GetDP Workshop, 22–23 April 2021

https://indico.cern.ch/event/1015906/

Transient Effects in Accelerators, Scalability and Large Models

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… and many thanks to the workshop organizers for the invitation!

Outline

I. Introduction
   a. High-Temperature Superconductors
   b. Dynamic effects in conductors, magnets, circuits

II. Method
   a. Coupled A-H Field Formulation
   b. Field-Circuit Coupling Interface
   c. Waveform Relaxation Scheme

III. Large scale applications (selected examples):
   a. Quench in an HTS Solenoid
   b. Dynamic field quality in the HTS dipole Feather-M2
   c. Quench in a simple NI coil
   d. Prototyping new stuffs – HALO

IV. Summary and Outlook

Introduction

Method

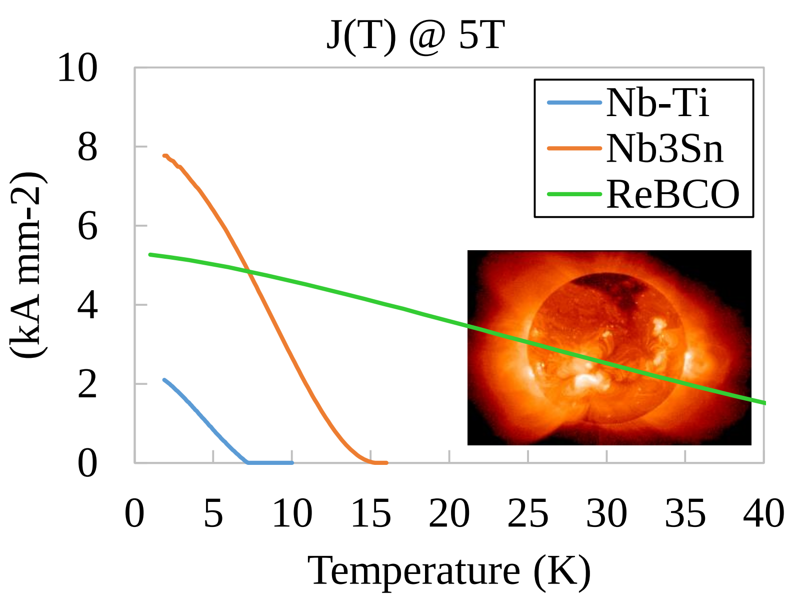
Large Scale Examples

Summary And Conclusions

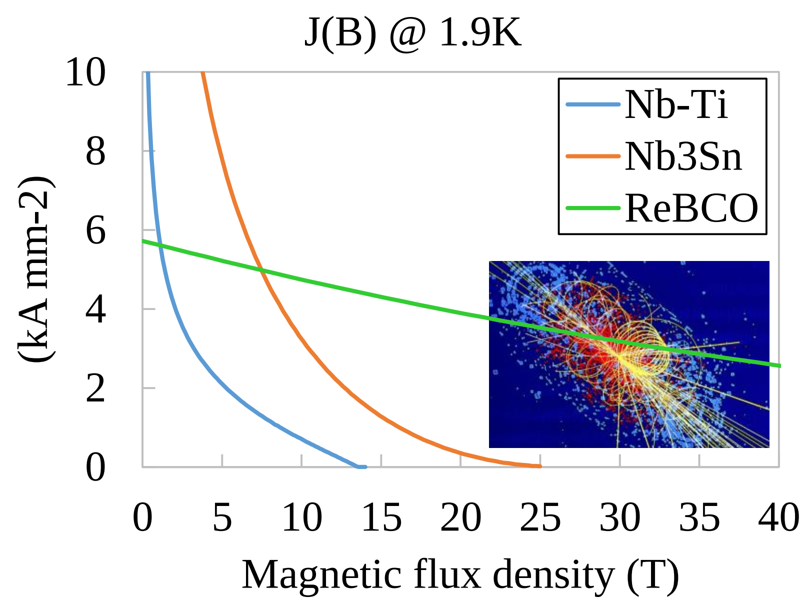
HIGH TEMPERATURE SUPERCONDUCTORS

Copper oxides (CuO_2) doped with rare earths (La, Bi-Sr-Ca, Y-Ga-Ba etc.)

Higher critical temperature and upper critical field with respect to the traditional low-temperature superconductors (LTS), such as Nb-Ti or Nb3Sn



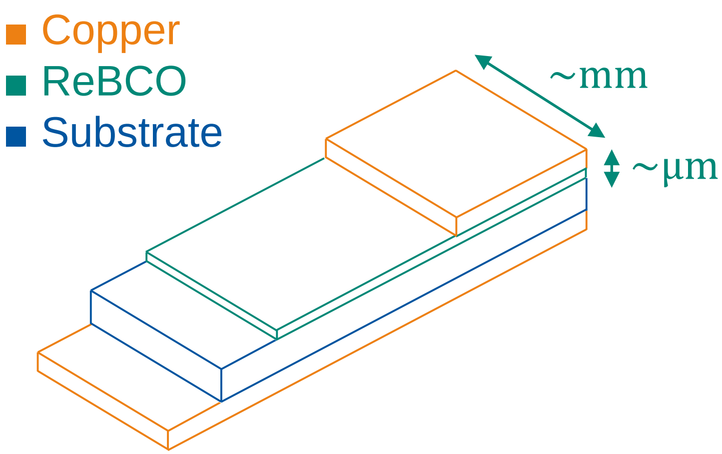
High-thermal load applications

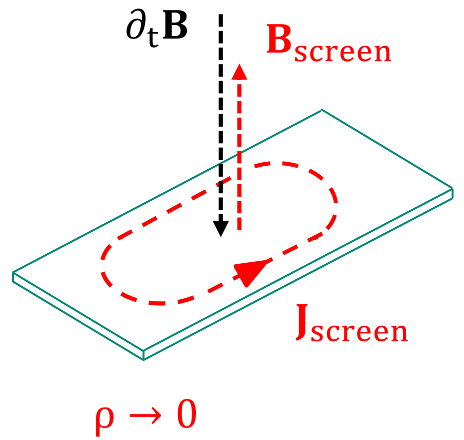


High-field applications

SCREENING CURRENTS

HTS tape in a time-dependent magnetic field $\partial_t \mathbf{B}$:





$\partial_t \mathbf{B}$ → Screening currents $\mathbf{J}_{\text{screen}}$

$\rho \to 0$ → Persistent magnetization $\mathbf{B}_{\text{screen}}$

Large filament size (5-12 mm) → large $\mathbf{B}_{\text{screen}}$

Magnetic field quality and thermal behavior, as principal Joule loss contribution

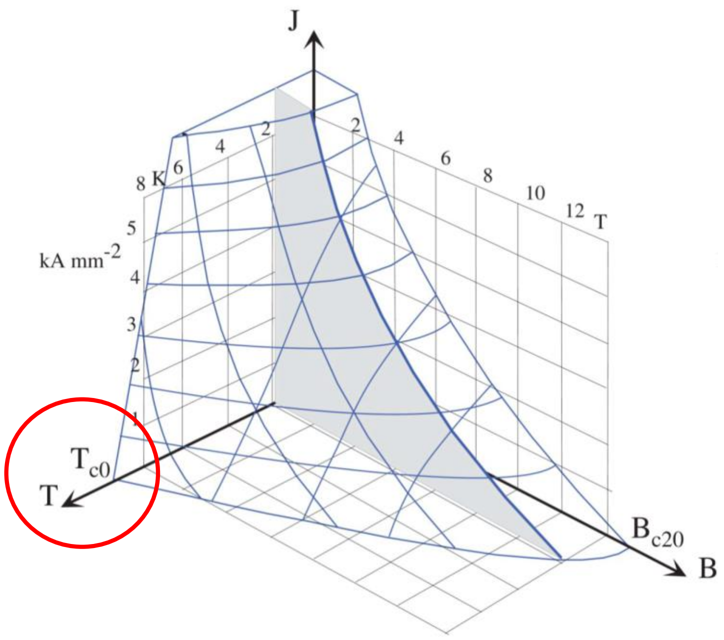
Inhomogeneous current density distribution → Detrimental impact on field quality

THERMAL DYNAMICS

Main contributors to the thermal dynamic of superconducting materials in accelerators:

- Motion
- Coupling currents
- Flux jumps
- Joule losses
- Particle Showers
- Heat leaks
- Magnetization loss
- Quench protection
- Cryo-failure

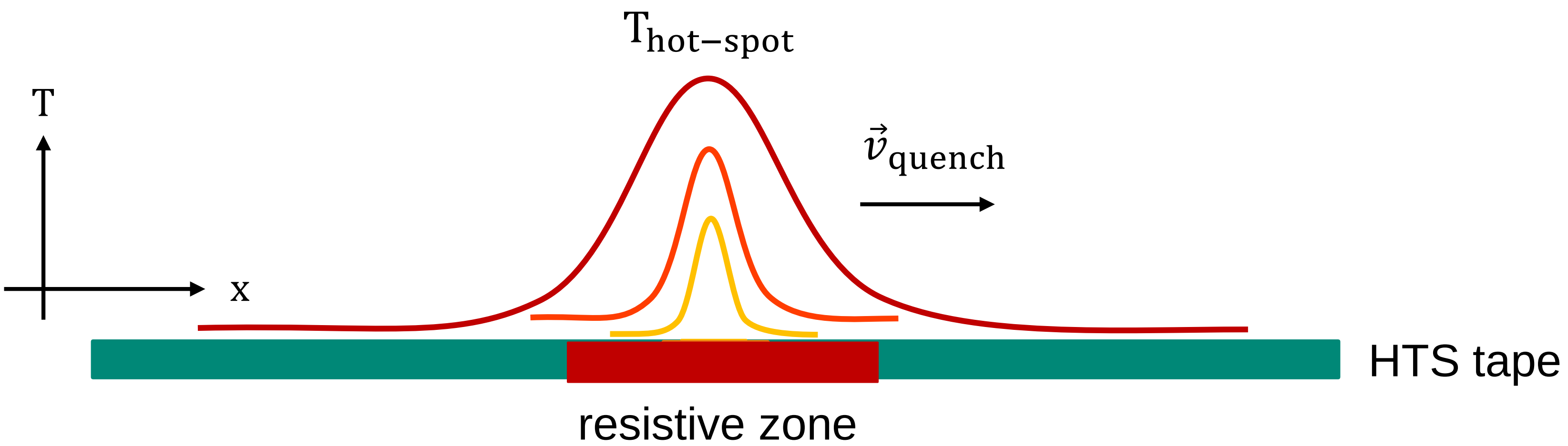
- Conduction
- Cooling
- Heat capacity



Nb-Ti critical current density surface $J_c(T, B)$

QUENCH

Local transition from superconducting to normal conducting state



Energy dissipated in the resistive zone

Potentially irreversible effects for high energy-density devices (accelerator magnets)!

