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HTS high-energy magnets for accelerators: Outlook and challenges in numerical modelling

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With the support of STEAM

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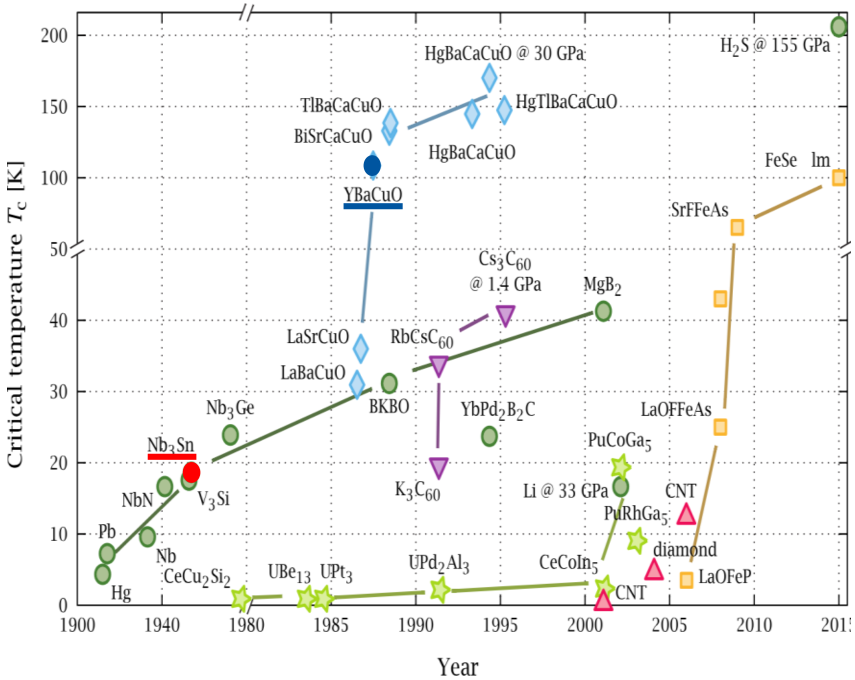
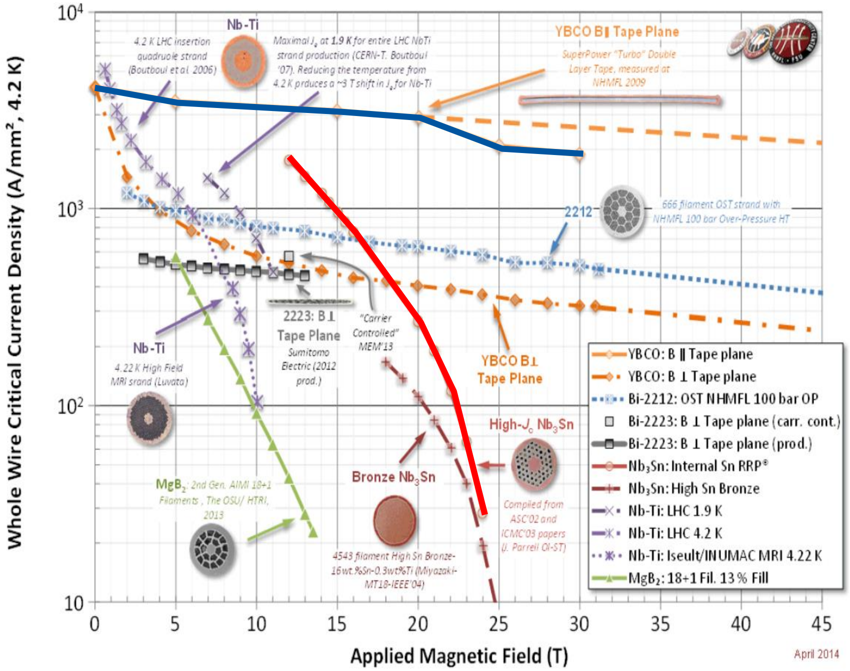
Outline

- Introduction to HTS
  - Why
  - How
  - Quench Protection
- Numerical Modelling
- Electrodynamics
- Benchmark Model
- Simplified Models, Alternative Formulations
  - 2-D Explicit
  - 2-D Homogenized
  - 1-D Thin Strip
  - Hybrid $T\!-\!A$ Formulation in 1-D Thin Strip

HTS in a Nutshell

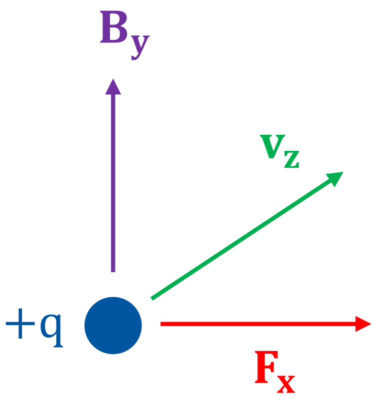
- Superconductors based on cuprate (CuO_2) compounds
- Doped usually with La, Bi-Sr-Ca, Y-Ga-Ba
- higher T_c and B_{c0} respect to the LTS





- High performance comes with high prices! $P_{HTS} \approx 1e^2\, P_{LTS}$ [\$/(kA · m)]
- .. But in the early 2000s the ratio was about $1e^3$

Why HTS?



