Progress of the BELFEM code part II: Development and Status

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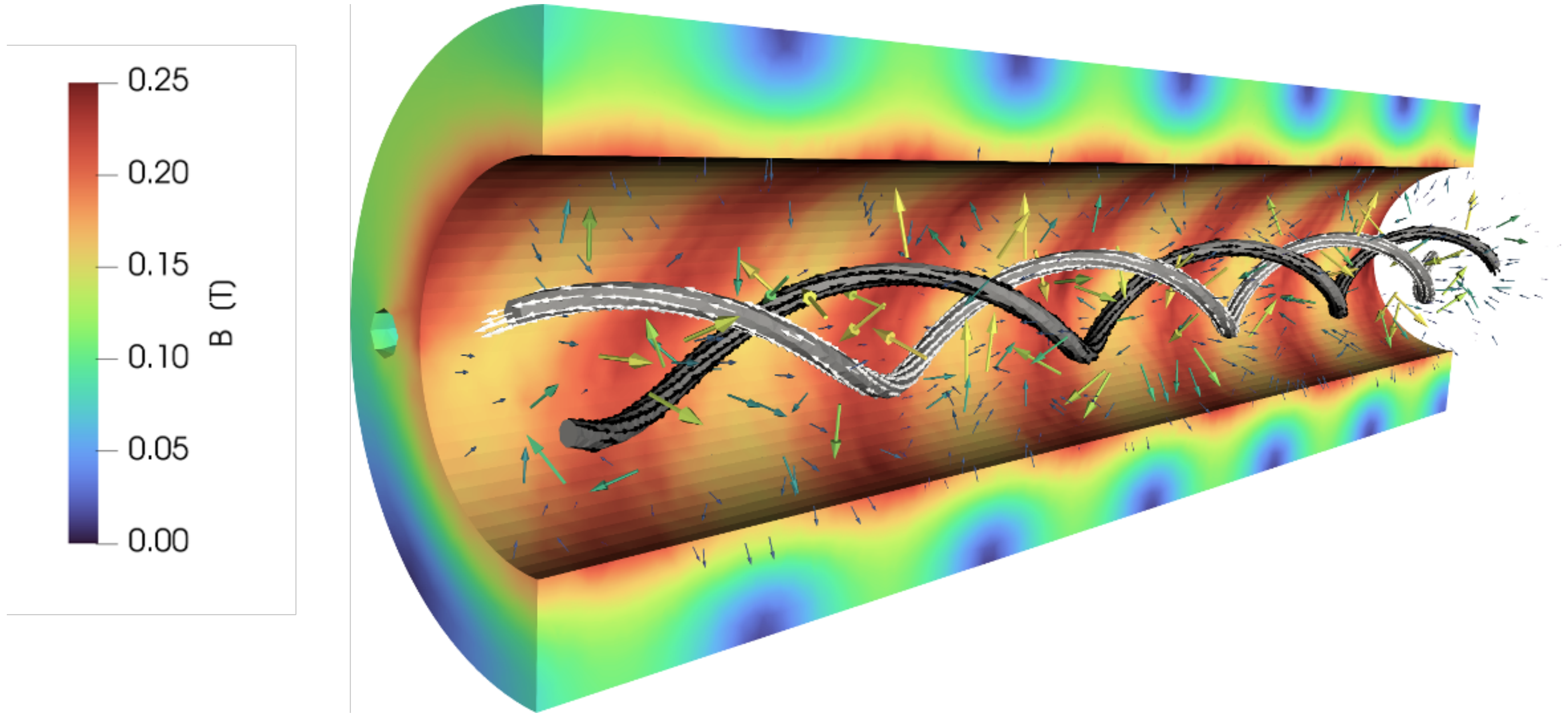


General

- workflow / user interface
- performance benchmark
- code structure
- current work packages

Thermal Modeling

- coupling with EM-Model
- proof of concept
- thin shell approach

Material Database

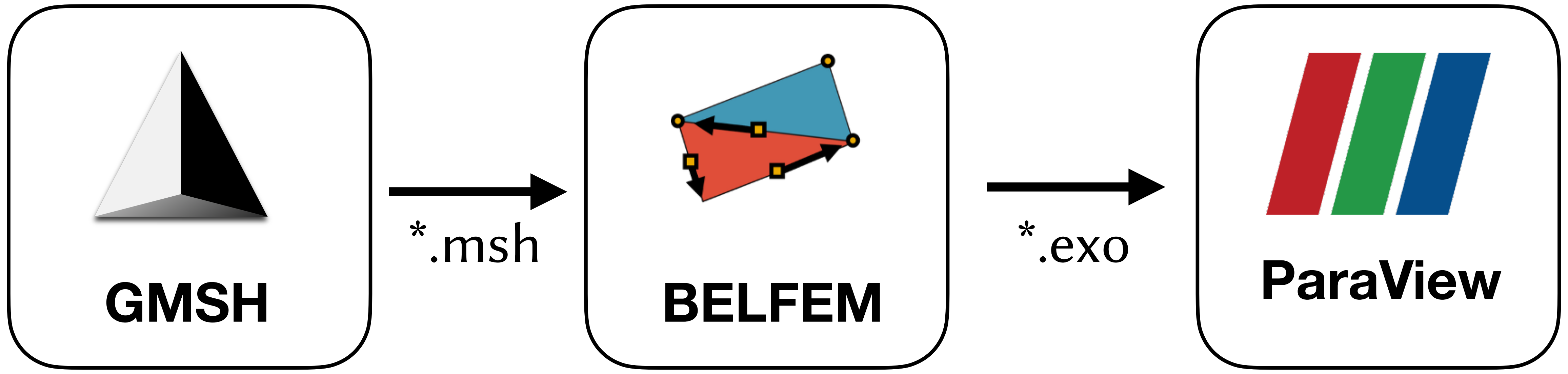
- Bulk data using splines
- Jc-scaling for REBCO

Workflow and User Interface

Goals of the BELFEM Project:

- provide state-of-the art framework for quench analysis and circuit model integration
- solve types of problems not yet supported in other codes
- be fast!
- user friendly code tailored to HTS cable and magnet design
- targeted to magnet engineers

Open source workflow:

