LA-UR-12-24518
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Intended for: Report

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Aug. 2012, LA-UR-12-XXXXX

GTRF Calculations Using Hydra-TH

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Abstract: This report describes the work carried out for completion of the Thermal Hydraulics Methods (THM) Level 3 Milestone THM.CFD.P5.05 for the Consortium for Advanced Simulation of Light Water Reactors (CASL). A series body-fitted computational meshes have been generated by Numeca's Hexpress/Hybrid, a.k.a. “Spider”, meshing technology for the V5H 3x3 and 5x5 rod bundle geometry used to compute the fluid dynamics of grid-to-rod fretting (GTRF). Spider is easy to use, fast, and automatically generates high-quality meshes for extremely complex geometries, required for the GTRF problem. Hydra-TH has been used to carry out large-eddy simulations on both 3x3 and 5x5 geometries, using different mesh resolutions. The results analyzed show good agreement with Star-CCM+ simulations and experimental data.

Milestone Execution Responsibility & Personnel

- J. Bakosi (LANL)
- Focus Area: THM
- CASL partners and staff:
  - Hydra-TH development and GTRF Calculations:
    M.A. Christon, M.M. Francois, R.R. Lowrie (LANL), R.R. Nourgaliev (INL)

- Contributors:
  - R. Pawlowski, T. Smith (SNL) – Meshing
  - E.E. Dominguez-Ontiveros, Y.A. Hassan (TAMU) – 5x5 experiments
  - R. Toedte, R. Sankaran (ORNL) – Visualization
  - J. Yan (WEC) – Star-CCM+ simulations

Milestone Description

- The THM.CFD.P5.05 L3 milestone focused on mesh generation and LES calculations with Hydra-TH for GTRF problems
- The milestone consisted of 5 sub-tasks:
    1) Implementation of run-time LES statistics into Hydra-TH
    2) Generation of Spider meshes for 3x3 and 5x5 rod bundles
    3) Implementation of passive and pressure outflow conditions
    4) New GTRF ILES calculations with Hydra-TH and analysis of results
    5) Documentation of results
- This milestone is a follow-up to L2:THM.CFD.P4.01, and provides data for L1:CASL.P5.02
- Level of effort approximately 6-7 man months (~$300k)

Implement Run-time LES Statistics (Task-1)

- In statistically stationary turbulent flows the means are computed by time-averages

$$\langle \phi \rangle \approx \frac{\sum_{i=1}^{N} \phi^i \Delta t^i}{\sum_{i=1}^{N} \Delta t^i}$$

- Higher-order statistics, e.g. the variance, are computed from the mean

$$\langle \phi'^2 \rangle = \langle (\phi - \langle \phi \rangle)^2 \rangle$$

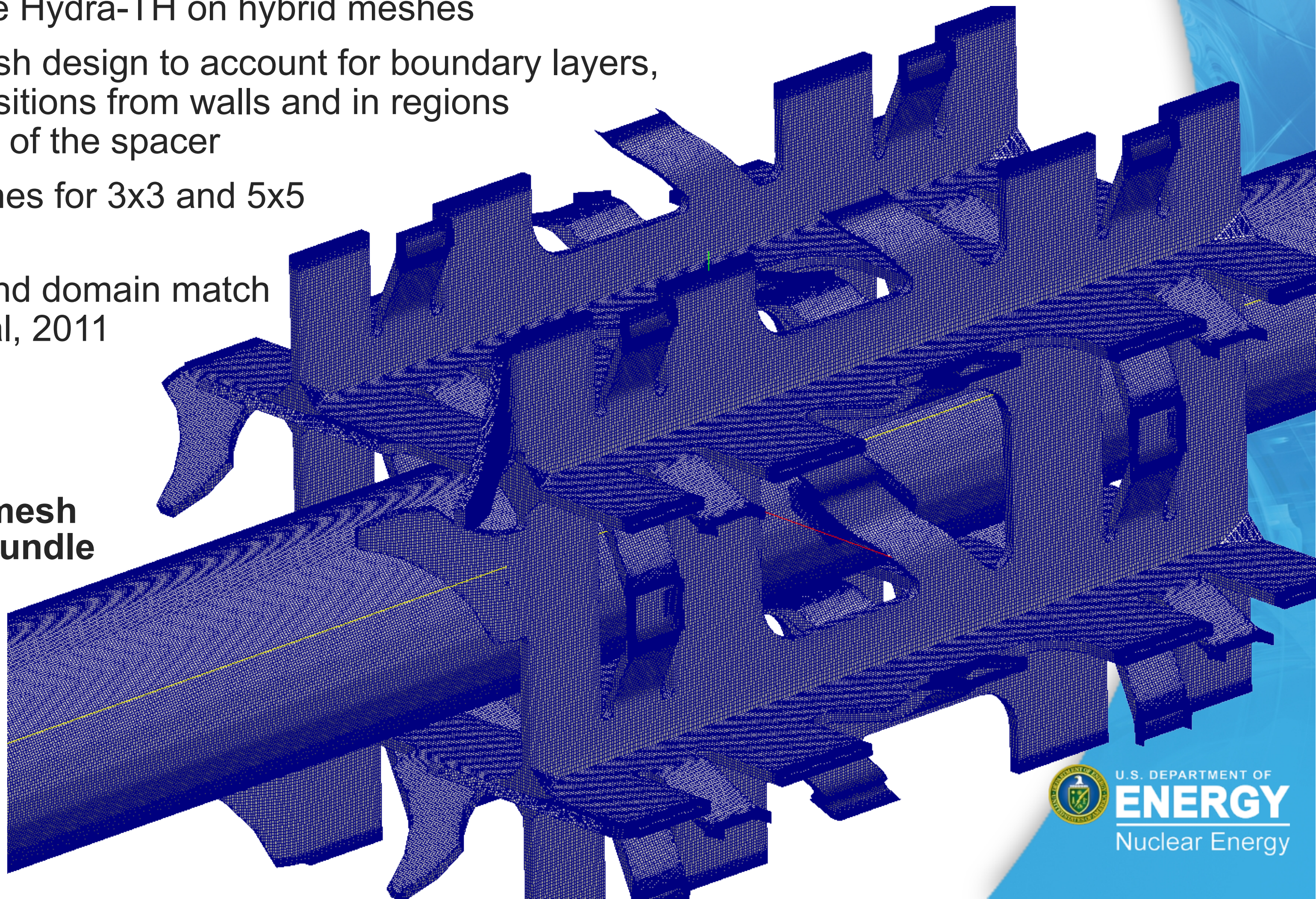
- Implementation in Hydra-TH
  - Computation of statistics is not a significant burden compared to the solution
  - General (*n*-correlations of scalars, vectors, tensors in cells, nodes, surfaces)
  - Easy to incorporate new statistics

Mesh Generation with Spider (Task-2)

Goals:

- Demonstrate Numeca's Hexpress/Hybrid (a.k.a. “Spider”) automatic hybrid meshing technology on GTRF
- Demonstrate Hydra-TH on hybrid meshes
- Improve mesh design to account for boundary layers, smooth transitions from walls and in regions downstream of the spacer
- Spider meshes for 3x3 and 5x5 rod bundles
- Geometry and domain match Elmahdi et al, 2011

