INTEGRATED
EM & THERMAL SIMULATIONS
WITH UPGRADED VORPAL SOFTWARE

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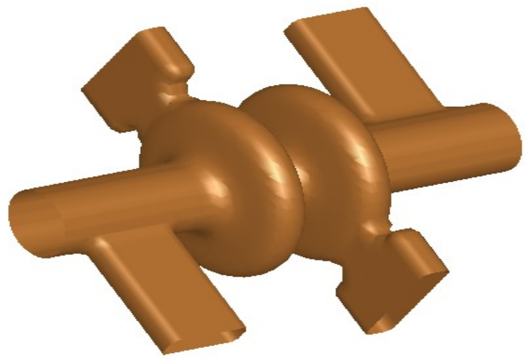
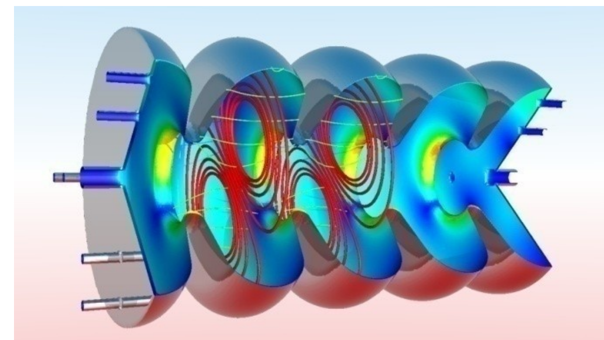
Summary of Talk

- Progress in Thermal Simulation Capability
- Benchmarking
  - EM
  - Thermal
- Cut-cell Finite-Difference Thermal Algorithm
- Ongoing Tasks

The evolution of multi-physics capability in Vorpal

- Vorpal is a Finite-Difference Time-Domain Electromagnetic Particle-In-Cell simulation tool, with a history of application to laser wakefield plasma accelerators, and srf cavity modeling.



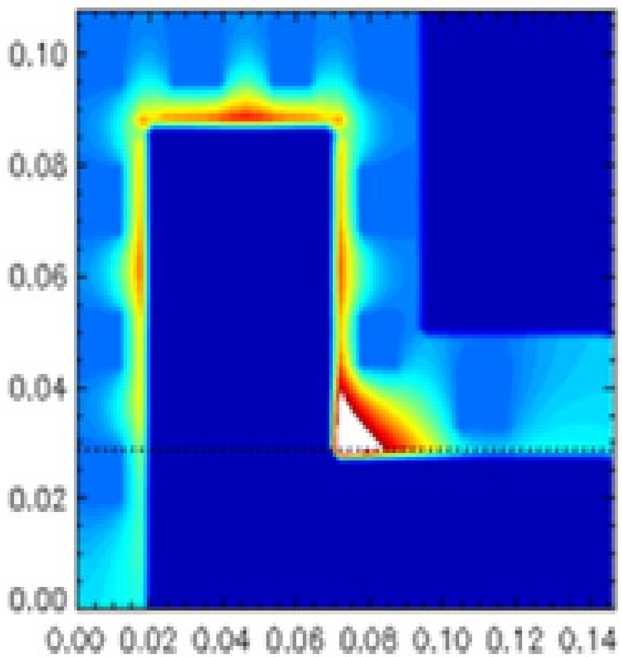


- But Vorpal also has general PDE solver capability … so … *in principle* … replace curl-operations with divergence-gradient, to go from Maxwell to heat conduction problem.
- This project has taken the idea from principle to realization.
  - Cut-cell geometry in both EM and thermal.
  - Cryogenic non-linear thermal properties.