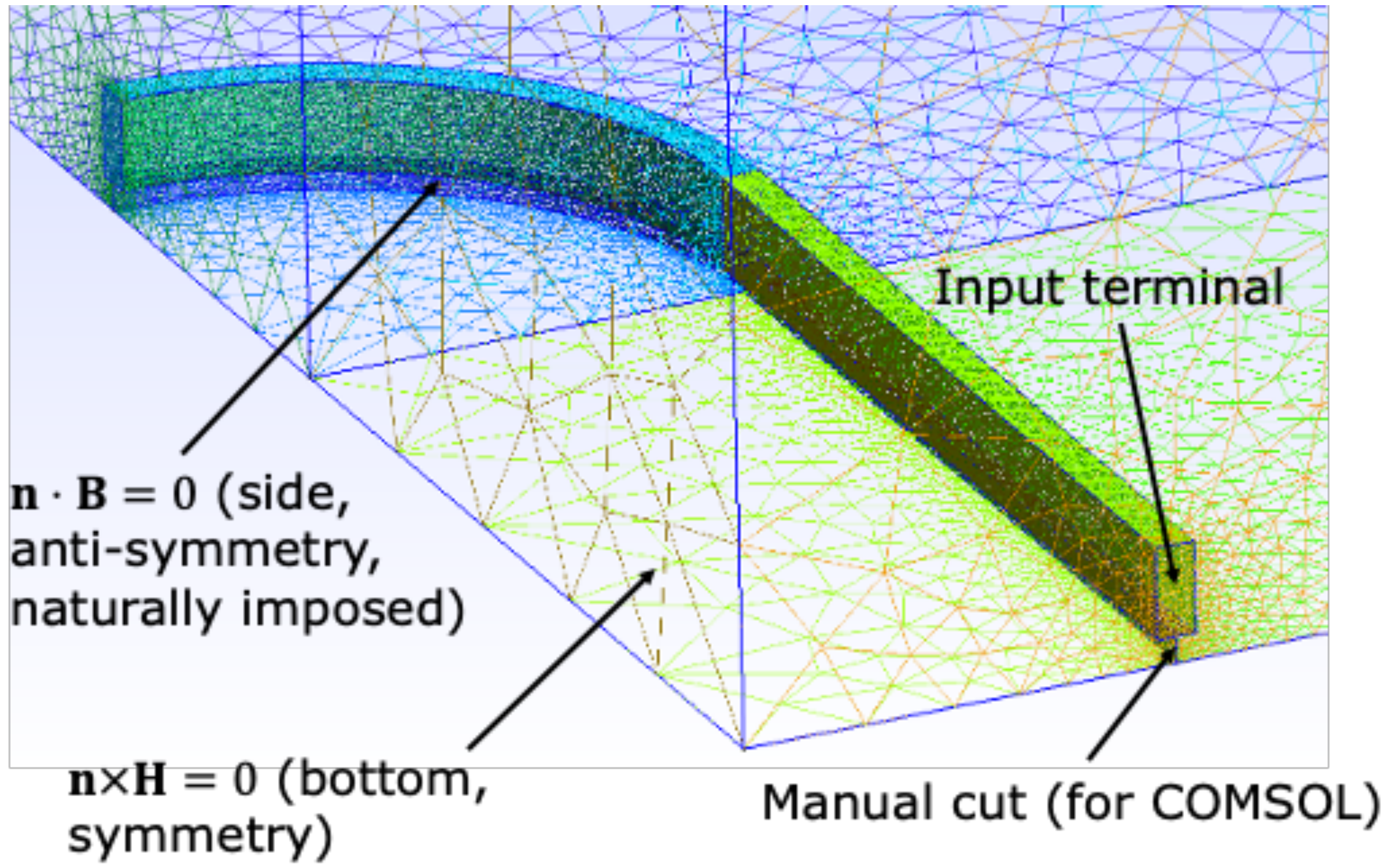


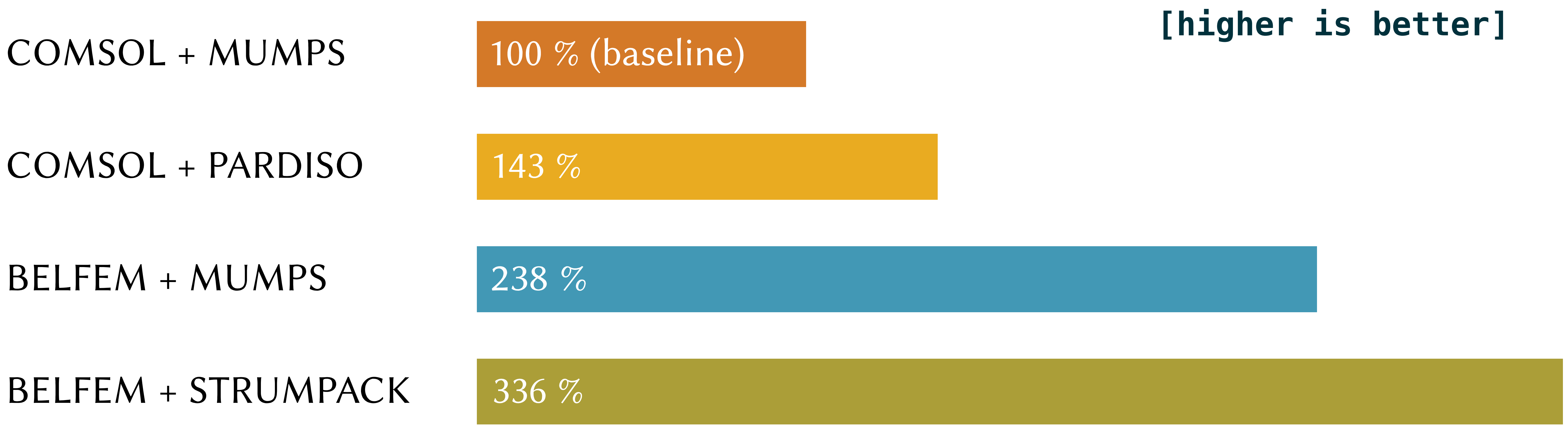
text-based input file:

```
topology
{
    thinshell : tape
    {
        sidesets : 1:3 ;
    }
    air
    {
        blocks : 1:2 ;
    }
}

boundary conditions
{
    current
    {
        input terminals  : 7@tape ;
        output terminals : 8@tape ;
        type : sine ;
        amplitude : 200 A ;
        period : 0.1 s;
        phase : 0 deg ;
    }
}
```