47M Spider mesh for 3x3 rod bundle



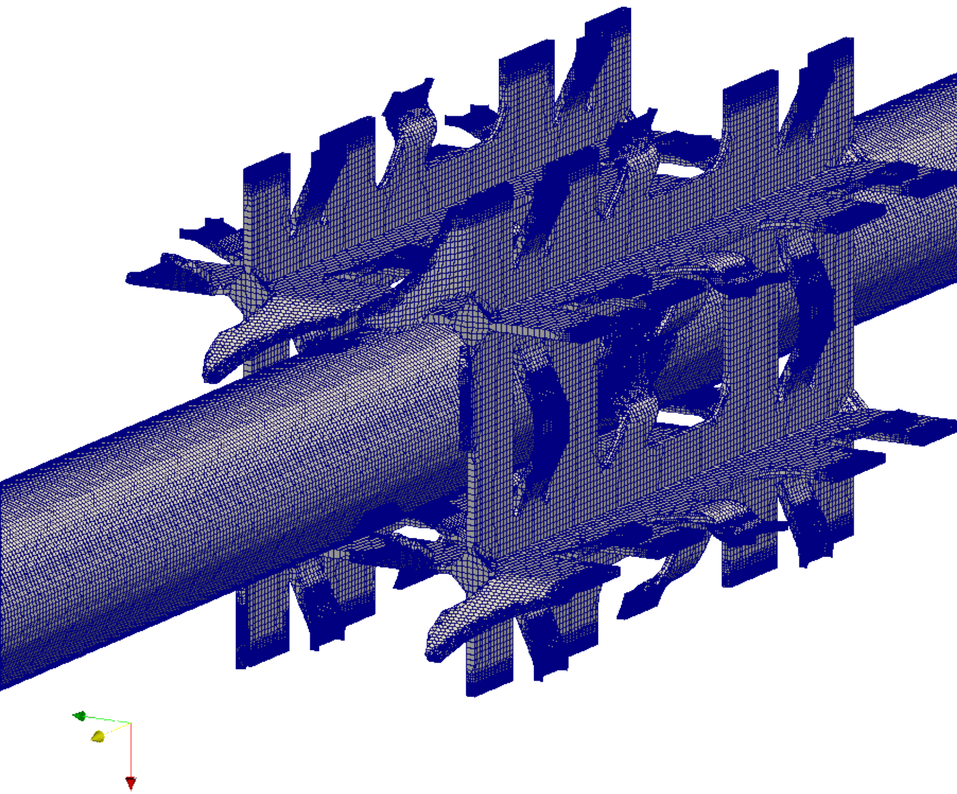
V5H Meshing Status

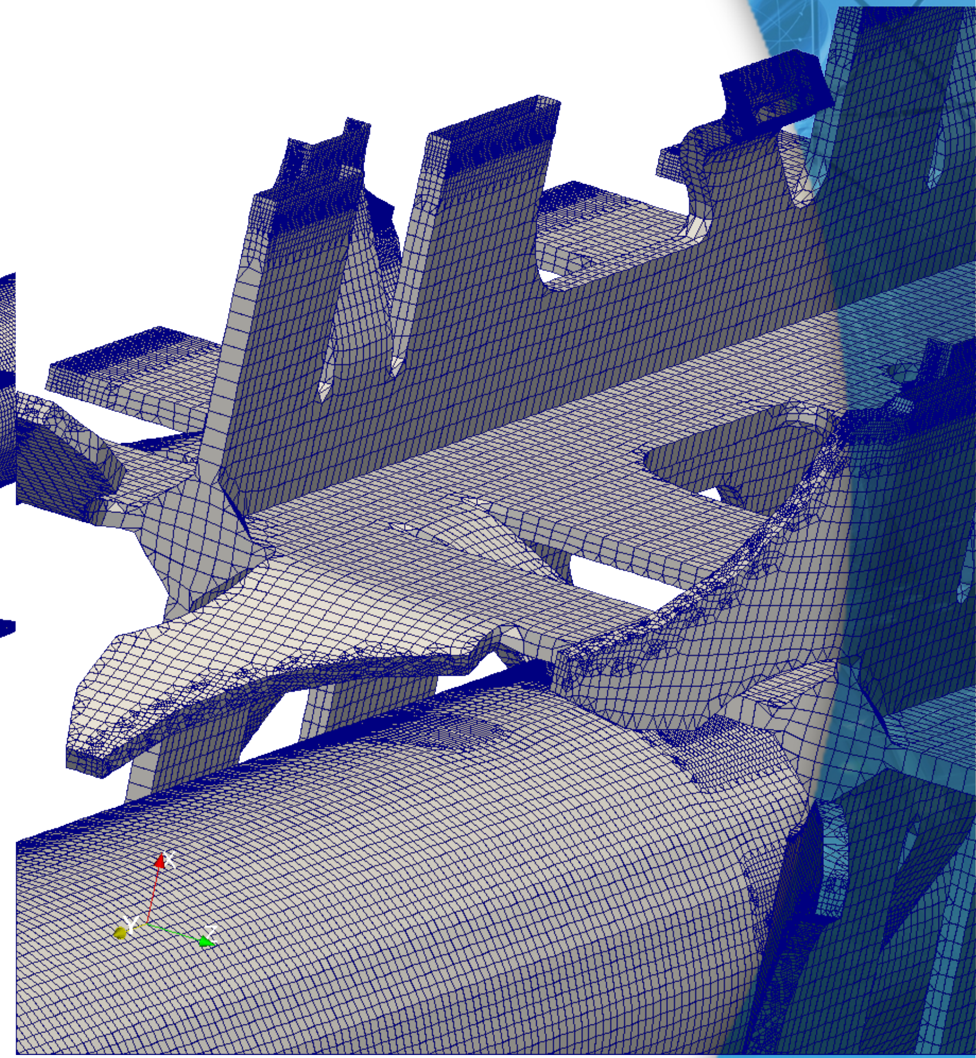
- 3x3 meshes generated: 2M, 7M, 30M, 47M, 80M, and 185M
- 5x5 meshes generated: 14M and 96M

Numeca's Hexpress/Hybrid (a.k.a. Spider) meshing technology

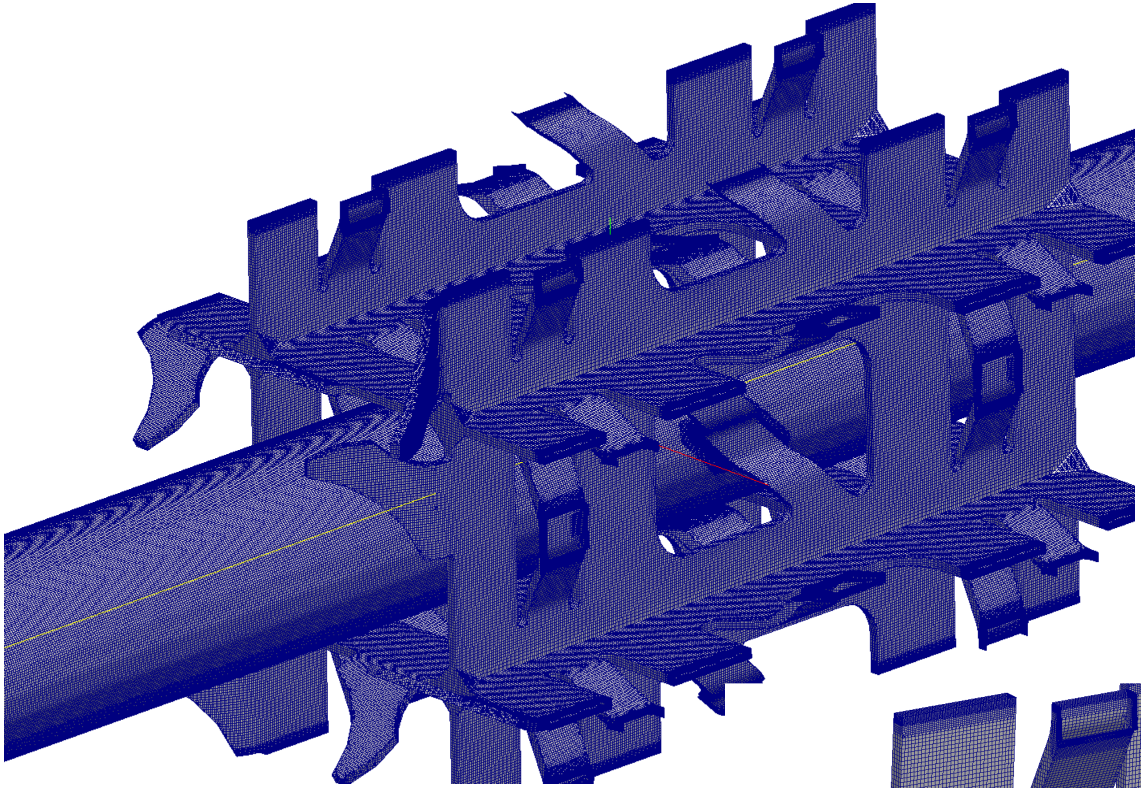
- **Fully automatic** mesh generation; text config file; batch mode
- Unstructured, hex-dominant, conformal hybrid meshes
- High quality viscous boundary layers
- Hole searcher to identify and close dirty CAD geometry
- Shared-memory parallel
- Memory requirements: 0.5GB / million cells
- **96M mesh in 80 mins** on 8-core workstation with 48GB RAM

