TE-MPE-PE Section Meeting

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HTS Screens for Field-Error Cancellation: Preliminary Experimental Results and Lessons Learnt

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STEAM

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Outline

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    a. Magnetic Field Quality in Accelerator Magnets
    b. Persistent Magnetization in HTS Tapes
    c. HTS-Based Magnetic Screens
2. Experimental Setup
3. Experimental and Simulation Results
    a. Measurements
    b. Analysis
    c. Numerical Extrapolation
4. Lessons Learnt, Conclusions and Next Steps

Introduction

Experimental Setup

Experimental and Simulation Results

Magnetic field Quality in Accelerator Magnets

Relevance: Stability of particle beams

Influence factors: Construction tolerances, dynamic effects (e.g., inter-filament coupling currents), iron, persistent magnetization

Quantification: Magnetic field multipole expansion

Normal B_i and skew A_i multipoles

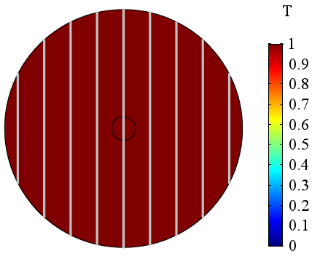
Example: dipole magnet

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

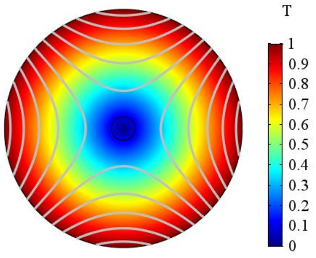
Total Harmonic Distortion Index:

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

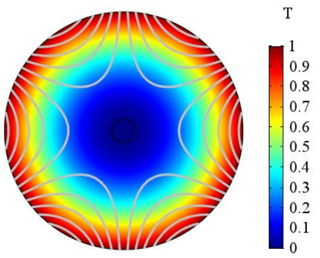
Good $\mathrm{THD}_1 < 10$



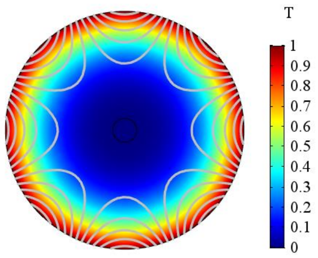
B_1 dipole



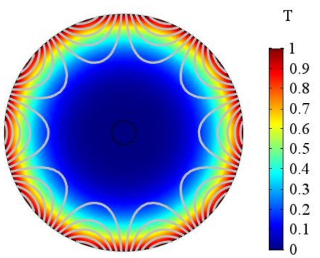
B_2 quadrupole



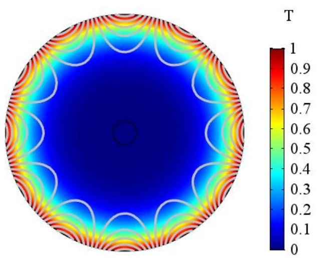
B_3 sextupole



B_4 octupole



B_5 decapole



B_6 dodecapole

Persistent Magnetization

Example:
HTS tape in a time-dependent magnetic field

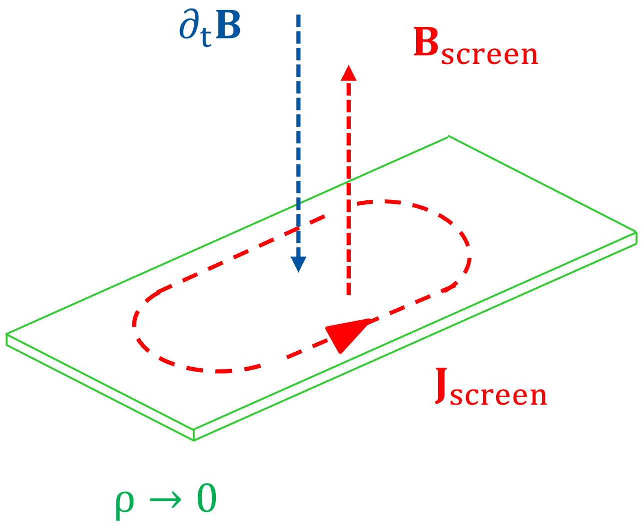
Field variation $\partial_t \mathbf{B}$:

- Screening (eddy) currents $\mathbf{J}_{\text{screen}}$
- Screening magnetic field $\mathbf{B}_{\text{screen}}$

Superconducting material $\rho \rightarrow 0$:

- $\mathbf{J}_{\text{screen}}$ time constant $\rightarrow \infty$
- $\mathbf{B}_{\text{screen}}$ due to persistent magnetization

Coils made of HTS tapes:
→ wide filaments (4~12 mm)
→ Significant $\mathbf{B}_{\text{screen}}$
→ Magnetic field quality degradation, especially at low current ($J_{\text{screen}} \gg J$)

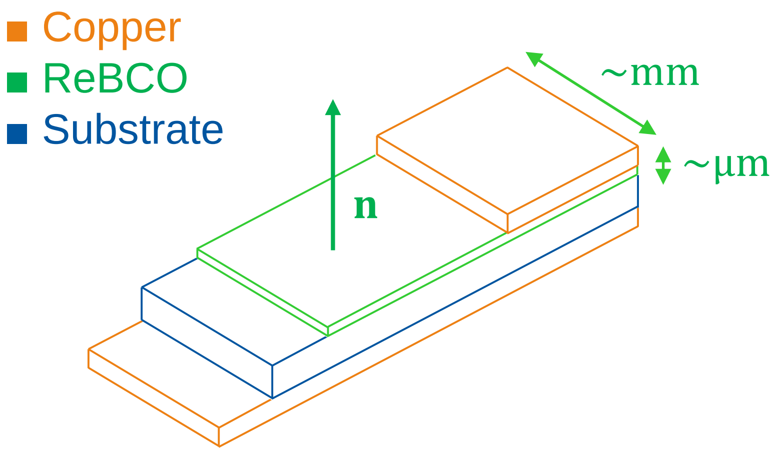


Superconducting tape in a magnetic field

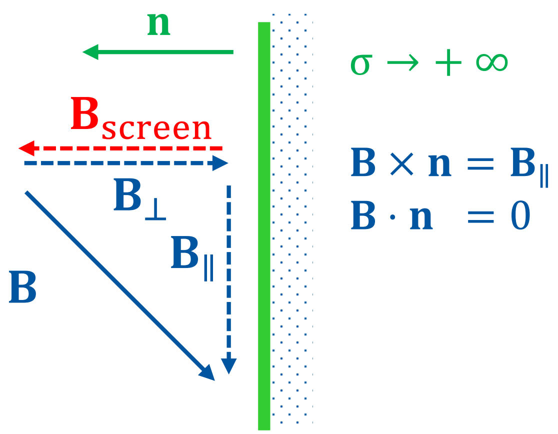
Perfect Electric Wall-Like Behaviour

Features of HTS tapes:

- high conductivity, $\sigma \to +\infty$
- high aspect ratio, ~ 1000



HTS tape layout



HTS tape seen as perfect electric wall

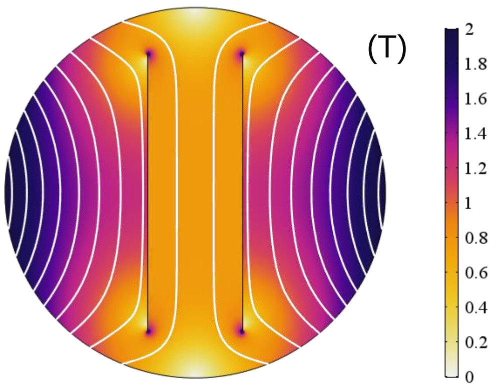
Persistent magnetization → HTS tapes behavior similar to a perfect electric wall

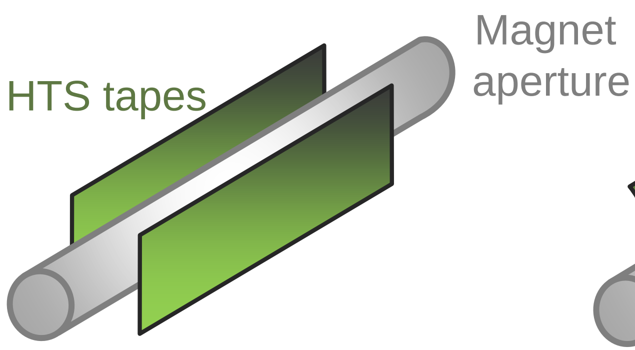
Magnetic Field Error Cancellation (1/2)

Our proposal:

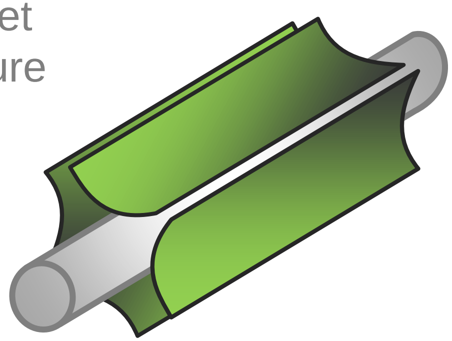
HALO - **H**armonics-**A**bsorbing **L**ayered **O**bject

1. Magnetic field lines shaped by screening currents
2. Orientation with the main field component (e.g. dipole)
3. Selective cancellation of undesired field components
4. Brick wall architecture → wider screening surface
5. Passive device

