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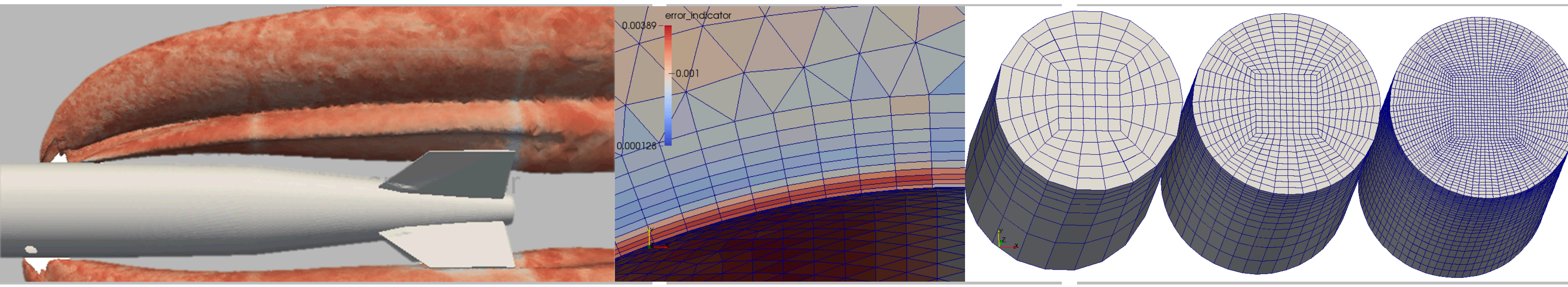

Offline Mesh Adaptivity for Fluid/Thermal Applications

VERIFICATION VALIDATION™

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Motivation
- Dynamic versus offline adaptivity
- Example: thermal
- Boundary layer adapt
- Example: RANS aero
- Summary

Motivation

- Solution verification: estimating and reducing uncertainty (error) from numerical approximations / discretizations
- Baseline method: compare solutions computed on different discretizations – using uniform refinement/re-meshing
- This is expensive but generally reliable
- Adaptive approaches seek to generate non-uniform discretizations with fine scale only where needed
- The result is acceptable accuracy at the lowest cost (ideally)
- What is the best way to perform adaptivity?

Dynamic vs. Offline Adaptivity

- Some problems optimally require dynamic adaptivity
  - Wave propagation, evolution of dynamic shocks
- Other problems are less dynamic and adaptivity may be applied as an outer loop, to a fixed subregion
- An example application is modeling of system response to an abnormal thermal environment
- Dynamic adaptivity may fail to be robust enough for complex multi-physics analysis
  - High cost to re-compute viewfactors in thermal radiation
  - Lack of robustness over all physics sub-models
  - Uncertain run-time (and no restart)
- Where possible we have compared the dynamic and the offline approach

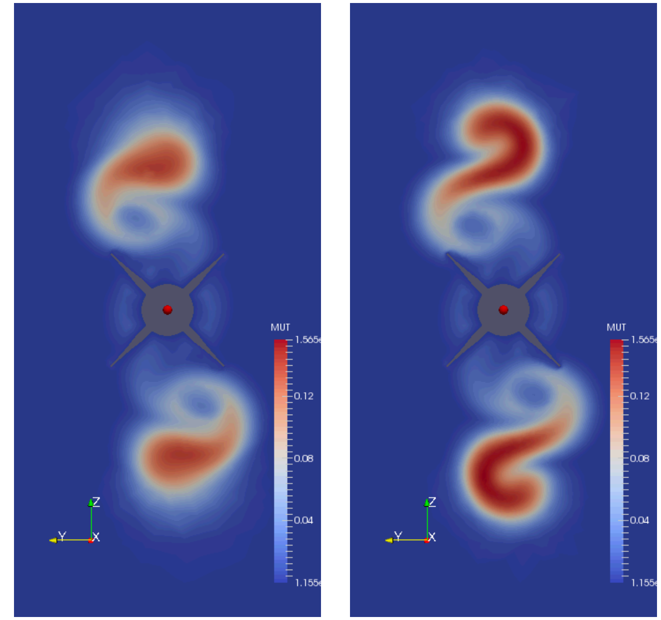
Related Work

- Optimization approaches (outer loop around transient)
  - Meidner and Vexler, *SIAM J. Control Opt* (2007)
- Block adaptivity in time
  - Carey, Estep, Johansson, Larson, and Tavener *SISC* (2010)
- Space-time adaptivity
  - Besier and Rannacher, *IJNMF* (2011)

Percept – Tools for Verification

Percept is a library that provides parallel capabilities tested up to tens of billions of element cells, for

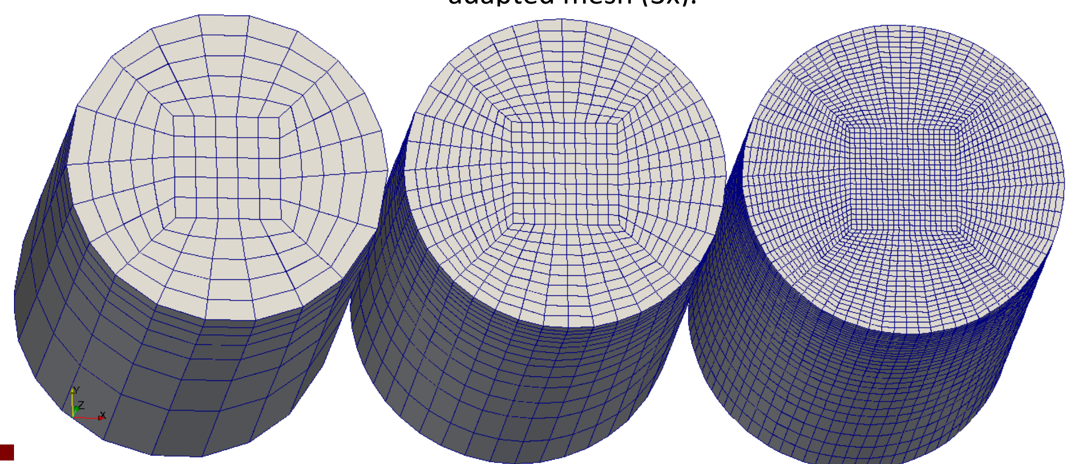
- AMR (Adaptive Mesh Refinement), creating conforming meshes with transition elements.
- UMR (Uniform Mesh Refinement) for mixed and hybrid meshes including Tet, Hex, Pyramid, Wedge, Shell, Bar elements.
- Offline and dynamic adaptivity and refinement.
- Respecting either a fitted CAD geometry or a fitted *mesh based geometry*.
- Promotion of linear elements to quadratic.



Rear view of vortices arising from B61 jet in cross flow using coarse mesh (left) and offline adapted mesh (3x).

Uniform refinement of open jet flow mesh. Detail near inlet where mesh is adapted using mesh-based approximate geometry.

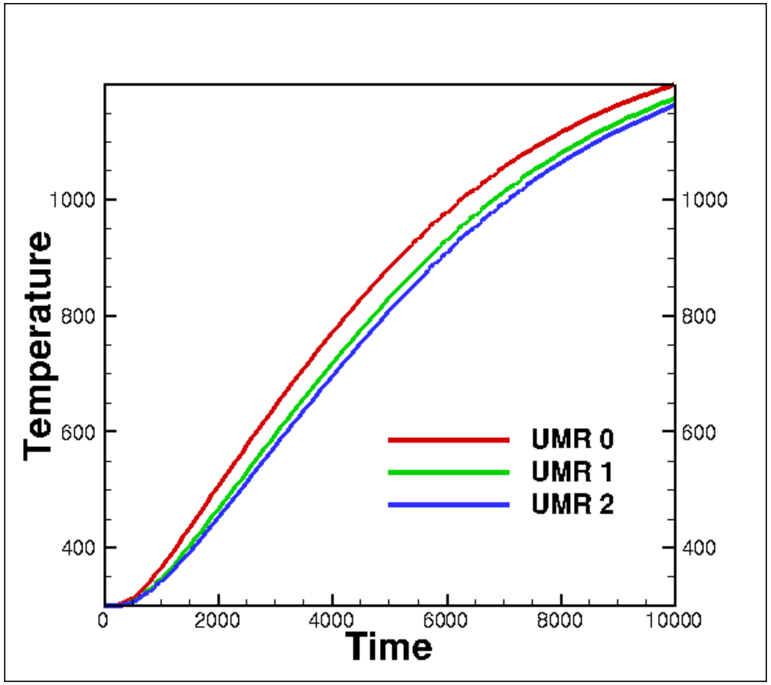
Base mesh is 60K elements. Goal is to refine to 20B elements for scaling study.