For a circular orbit $\boldsymbol{F}_{\text{Lorentz}} = -\boldsymbol{F}_{\text{centripetal}}$, hence

$$q(\mathbf{v} \times \mathbf{B}) = -\frac{mv^2}{\mathbf{r}} \text{ [N]}, \qquad r = \frac{mv^2}{qvB} \text{ [m]}$$

- q is the charge of a proton
- Relativistic coefficients $m = \gamma m_0, v = \beta c$
- $E_{tot} = \gamma m_0 c^2$
- Particle momentum $p = \beta\gamma m_0 c = \beta E_{tot}/c$
- $v \rightarrow c$
- p is given in [TeV/c]

$$r \approx 3 \frac{p_{\text{[TeV/c]}}}{B} \text{ [km]}$$

Just for fun
let us fit the actual LHC tunnel with HTS dipoles @ 1.9K, 30 T:

$$p \approx \frac{1}{3} \cdot \frac{27}{2\pi} \cdot 30 \approx 40 \text{ [TeV/c]}$$

For comparison, FCC with Nb_3Sn: $p = 50$ [TeV/c]
… not so far away after all!

Which HTS? How?

ReBCO - Rare Earth Barium Copper Oxide tape (1)

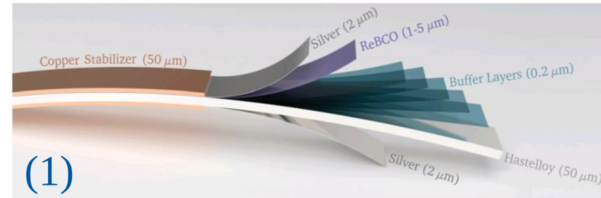
- Mature technology ($\sim 10^2$ m of tape and beyond)
- Cost driven by manifacturing process (cfr. BSCCO)
- Cost reduction expected

Tape features

- Very thin, wide shape, and multi-layers
- Tape as anisotropic mono-filament (e.g. $J_c(\bar{n} \cdot \bar{B})$)
- AC losses driven by large persistent currents
- Field quality limitations

Roebel transposition (2-3)

- One-century-old concept
- *Coil-able* cable, bended on the long edge
- Fully transposed tapes: even current distribution
- Aligned coil concept against AC losses



Source: Van Nugteren, J. *High temperature superconductor accelerator magnets*. Diss. Twente U., Enschede, 2016.

(2)

Source: Wikipedia

Source: CDS. Coiled Roebel cable (Henry Barnard, CERN). The cable was manufactured, using stainless steel tapes, at Karlsruhe Institute of Technology (KIT).

HTS Quench Protection?

HTS Features

- Great temperature margin: $\mathrm{T_{op}} \geq 5$ K in He gas, $T_{\mathrm{crit}} = 93$ K
- Nonlinear $\mathrm{C_p(T)}$, rapidly increasing (orders of magnitude)
- Smooth quench transition (power law E(J) , $n_{\mathrm{HTS}} \approx 20$, $n_{\mathrm{LTS}} \approx 40$)

$$E = \frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}$$

Consequences

- $v_{\mathrm{q,\,HTS}} \approx 1e^{-2}\, v_{\mathrm{q,\,LTS}}$ $\quad (\mathrm{v_q} \propto \mathrm{C_p(T)}^{-1})$
- $R_{\mathrm{q,\,HTS}}(t) \ll R_{\mathrm{q,\,LTS}}(t)$
- $\mathrm{T_{hotSpot,\,HTS}} \gg \mathrm{T_{hotSpot,\,LTS}}$
- $\mathrm{MQE_{HTS}} \geq 1e^{3}\ \mathrm{MQE_{LTS}}$: Actual quench protection technologies potentially ineffective

- Current redistribution in Roebel cable during a quench
- Stable overcritical currents, cooling system permitting (*)
- Slow thermal runaway, $1\mathrm{e}^1 - 1\mathrm{e}^2$ seconds (*)
- Reversible quench via $\mathrm{I_s}(t)$ modulation (*)

What if QPS worked as a Quench *Prevention* System?

(*) Van Nugteren, Jeroen, et al. "Powering of an HTS dipole insert-magnet operated standalone in helium gas between 5 and 85 K." *Superconductor Science and Technology* (2018).

Motivation

1. Availability, in a reasonable time horizon (*), of very high field (20T+) dipole magnets, based on 2nd generation HTS tape technology

2. Option for to HTS-based high energy accelerators for particle physics

3. Challenges for designing, operating and protecting circuits of series-connected HTS magnets

4. Important role of dedicated simulations in understanding the technological implications and issues.

For this reason, we will pursue the investigation on how to build a HTS-based particle-physics accelerator with the help of STEAM

(*) MT25, e.g. Powering_of_an_HTS_Insert-Magnet.pdf

Numerical modelling - 01

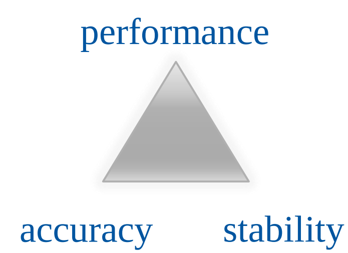
Definitions

Model:
mathematical representation of a physical behaviour (e.g. Maxwell’s equations).
Based on hypothesis and simplications.