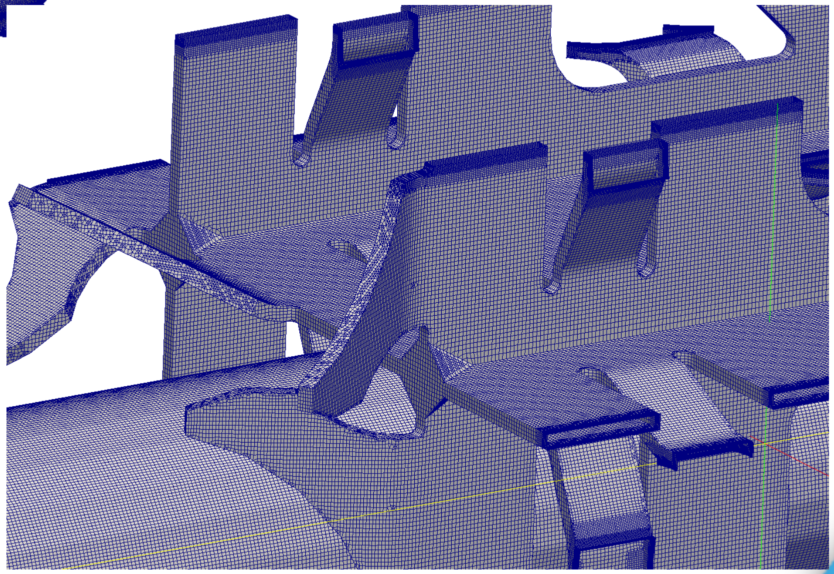
3x3 Spider Meshes: 7M



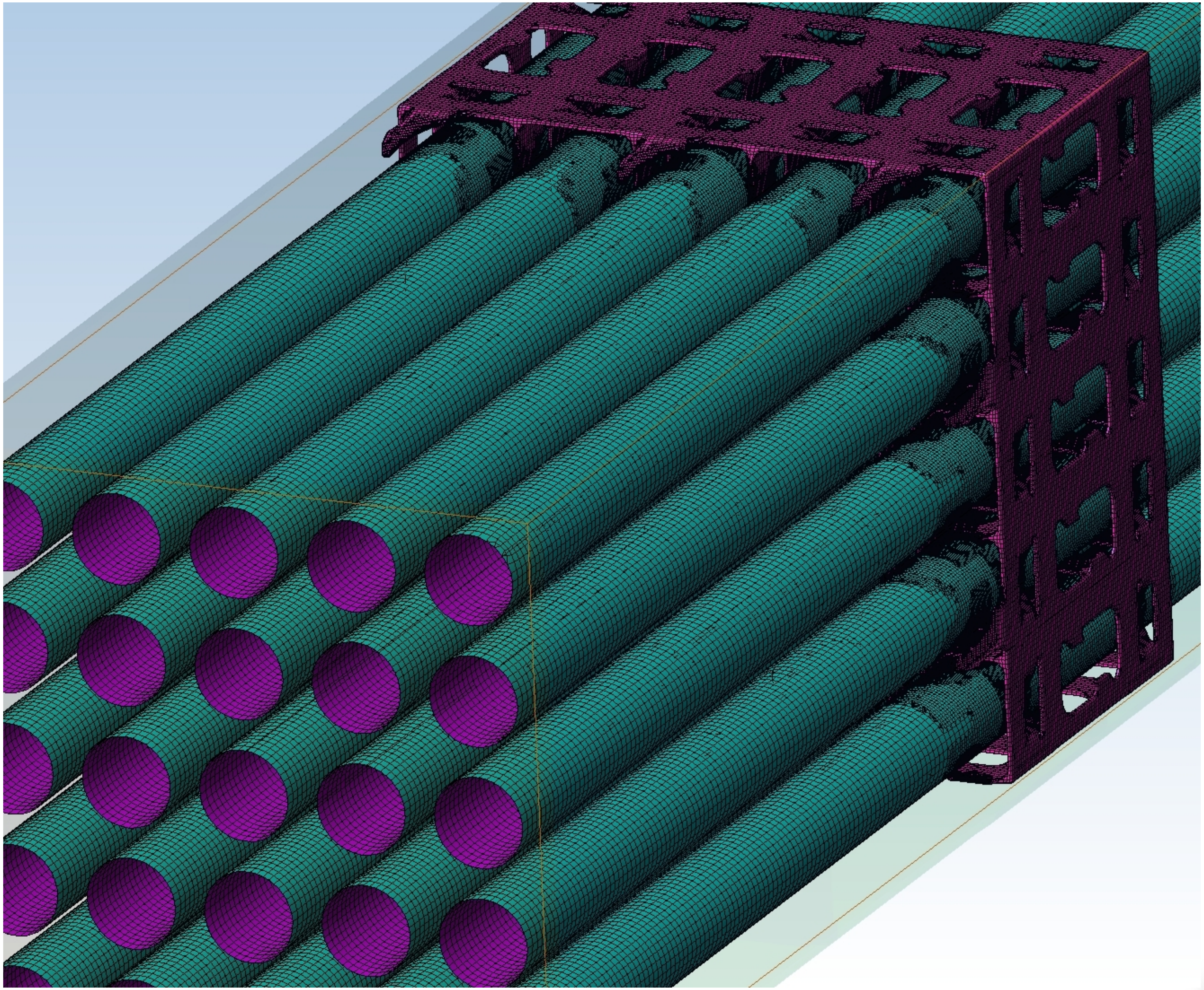


3x3 Spider Meshes: 47M





5x5 Spider Meshes: 14M



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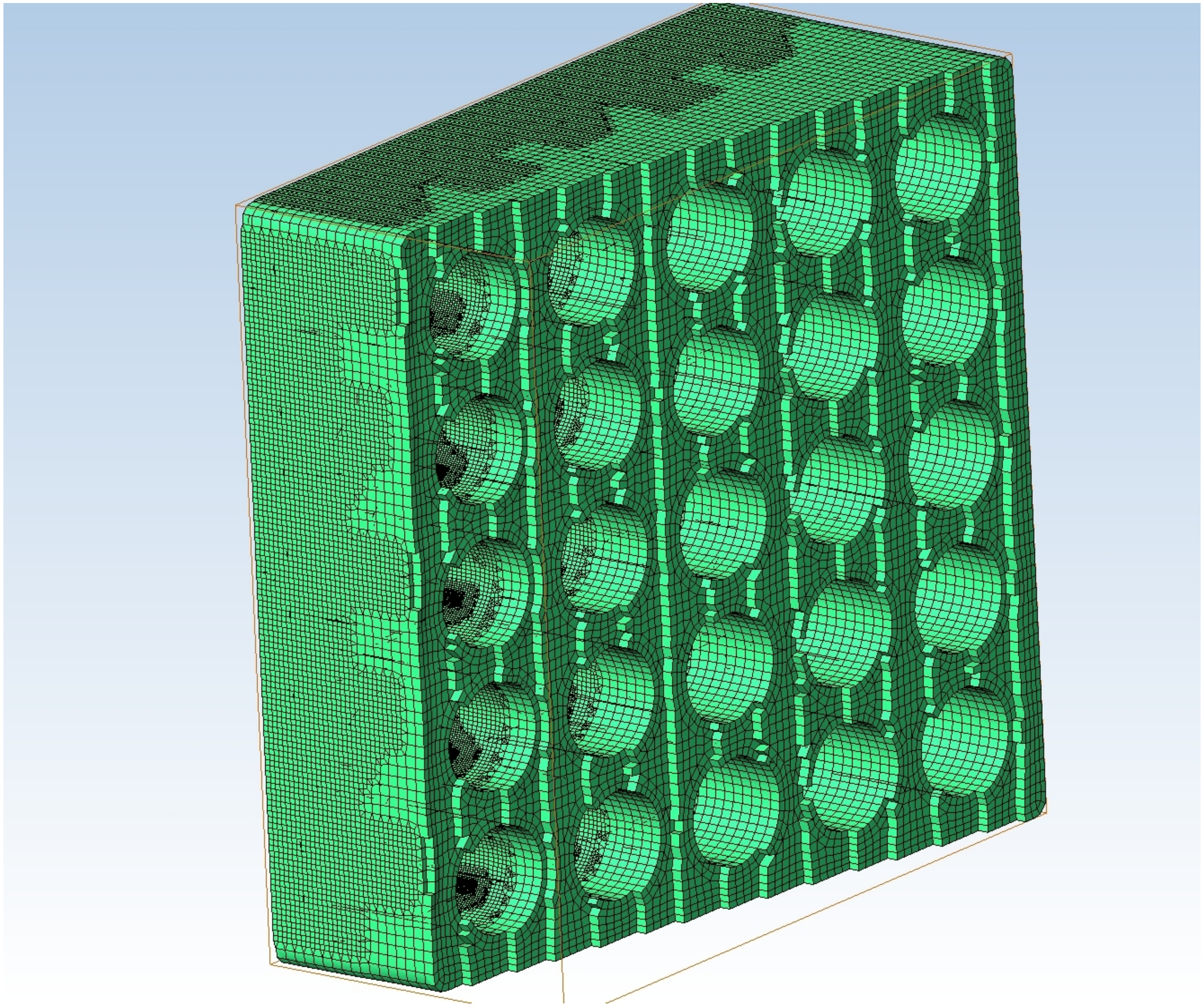
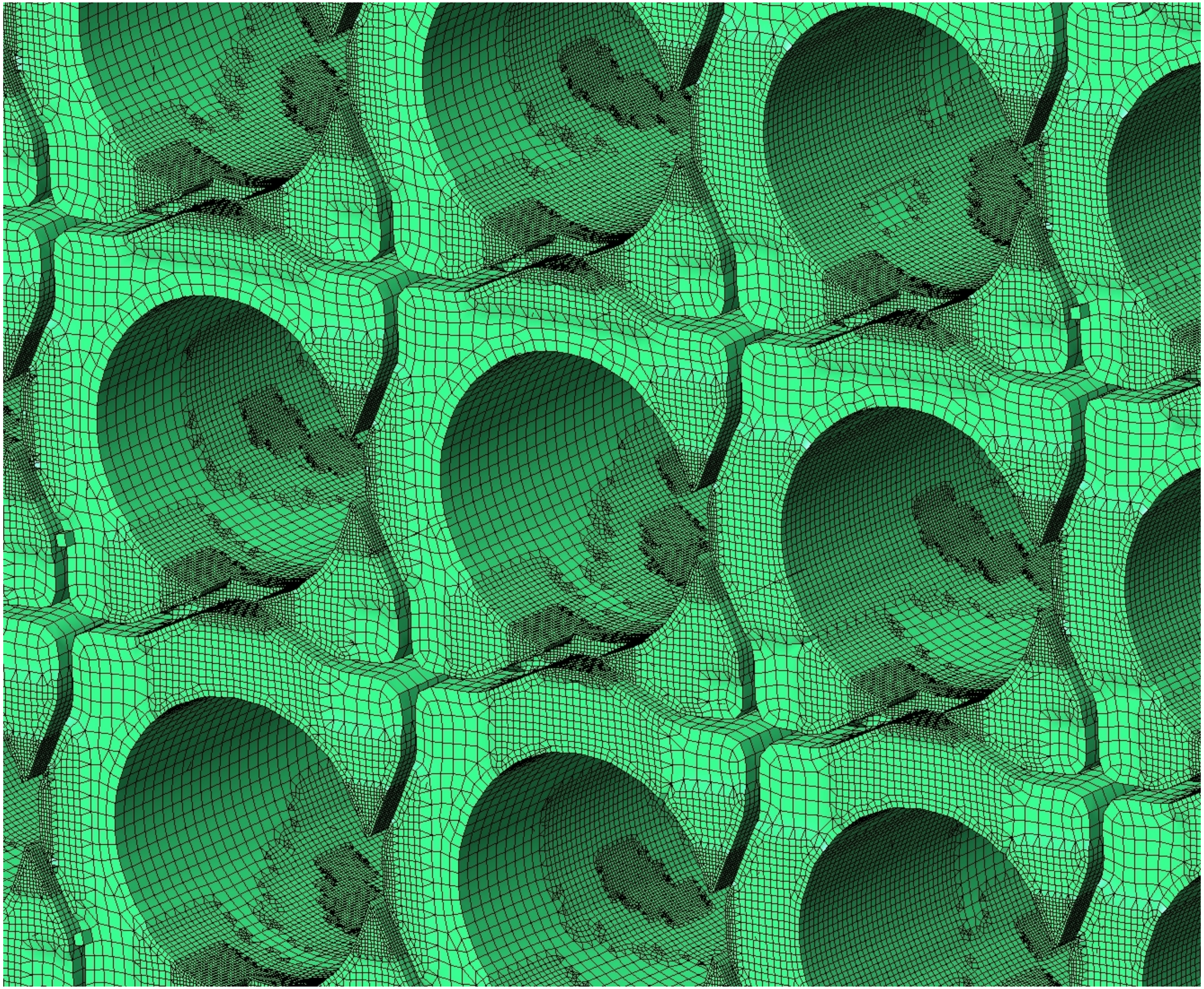
5x5 Spider Meshes: 14M