Thermal Example

Example: Transient Thermal

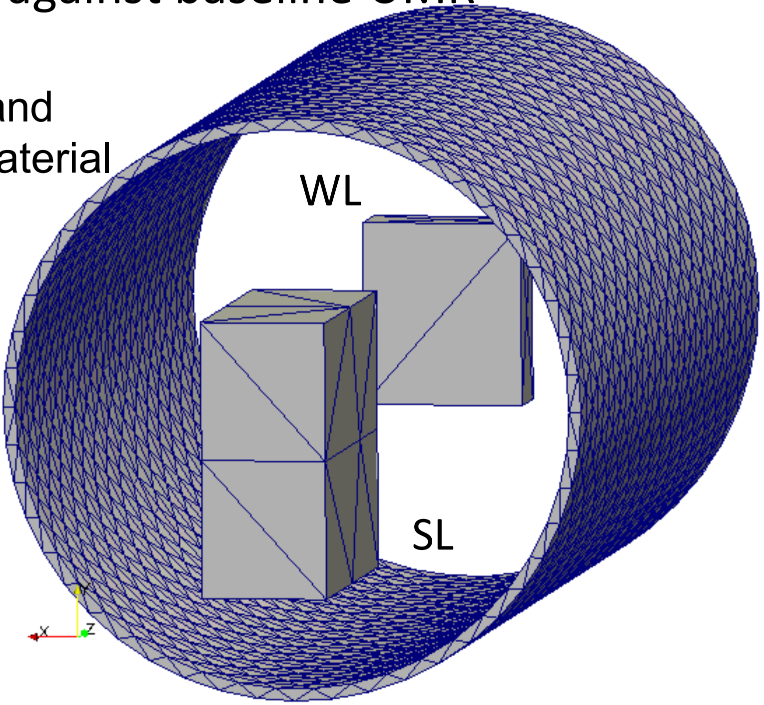
- Problem: Determine time history of temperatures within regions
- Physics: nonlinear heat conduction with radiative forcing (realistic properties and environment)
- QoIs are min/max/avg/point value of temperature over mock components (SL/WL)
- Goal: compare dynamic and offline adaptivity against baseline UMR



Time history of temperatures

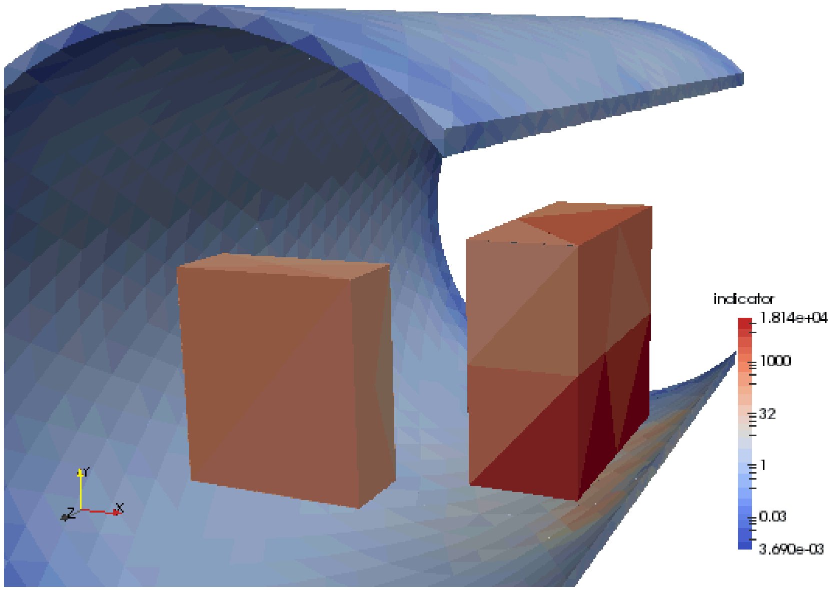
Three uniformly refined meshes (convergence)

Locations of components and case; foam material not shown

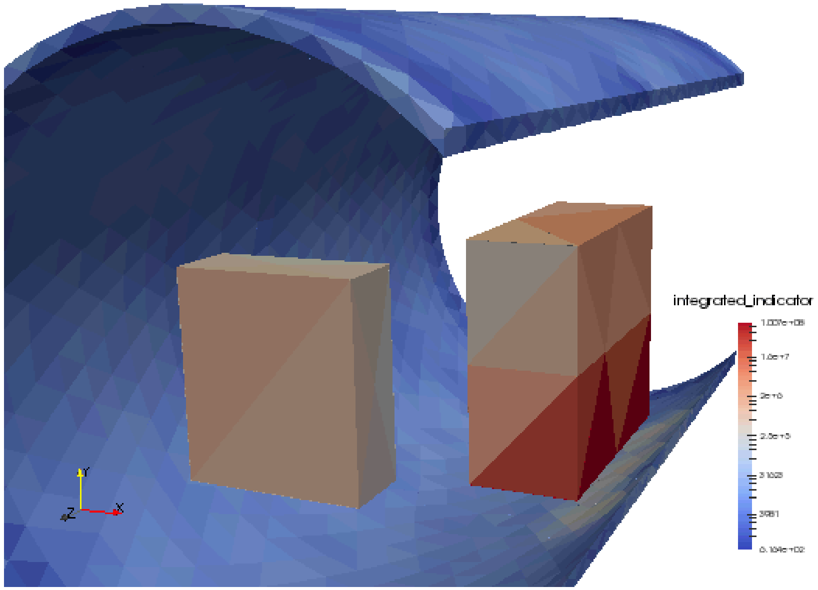


Spatial Error Indicators

- Local error indicator: error in local temperature gradients (using gradient patch recovery)
- For offline adaptivity, we integrate the element error contributions over the time interval
- This error indicator is **not** guaranteed to reduce the error for in our chosen QoIs



Instantaneous error indicator at t=4500



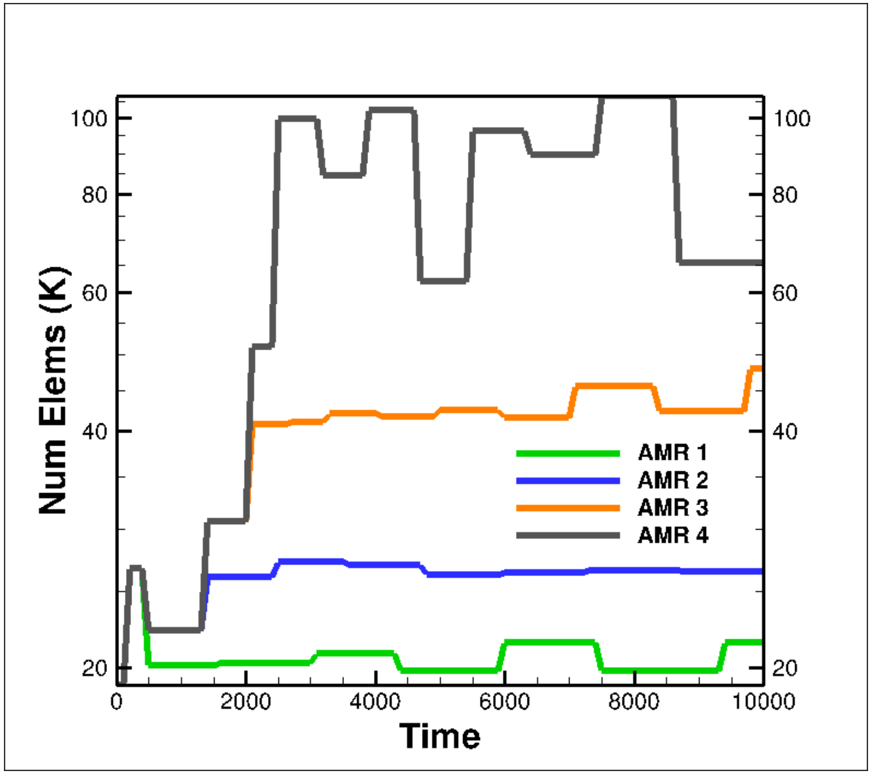
Time integrated error indicator

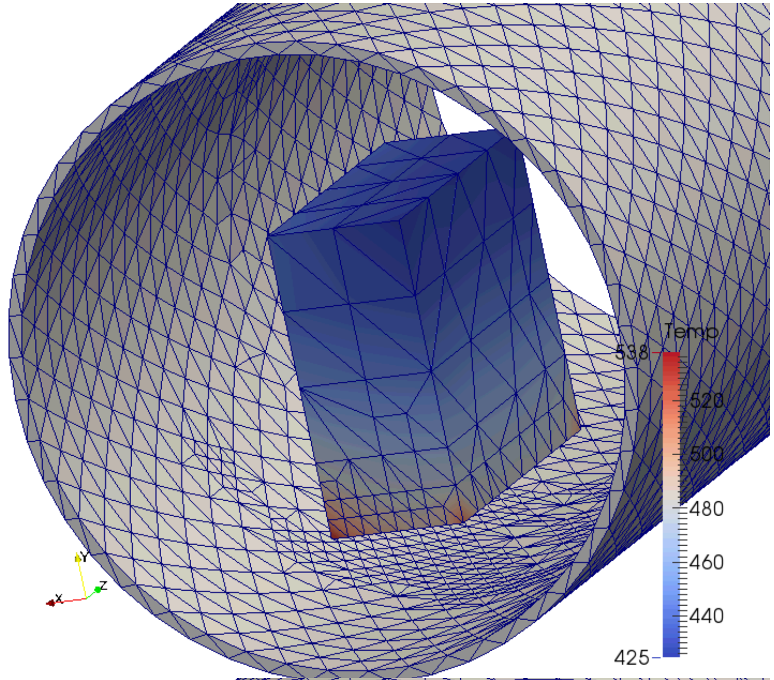
Adaptivity Strategies

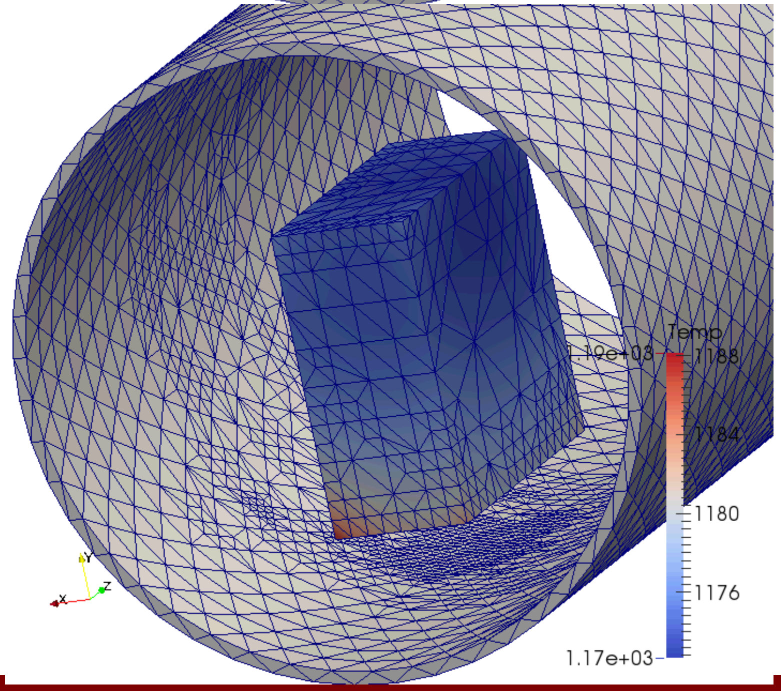
- Dynamic strategy:
  - Refine every N time steps (N=40) using **instantaneous** indicator
  - Let adaptive time stepping set time step
  - Increase max level of refinement (1,2,3,4) each run
  - Increase max number of elements (30K-100K)
- Offline strategy:
  - Refine elements with max error using **time integrated** indicator
  - Let adaptive time stepping set time step
  - Specialized code to handle transition elements offline
- Marking strategy: we used percent of max error (0.02)
- Convergence testing:
  - Compare to uniform refinement of the base mesh
  - Exact solution taken as extrapolation of three uniform meshes
  - Convergence rates between 1 and 2