Numerical method
Systematic approach (e.g. FEM) to
1. Describe a model in a discrete form,
2. Generate a system of equations that approximates the model
3. Solve system of equations

Solution invariant respect to the numerical method, not to the computational time

Numerical model
Combination of a model and a numerical method.
Trade-off between physical relevance and complexity.



Numerical modelling - 02

Features

- Dimensionality
- Resolution
- Predictive power

Formulation

- ODEs, PDEs, Ies
- Choice of “physics”
- Choice of variables (**A-V**, **T-*Ω***, **H** …)

Methods

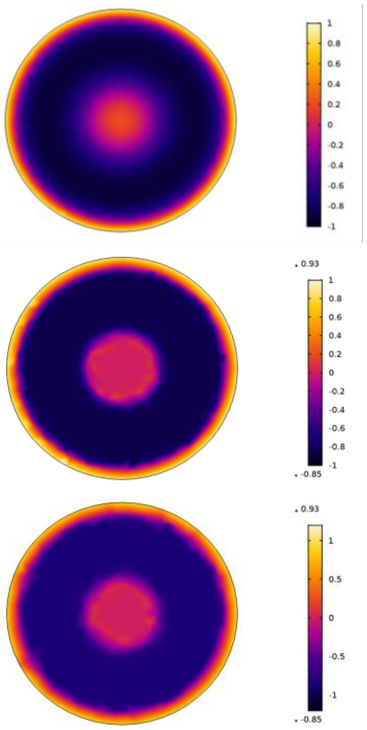
- Differential, Integral form
- Strong, Weak form, Energy functional approach
- finite differences, elements, volumes, equivalent networks

Formulation invariance

A-V
2nd order elem

H
edge elem

H
1st order elem



J/Jc

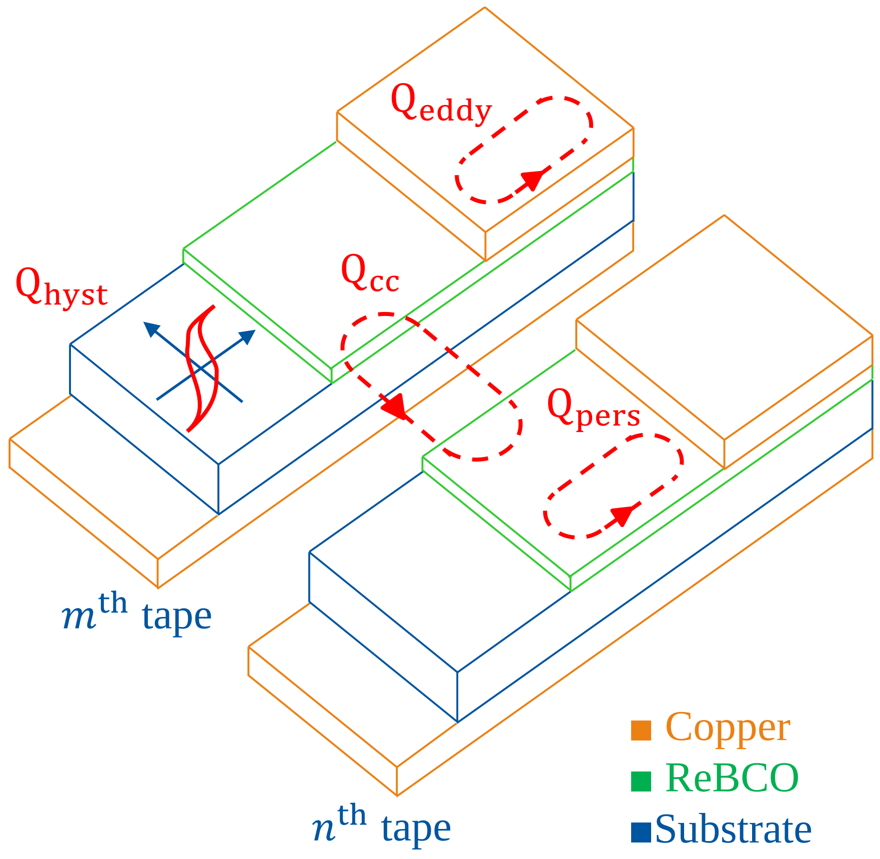
Electrodynamics - 01

- **Hysteresis** Q_{pers}**:**
  penetration and movement of the magnetic flux in the HTS

- **Eddy currents** Q_{eddy}:
  currents induced in the normal parts of the HTS tape

- **Coupling losses** Q_{cc}:
  currents coupling two or more tapes via normal conducting paths

- **Ferromagnetic losses** Q_{hyst}:
  hysteresis in the magnetic substrate (if any)



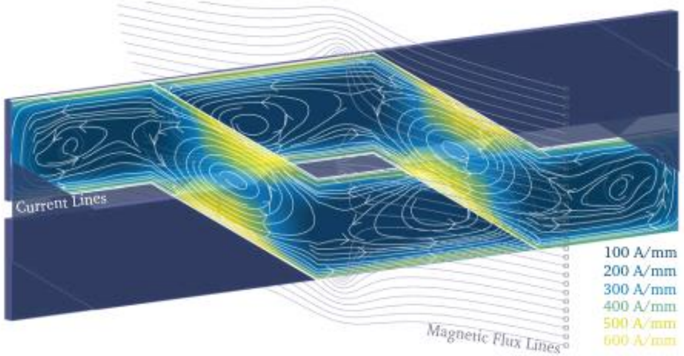
Grilli, Francesco, et al. "Computation of losses in HTS under the action of varying magnetic fields and currents." IEEE Transactions on Applied Superconductivity 24.1 (2014): 78-110.