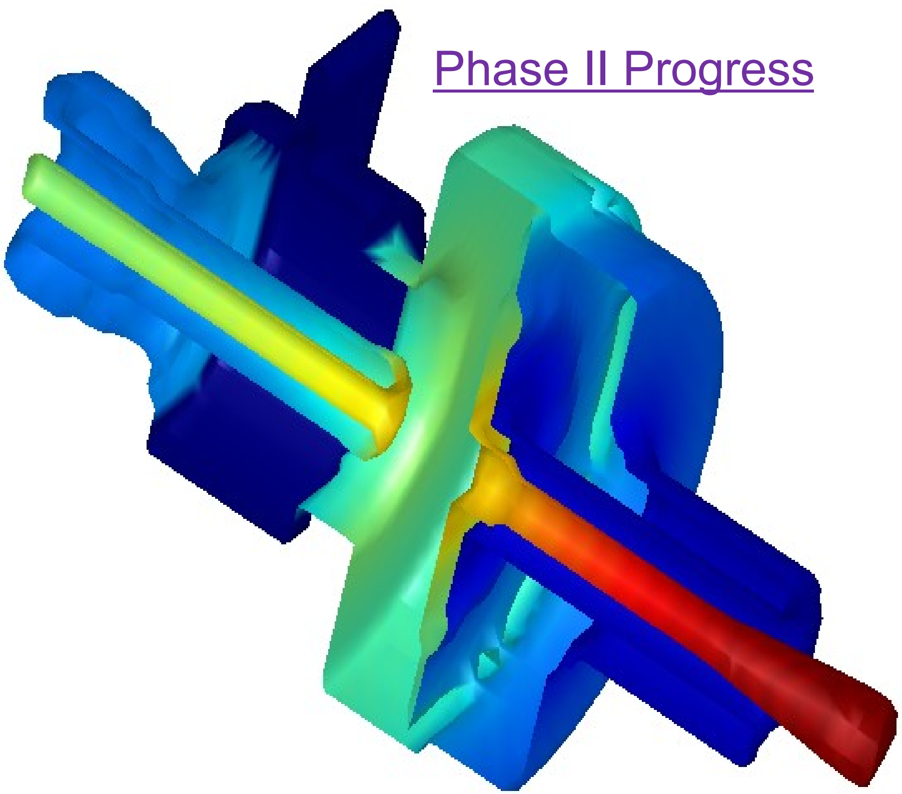
Vorpal thermal modeling capability is now well beyond proof-of-principle

- From very simplistic 2D geometry, confined to the grid planes ⇒ Cut-cell 3D geometry based on CAD input.
- From single material ⇒ arbitrary composition, allowing several order magnitude difference in thermal conductivity, k.

