Efforts on HTS Modeling and Code Development: Progress, Challenges, Opportunities

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March 21st, 2023

BERKELEY LAB

Outline

- **Introduction**
  - Theory Recap
  - Motivation
  - Project Goals
- **Last year's progress**
  - Solid Modeling (2D)
  - Thin Shell Modeling (2D)
  - Material Database
- **Current work in progress**
  - Thermal Coupling
  - Extension to 3D
- **Summary and Outlook**

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Why is HTS modeling so difficult?

- **highly nonlinear material laws**
  - power law for resistivity
  - critical current and depends on magnetic field and temperature
  - so does the thermal conductivity

→ lots of iterations needed for every time step
→ FEM generates ill-conditioned, non positive definite and non-symmetric matrices (=very difficult to solve)

"if solving nonlinear equations is like downhill skiing, solving nonlinear equations for HTS modeling is like skiing the double black diamond trail without poles"

Ohm's Law

$$\boldsymbol{e} = \rho\, \boldsymbol{j}$$

$$\rho = \frac{e_c}{j_c}\left(\frac{|\boldsymbol{j}|}{j_c}\right)^{n-1}$$

$$j_c = f\left(|\boldsymbol{B}|, \angle\boldsymbol{B}, T\right)$$

Fourier's Law

$$\dot{q} = -k\,\nabla T$$

$$k = f\left(T, |\boldsymbol{B}|\right)$$

$$c_p = f\left(T\right)$$

Mixed Formulations: a Quick Recap

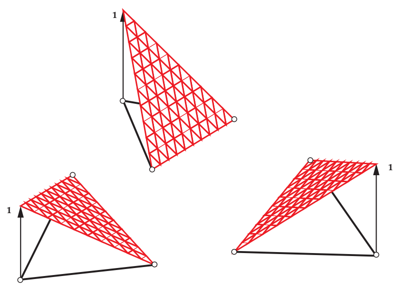
- **gaining significant interest over the last five years!**

- **goal:**
  - improve conditioning for system matrix
  - reduce degrees of freedom
    - $\longrightarrow$ faster computation

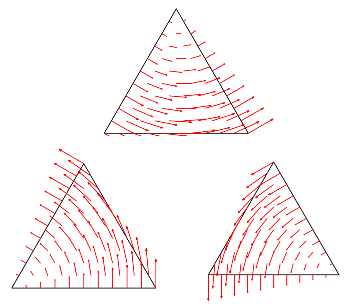
- **basic idea**
  - governing equations are domain specific
  - domains are connected over interfaces conditions

- **challenges**
  - user-friendliness
  - mesh generation and memory management
  - iterating over non-linear material models
  - matrices are difficult to solve (still ill conditioned, non symmetric, non-postive definite)

	Air / Vacuum	Conductor	Ferromagnetic Alloy
Governing Equation	$\nabla \times \boldsymbol{h} = \boldsymbol{0}$ Ampére-Maxwell	$\nabla \times \boldsymbol{h} = \boldsymbol{j}$ Ampére-Maxwell	$\nabla \times \boldsymbol{e} = \dot{\boldsymbol{b}}$ Faraday's Law
Degree of Freedom	$\boldsymbol{h} = -\nabla\,\phi$ Magnetic Scalar Potential	$\boldsymbol{h}$ Magnetic Field	$\boldsymbol{b} = \nabla \times \boldsymbol{a}$ Magnetic Vector Potential
Transport Law	none	$\boldsymbol{e} = \boldsymbol{\rho} \cdot \boldsymbol{j}$ Ohm's Law	$\boldsymbol{h} = \boldsymbol{\nu} \cdot \boldsymbol{b}$ Magnetic Law
Comment	minimal number of dofs	need edge elements	simple material law implementation



