Multiphysics modeling using Open-source FEM software: Elmerfem and Onelab

F. Trillaud(1)

Acknowledgment: E. Takala(2) on Elmerfem support and development

(1): Instituto de Ingeniería, UNAM, Mexico
(2): Elemental Reality Solutions (ERS), Finlandia

Content

Introduction:

Open-source solutions

Elmerfem <http://www.elmerfem.org/blog/>: developed by the Finnish CSC-IT Center for Science <https://www.csc.fi/en/home>

Onelab <https://onelab.info/>: developed by *Université de Liége* and *Université Catholique de Louvain* in Belgium

Case studies (objective: give an overview of capabilities):

1) Low Temperature Superconducting (LTS) coils - Quench model (Collaboration with Ciro Calzolaio - Magnet section, PSI):
   a) FEM
   b) FEM-Circuit

Superconducting Superbend BS3-5 for SLS2.0

2) Magnetostatics, thermal, fluid dynamics and structural mechanics
3) High Temperature Superconducting (HTS) coils and bulks: AC losses and trapped magnetic field

Open source solutions

Use existing open-source numerical tools as an alternative solution to “costly” commercial software

Costly: the core software is “relatively” inexpensive, one pays the extra modules, the diverse licenses and the support

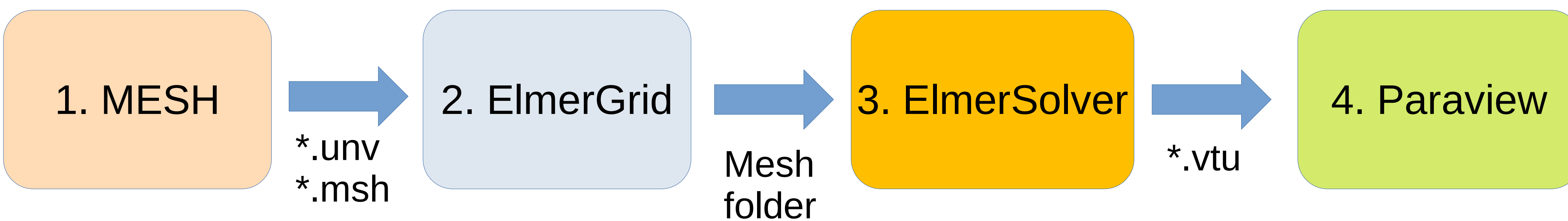
Large difference in price for academic and professional licenses

Open source	Commercial
Free	Costly
General / Targeted	General, module-based business model
High flexibility	Limited flexibility
Steep learning curve	Quick handling
Expandable	Depending on the quantity of user in need of specificity
TUI and sometime GUI	Mostly GUI
Coding skills required (python, C++)	Not promoted but possible for some software
Community-based support	Commercial support

Elmerfem in a nutshell

1. Elmerfem is essentially a FEM solver (ElmerSolver) built for large scale parallelization → High Performance Computing (HPC) < http://www.elmerfem.org/blog/>
2. The geometry and mesh is done elsewhere (mesh partitioning for parallelization)
3. Elmerfem provides the capability to convert external meshes to its own format (ElmerGrid)
4. Visualization using Paraview <https://www.paraview.org/>

Lead developer: Peter Råback <https://fi.linkedin.com/in/raback>



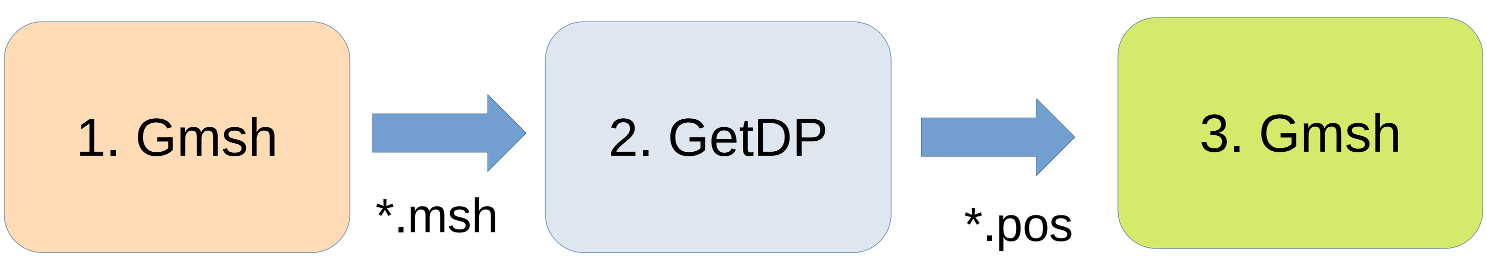
Onelab in a nutshell

Onelab: Gmsh and GetDP

Gmsh <https://gmsh.info/>: "*A three-dimensional finite element mesh generator with built-in pre- and post-processing facilities*" → simple geometries very good mesher

GetDP <https://getdp.info/>: "*A general environment for the treatment of Discrete Problems*" → finite element solver

Lead Developer: Christophe Geuzaine < https://people.montefiore.uliege.be/geuzaine/>



Geometry builder and mesher

From CAD to model: simplification of the geometry → removing complex geometries and details (bolts and nuts)

The geometry and mesh are done in Salome platform < https://www.salome-platform.org/>

In the present case, the mesher is Netgen <https://ngsolve.org/>

Netgen/NGSolve

Elmerfem

(Superconducting Superbend for SLS2.0, Ciro Calzolaio, Magnet section, PSI)

OS: Ubuntu 20.04LTS
Salome platform v9 $\rightarrow$ Geometry / mesh
Elmerfem v9: FEM solver / Postprocessor
Paraview: visualization

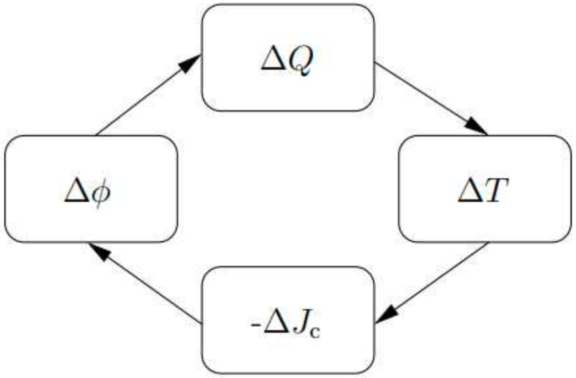
Case 1a and 1b: Quench model

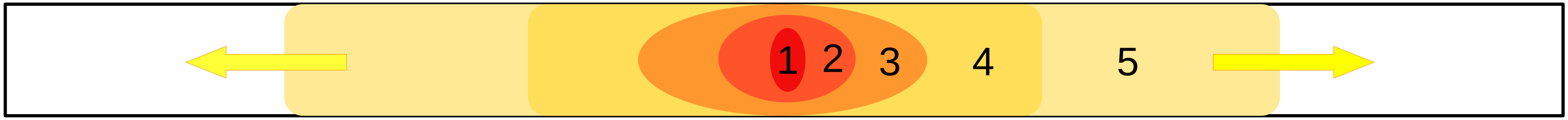
Superconducting magnets are prone to *quench*

Quench: a sudden loss of the superconducting state with a local energy dissipation leading to a heat propagation wave throughout the coil

<u>Quench process:</u>

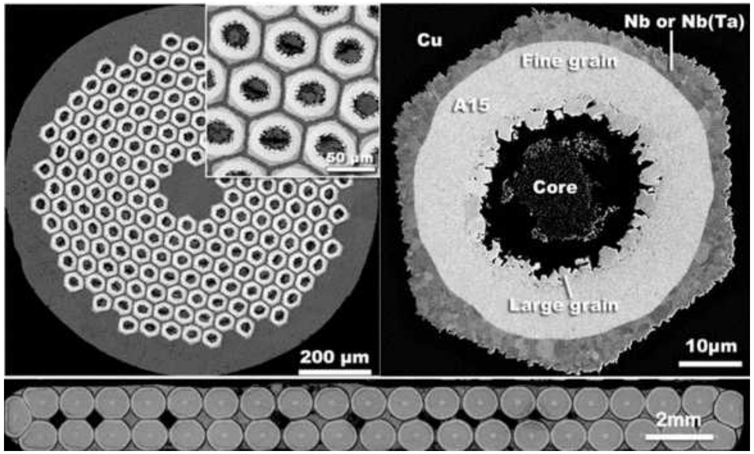
- 1: Initial normal zone (localized dissipation)
- 2-3: Diffusion (expansion of the dissipative zone)
- 4-5: Propagation (dissipative front at constant velocity)





Case 1a: Racetrack – SC superbend

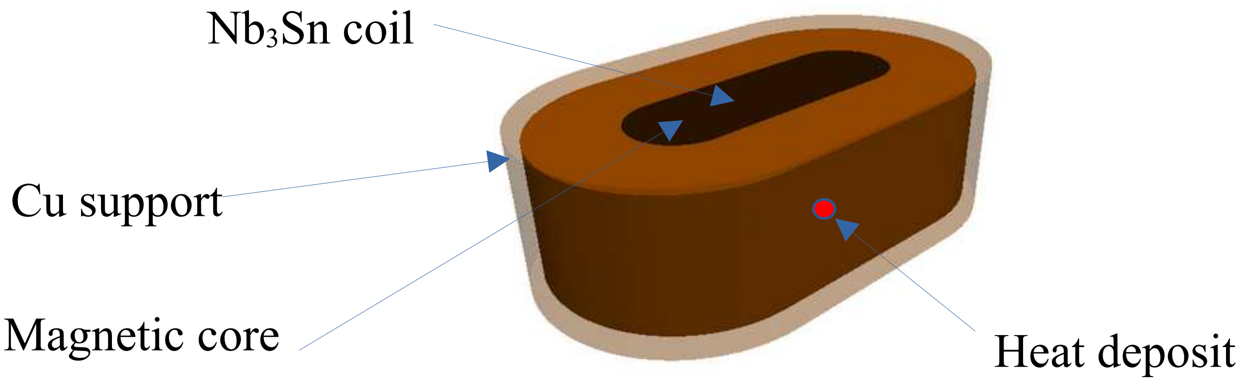
Racetrack coil wound with a composite material → anisotropic material properties

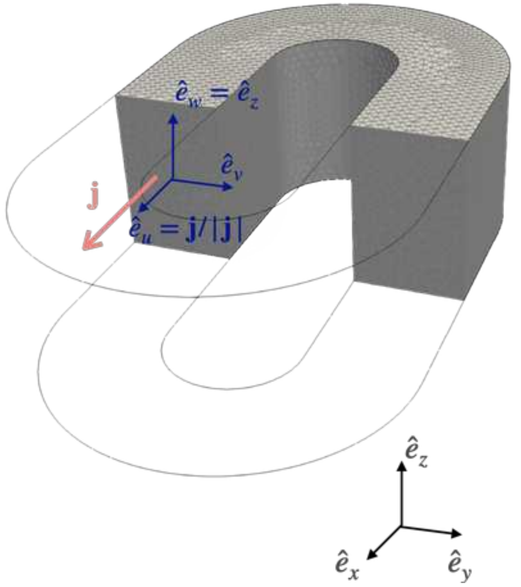


Homogenization of the electric properties and the heat capacity

Orthotropic tensor of heat conductivity in local coordinate system (matrix of transformation)