Phase I PoP



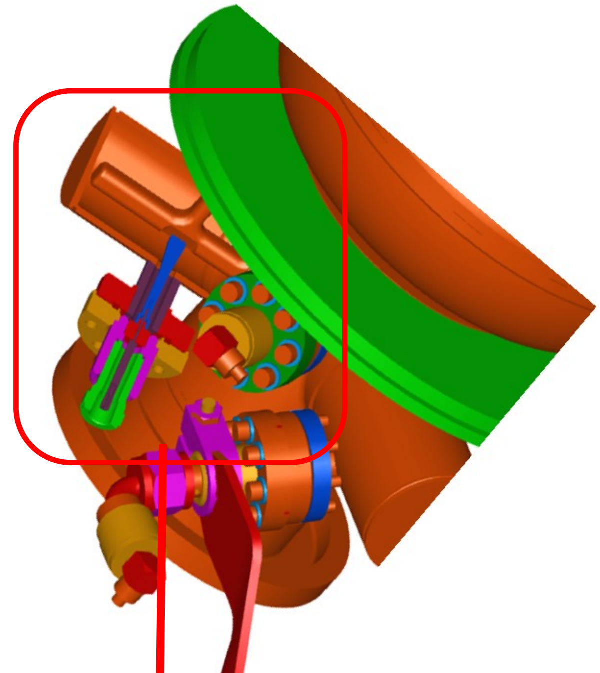
Phase II Progress

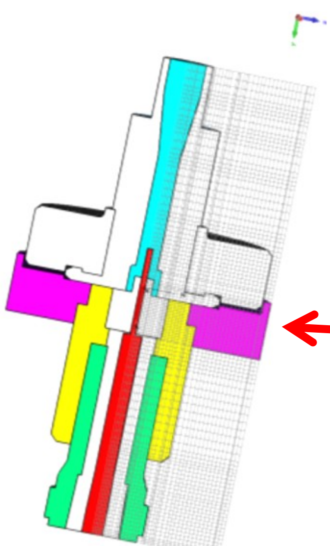


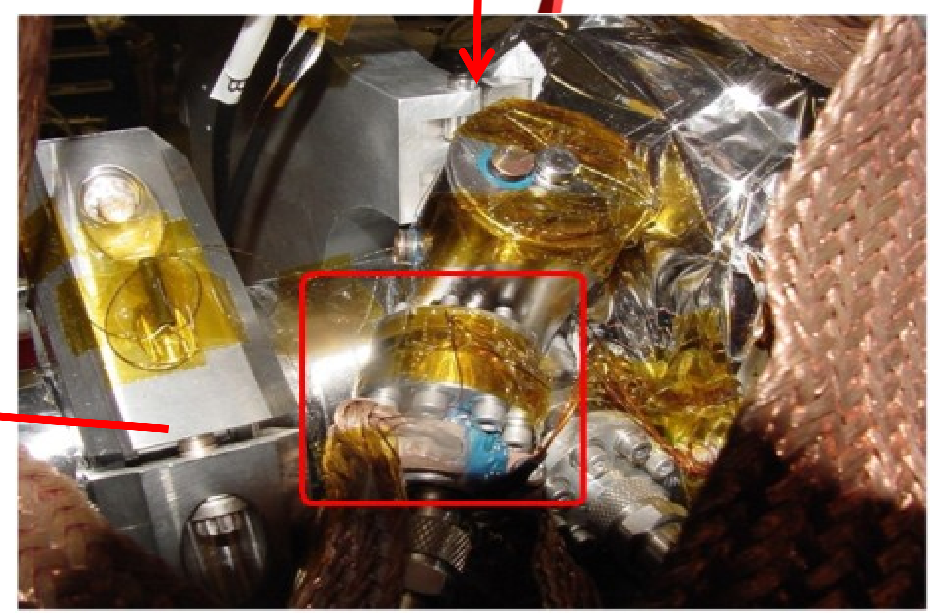
Capability is being tested on a specific benchmark problem

Benchmark is the HOM coaxial coupler feed-through, for which prior, and on-going, analysis exists, and for which laboratory measurement data exists.

(G. Wu, H. Wang, R. Rimmer, and C. Reece, "Electromagnetic simulations of Coaxial Type HOM Couplers," JLAB-ACC-05-418, also THP58 in Proceedings of 12th SRF Workshop, Cornell University, July 2005.)