Lagrange Elements

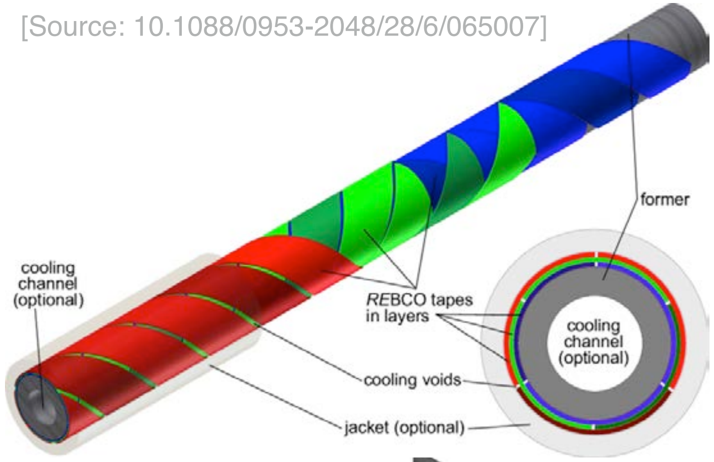


Nédélec Elements

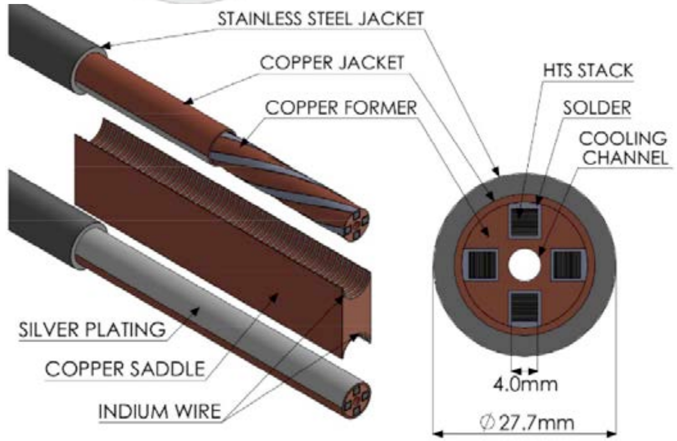
BELFEM: Motivation and Project Goals

- **have a custom C++ codebase that**
  - can predict quench behavior of HTS
    - ⟶ coupled electromagnetic-thermal simulation
  - is sufficiently fast
    - ⟶ uses state of the art h-ϕ formulation
    - ⟶ uses state of the art solver libraries
    - ⟶ uses state of the art parallelization
  - supports complex geometries and current sharing
    - ⟶ uses state of the art thin shell models
    - ⟶ need low level access to data structure
  - can handle highly nonlinear material properties
    - ⟶ custom database
    - ⟶ using 3D-B-splines to allow smooth derivatives

[Source: 10.1088/0953-2048/28/6/065007]



CORC®



VIPER

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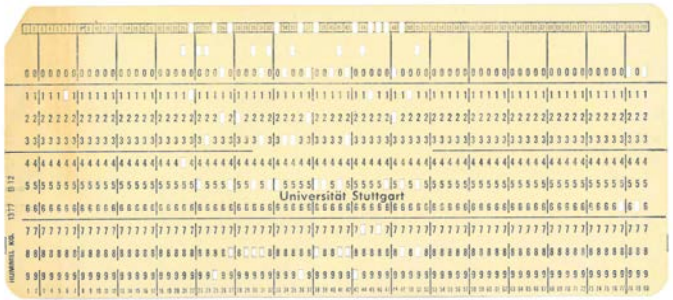
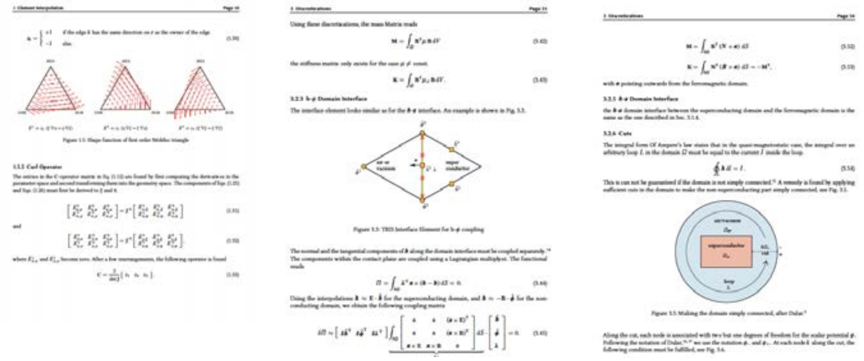
Codebase Requirements & Philosophy



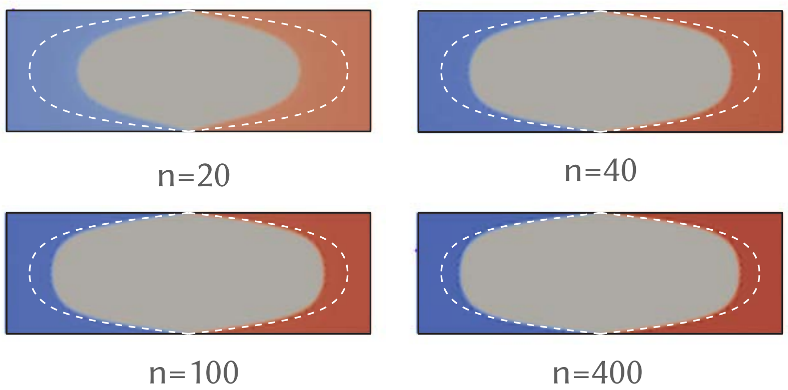
- **Flexibility & Maintainability**
  - consistent naming scheme of functions and classes
  - lots of comments in code!
  - modular structure
- **simple MATLAB-like dense linear algebra**
  - through ARMADILLO or BLAZE
- **text based interface tailored to magnet development**
  - ability to write scripts in BASH and Python
- **utilization of community software**
  - use open source data formats (GMSH, HDF5, Exodus II)
  - link against community libraries: MUMPS, PETSc, STRUMPACK, ...
- **be open source once mature**
  - Berkeley Lab specific BSD-3 like license

Last Year’s Progress

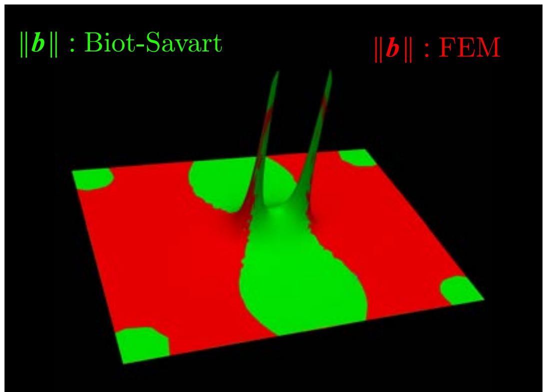
Solid Formulation Implemented & Validated