Electrodynamics - 02

Geometry and materials
- Large aspect ratio (~50)
- Multiple stack of tapes
- Nonlinear material properties

N.B. stretched picture!

AC losses
- 3D phenomenon, field vector - dependence
- Concentrated in the Roebel transposition
- Issue for field quality
- $Q_{pers}, Q_{hyst} \propto \overline{B}$
- $Q_{eddy}, Q_{cc} \propto \partial_t \overline{B}$



Source: Van Nugteren, J. *High temperature superconductor accelerator magnets*. Diss. Twente U., Enschede, 2016.

Quench
- Current redistribution – cross contact losses
- Propagation velocity, 3D phenomenon
- Non adiabatic, due to the time scale of propagation

Benchmark Model - 1

- Stack of 10x ReBCO tapes
- Scalable to an arbitrary number of units
- Suitable for computational cost analysis

- Tests in self field, conductor excitation
- Tests in background field, excitation via boundary conditions

Layer internal structure:

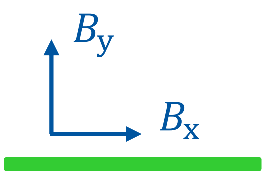
- Explicit 2-D domains
- Aspect ratio ~ 40

	h [m]	ρ [Ωm]
■ Copper	20e-6	1.97e-9
■ Silver	2e-6	2.7e-9
■ ReBCO	1e-6	$\rho_{SC}(B)$
■ Substrate	50e-6	1.25e-9
■ Copper	20e-6	1.97e-9

Benchmark Model - 2

Kim-like model [1] for material anisotropy

$$J_C(B) = \frac{J_{c0}}{\left(1+\left(\frac{k^2 B_x^2 + B_y^2}{B_0}\right)^{1/2}\right)^{\alpha}}$$



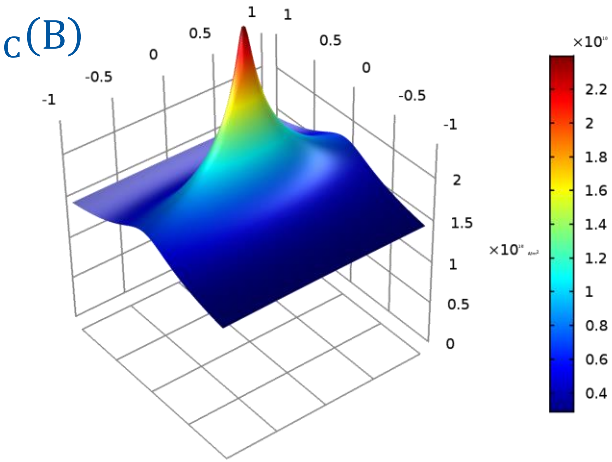
$\rho_{SC}(B)$ represented with a power-law [2]

$$\rho_{SC}(B) = \frac{E_c}{J_C(B)}\left|\frac{J}{J_C(B)}\right|^{n-1} = \frac{E_c}{J_C(B)}\left|\frac{E}{E_C}\right|^{1-\frac{1}{n}}$$

The model accounts for:

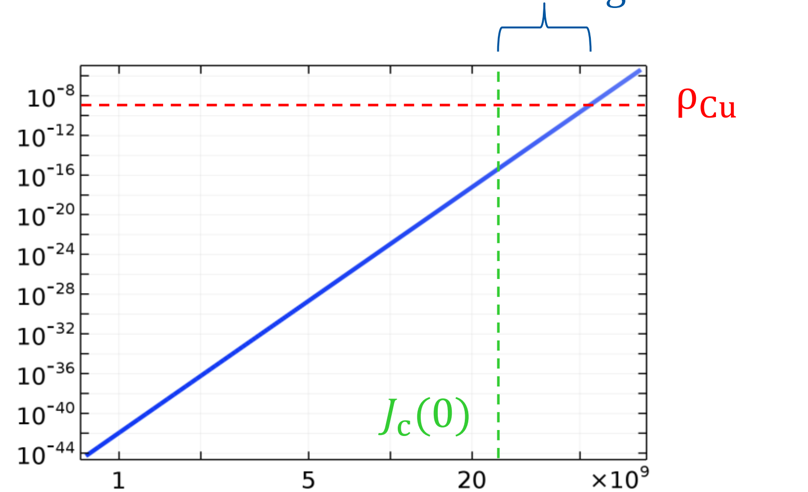
- B dependence
- Tape anisotropy
- Overcritical current densities

- $J_C(B)$



- $\rho_{SC}(0), \; J \in [0, \; 3\,J_C(0)]$

Overcritical region



[1] Y. B. Kim, C. F. Hempstead, A. R. Strnad, “Critical persistent currents in hard superconductors,” Phys. Rev. Lett., vol. 9, no. 7, p. 306, 1962.
[2] Y. B. Kim, C. F. Hempstead, and A. R. Strnad. "Flux-flow resistance in type-II superconductors." Physical Review 139.4A (1965): A1163.

