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Proposal for a passive field-harmonics absorber based on HTS technology, applied to a 20 Tesla HTS block coil magnet

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STEAM

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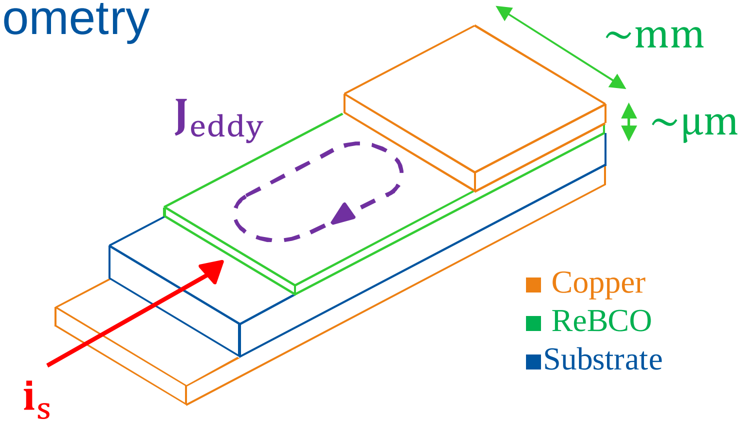
Outline

- Introduction
- Magnetic field quality
- HALO
    - Proof of concept
    - Case study
    - Results
- Summary

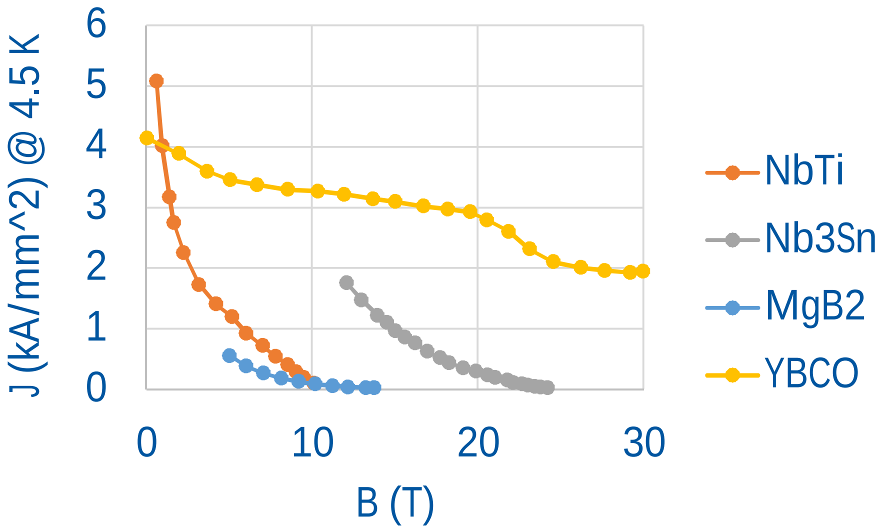
Introduction

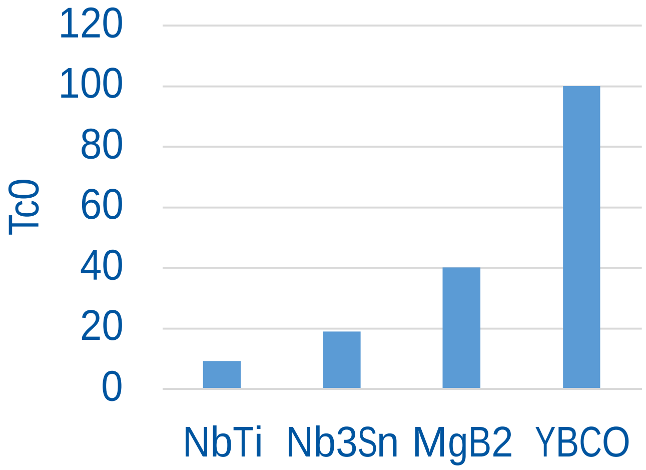
- Geometry



Resistivity:
Nonlinear, field dependent, anisotropic

$$\sigma_{SC}^{-1} = \frac{E_c}{J_c(\vec{B})}\left(\frac{J}{J_c(\vec{B})}\right)^{n-1}$$





Introduction

HTS tapes in accelerator magnets?

Outstanding magneto-thermal properties

- Superconducting state up to ≃ 100 Tesla, background field
- Critical temperature of ≃90 K, operations possible at 10 K (He-gas)

Concerns about magnetic field quality and control

- Large eddy currents induced during dynamic regime
- Eddy currents decay time potentially longer than the duty-cycle of the magnets
- Eddy currents as persistent magnetization, potentially large field errors

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

- Field harmonics absorber based on the HTS technology
- Passive, no external leads, no active control
- Minimal energy stored, no coupling only with fundamental field harmonics
- Inspired by the concept of the persistent current shim coils [1, p. 161]

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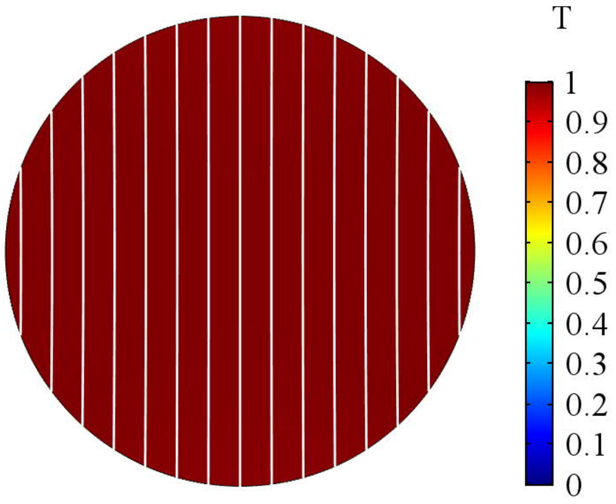
[1] Van Nugteren, Jeroen. High temperature superconductor accelerator magnets. Diss. Twente U., Enschede, 2016.

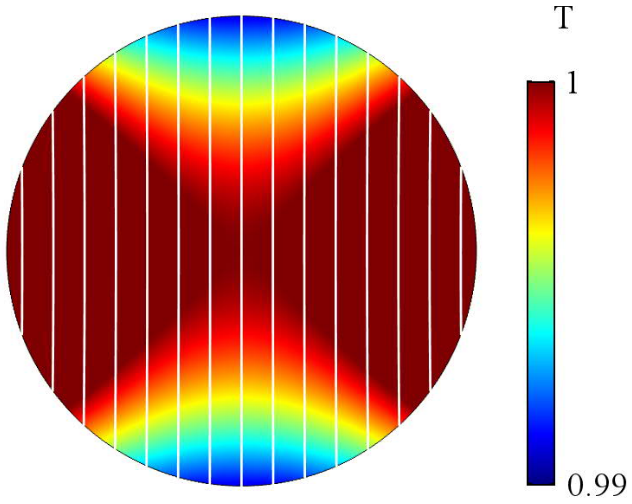
Magnetic Field Quality

What is “Magnetic Field Quality”

Consider a given dipole field living in a circular magnet aperture:



Magnetic field, [0, 1] T



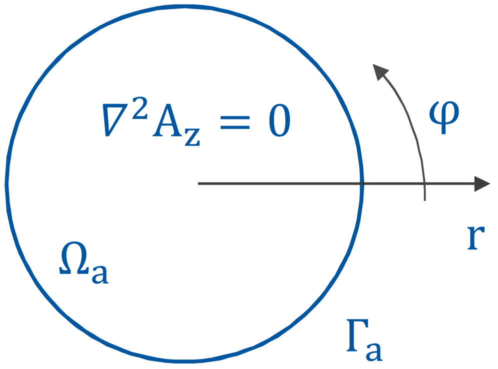
Magnetic field, [0.99, 1] T

- Same field, with different colour scale
- Not a perfect dipole, some “extra components” are present
- How do we **quantify** this field imperfection?

