How to Computationally Determine the Maximum Stable Operation Current of an HTS Magnet

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Outline

- Background
- Observation
- Vision
- Concretization
- Solution
- Summary

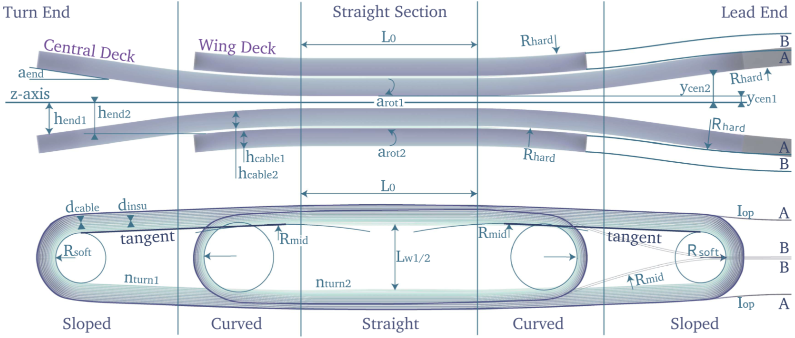
Background
Introduction

- Feather-M2.1-2: One of the world's first HTS dipole magnets (2017)
- The goal was to study the performance of Roebel type HTS cable
- Designed and constructed in the framework of EUCARD2 WP10.3 at CERN
- The test results are reported in [1]

[1] J. van. Nugteren *et al*, "Powering of an HTS dipole insert-magnet operated standalone in helium gas between 5 and 85 K" *Supercond. Sci. Technol.* vol. 31, no. 6, 2018, Art. ID. 065002.

Background

Feather-M2 geometry

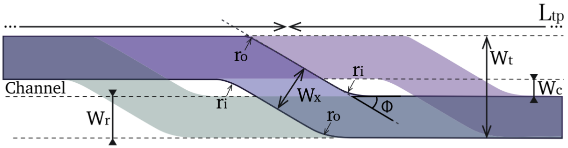


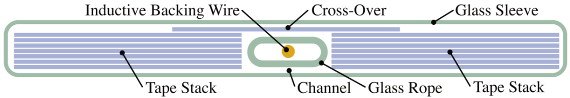
Description	Value
Magnet length	0.8 m
Total cable length	37 m
#turns in central deck	8
#turns in wing deck	4
Magnet self-inductance	166 μH
Stored energy at 6 kA/ 3 T	2.9 kJ

Background

Roebel cable

- REBCO tapes manufactured by Sunam
- Roebel cable assembly by SuperOx





Description	Value
Number of tapes	15
Total tape length	15×37 m = 555 m
Width	12 mm
Thickness	1.2 mm
Insulation thickness	0.1 mm

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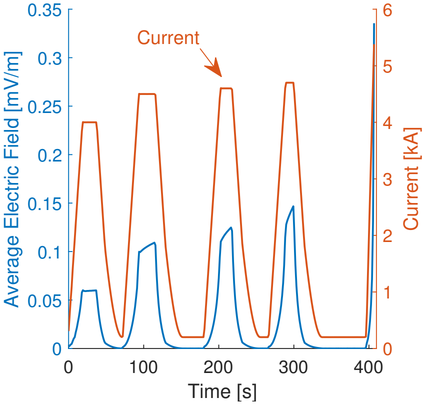
Observation

Experimental data from the Feather-M2 test performed at CERN

- Cooling: Forced flow helium gas ($T_{\mathrm{op}} = 21$ K)



E_0 [μV/m]	I_{c} [kA]
10	1.7
50	3.7
100	4.5

- What is the critical current (I_{c}) of this magnet?

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Vision

A need has risen:
Determine the maximum stable operation current for HTS magnets

- For LTS magnets I_c corresponds to the maximum current (high n-value)
- Feather-M2 was reported to correspond to n-values between 2.5-6
  - Current sharing inside the multi-strand cable
  - Cooling conditions
- What kind of definition for the maximum current would make more sense in case of HTS magnets than I_c?
- Essentially we want to determine **the maximum stable operation current for HTS magnets**

Vision

An idea: When is a magnet thermally stable?

- Intuition: **Cooling is greater** than **heat generation** over the magnet volume
- The maximum stable I_{op} can be found when cooling and heat generation are in balance
- What is needed to determine whether an operation current results in stable magnet operation or not?
  - A simulation tool that is capable of predicting thermodynamics in a system consisting of an HTS magnet and its cooling environment
  - A simulation platform equipped with a nonlinear optimization toolbox

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Concretization

Thermal model: Formulation

- Modelling decision: T homogeneous in the cable's cross-section
  - Heat generation in two fractions: Superconducting (sc) and normal conducting (nc)
  - The currents I_{sc}, I_{nc} are solved from

$$\begin{aligned} E_{\mathrm{sc}} &= E_{\mathrm{nc}} \\ I_{\mathrm{op}} &= I_{\mathrm{sc}} + I_{\mathrm{nc}} \end{aligned}$$