Performance Benchmark





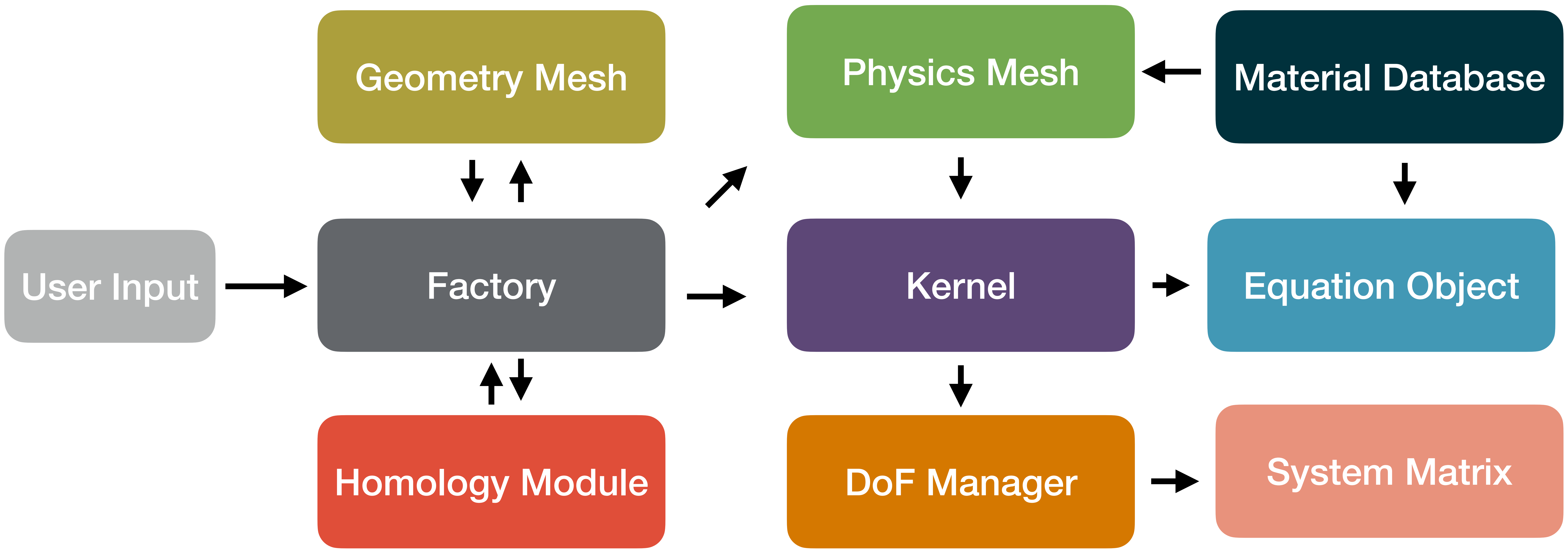
- bulk conductor
- same hardware and procs
- same mesh

- reduced overhead due to traditional element-wise implementation rather than equation based
- using of static condensation instead of Lagrange multipliers
- hierarchical matrix compression and low-rank approximations using STRUMPACK