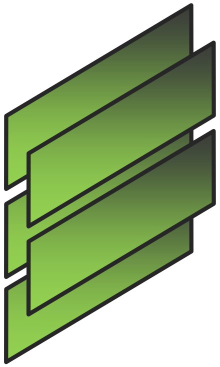




Dipole-field screen



Quadrupole-field screen



Brick wall architecture

Magnetic Field Error Cancellation (2/2)

Field homogeneity sought in many applications (beyond accelerator magnets):

1. Solenoids for fusion reactors
2. Hollow electron lenses
3. MRI and NMR machines
4. MHD systems in hypersonic aircraft
5. Hadron therapy

Relevant research (known up to date):

1. Magnetic cloaks for sensors [1,2]
2. Shim coils for MRI [3] and NMR [4] applications
3. Selective shields based on HTS tapes for solenoids [5]
4. “Magic magnet” concept [6]

[1] Gömöry, Fedor, et al. "Experimental realization of a magnetic cloak." Science 335.6075 (2012): 1466-1468.
[2] Tomków, Ł., et al. "Combined magnetic screen made of Bi-2223 bulk cylinder and YBCO tape rings—Modeling and experiments." *Journal of Applied Physics* 117.4 (2015): 043901.
[3] Tomków, Ł., et al. "Improvement of the homogeneity of magnetic field by the attenuation of a selected component with an open superconducting shield made of commercial tapes." *Journal of Applied Physics* 126.8 (2019): 083903.
[4] Frollo, I., et al. "Magnetic field homogeneity adjustment for magnetic resonance imaging equipment." *IEEE Transactions on Magnetics* 54.5 (2018): 1-9.
[5]Wang, T., et al. "A 3.35 T Actively Shielded Superconducting Magnet for Dynamic Nuclear Polarization Device." *IEEE Transactions on Applied Superconductivity* 26.4 (2016): 1-4.
[6] Van Nugteren, Jeroen. High temperature superconductor accelerator magnets. Diss. Twente U., Enschede, Enschede, 2016.

Introduction

Experimental Setup

Experimental and Simulation Results

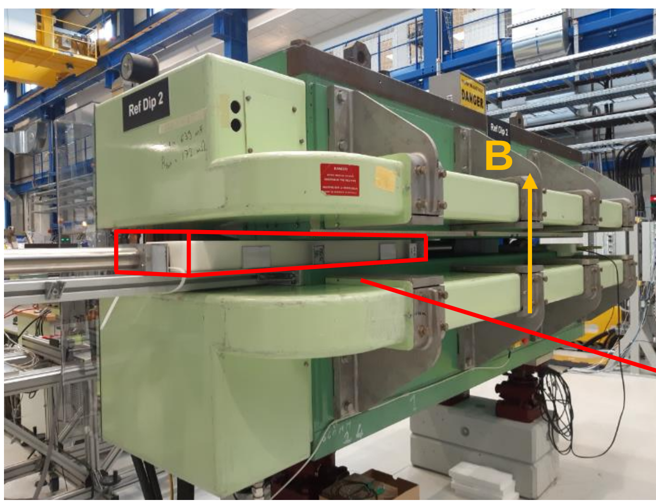
Experimental Setup (1/5)

Strategy: Screening effect quantified as differential measurement (rotating coil)

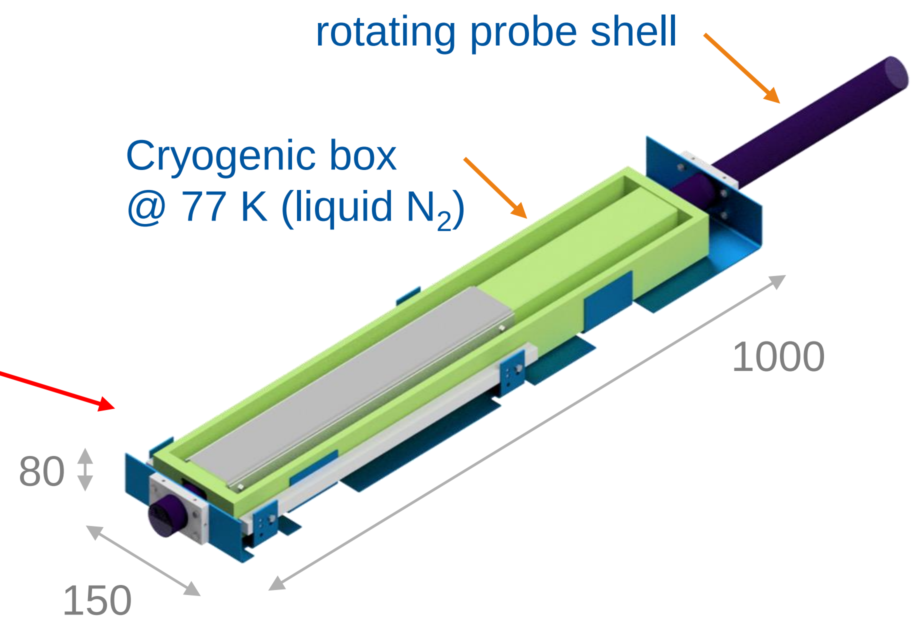
Reference: known magnetic field → dipole HB2 (Magnetic measurement Lab)

Procedure:

1. Introduction of a magnetic field distortion
2. Field correction by means of HTS screens



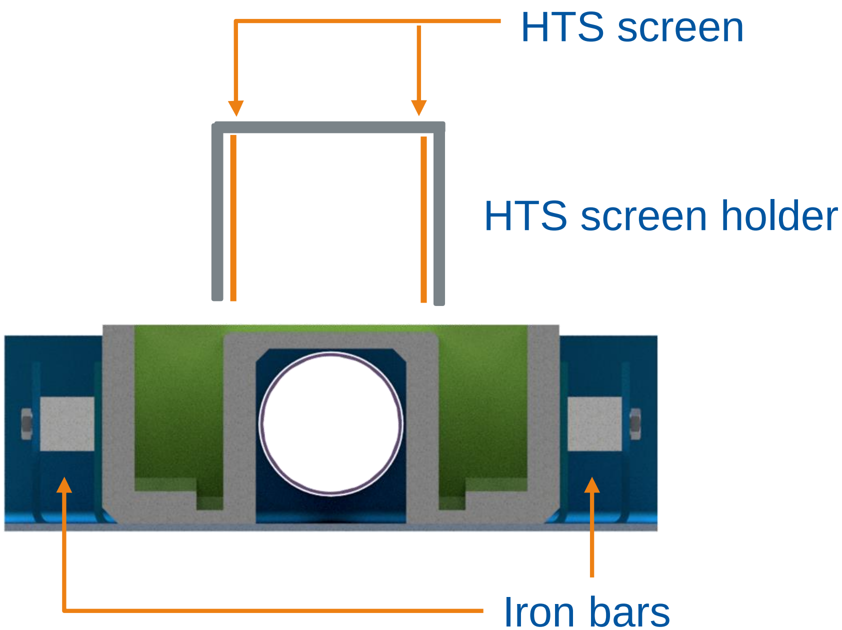
Normal conducting dipole
HB2 @ CERN



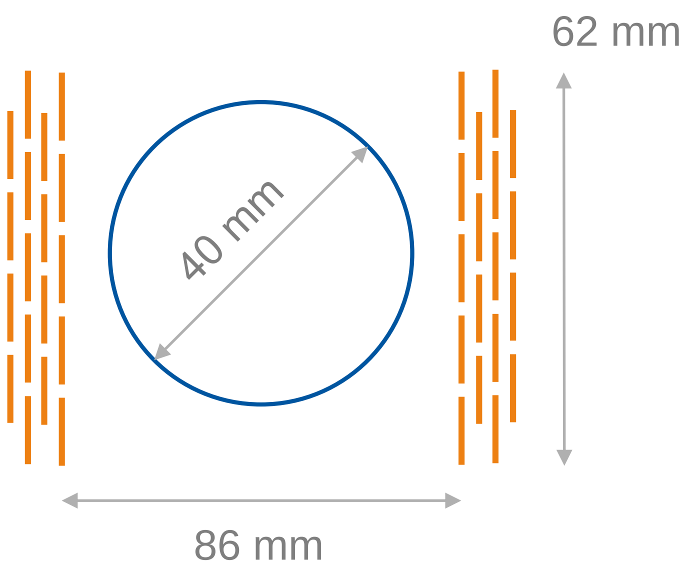
Experimental Setup (2/5)

Magnetic field error → iron bars

Magnetic field correction → HTS screen made of 4 layers of 5 tapes (18 meters)

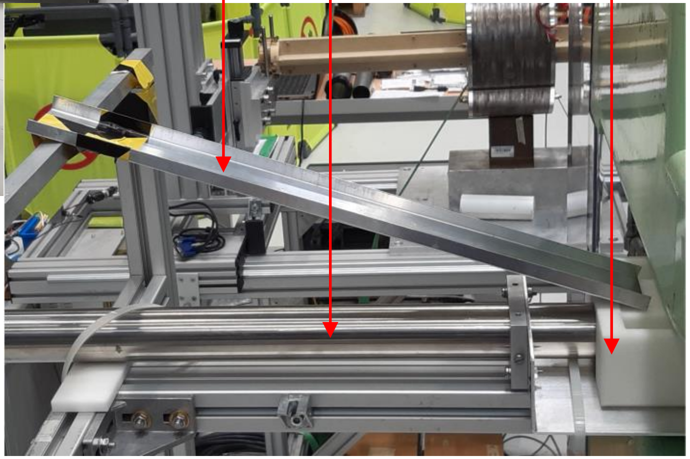


Cross section of the experimental setup



Cross section of the rotating probe and the HTS screen

Experimental Setup - Detail (3/5)