Magnetic Field Harmonics - 01

Magnet aperture Ω_a : 2D magnetostatic problem [2, p.237]

- $\vec{J} = 0$ (negligible currents and spatial charges)
- $\mu = \mu_0$ (vacuum magnetic permeability)
- Laplace equation for A_z, in cylindrical coordinates



General Solution:

$$A_z(r,\varphi) = \sum_{n=1}^{\infty} r^n[\gamma_n \sin(n\varphi) + \delta_n \cos(n\varphi)]$$

γ_n, δ_n integration constants

Magnetic field density in (r,φ):

$$B_r(r,\varphi) = \frac{1}{r}\partial_\varphi A_z(r,\varphi) = +\sum_{n=1}^{\infty} n r^{n-1}[\gamma_n \cos(n\varphi) + \delta_n \sin(n\varphi)]$$

$$B_\varphi(r,\varphi) = -\partial_r A_z(r,\varphi) = -\sum_{n=1}^{\infty} n r^{n-1}[\gamma_n \sin(n\varphi) - \delta_n \cos(n\varphi)]$$

γ_n, δ_n are determined by boundary conditions (Laplacian!)

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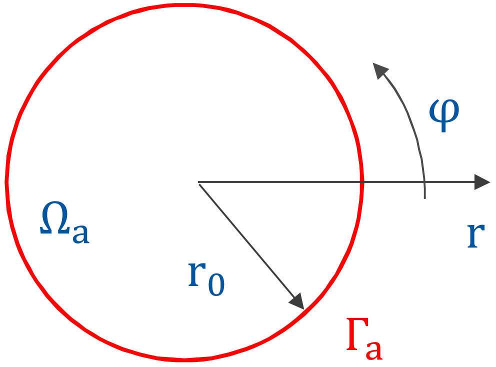
[2] Russenschuck, Stephan. Field computation for accelerator magnets: analytical and numerical methods for electromagnetic design and optimization. John Wiley & Sons, 2011.

Magnetic Field Harmonics - 02

$\vec{B}$ known on Γ_a (simulations, measurements), $\vec{B}$ as Fourier series expansion on r_0



$$B_r(r,\varphi) = \sum_{n=1}^{\infty} B_n(r_0)\cos(n\varphi) + A_n(r_0)\sin(n\varphi)$$
$$B_\varphi(r,\varphi) = \sum_{n=1}^{\infty} B_n(r_0)\cos(n\varphi) - A_n(r_0)\sin(n\varphi)$$

$$A_n(r_0) = \frac{1}{\pi}\int_0^{2\pi} B_r(r_0,\varphi)\sin(n\varphi),$$
$$B_n(r_0) = \frac{1}{\pi}\int_0^{2\pi} B_r(r_0,\varphi)\cos(n\varphi)$$

By comparison with the general solution

$$A_n(r_0) = \gamma_n n {r_0}^{n-1} = B_N a_n(r_0)$$
$$B_n(r_0) = \delta_n n {r_0}^{n-1} = B_N b_n(r_0)$$

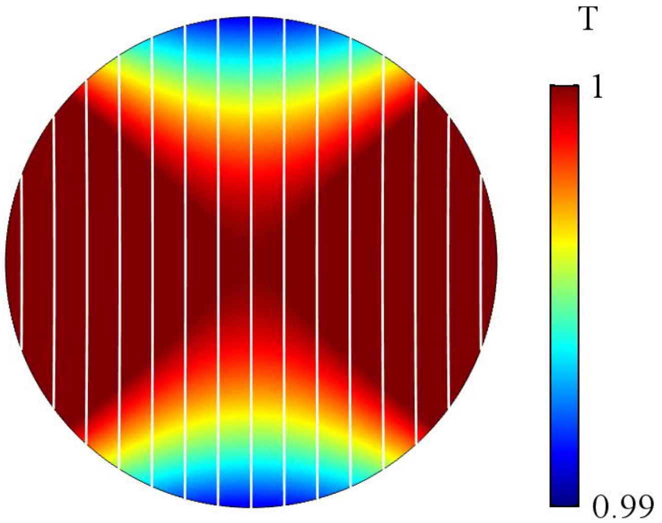
$b_n(r_0)$, $a_n(r_0)$ normal and skew and multipole coefficients related to main field B_N (e.g. N=1 dipole, N=2 quadrupole…)

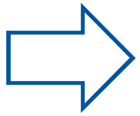
Distortion Factor

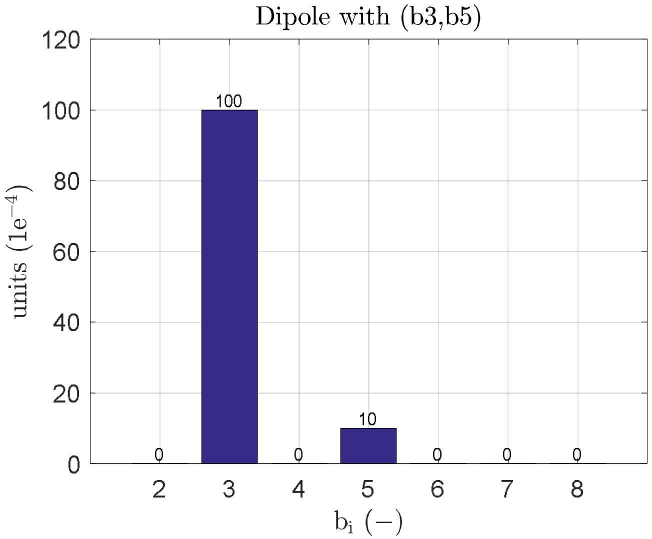
$F_d(r_0) = \sum_{n=1}^{k}[b_n(r_0)^2 + a_n(r_0)^2] \approx 1e^{-4}$ for a good field quality

…Back to the Dipole Field

Calculation of the normal multipole coefficients, via Fourier series expansion:







Magnetic field, [0.99, 1] T

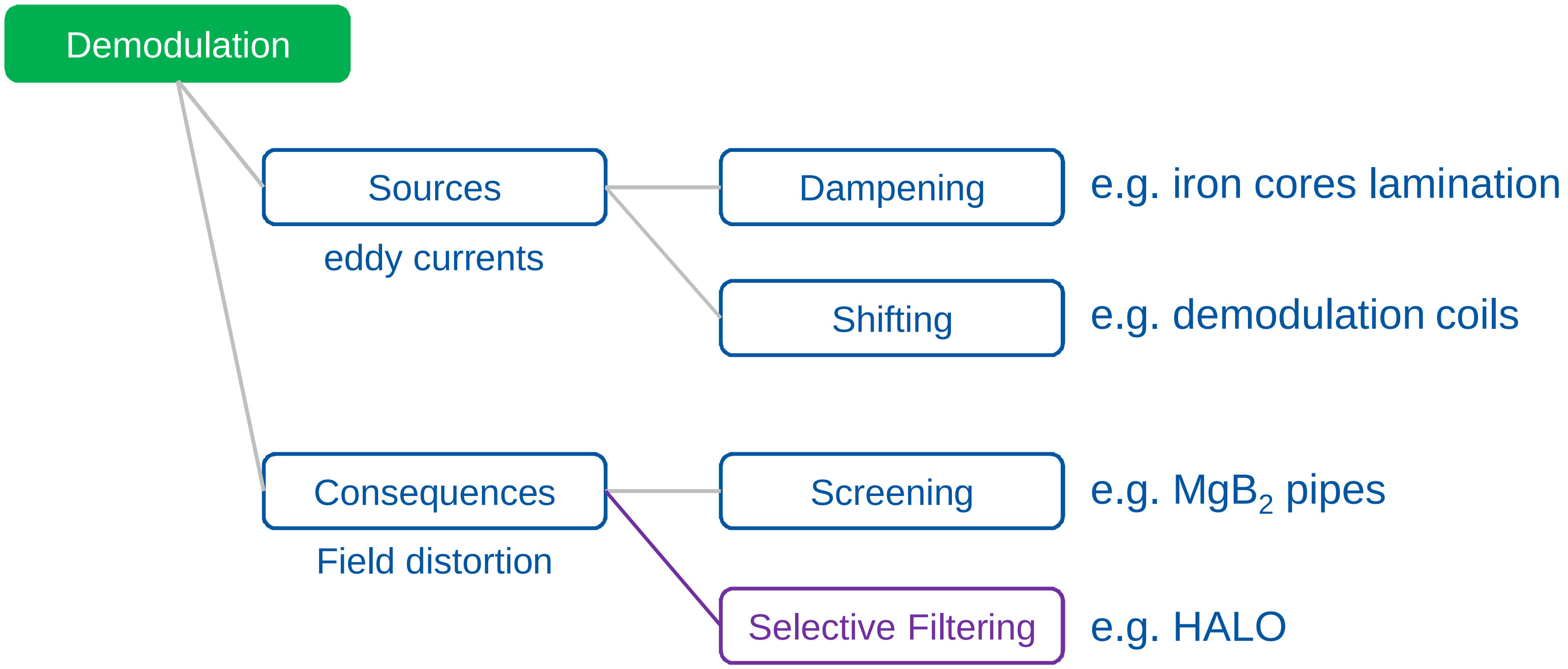
Normal multipole coefficients

- Dipole field affected by a b_3 (sextupole) and b_5 (decapole) components
- $F_d \approx 1e^{-2} \gg 1e^{-4}$ (…not so good field quality)
- **Systematic method** for the evaluation of the field quality

HTS Magnets

Magnetic field perturbed by large eddy currents:

Field demodulation problem



Demodulation

Sources

eddy currents

Dampening

e.g. iron cores lamination

Shifting

e.g. demodulation coils

Consequences

Field distortion

Screening

e.g. MgB_2 pipes

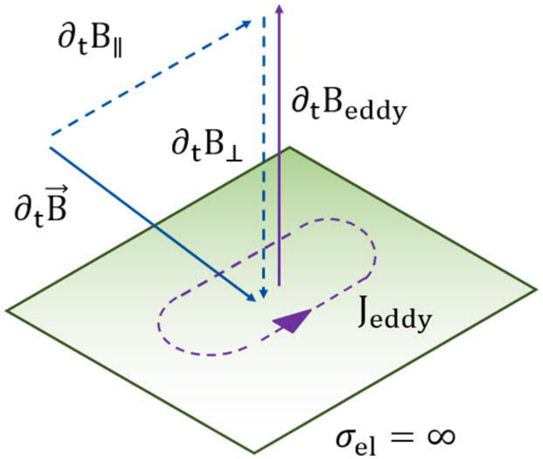
Selective Filtering

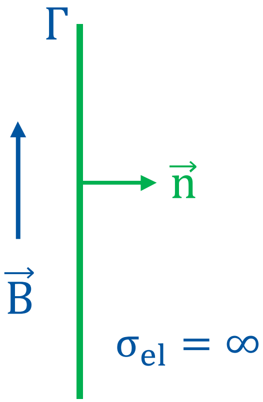
e.g. HALO

HALO

Proof of Concept

HALO based on the principle of perfect electric wall (PEW)





Perfect compensation of any field tangential component

No field relaxation, screening currents do not decay

The idea, in a nutshell:

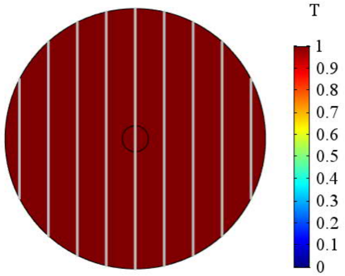
1. Introduction of a PEW tangential to the desired field lines configuration
2. Passive shield against field imperfections
3. Use of HTS tapes to approximate a PEW

Proof of Concept

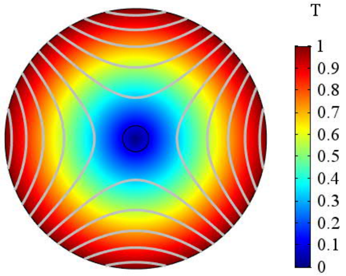
Aperture of an accelerator magnet: no spatial charges, no magnetization

- magnetic field as solution of the Laplace equation
- General solution as infinite sum of multipoles
- Multipoles can be used to create test fields

