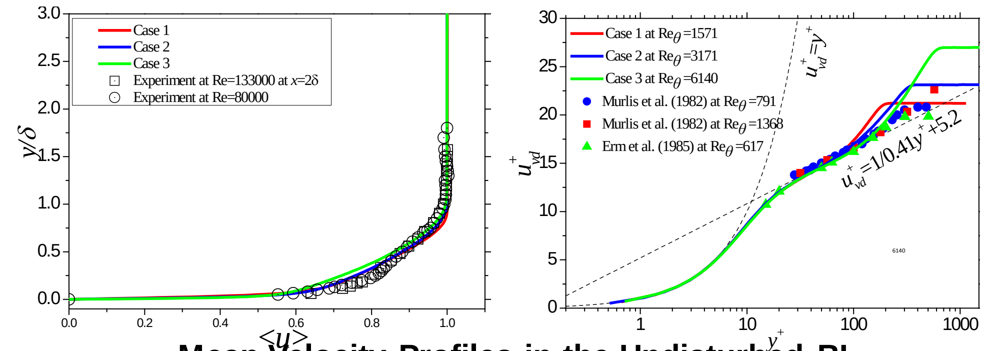
Expansion-Compression Corner



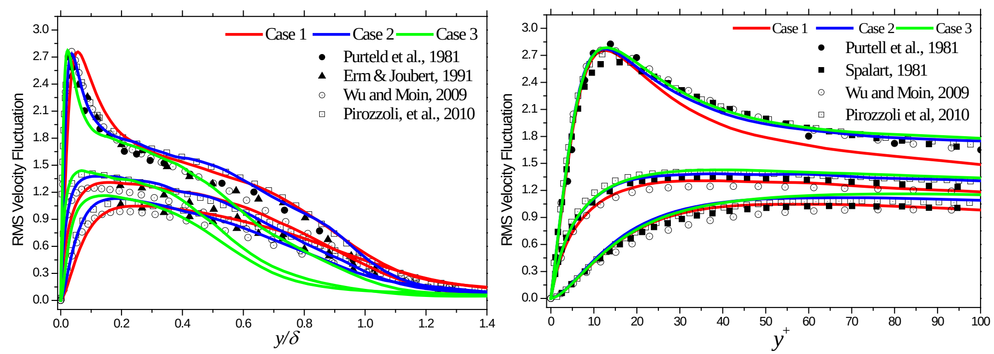
Wall Pressure



Skin friction



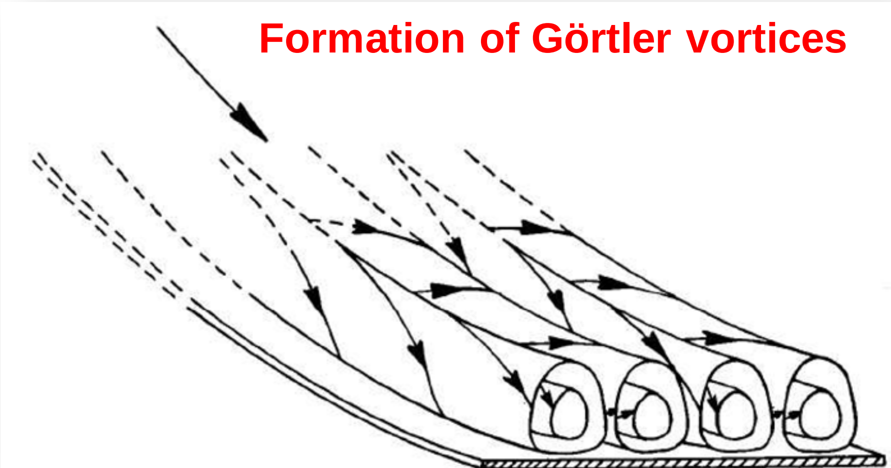
Mean Velocity Profiles in the Undisturbed BL