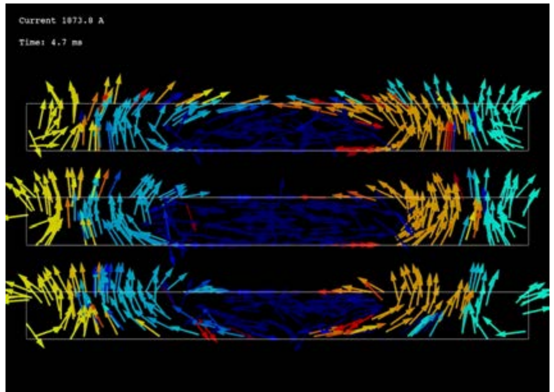
- **Mixed Formulation (solids)**
  - detailed derivation of h-Φ and h-a forms and element matrices
  - description and improvement of domain interfaces
  - proof of concept implementation in 2D
  - validation against Biot-Savart + Brandt
- **Invited Talk presented at HTS 2022 in Nancy, France**



current distribution validation against Brandt



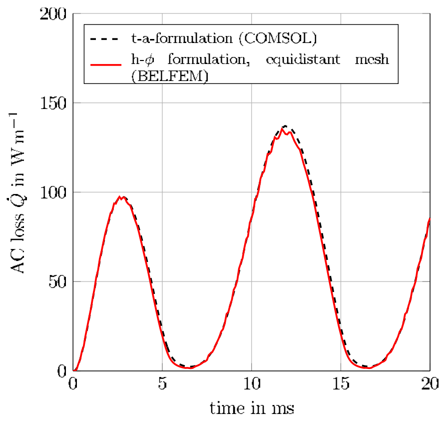
a-formulation of dipole

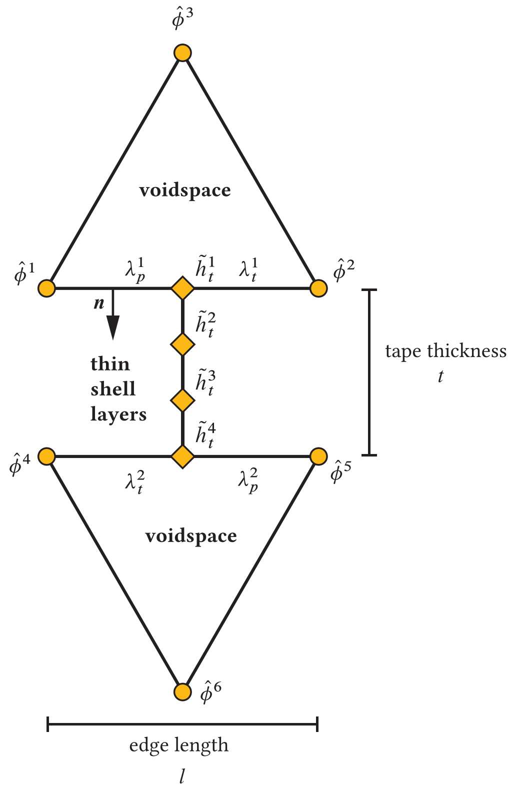


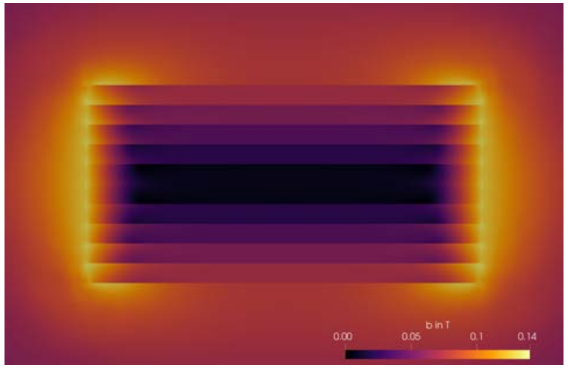
HTS stack (h-ϕ form)

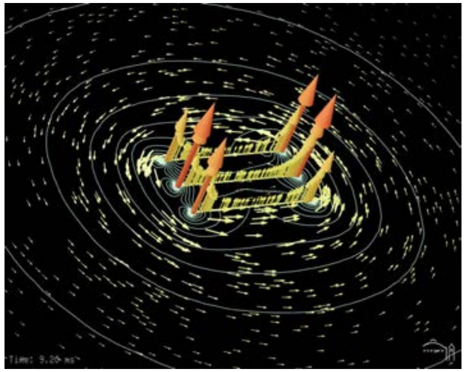
Thin Shell Formulation Implemented & Validated

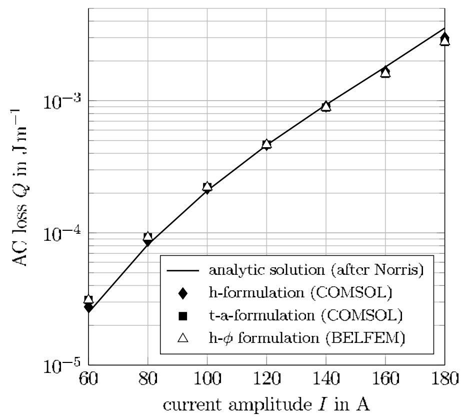
- **Mixed Formulation (thin shells)**
  - implementation of Alves-Element in 2D
  - validation against analytical methods + COMSOL / GetDP
- **Invited Paper for SuST 2023 (submitted)**
  - Christian Messe, Berkeley Lab
  - Nico Riva, MIT
  - Sofia Viarengo, Politecnico di Torino