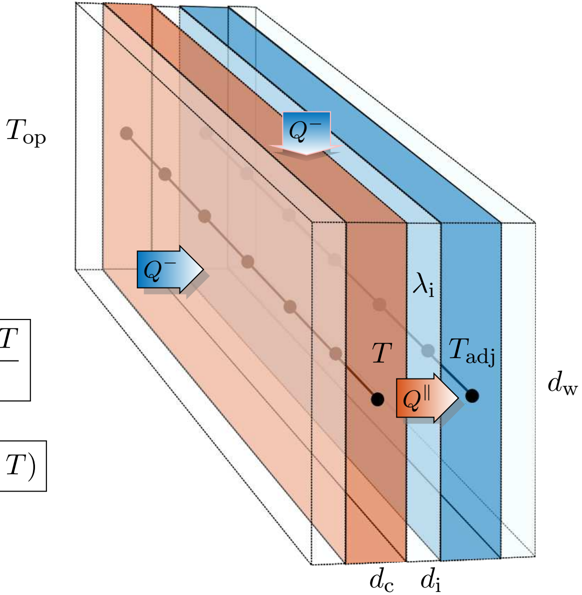
- Formulation of the thermal model

$$C_{\mathrm{V}} \frac{\mathrm{d}}{\mathrm{d}t} T = \frac{\mathrm{d}}{\mathrm{d}x}\left(\lambda \cdot \frac{\mathrm{d}}{\mathrm{d}x} T\right) + Q^{+} + Q^{-} + Q^{\parallel}$$

$$\begin{aligned} Q^{+} &= f_{\mathrm{sc}} \cdot E_{\mathrm{sc}} J_{\mathrm{sc}} + f_{\mathrm{nc}} \cdot E_{\mathrm{nc}} J_{\mathrm{nc}} \\ &= f_{\mathrm{sc}} \cdot E_0 \left(\frac{I_{\mathrm{sc}}}{\alpha \cdot I_{\mathrm{c}}(T, B, \theta)}\right)^{n} J_{\mathrm{sc}} + f_{\mathrm{nc}} \cdot \rho_{\mathrm{nc}} J_{\mathrm{nc}}^2 \end{aligned}$$

Concretization

Thermal model: Cooling & Thermal coupling between the cable turns

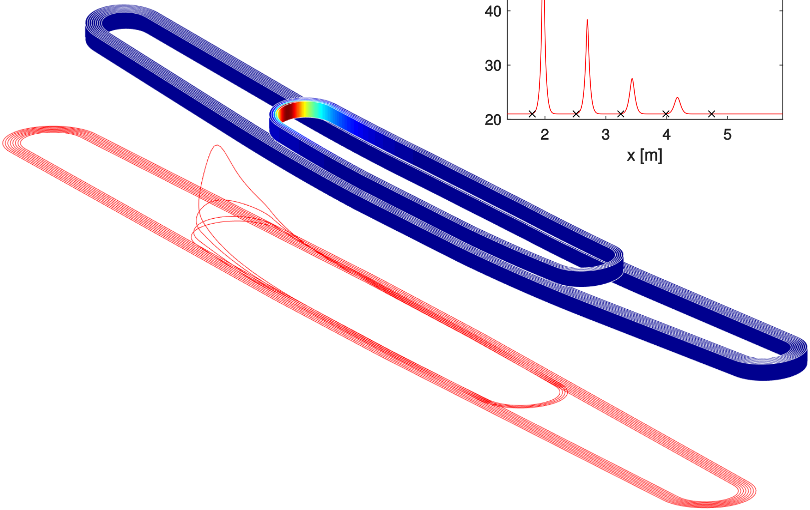


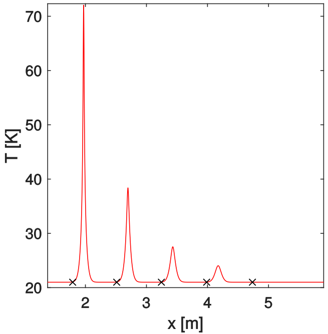
$$\boxed{Q^{\parallel} = \lambda_{\text{i}} \frac{T_{\text{adj}} - T}{d_{\text{i}}}}$$

$$\boxed{Q^{-} = h(T_{\text{op}} - T)}$$

Concretization

Thermal model: Visualization





Concretization

Thermal model: Uncertainties

- Some properties of the system are unknown or challenging to measure directly
- The thermal model is parametrized for E_0, α, n and h.
- The uncertain parameters can be determined by solving an inverse problem formulated as an optimization task

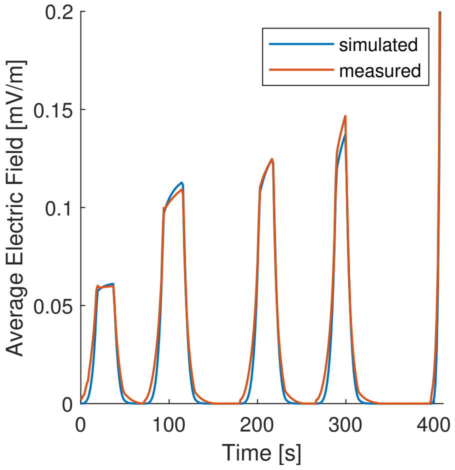
$$\min_{E_0,\alpha,n,h} \quad \int_{t_1}^{t_2} E_{\mathrm{m}}(t) - E_{\mathrm{s}}(t)\mathrm{d}t$$