5x5 Spider Meshes: 14M



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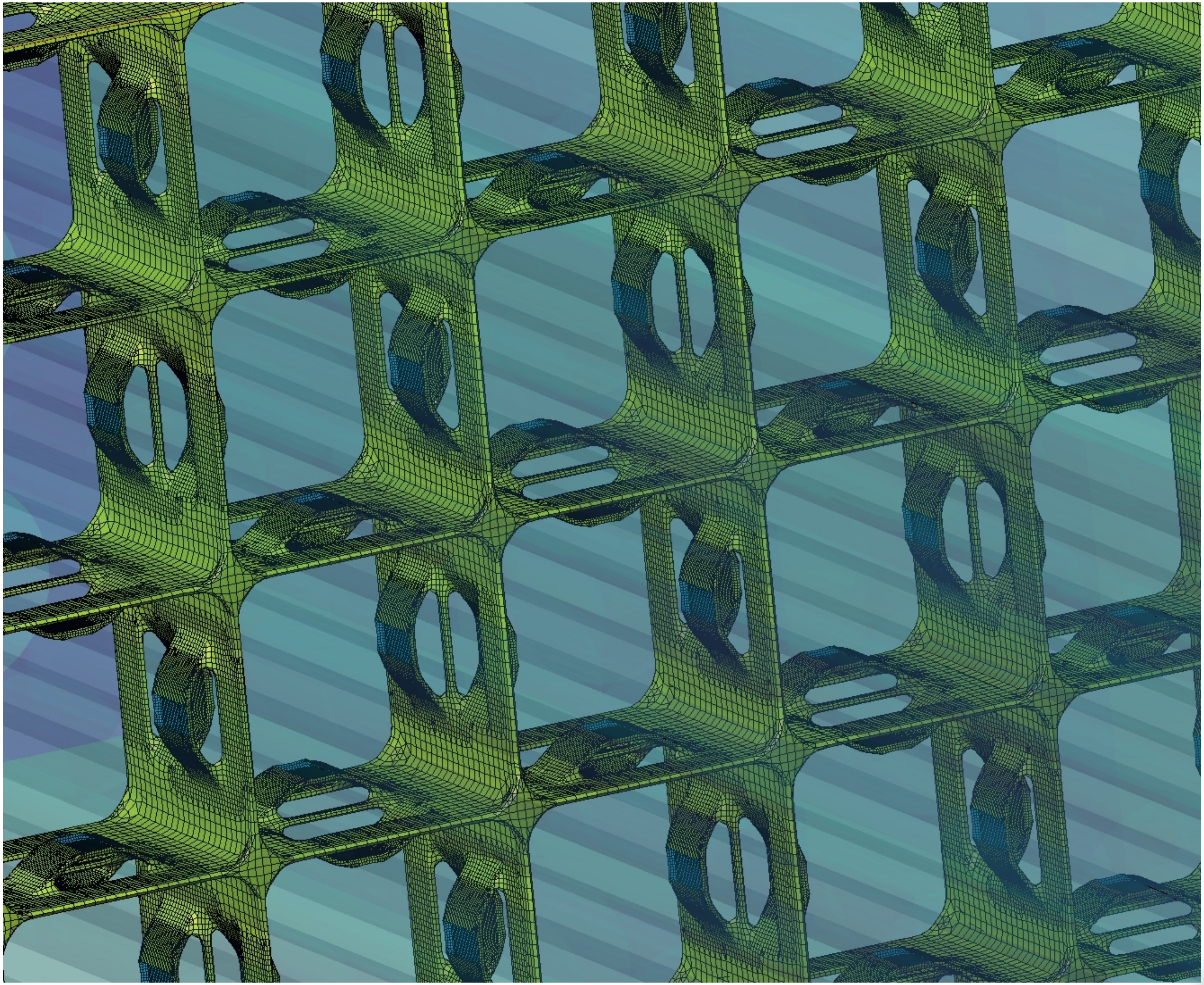
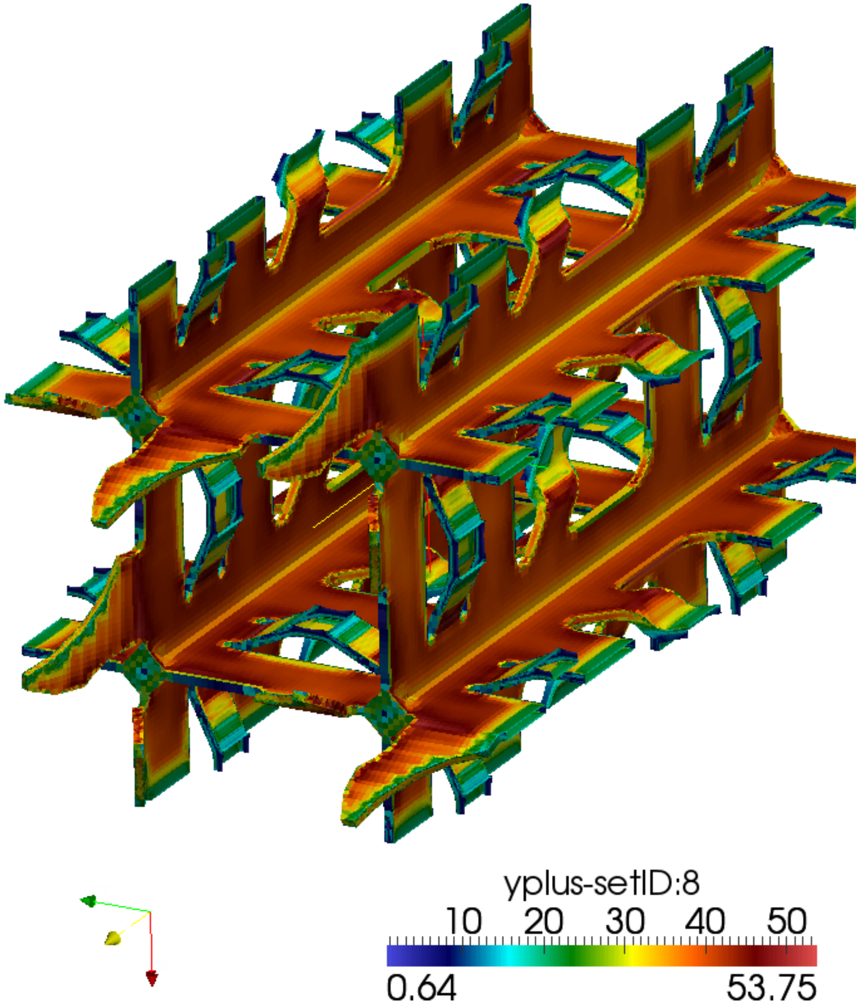
5x5 Spider Meshes: 14M

5x5 Spider Meshes: 14M

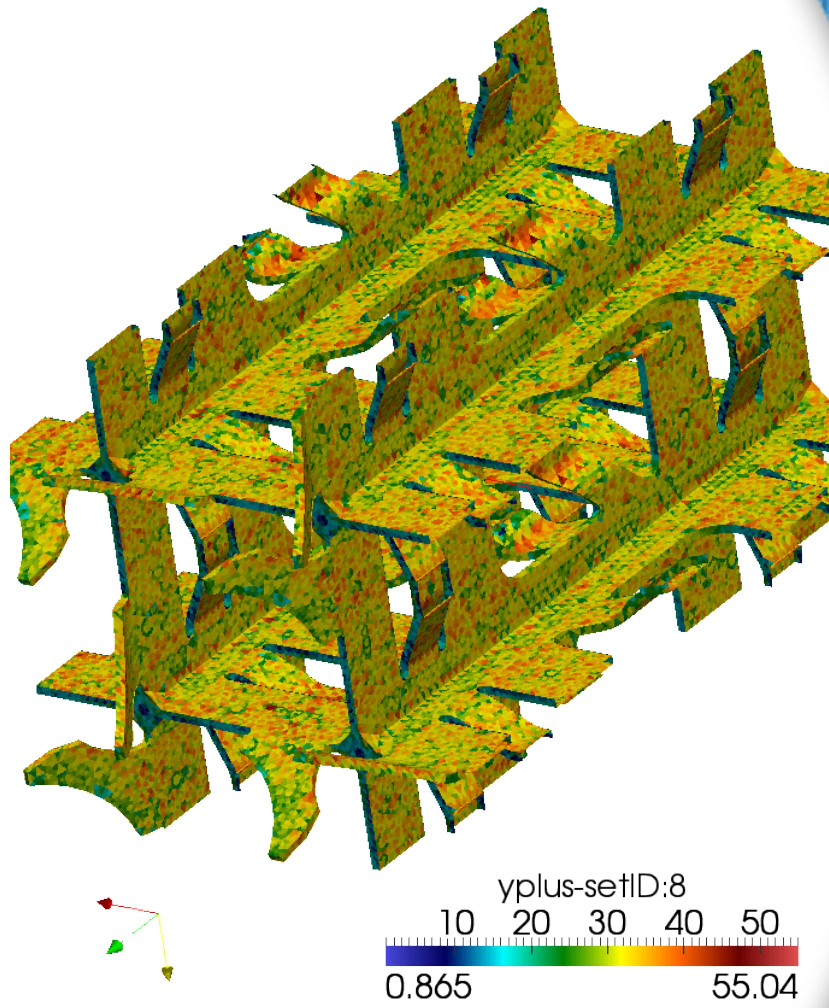


Mesh Assessment using y+

$$y^+ = \frac{y}{\nu}\sqrt{\frac{\tau_w}{\rho}}$$



y+ 7M Spider mesh



y+ 8.3M Cubit mesh

Desirable boundary meshes have uniform controlled y+ that is specific to the turbulence model

