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Magnetic Field Error Cancellation with HTS-Based Magnetic Screens

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STEAM

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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

Introduction (1/2) - Motivation

What if future particle accelerators will be based on HTS magnets?

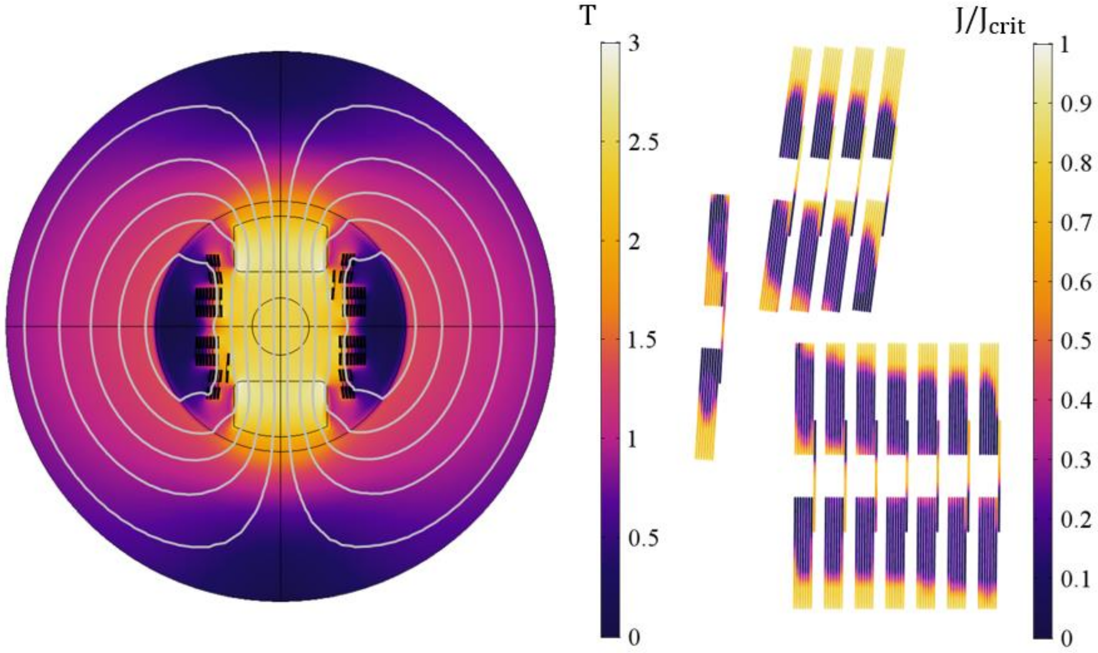
Topic:

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

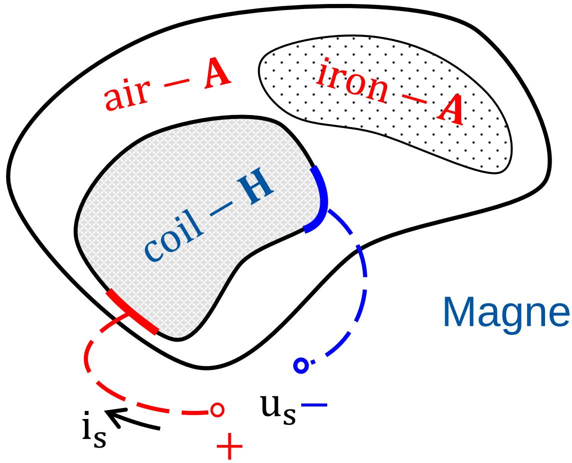
Introduction (2/2) - Theoretical Background

Formulation

Coupled **A-H** field formulation for time-domain analysis of HTS magnets [*]

Domain decomposition:

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



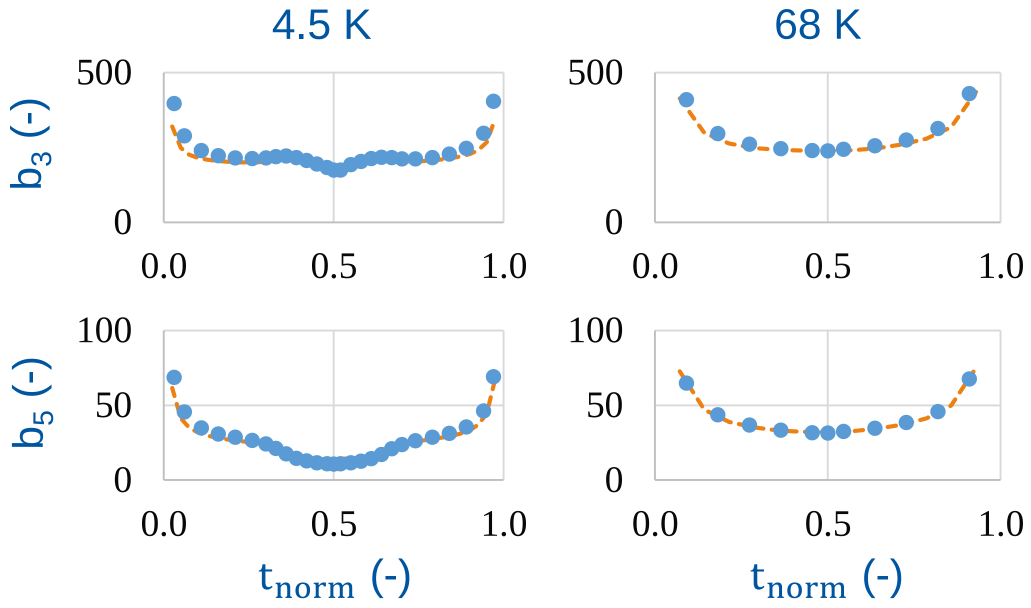
Magnet topology

Finite material properties → solver stability

Numerical Validation

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

Simulations (●) VS Experiments (- - -)



Very good agreement

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[*] Bortot, Lorenzo, et al. "A Coupled AH Formulation for Magneto-Thermal Transients in High-Temperature Superconducting Magnets." *arXiv preprint arXiv:1909.03312* (2019). Presented at COMPUMAG 2019.

Magnetic field Quality in Accelerator Magnets

Importance: Stability of particle beams

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

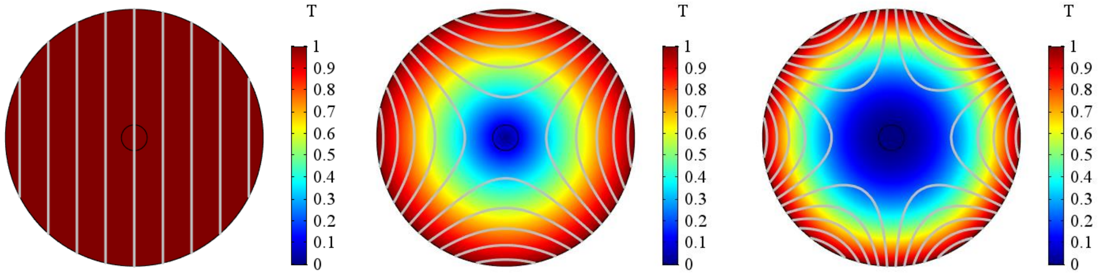
Quantification: Magnetic field as multipole series expansion, with $\mathrm{A}_i, \mathrm{B}_i$ skew and normal multipoles

Example: dipole magnet

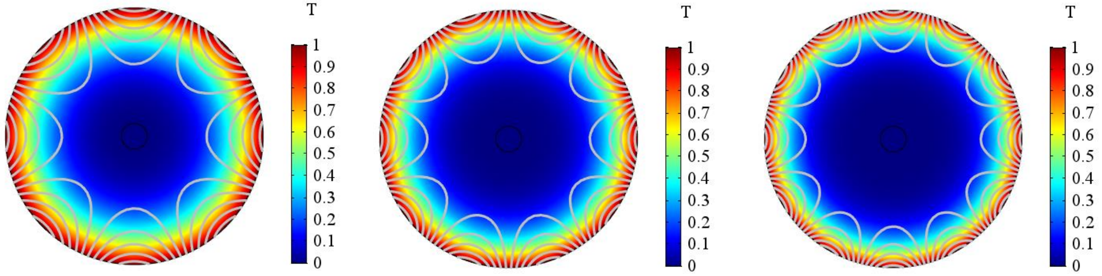
- B_1 dipole field, $(\mathbf{A}_{m\geq 1}, \mathbf{B}_{n\geq 2})$ **field error**

Total Harmonic Distortion:

$$\mathrm{THD}_1 = 1e^{-4} \frac{\left(\sum_{m=1}^{+\infty} \mathrm{A}_m^2 + \sum_{n=2}^{+\infty} \mathrm{B}_n^2\right)^{\frac{1}{2}}}{\mathrm{B}_1}$$