User Defined Functions (UDF)





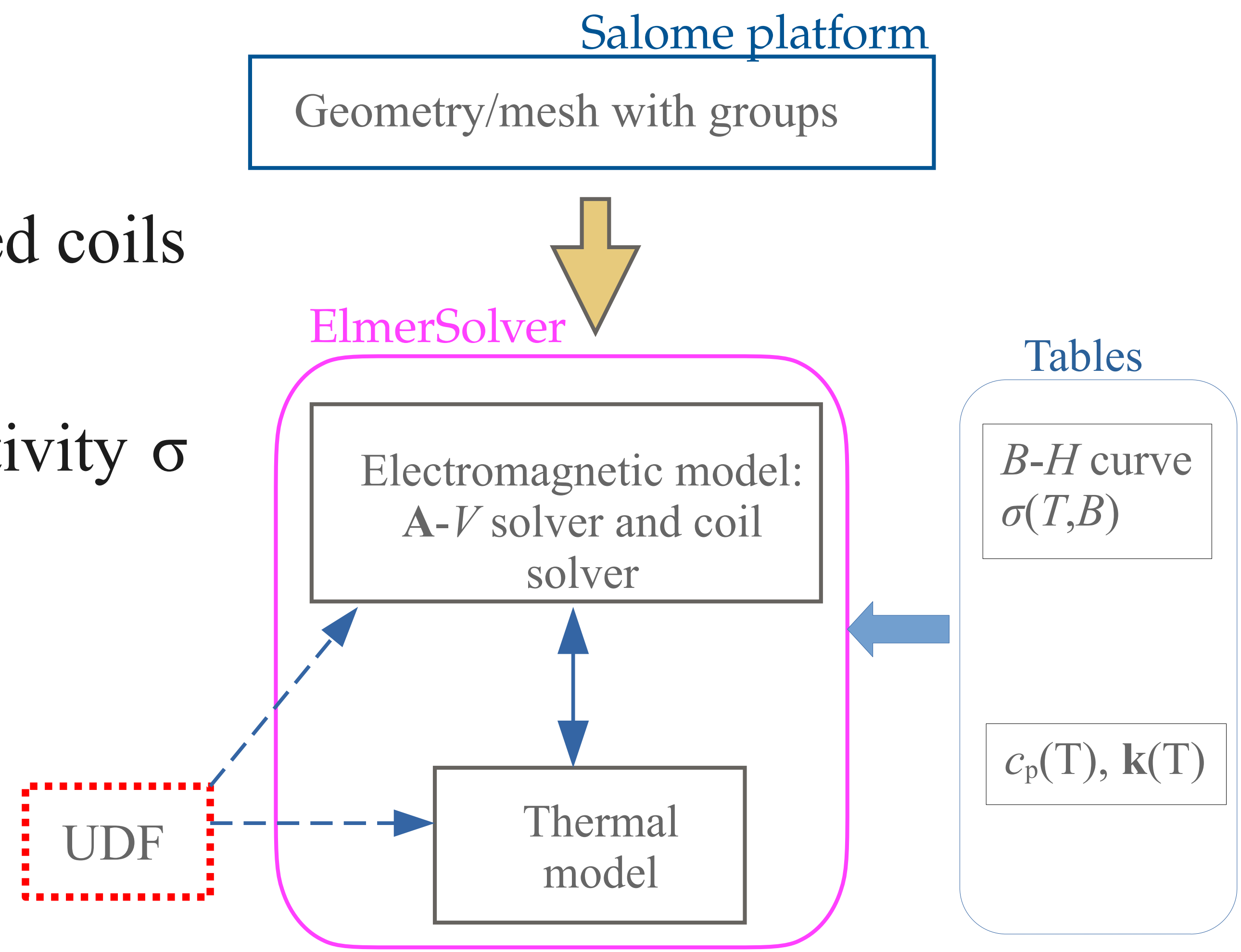
Case 1a: physics

Coupled physics: quasi magnetostatics and thermal

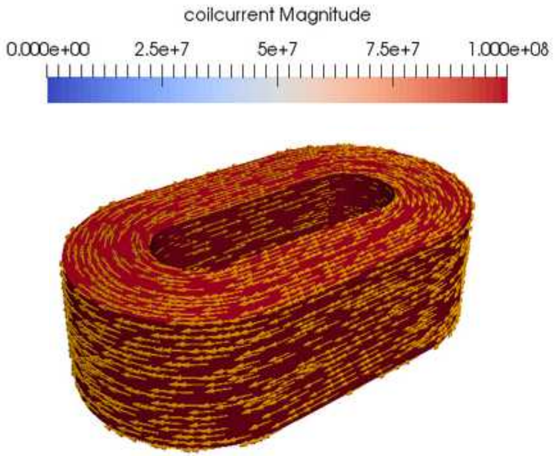
3D FEM model using closed coils

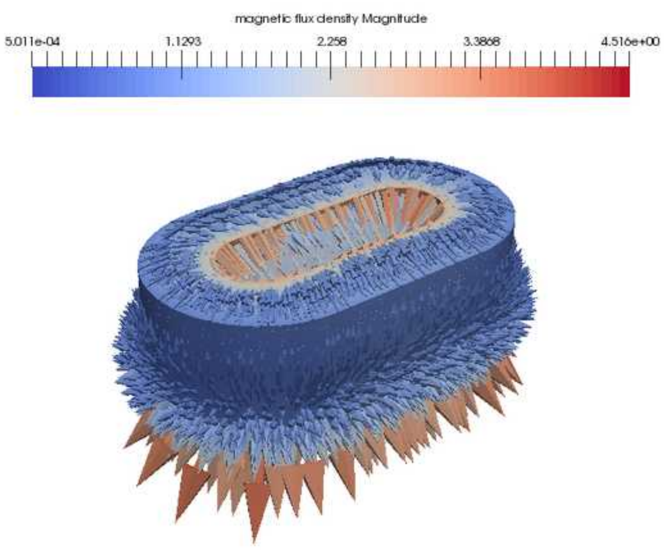
Transient solution

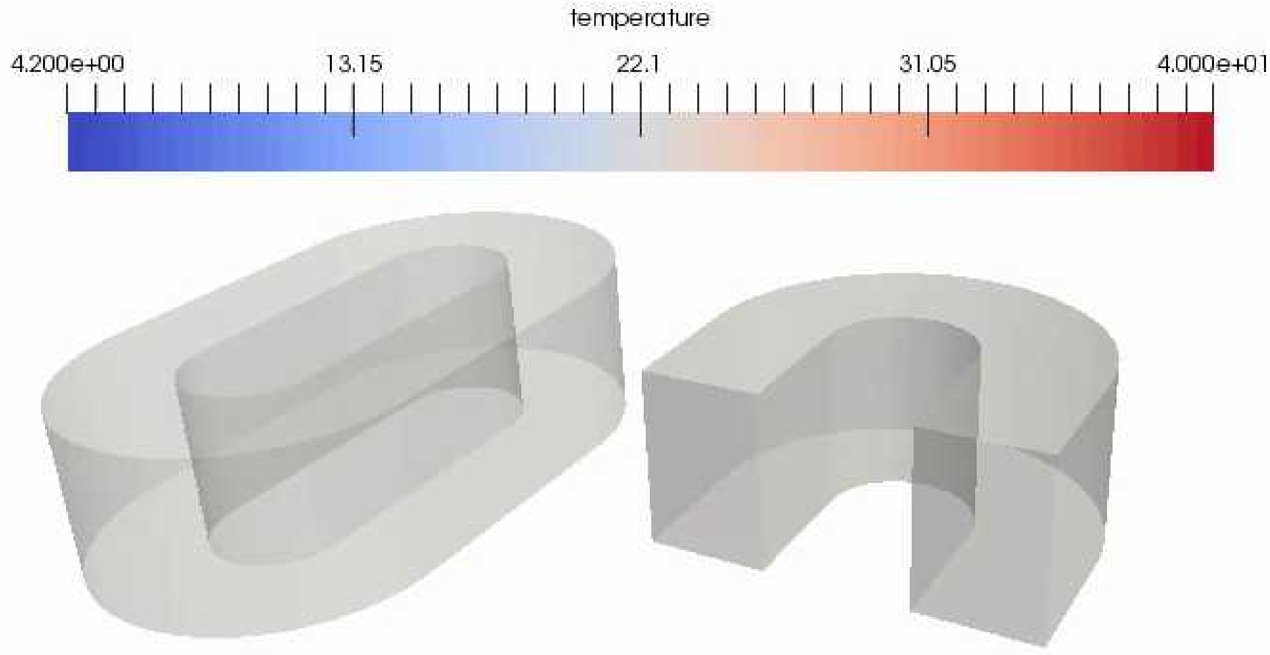
UDF for electrical conductivity σ and quench model