Mesh Assessment using y+

$$y^+ = \frac{y}{\nu}\sqrt{\frac{\tau_w}{\rho}}$$

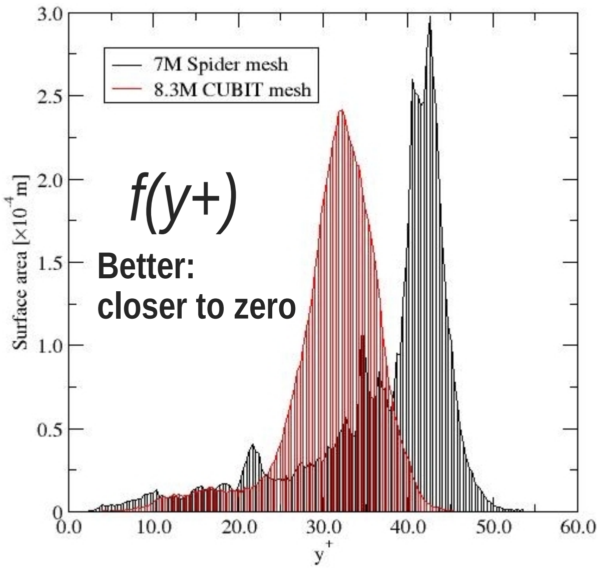
A priori quantitative mesh assessment for complex geometries

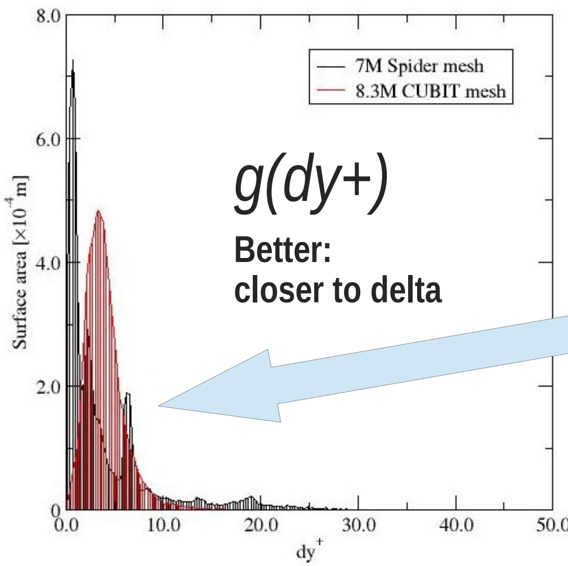
1) Average y+ – *How well the boundary layer is resolved?*

$$\langle y^+ \rangle \equiv \int y^+ f(y^+) \mathrm{d}y^+ \approx \sum y^+ f(y^+) \Delta y^+$$

2) Spatial uniformity of y+ – *How good is the mesh quality at walls?*

$$\mathrm{TV}(y^+) \equiv \int g(\mathrm{d}y^+) \mathrm{d}(\mathrm{d}y^+) \approx \sum g(\Delta y^+) \Delta(\Delta y^+)$$





Cubit spike shifted to right = Poor uniformity near walls = May lead to unphysically perturbed boundary layers

Implementation of Passive and Pressure Outflow Conditions (Task-3)

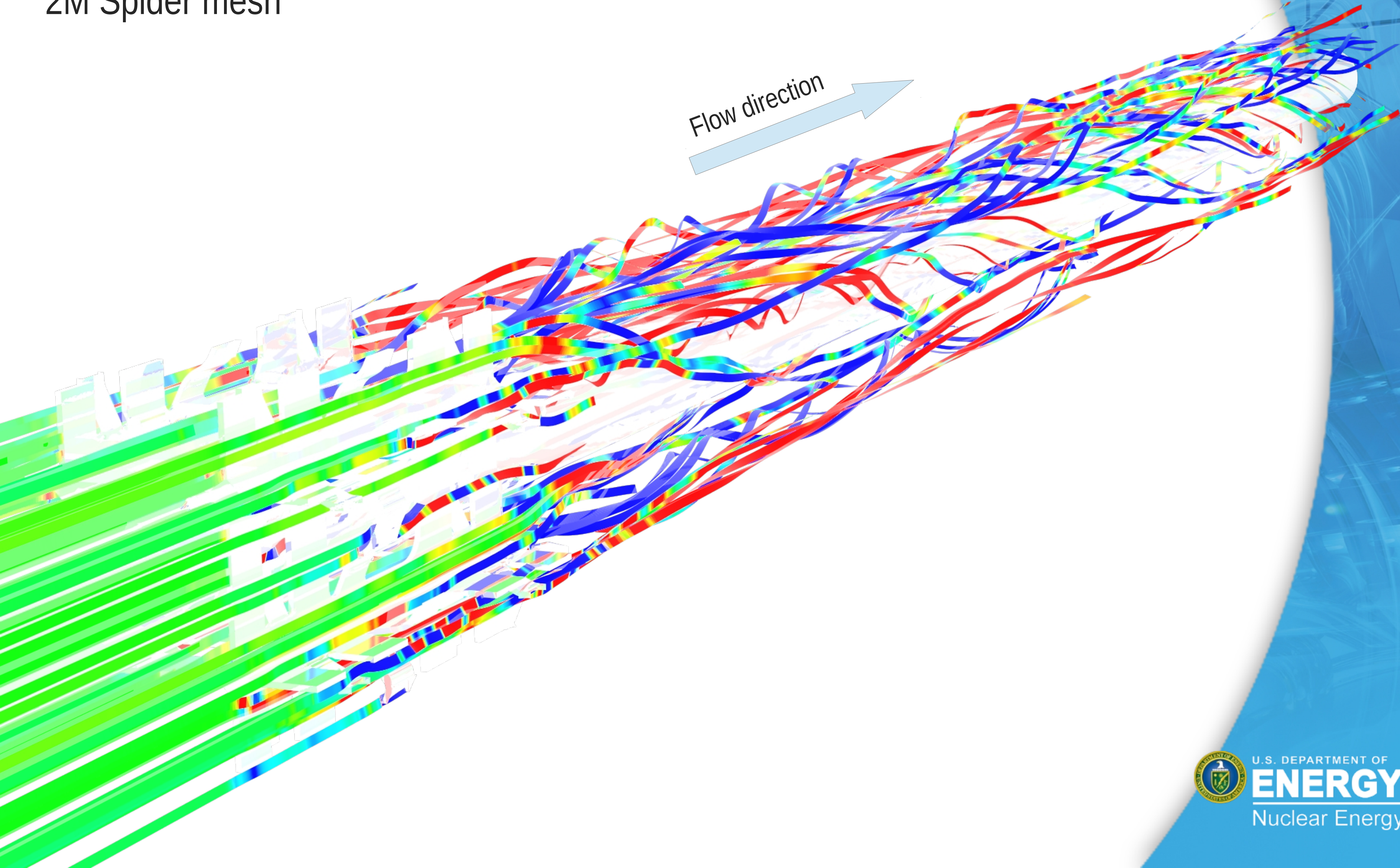
- Originally planned implementing periodic boundary conditions
  - Preliminary functionality completed, *however*
  - 5x5 meshing and runs were prioritized instead
- Passive and Pressure outflow conditions implemented
  - No significant difference in pressure field based on 2M LES run
  - Kept homogeneous Dirichlet for pressure and homogeneous Neumann conditions for velocity at outflow
  - For sufficiently long domains this is reasonable as demonstrated in milestone document

New ILES GTRF Calculations of Isothermal Turbulent Flow with Hydra-TH (Task-4)

- Purpose
  - Need to learn about the physics of the flow
  - Collect turbulence statistics
  - Validation of Hydra-TH with Star-CCM+ and experiments
  - Need baseline(s) for development of RANS model(s) for GTRF
  - Assess Cubit & Spider meshes
- 3x3 runs completed to *t=1s*:
  - Cubit: 672k, 1M, 3M, 6M, 12M
  - Spider: 2M, 7M (30M, 47M running)
- 5x5 run completed to *t=1s*:
  - 14M (96M running)

