Persistent Current Shim Coils for Accelerator Magnets

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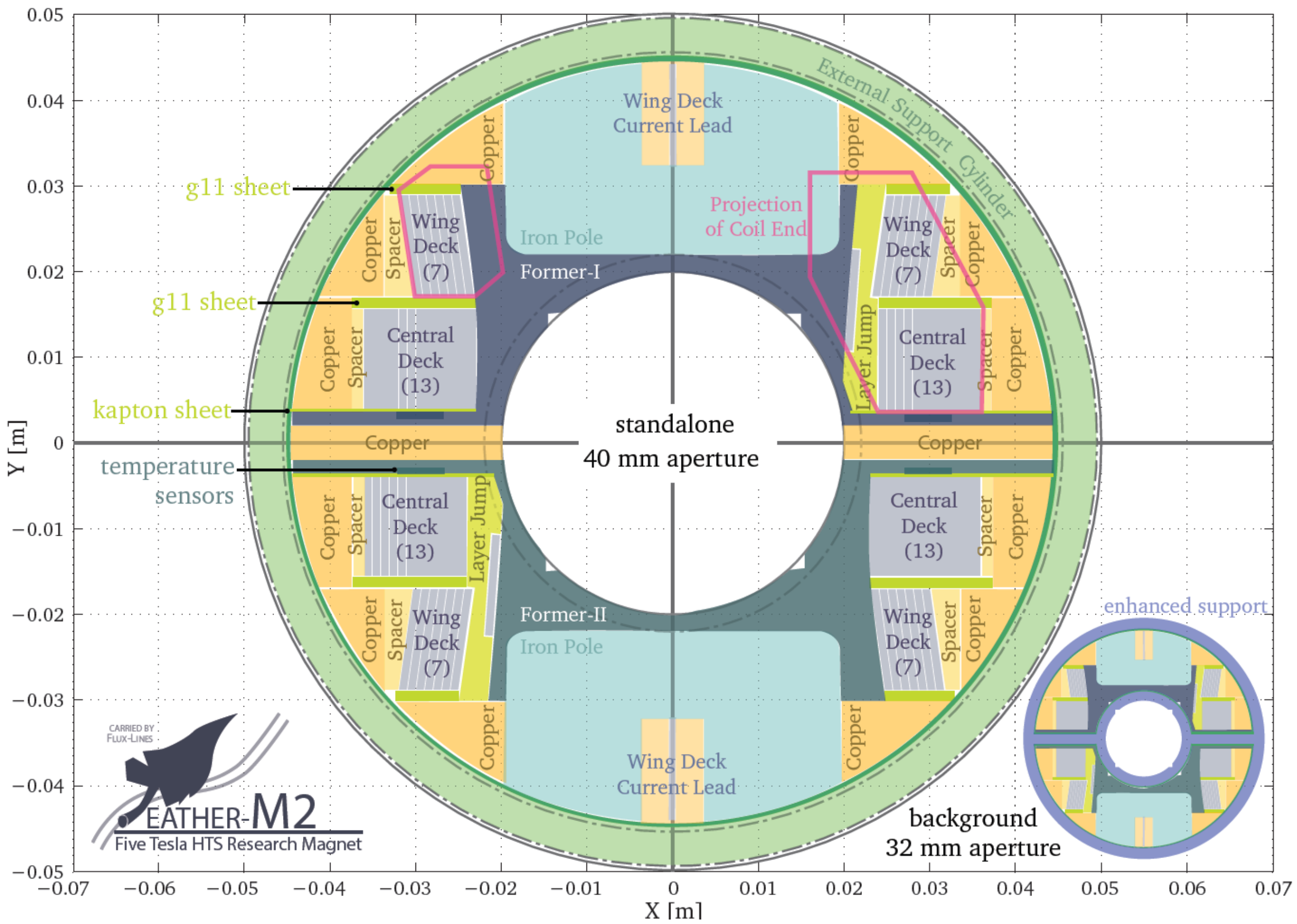
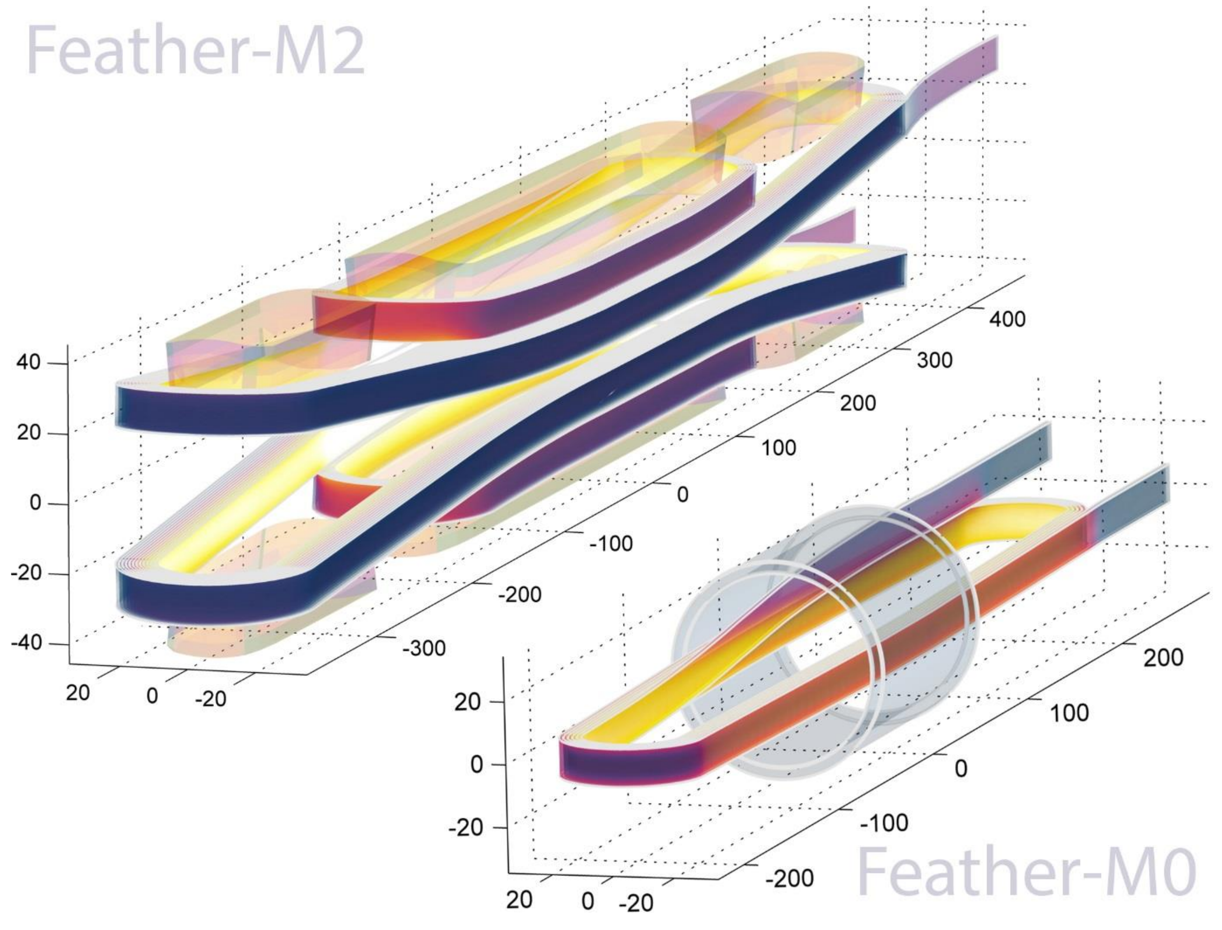
The Problem