Case 1a: some quench results







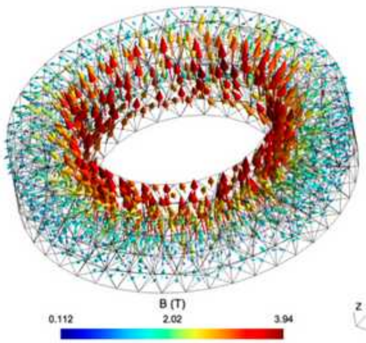
Case 1b: Coil with dumping resistor

Similar model but for a cylindrical coil

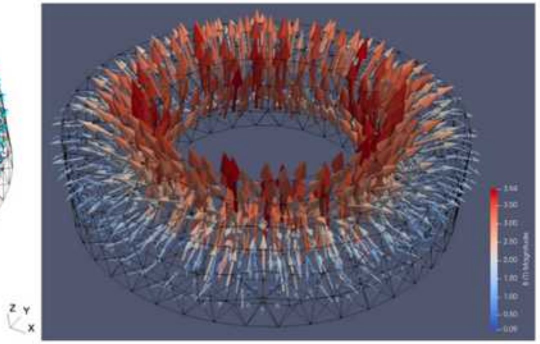
No magnetic core

Circuit coupling

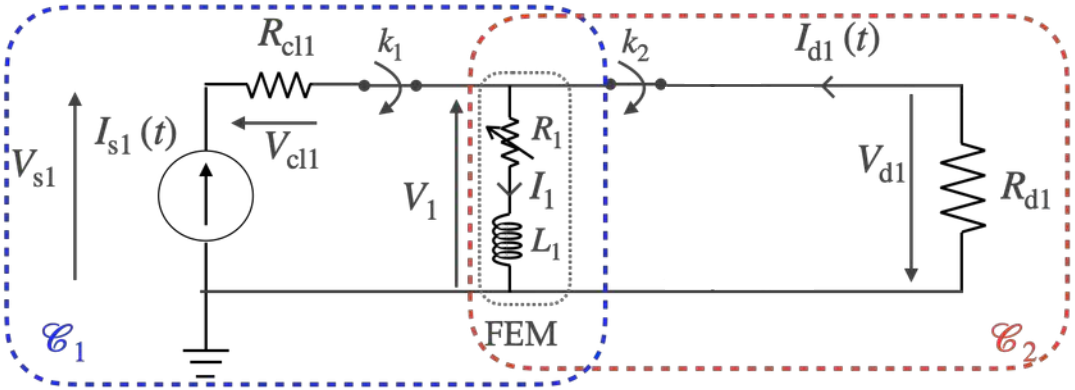
FEM cross-checked with Onelab

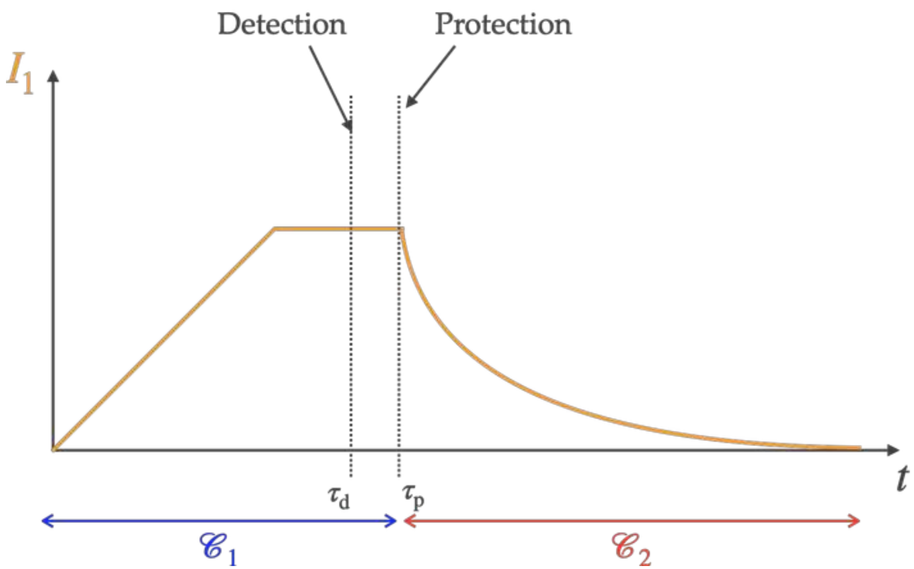


Onelab (Gmsh/GetDP)
https://onelab.info/



Elmerfem
http://www.elmerfem.org/blog/



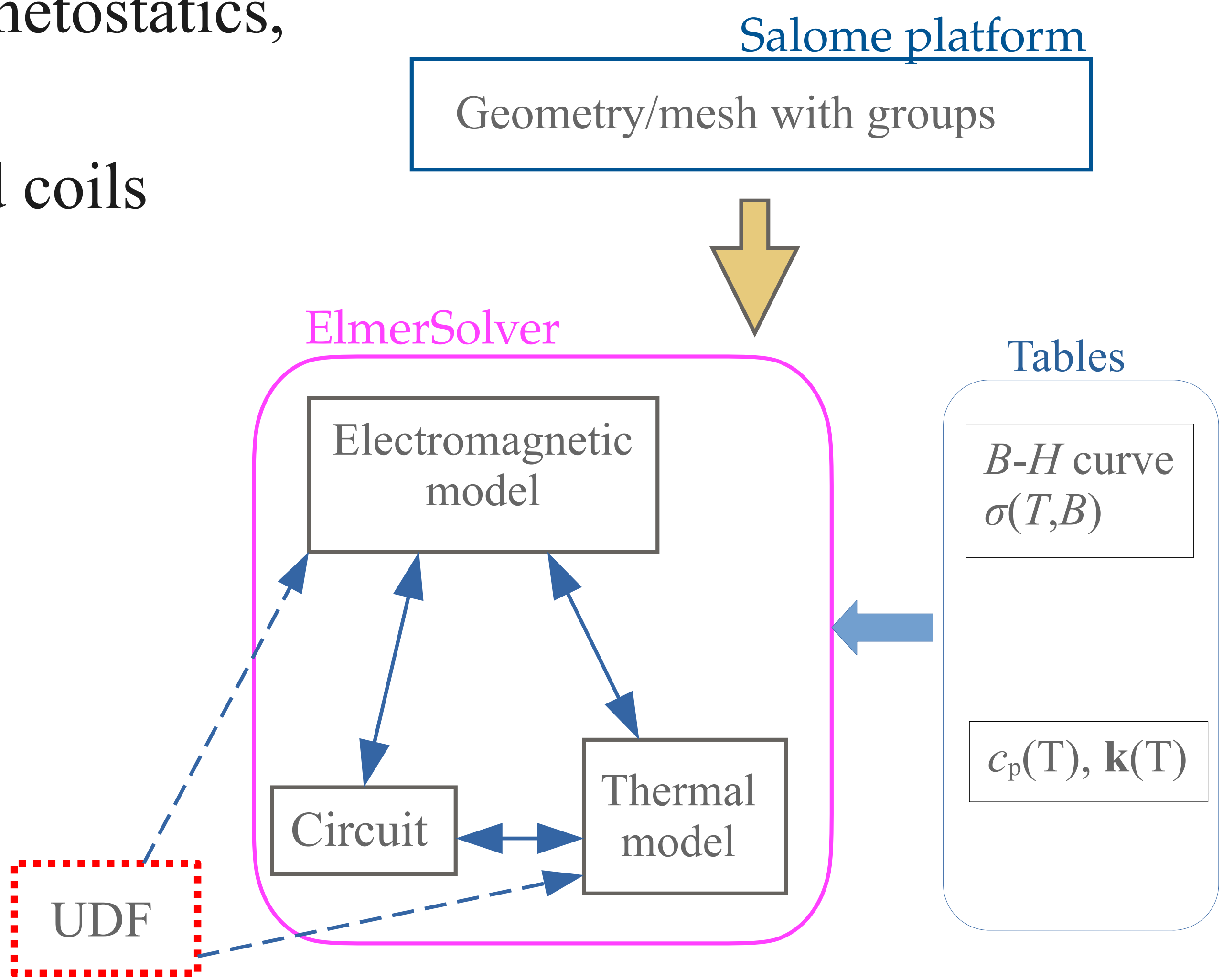


Case 1b: Circuit - FEM coupling