HTS characteristics:

- low heat diffusivity
- low $\vec{v}_{quench}$, small resistive zone, difficult to detect
- high $T_{hot-spot}$, potential damage in short time (tens of ms)

DYNAMIC EFFECTS IN ACCELERATORS (1/2)

Magnets (e.g. MB magnet)

$\sim 10^2$ coil turns, $\sim 10^4$ strands

Magnetic: magnetization, IFCC, ISCC, EM crosstalk…

Thermal: magnetization, IFCL, ISCL, quench, coolant…

Mechanic: Lorentz forces, thermal strain…

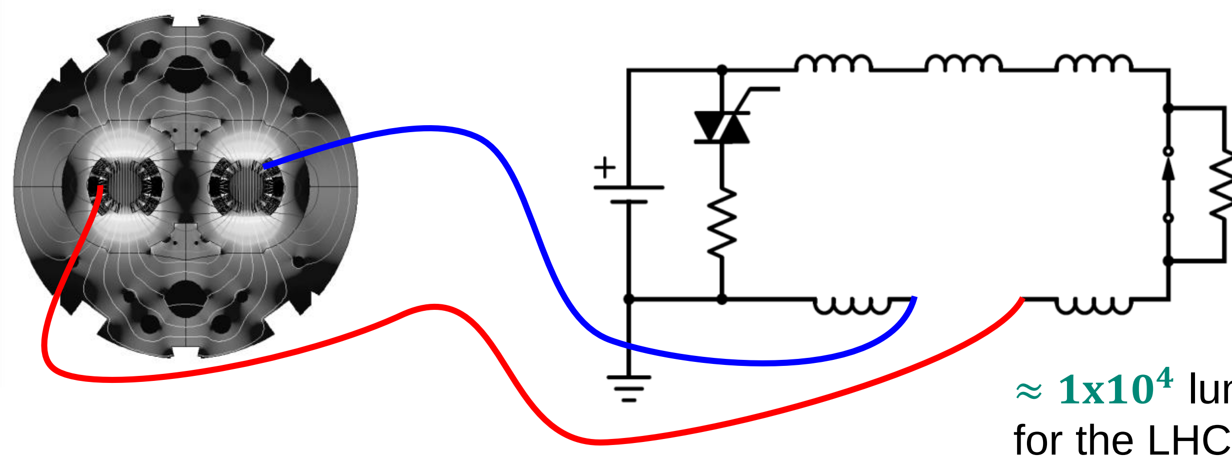
Circuit (e.g. LHC mains)

7 km long, 154 Magnets

Topological: Switches, thyristors, diodes

Electrical: Propagative phenomena, dynamic impedances (magnets) ,EM crosstalk

- …



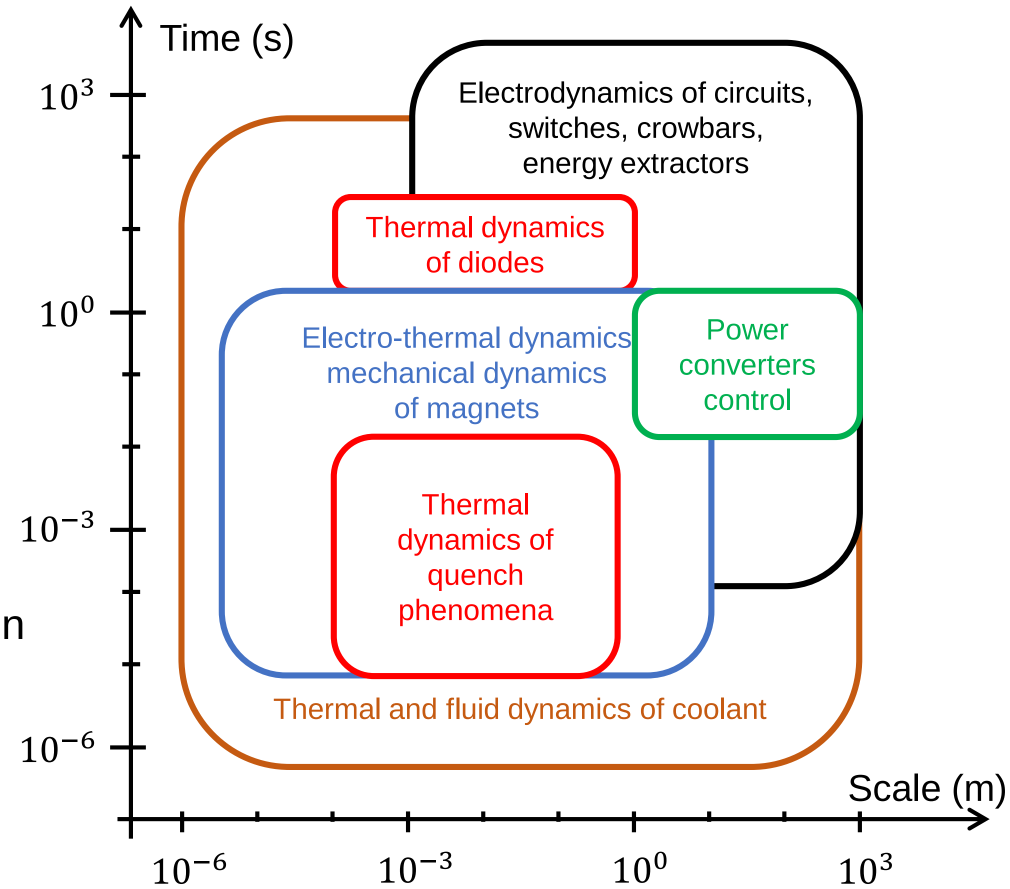
$\approx$ $\mathbf{1x10^4}$ lumped elements for the LHC mains

Field-Circuit Coupled Systems!

DYNAMIC EFFECTS IN ACCELERATORS (2/2)

Simulation challenges

- Complex components
- Cutting-edge technologies
- Physical size of devices
- Extreme ambient conditions
- Extremely fast phenomena (e.g. beam dynamics)
- …
- Mutual electro-thermo-dynamic interaction between circuit, power converters, magnets and protection systems



multi-physics multi-scale and multi-rate

FORMULATION

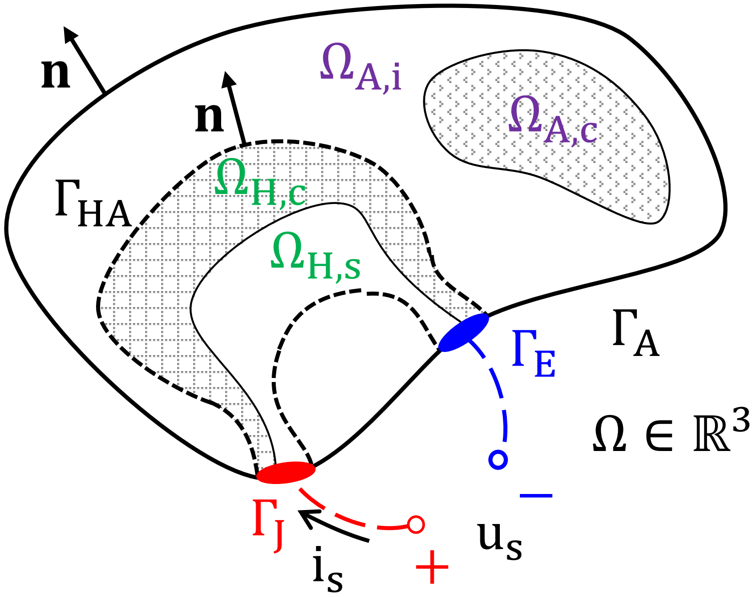
Magnet domain decomposition

$\Omega_H = \Omega_{H,s} \cup \Omega_{H,c}$ source region (coils):

- $\Omega_{H,s}$ superconductors $(\sigma \to +\infty)$
- $\Omega_{H,c}$ normal conductors

$\Omega_A = \Omega_{A,c} \cup \Omega_{A,i}$ passive region (Iron, air):

- $\Omega_{A,c}$ normal conductors
- $\Omega_{A,i}$ insulators $(\rho \to +\infty)$



Field equations (see also Julien's presentation)

$$\nabla \times \rho \nabla \times \mathbf{H} + \mu \partial_t \mathbf{H} + \nabla \times \boldsymbol{\chi}\, u_s = 0 \qquad \mathbf{H} \text{ formulation in } \Omega_H$$

$$\nabla \times \nu \nabla \times \mathbf{A}^\star + \sigma \partial_t \mathbf{A}^\star = 0 \qquad \mathbf{A}^\star \text{ formulation in } \Omega_A$$

$$\rho_m C_p \partial_t T - \nabla \cdot k \nabla T - \mathbf{J} \cdot \rho \mathbf{J} = 0 \qquad \text{Heat balance equation } T \text{ in } \Omega$$

$$\int_{\Omega_H} \boldsymbol{\chi} \cdot \nabla \times \mathbf{H}\, d\Omega = i_s \qquad \text{Current constraint}$$

$$\boldsymbol{\chi} = -\nabla \xi, \qquad \xi : \ \nabla \cdot \sigma \nabla \xi = 0 \qquad \text{Voltage distribution function}$$

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SEMI-DISCRETE PROBLEM

Discretization functions

- Edge elements for $\mathbf{H}$, $\mathbf{A}^{\star}$ (1st and 2nd order)
- Nodal elements for $\boldsymbol{\chi}$, T (1st order)

$$\begin{bmatrix} \mathbf{K}^{\nu}+\mathbf{M}^{\sigma}\frac{\mathbf{d}}{\mathbf{dt}} & -\mathbf{Q} & \mathbf{0} & \mathbf{0} \\ \mathbf{Q}^{\mathrm{T}} & \mathbf{K}^{\rho}+\mathbf{M}^{\mu}\frac{\mathbf{d}}{\mathbf{dt}} & -\mathbf{X} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{\mathrm{T}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{K}^{\kappa}+\mathbf{M}^{\rho}\frac{\mathbf{d}}{\mathbf{dt}} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{a} \\ \mathbf{h} \\ \mathbf{u_s} \\ \mathbf{t} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{i_s} \\ \mathbf{q}(\cdot) \end{bmatrix}$$

$\mathbf{A}^{\star}$ form

$\mathbf{H}$-form

Field coupling

Heat Balance

Circuit coupling

Finite material properties, bounded condition number → Solver stability ☺

Observations:

- Electric ports Γ_{J} and Γ_{E} as connections with the external circuit
- $\mathbf{u_s}, \mathbf{i_s}$ → r-th winding as one-port component, with impedance Z_r: $u_r = Z_r i_r$

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FIELD-CIRCUIT COUPLING

Interface derivation

Schur complement applied in the semi-discrete problem

Assumption $\mathbf{K}^{\nu}+\lambda\mathbf{M}^{\sigma}$ positive-definite (true for gauged $\mathbf{A}^{\star}$) → Invertible

Interface derived as optimal Schwarz transmission condition for linear systems

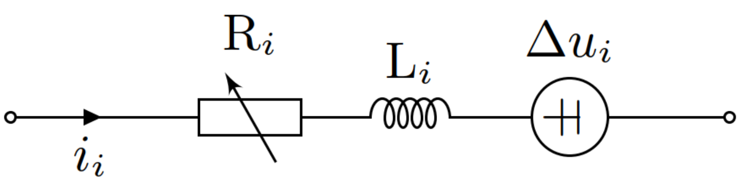
$$\mathbf{Z}(\mathrm{j}\omega) = [\,\mathbf{X}^{\mathrm{T}}\,[\,\mathbf{K}^{\rho} \;+\; \mathrm{j}\omega\mathbf{M}^{\mu} \;+\; \mathbf{Q}^{\mathrm{T}}[\,\mathbf{K}^{\nu} \;+\; \mathrm{j}\omega\mathbf{M}^{\sigma}\,]^{-1}\,\mathbf{Q}\,]^{-1}\mathbf{X}\,]^{-1}$$

resistive term — $\mathbf{H}$-flux — $\mathbf{A}^{\star}$-flux — eddy currents term

Approximation of derivatives in time domain (e.g. Taylor expansion series)

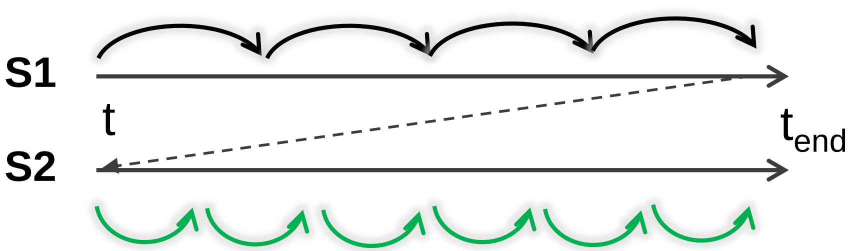
$$\mathbf{Z}(\mathrm{j}\omega) \approx \mathbf{Z}(0) + \mathrm{j}\omega \left.\frac{\partial \mathbf{Z}(\mathrm{j}\omega)}{\partial \mathrm{j}\omega}\right|_{\mathrm{j}\omega=0}$$

$$\mathbf{u_s} \approx \mathbf{R}\mathbf{i_s}(\mathrm{t}) + \mathbf{L}\frac{\mathrm{d}}{\mathrm{dt}}\mathbf{i_s}(\mathrm{t})$$