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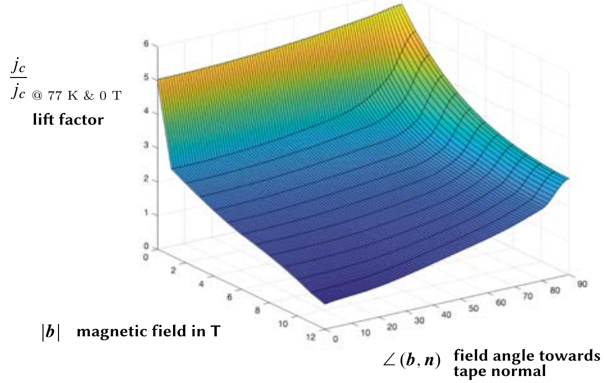
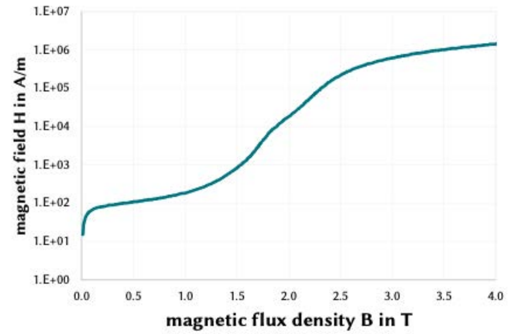
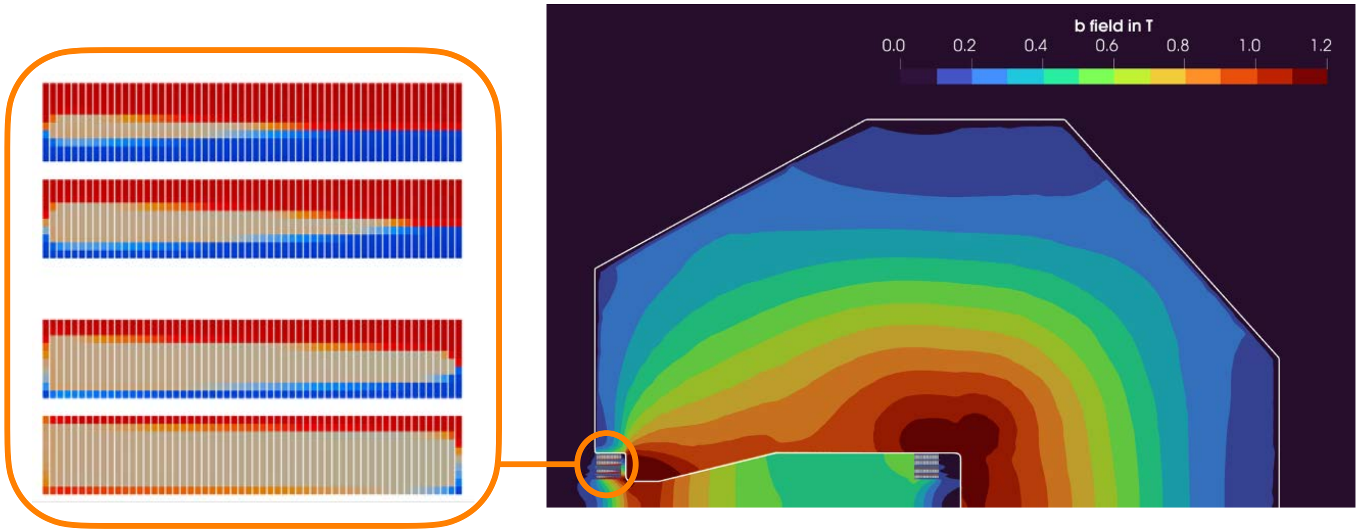
Last Year's progress: Application to Gantry Magnet

- **Gantry Magnet Field Quantity Simulation**
  - proof of concept for complicated structure (254 individual tapes of BSCCO 2223)
  - highly nonlinear material properties
  - poster presentation at ASC 2022, HI

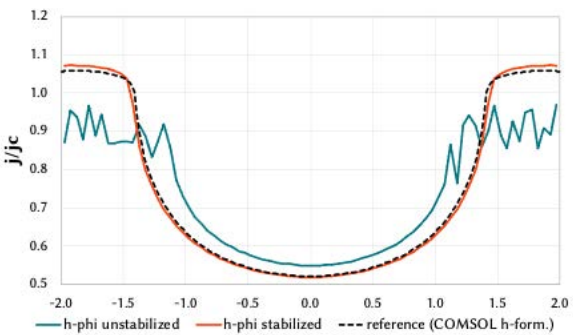






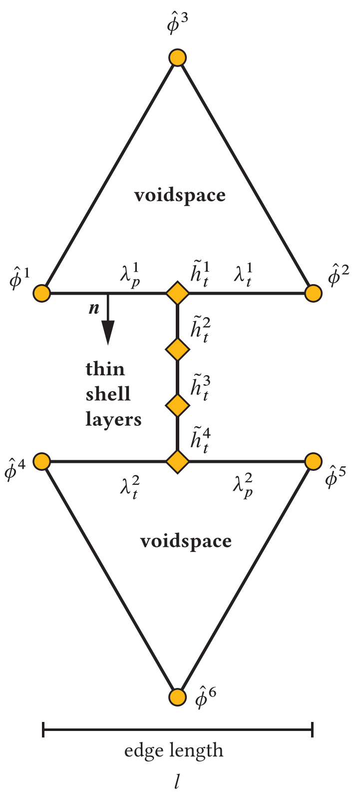
Misadventures: Application to Gantry Magnet

- **Challenges**
  - a-ϕ interface unstable for highly nonlinear ferromagnet under high magnetic fields
    ⟶ current subject of research
  - second order implementation oscillates
    ⟶ considering research project
    in cooperation with CU Boulder

