Magnetic Field Error Cancellation with HTS-Based Magnetic Screens

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Outline

1. Motivation and Theoretical Background
2. Magnetic Field Quality in Accelerator Magnets
3. Persistent Magnetization in HTS Tapes
4. HTS-Based Magnetic Screens
5. Numerical Simulations
6. Conclusions and Next Steps
What if future particle accelerators will be based on HTS magnets?

**Topic:**
Numerical methods for large-scale superconducting technologies

**Research question:**
Transient effects in HTS accelerator magnets, with emphasis on:
- Quench protection
- Magnetic field quality

Feather M2 magnet. Left: Magnetic flux density. Right: current density distribution in the coil
Introduction (2/2) - Theoretical Background

Formulation
Coupled $\textbf{A}$-$\textbf{H}$ field formulation for time-domain analysis of HTS magnets [*]

Domain decomposition:
- $\textbf{A}$ (Wb/m) where $\sigma \to 0$ (e.g. air, iron)
- $\textbf{H}$ (A/m) where $\rho \to 0$ (e.g. coils)

Numerical Validation
Magnetic field quality analysis in the HTS dipole insert-magnet Feather M2

Simulations (●) VS Experiments (---)

Finite material properties $\rightarrow$ solver stability

Very good agreement

Magnetic field Quality in Accelerator Magnets

**Importance:** Stability of particle beams

**Influence factors:** mechanical tolerances, dynamic effects, iron saturation, **persistent magnetization**

**Quantification:** Magnetic field as multipole series expansion, with $A_i, B_i$ skew and normal multipoles

**Example:** dipole magnet
- $B_1$ dipole field, $(A_{m \geq 1}, B_{n \geq 2})$ field error

**Total Harmonic Distortion:**

$$\text{THD}_1 = 1e^{-4} \left( \sum_{m=1}^{\infty} A_m^2 + \sum_{n=2}^{\infty} B_n^2 \right)^{\frac{1}{2}} B_1$$

Magnetic field representation by means of a multipole series expansion
Issue: Persistent Magnetization in Superconductors

Superconducting coil in a changing magnetic field $\partial_t B$

- Screening currents $J_{\text{screen}}$
- Screening magnetic field $B_{\text{screen}}$
- $\sigma \to +\infty \rightarrow$ no decay $\rightarrow$ persistent magnetization

Smaller filaments $\rightarrow$ smaller $B_{\text{screen}}$

Coils made of HTS tapes:

- Wide filaments, 4-12 mm $\rightarrow$ ~1000x more than in Nb-Ti / Nb$_3$Sn strands!
- Significant $B_{\text{screen}}$
- Magnetic field quality degradation, especially at low current

$\rightarrow$ Potential showstopper for accelerator magnets
.. but the Problem may also be the Solution!

**Thin layer approximation:**
High aspect ratio (~1000), HTS thickness neglected

**Observation:**
Selective field-cancellation

**Example:**
Selective field-cancellation for dipole field

HTS tapes can shape the magnetic field!
Magnetic Field Error Cancellation

Idea
HTS-based magnetic screen for magnetic field errors in the magnet aperture

Key Features

- Tapes aligned with main magnetic field component
- Persistent magnetization $\rightarrow$ screening of field errors
- Brick wall geometry $\rightarrow$ effective tape width increased
- Passive device

HALO: Harmonics-Absorbing Layered Object
Proof Of Concept

Key Ingredients:
1. Reference magnetic field
2. Source of magnetic field error
3. Correction of the magnetic field error

→ Differential field quality measurement

Normal conducting dipole MCB22
@ Magnetic Measurement Lab (Bdg. 311), CERN

Cryogenic box @ 77 K (liquid N$_2$)
Currently under construction
Proof Of Concept (cont’d)

Cross sectional view of the rotating probe and the magnetic screen

- **Slots for the magnetic screen (field correction)**
- **Iron bars (field error)**
- **Holder**
- **Magnetic screen**
  - (18 meters of HTS tape)

- 62 mm
- 86 mm
- 40 mm
Simulations: Magnetic field in the HB2 Dipole

Magneto-quasistatic analysis

- 100 mT peak field in the aperture
- 10 A/s ramp rate, then plateau
Simulations: Magnetic Screen Baseline Design

Simulation of field quality (*) for:
- Iron bars scenario → field error
- Magnetic Screen scenario → field correction

Comparison of field quality: Magnetic field multipoles

> 80% reduction of total harmonic distortion

(*) Care needs to be taken in FEM. Mesh sensitivity analysis has been carried out.
Simulations: Magnetic Screen Optimized Design

Optimization

• ↑↑↑ Increased no. of layers $\rightarrow$ Compensation for skew multipoles $a_i$
• ↑↑↑ Increased no. of tapes per layer $\rightarrow$ Compensation for normal multipoles $b_i$

![Graph showing the relationship between number of layers and THD](image)

Significant reduction of the field error!
Conclusions and Next Steps

Use of HTS tapes in accelerator magnets:
→ Magnetic field quality errors (especially at low current) due to persistent magnetization

HTS-based magnetic screens for magnetic field correction
→ Passive device to cancel undesired field multipole components in the magnet aperture

Next Steps
1. Finalization of the first magnetic screen prototype
2. Experimental campaign, performance analysis
3. Prototype within an accelerator magnet

Thank you for your attention!
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Annex
Simulations: Magnetic Screen Baseline Design

Comparison of field quality (*) in:
- Iron bars scenario → field error
- Magnetic Screen scenario → field correction

- Iron bars scenario
- Magnetic Screen scenario

> 80% reduction of total harmonic distortion

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