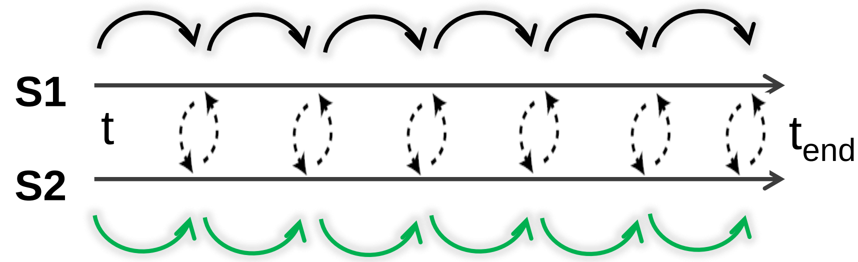


TIME-DOMAIN COUPLING

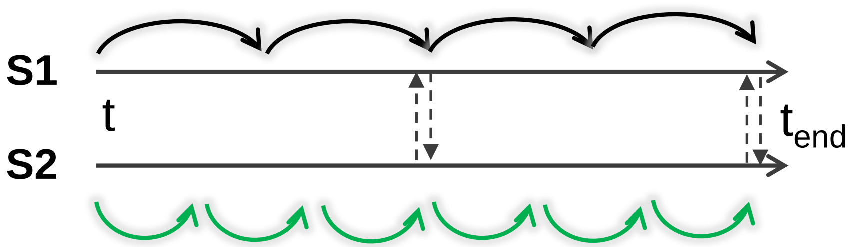
One-way coupling / Parameter extraction



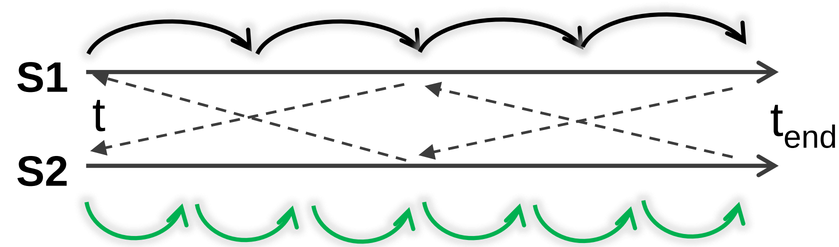
Strong coupling



Weak coupling



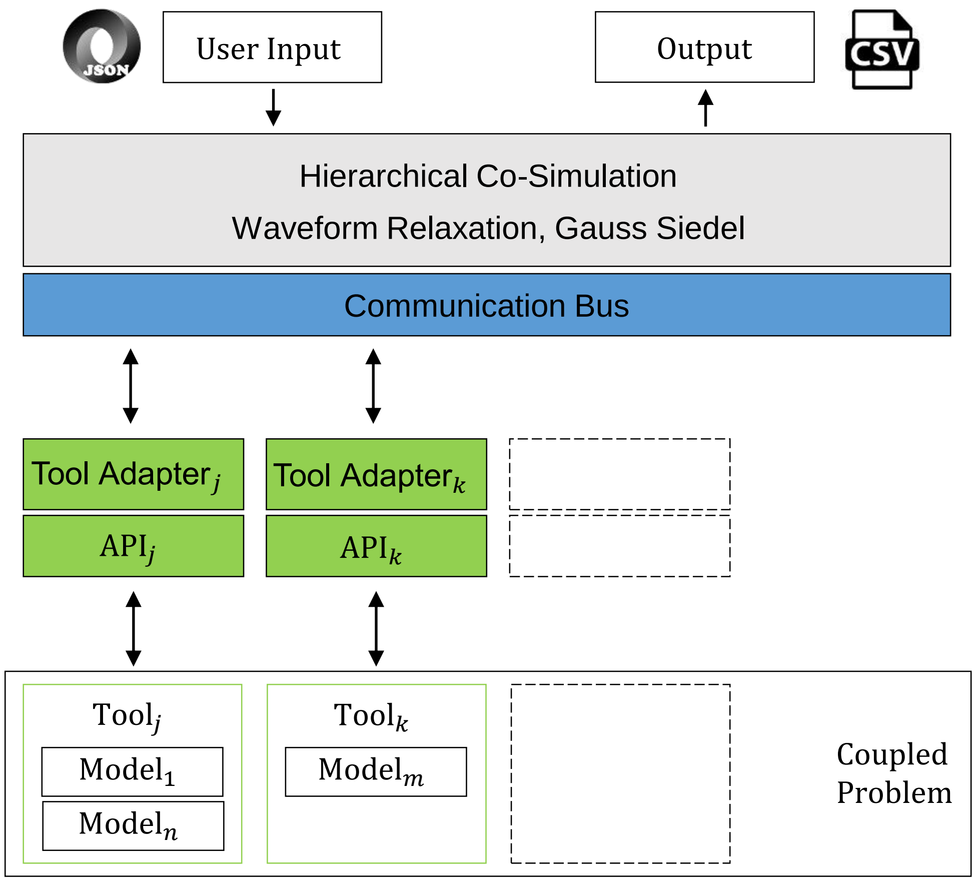
Waveform relaxation / Dynamic iteration



Multirate systems

- Fast System → small steps, slow System → large steps
- Different time steps for efficiency
- Different solvers since different nature of the problem

COSIMULATION FRAMEWORK



Top Layer

- Hierarchical co-simulation algorithm
- Waveform relaxation, Gauss-Seidel scheme

Middle Layer

- Communication bus, common interface
- Standard set of rules for data exchange

Bottom Layer

- Interpreter (framework vs. simulation tools)
- Tool-oriented (single adapter for multi-models)

STEAM (*)

Lean, Modular, Expandable

(*) https://espace.cern.ch/steam

REMARKS

Strong form: $F(r,t) = 0$ in Ω

Weak form: $$\int F(r,t) \cdot w \, d\Omega = 0$$

Semi-discrete form: $$F_i \int w_i \cdot w_j \, d\Omega = 0$$ with $F(r,t) \approx \sum w_i F_i$

Space discretization and time-integration via FEM solvers

Weak field formulation → general description of the field problem

Well-documented coupling interfaces → ready to be used

Tool adapters in the co-simulation framework → tool independent

Numerical examples in COMSOL, but **the approach is completely general!**

Introduction

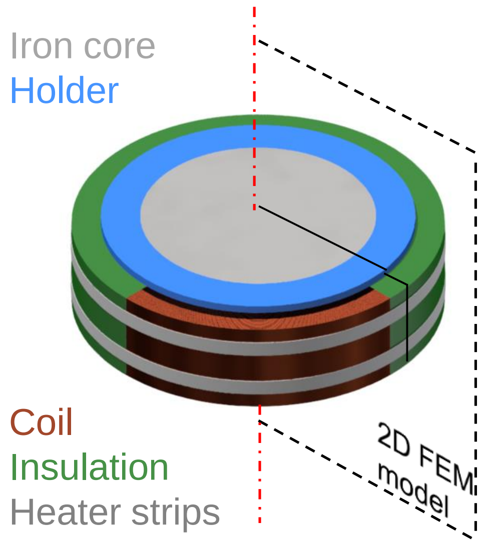
Methods

Large Scale Examples

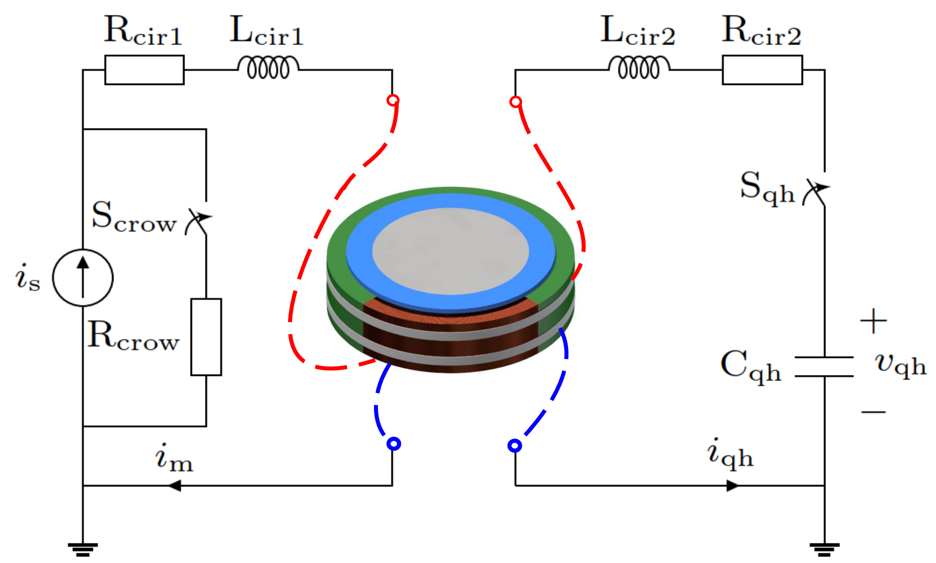
Summary And Conclusions

(A) PROBLEM SETTING

HTS solenoid protected by quench heaters



Rendering of the HTS solenoid (*)

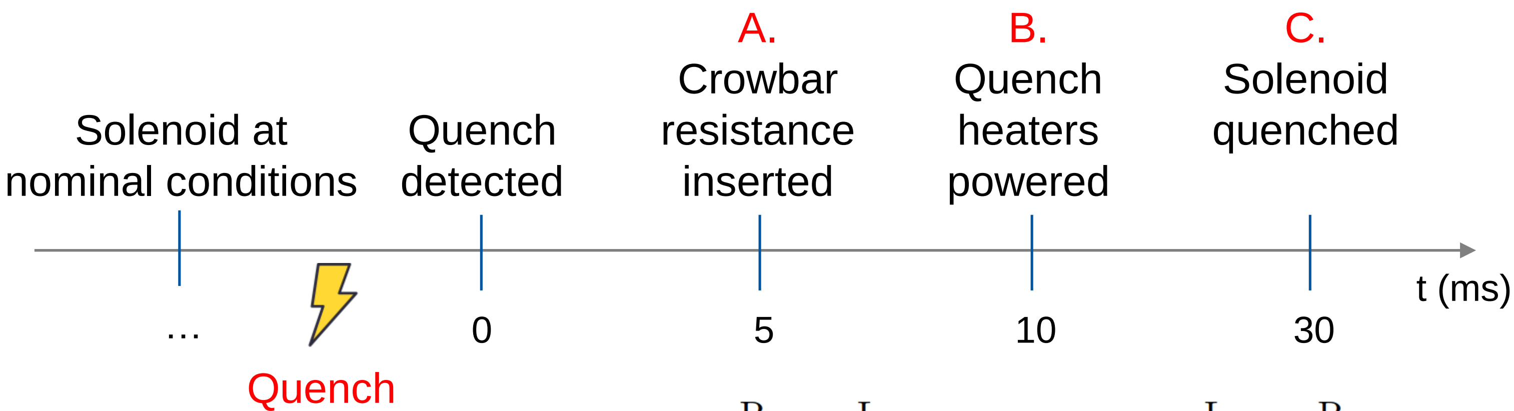


Electrical layout (**)

Electro-magneto-thermal coupling between the solenoid and the quench heaters!