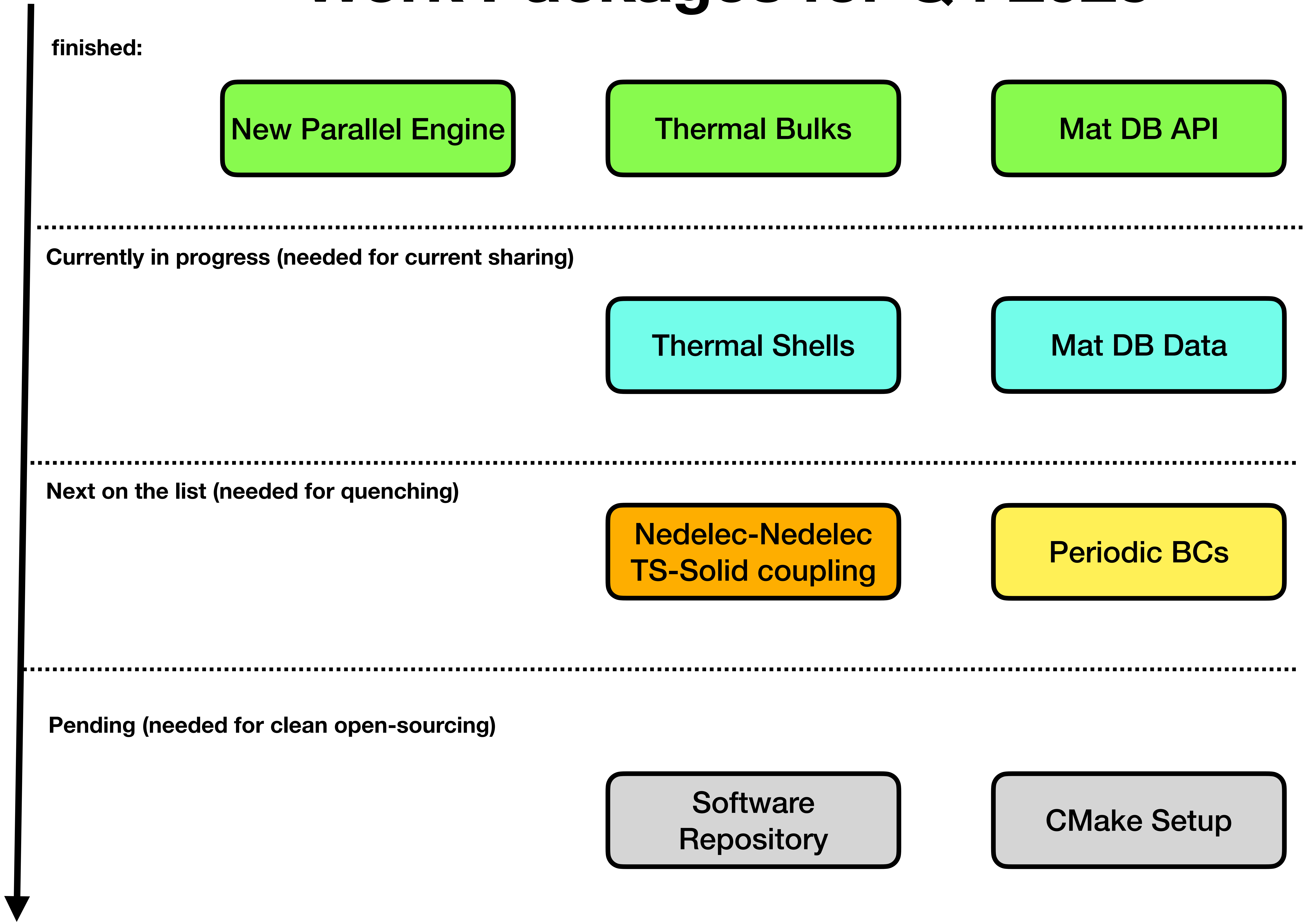
Code Organization

Core Features

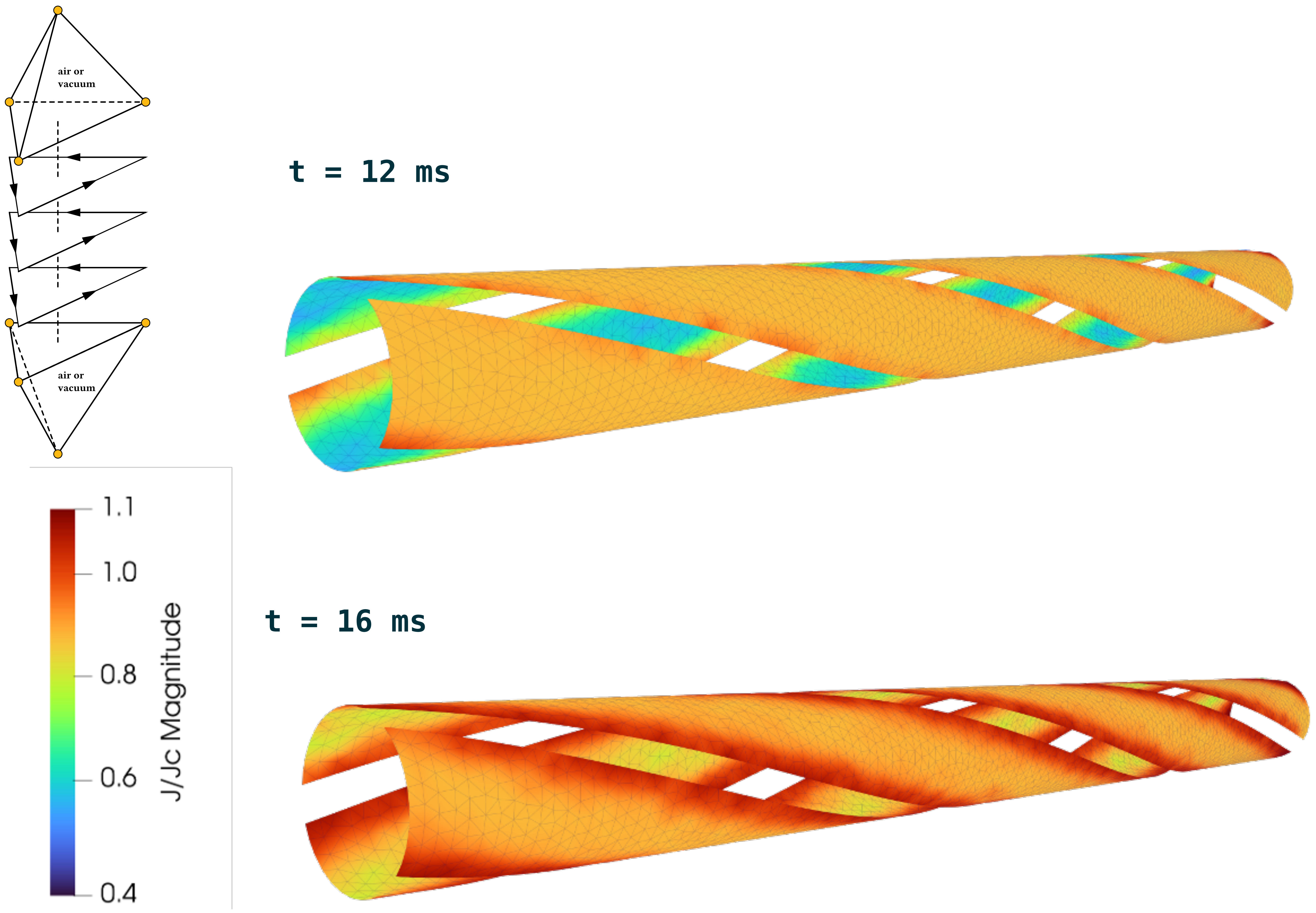
- high modularization
  ⟶ easier to maintain and extend
- relying on standard open source libraries in scientific computing
  ⟶ e.g. BLAS/LAPACK, PETSc, ...
- parallelization using MPI
  ⟶ ability to run on HPC



Work Packages for Q4 2025



h-ϕ Thin Shell Model



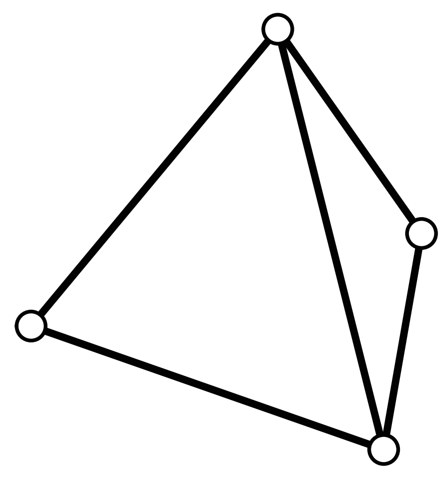
Model overview:

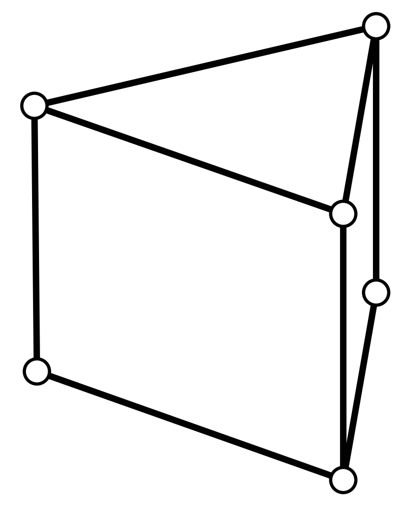
- based on model from Alves et al, 2021*
  - → perpendicular h-components are assumed constant along thickness, in-plane component varies
  - → but: can capture perpendicular current!
- domain interface using static condensation
  - → significantly better matrix conditioning than Lagrange multipliers
- cable layers resolved in model
  - → no homogenization methods needed
- supported boundary conditions per tape
  - current (Dirichlet)
  - voltage (Neumann)
  - integral constraint, eg. $\Sigma I_i = I$
  - coupling to electronic circuit network model.