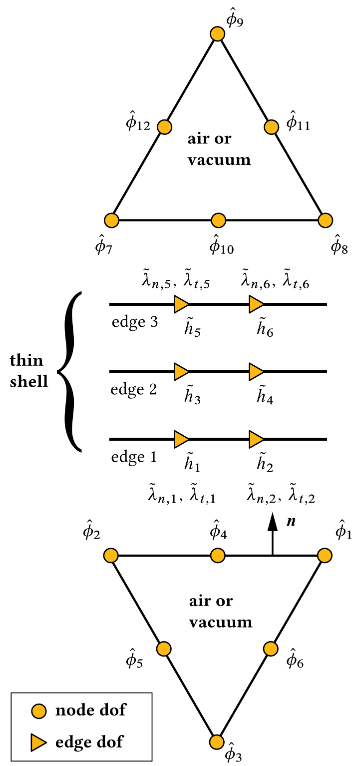


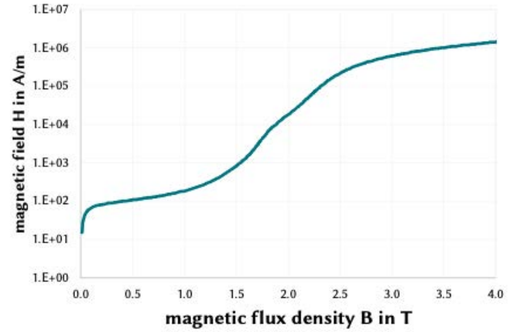
oscillation with 2nd order model

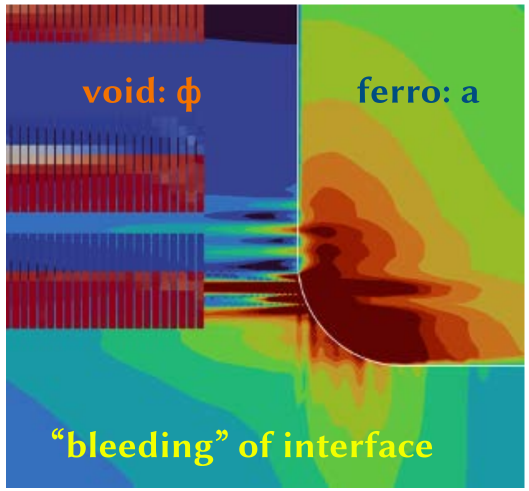
1st order model



2nd order model

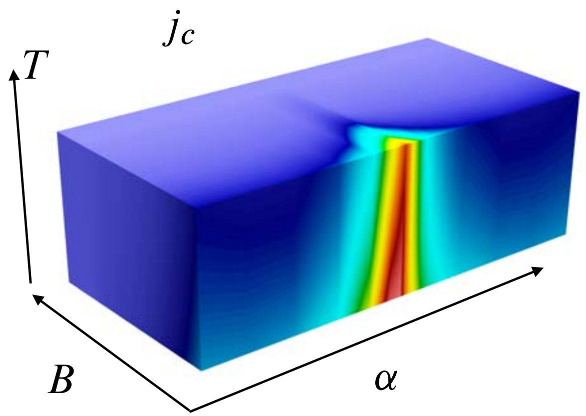


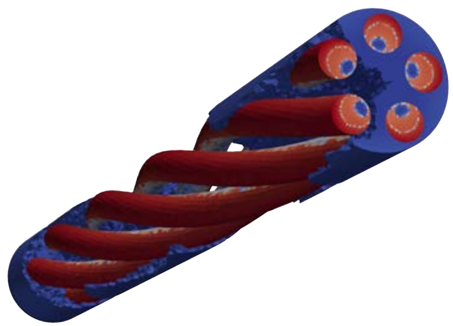




Last Year's progress: Material Database

- **Material Database**
  - can provide properties depending on up to three parameters
    e.g. ρ, jc, cp, k, E, G, α ...
    currently free: Copper, Silver, Hastelloy, ...
  - values precomputed in lookup tables
    ⟶ very fast evaluation
  - utilizes B-Splines with up to third order (smooth derivatives!)
    ⟶ very suitable for Newton-Raphson and Picard Maneuver
  - stand alone database for use in other codes
    ⟶ uses HDF5 as data format
- **Coupled against SparseLizard**
  - results presented at ASC 2022, HI
  - results published in SuST 2022, Halbach et al.
    DOI: 10.1109/TASC.2023.3240389
- **Consider publishing under open source license**
  ⟶ interest in the community?





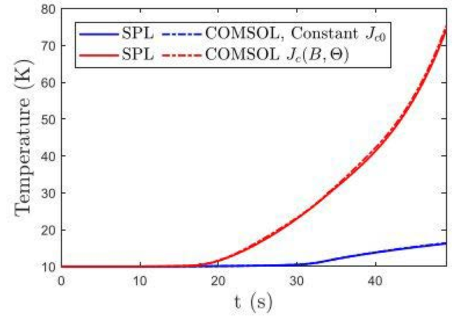


Fig. 5

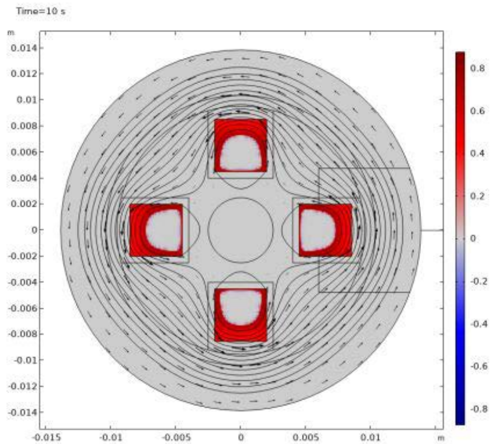


Fig. 6

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Last Year's progress: Theory Refinement