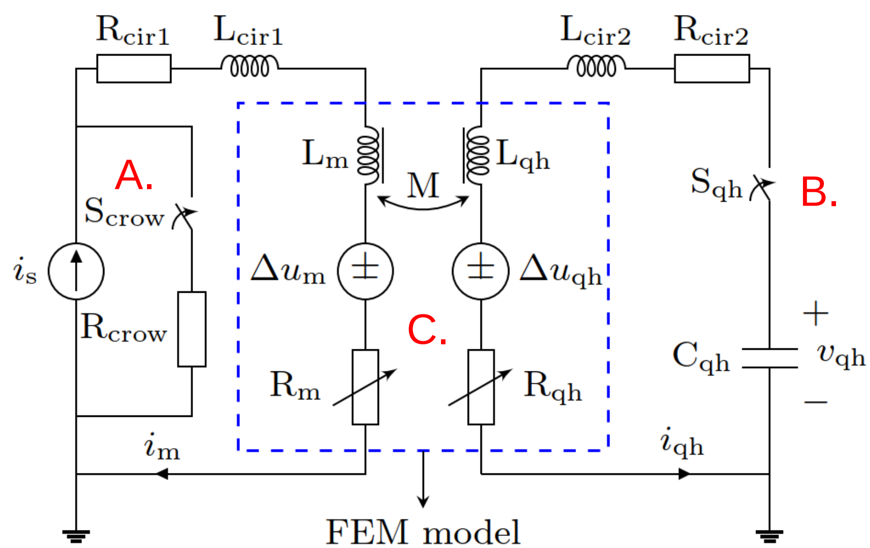
(*) Material properties available at https://gitlab.cern.ch/steam/steam-material-library
(**) Circuit parameters in appendix

(A) SIMULATION SETUP



$R_{crow} + R_m$ discharge the current in the solenoid, limiting the peak temperature in the superconducting coil

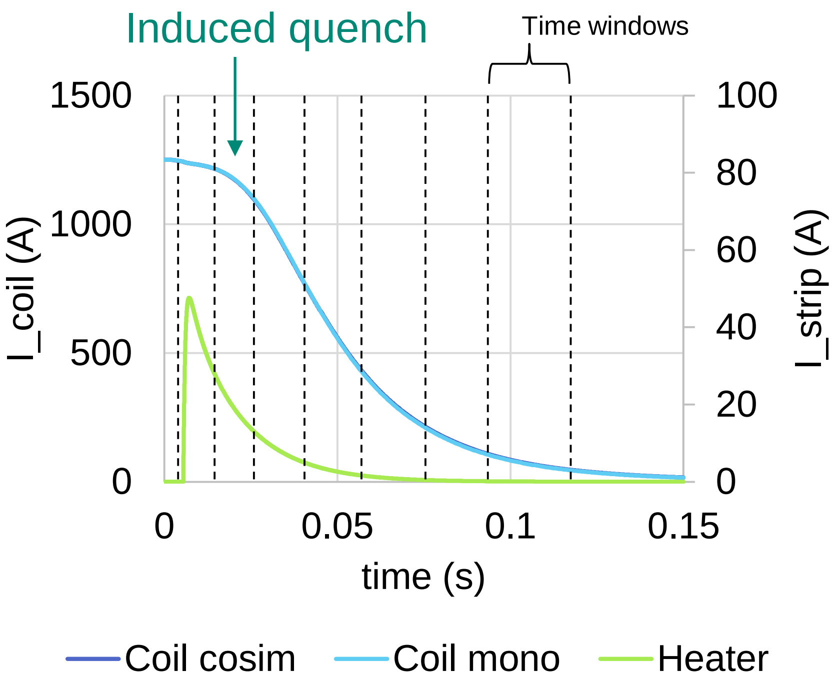
R_m determined by the quench dynamics within the solenoid



COMSOL LTspice

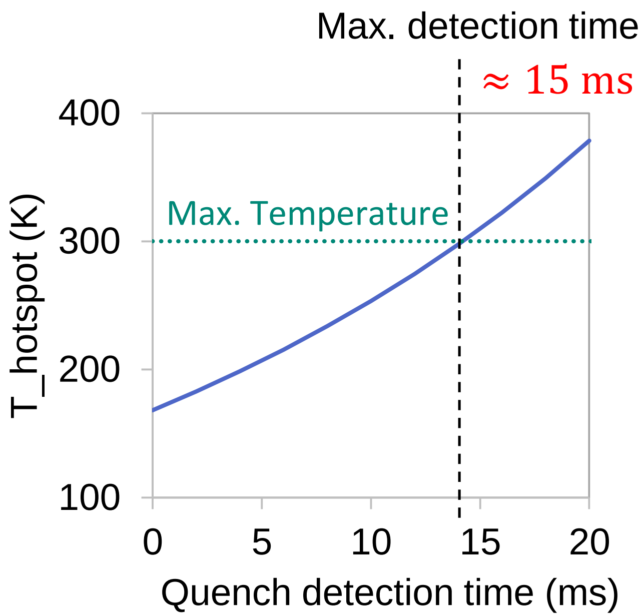
(A) NUMERICAL RESULTS (1/2)

Circuital currents



Current decay in the coil (left) and current discharge in the heater strips (right)

Peak temperature



Adiabatic hotspot temperature in the coil, as a function of the quench detection time

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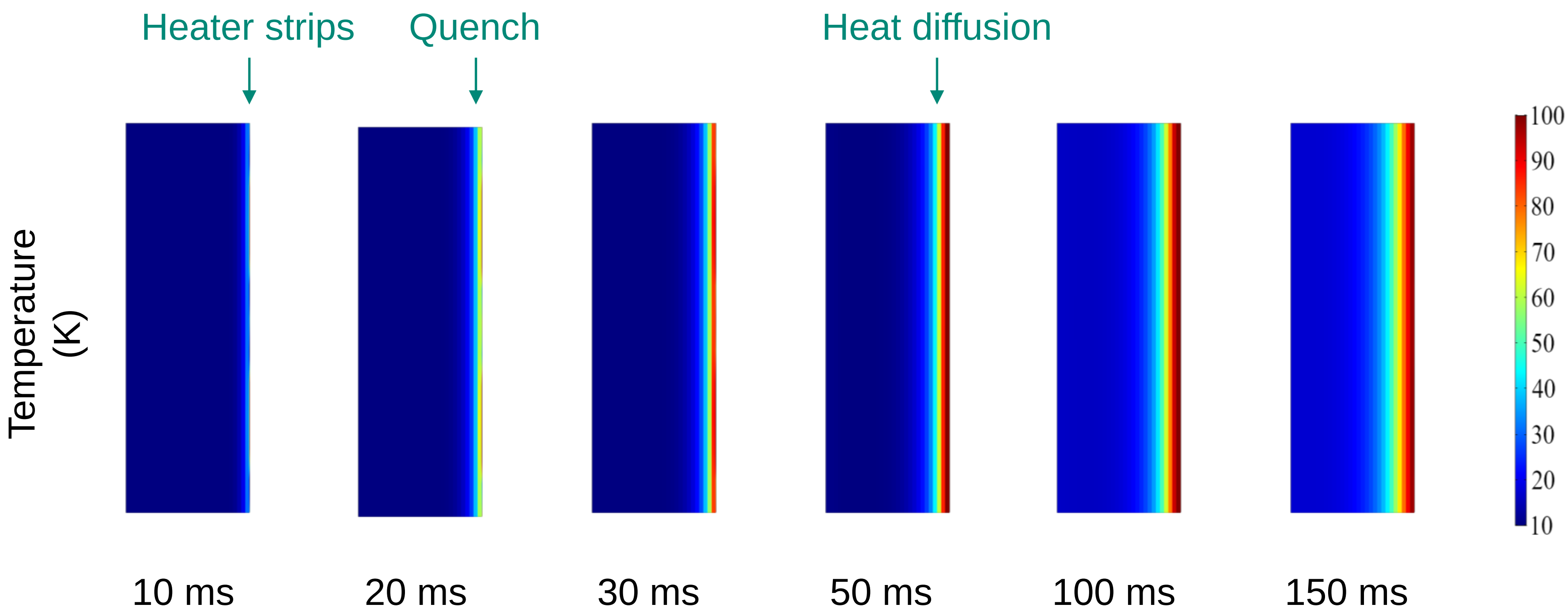
(A) NUMERICAL RESULTS (2/2)

Temperature in the coil cross section



Temperature distribution in the superconducting coil, as a function of time

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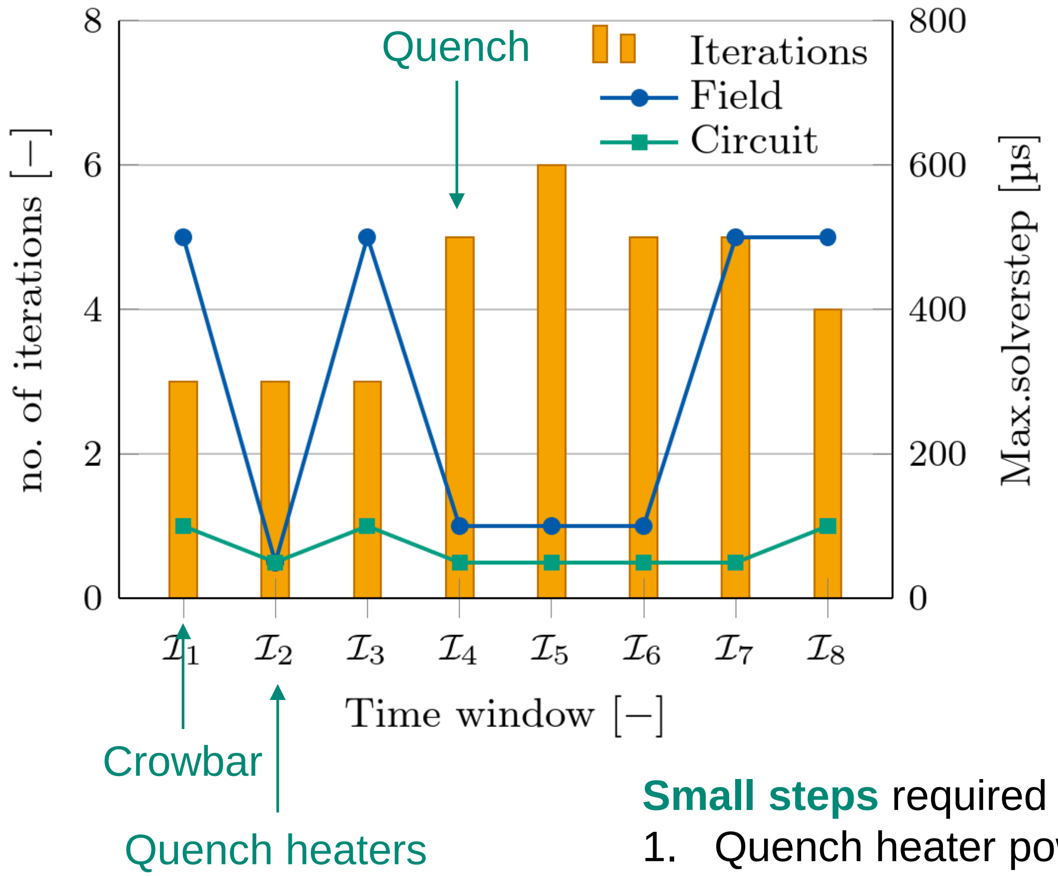
(A) TIME STEPPING

Maximum time step for each solver, for each time window

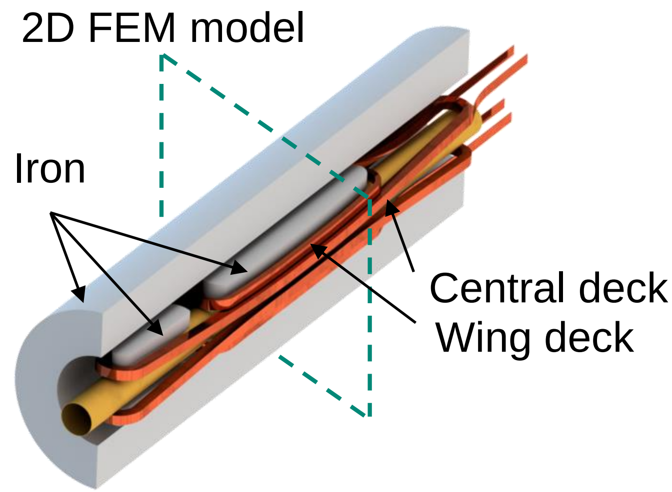


Small steps required for:

1. Quench heater powering
2. Quench transition

(B) PROBLEM SETTING (1/3)

Feather-M2 HTS insert dipole magnet



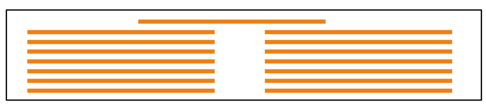
Main features:

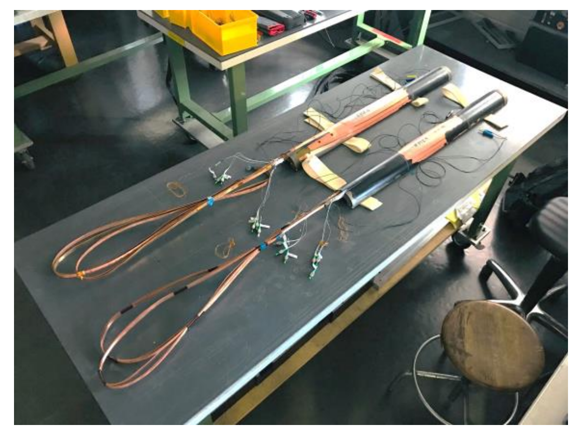
- Aligned coil concept
- Coil made of two central and wing decks
- Roebel cable, fully transposed tapes

2D model:

- Layer jumps → 4-quadrant
- 48 turns, 720 tapes

Cable cross section





Photos courtesy of J. Van Nugteren

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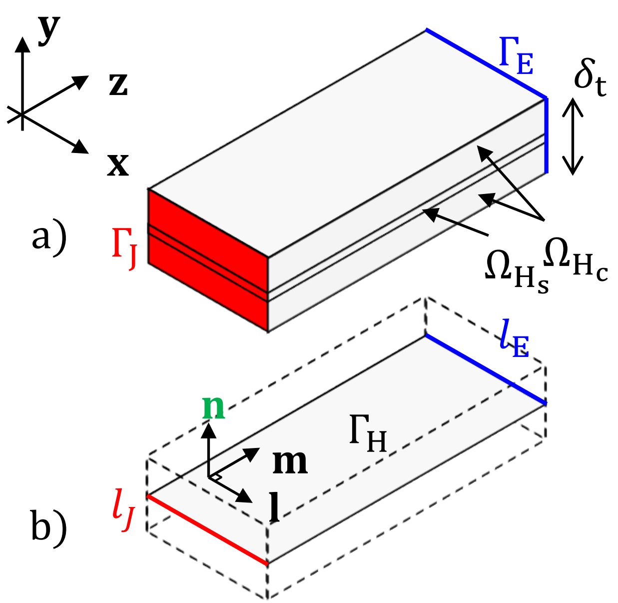
(B) PROBLEM SETTING (2/3)

Thin shell approximation

No current density variation along δ_t

Homogenized resistivity ρ_{eq}

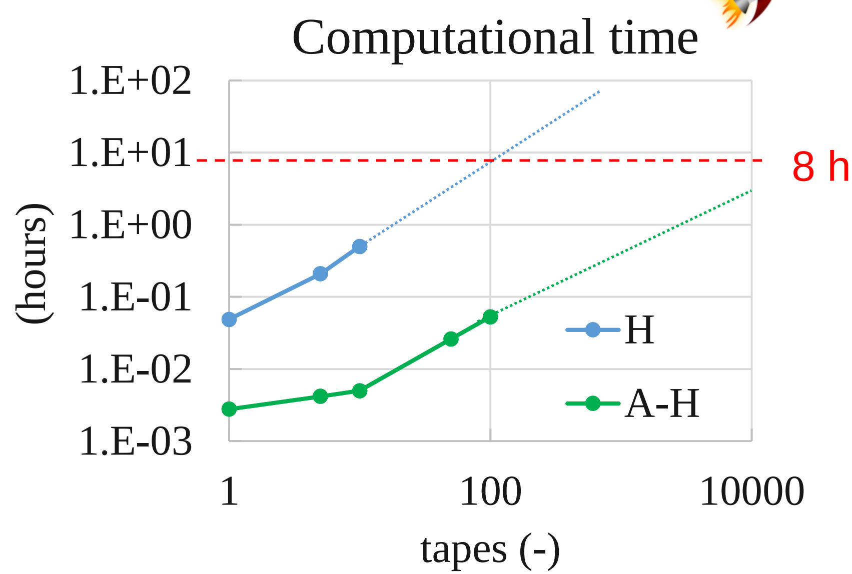


Scalar field problem → **nodal elements**

Computational cost (*)

Comparison on a test problem

Tapes stacked on top of each other



Reduction of **two orders of magnitude**

(*) CPU: Intel Core i7-3770 @ 3.40GHz. RAM: 32 Gb. OS: Win 10

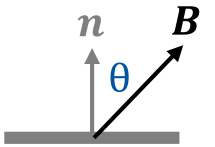
(B) PROBLEM SETTING (3/3)

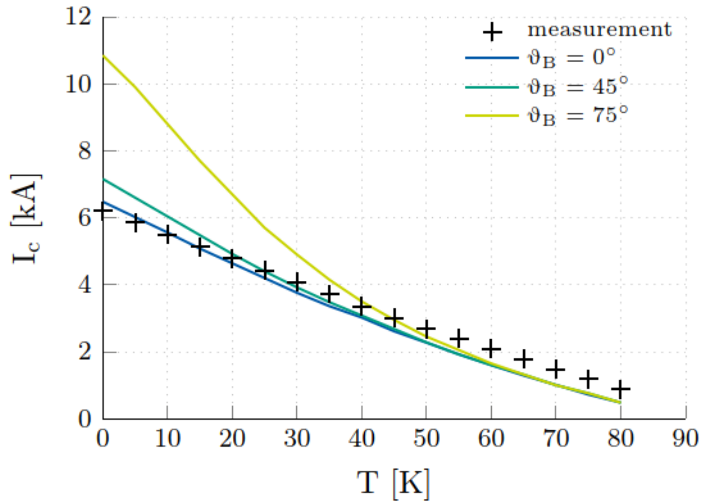
Modelling of Jc (T, B, θ)

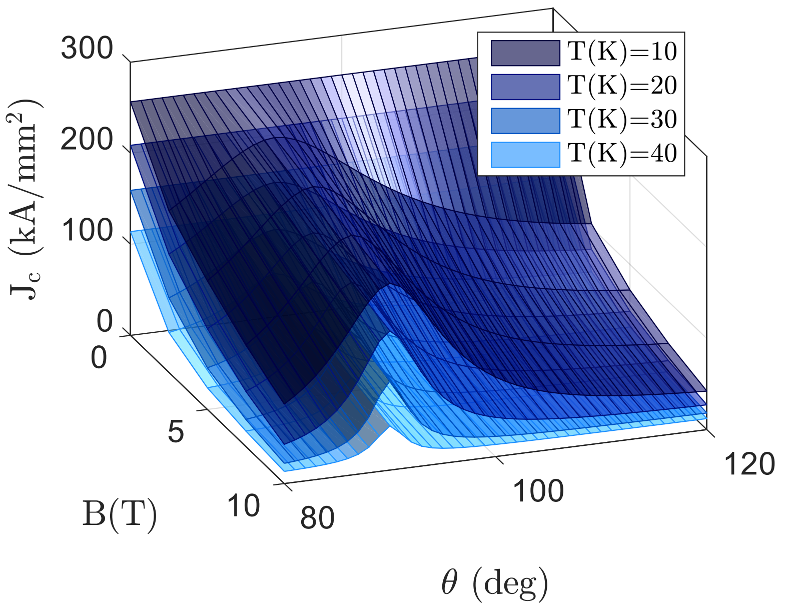
J_c data available only at $T = 77$ K → Lift factor

Lift factor calibrated with the measured critical current I_c

Angle dependency gauged at $\theta = 30°$ (magnetostatic simulation)





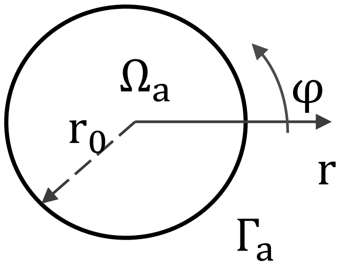


Anisotropy included in the model, but uncertainty on material properties

(B) SIMULATION SETUP

Field quality

In the magnet aperture Ω_a, $\Delta A_z = 0$



General Solution: Fourier expansion series

$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \underbrace{nr^{n-1}}_{A_n(r)} \gamma_n \cos(n\varphi) + \underbrace{nr^{n-1}}_{B_n(r)} \delta_n \sin(n\varphi)$$

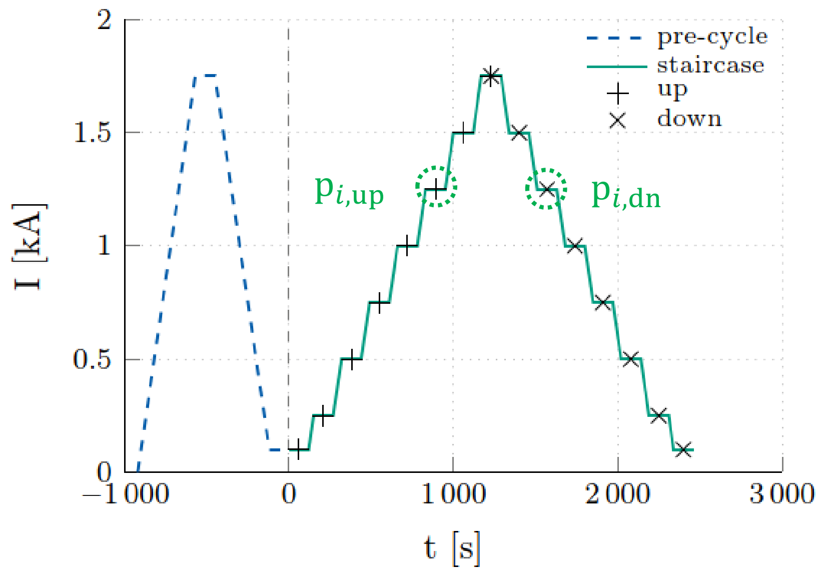
$A_n(r)$, $B_n(r)$ skew and normal magnetic field multipoles calculated along Γ_a