* see: 10.1088/1361-6668/ac3f9, 10.1109/tasc.2022.3143076

Thermal Modeling

- **sequential iteration within timestep iteration:**
  - EM and thermal model have access to each other's fields
  - models select specialized database APIs for HTS and Metal-type materials
- **Modeling approach**
  - Solids : classic Lagrange-Type finite elements
  - Shells: considering finite volume model for better performance and stability





EM-Model (h-ϕ formulation)

$$\rho\left(\vec{j},\vec{b},\vec{n},T\right)$$

$$\dot{q}_v = \rho\, j^2$$

$$\vec{b} = \mu_0\, \vec{h}$$

T

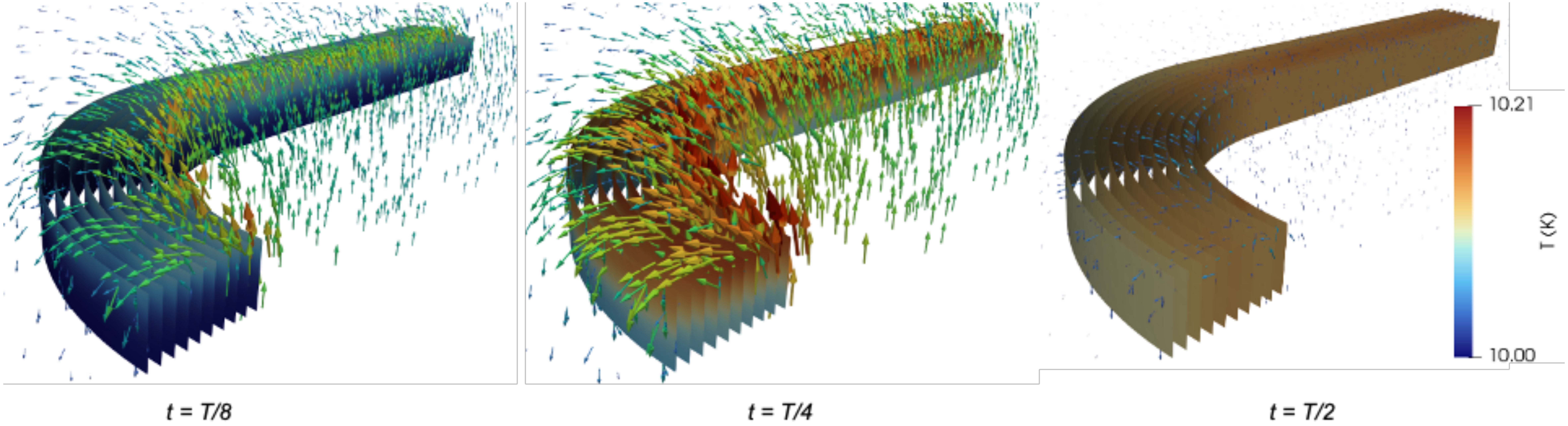
Thermal Model

$$c_p\,(T) \qquad \lambda\left(\vec{j},\vec{b},\vec{n},T\right)$$

Thermal Modeling: Proof of Concept

Proof of concept for thermal coupling

- using solid elements for thermal modeling
- using constant material properties for testing
- demonstrated code's ability to handle multiphysyical problem



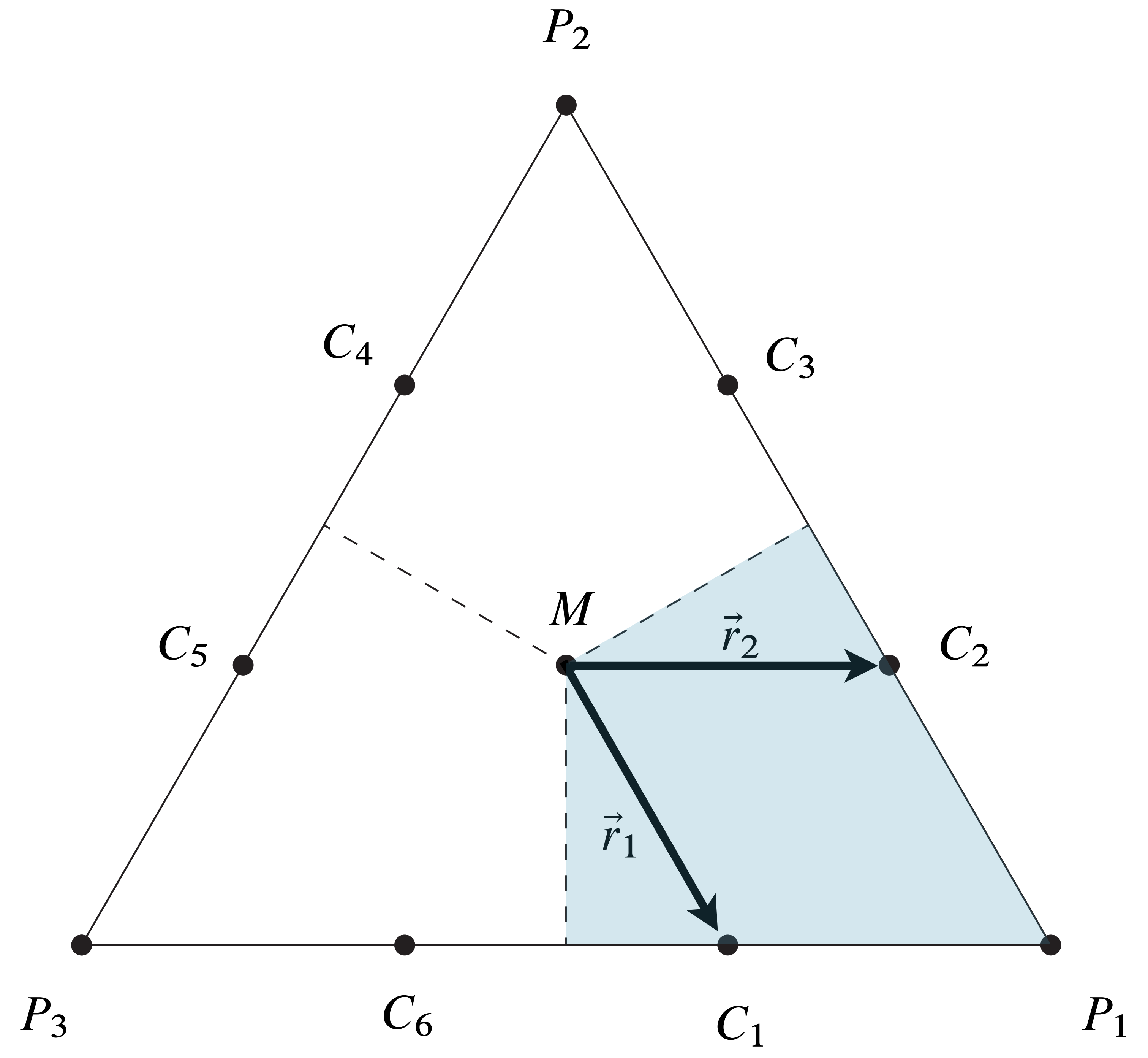
Multipoint Flux-Approximation for TS

Why not FEM for thermal modeling?