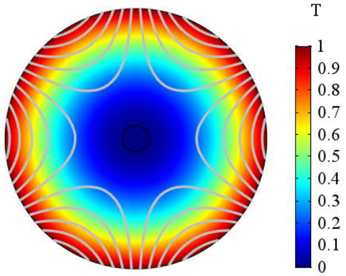
B_2



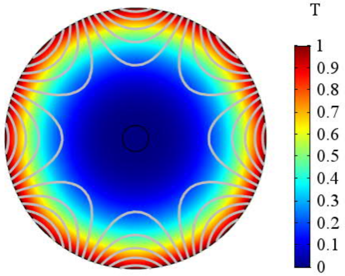
B_4



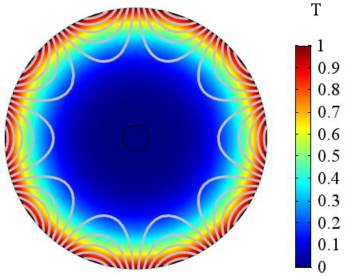
B_6



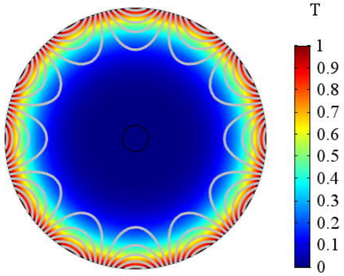
B_8



B_{10}



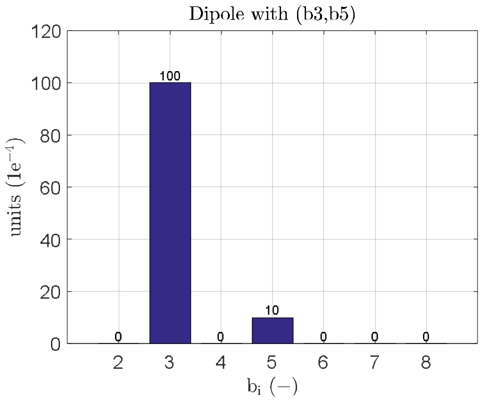
B_{12}



Proof of Concept

Compensation of magnetic field distortion by means of HALO

- Dipole affected by b3, b5 multipoles



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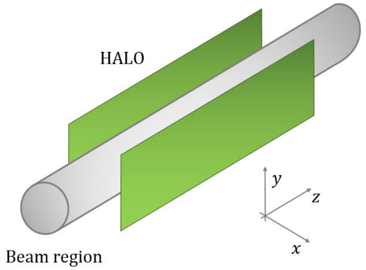
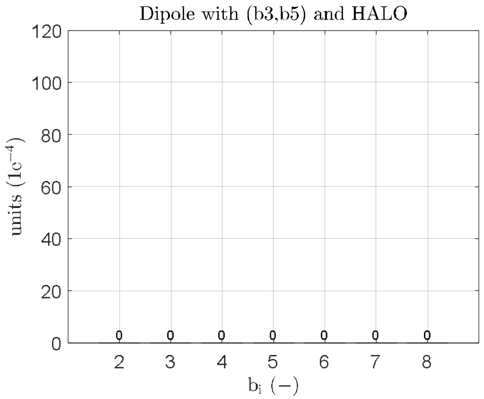
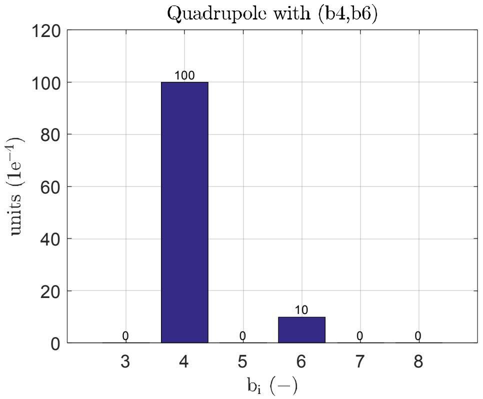




- Quadrupole and b4, b8 multipoles



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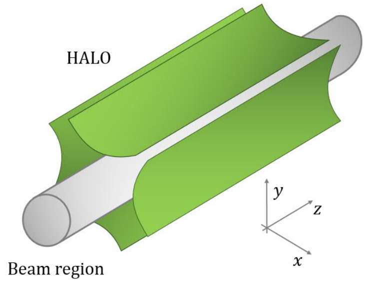
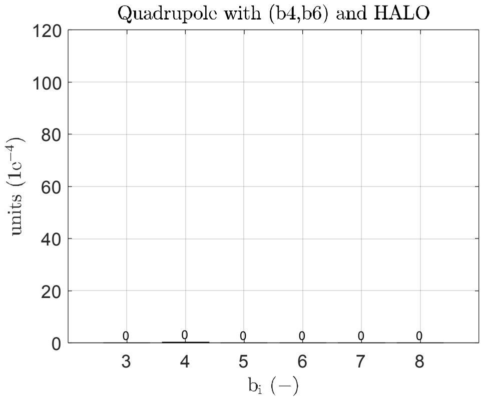
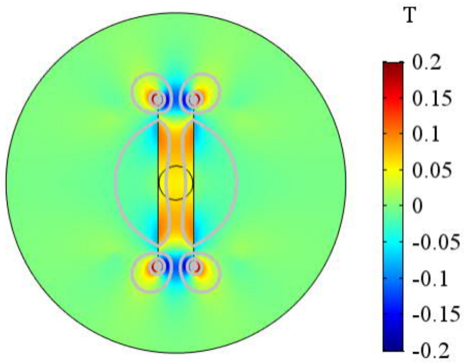




Proof of Concept

Compensation of magnetic field distortion by means of HALO

- Net magnetic field and current distribution in HALO, for the dipole



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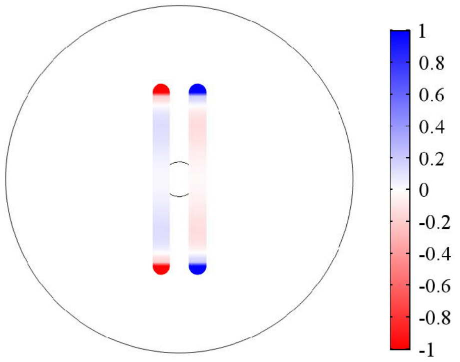
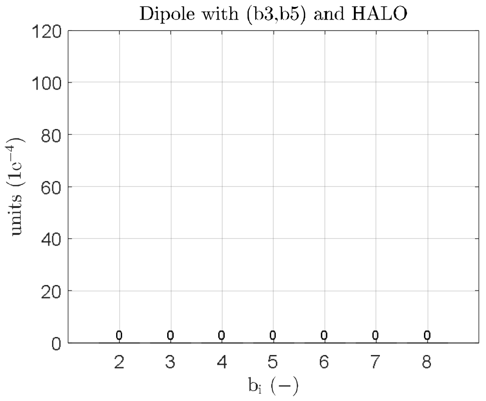
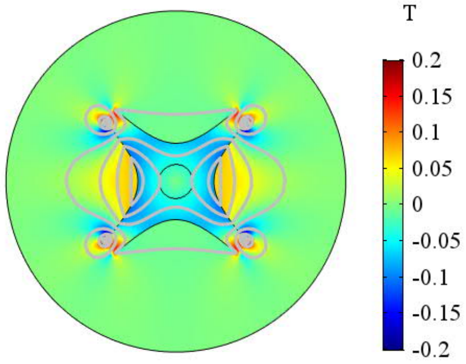




- Net magnetic field and current distribution in HALO, for the quadrupole



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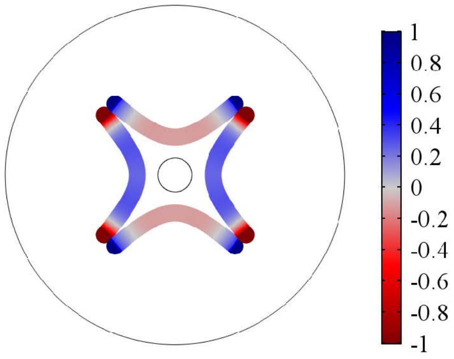
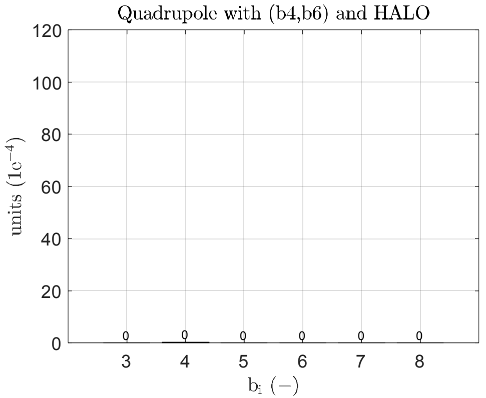
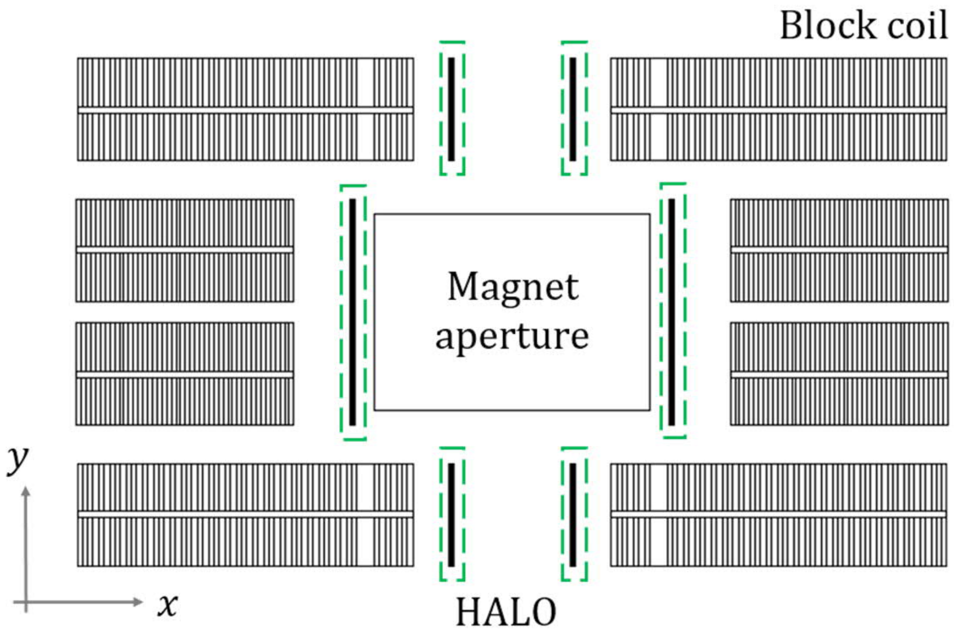