Source current

Pre-cycle → first magnetization

Steps of 250 A, plateaus of 120 s: decay of inductive effects

$\{p_{i,up}, p_{i,dn}\}$ Evaluation points



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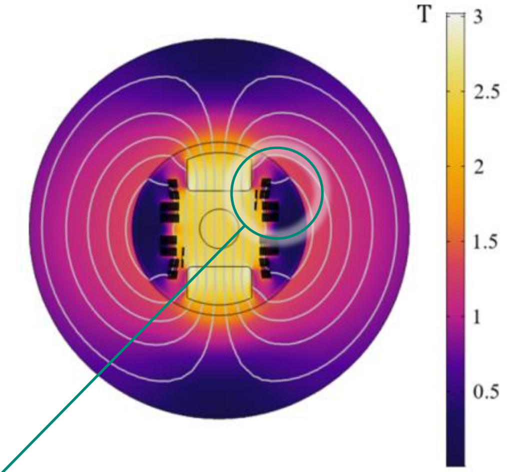
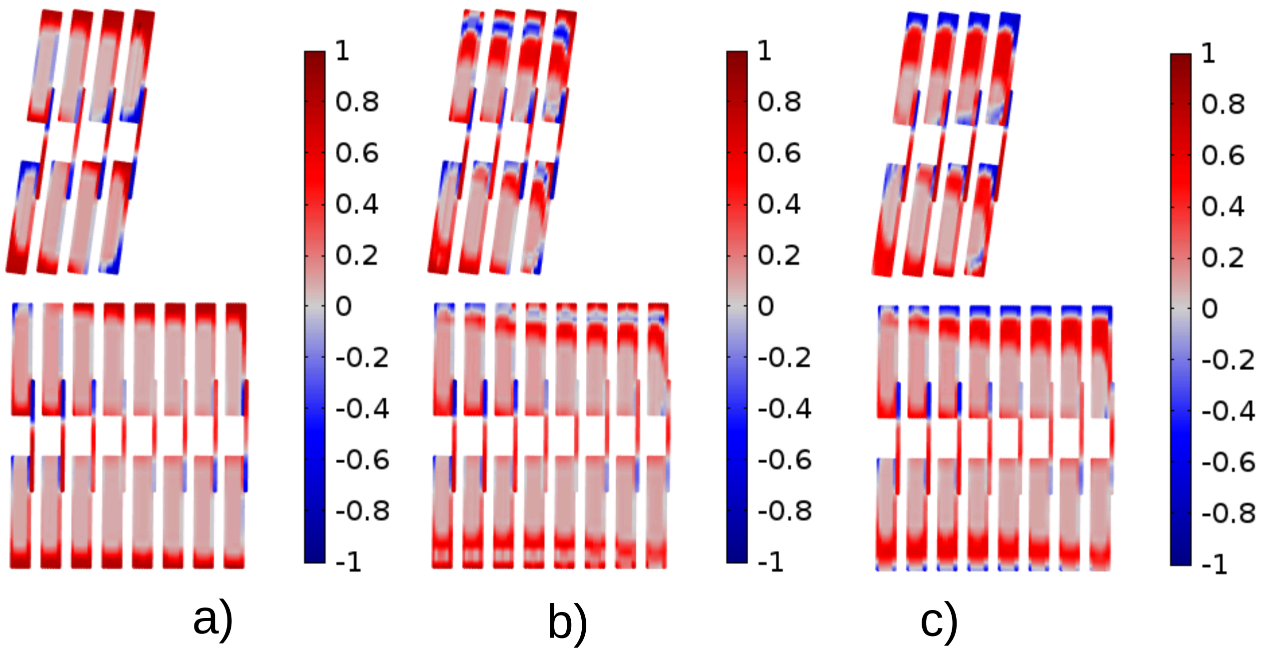
(B) NUMERICAL RESULTS (1/2)



Computational time
0.5 h (*) for about 120k DoF

Current density plots: same source current, different time steps



Normalized current density in the coil (first quadrant)

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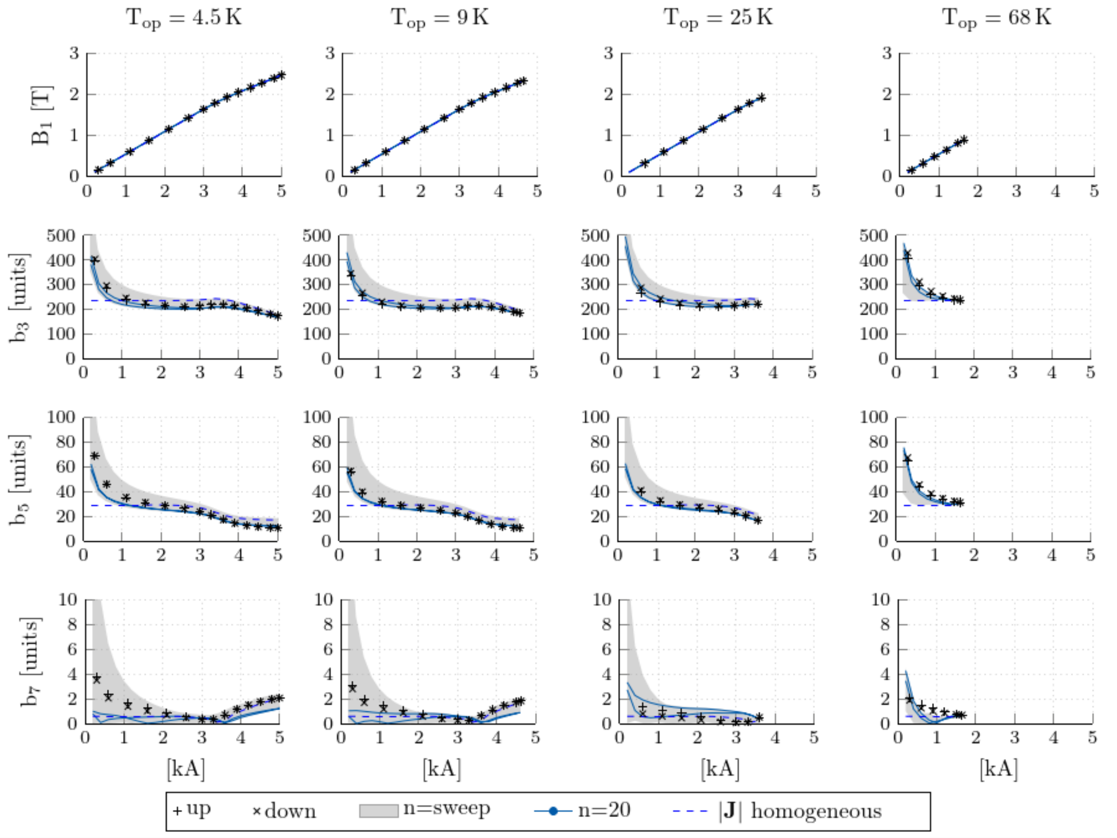
(*) CPU: Intel Core i7-3770 @ 3.40GHz. RAM: 32 Gb. OS: Win 10

(B) NUMERICAL RESULTS (2/2)

Magnetic field quality

Multipole expansion series as function of current, for different temperatures



Very good agreement with measurements

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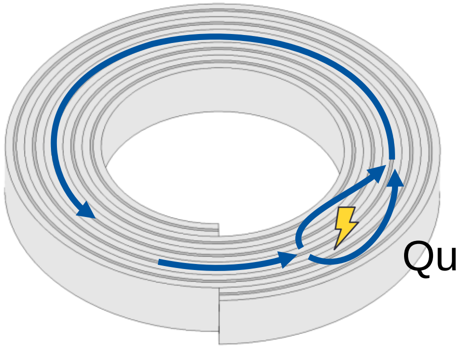
(C) PROBLEM SETTING (1/2)

No insulation (NI) coil

Main features:

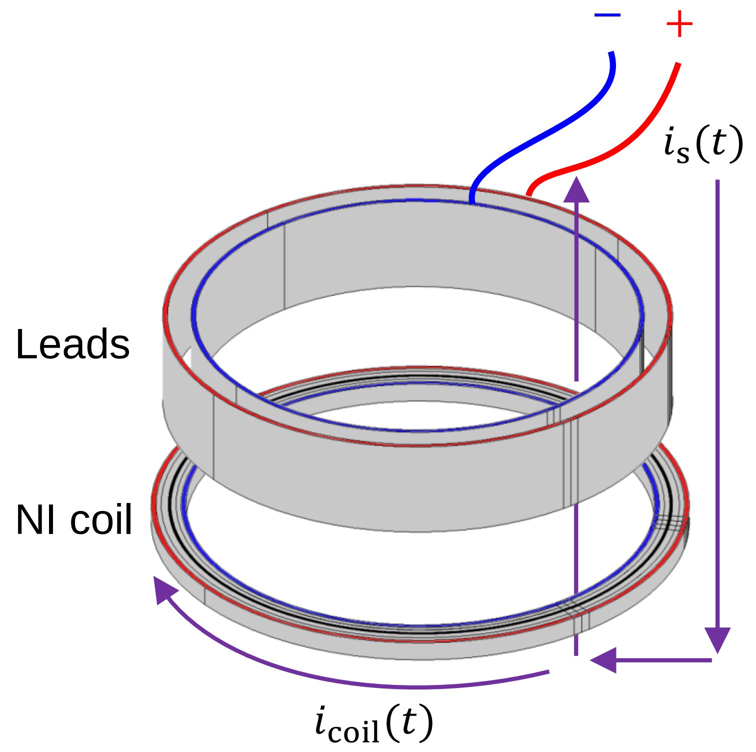
- Current bypass for quench zones
- Limitation of peak temperature
- Large screening currents in field dynamics
- Unbalanced Lorentz forces during quench



Electrical layout

Coil clamped with two copper rings

Leads as two concentric hollow cylinders



(C) PROBLEM SETTING (2/2)

Scale challenge:

ReBCO ≪ Tape ≪ Coil

Up to tens of pancakes, thousands of turns

Mesh size: $\approx n_{\mathrm{2D}} n_{\mathrm{tape}} 2\pi r_{\mathrm{coil[mm]}}\ n_{\mathrm{pancake}}$

Example: 100 elements per tape cross section, 100 tapes, 10 mm radius

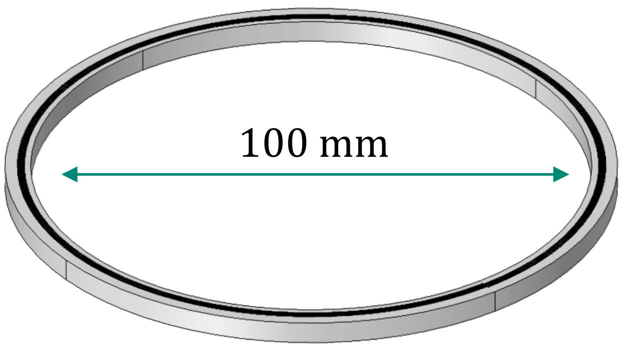
→ $\approx \sim 10^6$ elements per pancake

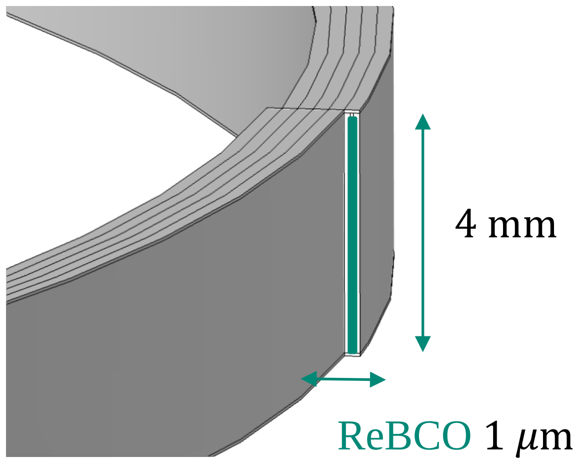
Case study:

Five-turns in one pancake

Copper-coated ReBCO tape, no solder

4 mm wide tape, $\mathrm{I_c} = 1\ \mathrm{kA}$

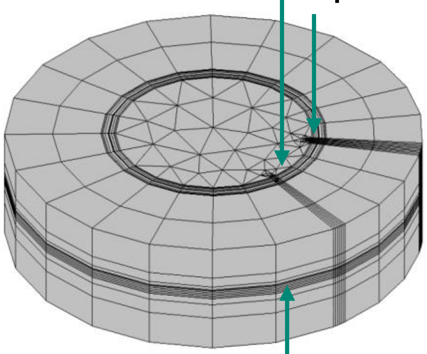


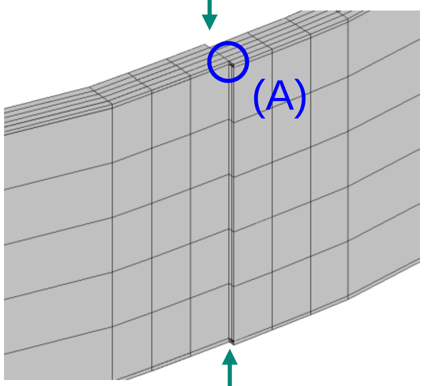


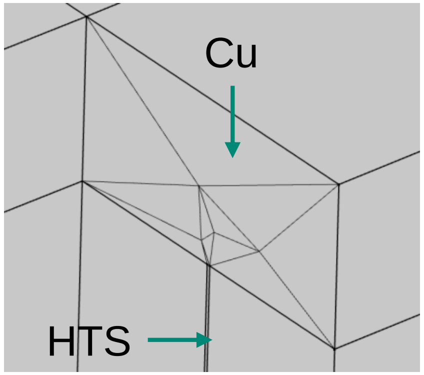
(C) MESH

Main features

- Mapped mesh in the tape cross section
- Triangular mesh in the tape ends
- Hexahedrons and prisms along the coil
- $\sim 4 \times 10^4$ elements, 1.1×10^5 dof