Slide for LN2

Rotating-coil tube

Foam box

Motor drive for rotating coil

DAQ system

HALO setup

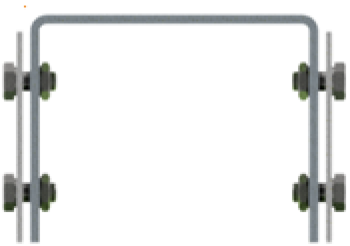
Reference dipole

Experimental Setup - Detail (4/5)

Initial idea: aluminum counter-plates on the holder sides

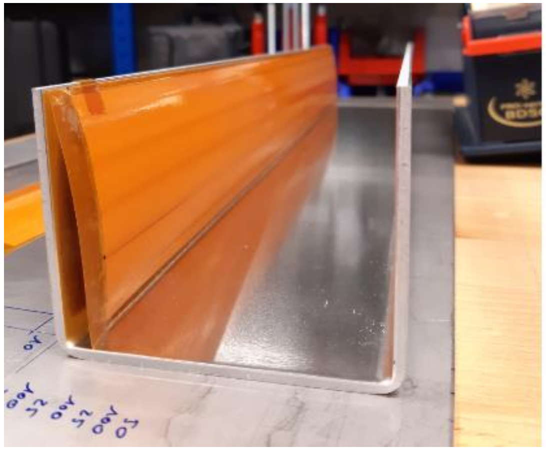
Counter-plates deformation during cool-down

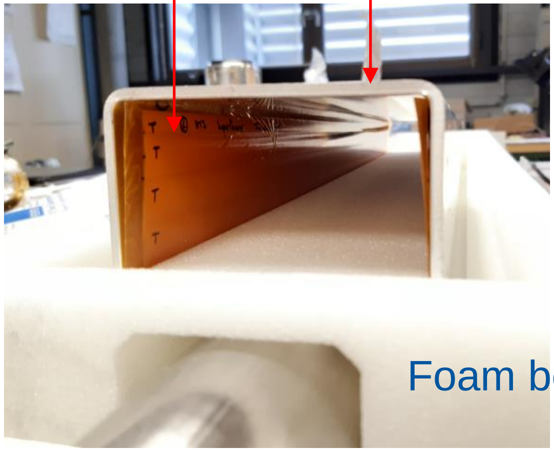
→ HTS tapes blocked between holder and foam box



HTS Screen

HTS holder





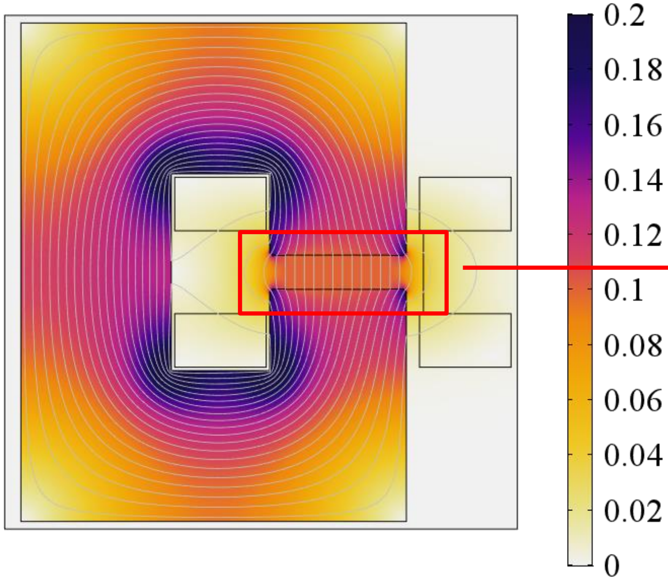
Foam box

HTS holder and screen (left), and their assembly into the foam box

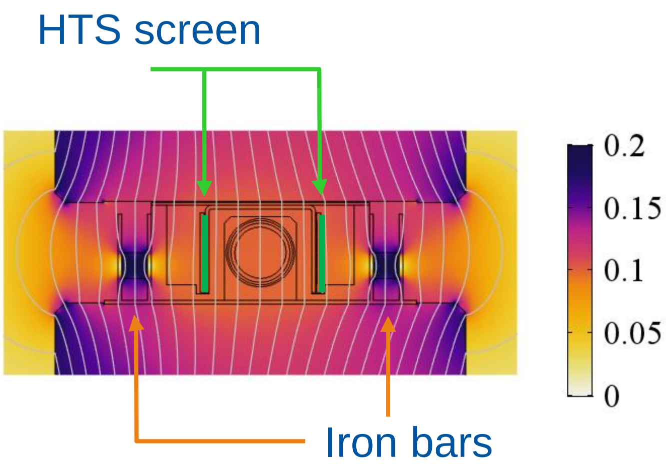
Experimental Setup (5/5)

Magnetoquasistatic 2D simulations:

- Numerical model based on the FEM method
- Field problem described by a coupled A-H field formulation for HTS applications [1]
- Implementation in COMSOL as weak formulation (no tool dependencies)



Magnetic flux density, in (T), in the HB2 Dipole



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

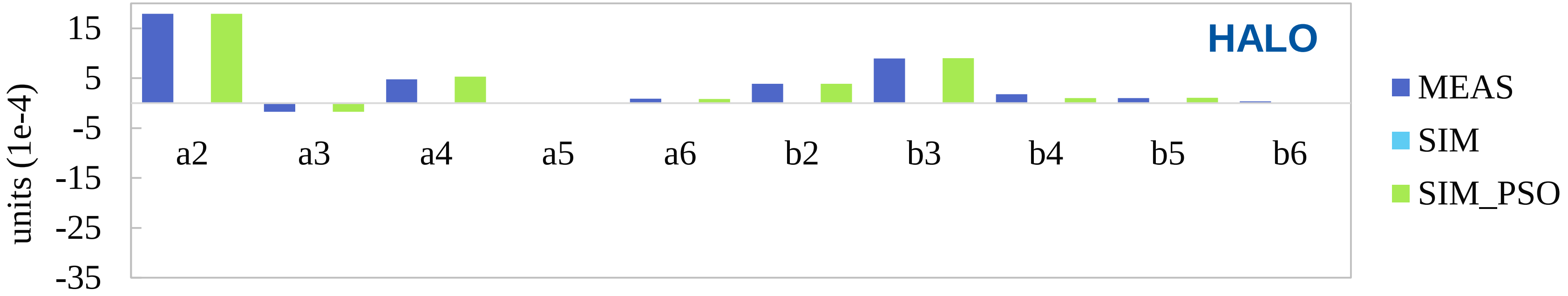
[1] Bortot, L., et al. "A Coupled A–H Formulation for Magneto-Thermal Transients in High-Temperature Superconducting Magnets." IEEE Transactions on Applied Superconductivity 30.5 (2020): 1-11.

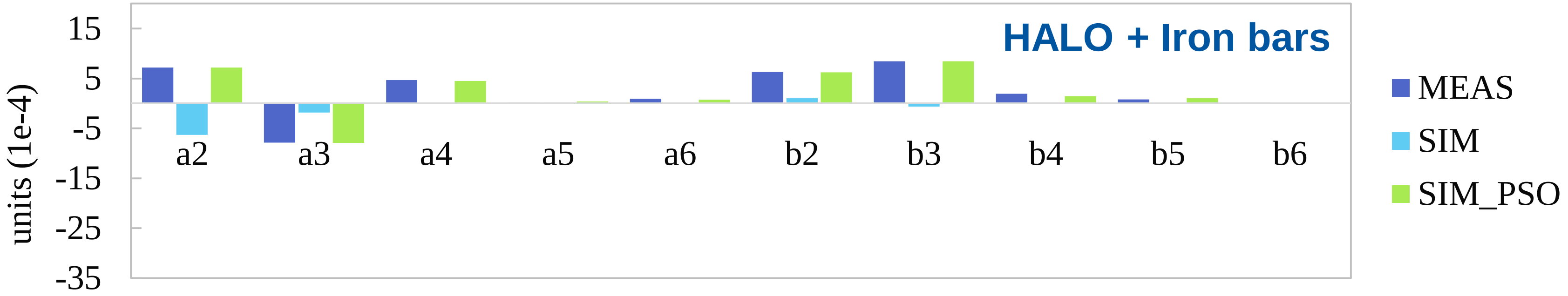
Introduction

Experimental Setup

Experimental and Simulation Results

Measurements (1/3)

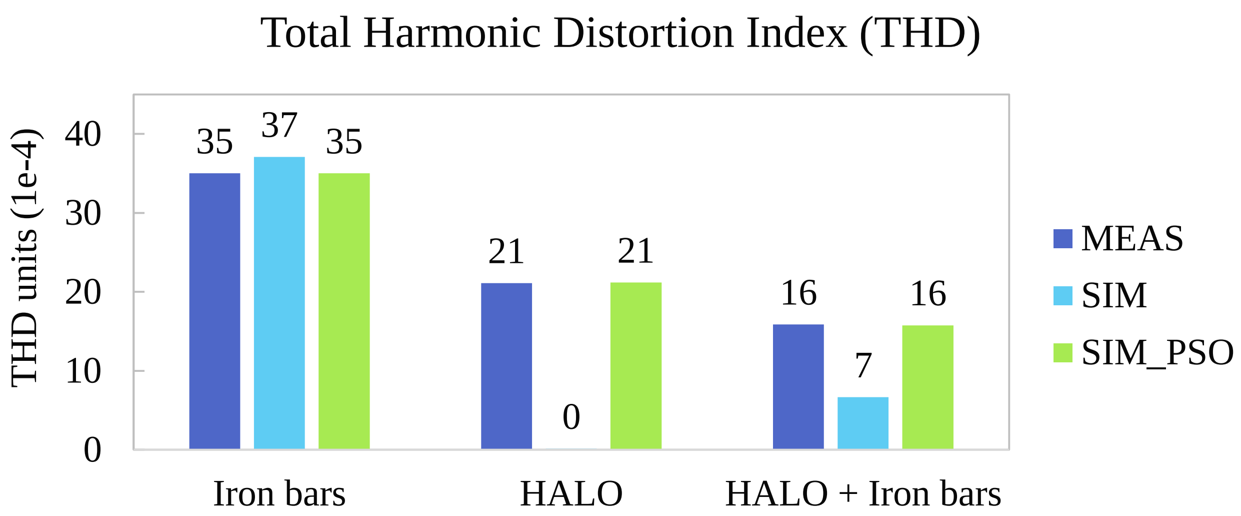




Measurements (2/3)