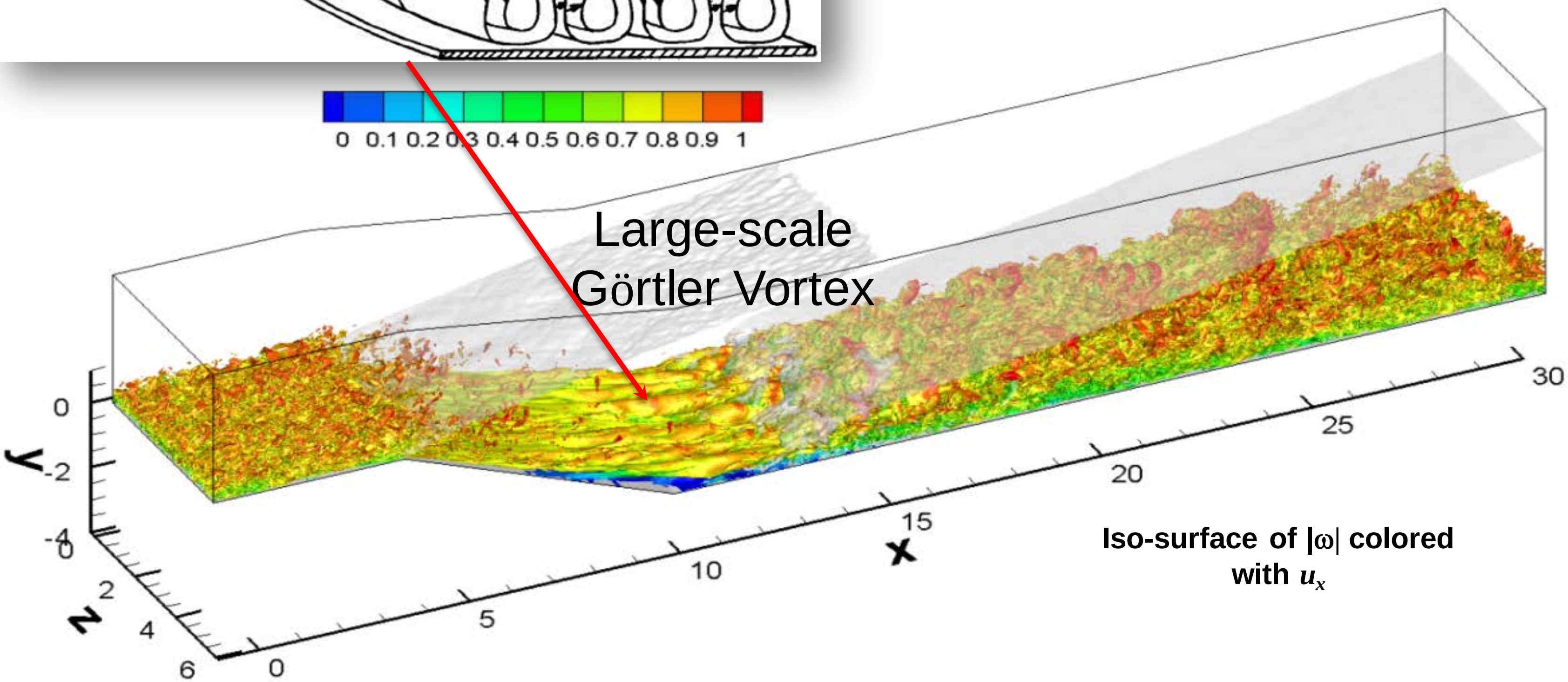


Turbulence Velocity Intensities in the Undisturbed BL

Flow Mechanisms

- Gortler Vortex



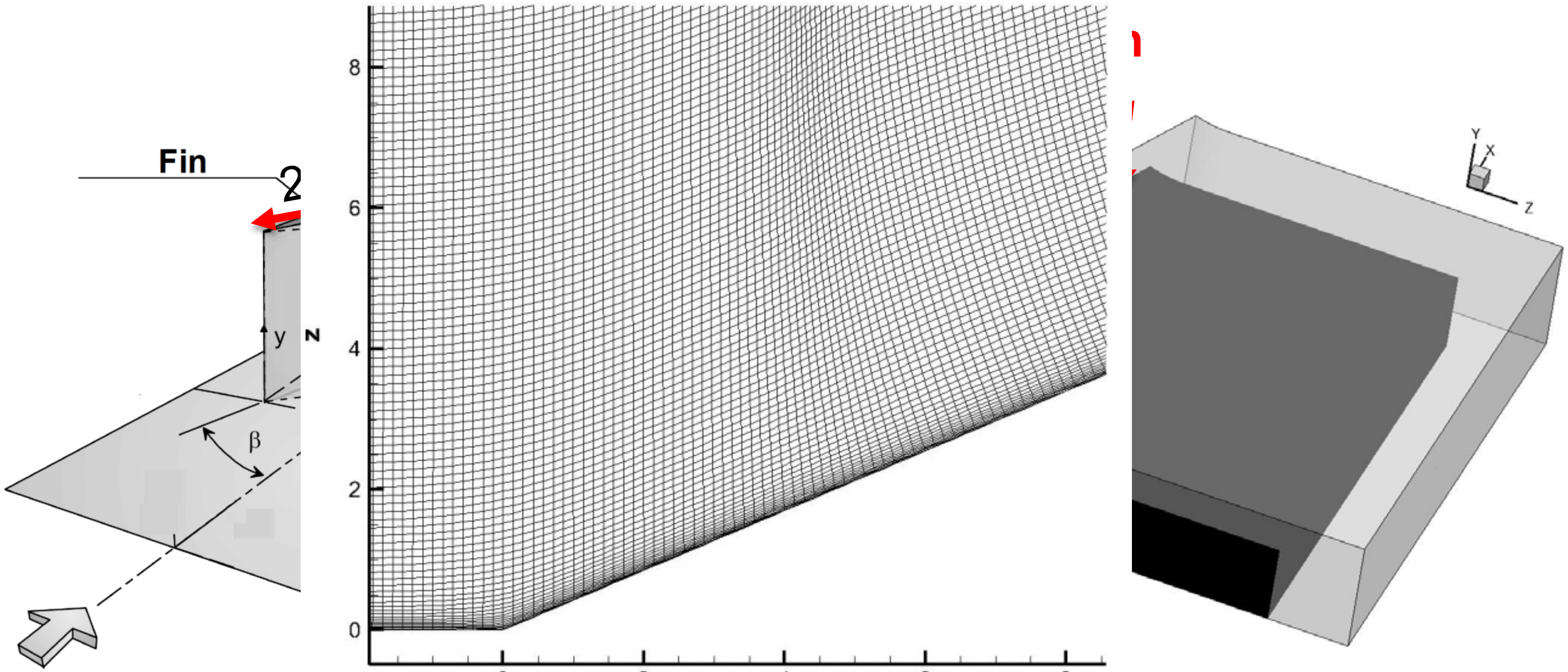


Iso-surface of |ω| colored with u_x

Jian Fang, Yufeng Yao, Alexandr A. Zheltovodov, Zhaorui Li, and Lipeng Lu, Direct numerical simulation of supersonic turbulent flows around a tandem expansion-compression corner, Physics of Fluids, 2015, 27, 125104