HTS Development, Dynamic Field Quality, Magnetization Currents

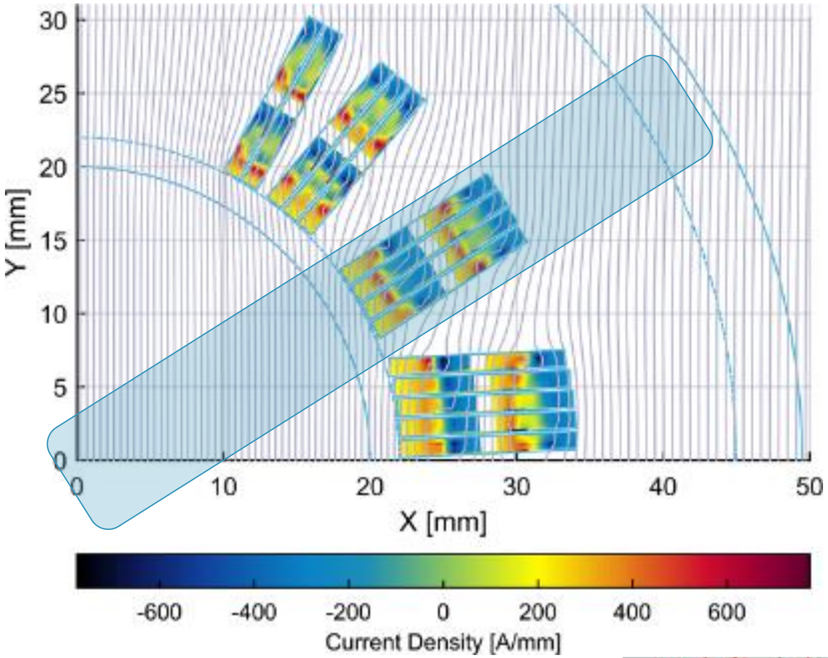
HTS Development



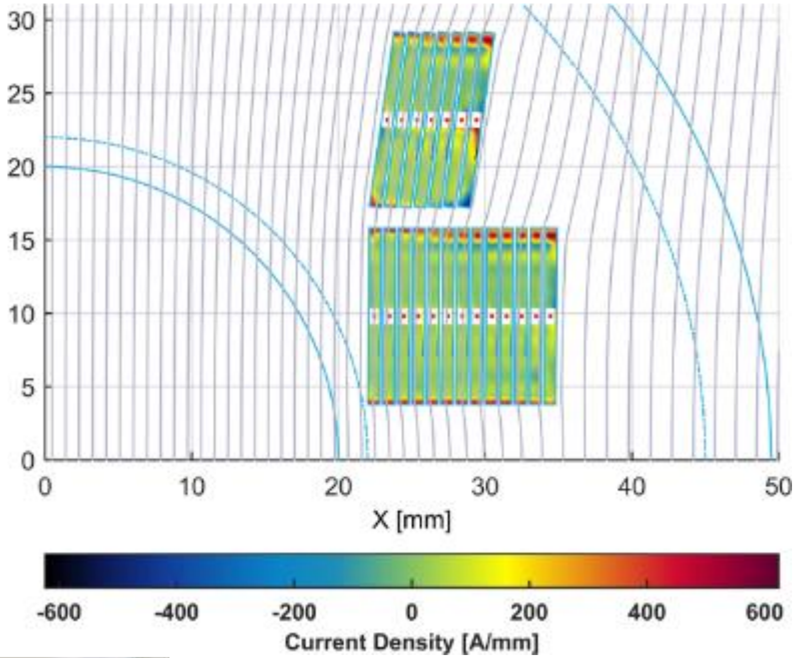


DYNAMIC FIELD QUALITY

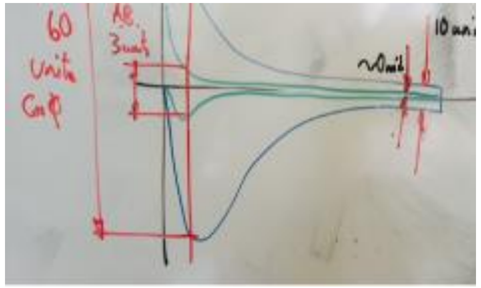
Cos theta design



Aligned Block design



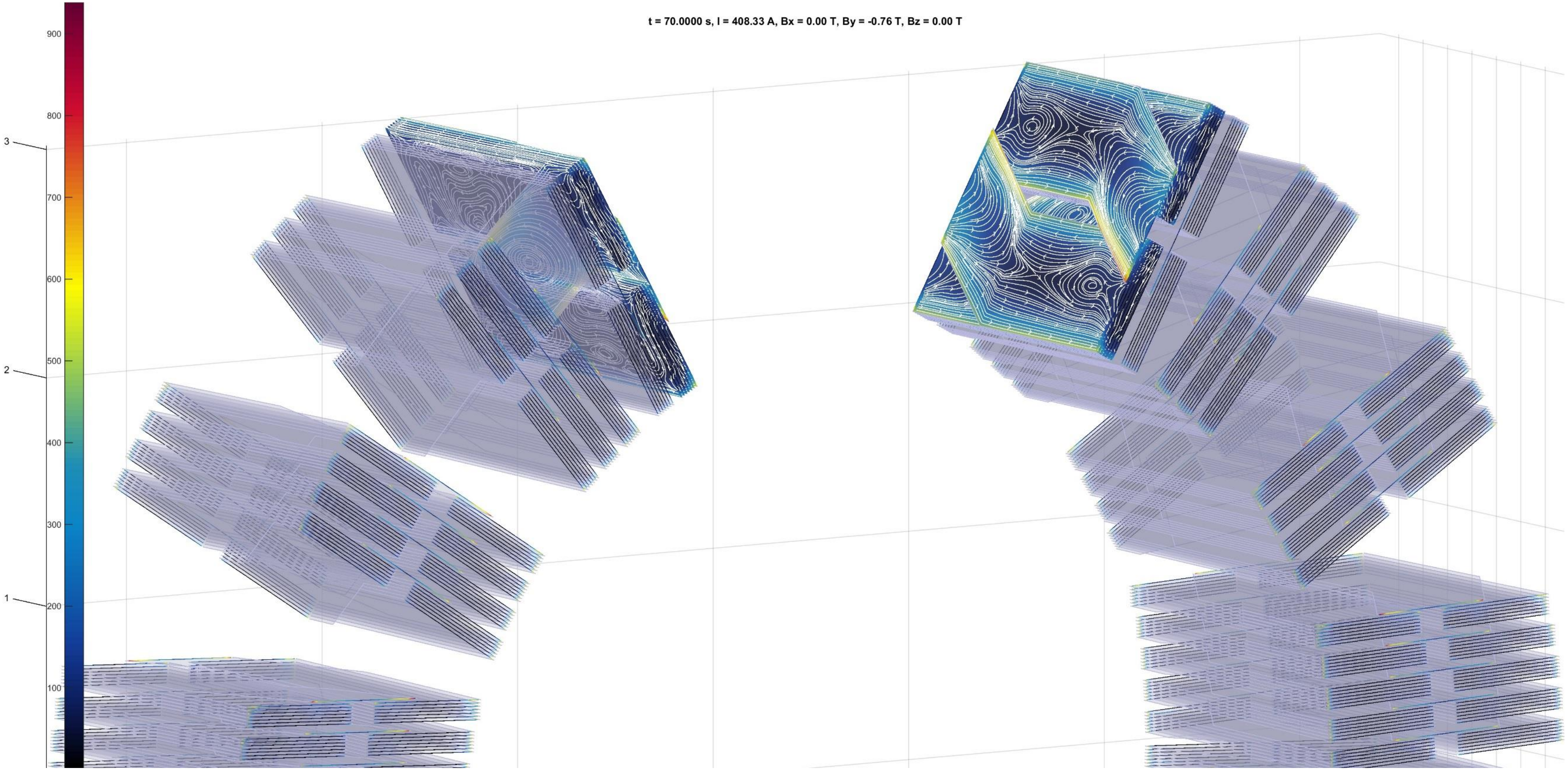
*"b3, 60 unit's variation at low field reducing to < 20 units at high field. b5 and b7 we see ~ 10 units variation, then converge to low values at high field."**



First simulation give b3 , 3units at low field