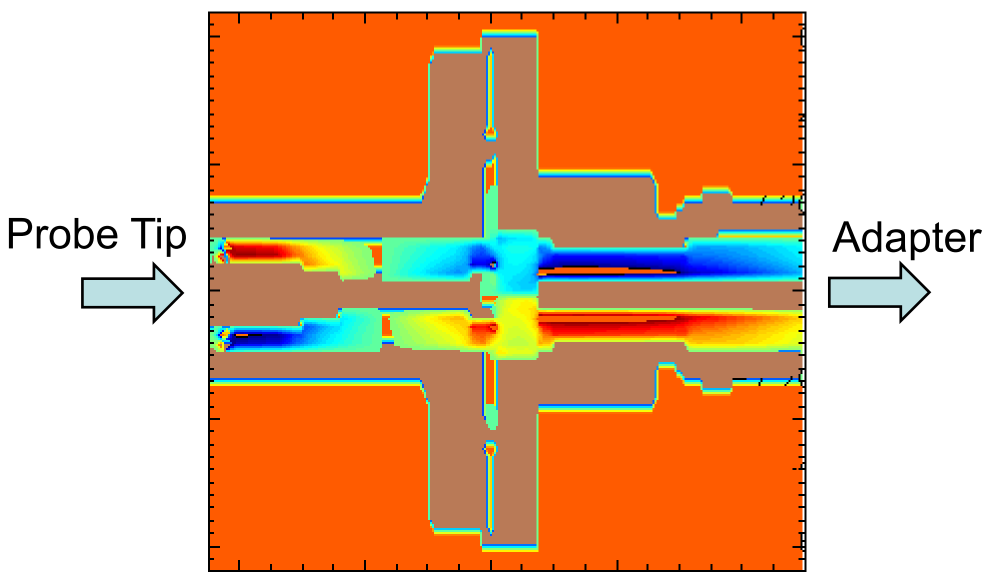


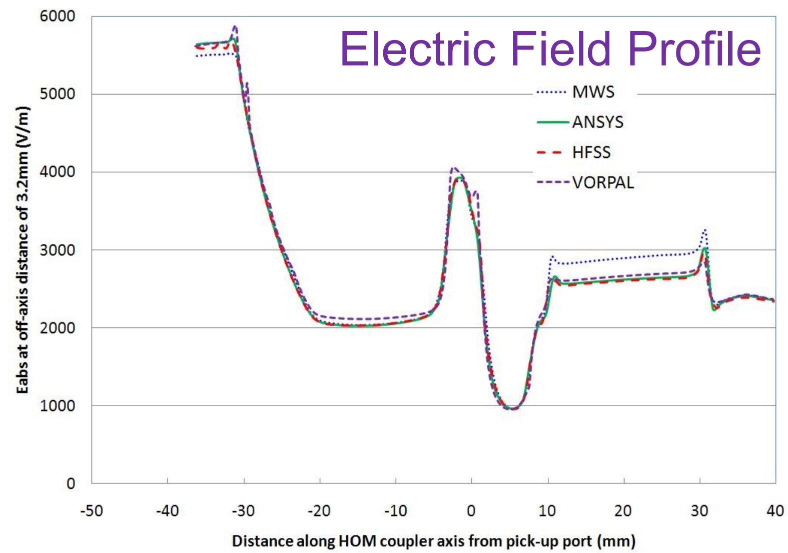


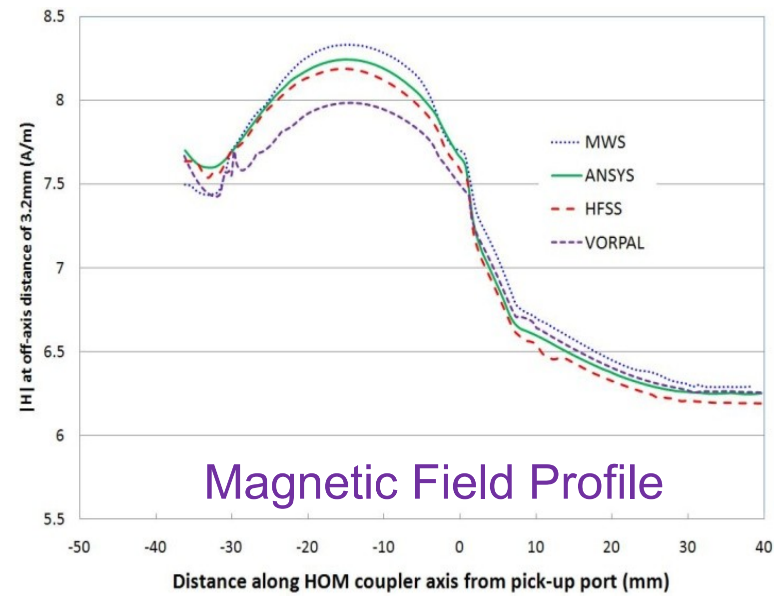
Electromagnetic code benchmark is consistent

(See Poster TUP107, G. Cheng *et al.*, this conference.)

- The outer coaxial probe tip of the coupler is extended to form a coaxial line.
- 1 watt power is fed into probe end.
- Electric and magnetic profiles, S11, and S21, from MWS, ANSYS, HFSS, and Vorpal are compared.
- Excellent E field, B field more sensitive to grid resolution.