Coupled physics: quasi magnetostatics, thermal and circuit

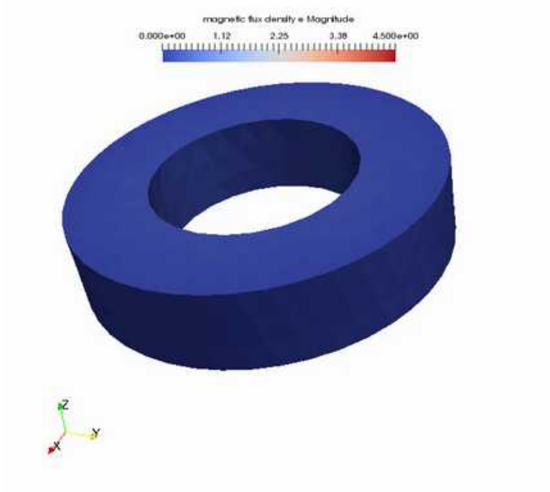
3D FEM model using closed coils

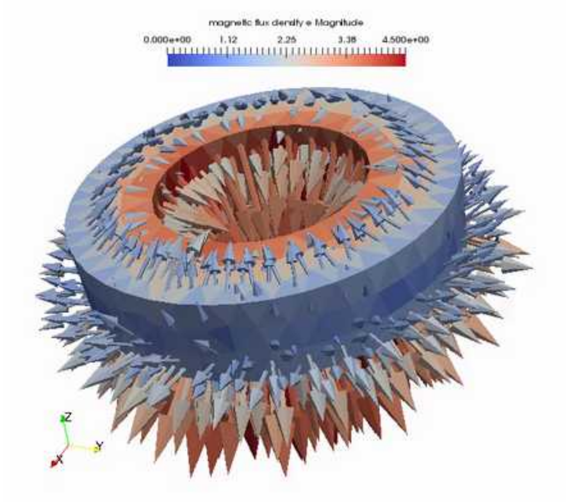
Transient solution

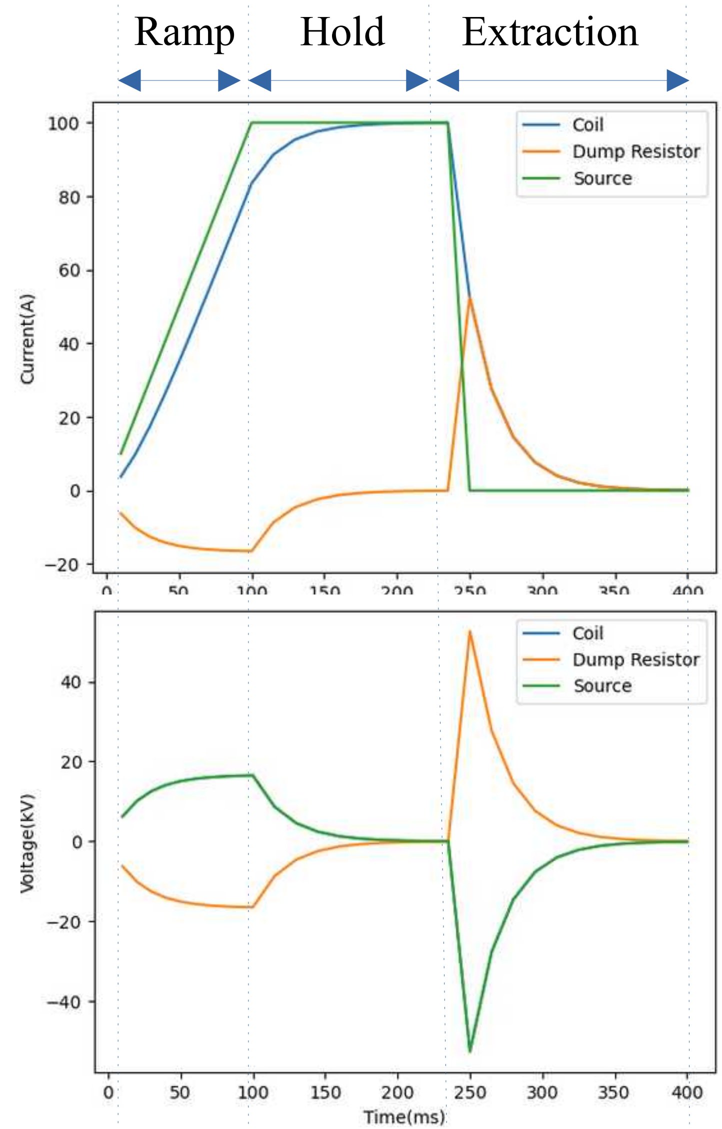


Case 1b: Some circuit-FEM results

Extraction of global variables (python code): voltage and current





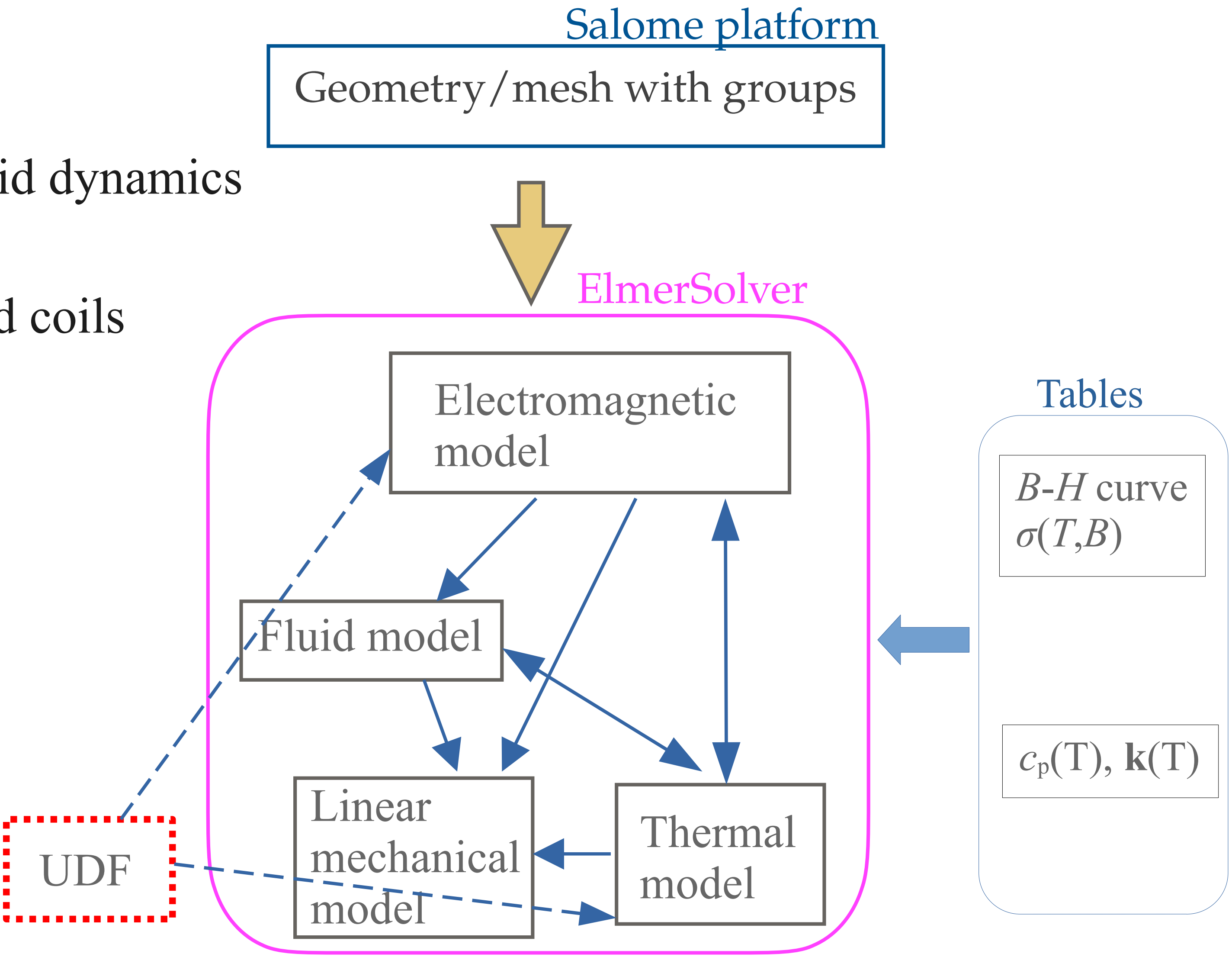


Case 2: Multiphysics

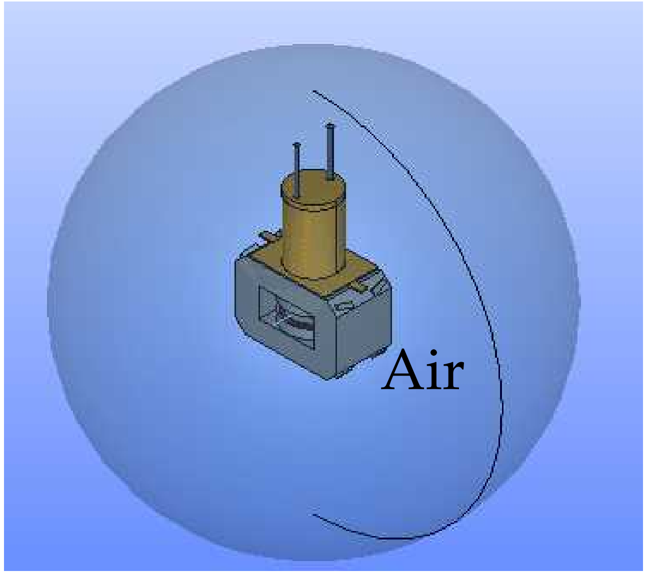
Coupling physics: quasi magnetostatics, thermal, fluid dynamics and structural mechanics