THD index from the multipole series in the previous slide

$$Q_{THD} = \frac{THD_{Iron}}{THD_{HALO+Iron}}$$

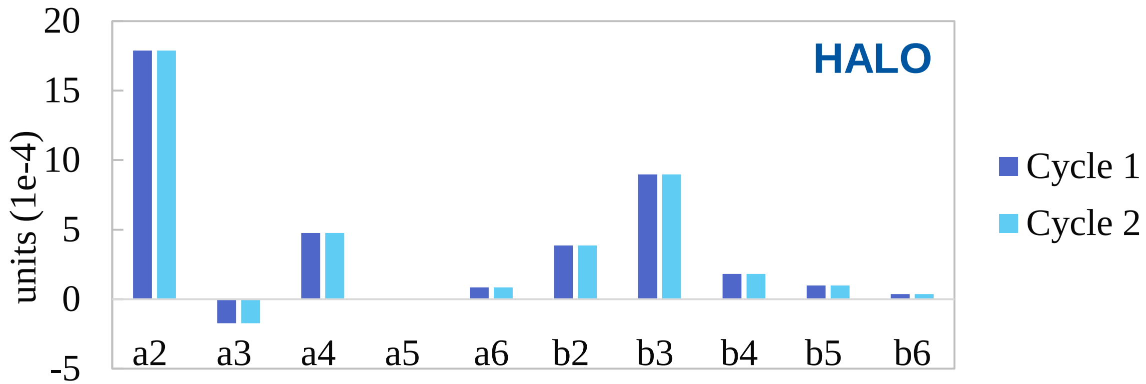


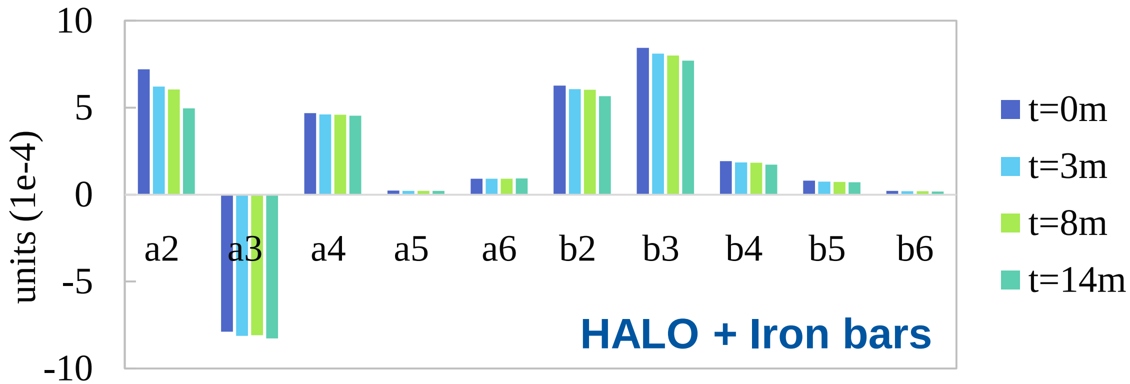
Observations:

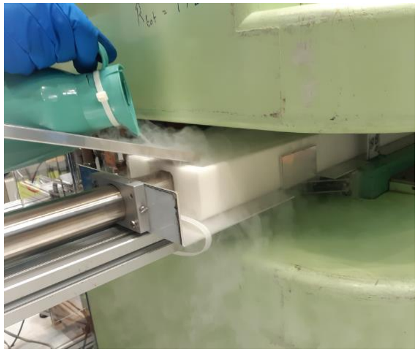
- Screen error ≈ Iron bars → figure of merit $Q_{THD} = 2.2$, expected 5.6
- Random compensation of a_2 leading to apparent field improvement

→ Difficult to draw conclusions on field error cancellation

Measurements (3/3)







Temperature control system

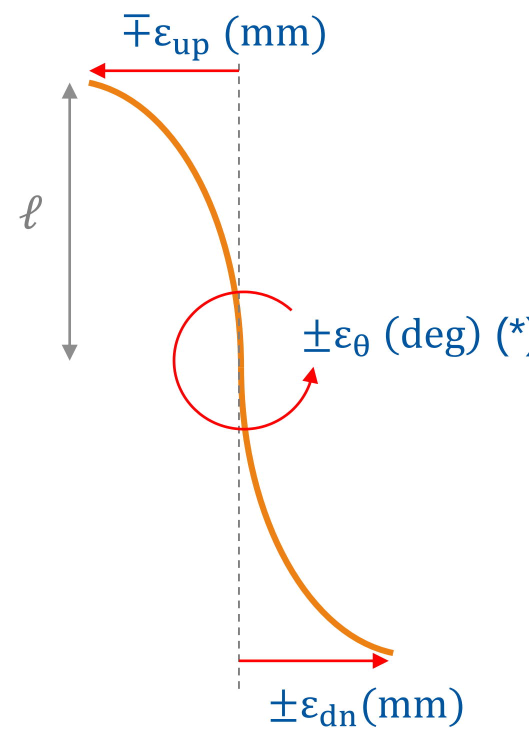
Observations:

- Measurements reproducibility
- Screening currents persistency (up to temperature uncertainty)

Analysis (1/3): Visual inspection

Post-mortem visual inspection of the experimental setup:

Undesired gap between holder and foam box



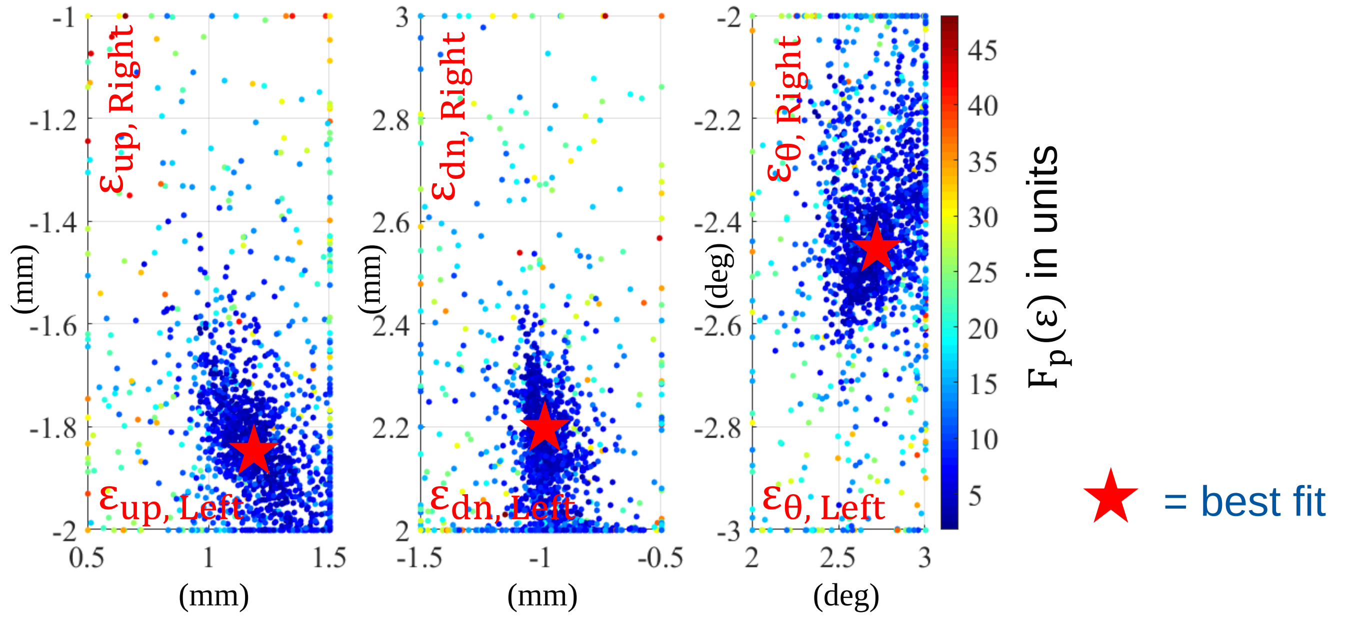
Screen deformation added to the model by means of parabolae with three DoFs (educated guess)

(*) $\pm\varepsilon_{\ell(\theta)} = \ell \sin(\pm\varepsilon_{\theta})$ (mm)