- **Visiting Professor Frédéric Sirois, Polytechnique Montreal**
  - review of current state of the art
  - discussion of domain interfaces, quench simulation and current sharing
  - frequent meetings with former PhD Students Bruno Alves and Alexandre Arsenault
  - lots and lots of hours in front of the whiteboard!
  - organized a five months visit of PhD student Gregory Giard

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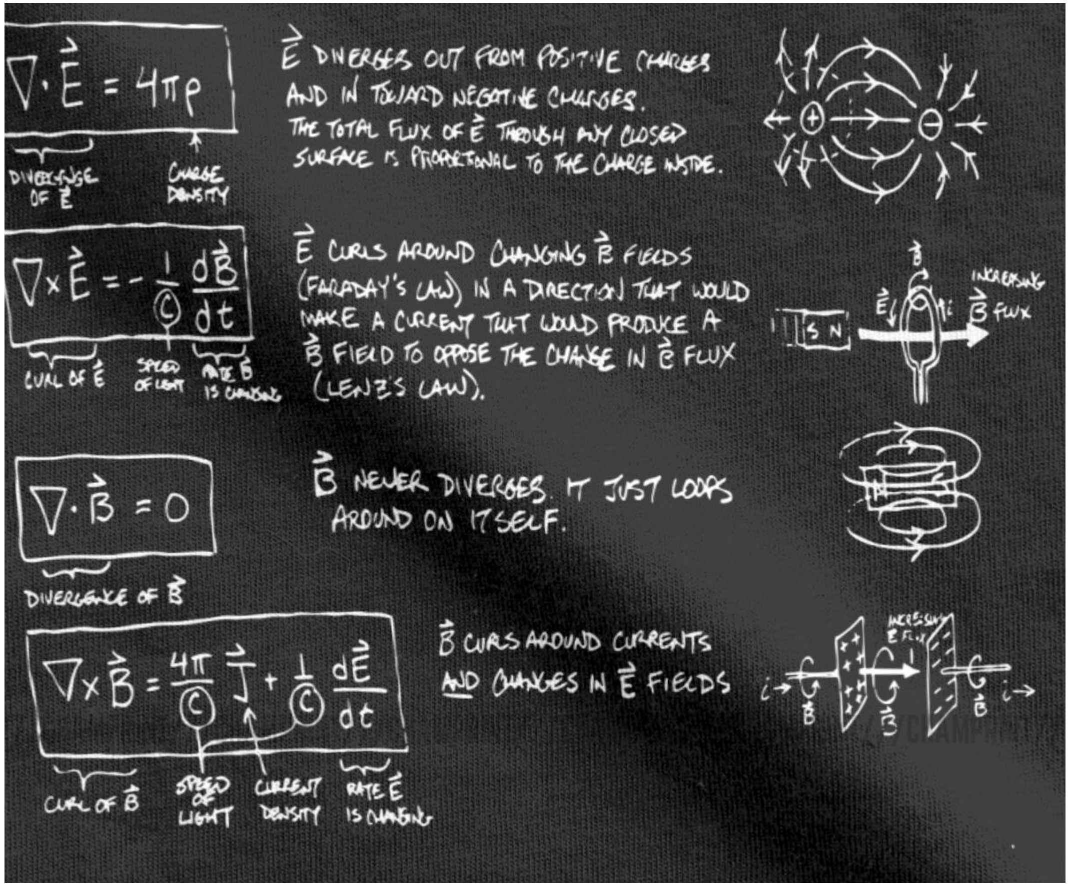
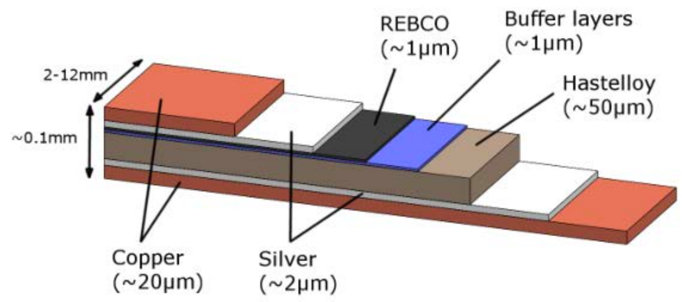
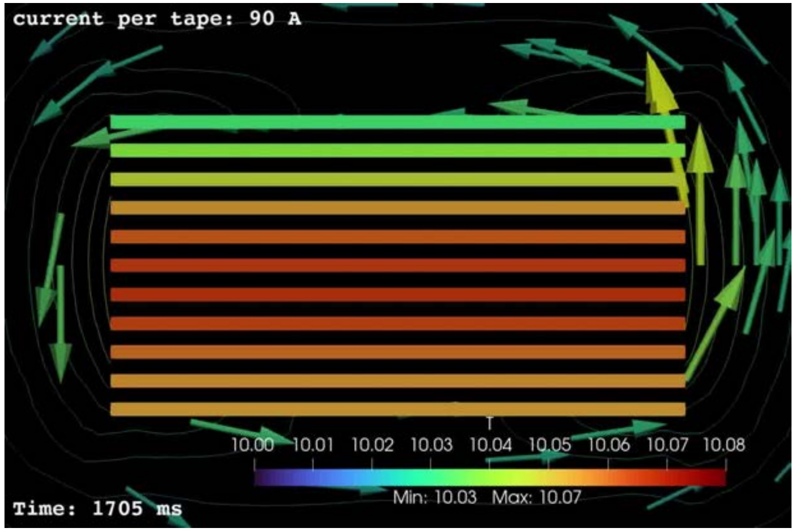