Results: Dynamic AMR

- Growth in number of elements over time until we hit the maximum allowed
- Low number of elements initially
- Cost associated with changing mesh frequently during simulation

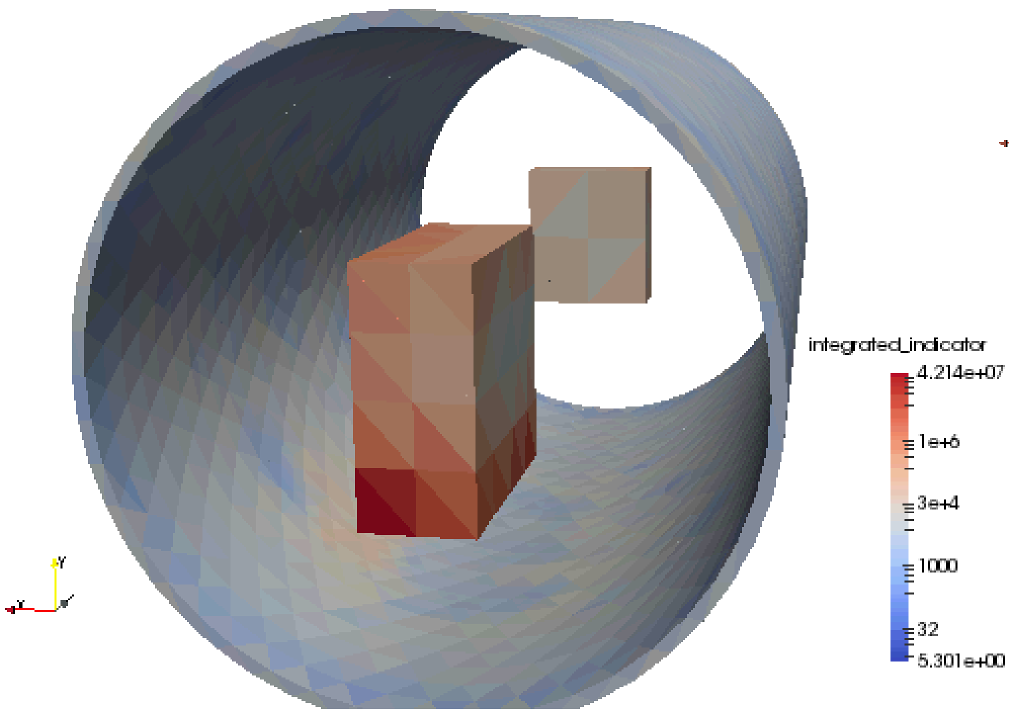




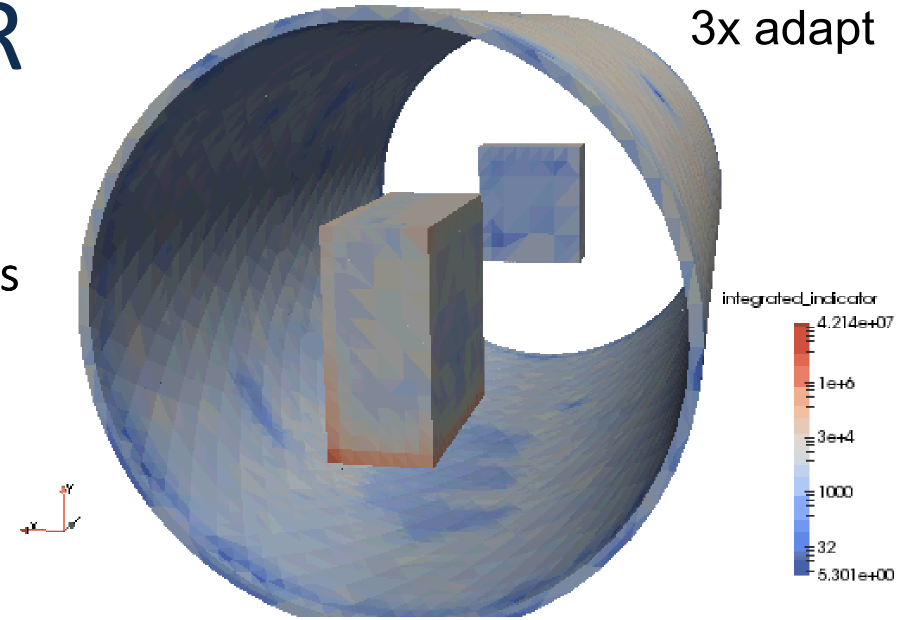


Results: Offline AMR

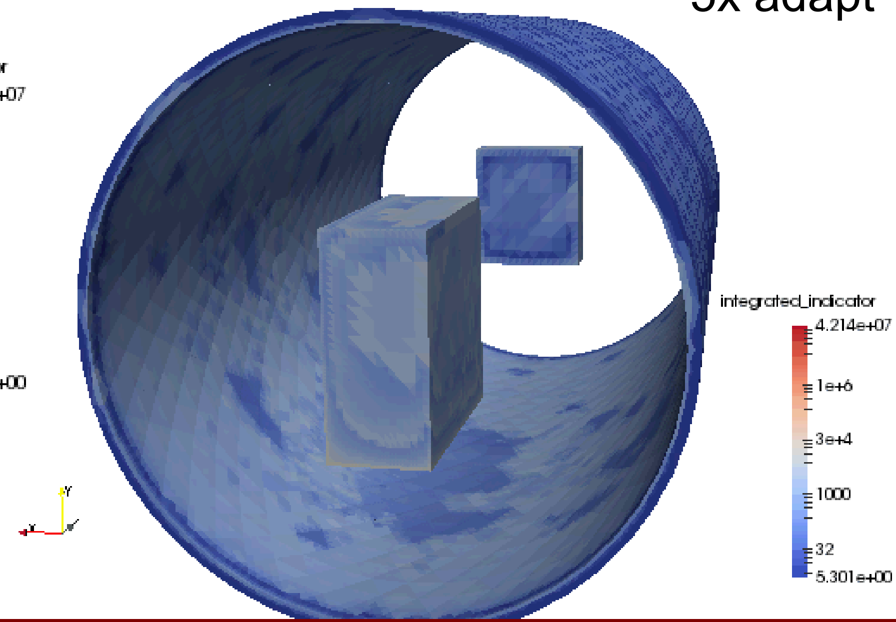
- Time integrated indicator for 1,3,5 levels of offline adaptivity
- Log scale using same scale for all plots