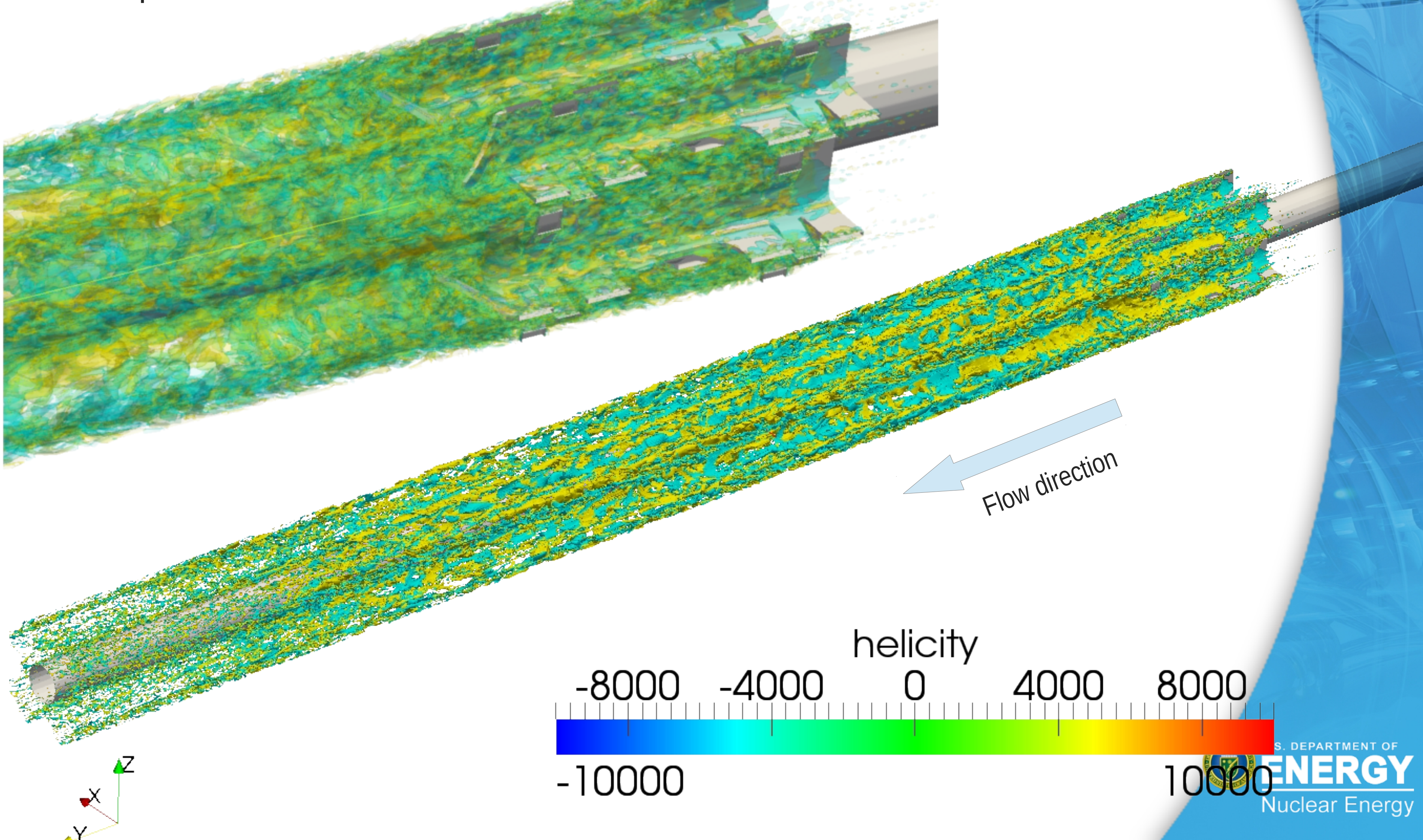
Pretty pictures

Instantaneous velocity streamlines colored by helicity $(\mathbf{v} \cdot \omega)$
2M Spider mesh



Pretty pictures

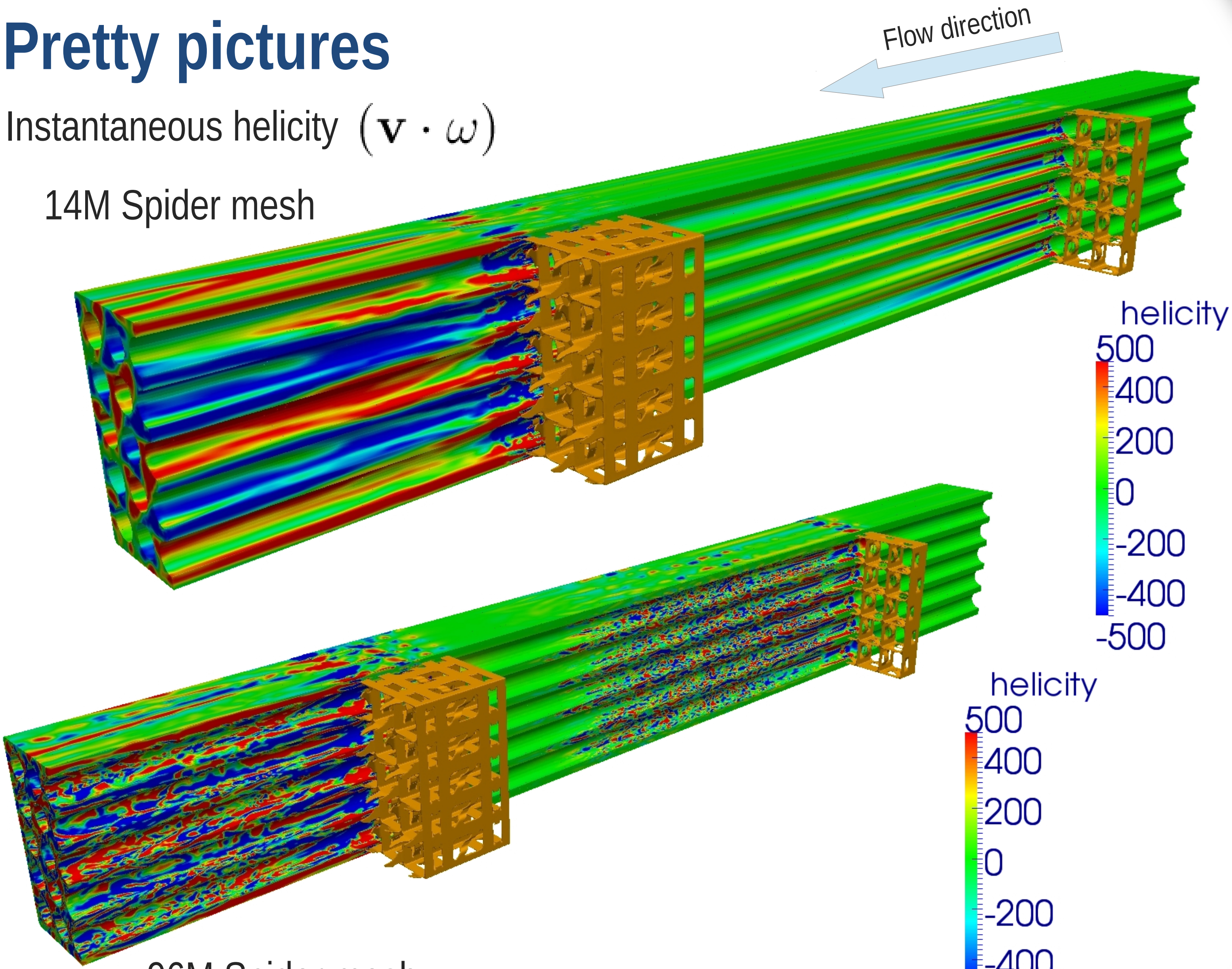
Instantaneous helicity isosurfaces $(\mathbf{v} \cdot \omega)$
47M Spider mesh