B_1 dipole B_2 quadrupole B_3 sextupole



B_4 octupole B_5 decapole B_6 dodecapole

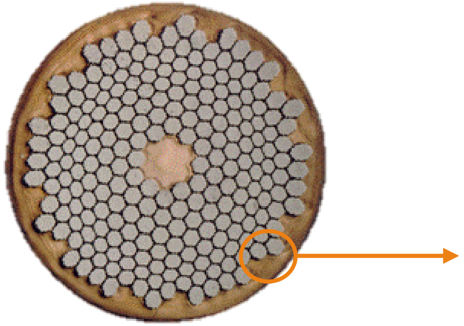
Magnetic field representation by means of a multipole series expansion

Issue: Persistent Magnetization in Superconductors

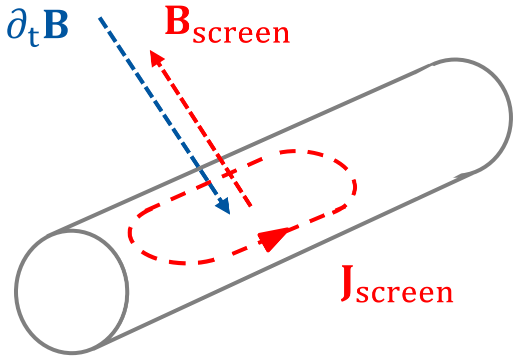
Superconducting coil in a changing magnetic field $\partial_t \mathbf{B}$

- Screening currents $\mathbf{J}_{\mathrm{screen}}$
- Screening magnetic field $\mathbf{B}_{\mathrm{screen}}$
- $\sigma \to +\infty$ → no decay → persistent magnetization

Smaller filaments → smaller $\mathbf{B}_{\mathrm{screen}}$



Example:
LHC Nb-Ti strand



Filament magnetization

Coils made of **HTS tapes**:

- Wide filaments, 4-12 mm → **~1000x more than in Nb-Ti / Nb_3Sn strands!**
- Significant $\mathbf{B}_{\mathrm{screen}}$
- **Magnetic field quality degradation**, especially at low current

→ Potential showstopper for accelerator magnets

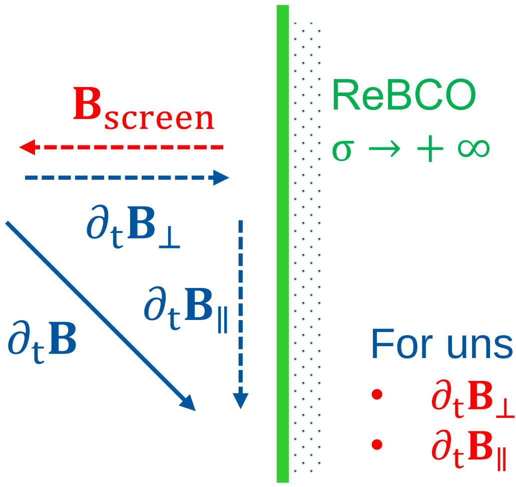
.. but the Problem may also be the Solution!

Thin layer approximation:

High aspect ratio (~1000), HTS thickness neglected

Observation:

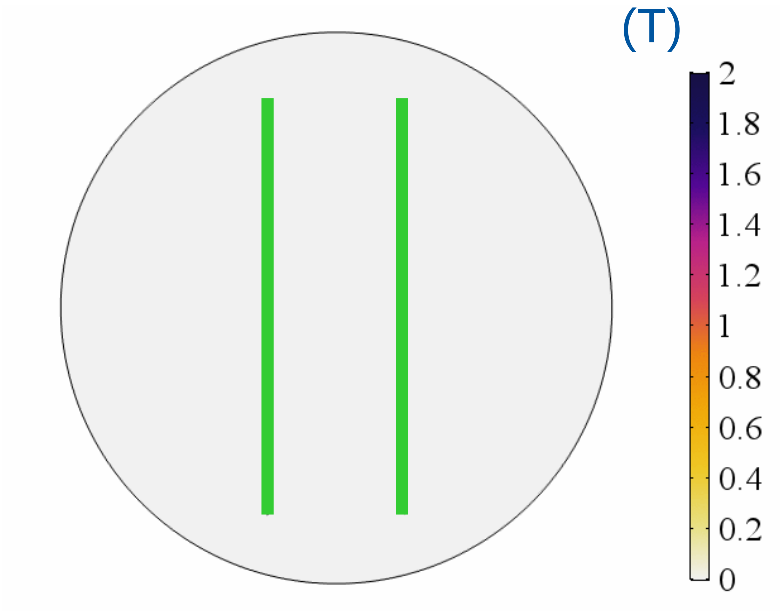
Selective field-cancellation



For unsaturated tapes:
- $\partial_t \mathbf{B}_\perp$ is canceled
- $\partial_t \mathbf{B}_\parallel$ is unchanged

Example:

Selective field-cancellation for dipole field



ReBCO tapes in external magnetic field

HTS tapes can shape the magnetic field!