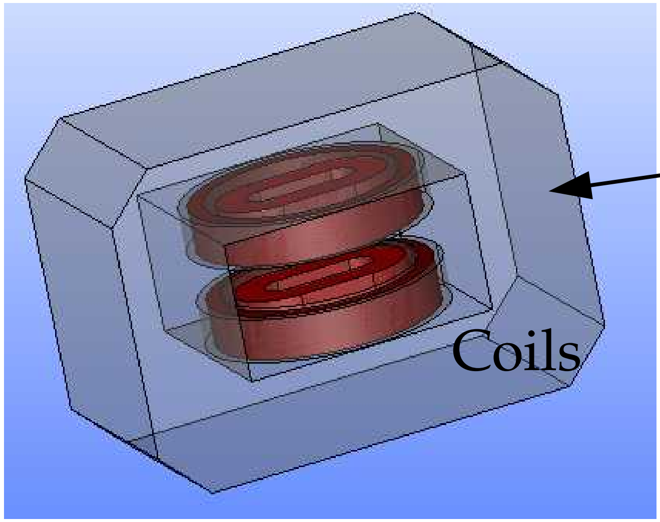
3D FEM model using closed coils

Transient solution

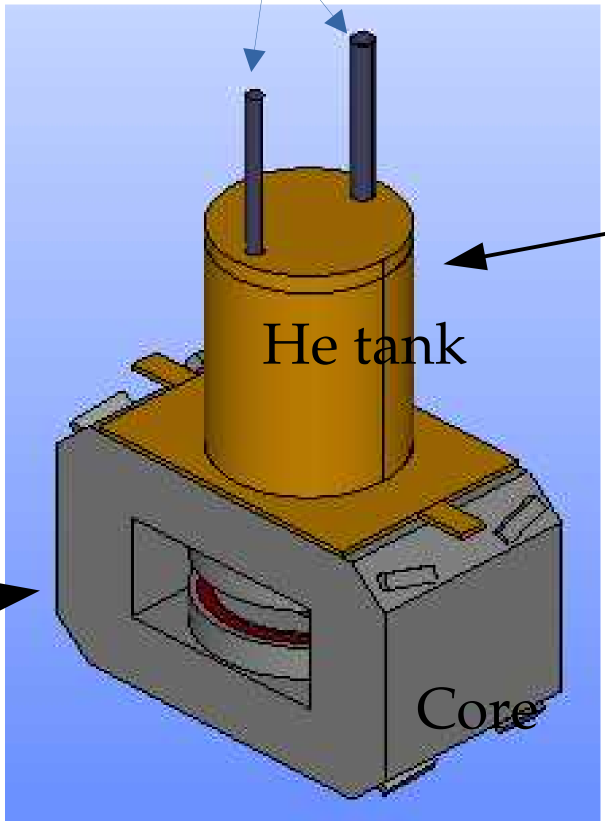


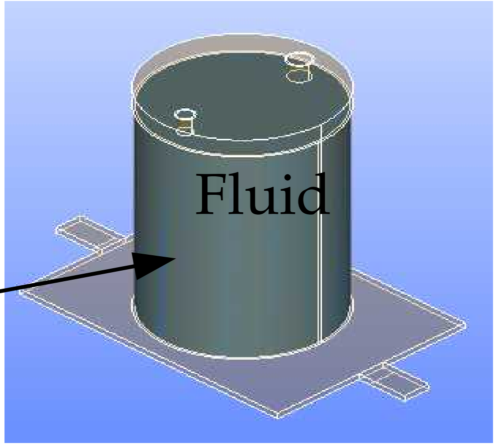
Case 2: Geometric model – SC superbend





He tank inlet/outlet

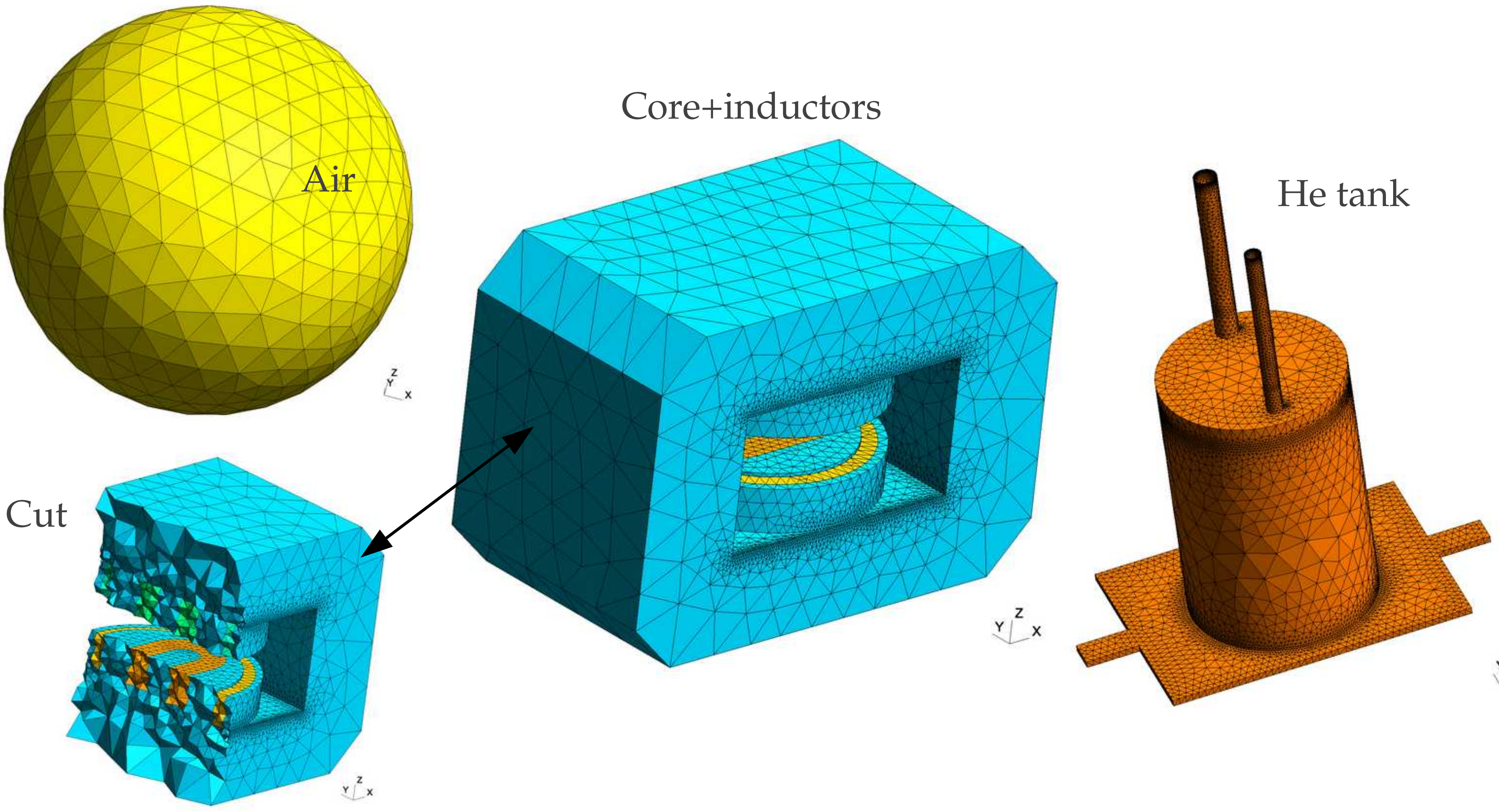




Geometric model done in Salome platform

A group of geometry associated to material properties and physics

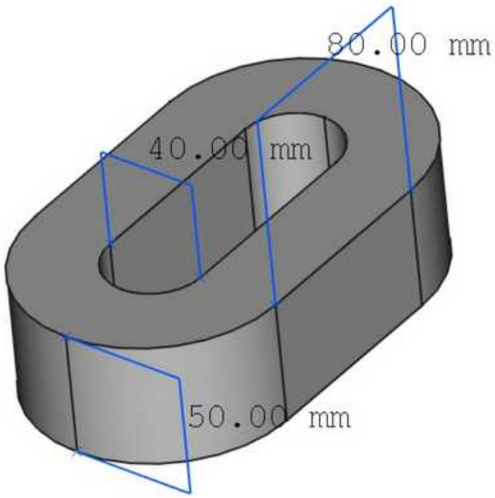
Case 2: Mesh



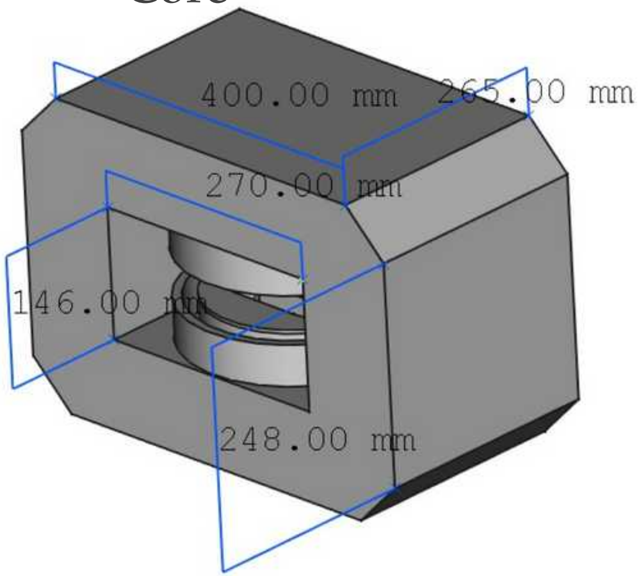
Case 2: Dimensions

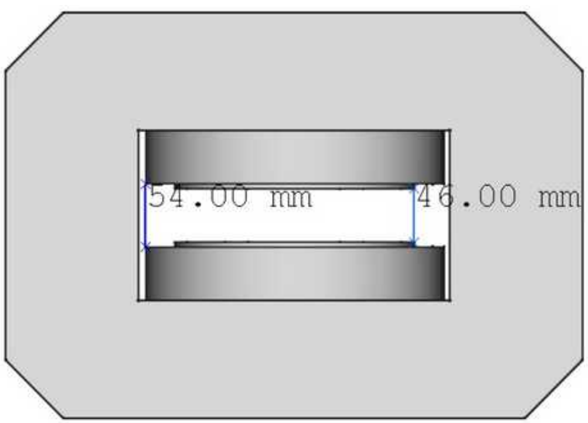
Measurements carried out in FreeCAD based on STEP files (https://www.freecadweb.org)

Racetrack

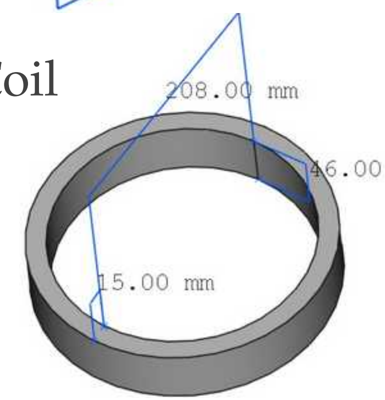


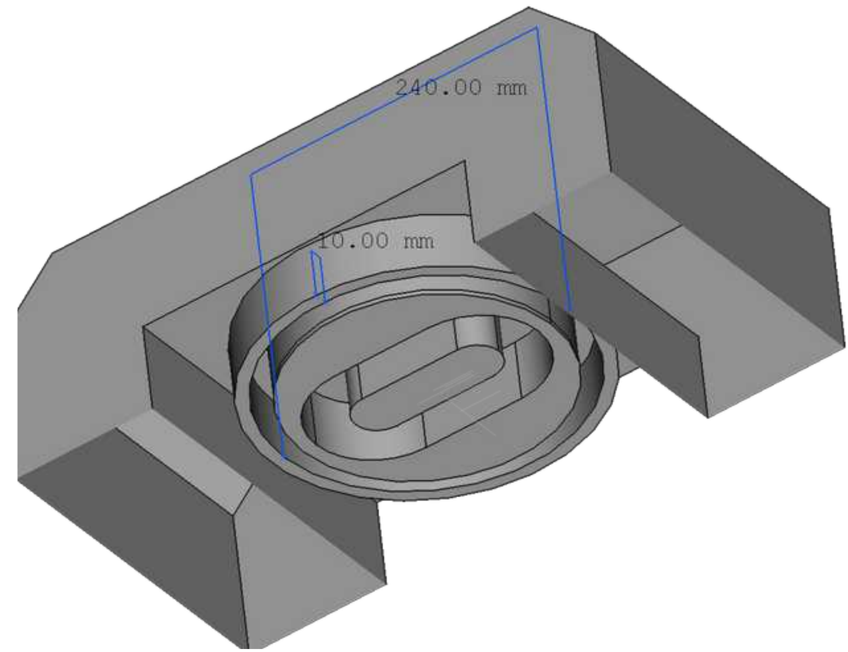
Core





Coil





Case 2: Sources and boundaries

Sources:

(1) Volumetric heat source: 1 mm (diameter) x 15 mm (long) for splices

(2) Heat radiation: tank surface and He inlet/outlet

(3) Magnetic forces: coils

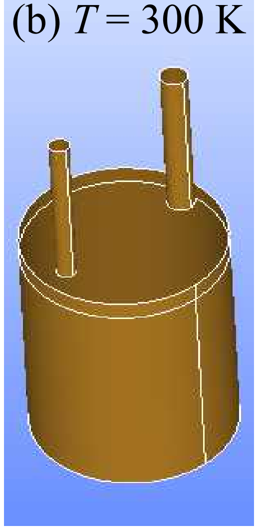
Boundary conditions:

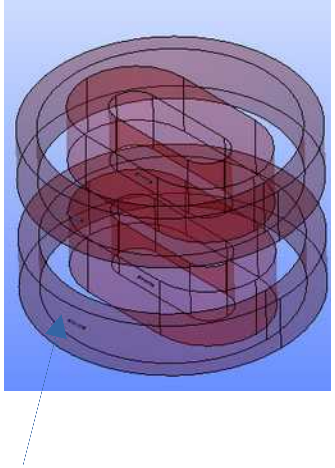
(a) Air boundary: magnetic vector potential **A** and electrical scalar potential V equal to 0

(b) Fixed temperature at 300 K: He inlet/outlet

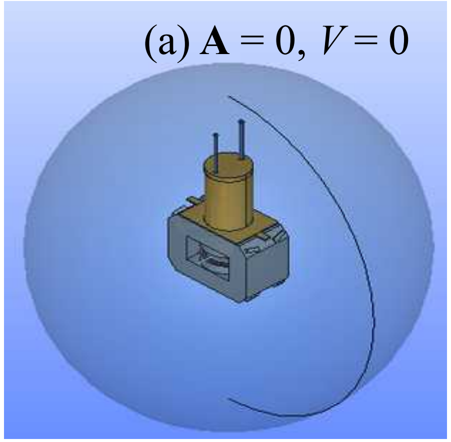
(c) Fixed displacements (**d** = 0): 8 straps of the magnetic core

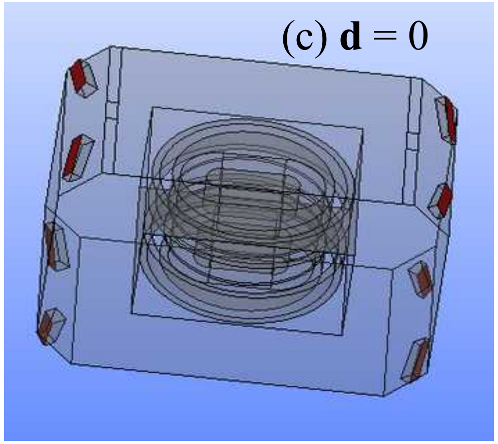
(d) Inlet/outlet: velocity **v** and pressure p, no slip on surfaces