1x adapt

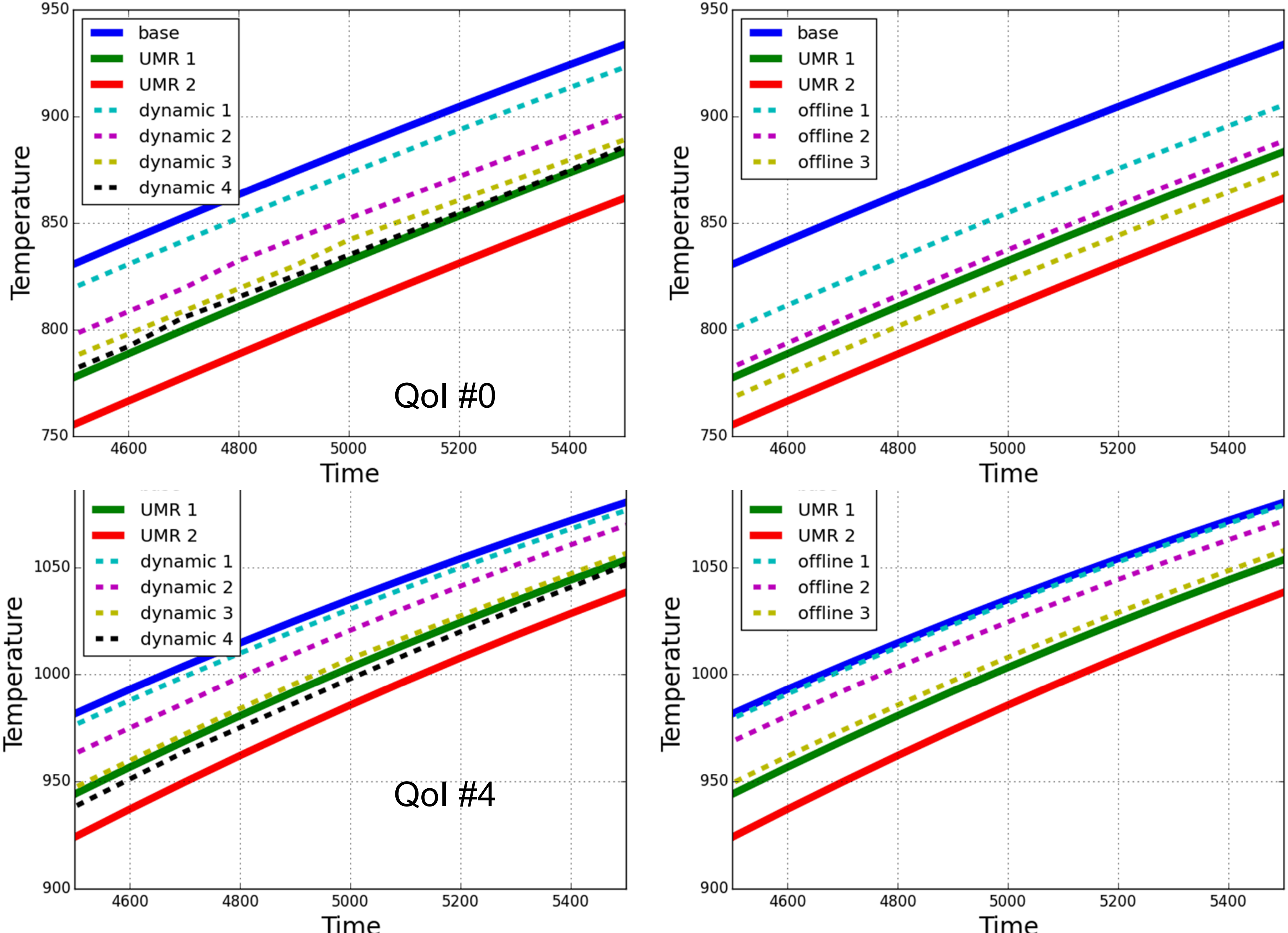


3x adapt

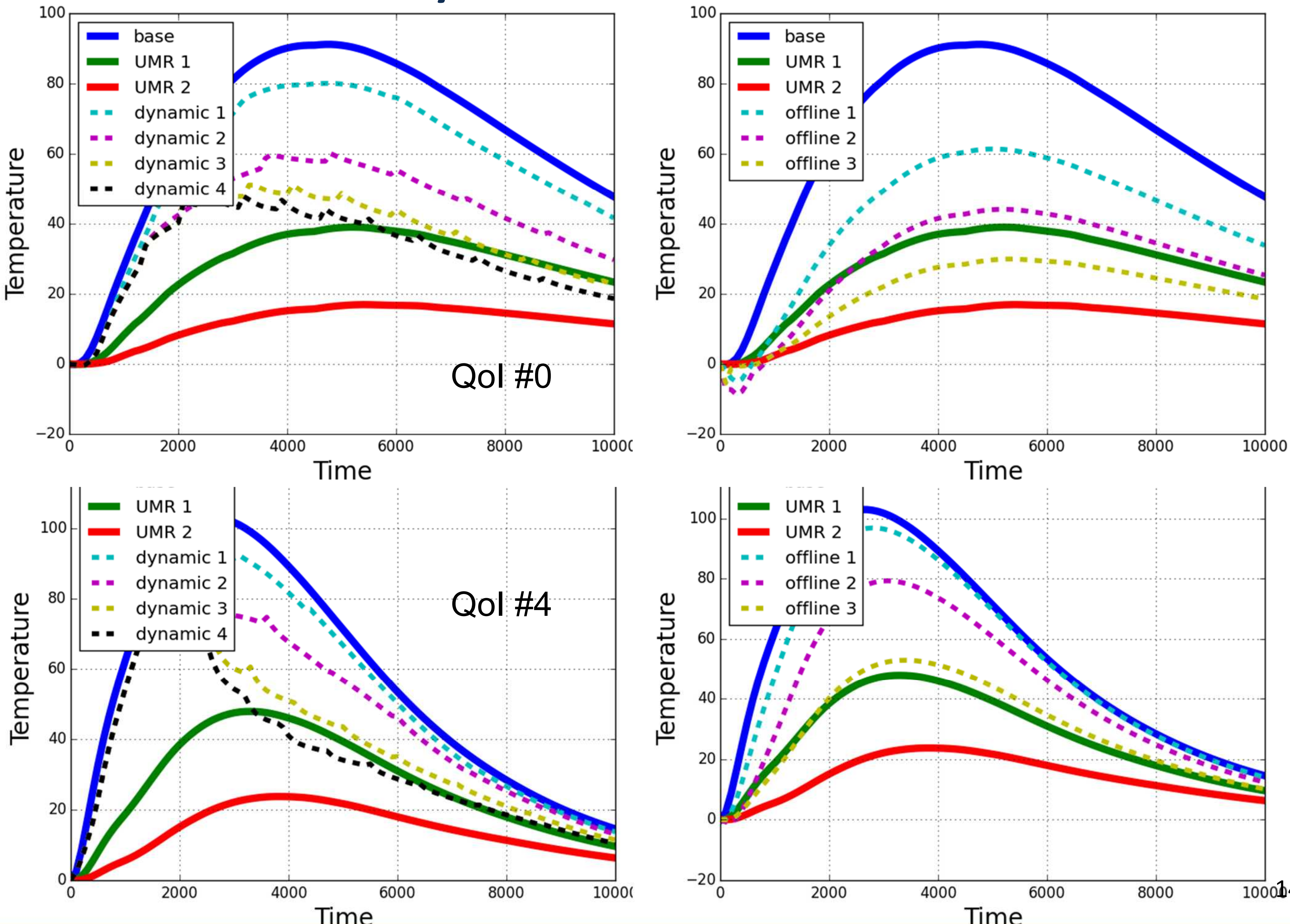


5x adapt

QoI Convergence: Dynamic vs Offline

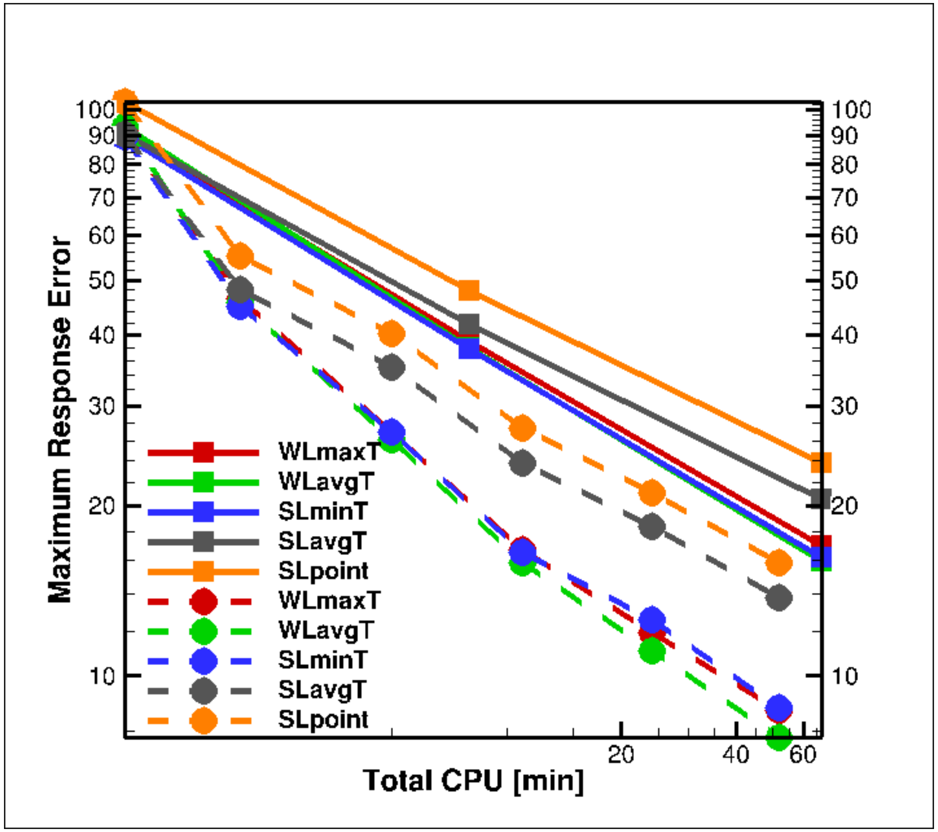


QoI Error: Dynamic vs Offline



Errors and Cost: Offline Adaptivity

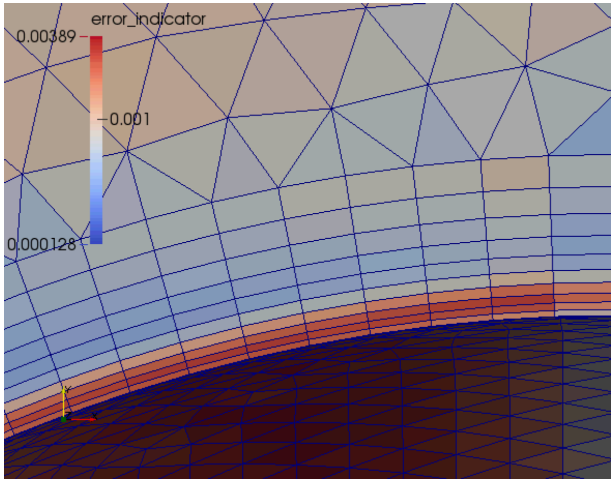
- Plot total CPU time vs error
  - solid = UMR, dashed = offline adapt
- Adaptivity always reduced errors for all QoIs similar to UMR
- Cost of adaptivity is always less than UMR
  - Includes cost of previous adapted solution
- Error indicator cost has been ignored since we have uncovered a performance issue that will be resolved soon.
- Did not yet compare to performance of dynamic adaptivity