Pretty pictures

Instantaneous helicity $(\mathbf{v} \cdot \omega)$

14M Spider mesh



96M Spider mesh

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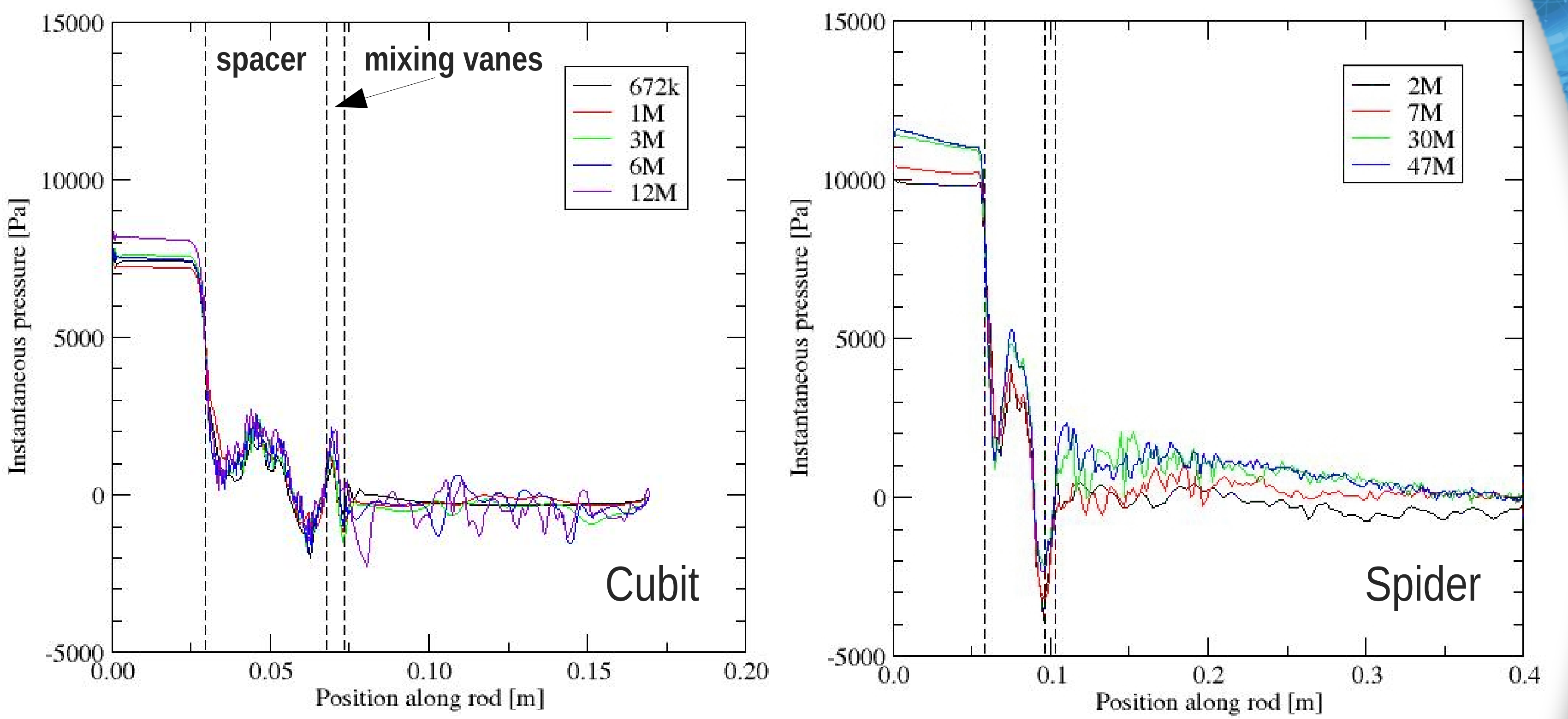
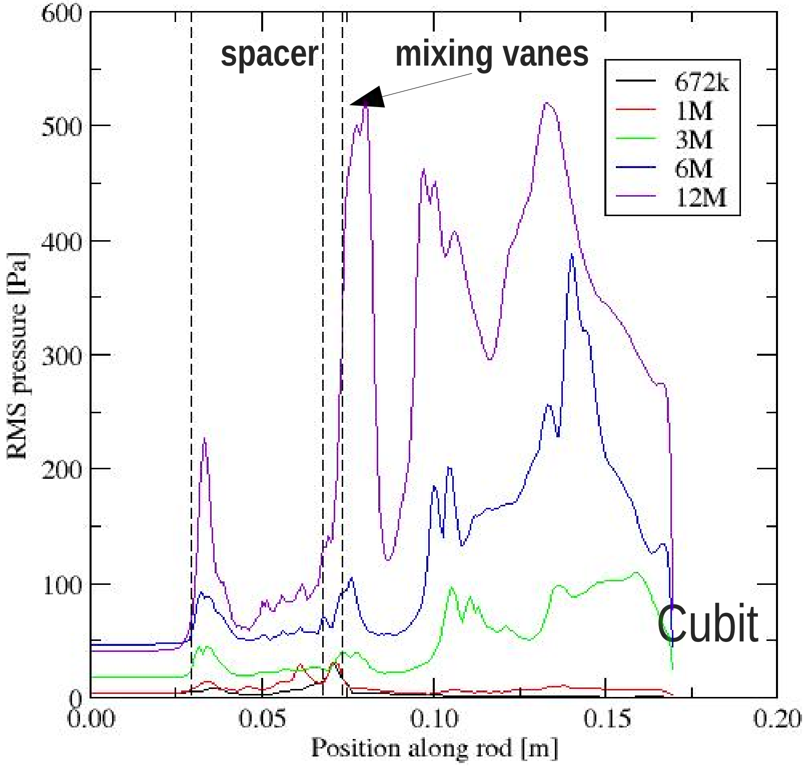
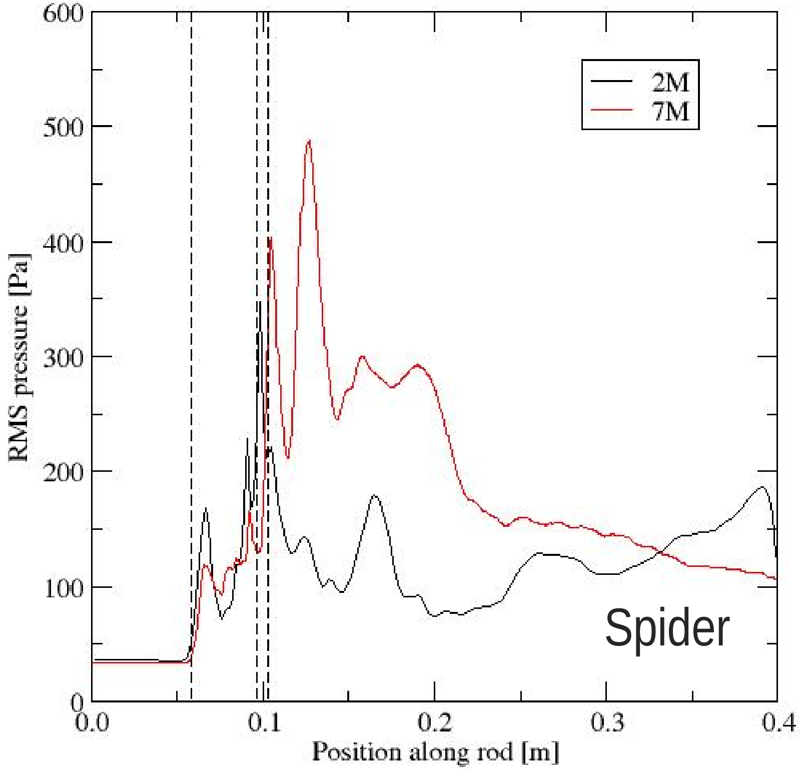
Main findings based on 3x3



- Pressure profiles significantly different between Spider and Cubit
  - Different mesh generation technology
  - ~50% shorter domain length for Cubit meshes
  - Inadequate mesh resolution

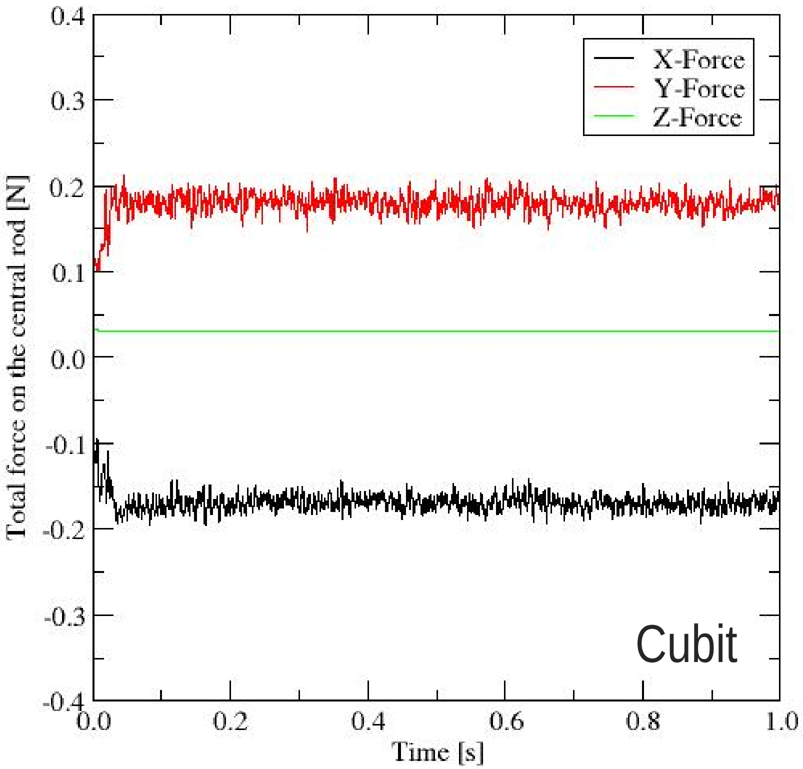
Main findings based on 3x3

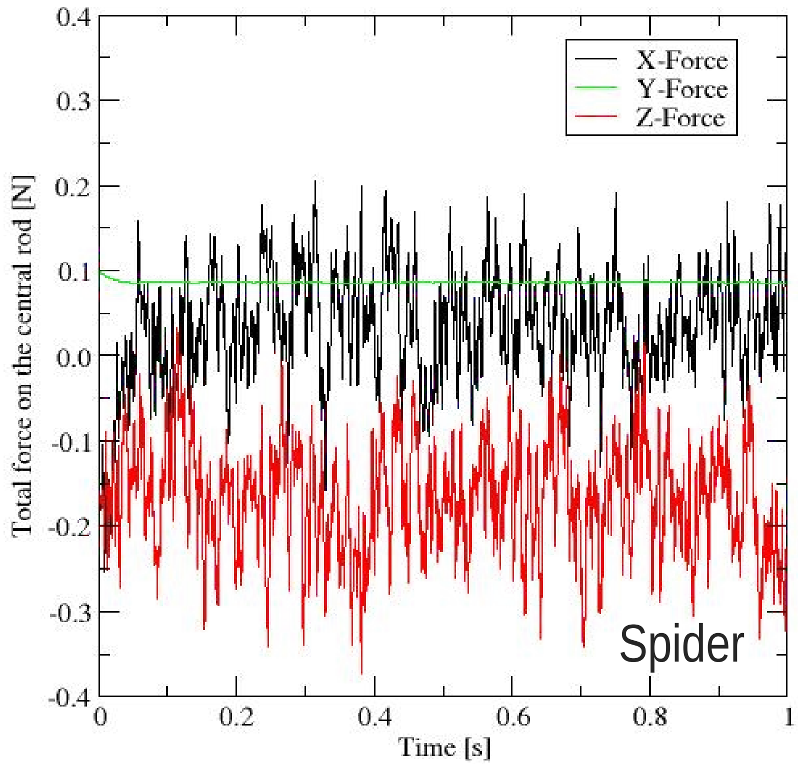




- RMS pressure profiles significantly different between Spider and Cubit
  - TKE (and RMS pressure) should peak at mixing vanes
  - Cubit RMS pressures peak far downstream, increase with refinement