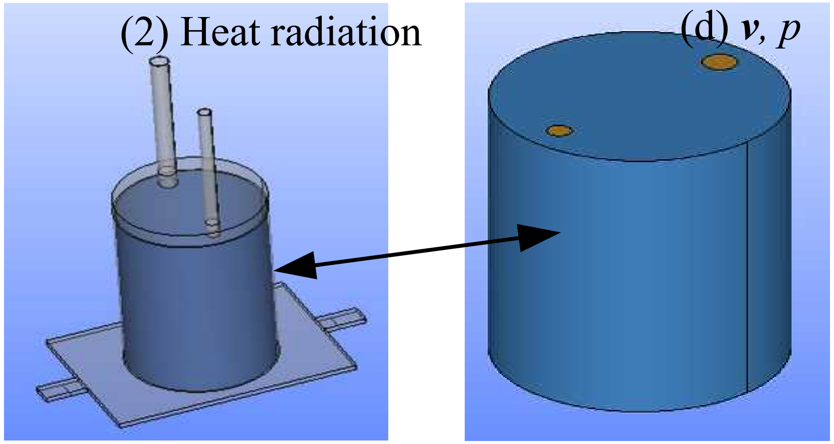




(1) Heat sources
(3) Lorentz force

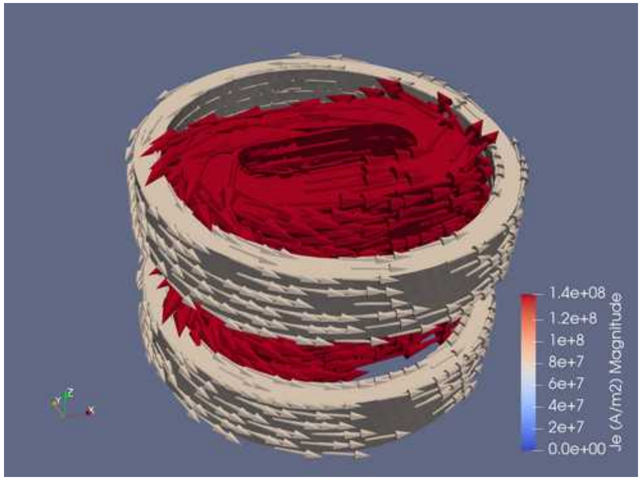




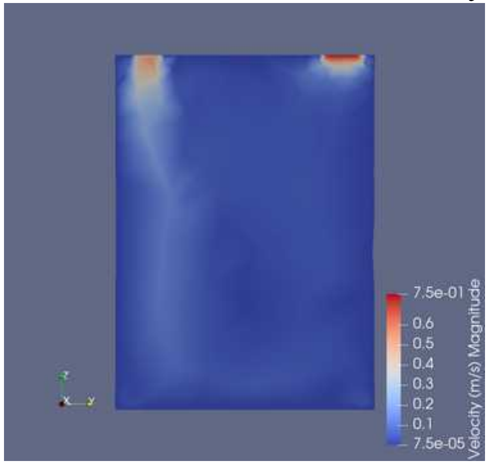


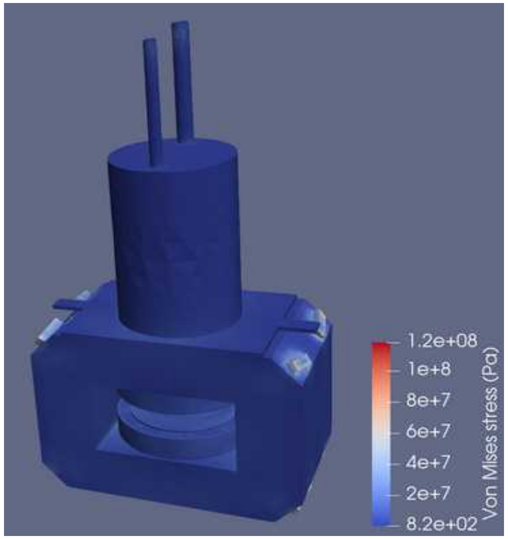
Case 2: Some results (Paraview)

coilcurrent



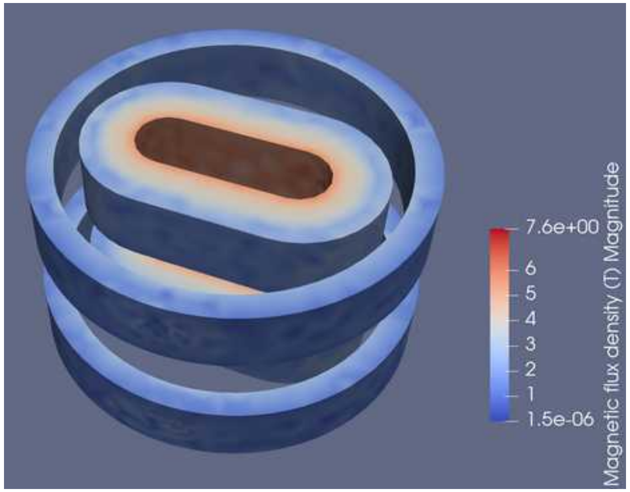
Fluid velocity



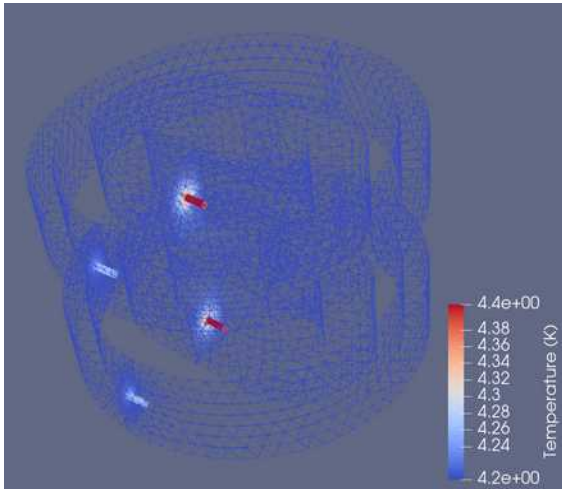


Stresses

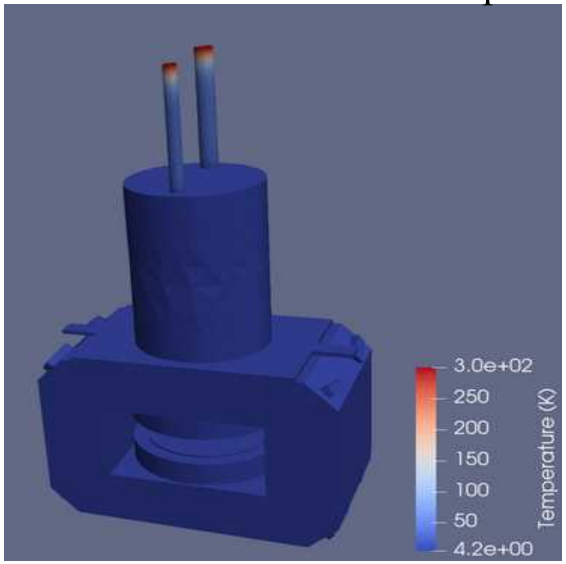
Magnetic flux density



Temperature at splices



Temperature



Onelab
(Gmsh/GetDP)

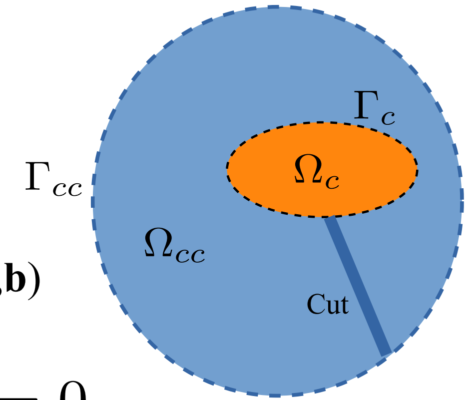
OS: Ubuntu 20.04LTS
Gmsh 4.10.1

Case 3a: HTS coils

AC losses in REBCO or BSCCO coils made of several turns

Solver templates provided at: http://www.life-hts.uliege.be/

In this case, a custom-made simplified solver was used



Resistivity: $\rho(\mathbf{J},\mathbf{b})$

$$\nabla \times \rho \nabla \times \mathbf{h} + \partial_t \mathbf{b} = 0$$

$$\mathbf{h}(t=0) = 0 \quad \rightarrow \quad \nabla \cdot \mathbf{b} = 0$$

$$\mathbf{b} = \mu_0 \mathbf{h}$$

$$\mathbf{J} = \nabla \times \mathbf{h}$$

<u>Case study</u>:

Axisymmetric transient model

H-φ formulation of Maxwell equations

38 turns of Type H DI-BSCCO Sumitomo tapes

Non-inductive coil

Coupling FEM-Circuit

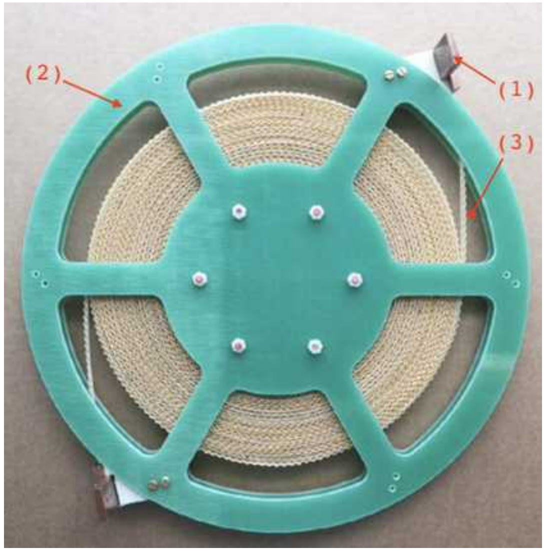
$$\mathbf{h} = \sum_{\mathbf{e}_i \in \mathcal{E}} a_{e,i} \mathbf{e}_i + \sum_{v_i \in \mathcal{N}} a_{n,i} \nabla (v_i) + \sum_{k \in \mathcal{C}} I_k \mathbf{c}_k$$

1st order Whitney — 1st order Lagrange — Thick cuts

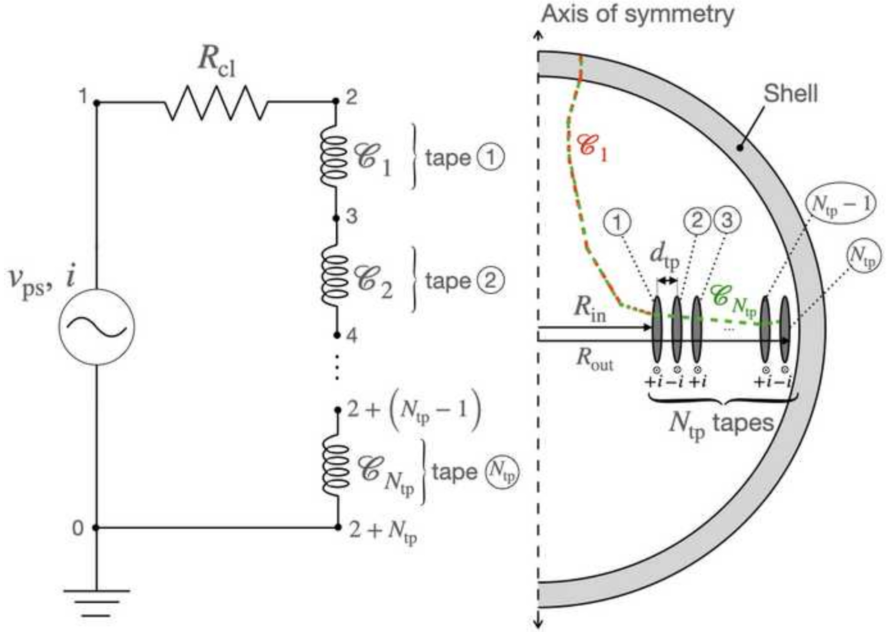
To couple with external circuit

Weak form: $$\int_{\Omega_c} \rho \nabla \times \mathbf{h} \cdot \nabla \times \mathbf{h}^\star \mathrm{d}\Omega + \int_{\Omega} \partial_t (\mu \mathbf{h}) \cdot \mathbf{h}^\star \mathrm{d}\Omega - \int_{\Gamma_c} [\underbrace{(\rho \nabla \times \mathbf{h})}_{\mathbf{e}} \times \mathbf{n}] \cdot \mathbf{h}^\star \mathrm{d}\Gamma = 0$$