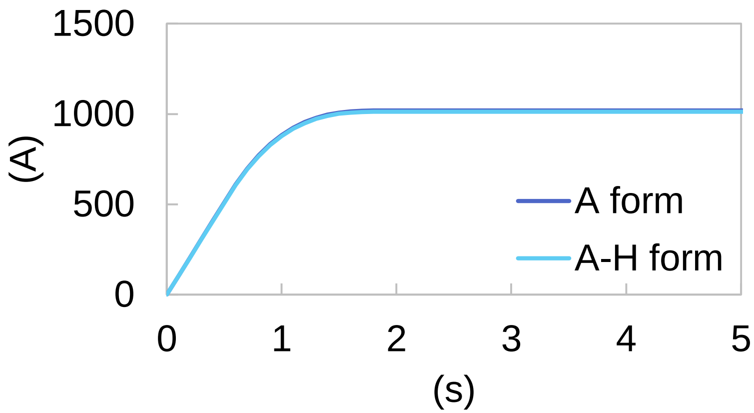


Detail of the tape end (A)

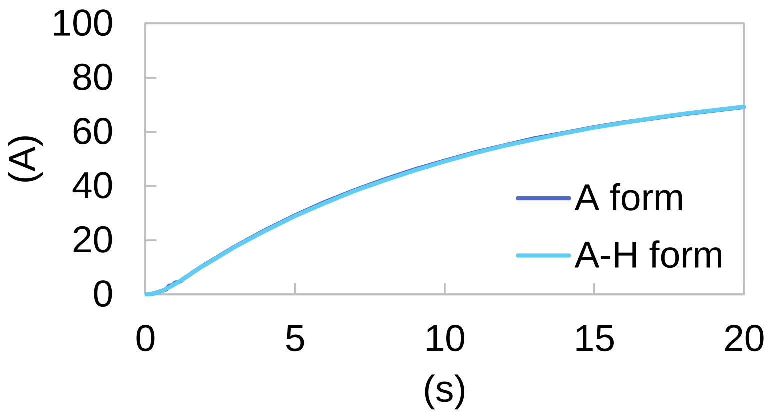
(C) MODEL VERIFICATION

Constant material properties → Speedup, traditional formulations

Comparison with the COMSOL in-built $\mathbf{A}^{\star}$-formulation (mf module)



Coil current as a function of time



Detail of the initial coil current

Verification of the implemented equations

not of the behaviour of the superconducting material

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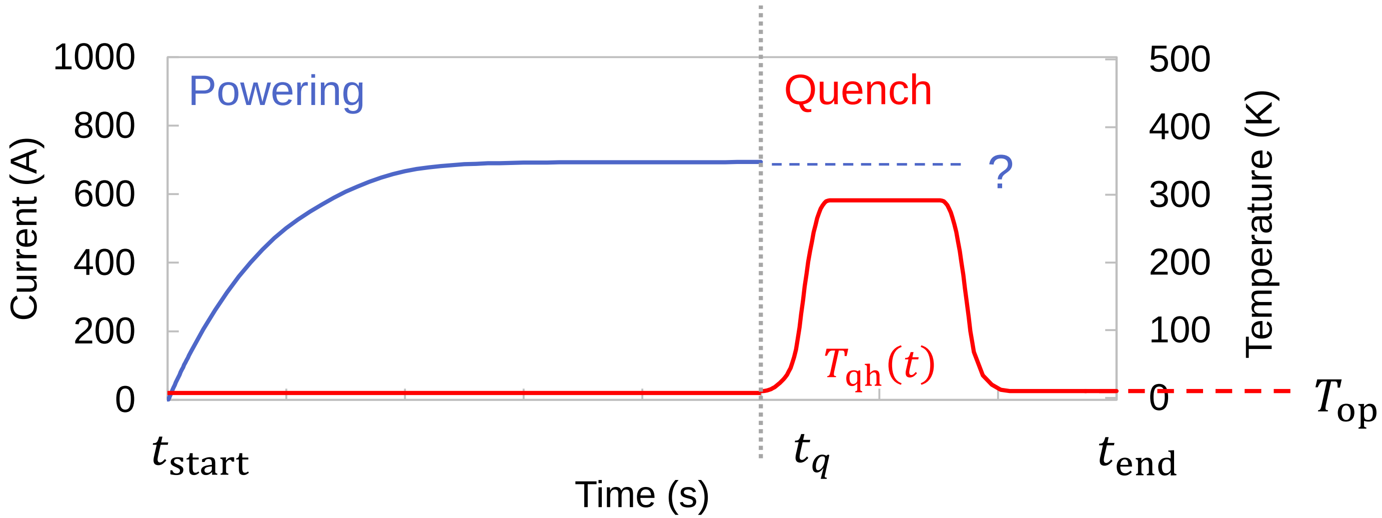
(C) SIMULATION SETUP

Constant voltage U_s applied to the coil:

$u_s(t) = U_s \quad \forall t \in [t_{\text{start}}; t_{\text{end}}]$

Spot heater modeled a Dirichlet boundary condition $T_{\Gamma,\text{dir}}(t)$ for temperature:

$$T_{\Gamma,\text{dir}}(t) = \begin{cases} T_{\text{op}} & \text{if } t \leq t_q \\ T_{\text{qh}}(t) & \text{if } t > t_q \end{cases}$$



Current profile at the coil leads Temperature of the spot heater

(C) NUMERICAL RESULTS (1/2)

Temperature in the spot heater region

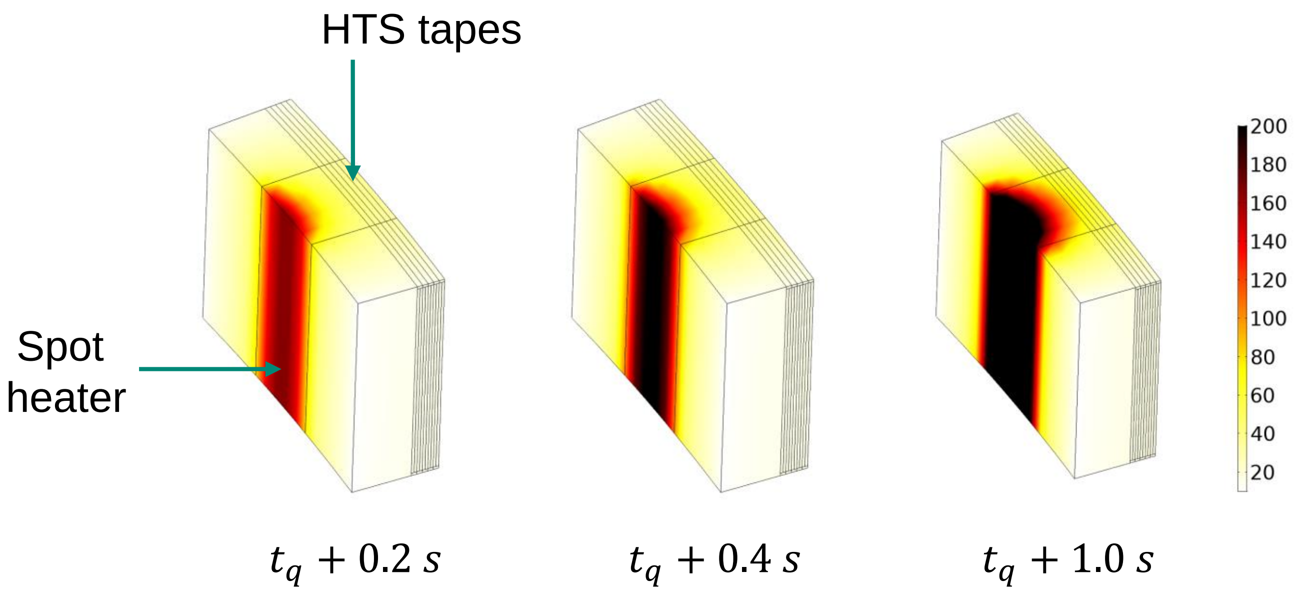


Figure: temperature distribution in the coil, detailed for the spot heater region

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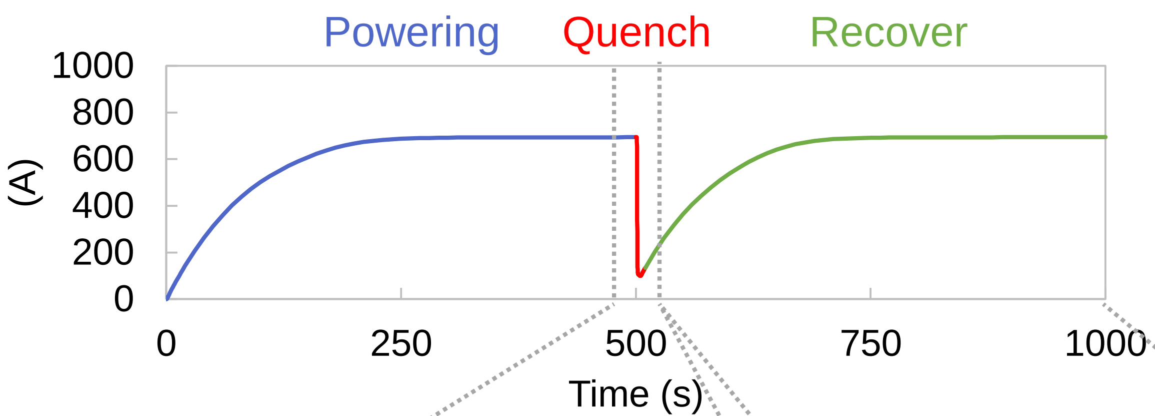
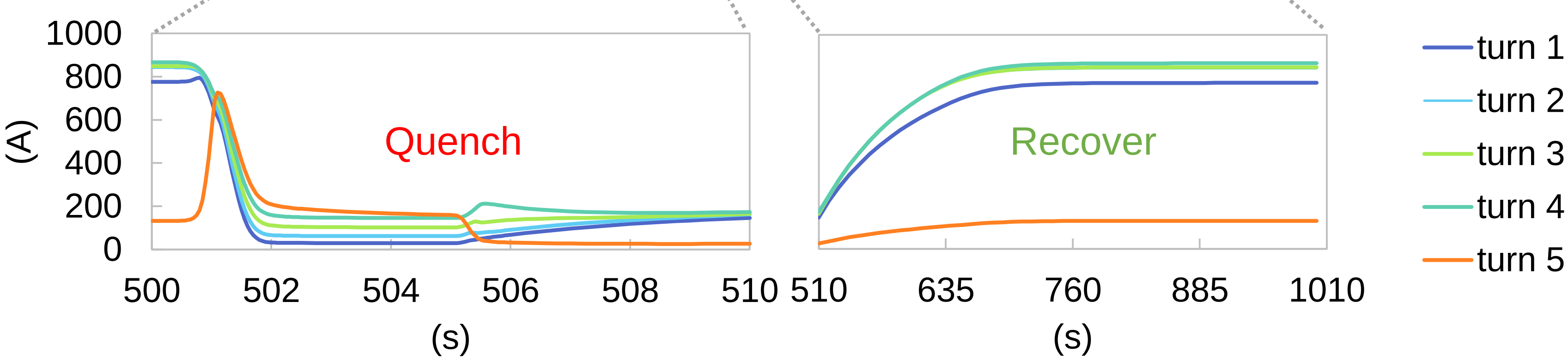
(C) NUMERICAL RESULTS (2/2)

Current dynamics at the coil leads



Computational time (*):
Powering: 20 min
Quench: 50 min
Recover: 15 min

Current redistribution between the tapes (Turn numbering from inside to outside):