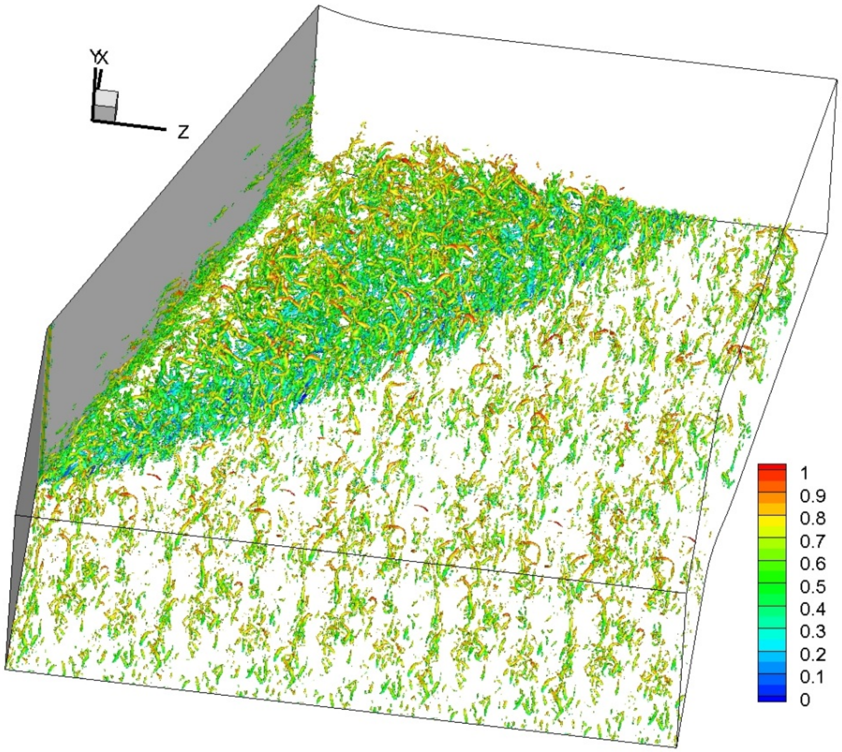
3D SWTBLI

- **Hypersonic Single Fin**
  - Mach=5.0 ; Deflection Angle: β=23°
  - $Re=37\times10^6/m$, $Re_\delta=1.4\times10^5$
  - Mesh: 1040×240×1420