- magnetic degrees of freedom sit on edges, but thermal degrees of freedom sit on nodes
  - ⟶ noise due to mismatch
  - ⟶ risk of numerical instabilities
- node-bound dofs could damp extreme temperature regions in the quench region
  - ⟶ model might not catch temperature spike

Advantages of Finite Volumes (MPFA-O)

- extremely robust
  - ⟶ great with highly nonlinear material properties
- can capture high temperature gradients
  - ⟶ better handling of hot-spots
- enforces flux consistency between elements
  - ⟶ more conservative than FEM

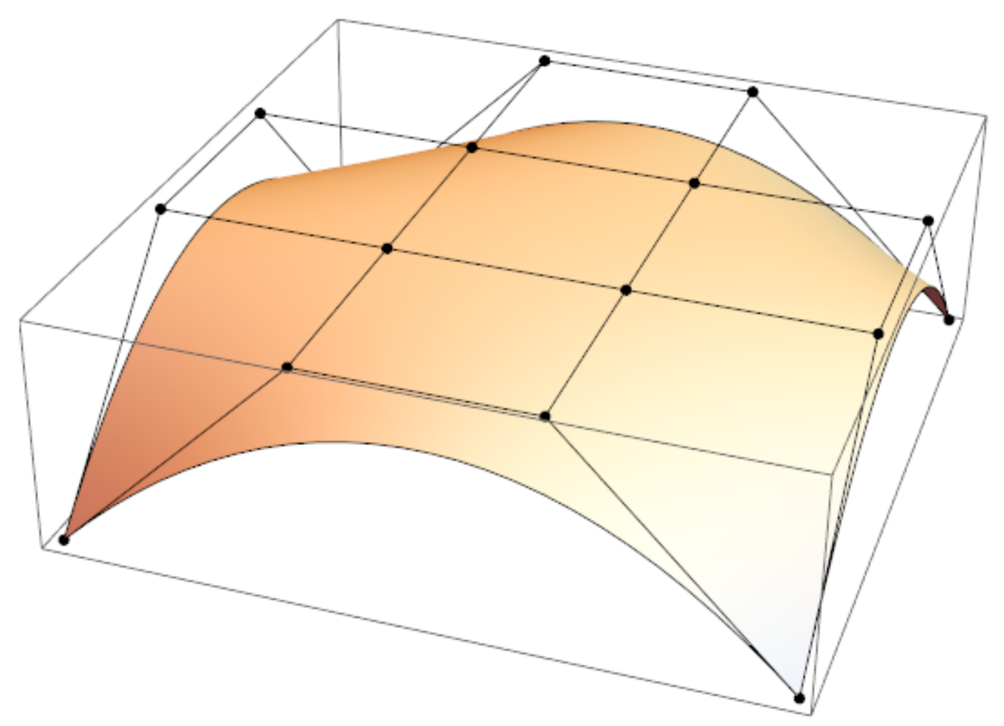


implementation is work in progress

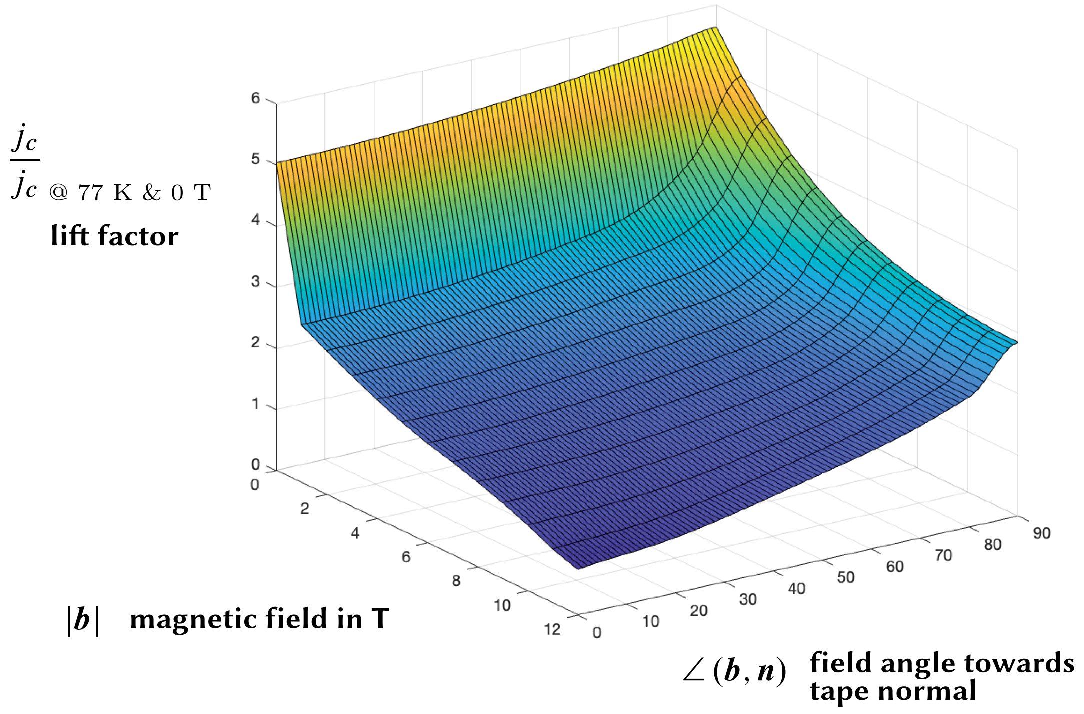
Material Database

Core Features

- Spline-based lookup tables
  - ⟶ very fast
  - ⟶ C2-continuity results in better convergence of timestep iteration.
- special interfaces for
  - Copper, Silver : j-B-dependency in ρ and λ (Kohler Model)
  - HTS model : specialized jc-functions or precomputed lookup tables



B-Spline surface



smoothed BSCCO dataset

Property Functions

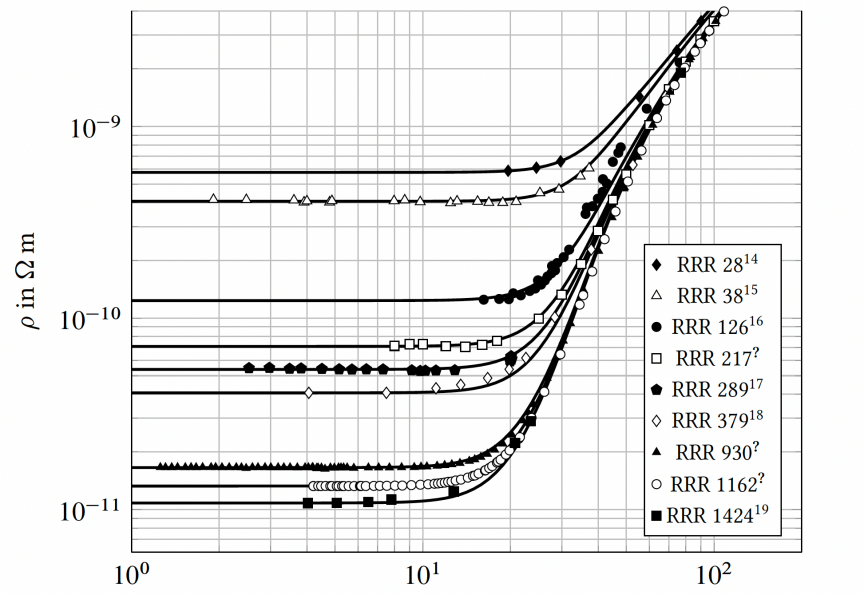
- j_c(T,B,j,n)
- ρ(T,B,j,n)
- λ(T,B,j,n)
- c_p(T)
- E(T), ν(T)
- α(T)