Case Study

A practical case study:

- 20 Tesla HTS dipole [3], based on double pancake block coil design
- HALO added to the baseline design



Cross section of the 20 Tesla dipole

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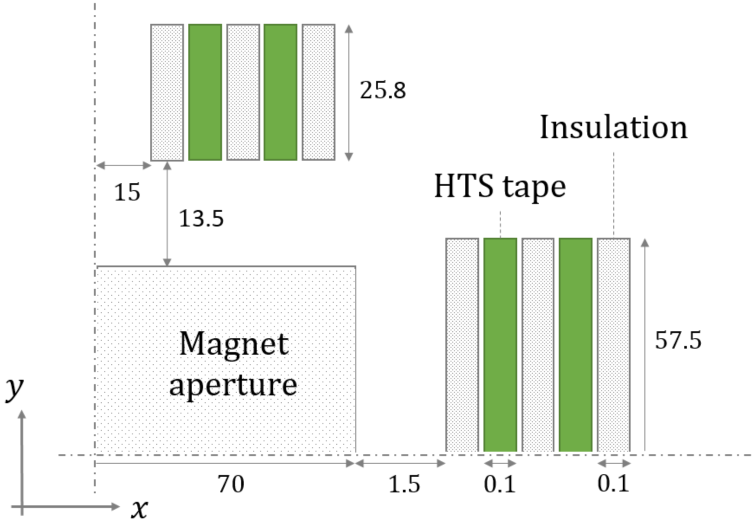
[3] Van Nugteren, Jeroen, et al. "Toward REBCO 20 T+ Dipoles for Accelerators." IEEE Transactions on Applied Superconductivity28.4 (2018): 1-9.

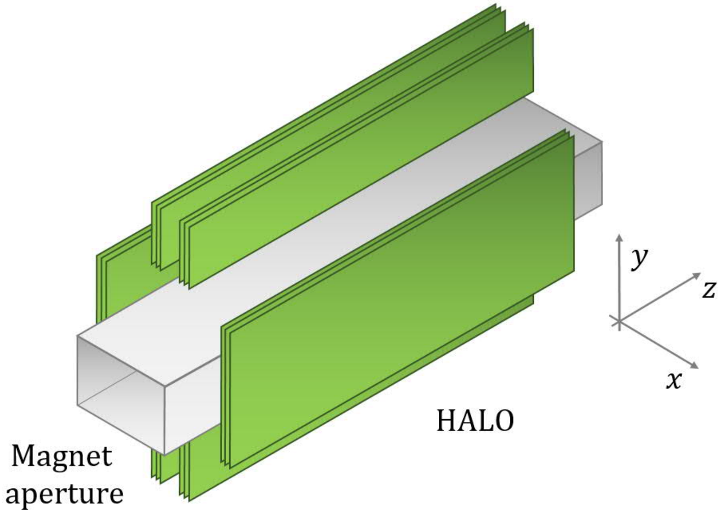
A Closer Look to the design

Geometry:

- Multiple tapes per stack, tapes individually insulated
- Multiple stacks, due to mechanical constraints
- No optimization, just an educated guess



HALO geometry



3D rendering

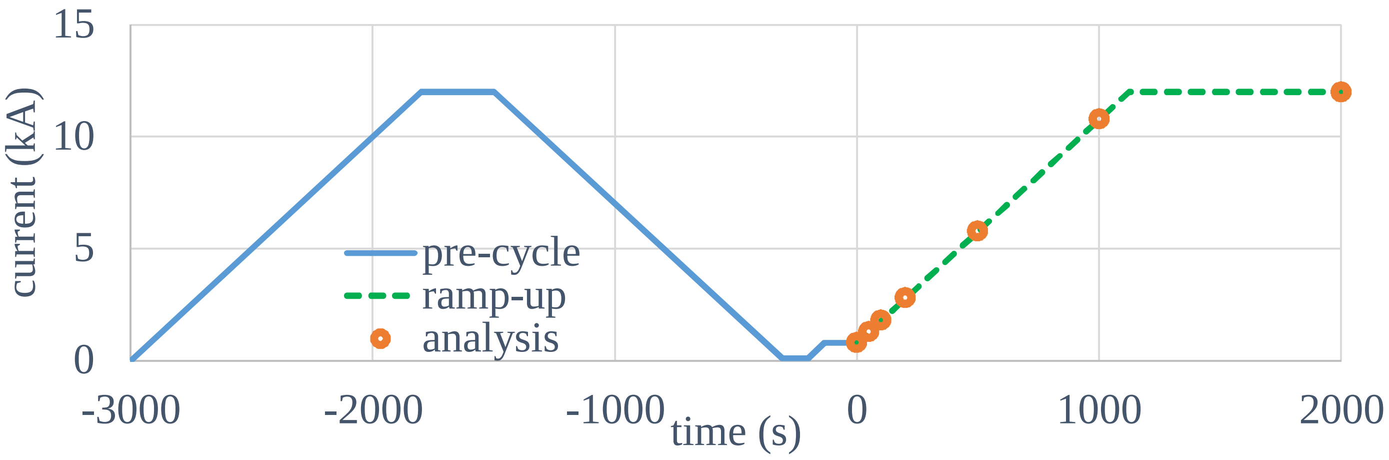
Case Study

Incremental analysis:

Eddy currents in the coil and in HALO

	Scenairo	Coil	HALO
1	No eddy	No	No
2	Eddy	Yes	No
3	HALO	Yes	Yes

- i_{nom} = 12 kA, $\partial_t i\,|_{max}$ = 10 A/s
- Pre-cycle for magnetizing the cable
- Steady state held for ~8 hours