Magnetic Field Error Cancellation

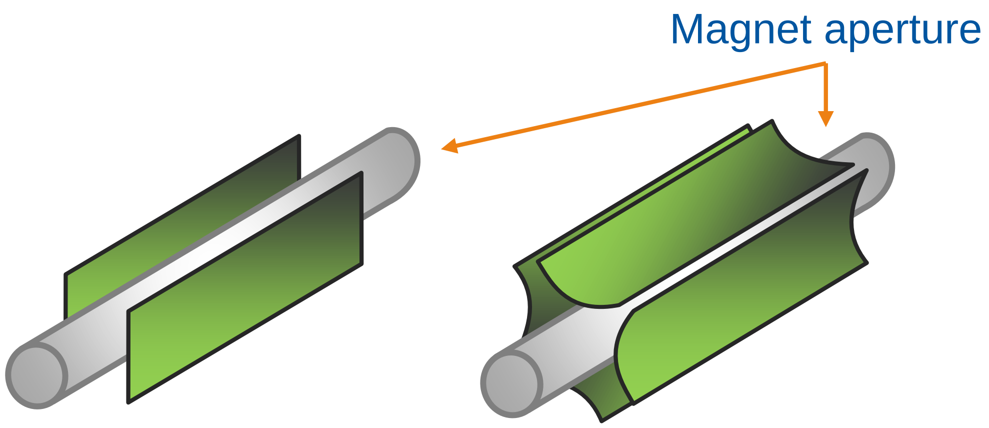
Idea

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

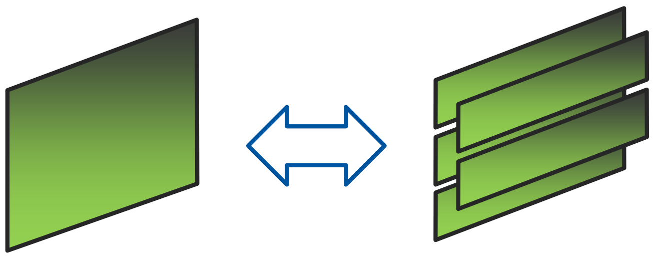
Key Features

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

HALO: **H**armonics-**A**bsorbing **L**ayered **O**bject



Screens for dipoles (left) and quadrupoles (right)