(*) Intel Xeon CPU E5-2667 v4 @ 3.40GHz 128 GB of RAM Windows 7 OS

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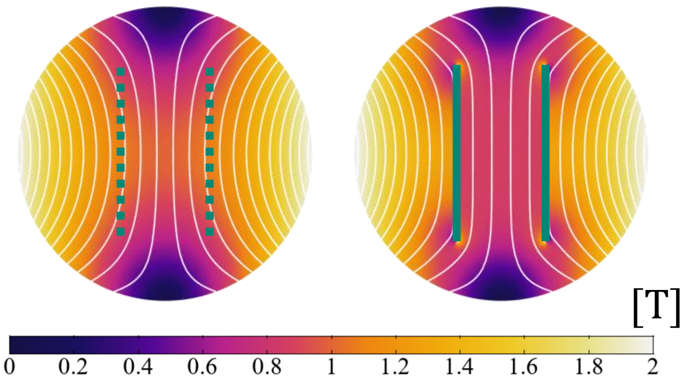
(D) PROTOTYPES DEVELOPMENT (1/2)

HALO:
Harmonics-Absorbing Layered Object

Key features:

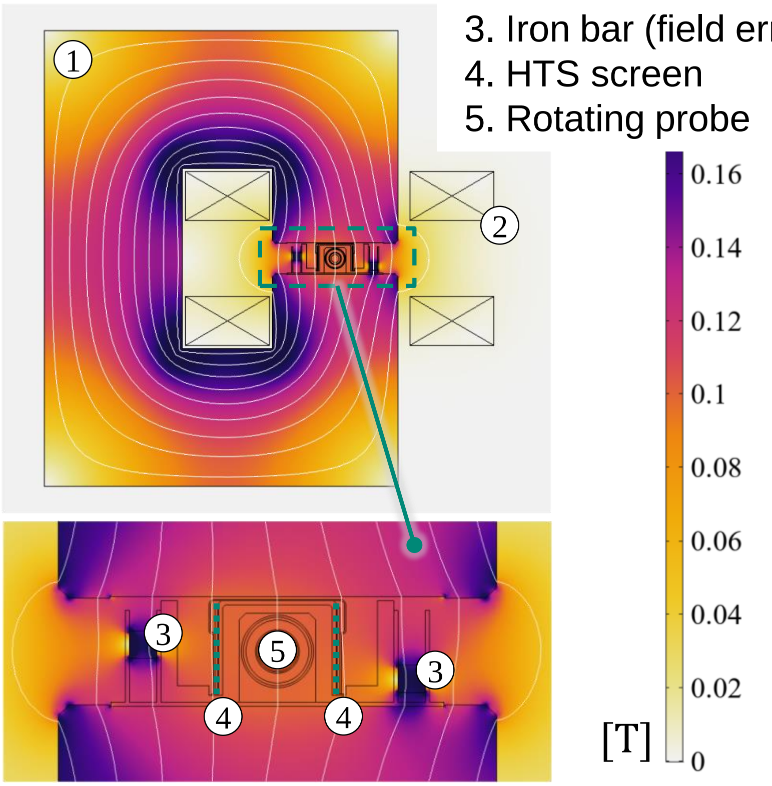
1. Magnetic field lines shaped by persistent screening currents
2. Cancellation only of undesired field components (static and dynamic)
3. Passive and self-regulating



Quasi-perfect electric wall

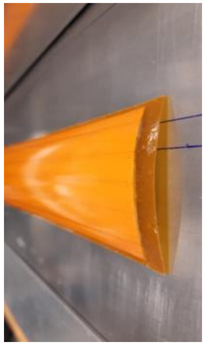
Proof of concept design

1. Iron yoke
2. Coil
3. Iron bar (field error)
4. HTS screen
5. Rotating probe

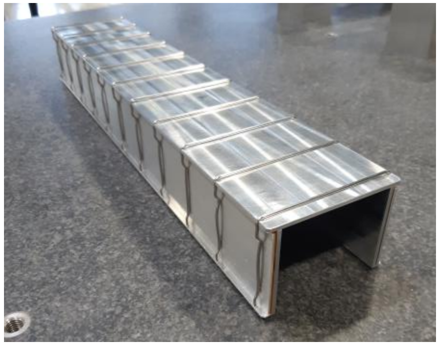


(D) PROTOTYPES DEVELOPMENT (2/2)

Experimental setup



HTS screen

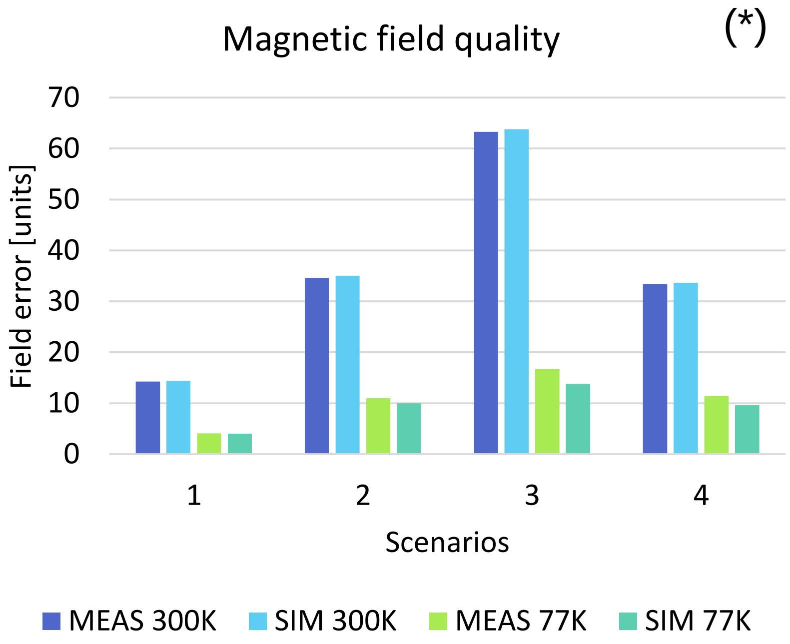


Screen holder

Experimental setup at cold

Experimental and numerical result

Magnetic field quality (total harmonic distortion) in the magnet aperture, without and with HALO



2~4 factor in field quality improvement

(*) L. Bortot et al., https://arxiv.org/abs/2103.14354 preprint.

CONCLUSIONS AND OUTLOOK

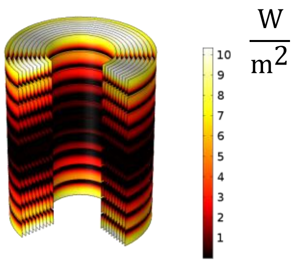
Conclusions

1. Transient effects in accelerators: **multi physics, scale and rate** phenomena
2. **Specialized models** + **Co-simulation** for multi rate problems
3. **A-H coupled field formulation** for superconductors
4. **High sensitivity** to tape parameters **characterization** of paramount importance

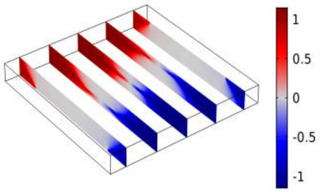
Outlook – HTS models

1. **Very Good understanding about 2D models**
   What is missing?
   What are the next challenges?

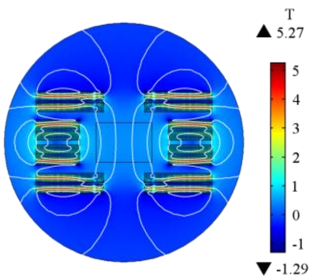
2. **Major challenge in full-scale 3D models**
   Brute-force (cluster computing)?
   Homogenization (anisotropic resistance)?



Ohmic loss distribution in a HTS solenoid



normalized induced current in a HTS bulk



Persistent magnetization in a block-coil dipole

Thank you for your attention!

Contact: lorenzo.bortot@cern.ch

Annex

HTS SOLENOID: CIRCUIT PARAMETERS

Parameter	Unit	Value	Description
$i_s(t)$	[A]	-	Source current
$v_{qh}(t)$	[V]	-	Capacitor voltage
S_{crow}	[-]	-	Crowbar switch
S_{qh}	[-]	-	Quench heater switch
R_{crow}	[μΩ]	175	Crowbar resistance
R_{cir1}	[μΩ]	25	Circuit resistance
R_{cir2}	[mΩ]	10	Circuit resistance
L_{cir1}	[μF]	10	Circuit Inductance
L_{cir2}	[μF]	500	Circuit Inductance
$R_m(T_{op})$	[nΩ]	<5	Coil quench resistance
$R_{qh}(T_{op})$	[Ω]	4.5	Quench heater resistance
$L_m(I_s)$	[μF]	50.7	Coil inductance
$L_{qh}(I_s)$	[μF]	2.7	Quench heater inductance
$M(I_s)$	[μF]	0.4	Mutual inductance

CONVERGENCE RATE

Definitions, at iteration i:

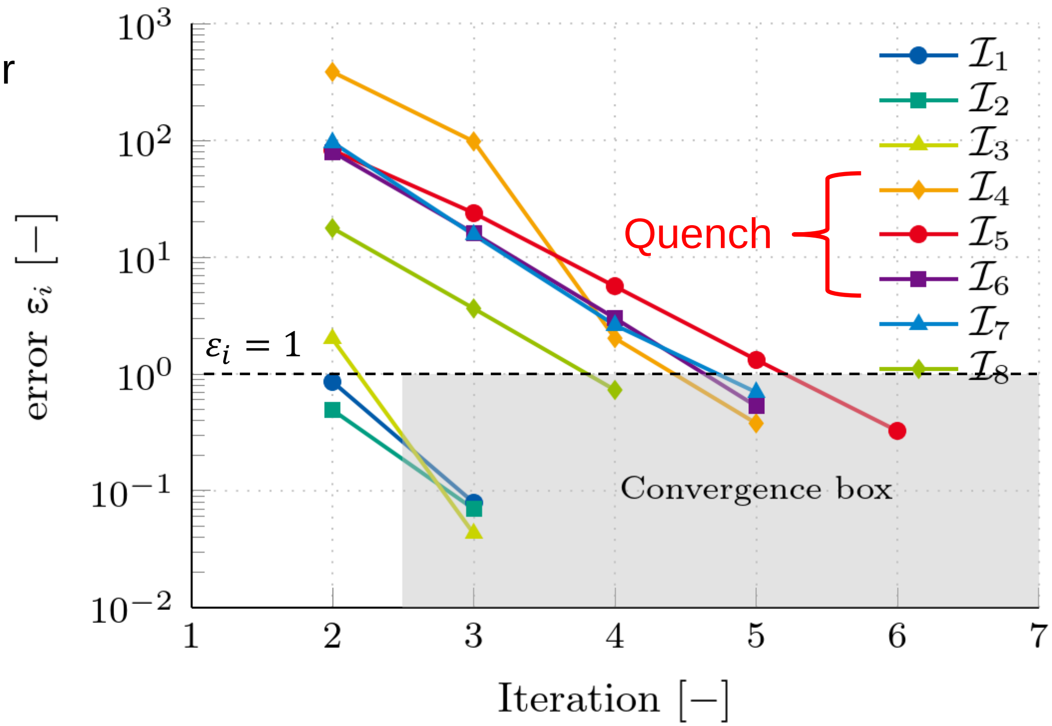
- x_i signal (current in the magnet)
- ε_{abs} ε_{rel} absolute & relative error
- ε_i convergence error
- $\mathrm{F_{conv}}$ convergence flag

$$\varepsilon_i = \max\left(\frac{|x_i - x_{i-1}|}{\varepsilon_{abs} + |x_i|\varepsilon_{rel}}\right), \quad i \geq 2$$

$$\mathrm{F_{conv}} = \begin{cases} 0, & \text{if} \quad i < 2 \\ \varepsilon_i < 1, & \text{if} \quad i \geq 2 \end{cases}$$

Enforcement of at least three iterations per time window

$\varepsilon_{abs} = 0.001$
$\varepsilon_{rel} = 0.25$



Quench as abrupt change in resistivity
→ High influence on the solenoid current
→ More iterations needed!