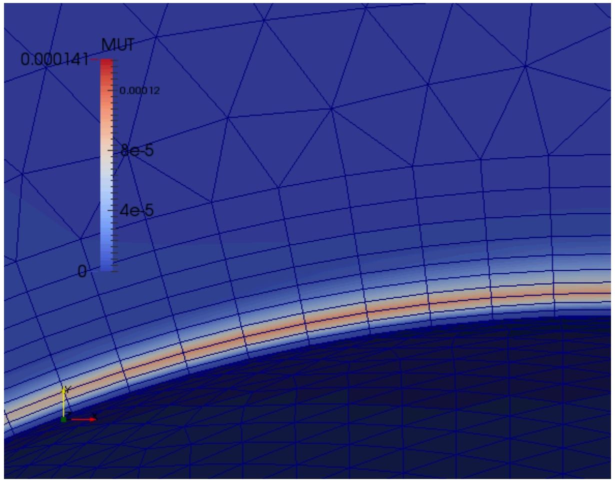


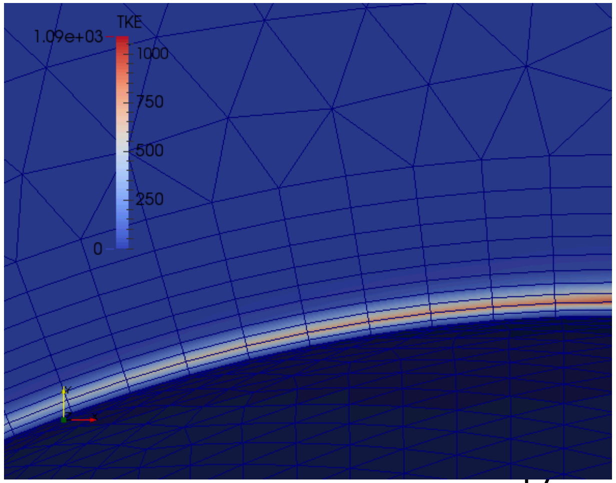
RANS Aero Example

Boundary Layer Refinement

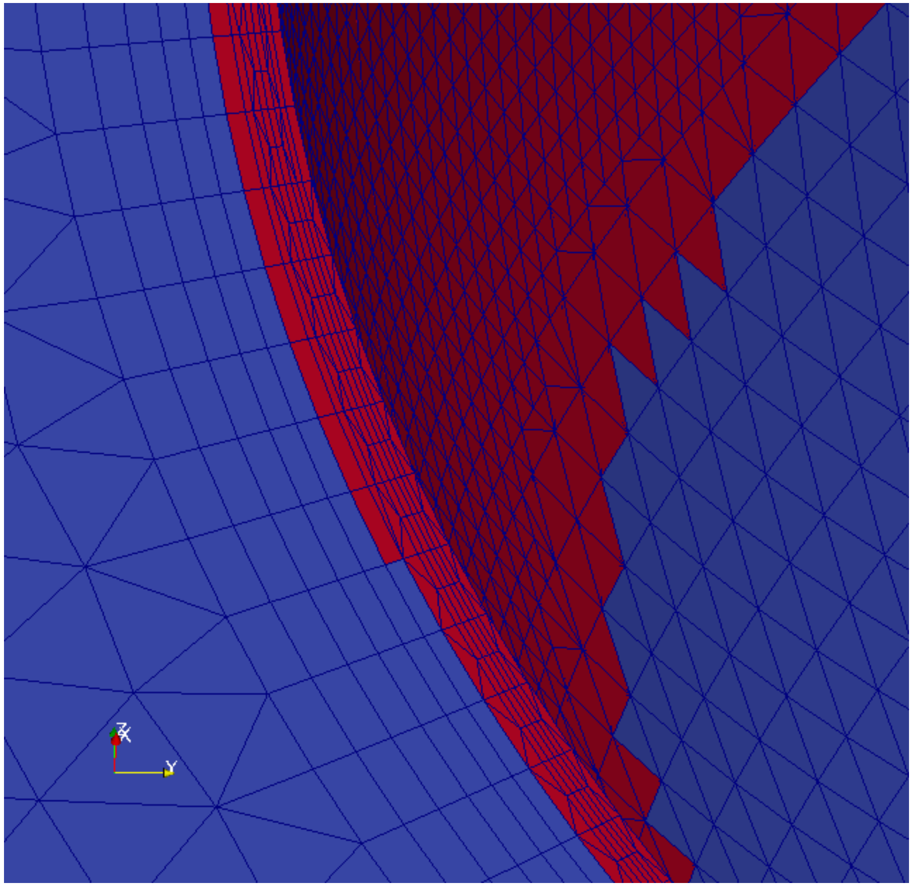
- Meshes for high Re fluid flow often use boundary layer meshes
- Our adaptivity code is based on tet elements, so we are using mainly tet meshes for free flow
- Boundary layers are captured using wedge elements based on surface triangulations
- It is desirable to maintain smooth normal spacing within boundary layer meshes – this puts a constraint on the adaptivity



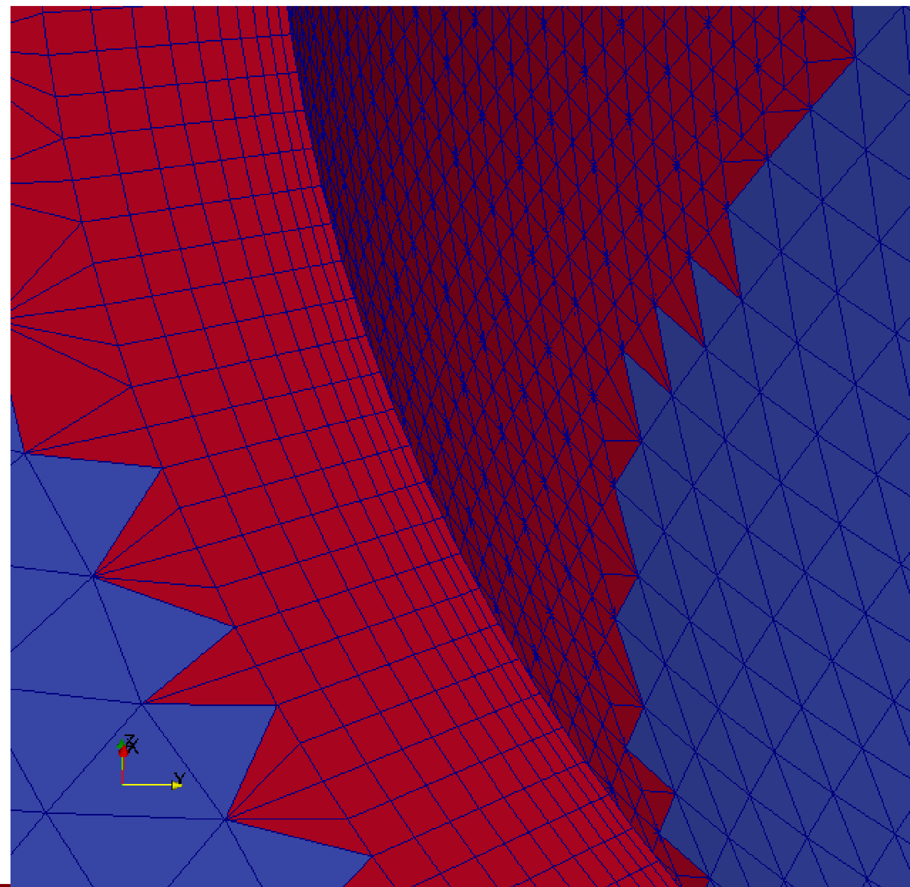




Turbulent Sphere: Adapted Meshes



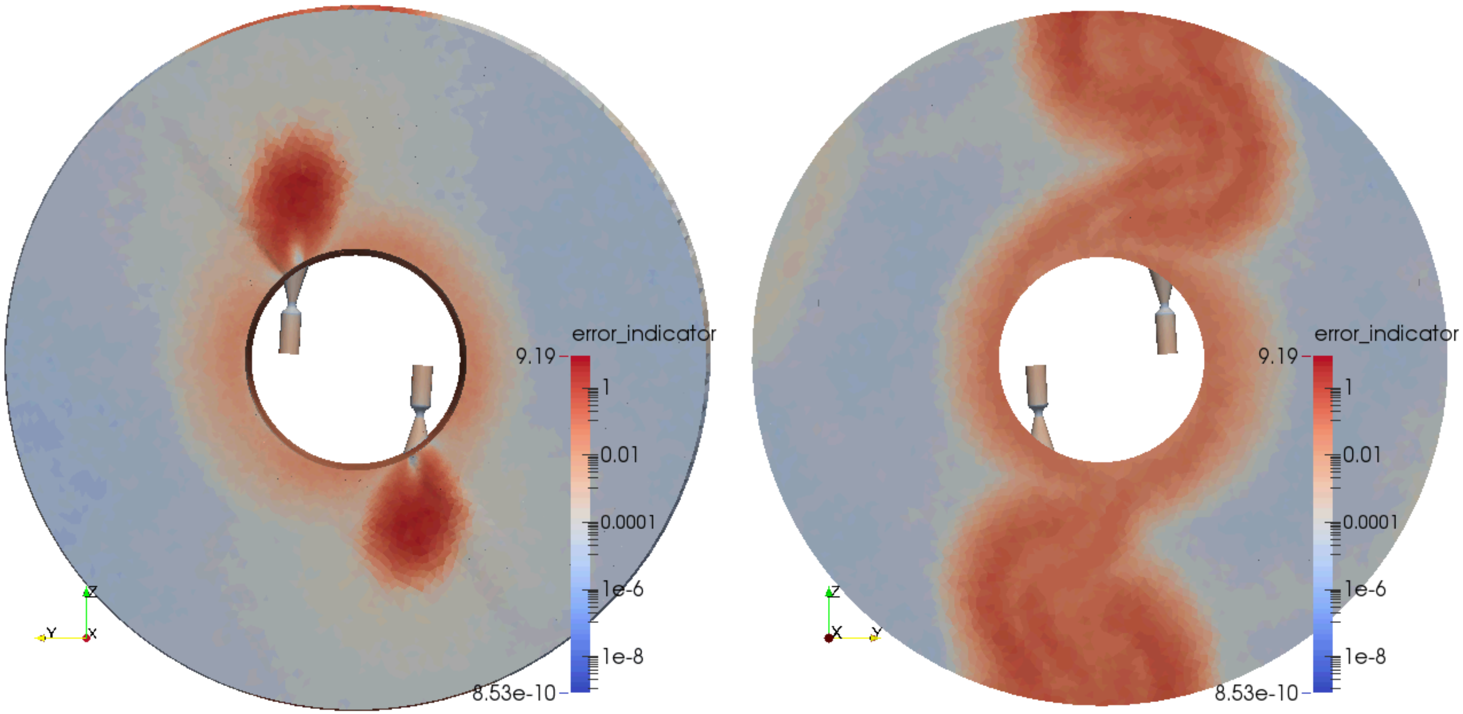
- Special handling of boundary layer refinement (wedges) enables consistent boundary layer thickness even under local refinement
- No tet elements created in the boundary layer!