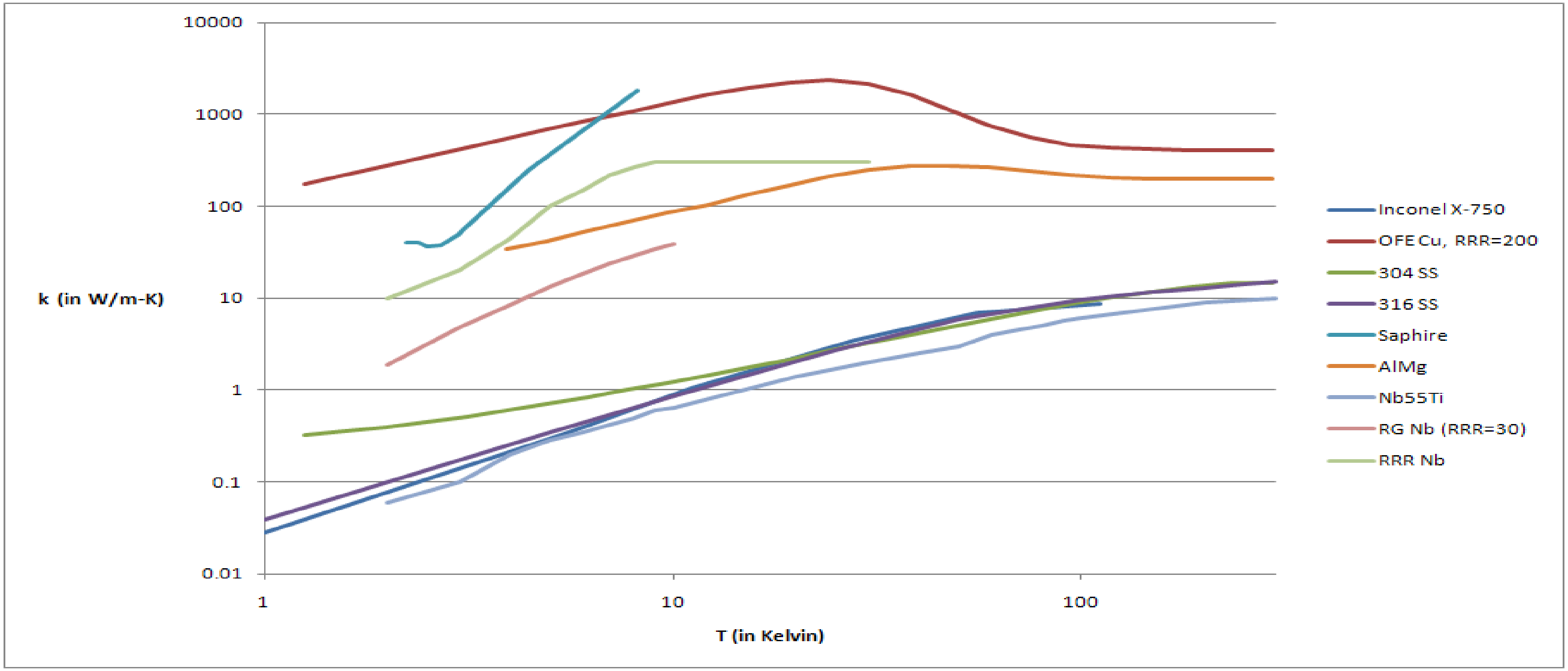






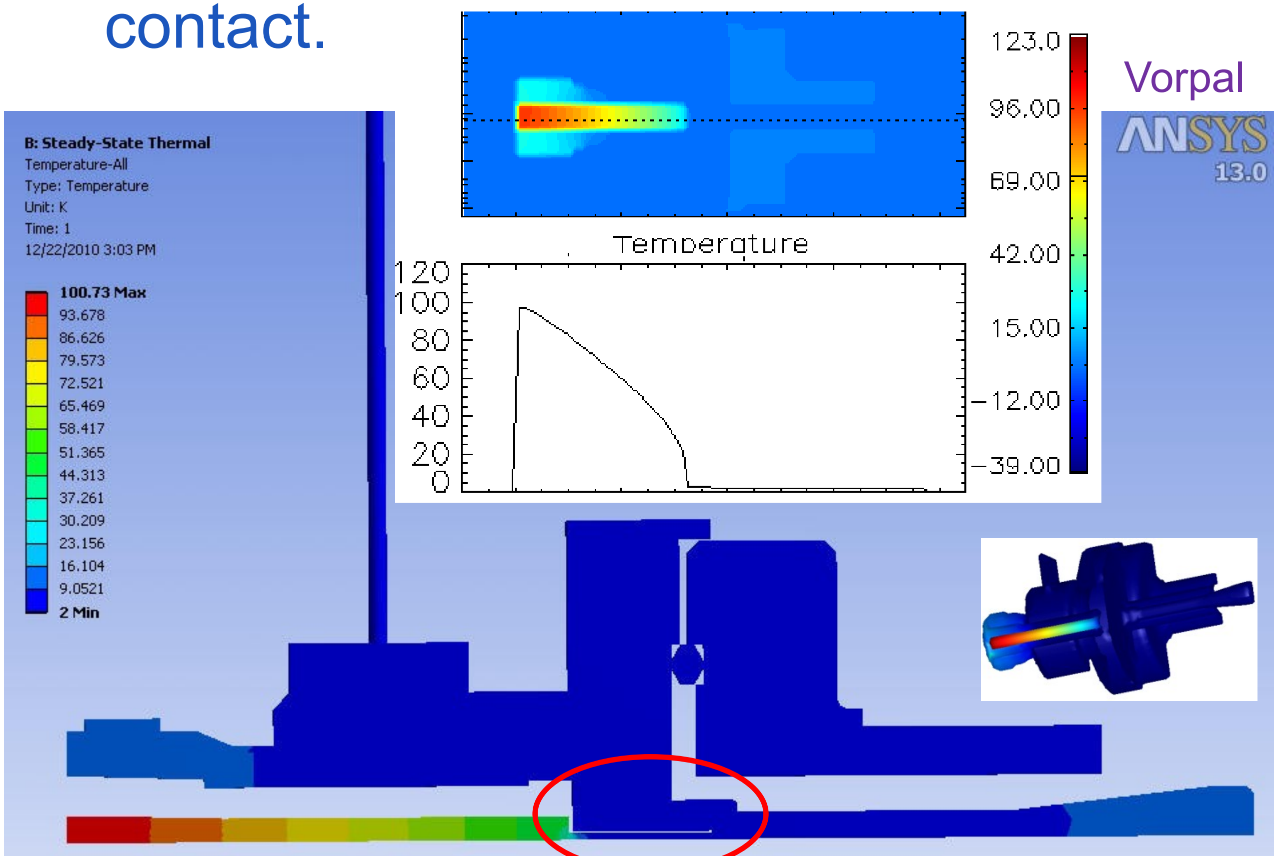
Variety of materials makes the thermal problem challenging