Benchmark Model - 3

- H-formulation for eddy current problems (Faraday + Ampere + Constitutive Law)

$$\mu\partial_t \mathbf{H} + \nabla \times \mathbf{E} = 0$$
$$\nabla \times \mathbf{H} = \mathbf{J}$$
$$\mathbf{E} = \rho\nabla \times \mathbf{H}$$

- In 2-D, $\mathbf{H} = (H_x, H_y, 0)$, $\mathbf{E} = (0, 0, E_z)$

$$\mu\partial_t H_x + \partial_y E_z = 0$$
$$\mu\partial_t H_y - \partial_x E_z = 0$$
$$E_z = \rho(J_z)\, J_z$$
$$J_z = \partial_x H_y - \partial_y H_x$$

- J_z is not a state variable. Imposed via integral equations (one per conductor)

$$I_{ext} = \int J_z d\Omega_c$$

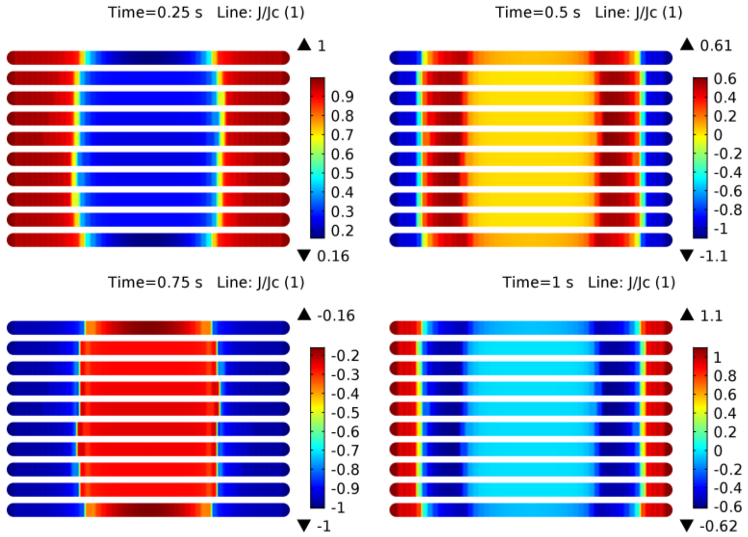
- Gass Law $\nabla \cdot \left(\mu\partial_x H_x + \mu\partial_y H_y\right) = 0$ is enforced using curl-conforming, first order edge elements [3]. No need of extra constraints.

[3] Brambilla R., Grilli F., and Martini M. "Development of an edge-element model for AC loss computation of high-temperature superconductors." Superconductor Science and Technology 20.1 (2006): 16.

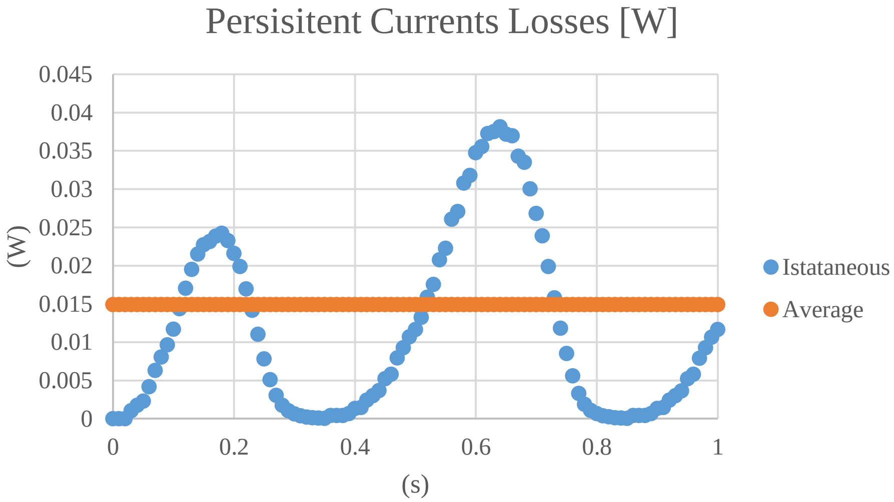
Benchmark Model - 4

- Analysis
  Stack of coils in self field, $I_{ext}(t) = I_0 \sin(2\pi f)$
  Same current for each tape