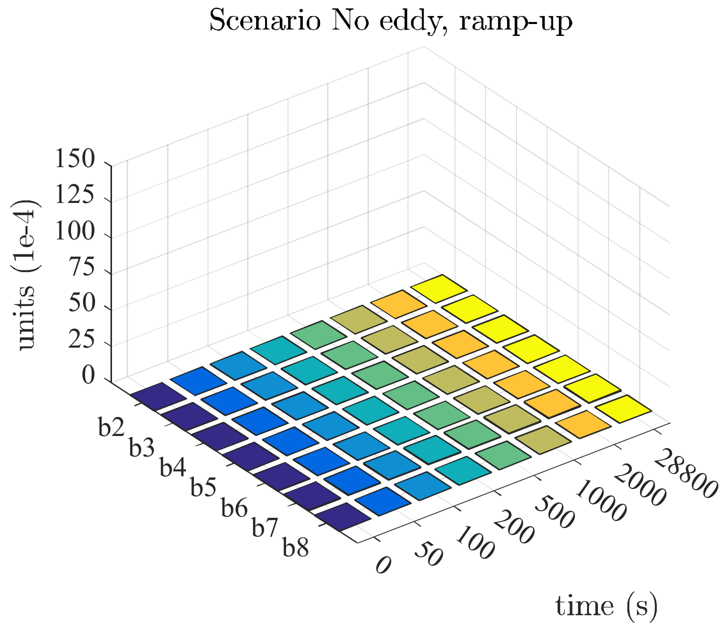


t (s)	0	50	100	200	500	1000	2000	28800
I (kA)	0.8	1.3	1.8	2.8	5.8	10.8	12	12

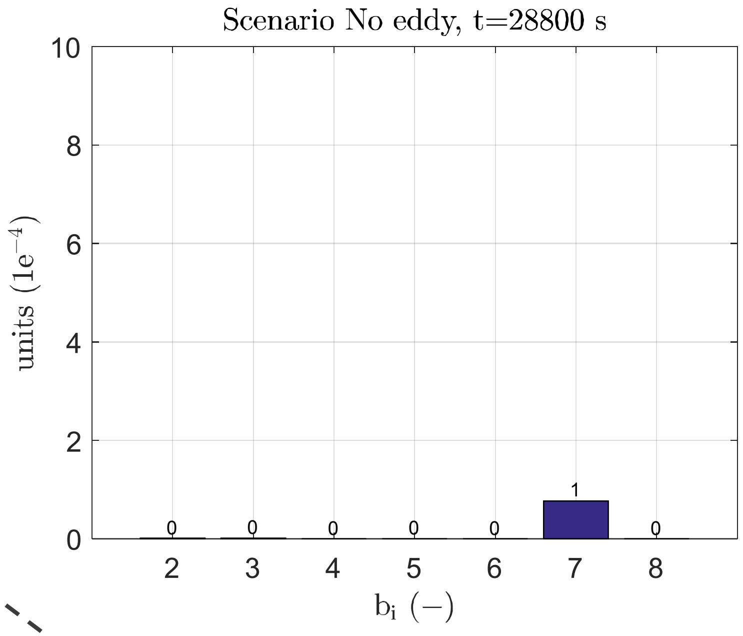
Scenario 1: No eddy

No dynamic effects are taken into account

- Magnetic field almost as ideal dipole
- On the right, magnetic field at the end of pre-cycle



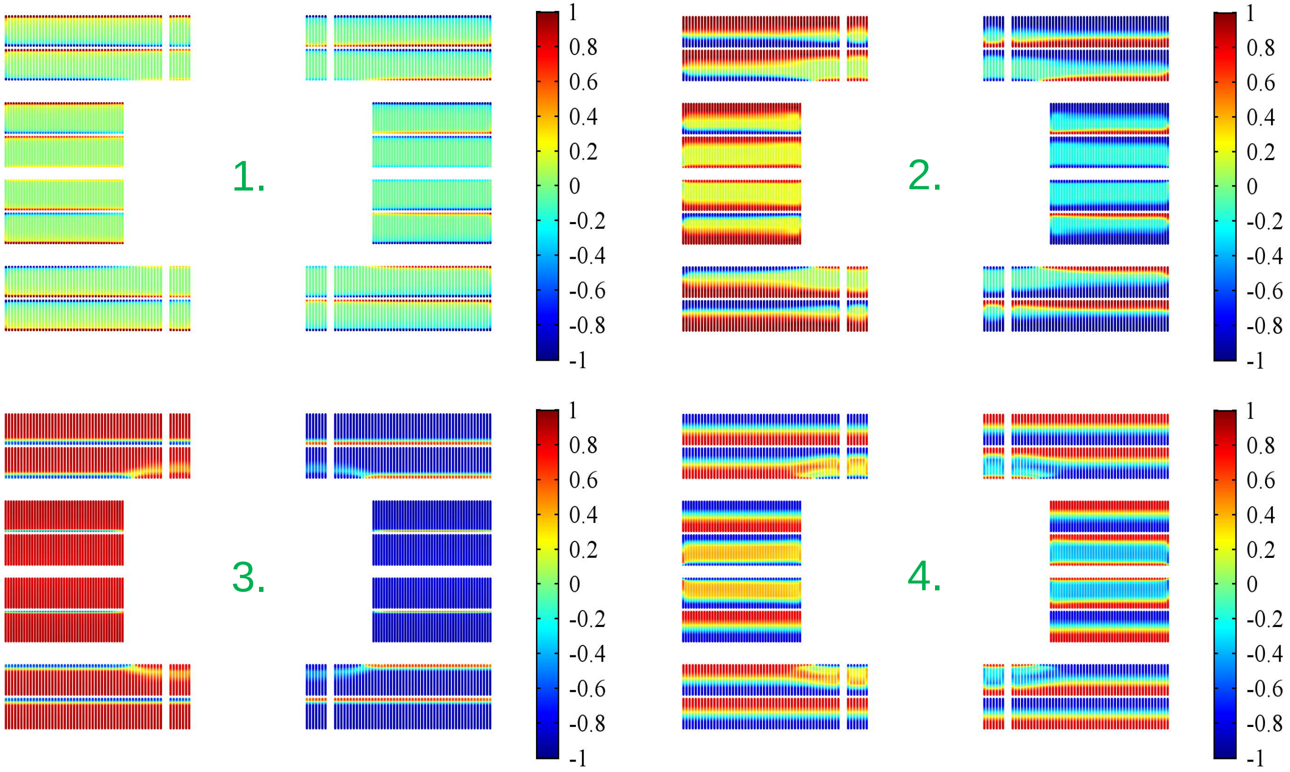
Field harmonics, in units (1e-4), as function of time, during the ramp up



Snapshot after 8 hours

Scenario 2: Eddy

Dynamic effects in the coil:
magnetization during the pre-cycle, due to persistent eddy currents



1.
T = -2900 s
$\partial_t i = 10$ A/s

2.
t = -2500 s
$\partial_t i = 10$ A/s

3.
t = -1500 s
$\partial_t i = 0$ A/s

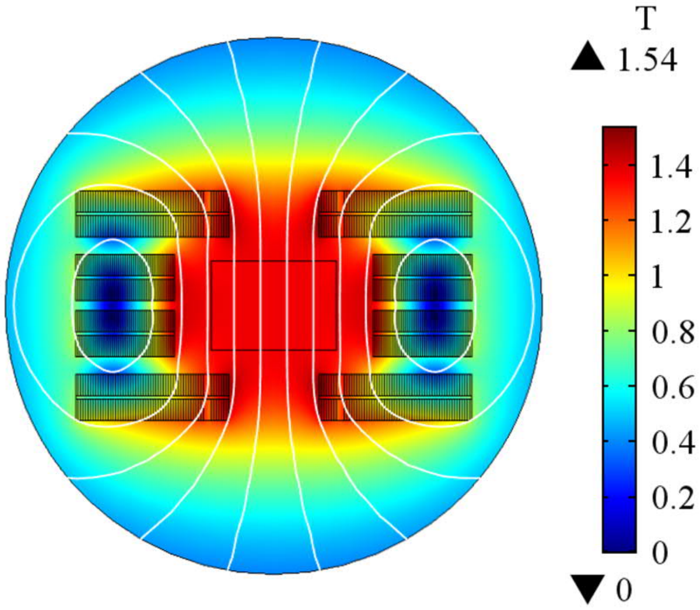
4.
t = 0 s
$\partial_t i = 0$ A/s

Normalized current density distribution in the coil

Scenario 2: Eddy

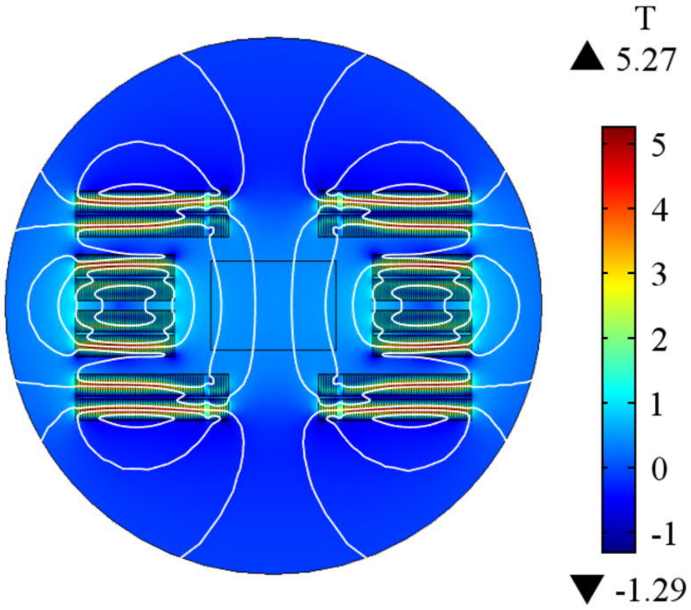
Comparison of the magnetic field density, without and with eddy currents in the coil