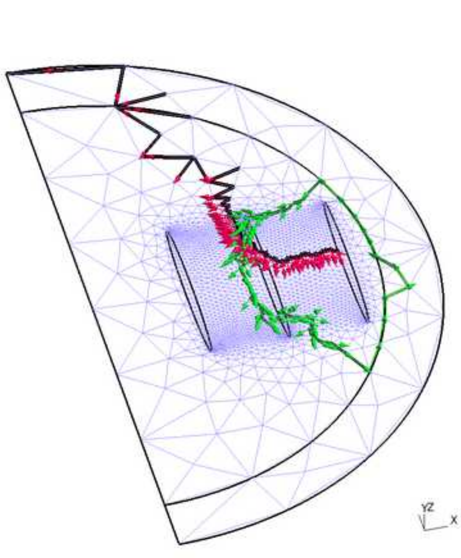
Case 3a: Model, geometry and mesh



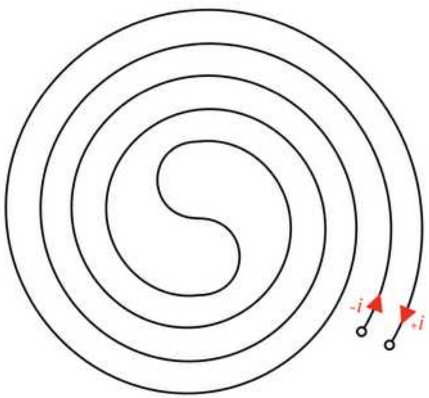
(1): Cu terminal
(2): G11 support
(3): BSCCO tape + wavy plastic insulation



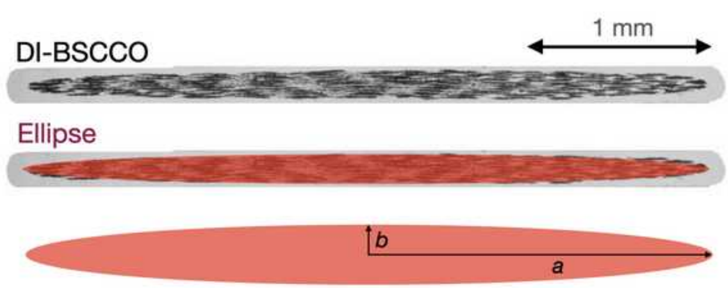
Coupling circuit model and FEM



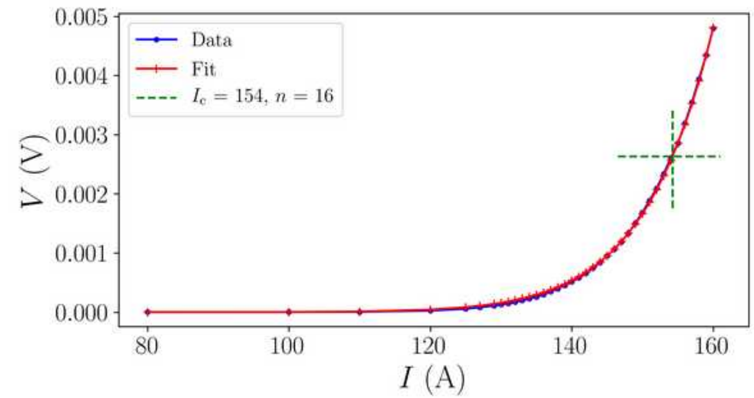
Example of thick cuts for three turns



Non inductive coil: winding pattern



Simplification of geometry



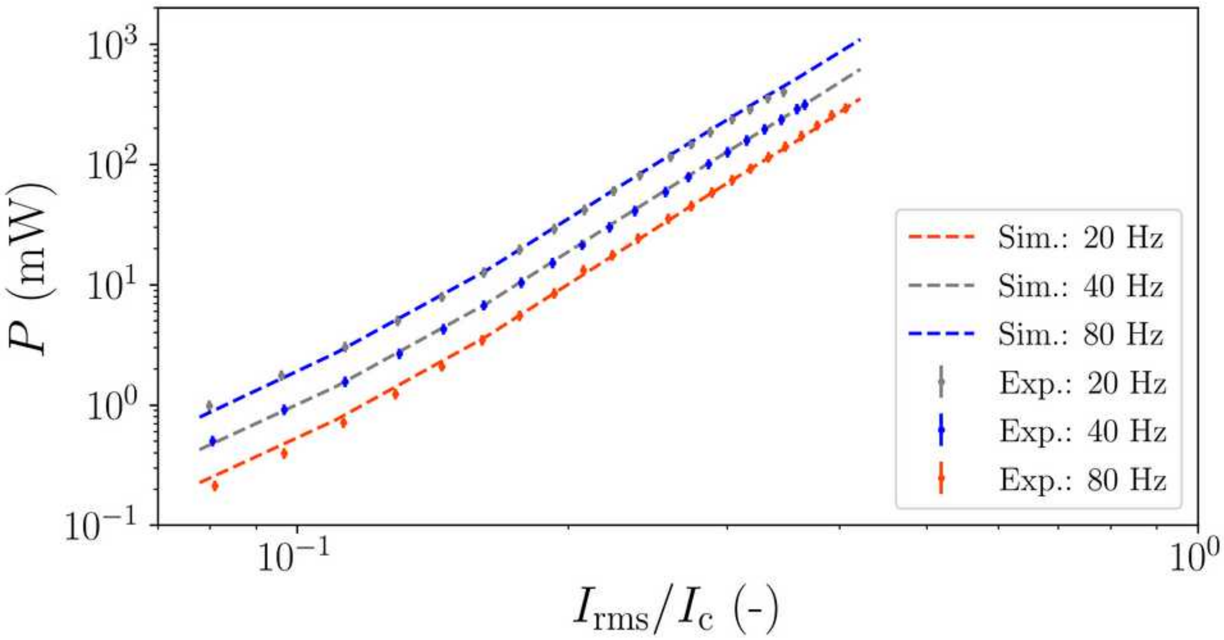
V-I characteristics of the coil at 77 K

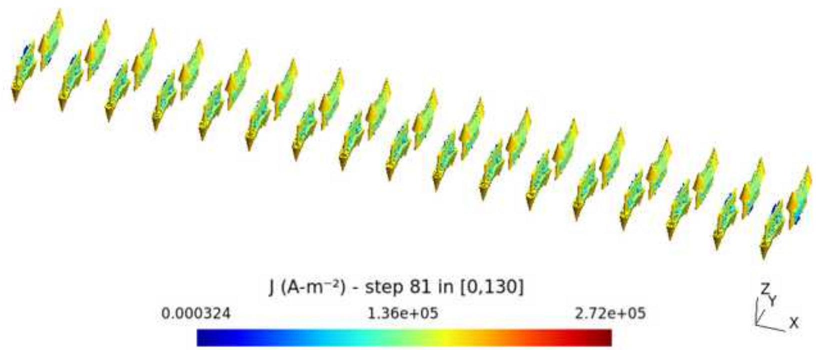
Case 2a: Some results on AC losses

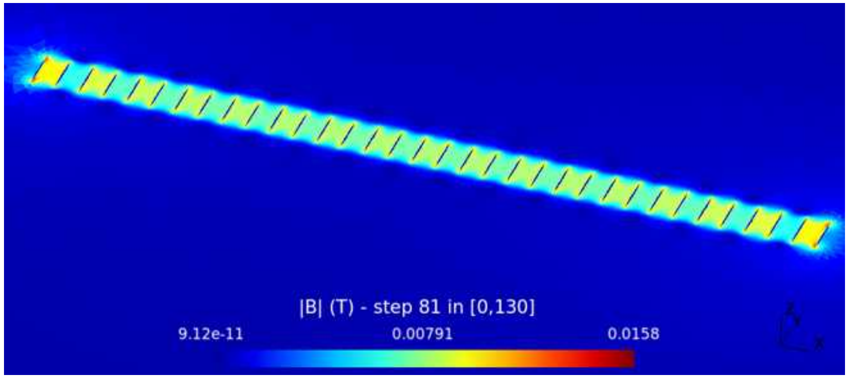
Comparison numerical results and experimental data on the AC losses at 77 K in LN2

Adjustment of J_c to get the best agreement

$$\rho = \frac{E_c}{J_c^n} J^{n-1} \qquad J_c = J_c(\mathbf{b})$$







Case 3b: Magnetization of bulks

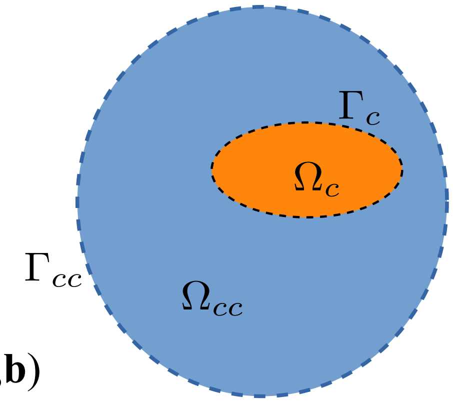
Bulks made of REBCO (“Re” for Rare earth)

Pulsed-field magnetization (PFM)

Computation of remanent magnetic flux

Solver templates provided at: http://www.life-hts.uliege.be/

In this case, a custom-made simplified solver was used



Resistivity: $\rho(\mathbf{J},\mathbf{b})$

$$\nabla \times \rho \nabla \times \mathbf{h} + \partial_t \mathbf{b} = 0$$

$$\mathbf{h}\,(t=0) = 0 \;\Rightarrow\; \nabla \cdot \mathbf{b} = 0$$

$$\mathbf{b} = \mu_0 \mathbf{h}$$

$$\mathbf{J} = \nabla \times \mathbf{h}$$

<u>Case study</u>:

Axisymmetric transient model

H-φ formulation of Maxwell equations

REBCO bulk: 3 cm in diameter for 1,5 cm thick

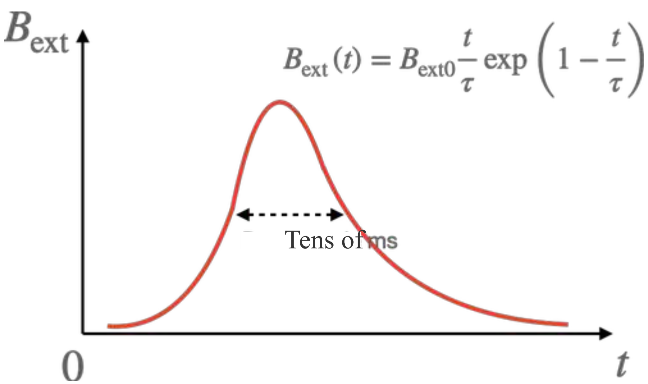
$$\mathbf{h} = \sum_{\mathbf{e}_i \in \mathcal{E}} a_{e,i}\mathbf{e}_i + \sum_{v_i \in \mathcal{N}} a_{n,i} \nabla (v_i)$$