Analysis (2/3): Parameters Fitting

Particle Swarm Optimizer (PSO) (*) : $\mathbb{R}^6 \rightarrow \mathbb{R}$ where

- $\mathbb{R}^6$: $\{\varepsilon_{\mathrm{up}}, \varepsilon_{\mathrm{dn}}, \varepsilon_{\theta}\} \times 2$ (two screens)
- $\mathbb{R}$: $\mathrm{F_p}(\varepsilon) = \sum_{i=1}^{6}\left(\left|a_i^{\mathrm{meas}} - a_i^{\mathrm{sim}}\right| - \left|b_i^{\mathrm{meas}} - b_i^{\mathrm{sim}}\right|\right)$ penalty function,
- HALO standalone dataset



Projections of the penalty function from the $\mathbb{R}^6$ parametric space

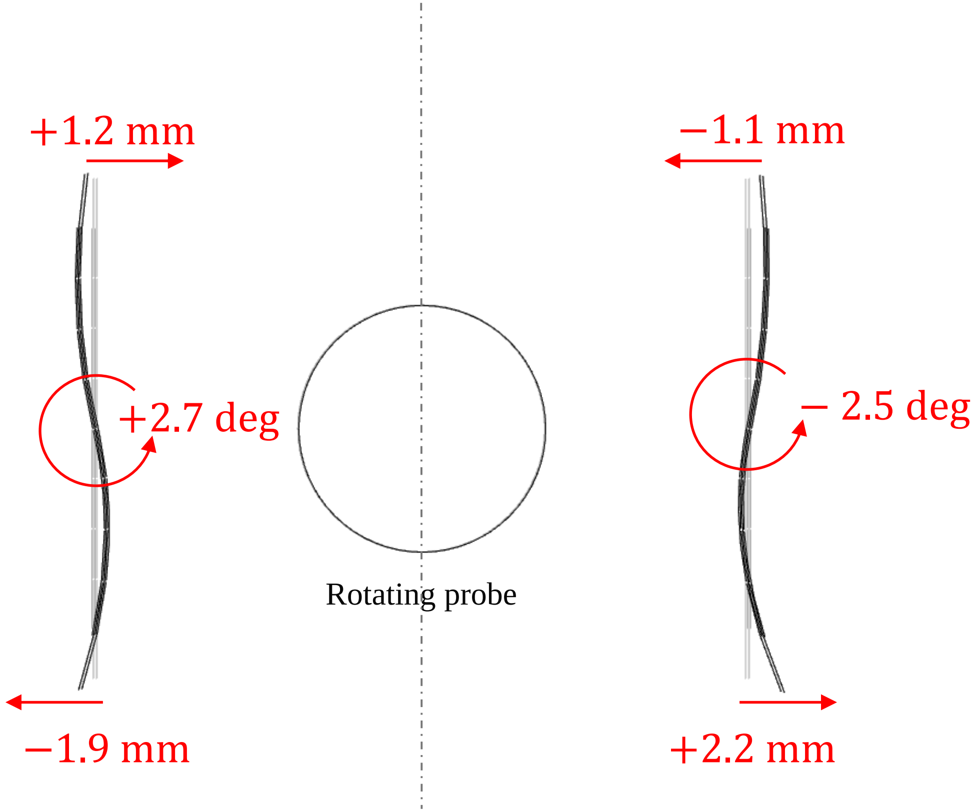
(*) CAVEAT: Inverse problem, with infinite solutions. The optimizer works in a functional subspace which is determined a-priori by the educated guess on the mechanical deformation. Although the solution is arbitrary, it is still useful to understand the behavior of the screen.

Analysis (3/3): Geometrical Deformation

Best-fit results from the PSO algorithm

Observations on deformation:

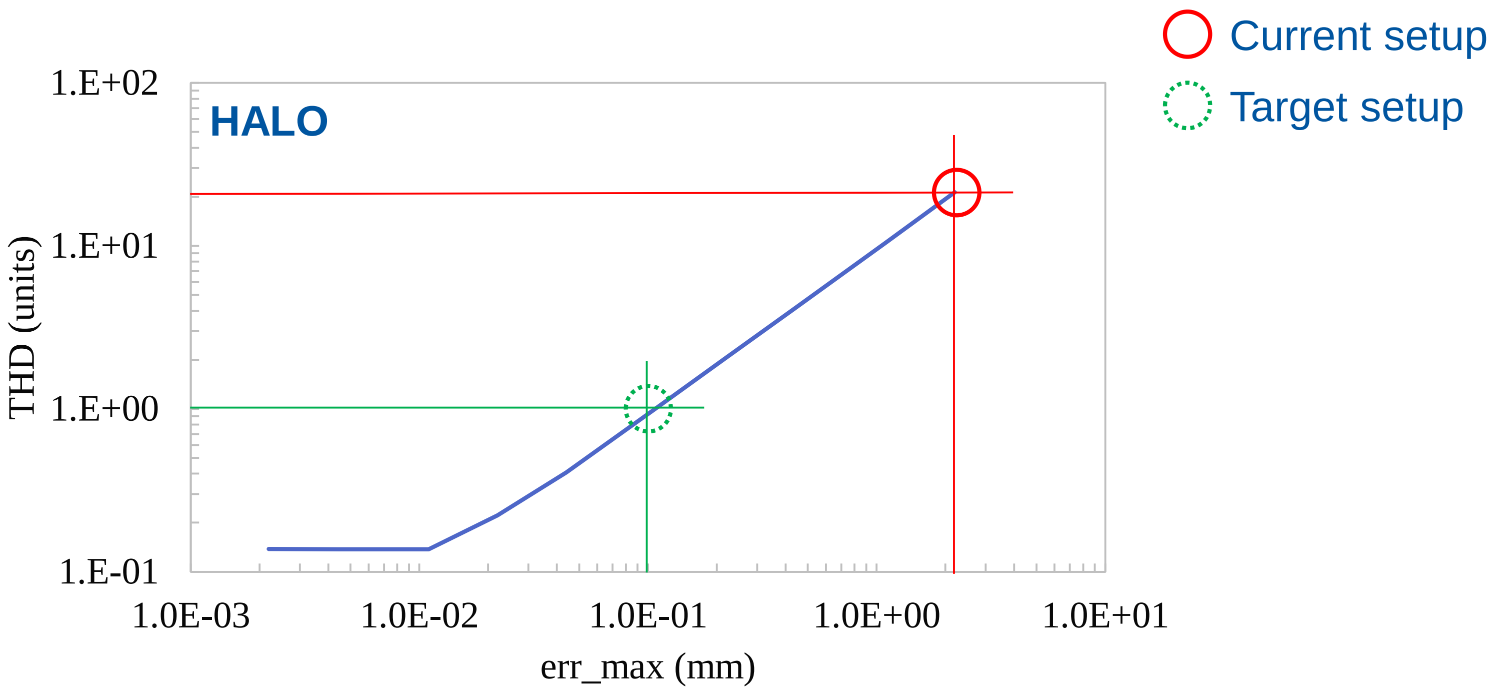
- Relevant, > 2 mm
- Consistent with the displacements observed in the visual inspection
- Slightly symmetric, in accordance with the symmetric layout of the assembly



Geometrical deformation of the HTS screens (enhanced by a factor 5 for graphical rendering)

Extrapolation (1/2): Screen Error

Application of a scaling factor k_ε to geometrical errors $\{\varepsilon_{up}, \varepsilon_{dn}, \varepsilon_{\ell(\theta)}\}$:



If $\max\{\varepsilon_{up}, \varepsilon_{dn}, \varepsilon_{\ell(\theta)}\} \leq 0.1$ mm (i.e. $k_\varepsilon \cong 20$) → THD ≤ 1 unit

Extrapolation (2/2): Field Correction

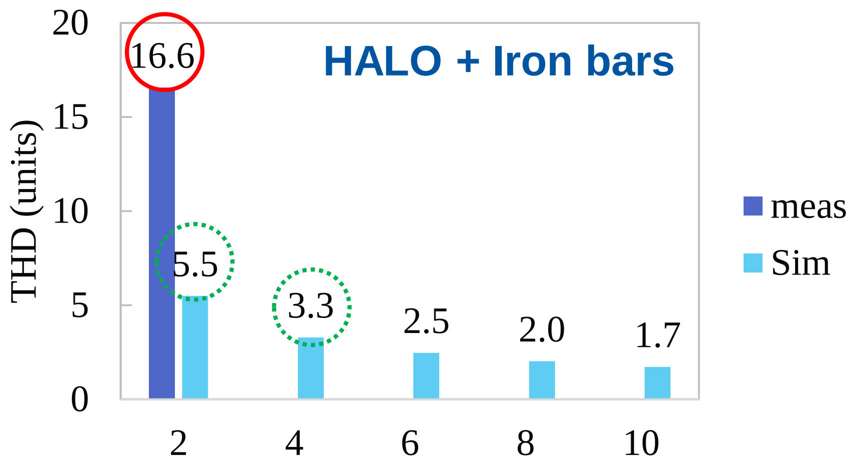
Assumption: geometrical error $\leq 0.1\ \mathrm{mm}$

Field correction improvement by:

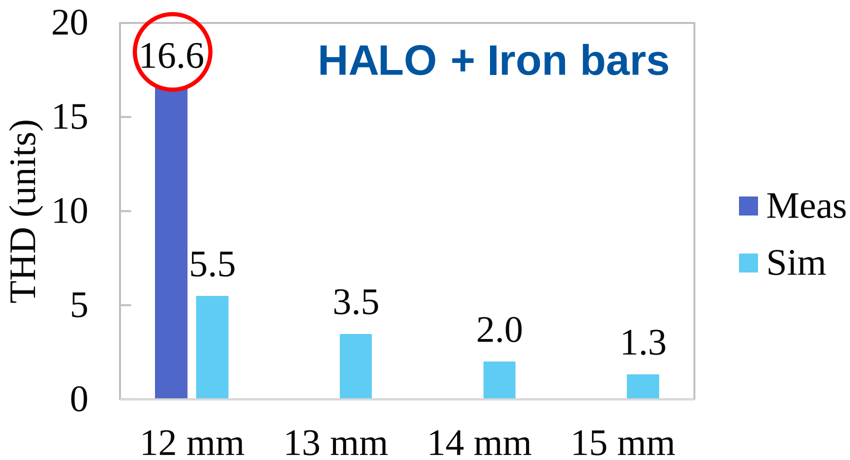
1. More HTS layers
2. Longer HTS layers (for reference)

Current setup

Target setup



THD, function of the HTS layers



THD, as a function of the tape width

Q_{THD} = 2.2 → 6.4 (improved geometry) → 10.6 (HTS layers doubling)

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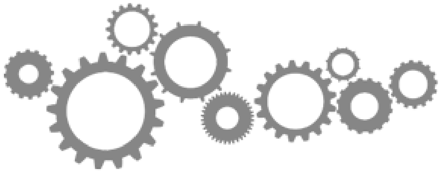
Lessons Learnt



Design

- Curvature in the HTS screen → face-to-face tape-stacking
- Geometrical error → tolerance of 0.1 mm
- Geometrical error → mechanical regulation for the HTS holder
- Mechanical deformations → avoid metal folding in manufacturing (expensive)

Experiment

- Alignment at 300 K $\nRightarrow$ alignment at 77 K
- Rotating-probe tube freezing, time-at-cold limited to ~10-15 minutes
- Iron bars mounting without removing the experimental setup from the magnet

Analysis

- Higher Q_{THD} needed for a convincing proof-of-concept
  - Reduced screen error → high improvement
  - Increased field distortion (more iron) → small improvement with the current design
    Second HTS layer helpful

Conclusions

Highly non-standard experimental campaign successfully completed

1. Reproducibility of results, persistency of the screening currents
2. Sensitivity not fully satisfactory for a proof of concept

Validation of the coupled-field formulation (developed for HTS applications)

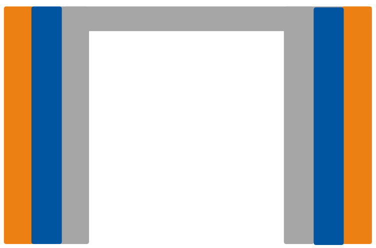
1. Numerical simulations in agreement with measurements
2. Useful insights for improving the design of the HTS screen
3. Extrapolation shows relevant margins for improvement

Next Steps

Second experimental campaign with improved holder design. Tentative proposals:

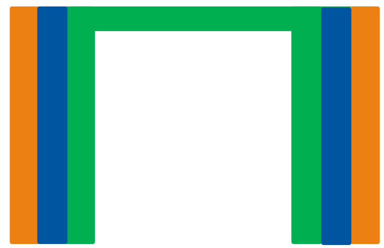
Materials:
- Stainless steel (machined)
- G10 (machined)
- Stycast
- HTS screen

1 Steel + glue



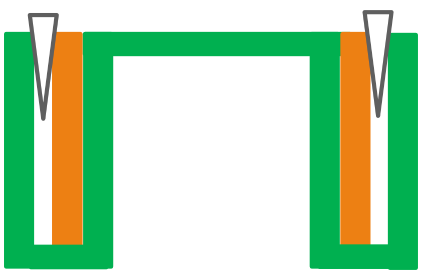
Simple
No regulation
Screen flattening by gluing

2 G10 + glue



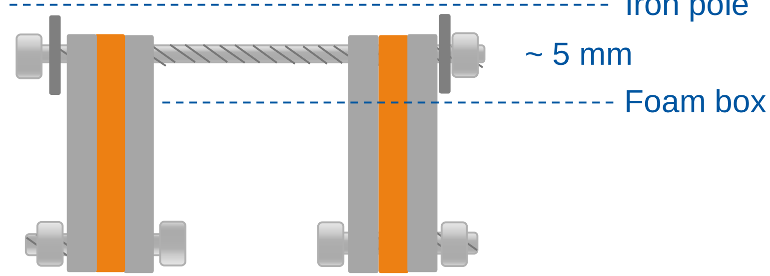
Simple(r)
No regulation
Screen flattening by gluing

3 G10 + slots + shims



Partial regulation
Screen flattening by compression
1 mm wide, 60 mm deep slot

4 Steel plates + bolts



Regulation via washers
Screen flattening by compression
Complex
Space constraint: ~ 5 mm in the bridge gap

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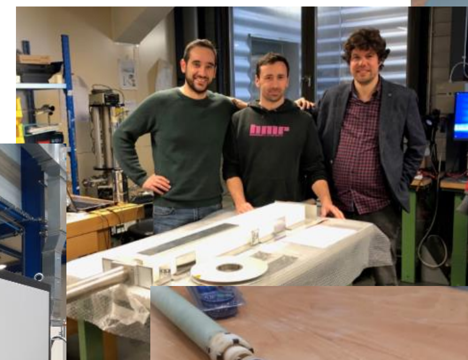
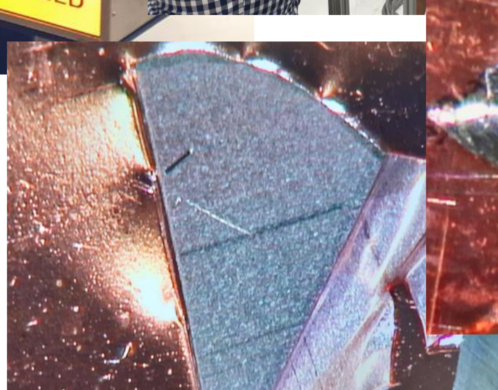
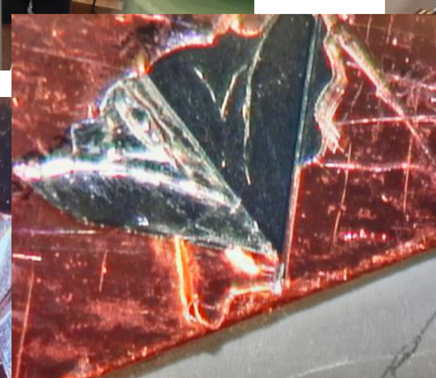
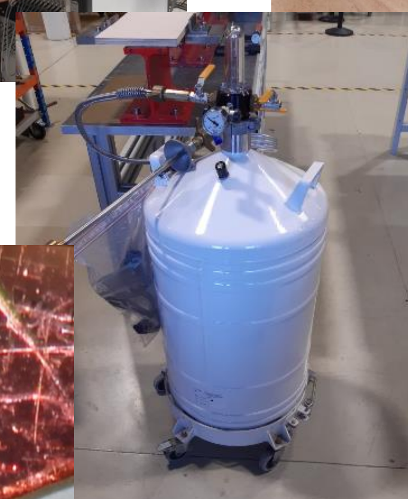
Thank you for your support!