time = 0 s



Magnetic field distribution,
no eddy currents in the coil

time = 0 s

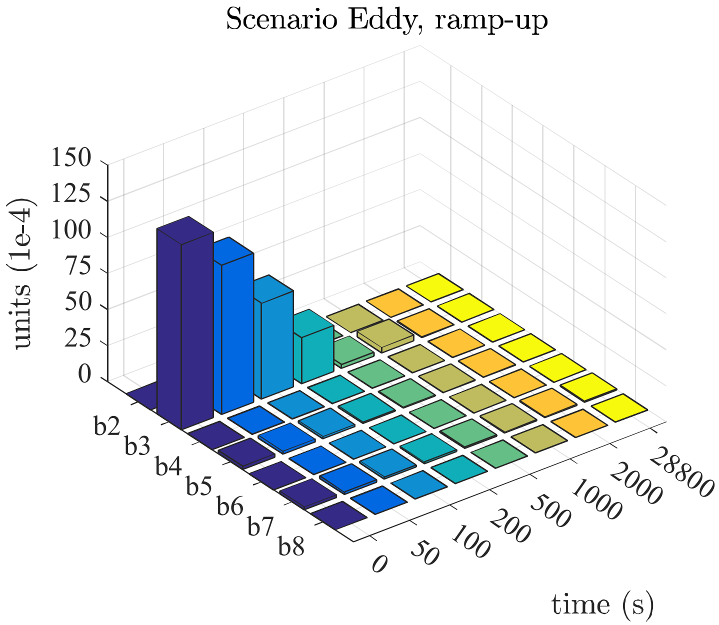


Net magnetic field induced by the
eddy currents in the coil

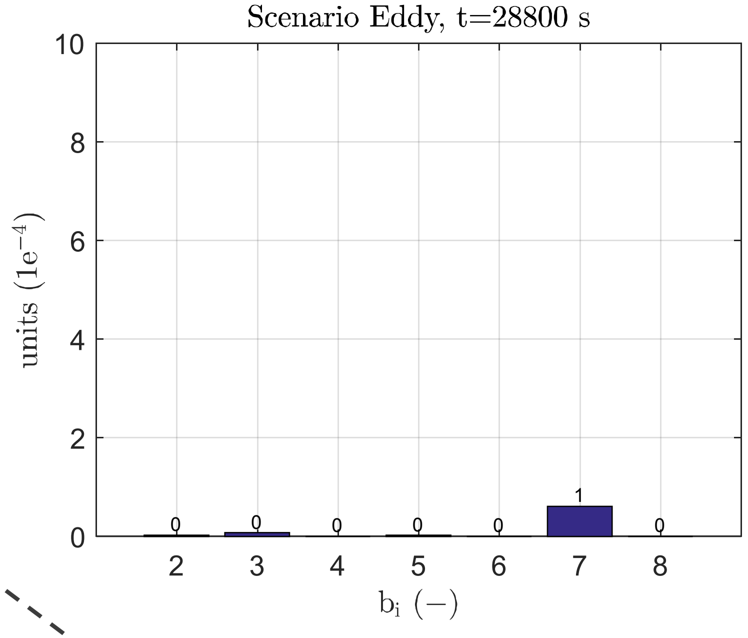
Scenario 2: Eddy

Dynamic effects in the coil are taken into account

- Strong b_3 component introduced by eddy currents
- On the right, magnetic field at the end of pre-cycle



Field harmonics, in units (1e-4), as function of time, during the ramp up

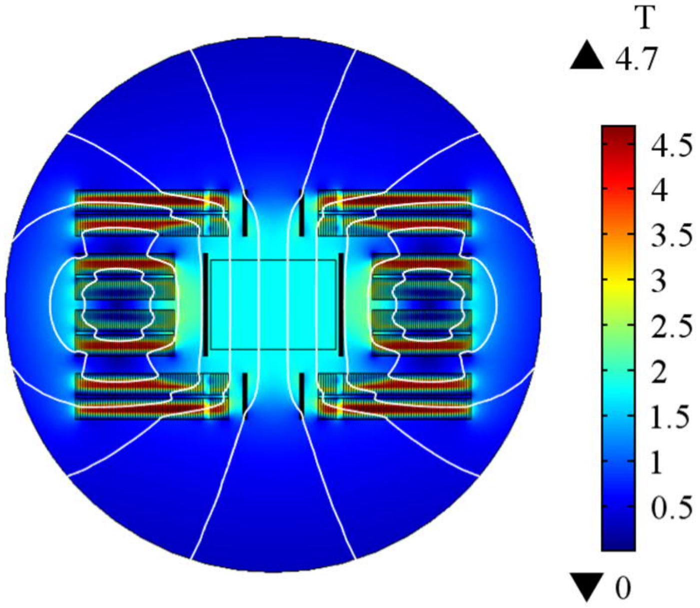


Snapshot after 8 hours

Scenario 3: HALO

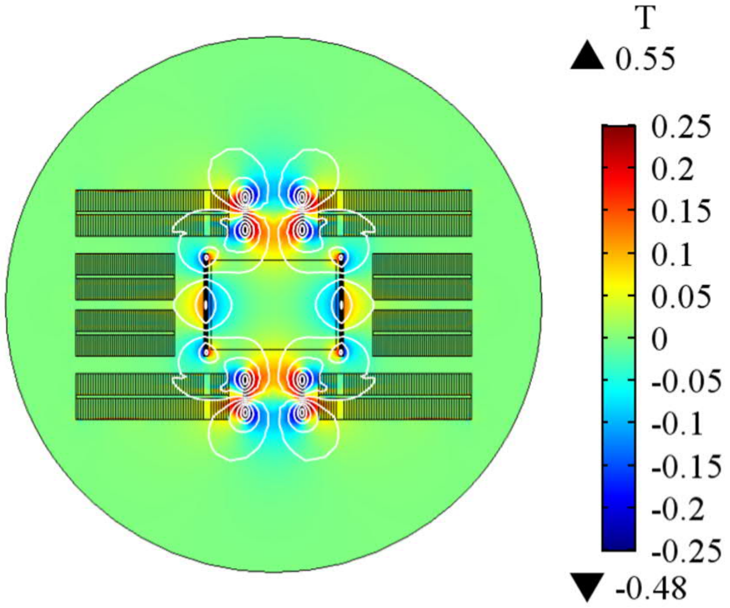
Dynamic effects in the coil are taken into account