Current Work in Progress

Work in Progress: Thermal Coupling

- **Extension of Alves-Element with Thermal Model**
  - each layer is modeled individually using lumped masses
    ⟶ no mixture rule required
    ⟶ very stable convergence
  - implicit coupling of physical fields
    ⟶ using STRUMPACK to solve quasi-magneto-static problem
    ⟶ using PETSc (GMRES) to solve thermal problem
- **Gregory Giard (visiting PhD student, Politechnique Montreal)**
  - improvement of domain interfaces
  - adaptive relaxation method
  - extension of thermal model to 3D
- **Erik Schnaubelt (PhD student at CERN / TU Darmstadt)**
  - defining benchmark problems + validation against COMSOL

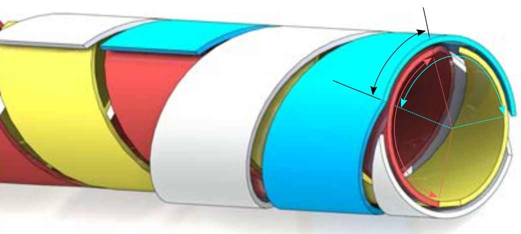


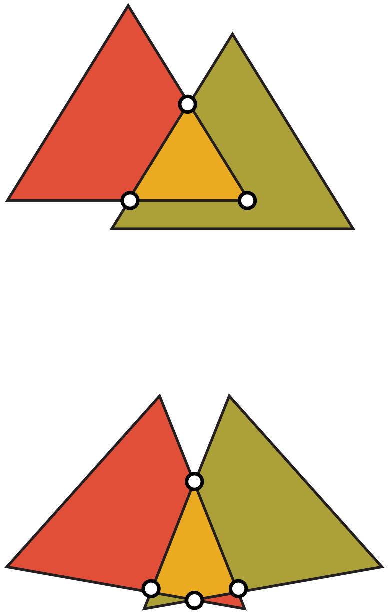


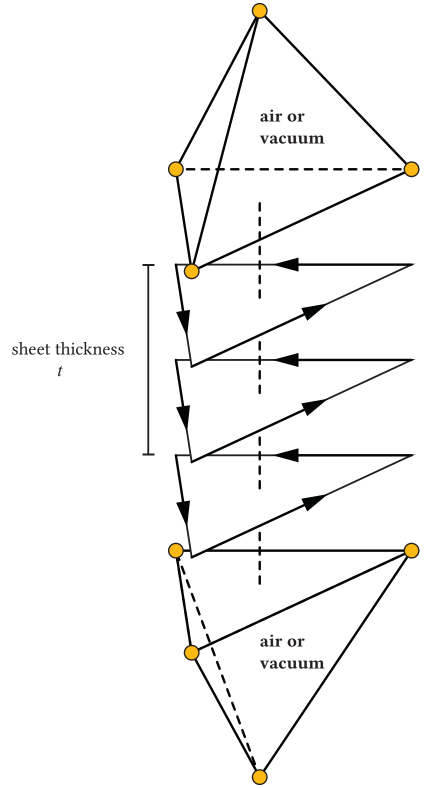
Work in Progress: Extension to 3D

Goal: Thermal-Magnetostatic Modeling of CORC cables

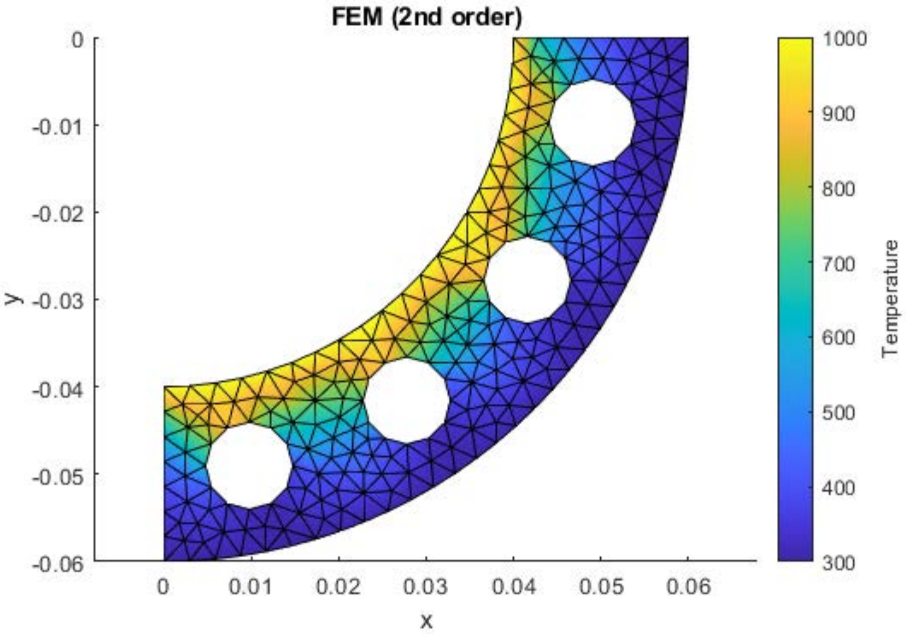
- proof of concept already demonstrated by Bruno Alves
- implementation of magnetic model in BELFEM
- implementation of lumped mass model for 3D
- improvement of geometry engine
- first thoughts about current sharing
- definition of benchmarks