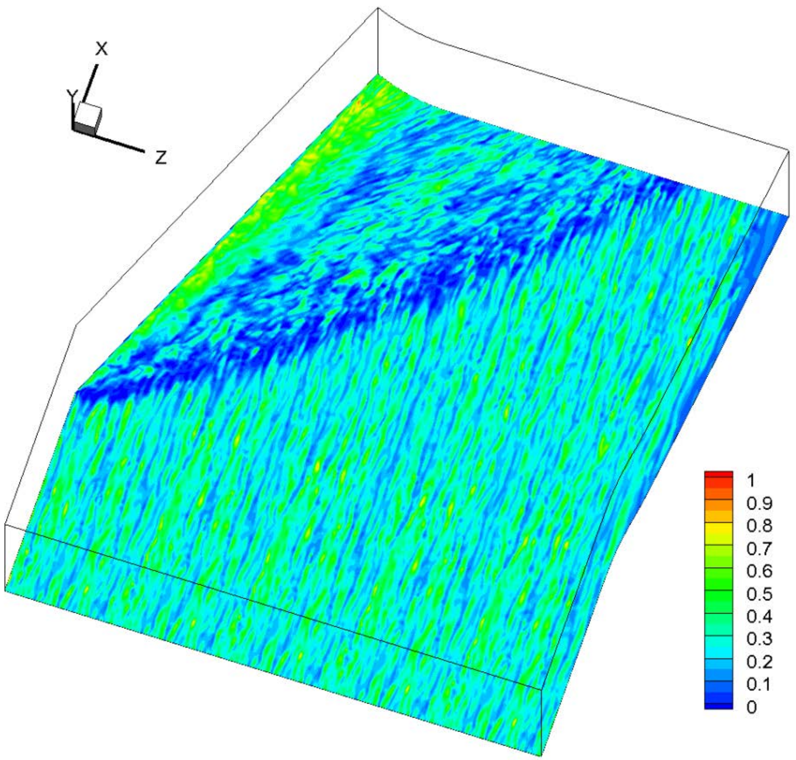


•Sketch map of the domain

3D SWTBLI

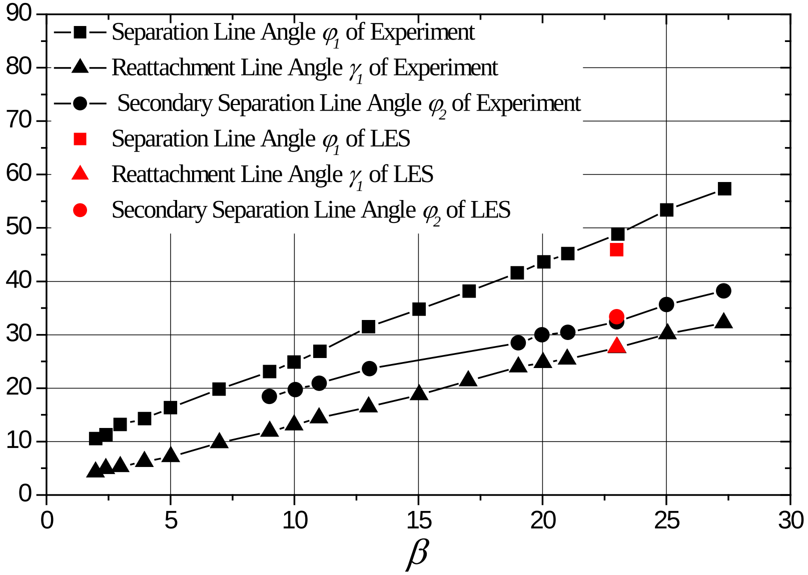


Turbulent Coherent Structures & Shock Surface

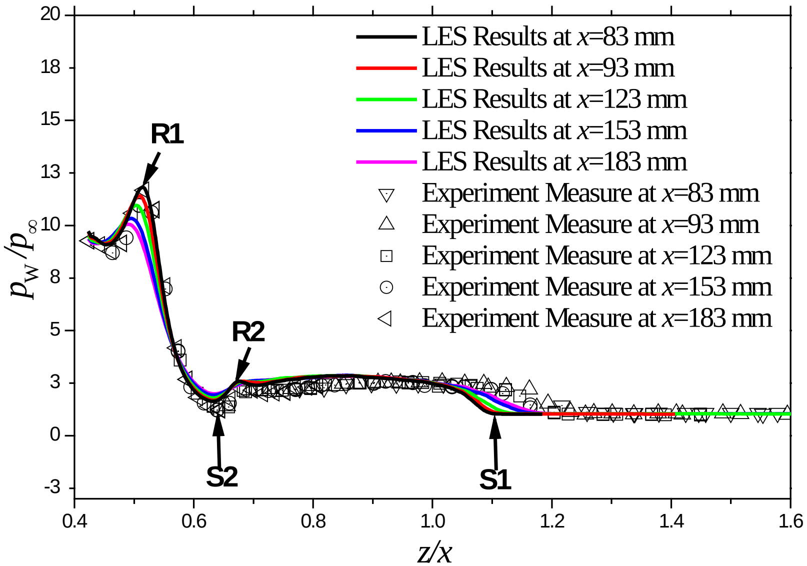


Near Wall Velocity Streaks

3D SWTBLI

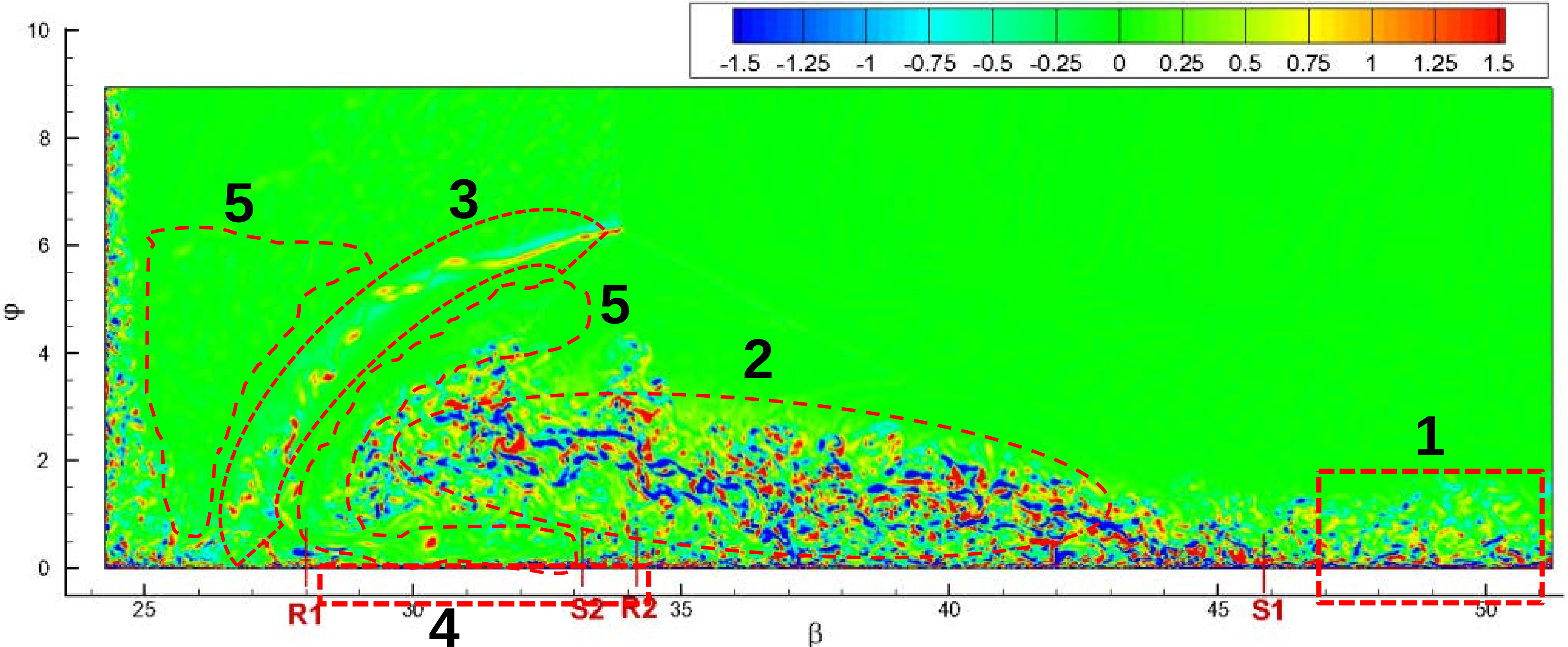


•Characteristic Angles



•Wall Pressure

Flow Mechanisms



•Instantaneous Vorticity Fluctuations

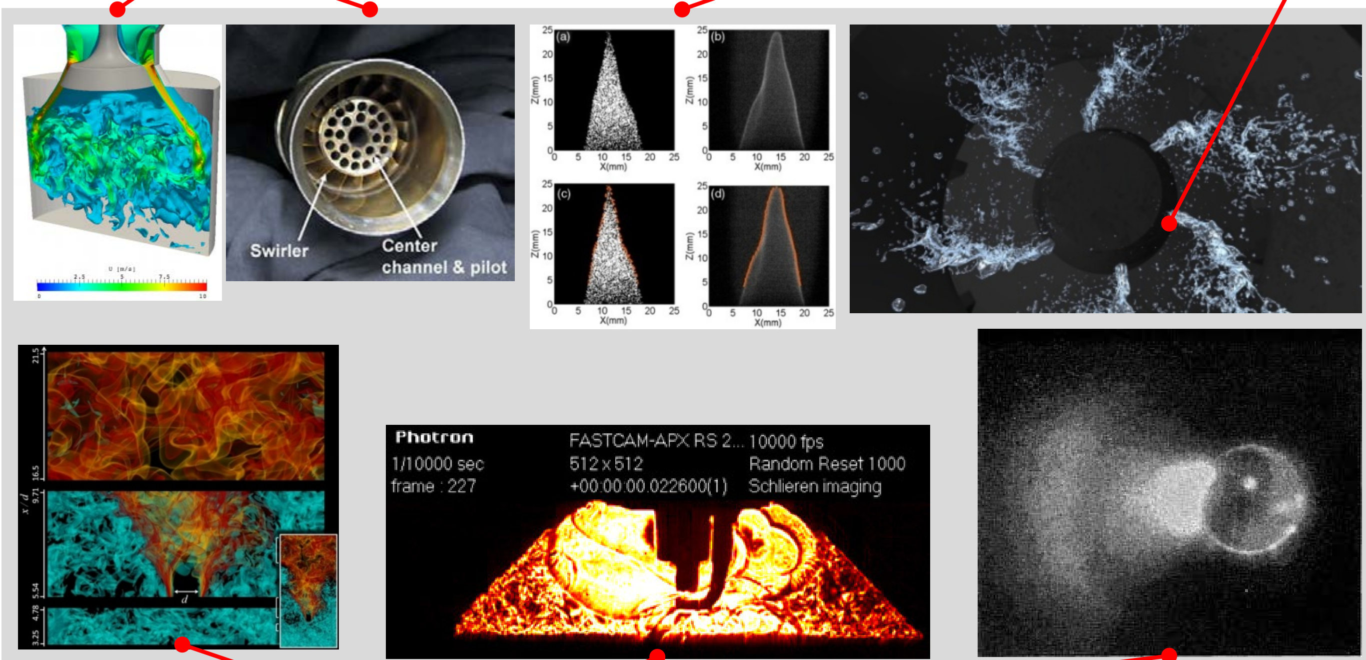
- **Zone 1: Undisturbed Wall Turbulence**
- **Zone 2: Separated Free-Shear Turbulence**
- **Zone 3: Jet Flow**