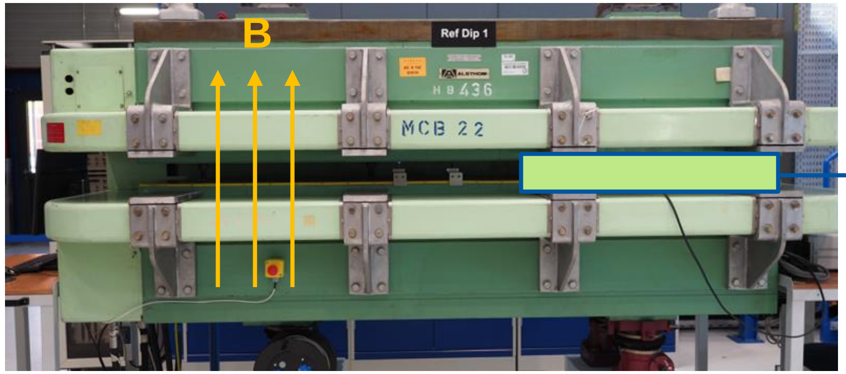
Brick wall geometry

Proof Of Concept

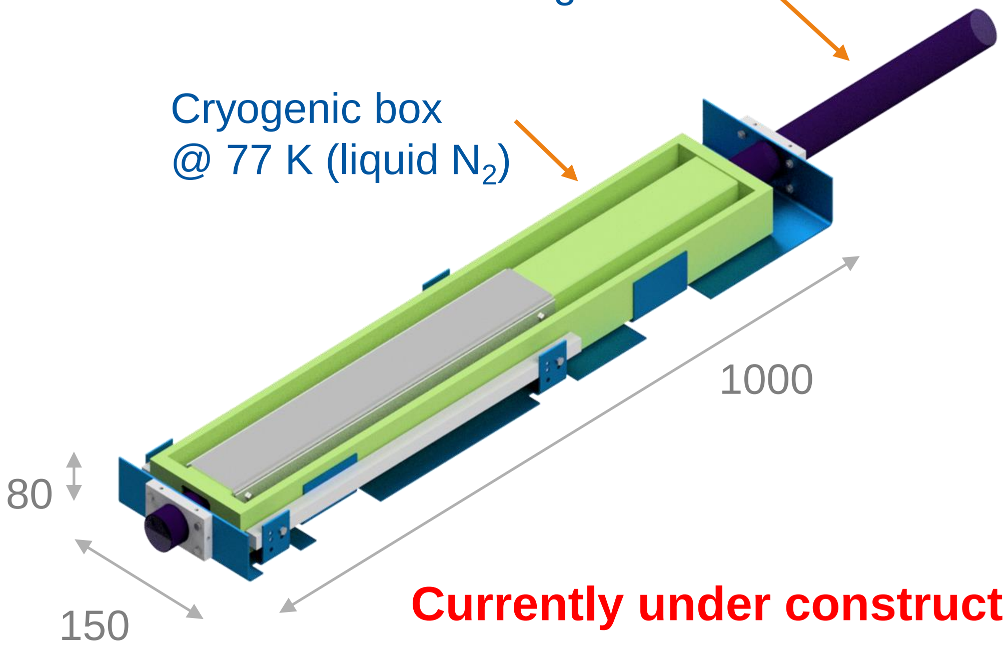
Key Ingredients:

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

→ Differential field quality measurement

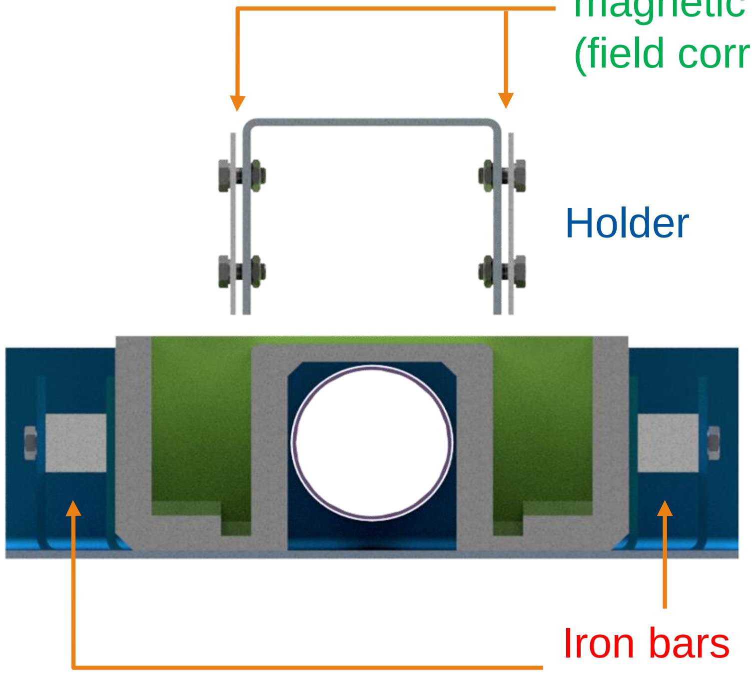


Normal conducting dipole MCB22
@ Magnetic Measurement Lab (Bdg. 311), CERN



Currently under construction

Proof Of Concept (cont’d)

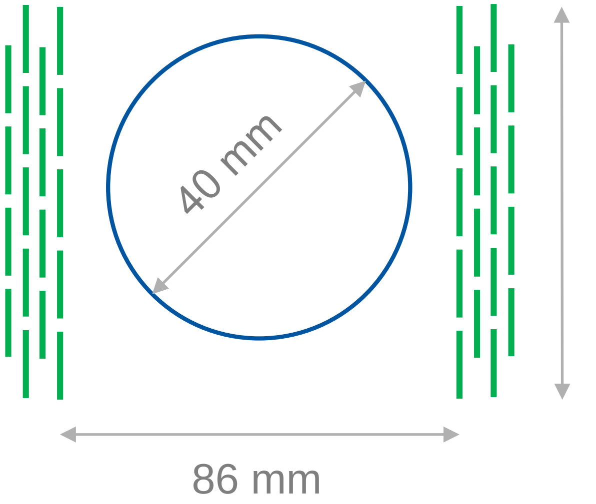


Slots for the magnetic screen (field correction)

Holder

Iron bars (field error)