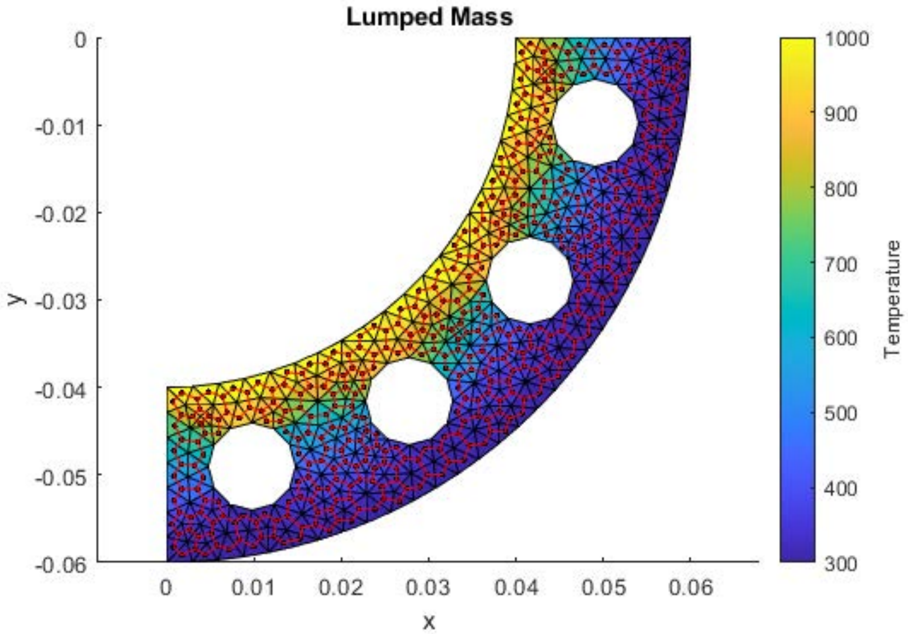


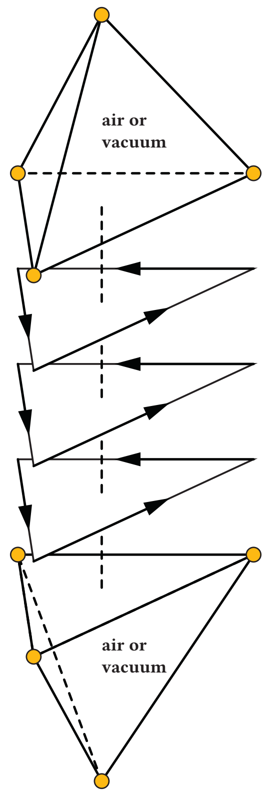




Benchmark: Lumped Mass Model for Triangles



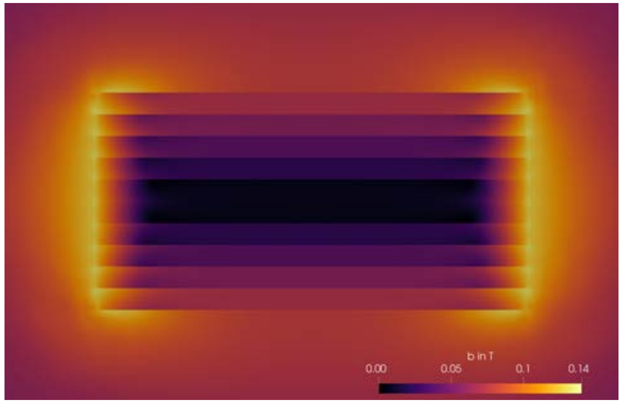


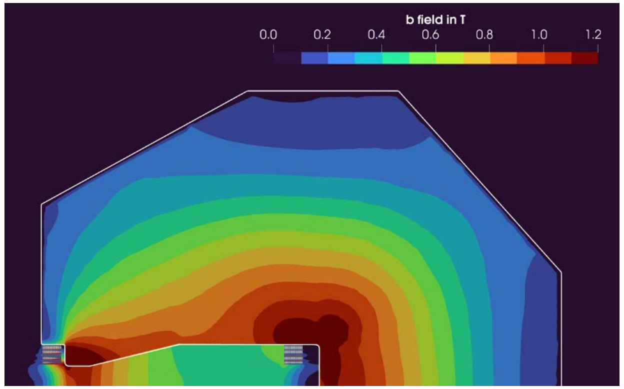


- **benchmark**
  - arbitrary geometry with strong gradients
  - goal: prove that lumped mass model works for triangles
  - result: very promising!

Summary and Outlook

Summary





- developing a finite-element framework tailored to HTS cable & magnet development needs
- support modern mixed formulations such as h-a and h-ϕ
- support thin shells & multi-physics (work in progress)
- code designed to run in parallel on HPC node
- writing textbook-like theory manual
- working on a stand alone material database

Outlook

during the next months:

- improve domain interfaces
- complete validation for thin shell implementation for and h-ϕ
- complete work on TS-quenching

during this year:

- finalize implementation of 3D model (together with Gregory Girard)
- work on geometry-preprocessor for 3D current sharing
- benchmark against simple experiments
- further improvements and code hardening
- streamline workflow for real world applications

future plans:

- work on cryogenic fluid database for cooling
- second order thin shells (PhD thesis?)
- publish code under BSD-3-like license