Adapting using standard hybrid adaptivity produces unwanted tet elements in the boundary layer near the surface

Example: RANS Aero

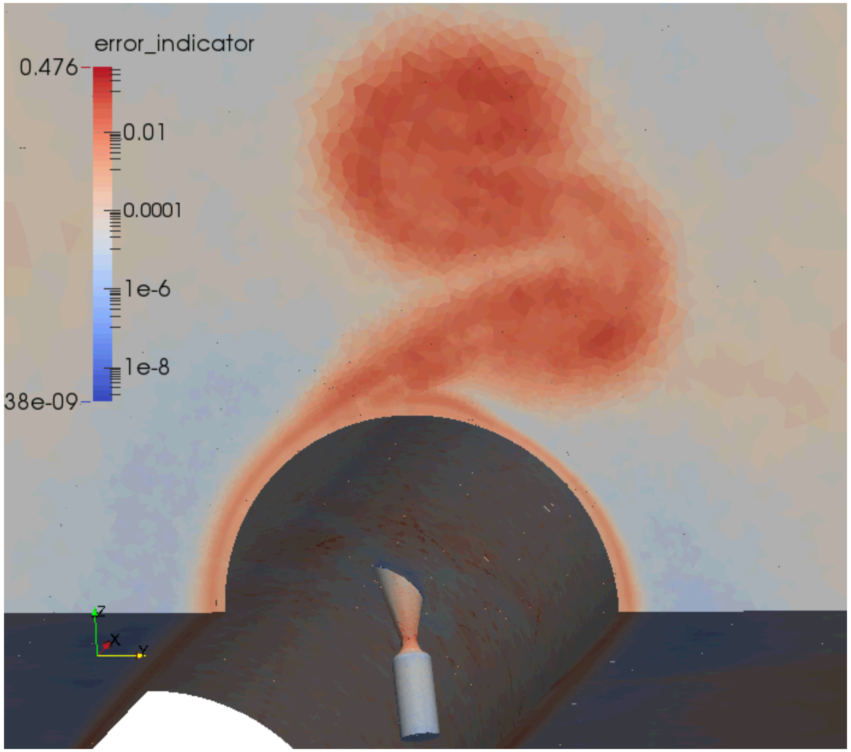
- For steady RANS flows, offline adaptivity is appropriate
- We can initialize flow variables on adapted meshes using converged solutions computed on coarser meshes
- Application: Jet in cross flow around object. Compute forces and moments on fins.
- Error indicator is local error in fluxes (local truncation error)

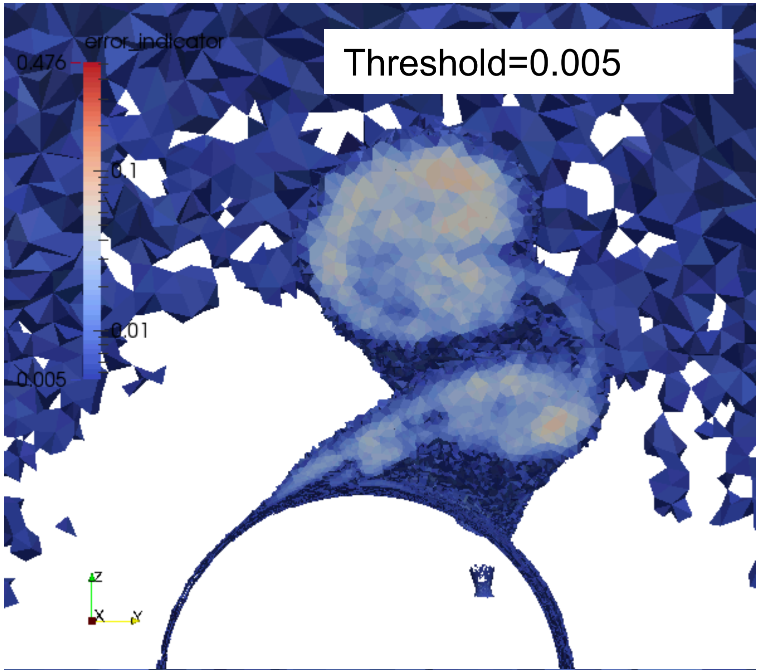


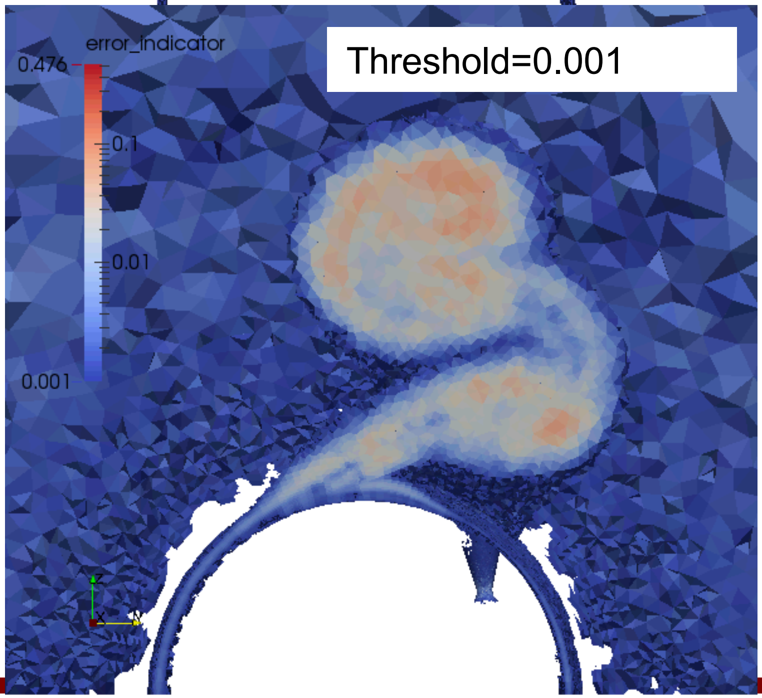
Error indicator distribution near jets (left) and downstream (right)

RANS Aero: Marking

- Model is all tet mesh (9M elems)
- Indicator locates vortices, boundary layers, jet interactions, and inflow regions
- Offline approach allows user more control over the adapted mesh creation.