Increasing at high field 20 T

However modelling assumption assume perfect cable geometry and zero thickened REBCO layer (reality 0.001mm)

Artwork Showing Magnetization Currents



The Idea

Persistent Current Shim coils, Circuit, Geometry, Helical Coils

Persistent Current Shim Coils

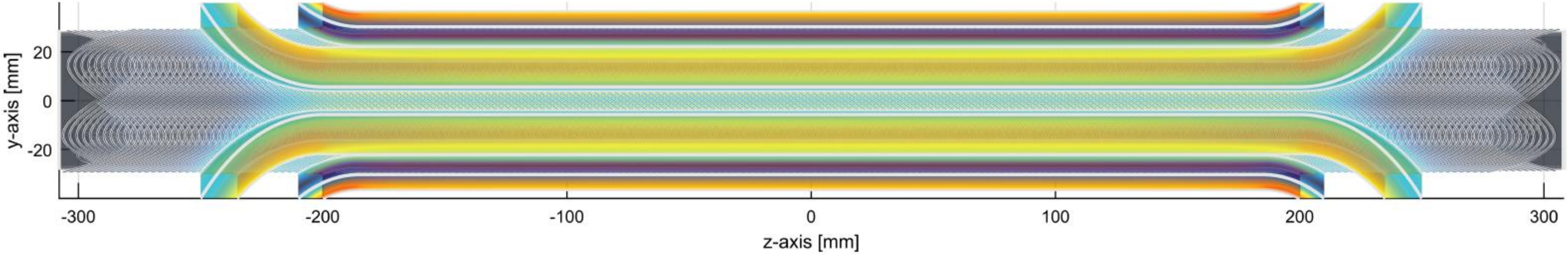


Fig. 3. The geometry of the dipole used for the calculations. The dipole consists of two racetracks, bend over the z-axis, per pole. For demonstration purposes, inside the aperture a sextupole shim coil is shown.