- Reference results



J_z/J_c field map



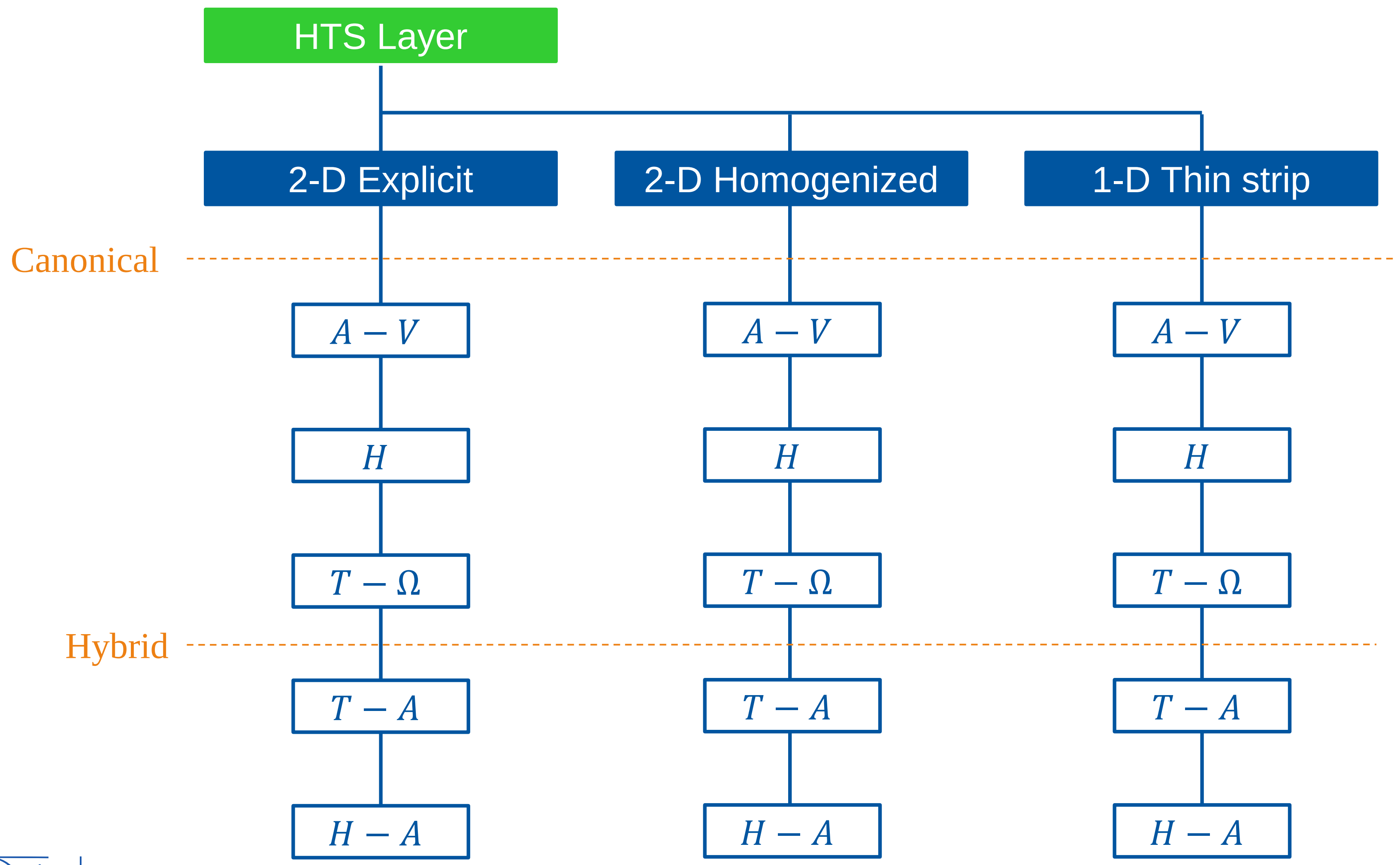
$$P = \int J_z E_z d\Omega_c \qquad Q = \frac{1}{T}\int_0^T \int J_z E_z d\Omega_c \, dt$$

Computational time (*): 1200 s

(*) Intel(R) Core(TM) i7-3770 CPU @ 3.40 GHz - 32 GB RAM

Simplified Models, Alternative Formulations

- The key issue is represented by how the HTS tape is modeled



2-D Explicit

HTS Layer

2-D Explicit

$A - V$
- Fast (5x), Flux linkage trough **A**
- Unstable

H
- Stable
- Expensive, φ [Wb]

$T - \Omega$
- φ

$T - A$
- φ

$H - A$
- φ

- **A** nonlinear due to ρ_{SC}
- $\partial_t A$ calculated in a discrete way
- instability in Newton convergence
- Artificial stabilization [4]

$$\rho^*_{sc}(B) = \frac{E_c}{J_C(B)}\left(k_{stab} + \left|\frac{J}{J_C(B)}\right|^{n-1}\right)$$

$$k_{stab} \approx 1e^{-3}$$

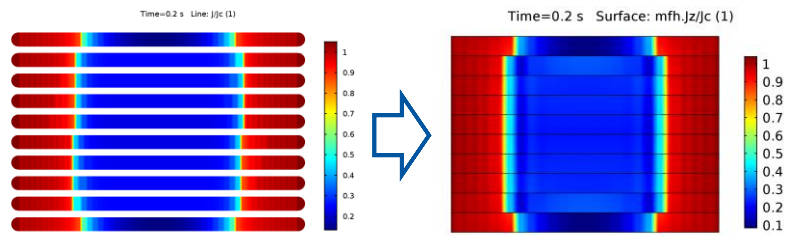
[4] Grilli, Francesco, et al. "Finite-element method modeling of superconductors: From 2-D to 3-D." IEEE Transactions on Applied Superconductivity 15.1 (2005): 17-25.