time = 0 s



Magnetic field distribution

time = 0 s

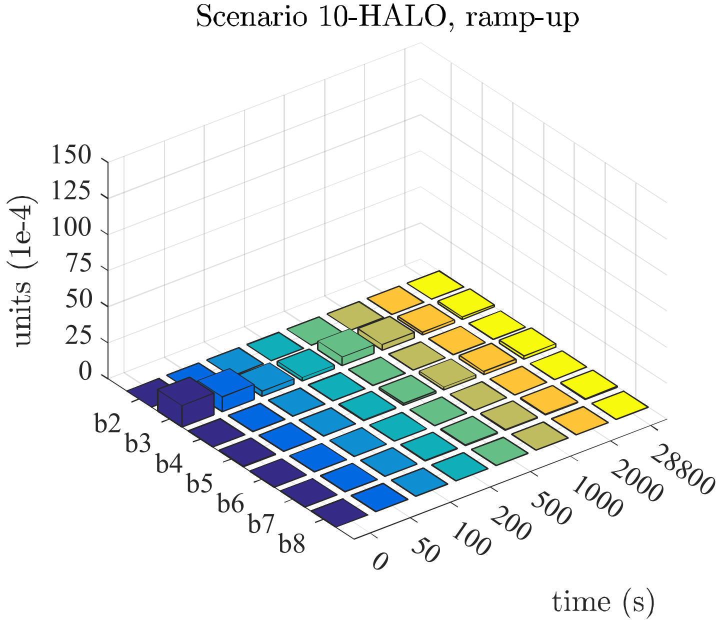


Net magnetic field induced by the HALO device

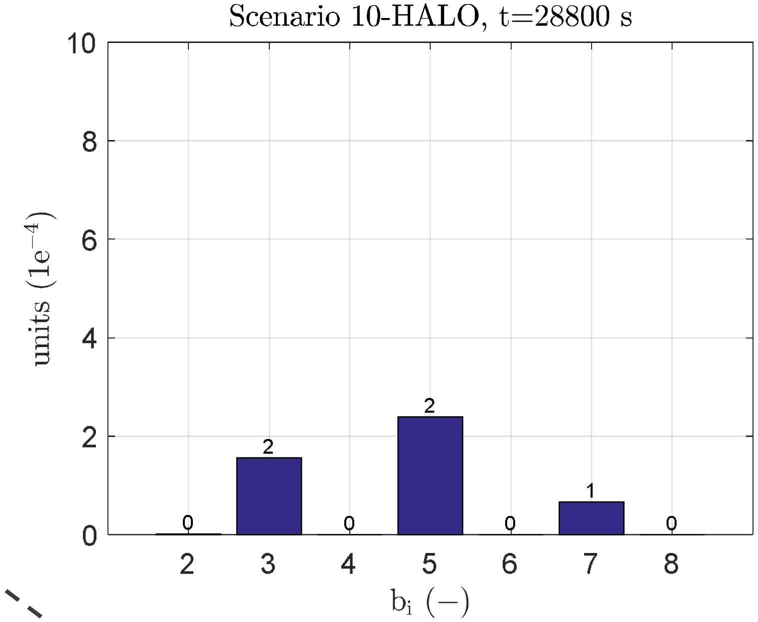
Scenario 3: HALO

Dynamic effects in the coil are taken into account

- Magnetic field almost as ideal dipole
- On the right, net magnetic field introduced by HALO



Field harmonics, in units (1e-4), as function of time, during the ramp up

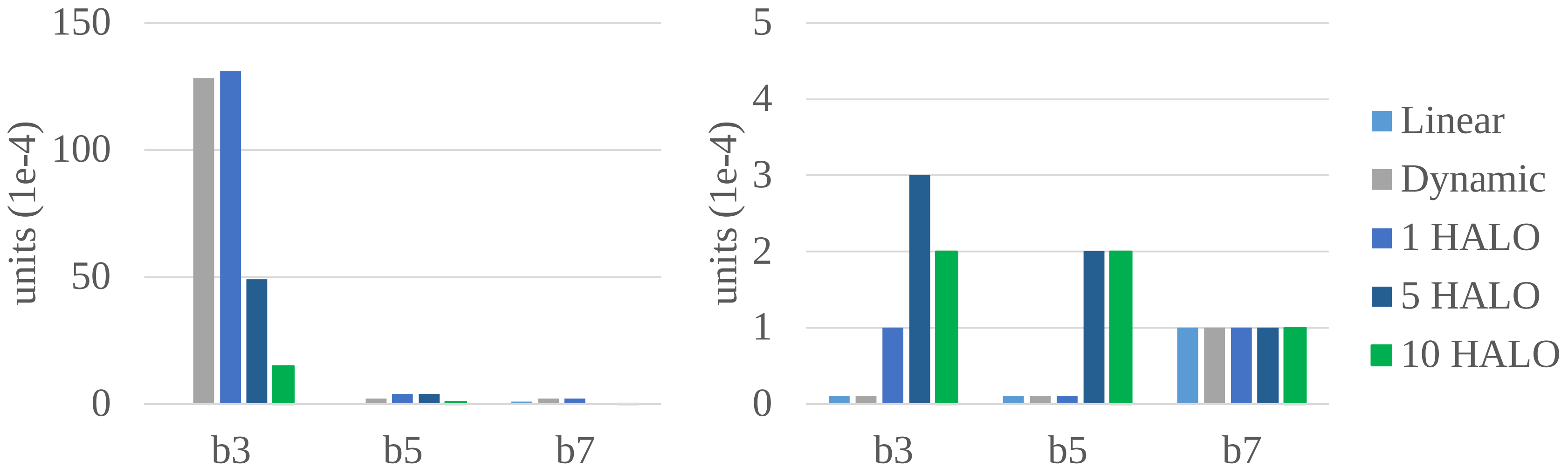


Snapshot after 8 hours

Results

Field harmonics in three scenarios, for both the beginning and the end of the ramp-up

- HALO simulated with an increasing number of HTS foils (1,5,10)



t = 0 s

t = 28800 s

About the 10-tapes HALO:

- b_3 reduced by one order of magnitude (15 units)
- residual b_3, b_5 components at t = 28800 s

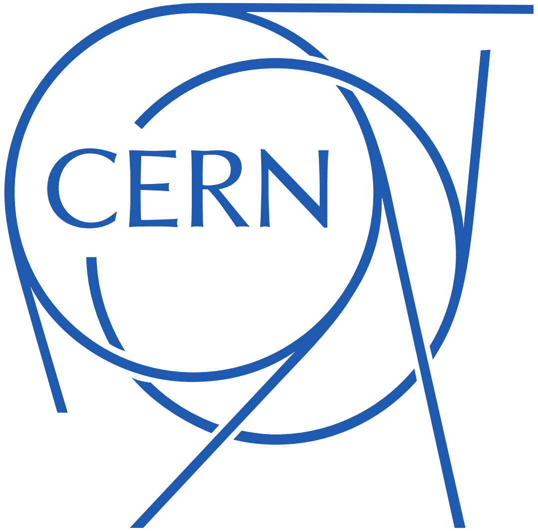
Conclusions

1. Perfect electric wall successfully exploited to correct the multipole errors of an arbitrary magnetic field
2. HTS tapes assembled in stacks, as approximation of a perfect electric wall: A passive harmonics absorber (HALO)
3. Realistic case study (20 Tesla dipole):
   worst field conditions at low current, in dynamic current regime

- In dynamics, HALO reduces the b_3 component by one order of magnitude, without introducing other multipoles
- At regime, few units of b_3 and b_5 are introduced. Correction via both optimizing HALO and the magnet design.

Further Studies

- HALO geometrical optimization
- HALO quench protection (magneto-thermal analysis)
- Quench-induced mechanical stresses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