- **Zone 4: Regenerated Wall Turbulence**
- **Zone 5: Low-Turbulence Region**

Jian Fang, Yufeng Yao, Alexandr A. Zheltovodov, and Lipeng Lu, Investigation of Three-Dimensional Shock Wave/Turbulent-Boundary-Layer Interaction Initiated by a Single Fin, AIAA Journal, 2017. Vol. 55, No. 2: 509-523.

Next-Gen Code for UKCTRF

Geometry Complexity
- Swirler
- Piston
- Igniter
- Spray

Interface
- Flame front
- Gas/Liquid interface
- Droplets surface



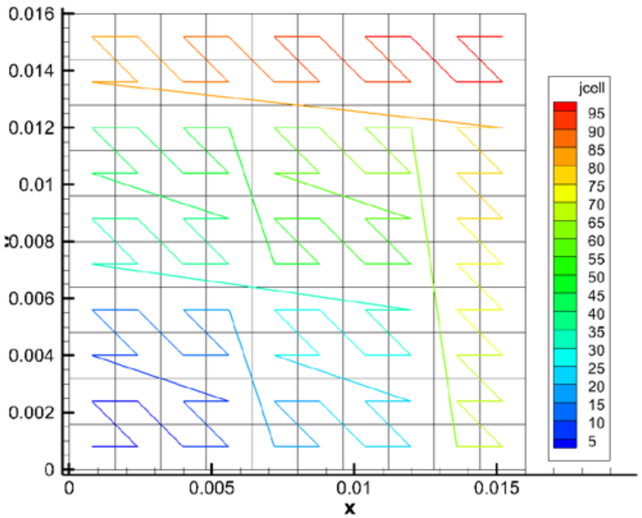
Scale-variety
- Turbulence
- Flame
- Shock-wave
- Droplets