2-D Homogenized

HTS Layer

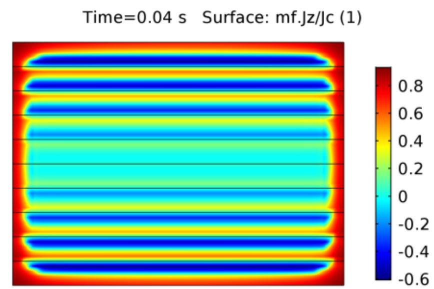
2-D Homogenized

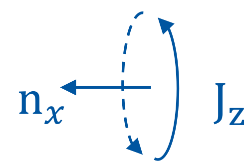
- $A-V$
  - $\partial_y J_z$
  - Unstable
- H
  - Fast (20x)
  - $\partial_y J_z$, φ
- $T-\Omega$
  - φ
- $T-A$
  - φ
- $H-A$
  - φ



[5,6]

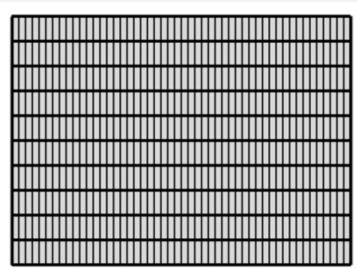
- $A-V$





Numerical artifact

- H



- **H**, 1st order elements
- **J**, 0th order
- If no nodes in the tape along y, then $\partial_y J_z = 0$ is imposed by the mesh

[5] Clem, John R., J. H. Claassen, and Yasunori Mawatari. "AC losses in a finite Z stack using an anisotropic homogeneous-medium approximation." Superconductor Science and Technology 20.12 (2007): 1130.
[6] Zermeno, Victor MR, et al. "Calculation of alternating current losses in stacks and coils made of second generation high temperature superconducting tapes for large scale applications." Journal of Applied Physics 114.17 (2013): 173901.

1-D Thin Strip

HTS Layer

1-D Thin Strip [7]

$A - V$
- Fast (10x)
- Unstable

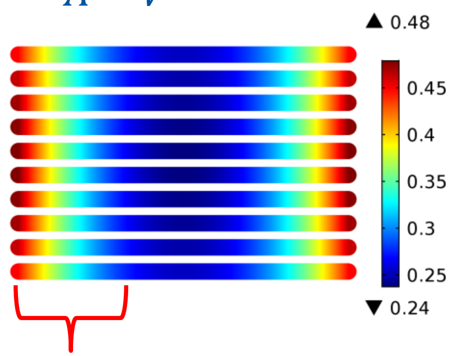
H
- Not available
- φ

$T - \Omega$
- φ

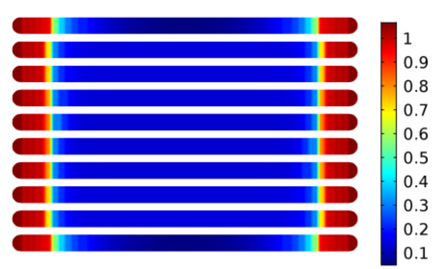
$T - A$
- φ

$H - A$
- φ

- $A - V$



- ρ_{SC} limited to $\sim 10^{-20}$
- Field penetration
- Transition zone too wide