Cross sectional view



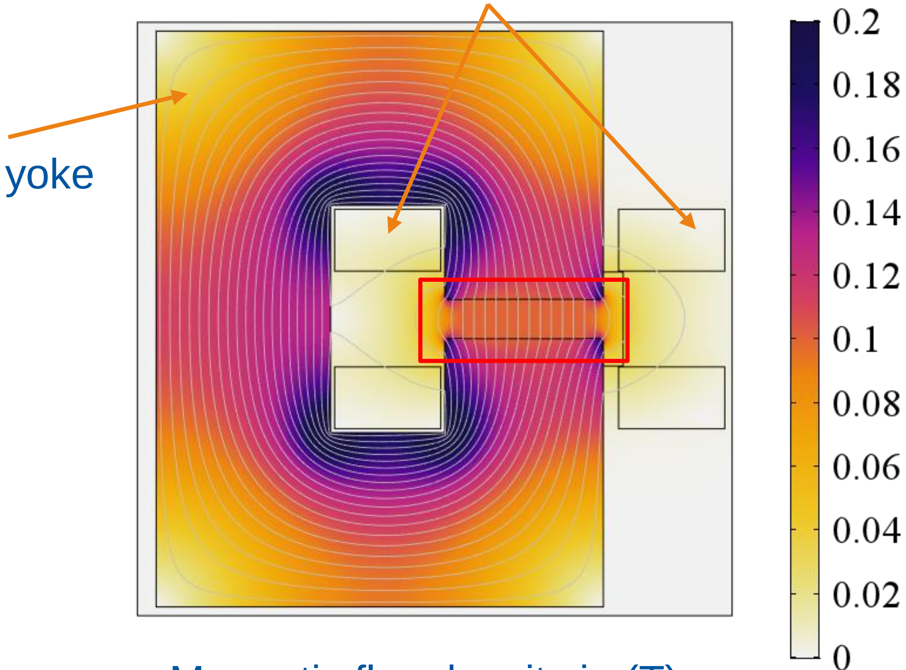
magnetic screen
(18 meters of HTS tape)

Cross sectional view of the rotating probe and the magnetic screen

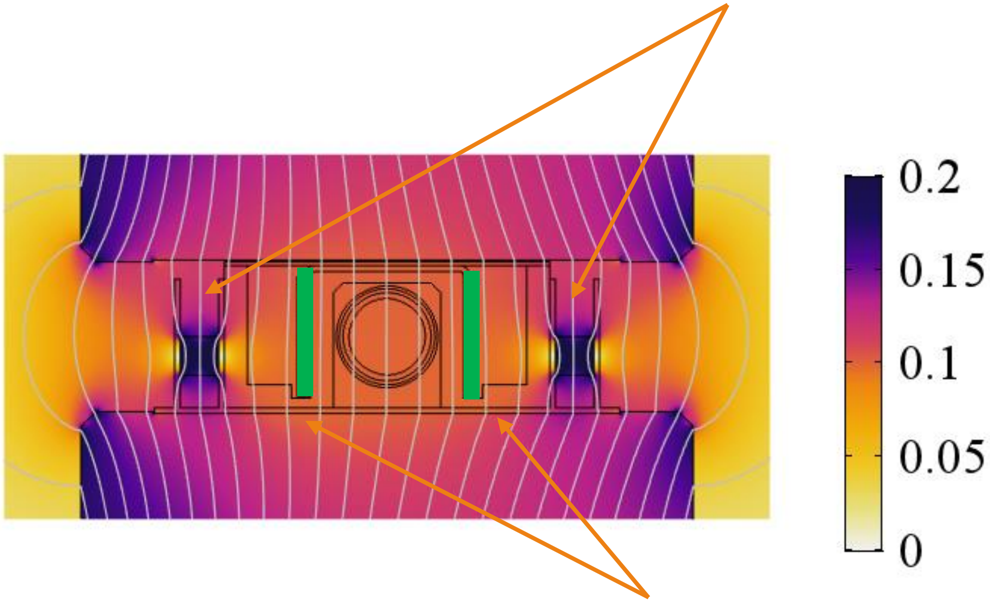
Simulations: Magnetic field in the HB2 Dipole

Magneto-quasistatic analysis

- 100 mT peak field in the aperture
- 10 A/s ramp rate, then plateau



Magnetic flux density in (T)