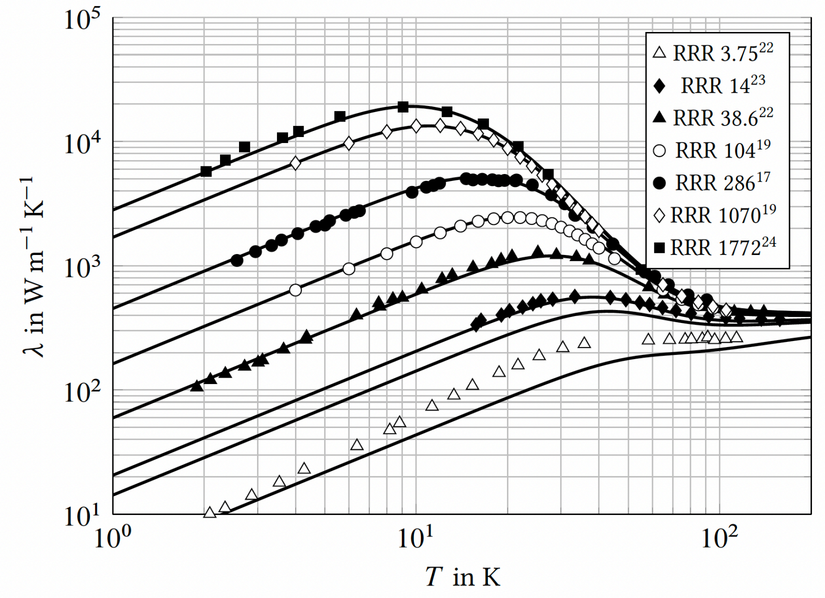
Bulk Material Properties

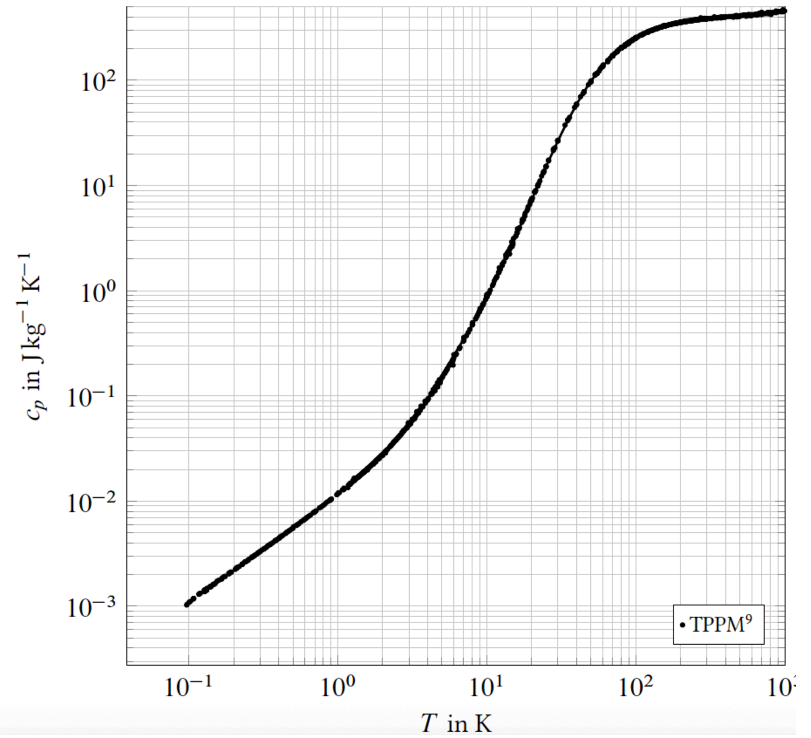
- YBCO
- Copper, arbitrary RRR
- Silver, arbitrary RRR
- Hastelloy C276

B-H Curves

- ROXIE default iron
- AISI 1010







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* see: 10.1088/1361-6668/ac3f9, 10.1109/tasc.2022.3143076

Jc-Scaling Model for REBCO

Core Features

- Extension of Hilton model for Single-Peak behavior*

- tailored for high field magnet applications
  - ⟶ temperature and field dependent data
  - ⟶ considers field angle