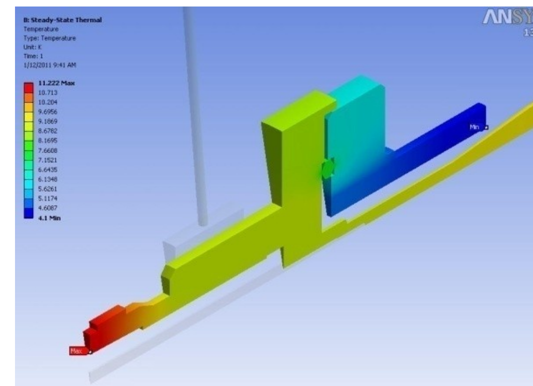
- There are a dozen parts to this assembly, made from ten different materials, with nearly 10^5 variation in thermal conductivity, *k*(T).
- Fully non-linear temperature dependent *k*(T) is implemented.
- Present static-solver is an accelerated Richardson iteration, but copper-stainless interface slows convergence. A more capable implicit solve will be used in the future, both for convergence, and for time-dependence.

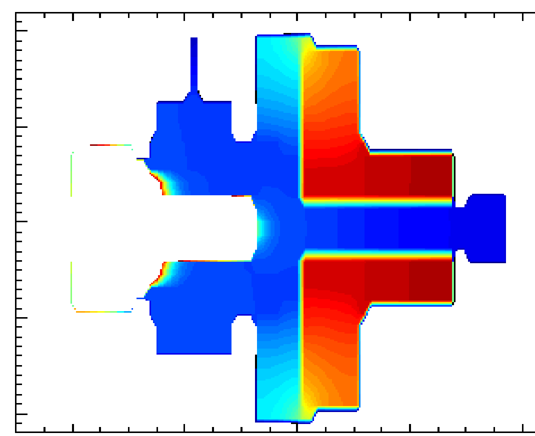


Thermal code & measurement benchmark is in progress

- Fixed heat flux, 50 milliwatts, from warm coax line into feed-through, with cryogenic coolling, 2K, on strap.
- Compare ANSYS, Vorpal, and measurement. Adapter's center coax is hottest, at ~100 K. Sensitive to bushing contact.