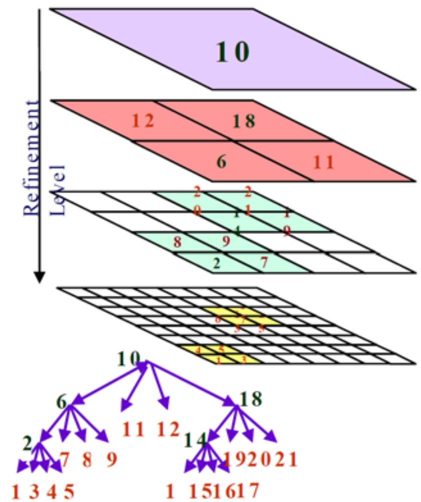
Next-Gen Code for UKCTRF

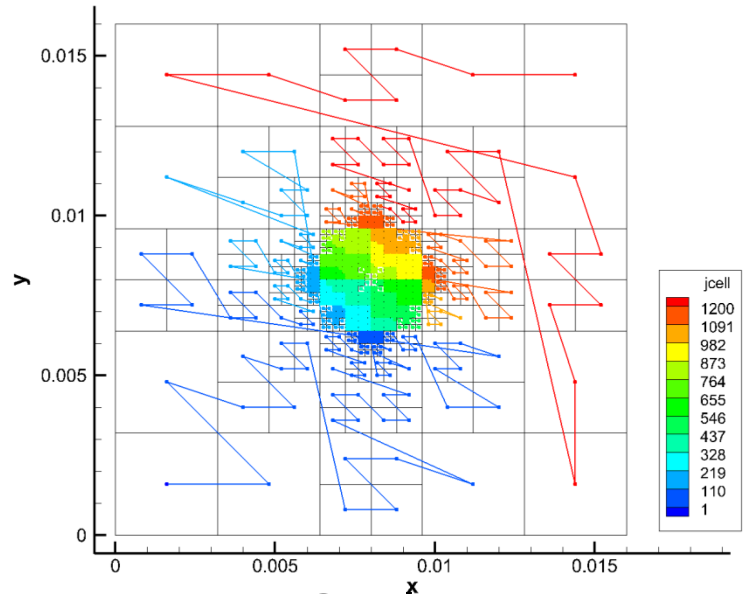
- **HAMISH Code**
  - First developed at CUED.
  - To solve the compressible Navier-Stokes equations with species mass fraction equations and chemical reactions.
  - Finite volume method using a 2^{nd}-order spatial scheme.
  - Runge-Kutta time stepping with sub-steps.
  - Morton-code based unstructured dataset.
  - Octree-based AMR.
  - MPI+domain decomposition paralization.