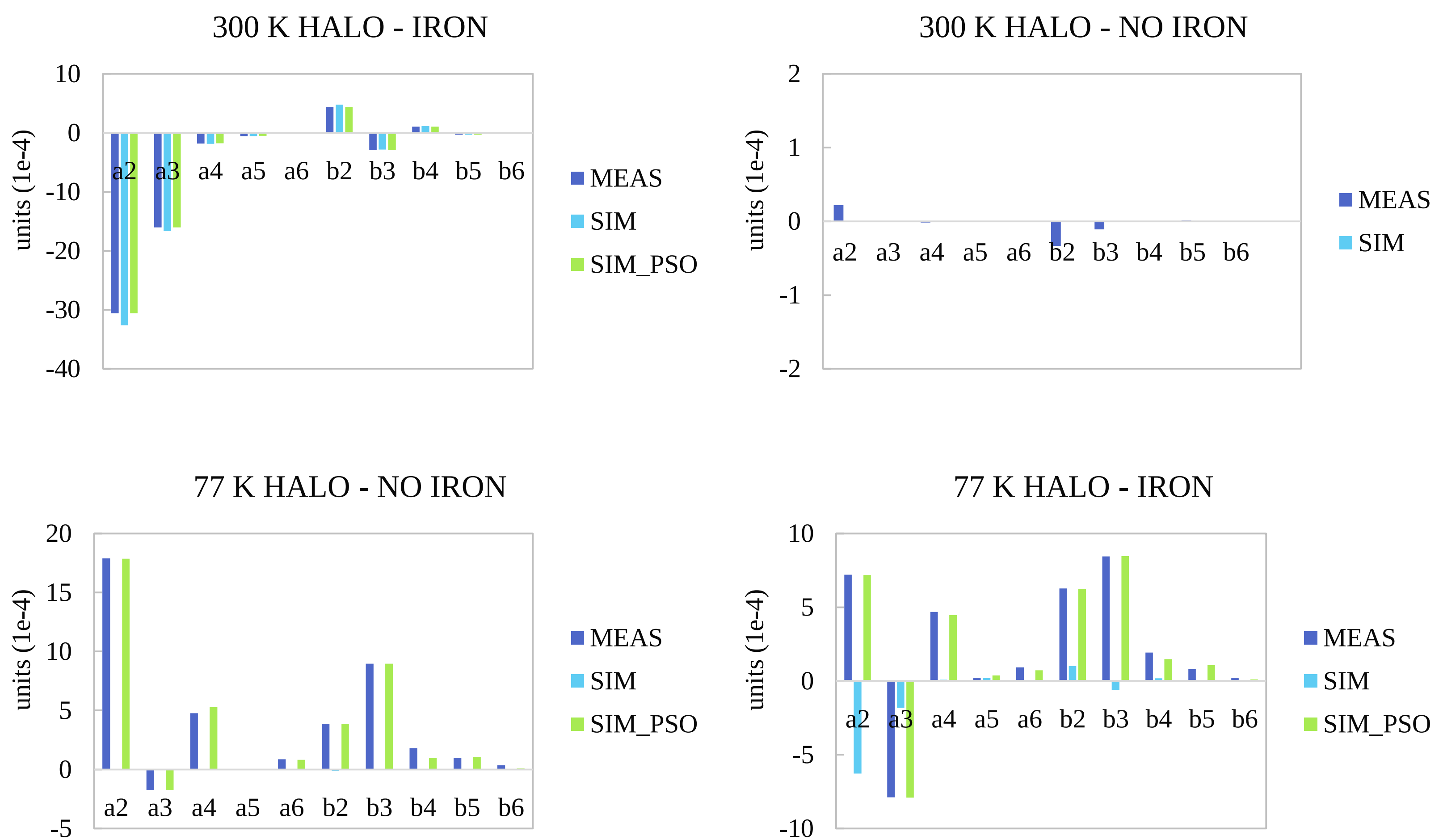






Annex

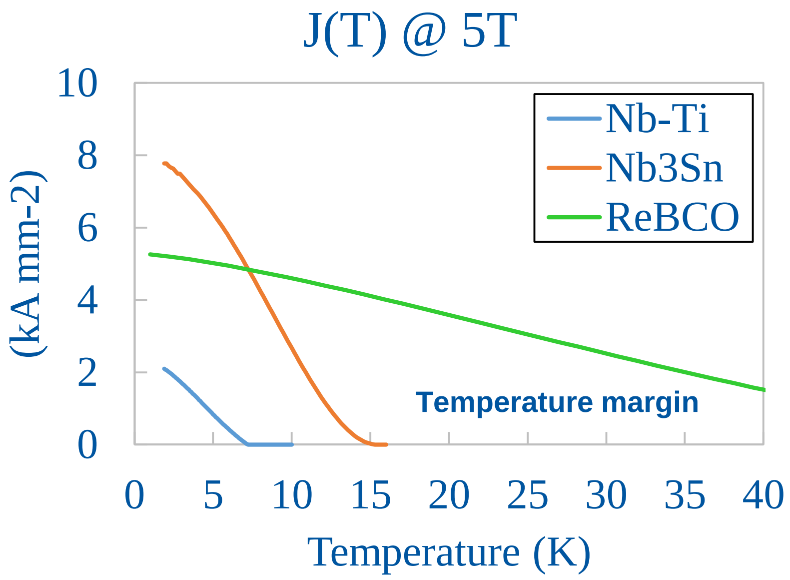
Results - Overview

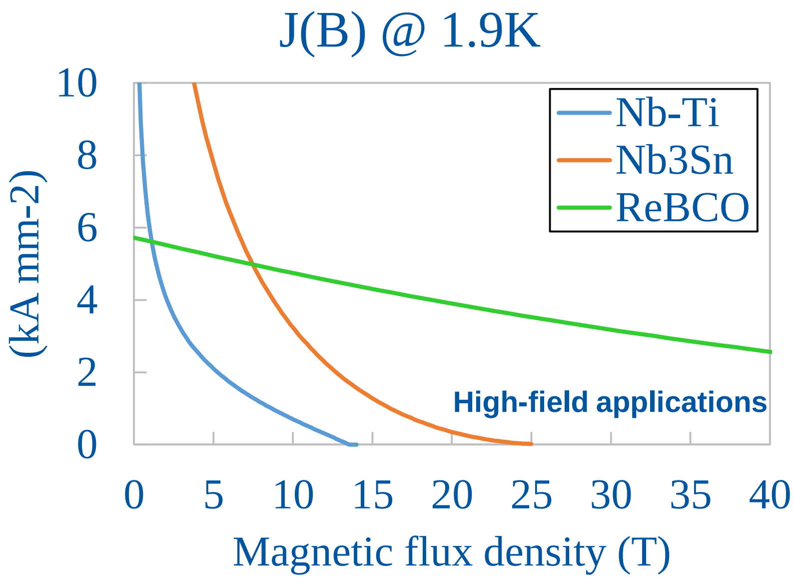


High-Temperature Superconductors (HTS)

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

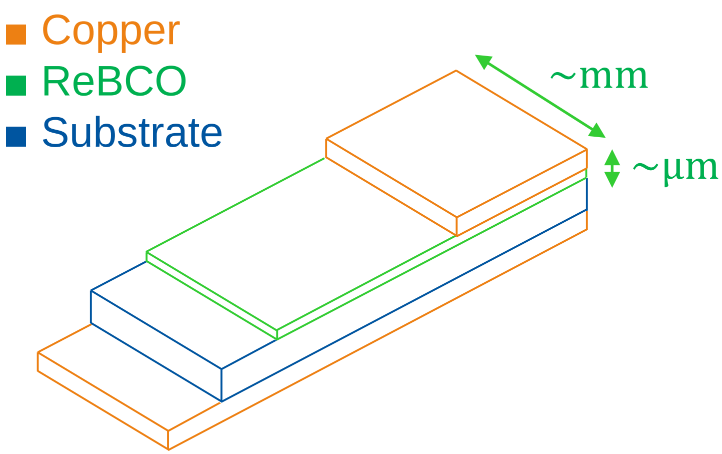
Higher critical temperature and coercive field with respect to the traditional low-temperature superconductors (LTS), such as Nb-Ti or Nb3Sn

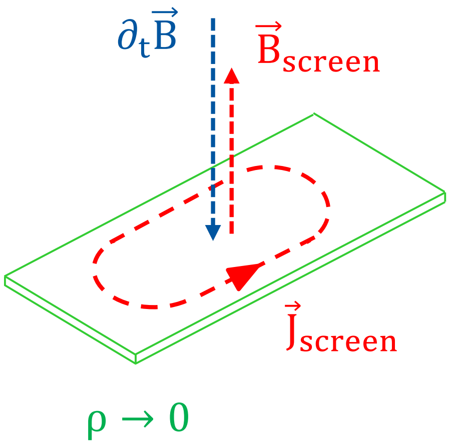




Transient Effects: Screening Currents in HTS

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





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

$\rho \rightarrow 0$ → Persistent magnetization $\vec{B}_{screen}$

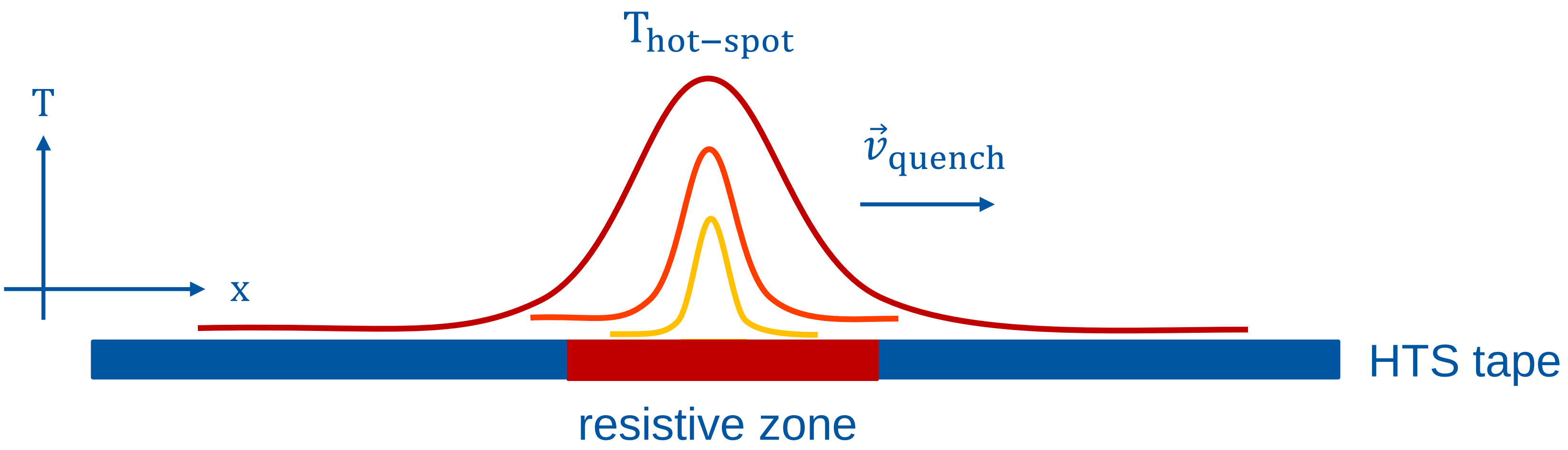
Large filament size (5-12 mm) → large $\vec{B}_{screen}$

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

Inhomogeneous current density distribution → Solid conductors!