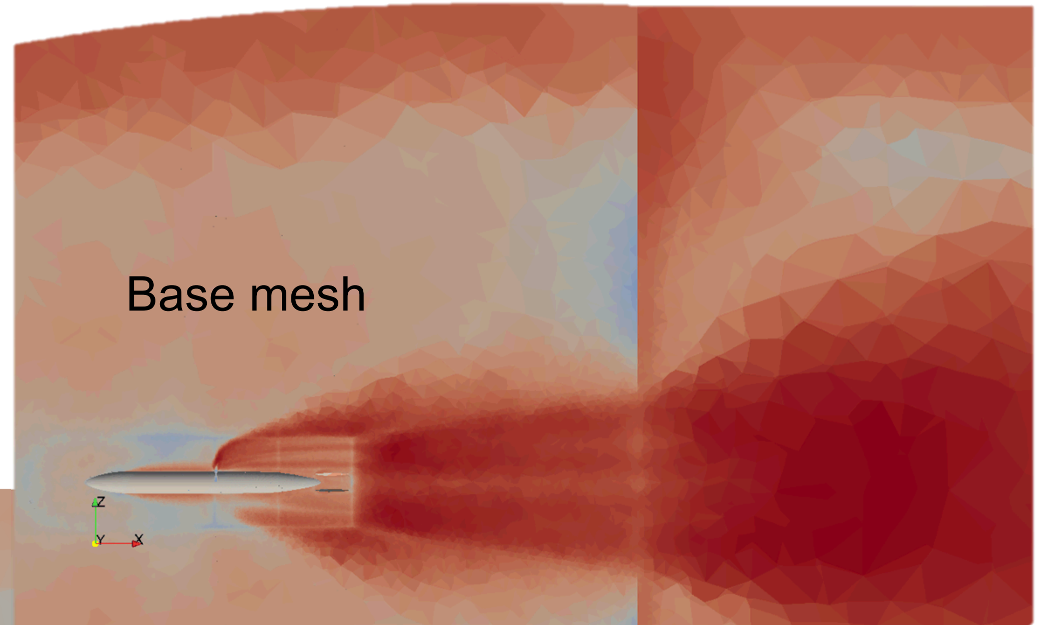


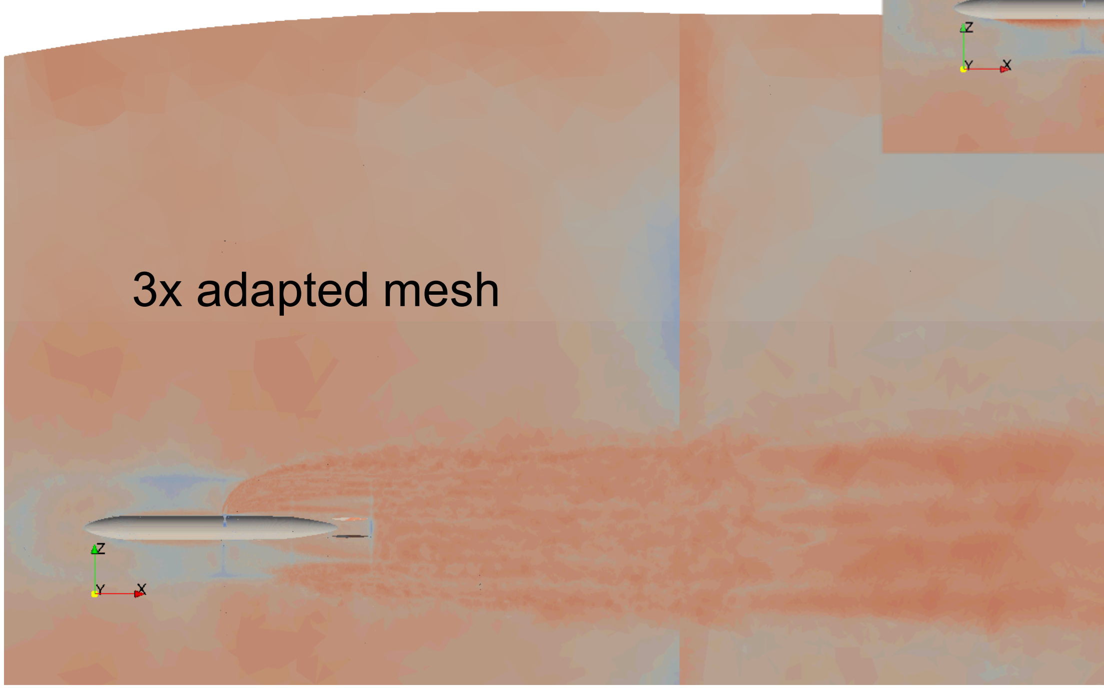




Reduction of Error Indicator

- Error distribution on coarse mesh along cut plane (aligned with jet)
- Errors at jet/xflow, downstream, boundary condition, even spurious internal interface flagged

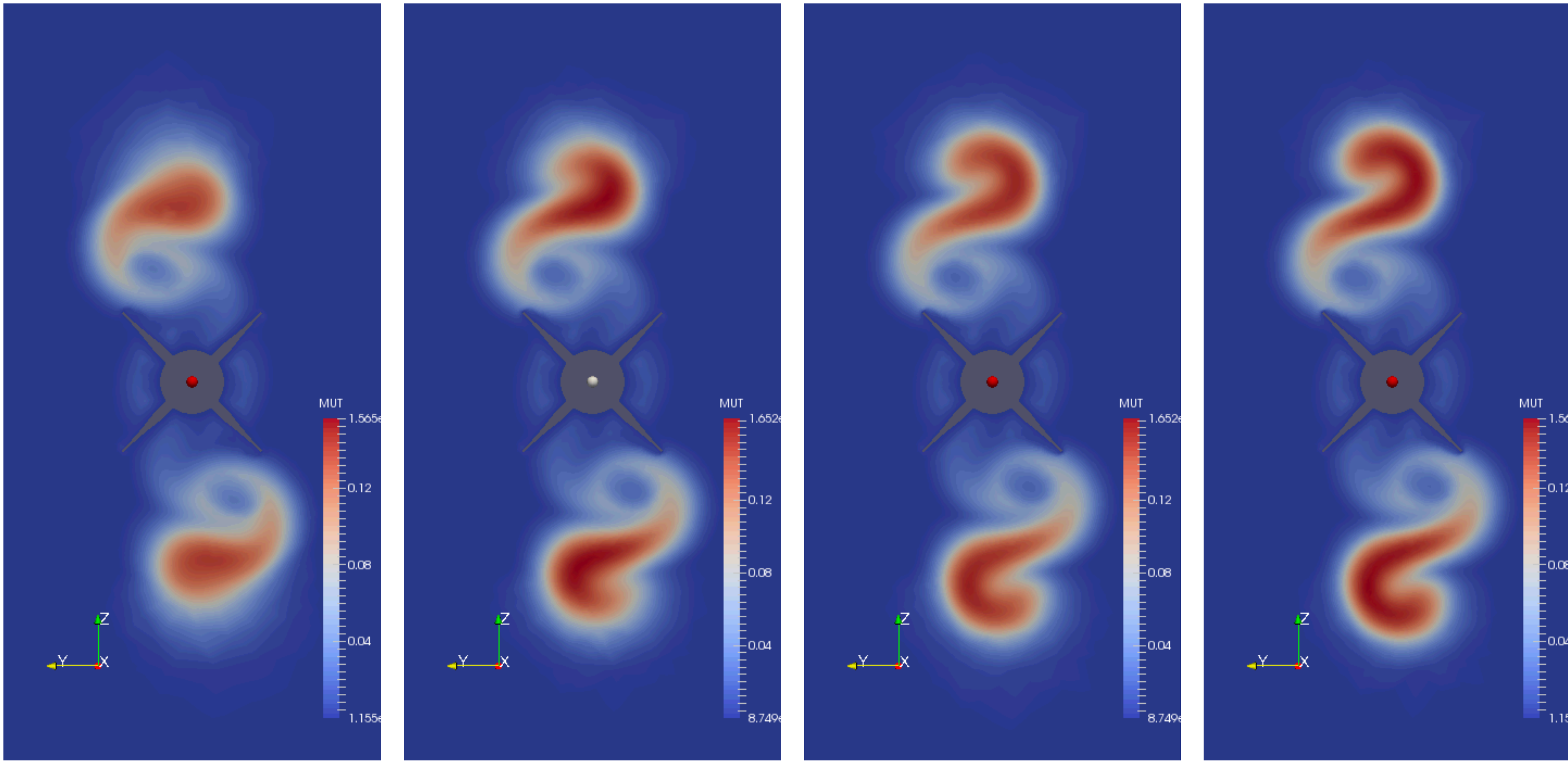




- Error distribution on 3x adapted mesh (same log scaling)
- No restriction on refinement reduces error indicator everywhere

Vortices Near Fins

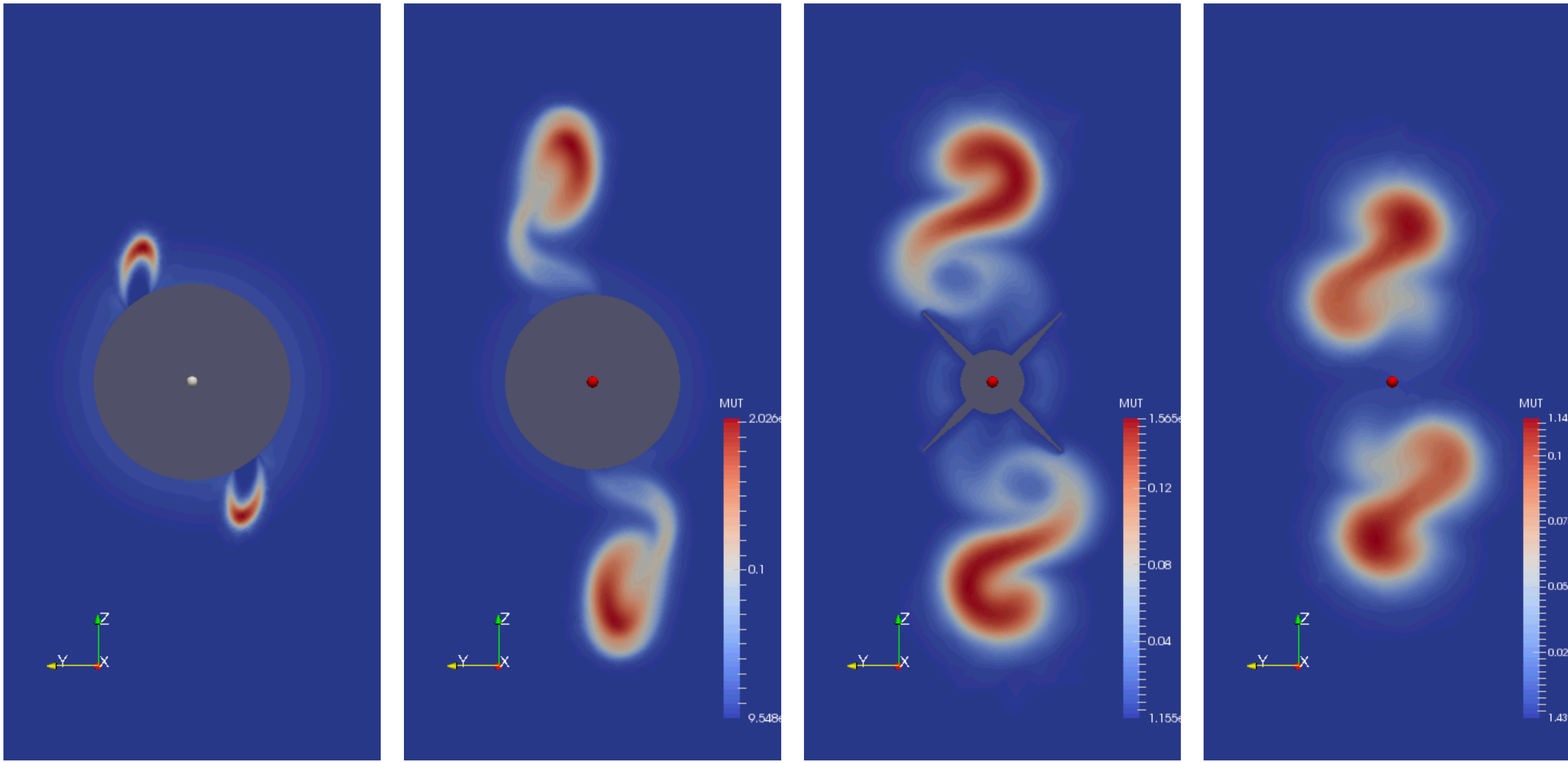
- Vortices at cut-planes using contours of turbulent viscosity