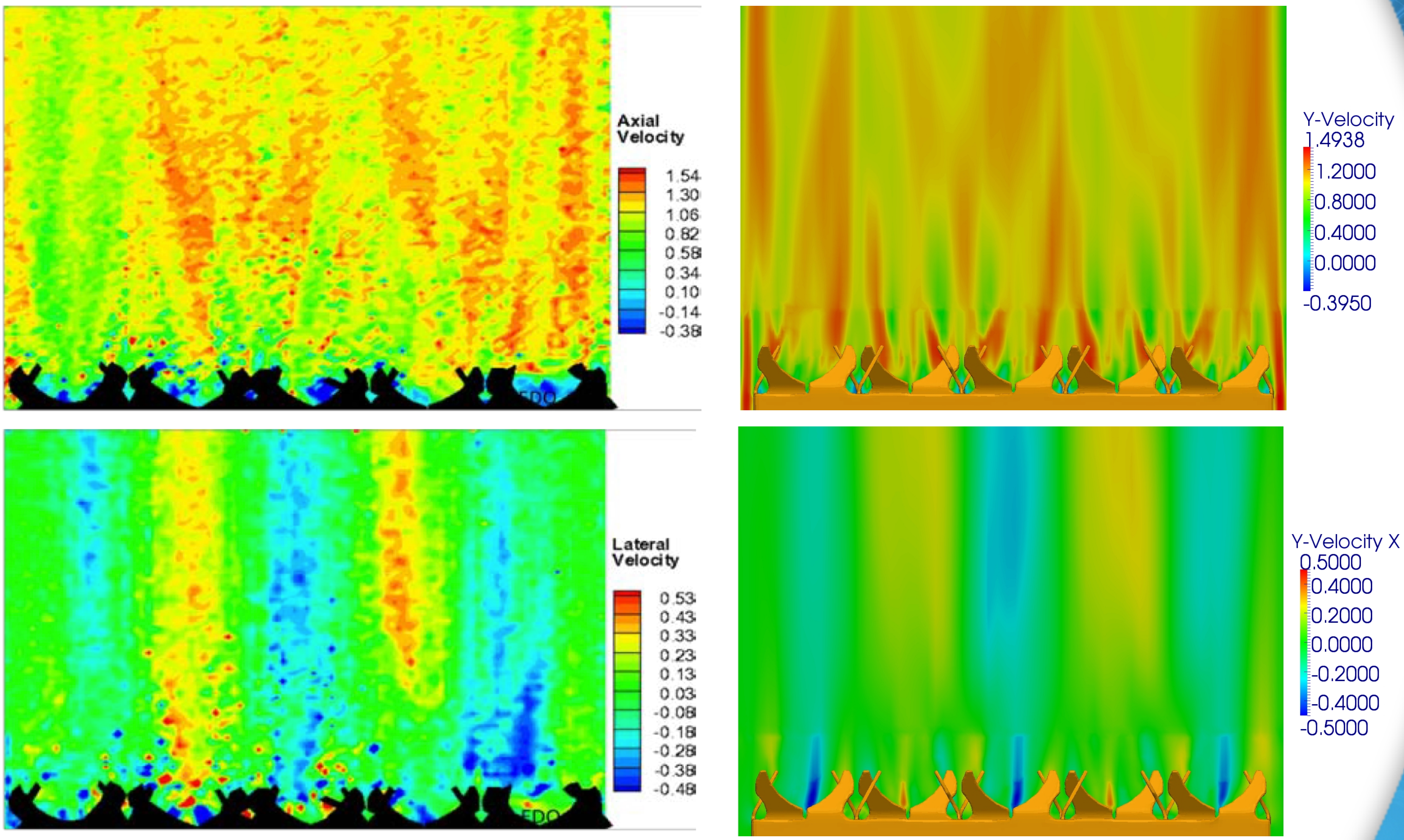
Main findings based on 3x3





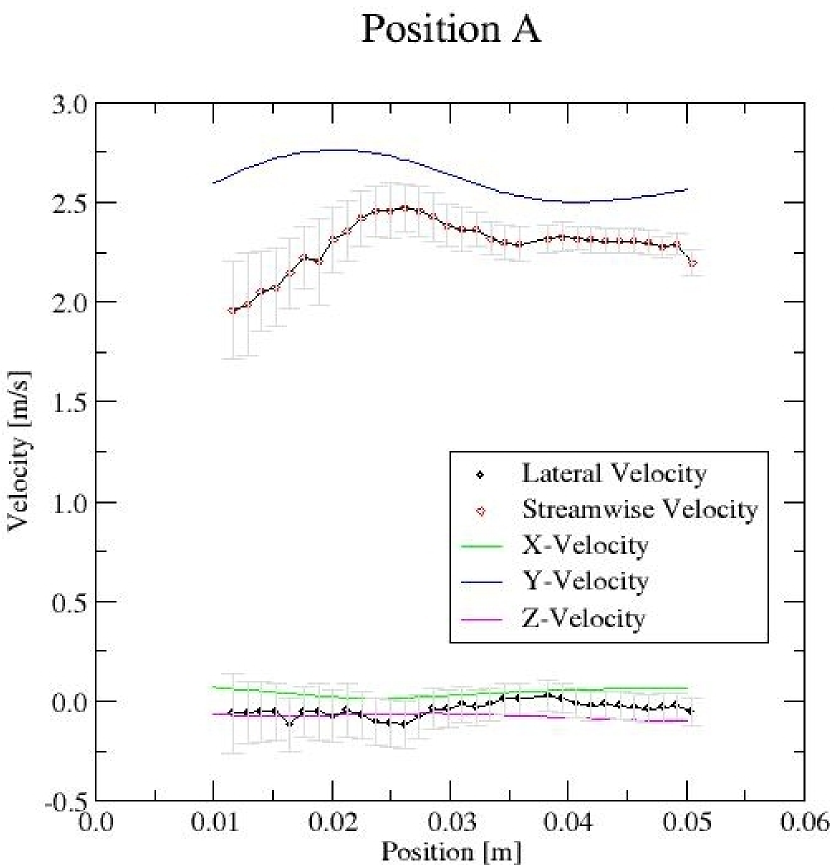
- RMS forces differ by an order of magnitude between Spider and Cubit
  - Increased force amplitudes appear to be due to better wall-resolution
  - Note: coordinate system is rotated C(x, y, z) = S(x, -z, y)

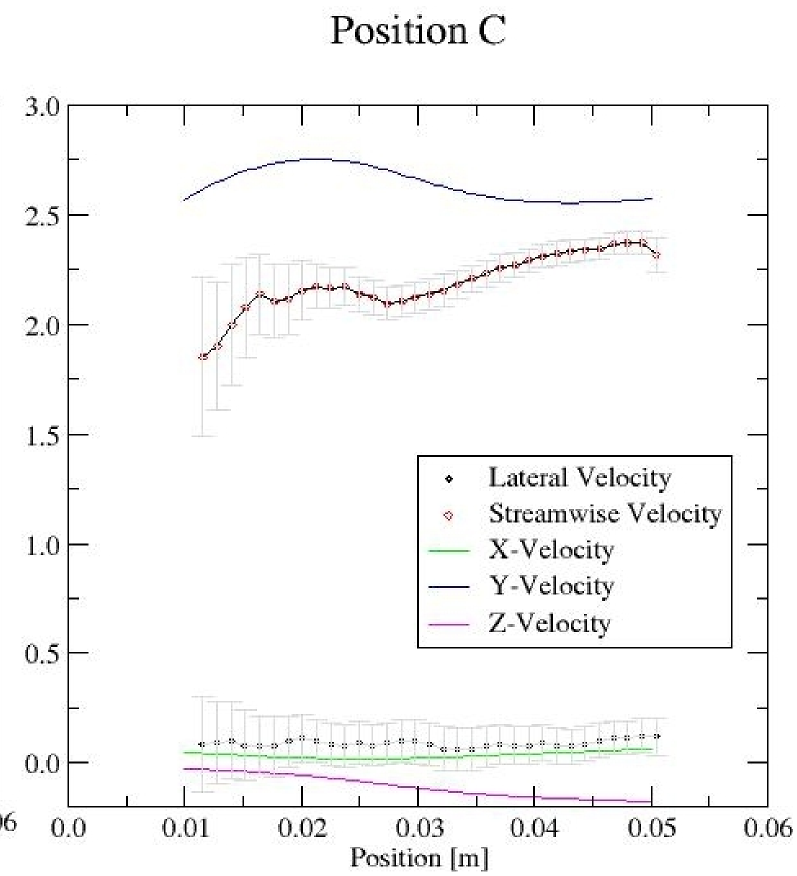
Preliminary findings based on coarse 14M 5x5



Predicted mean peak velocities within 5% of experiments

Preliminary findings based on coarse 14M 5x5





Predicted mean velocity profiles show correct trend

- 14M too coarse to accurately predict mean velocity (let alone RMS)
- 96M run underway

Summary

- THM.CFD.P5.05 L3 milestone focused on mesh generation and LES calculations with Hydra-TH for GTRF problems
- **Conclusions**
  1) Numeca's Hexpress/Hybrid (Spider) is excellent for mesh generation for arbitrary complex geometries
  2) Generated & assessed Spider meshes for 3x3 and 5x5 rod bundles
  3) New GTRF calculations with Hydra-TH show good agreement with Star-CCM+ and experiments
  4) RMS forces on rod inadequate with Cubit meshes
- **Future directions**
  1) Power-law-graded boundary-layer meshes
  2) Turbulence models other than ILES
  3) Development of RANS models
  4) Fluid-Solid/Structure Interaction