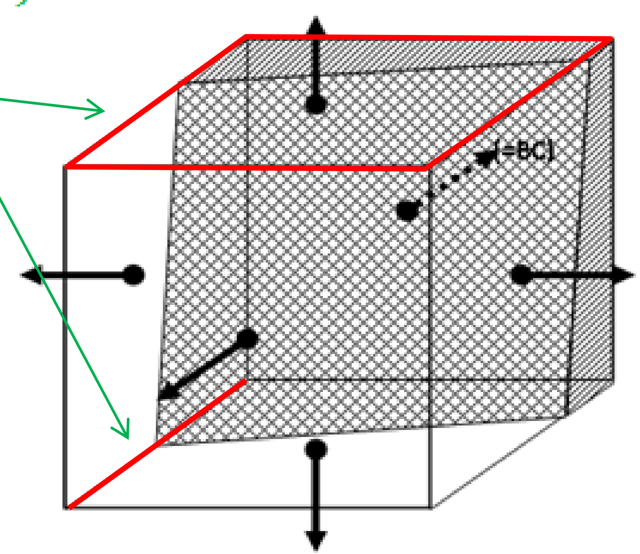


Our finite-difference based thermal analysis is somewhat novel

- We are doing finite-difference based thermal analysis, rather than finite-element. For accurate geometry, we've extended the "cut-cell" idea, which we use for EM, over to thermal.
- Yee-cell finite-volumes treatment, $c\int \partial_t T \, d^3V = -\oint \mathbf{Q} \cdot d\mathbf{A}$ with temperature at center of cell, heat-flux at faces of cell. Thermal conductivity, *k*(T), evaluated for each face.
- A choice to make for heat flux: $\mathbf{Q} = -k(T)\nabla T$

  accurate parallel, $kdA = \int kdA$

  accurate serial, $k^{-1}dl = \int k^{-1}dl$
- Have chosen accurate parallel, since this treats strong material discontinuity.
- Improvements to this are being considered, for better serial transport.



$$\partial_t \int CT \cdot d^3V = -\oint \mathbf{Q} \cdot d\mathbf{A}$$

Implementations are designed for reusability

- Heavy use of “macros” pre-processing capabilities hides much of the usual input file detail that is not physics related.
- Macros are “part-based”, for example:

```
# import and specify physical geometry
newCADpart(part02InnerNadapter,   Inconel_X750, HOMFeedThru(02).stl)
newCADpart(part03gasket,          AlMg,         HOMFeedThru(03).stl)
newCADpart(part04smallDiaSaphire, Saphire,      HOMFeedThru(04).stl)
newCADpart(part06OuterNadapter,     SS_304,     HOMFeedThru(06).stl)
newCADpart(part07portTube,        Nb_RG,        HOMFeedThru(07).stl)
newCADpart(part08interiorFlange,  Nb55Ti,       HOMFeedThru(08).stl)
newCADpart(part09sleeve,          Cu_OFE_200,   HOMFeedThru(09).stl)
newCADpart(part10exteriorFlange,  SS_316L,      HOMFeedThru(10).stl)
newCADpart(part11bigDiaSaphire,   Saphire,      HOMFeedThru(11).stl)
newCADpart(part12probeTip,        Nb_RRR,       HOMFeedThru(12).stl)
newExpressionPart(bracket, Cu_OFE_200,   pipe(y-YBGN_BRACKET,z,x,...
newExpressionPart(strap,   Cu_OFE_strap, box(x-XBGN_STRAP,y-YBGN_STRAP,z,...

addHeatSource(adapterHeatSource00,IX0_ADAPTER_SOURCE,IY_ADAPTER_SOURCE,...

addHeatStation(probeStationMM,IXM_PROBE_SOURCE,IY_PROBE_STATION,...
```

- A more “user friendly” wrapping of macros is topic of inquiry.

Ongoing Work for Phase II, Year 2

- Additional benchmarking and design analysis.

- New thermal solver
  - First as a fixed coefficient matrix inversion.
  - Then as a non-linear iteration on coefficients.
  - Ultimate purpose is legitimate time-dependant modeling, particularly of a quench event.
- Better computational efficiency
  - Some fields over surface domain, rather than entire volume.
  - Consolidation of material operations, cut-cell k(T) especially.
- Application of non-uniform grid.
- Additional multi-physics
  - Non-linear magnetic material, for example.

Summary

- We have realized much of the hoped-for capability from the original proof-of-principle thermal analysis.

- We've produced a fairly novel finite-difference cut-cell thermal simulation capability that interacts easily with the pre-existing cut-cell electromagnetic modeling capability.

- We've benchmarked the new capability on a coaxial HOM coupler feed-through.

- We're ongoing with the 2^{nd} year of the Phase II SBIR.