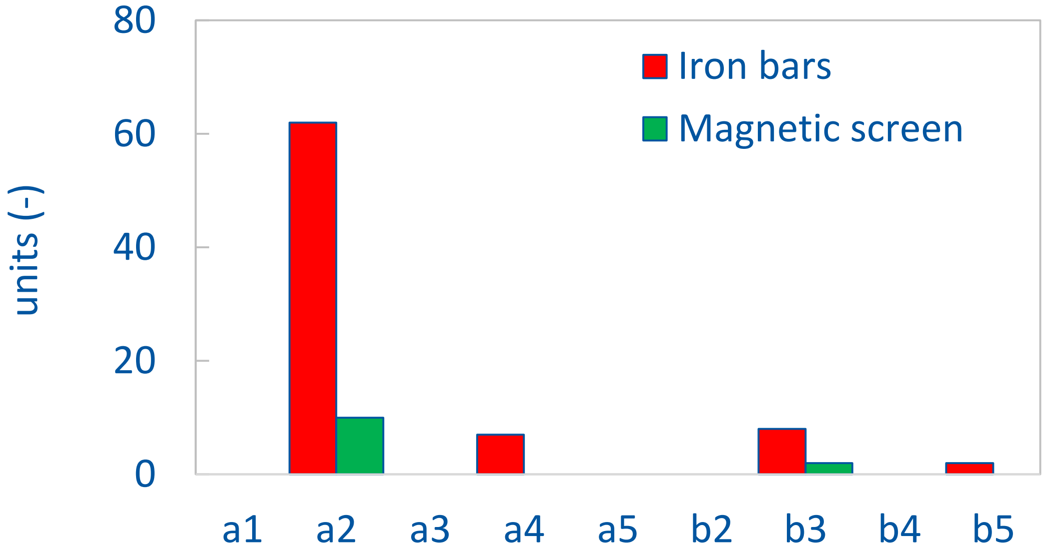


Magnetic flux density in (T) in the magnet aperture, with iron bars

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

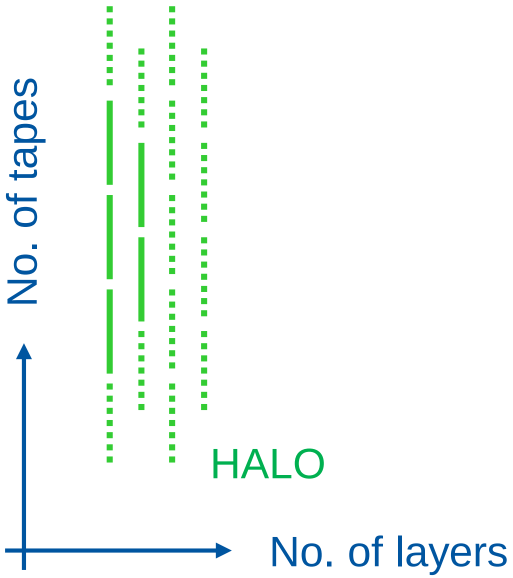
> 80% reduction of total harmonic distortion

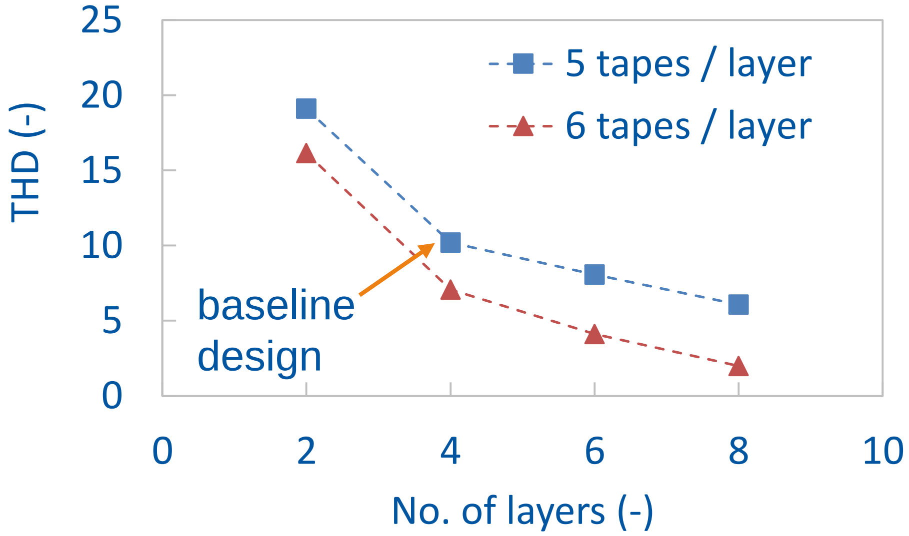
(*) Care needs to be taken in FEM. Mesh sensitivity analysis has been carried out.

Simulations: Magnetic Screen Optimized Design

Optimization

- ↑↑↑ Increased no. of layers → Compensation for skew multipoles a_i
- ↑↑↑ Increased no. of tapes per layer → Compensation for normal multipoles b_i





Significant reduction of the field error!