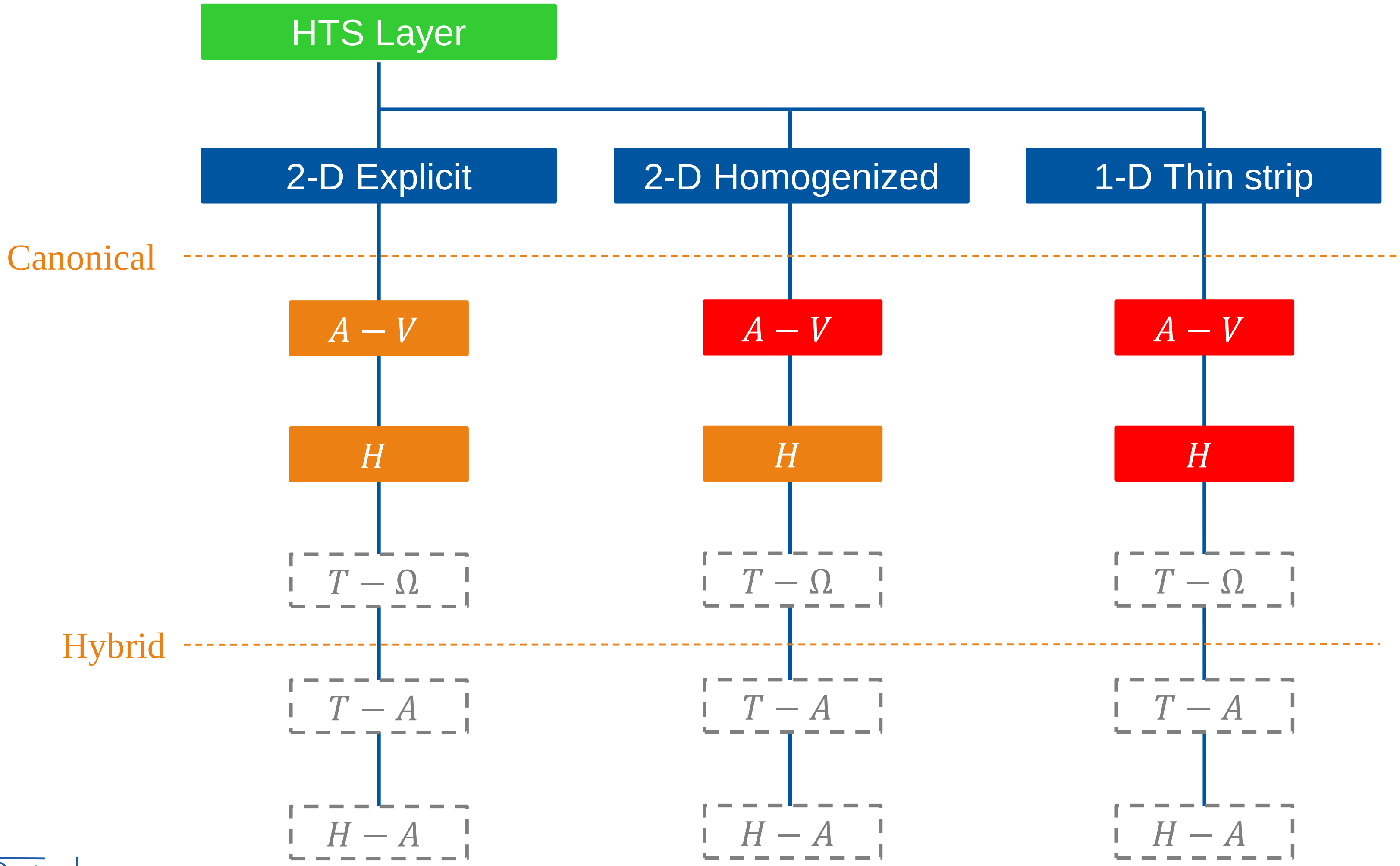


- Reference solution

[7] Ichiki, Y., and H. Ohsaki. "Numerical analysis of AC losses in YBCO coated conductor in external magnetic field." *Physica C: Superconductivity* 412 (2004): 1015-1020.

Alternative Models and Formulations

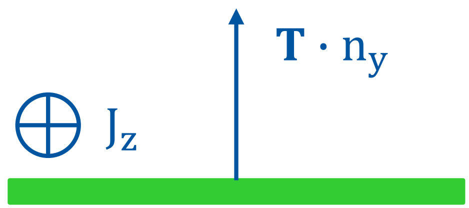
- Outlook



Hybrid $T\!-\!A$ Formulation in 1-D Thin Strip

- Optimal for 2-D large scale superconducting coils ($\sim 10^3$ tapes) [8]

$$\nabla \times \mathbf{T} = \mathbf{J}$$
$$\nabla \times \rho \nabla \times \mathbf{T} = -\partial_t \mathbf{B}$$
$$\nabla \times \mathbf{A} = \mathbf{B}$$
$$\nabla \times \nu \nabla \times \mathbf{A} = \mathbf{J}$$



- In 2-D, $\mathbf{J} = (0,0,J_z)$, $\mathbf{T} = (0,\mathrm{T}_y,0)$

$$\partial_x \mathrm{T}_y = \mathrm{J}_z$$
$$\partial_x(\rho \partial_x \mathrm{T}_y) = \partial_t \mathrm{B}_y$$
$$\nabla \cdot (\nu \nabla A_z) = -\mathrm{J}_z$$
$$\mathrm{B}_x = \partial_y \mathrm{A}_z$$
$$\mathrm{B}_y = -\partial_x \mathrm{A}_z$$

With continuity conditions on $\partial\Omega_{\mathrm{coil}}$

$$\mathrm{E}_{z,T} \rightarrow \mathrm{E}_{z,A}$$
$$\mathrm{B}_{n,A} \rightarrow \mathrm{B}_{n,T}$$

How to:

- Excite a coil
- Define $\boldsymbol{\zeta}_c : \nabla \times \boldsymbol{\zeta}_c = \chi_c$
- Calculate $\varphi = \int \boldsymbol{\zeta}_c \cdot \mathbf{H}\, d\Omega_c$

[8] Liang, Fei, et al. "A finite element model for simulating second generation high temperature superconducting coils/stacks with large number of turns." Journal of Applied Physics 122.4 (2017): 043903.

Conclusions

1. HTS technology possibly mature to be used in real accelerator magnets.

2. Slightly different magnetothermal behavior respect to LTS

3. 2-D modelling of the HTS tape to be avoided.

4. $\mathrm{A} - \mathrm{V}$ formulation intrinsically unstable. How to prove it?

5. Homogenization speeds up the solution by one order of magnitude.
   $\partial_y J_z = 0$ has to be enforced (nontrivial)

6. 1-D thin strip is promising, though not available in the H form (in COMSOL at least)

7. Equivalent magnetization as potential solution.
   Transport and induced current densities cannot be separated (cfr. LTS)

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