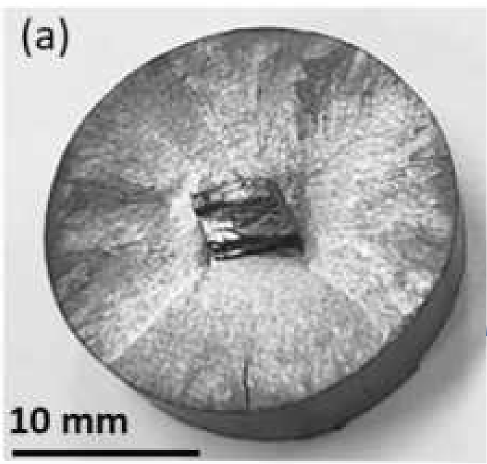
1st order Whitney

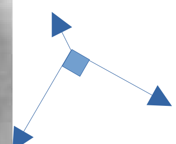
1st order Lagrange

Weak form: $$\int_{\Omega_c} \rho \nabla \times \mathbf{h} \cdot \nabla \times \mathbf{h}^\star \mathrm{d}\Omega + \int_{\Omega} \partial_t (\mu \mathbf{h}) \cdot \mathbf{h}^\star \mathrm{d}\Omega = 0$$

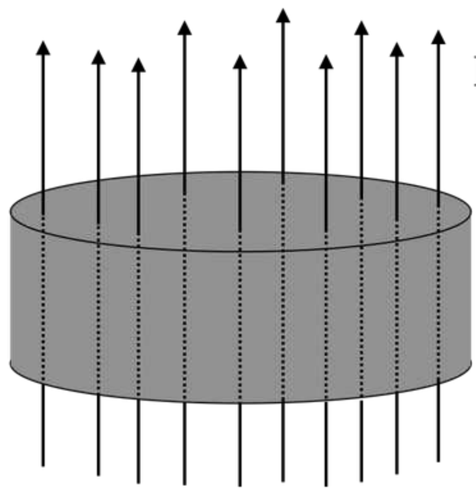
Case 3b: Model, geometry and mesh

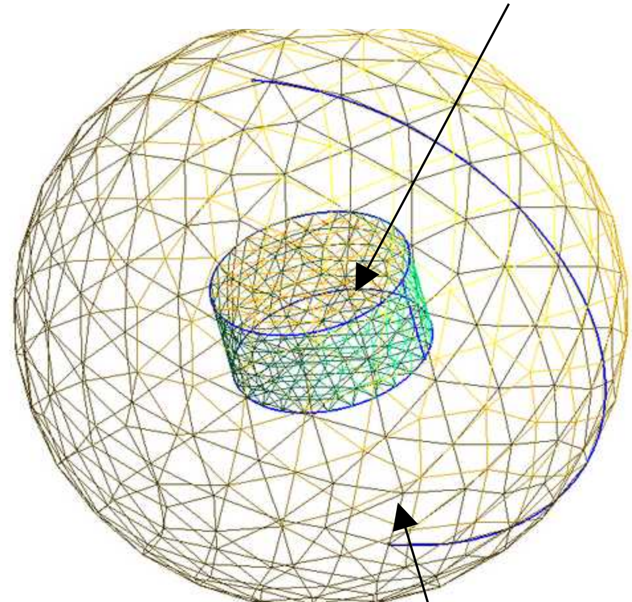






Example of YBCO single-seed bulk (top-seeded melt growth)





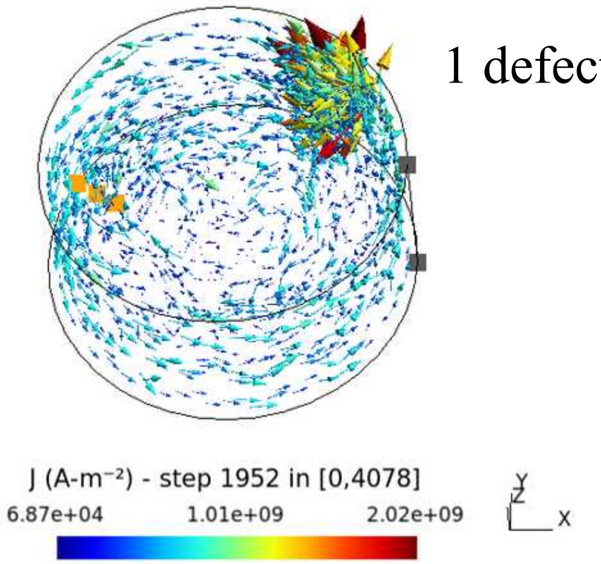
(a): S. Pinmangkorn, et al., J Supercond Nov Magn 33, 1667–1673 (2020). https://doi.org/10.1007/s10948-019-05405-0

Case 3b: Some results on magnetization

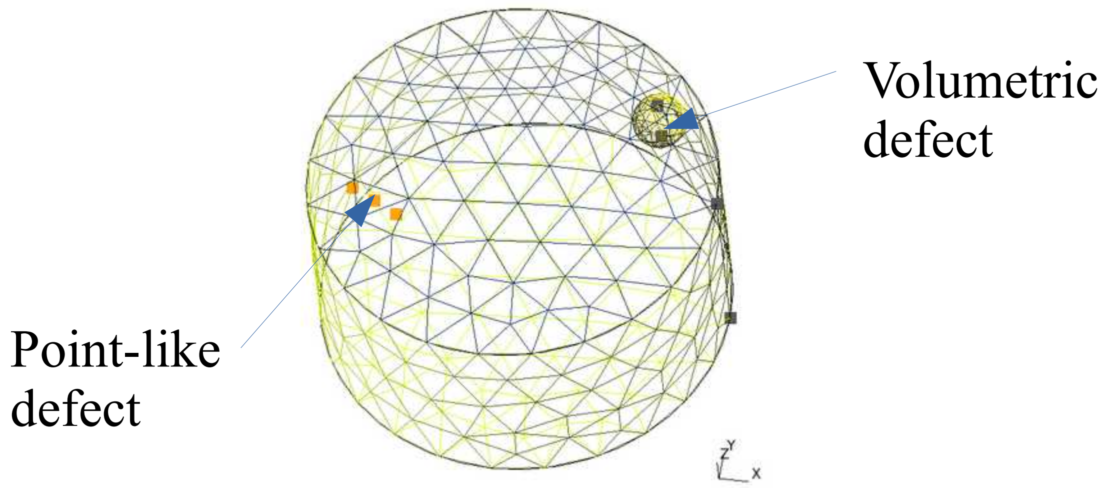
Orthotropic material (ab plane and c axis)

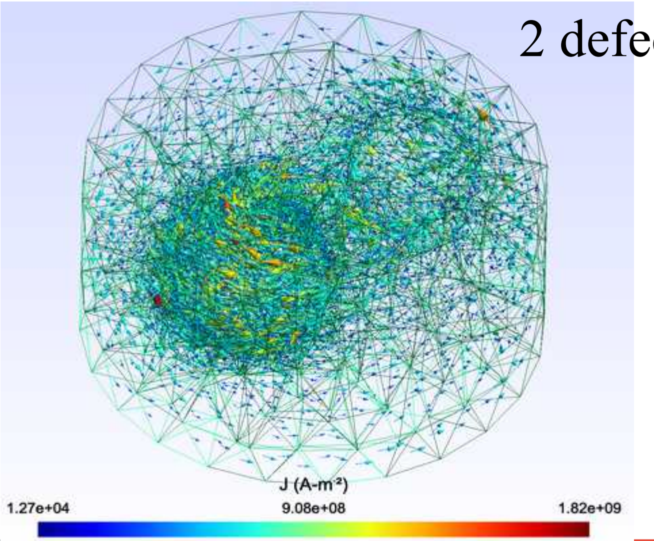
Example of induced current densities with large defect

More complicated model with mechanical and thermal coupling in Zero-Field cooling conditions: (a) and (b)



1 defect





2 defects

(a): F. Trillaud et al, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 3, APRIL 2016
(b): F. Trillaud et al, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 28, NO. 4, JUNE 2018

Feedback on Elmerfem and Onelab

Elmerfem (Linux/Windows): inherently scalable, TUI interface through *.sif file input to ElmerSolver. Includes a GUI. Possibility to implement own solvers and models through subroutines and functions through UDF. Webinar: http://www.elmerfem.org/blog/general/elmer-webinar/

Onelab (cross-platform): GUI programmed through TUI. GetDP not paralallelized. Flexibility through an abstraction layer for implementing one's linearized weak form. Trendy relying on Gmsh popularity. Projects targeting multiphysics modeling at CERN (GetDP worshop: https://indico.cern.ch/event/1015906/)

	Friendliness (1 to 10)*	GUI / TUI	Scalability	UDF	Speed	Abstraction (1 to 10)	Size of community and re-activeness
Elmerfem	8	YES / YES	YES	YES	Fast	3	Comparable
Onelab	5	YES(1) / YES	NO(2)	YES	Slow	9	

*: 1 = poor, 10: very good
(1): need for coding
(2): For scalable solution, new development GmshFEM see: https://indico.cern.ch/event/1015906/contributions/4265042/attachments/2230862/3780011/gmshfem.pdf

Conclusion

15 years of using open-source FEM software (mainly: Elmerfem, Onelab, Code_Aster, openfoam)

Focus on Elmerfem for LTS magnets and GetDP for HTS coils and bulks → dedicated tools:

- ➔Ongoing development of UDF for Elmerfem for multiphysics modeling (main case study: SC superbend)
- ➔Building more efficient solvers for GetDP (Moving to GmshFEM?)

Personal note: Elmerfem is probably the most interesting alternative to multiphysics FEM software such as COMSOL Multiphysics for beginners

Some level of coding is required for all the open-source software. However it is somehow compensated by the freedom and support received by other free users

Next steps: short and mid term (< 4 years)

1. Improve the FEM-circuit coupling in Elmerfem (involvement of Eelis Takala from *Elemental Reality Solutions*): diode model and convergence improvements [**priority 1 - 2022, duration: 2 years**]

2. Benchmarking of Elmerfem with COMSOL Multiphysics: quench and multiphysics models → critical task [**priority 2 – 2023: duration 2 years**]

3. Explore non-linear structural mechanics in Elmerfem (ElasticSolver) [**priority 3 - 2024, duration: TBD**]

4. Improved on the existing generic solver written by J. Dular in GetDP

<http://www.life-hts.uliege.be/> [**priority 1 - 2023, duration: 1 year**]

Percent work: 25%

Thank you for your attention

Frederic Trillaud
ftrillaudp@gmail.com