Next-Gen Code for UKCTRF

- **AMR in HAMISH (h-refinement)**







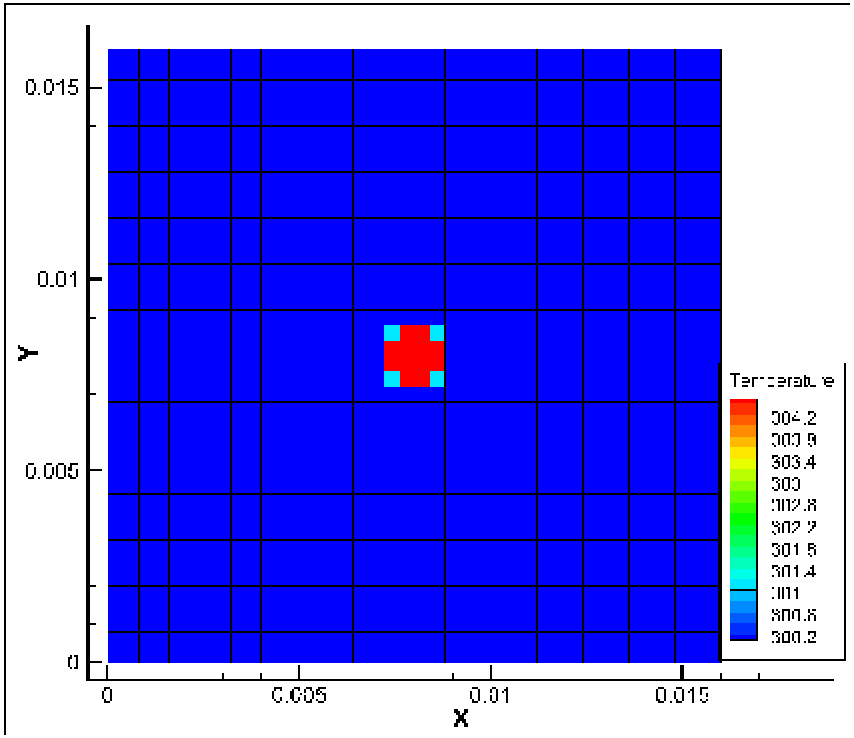
M-Code

Tree data structure

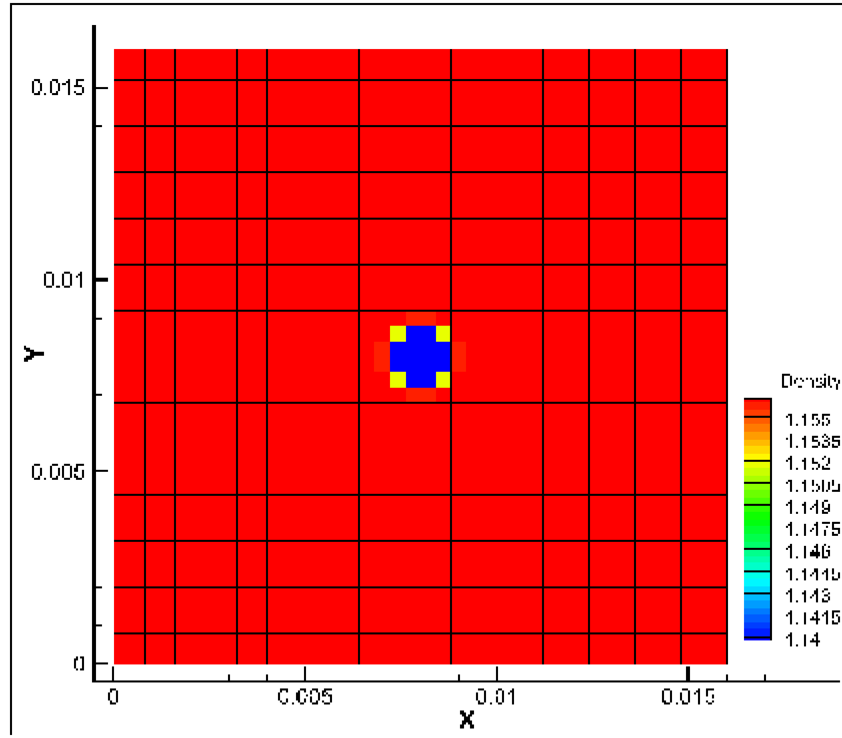
M-Code+Tree

Binary tree/Quadtree/Octree

Next-Gen Code for UKCTRF

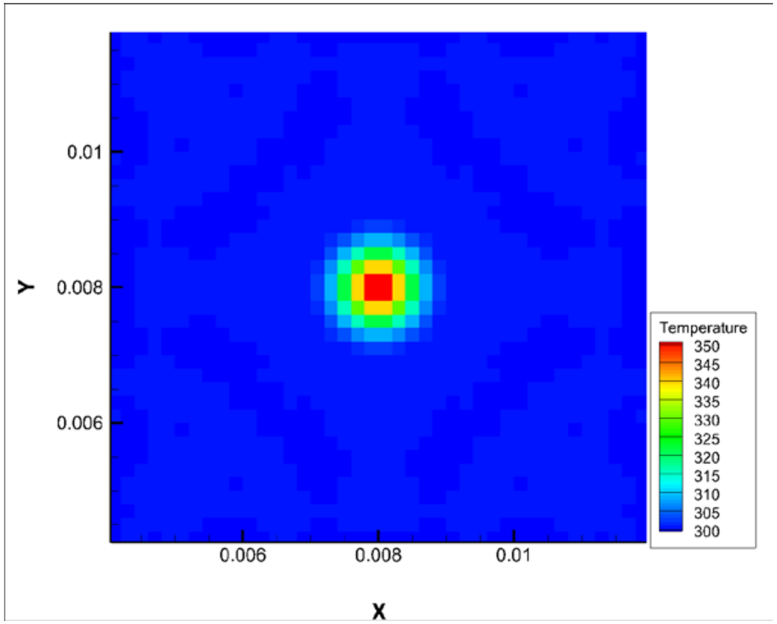


Temperature

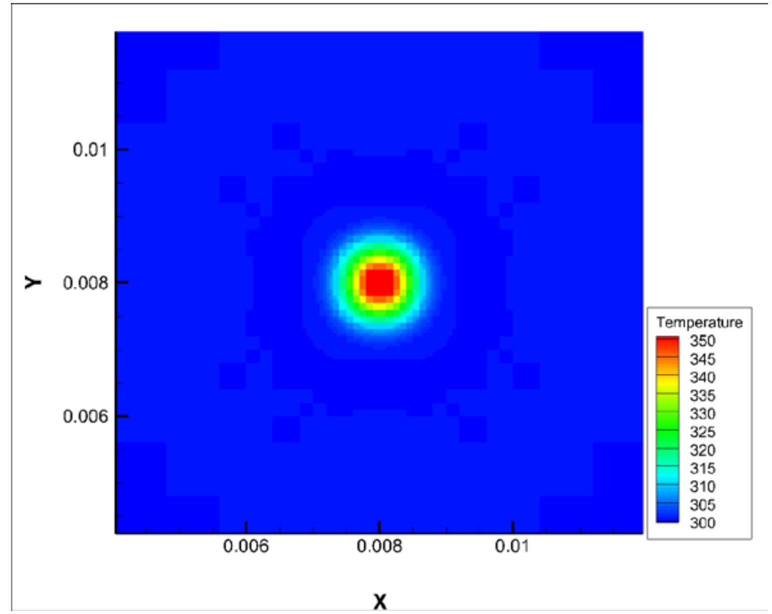


Density

Next-Gen Code for UKCTRF



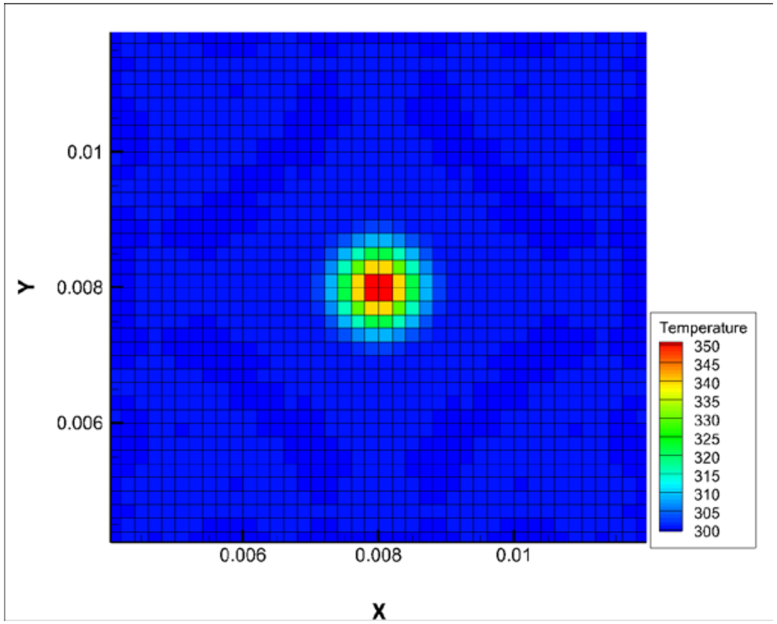
HAMISH with Fixed Mesh of **6400** cells