Table 1: Optimal parameters

parameter	value	unit
E_0	110	μV/m
α	1.8	
n	2.92	
h	86.2	W/m^2

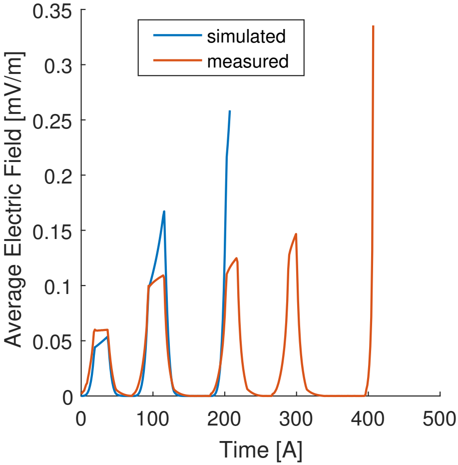
Concretization

Thermal model: Comparing simulation results with the measurements



Concretization

Thermal model: No cooling



Concretization

Defining stable operation current

- Heat generation P in the winding volume Ω:

$$P(t) = \int_{\Omega} Q^{+} \, \mathrm{d}\Omega \ [\mathrm{W}]$$

- Cooling capacity C over the magnet surface $\partial\Omega$:

$$C(t) = \int_{\partial\Omega} Q^{-} \, \partial\Omega \ [\mathrm{W}]$$

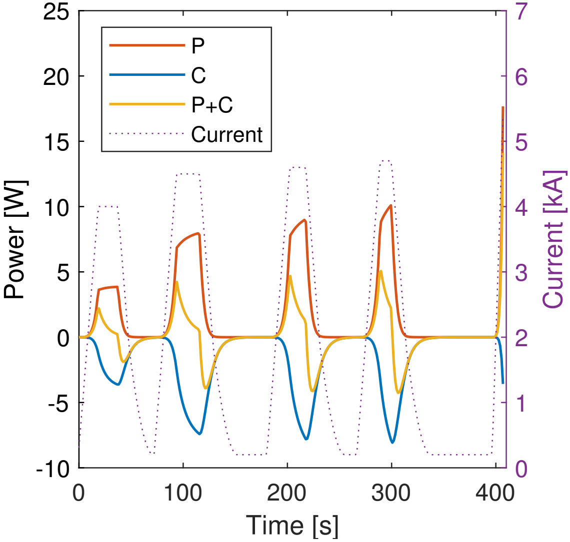
Definition

A constant operation current I, **is a stable operation current** iff the cooling power is greater or equal to the heat generation when $t \to \infty$, that is

$$\lim_{t\to\infty} (P + C)(t) \quad \leq \quad 0$$

Concretization

Investigating the interplay between heat generation and cooling



Concretization

Finding the maximum stable operation current

- An approximation of the previous **Definition**:
  - Simulation time limit, t_0, has a finite value
  - The time-derivative is included as a short term forecast of the power balance evolution
  - The search space is constrained by
    1. The time-derivative of $(P + C)$: Equal to zero or negative
    2. Cooling: Greater or equal to generated heat

The maximum stable operation current can be found by solving the optimization problem

$$\begin{array}{rrcl} \max\limits_{I} & I & & \\ \text{s.t.} & \frac{d}{dt}\left(P(t) + C(t)\right)_{t=t_0} & \leq & 0 \\ & P(t_0) + C(t_0) & \leq & 0 \end{array}$$

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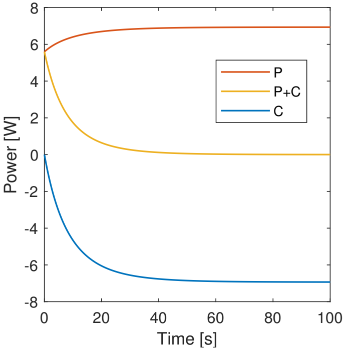
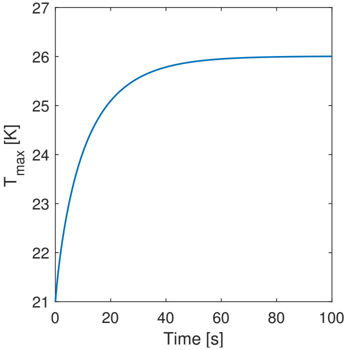
Solution

The maximum stable operation current

- For the simulation time limit of 100 s, the maximum stable operation current is 4394 A





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- We demonstrated how an observation can lead to concreteness guided by a vision and creativity
- A definition for the maximum stable operation current for HTS magnet was proposed
- A methodology was presented for determining the maximum stable operation current
- Cooling is important to take into account in thermal simulations
- I_c of an HTS magnet is a somewhat arbitrary quantity