Transient Effects: Quench in HTS

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)

Formulation

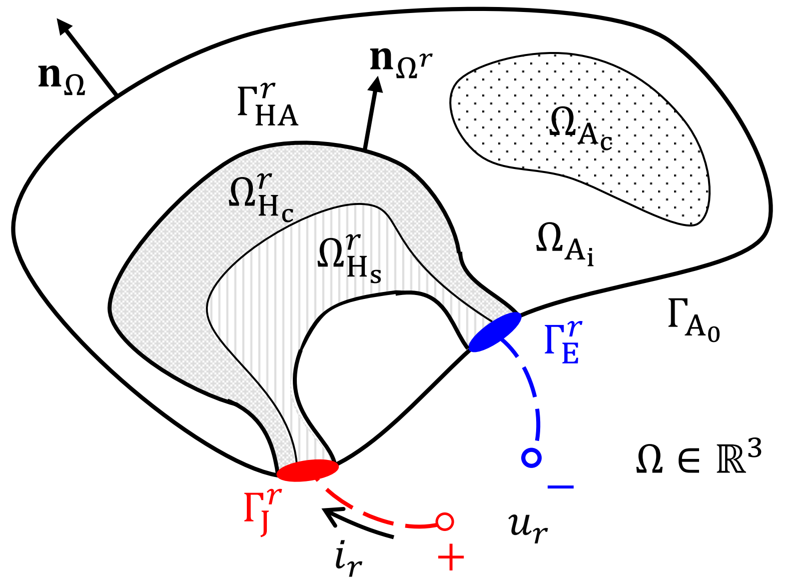
Domain decomposition

Ω_H^r source domain (r-th winding)

- $\Omega_{\mathrm{H_s}}^r$ and $\Omega_{\mathrm{H_c}}^r$ for superconducting and normal conducting parts

Ω_A source-free domain

- Ω_{A_c} and Ω_{A_i} for normal conducting and insulating materials



Strong formulation

for $r = 1, \dots, N_r$ windings:

- $\vec{A}^{\star}$ in Ω_A : reduced magnetic vector potential
- $\vec{H}$ in Ω_H^r : magnetic field strength

Ampere Maxwell
$$\nabla \times \mu^{-1} \nabla \times \vec{A}^{\star} + \sigma \partial_t \vec{A}^{\star} = 0 \text{ in } \Omega_{\mathrm{A}}$$

Faraday
$$\nabla \times \rho \nabla \times \vec{H} + \partial_t \mu \vec{H} + \nabla \times \vec{\chi}_r u_{\mathrm{r}} = 0 \text{ in } \Omega_{\mathrm{H}}^r$$

Algebraic constraint
$$\int_{\Omega_{\mathrm{H}}^r} \vec{\chi}_r \cdot (\nabla \times \vec{H})\, \mathrm{d}\Omega = i_r$$

Discrete Problem

$\vec{A}^{\star}$, $\vec{H}$ discretized via Nédélec-type shape functions

$$
\begin{bmatrix}
\mathbf{K}^{\nu} + \mathbf{M}^{\sigma}\frac{\mathrm{d}}{\mathrm{dt}} & -\mathbf{Q} & \mathbf{0} & \mathbf{0} \\
\mathbf{Q}^{\top}\frac{\mathrm{d}}{\mathrm{dt}} & \mathbf{K}^{\rho} + \mathbf{M}^{\mu}\frac{\mathrm{d}}{\mathrm{dt}} & -\mathbf{X} & \mathbf{0} \\
\mathbf{0} & \mathbf{X}^{\top} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{K}^{\mathrm{k}} + \mathbf{M}^{\rho}\frac{\mathrm{d}}{\mathrm{dt}}
\end{bmatrix}
\cdot
\begin{bmatrix} \mathbf{a} \\ \mathbf{h} \\ \mathbf{u}_{\mathrm{s}} \\ \mathbf{t} \end{bmatrix}
=
\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{i}_{\mathrm{s}} \\ \mathbf{q}(\cdot) \end{bmatrix}
$$

Ampere-Maxwell

Faraday

Heat Balance

Field coupling

Circuit coupling

Finite material properties, bounded condition number → Solver stability ☺

Observations:

- Electric ports used as connections with the external circuit
- u_s, i_s → Each winding as one-port component, with impedance Z_r: $u_r = Z_r i_r$

Assumption:

- $(K^{\upsilon} + \lambda M^{\sigma})$ positive-definite (true for gauged $\vec{A}^{\star}$, e.g. via tree-cotree gauge)

Field-Circuit Coupling Interface

Field-circuit coupling interface (Schwarz transmission condition for linear systems):

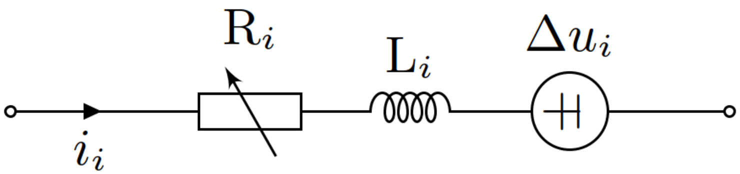
$$\mathbf{Z}(j\omega) = \left[\mathbf{X}^\top \left[\mathbf{K}^\rho + j\omega\mathbf{M}^\mu + \mathbf{Q}^\top \left[\mathbf{K}^\nu + j\omega\mathbf{M}^\sigma\right]^{-1}\mathbf{Q}\right]^{-1}\mathbf{X}\right]^{-1}$$

- $\mathbf{K}^\rho$: resistive term
- $j\omega\mathbf{M}^\mu$: $\vec{H}$-flux
- $\mathbf{K}^\nu$: $\vec{A}$-flux
- $j\omega\mathbf{M}^\sigma$: Eddy currents

In time domain:

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

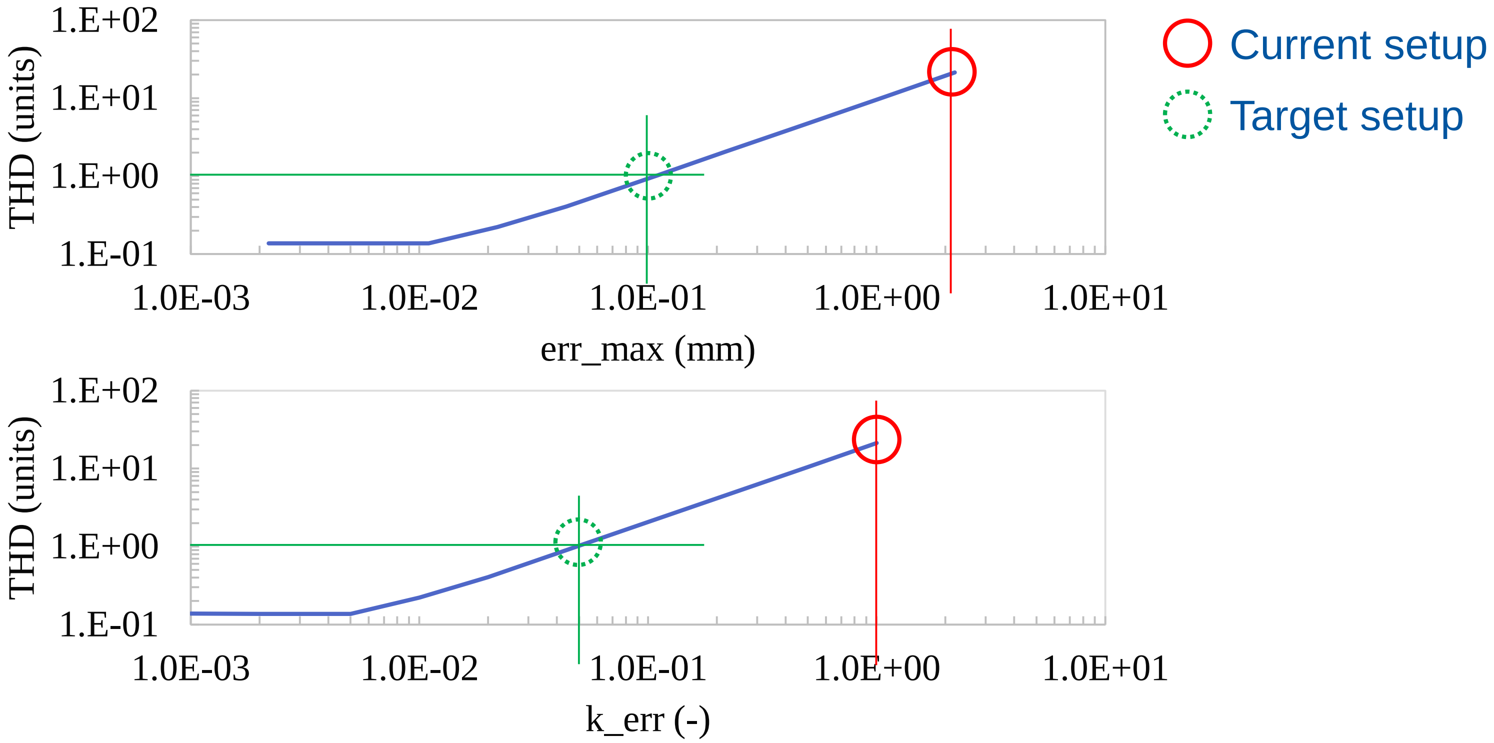
$$\mathbf{u}_\mathrm{s}(t) \approx \mathbf{R}\mathbf{i}_\mathrm{s}(t) + \mathbf{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}_\mathrm{s}(t)$$



Linearized field-circuit coupling interface for solid conductors

Extrapolation (1/2): Screen Error

Application of a scaling factor k_ε to geometrical errors $\{\varepsilon_{up}, \varepsilon_{dn}, \varepsilon_{\ell(\theta)}\}$:



If geometrical error is improved by a factor 20 ($k_\varepsilon \leq 0.05$)

i.e. $\max\{\varepsilon_{up}, \varepsilon_{dn}, \varepsilon_{\ell(\theta)}\} \leq 0.1$ mm → THD of the screen ≤ 1 unit

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