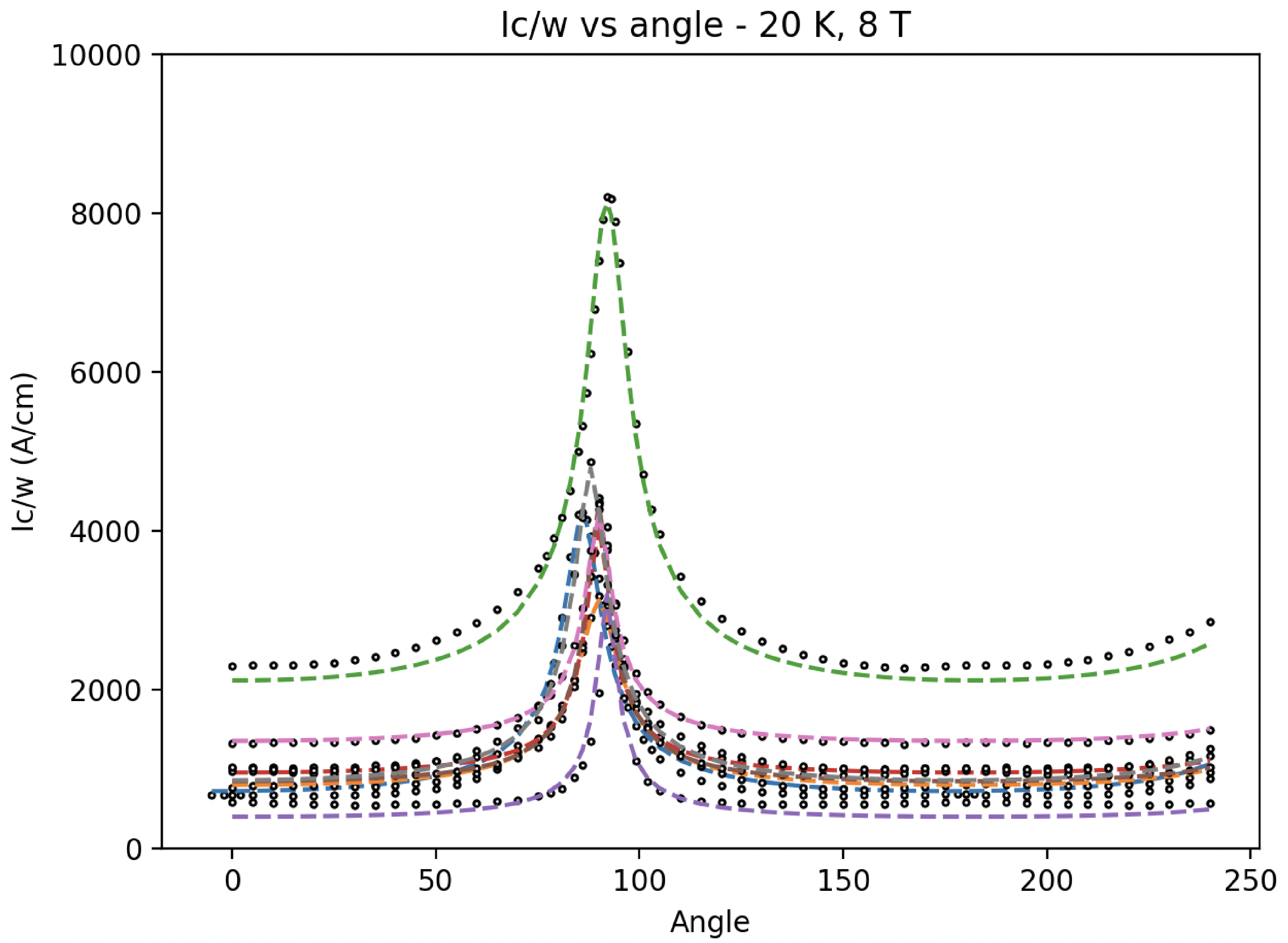
- fitted to experimental data from 8 different tape suppliers

- conservative extrapolations to unmeasured fields strengths up to 20 T and down to 4 K

$$I_c(B,T,\theta) = I_{c,min}(B,T) + \left[I_{c,max}(B,T) - I_{c,min}(B,T)\right]\frac{\omega f(\omega,\theta,\theta_0) - 1}{\omega - 1}$$

Temperature and magnetic field magnitude

Magnetic field orientation



[curtesy of Jean-François Crouteau]

* see: 10.1088/0953-2048/28/7/074002

Outlook

EUCAS 2025:

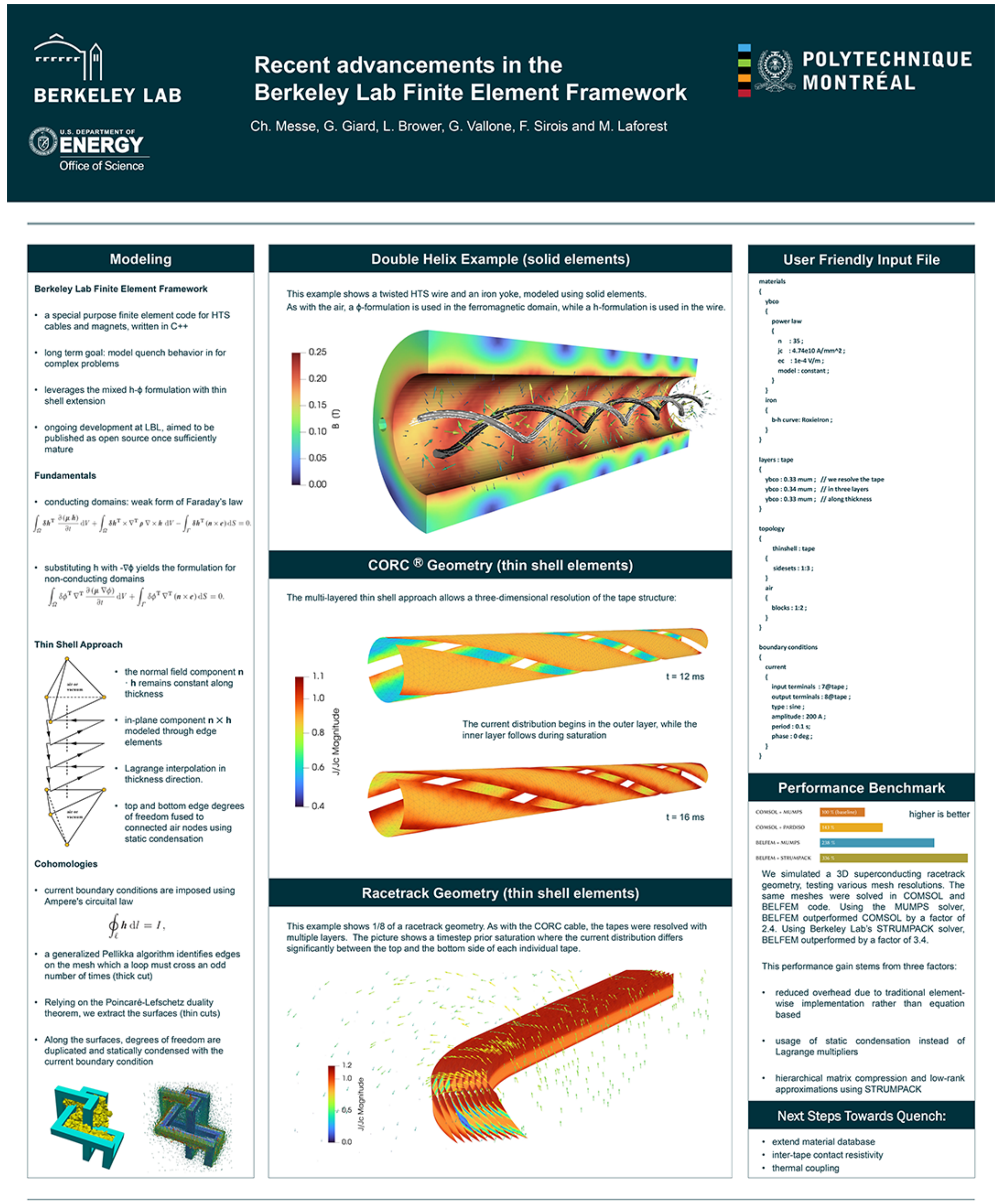
- poster presentation and invited flash talk + podium discussion
  - → very encouraging feedback

Work in Progress

- currently working on thermal model and material database
  - →proof of concept results very promising

Next Big Tasks

- periodic boundary conditions
- inter-tape current sharing
  - →quench simulation



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