Conclusions and Next Steps

Use of HTS tapes in accelerator magnets:

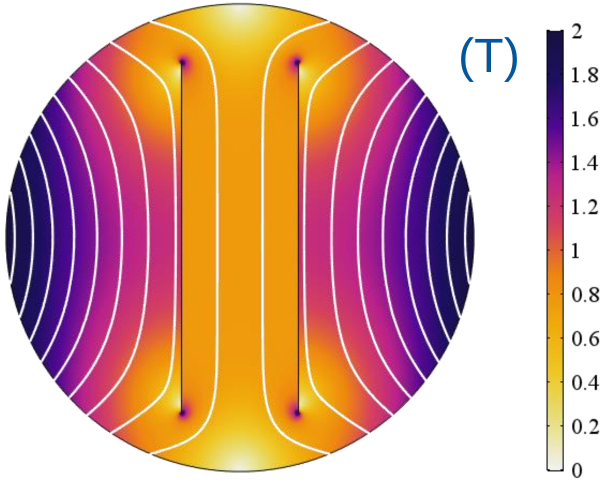
→ Magnetic field quality errors (especially at low current) due to persistent magnetization

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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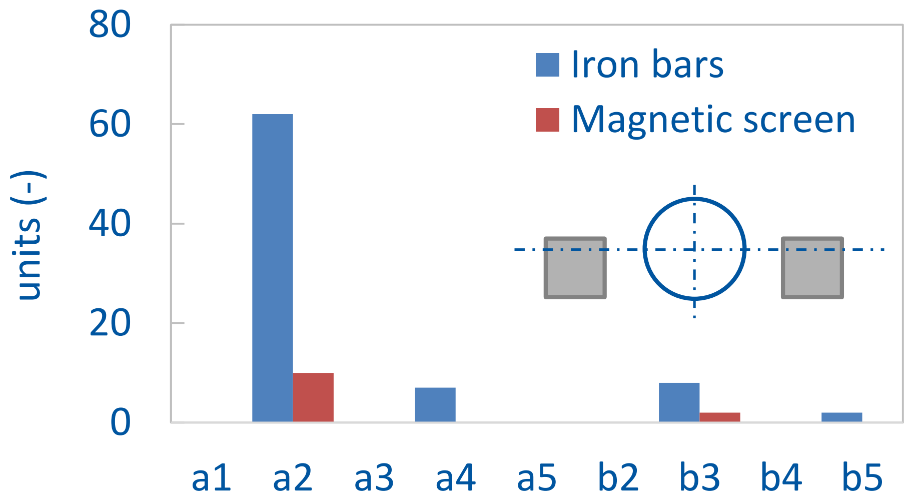
Annex

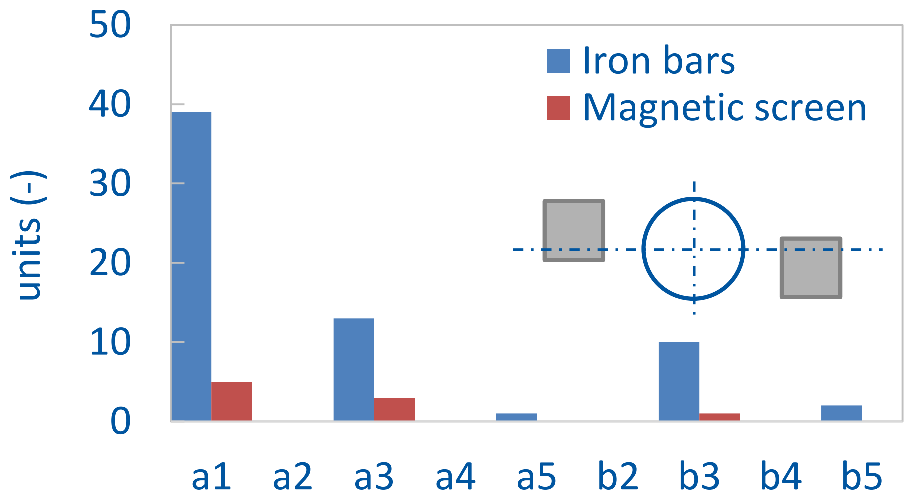
Simulations: Magnetic Screen Baseline Design

Comparison of field quality (*) in :

- Iron bars scenario → field error
- Magnetic Screen scenario → field correction



Magnetic field multipoles.
Iron bars in symmetric configuration



Magnetic field multipoles
Iron bars in non symmetric configuration

> 80% reduction of total harmonic distortion

(*) Care needs to be taken in FEM. Mesh sensitivity analysis has been carried out.