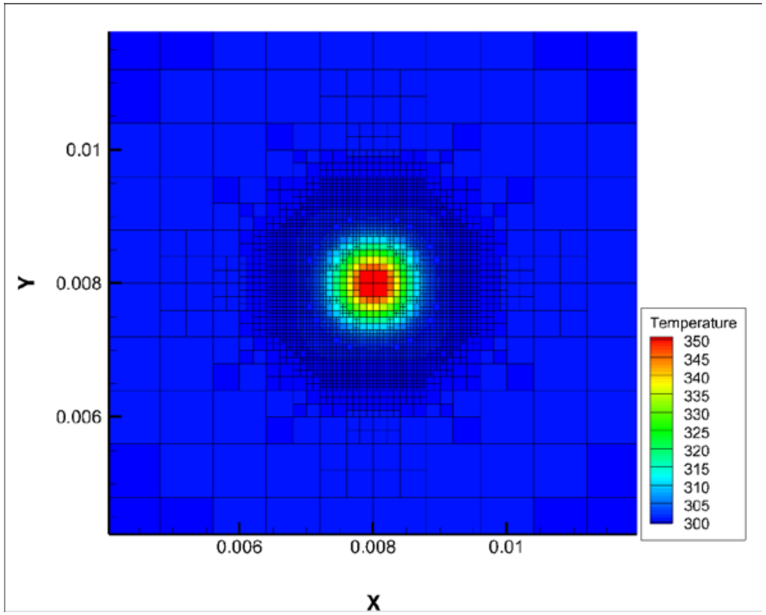
HAMISH with Adaptive Mesh of **3676** cells

Temperature at t=0.001

Next-Gen Code for UKCTRF



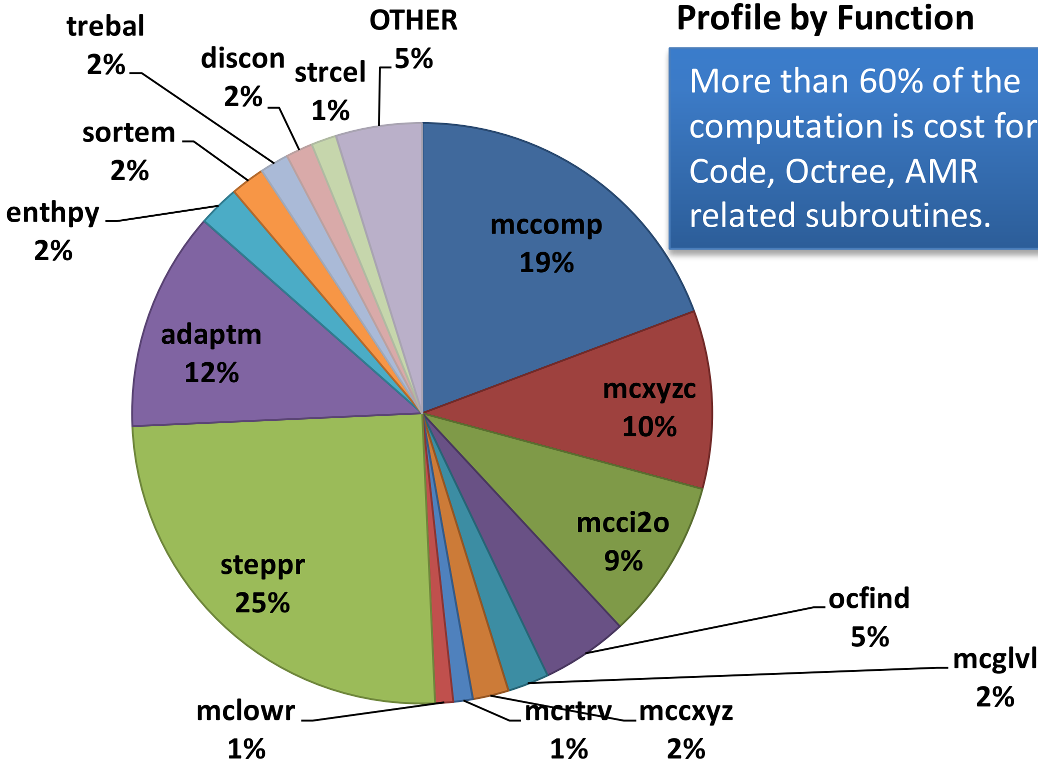
HAMISH with Fixed Mesh of **6400** cells



HAMISH with Adaptive Mesh of **3676** cells

Temperature at t=0.001

Next-Gen Code for UKCTRF



More than 60% of the computation is cost for M-Code, Octree, AMR related subroutines.

MCCOMP	Compares two Morton codes in their entirety
MCXYZC	Converts xyz coordinates into a Morton code at the specified level
MCCI2O	Converts an encoded integer array to an octal string
OCFIND	Searches the local Octree using a given Morton code
STEPPR	Time stepping of the solution, including calculating RHS
ADAPTM	Adapts the spatial mesh

Conclusions

- Thanks to ARCHER that a series of DNS/LES of SWTBLI flows can be done and the quality of the results is proved to be good.
- New flow structures and mechanisms are discovered based on the analysis of the data.
- AMR solver could be a game changer, although it is hard in term of coding.

Future Plans

- Improve performance of ASTR in terms of I/O and vectorization
- Improve the parallel performance and load balance of HAMISH
- Add more functionalities to HAMISH.

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