base | 1x adapt | 2x | 3x

Vortex Development

- Vortices (finest adapted mesh 3x) using contours of turbulent viscosity

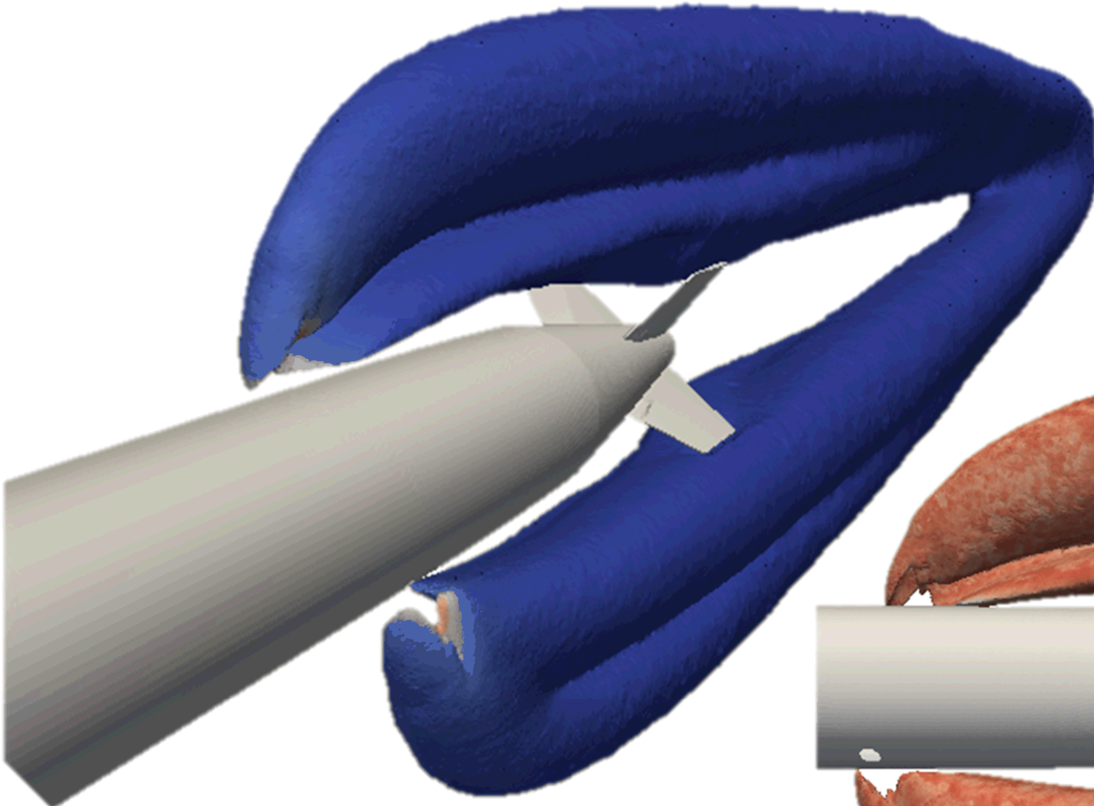


Near jets

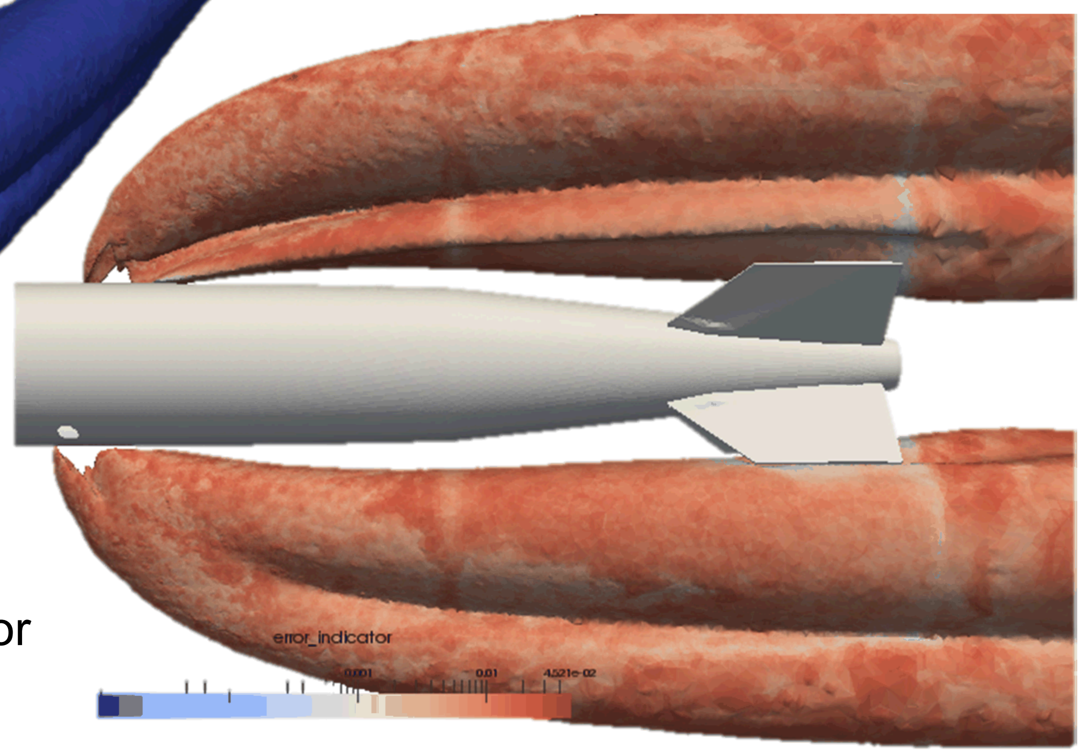
Further downstream

Vortex Iso-Contours

- Vortices (finest adapted mesh 3x) using contours of turbulent viscosity



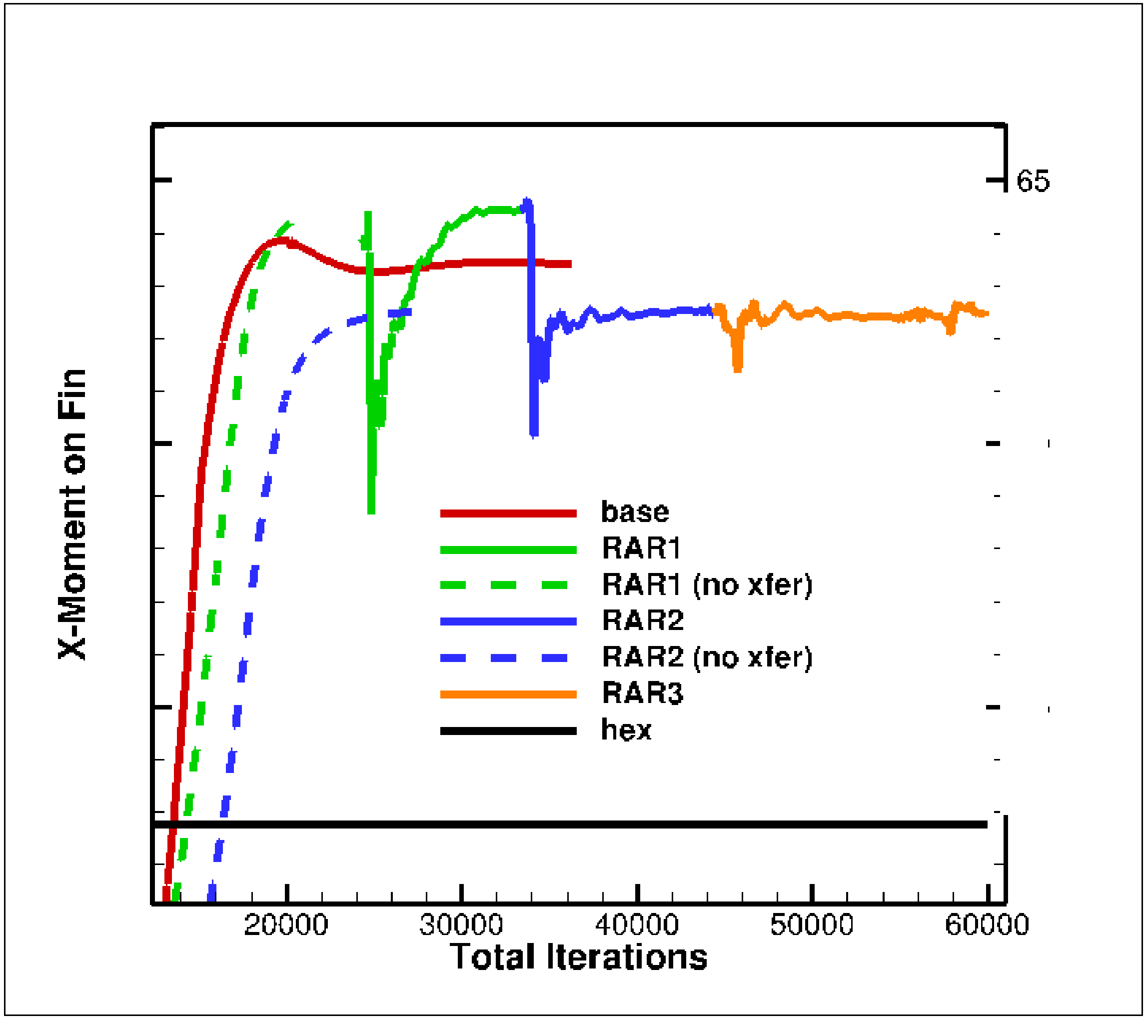
Turbulent kinetic energy



Error Indicator

Axial Moment Convergence

- Initially we could not transfer solutions to adapted meshes (see cases w/dashed lines)
- Transfer for hybrid adapted meshes significantly improves runtimes (note that adapted meshes converge to same value regardless of initial condition)
- We see acceptable convergence under adaptive refinement (no UMR solution available)



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- Travis Fisher (SNL, Aero developer)

Summary

- Offline adaptivity has clear advantages for robustness over dynamic adaptivity (and potentially accuracy)
- For many physics, it may produce reasonable meshes, especially for parabolic problems (heat transfer, incompressible flow)
- For highly dynamic problems, an efficient dynamic adaptivity implementation may perform better

Continuing Work

- Quantifying when offline adaptivity is preferred in transient fluid/thermal calculations
- Improved error indictors for fluids: error transport equations