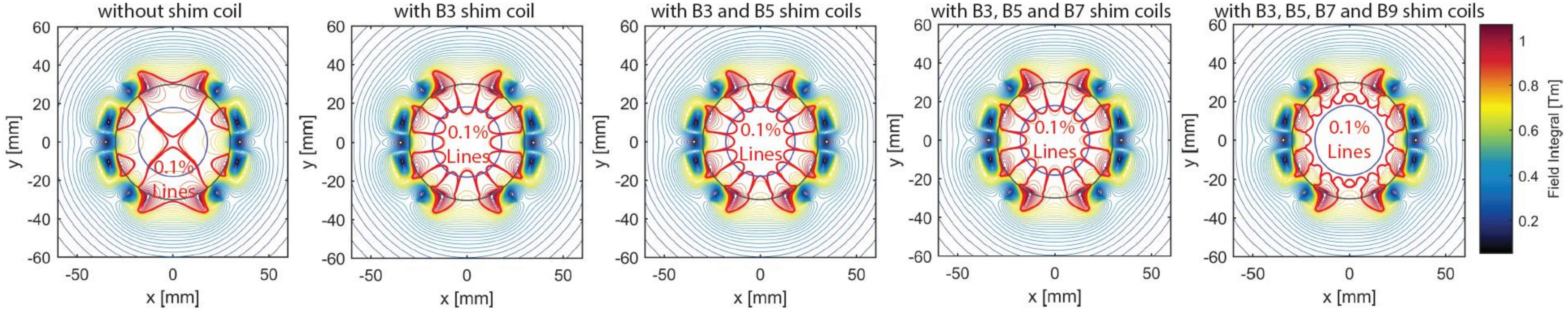


Fig. 8. Magnetic field integrated in the direction of the z-axis over the magnetic length of the shim coils, for the case where the shim coil is longer than the magnet itself. The integration is performed separately for the x- and y-components, after which the integrated components are used to determine the magnetic field magnitude. The red line encloses the region where the field integral deviates less than 0.1% from the field integral on the z-axis.

THE CIRCUIT AND CONCEPT

$$\frac{dI_2}{dt} = \frac{M_{12}}{L_2}\frac{dI_1}{dt},$$

- The shims are connected in persistent mode
- By topology the current induced in the resistanceless shim coil cancels out only one harmonic component of the field, independent of the origin, acting as a filter.
- Multiple shim coils can be nested to filter out several (different) harmonics.
- This shifts the issues concerning field quality, away from the coil pack such that these main windings can be optimized for current density and efficiency.
- The current in the shim can be calculated by approaching the system as a transformer. Inductance calculations are not straight forward.
- A heater allows for resetting the current

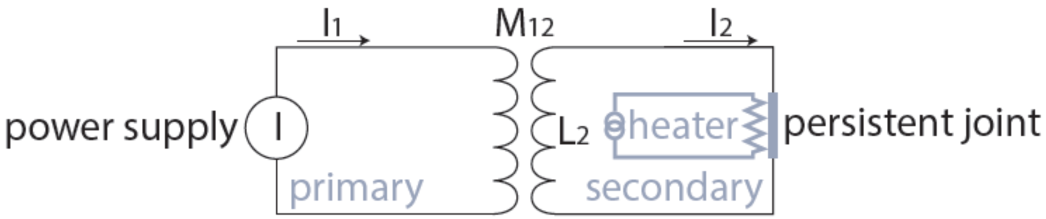


Fig. 4. The circuit diagram used in the numerical model to calculate the induced current in each of the shim coils.

TABLE II

INTEGRATED HARMONIC CONTENT, AT 18 mm RADIUS, OVER THE FULL LENGTH OF THE COMBINED COIL (SHIM + DIPOLE).

shim coils (with R)	b_3 [units]	b_5 [units]	b_7 [units]	b_9 [units]
none	−419.9	−24.5	−29.1	−42.9
B_3	0.18	−24.49	−29.1	−42.9
B_3-B_5	0.23	−0.22	−29.1	−42.9
B_5-B_3	0.18	−0.26	−29.1	−42.9
B_3-B_5-B_7	−0.93	−0.27	−0.22	−42.9
B_7-B_5-B_3	−0.19	−0.27	−0.53	−42.9
B_3-B_5-B_7-B_9	−0.09	−0.22	−0.27	−0.56
B_9-B_7-B_5-B_3	0.19	−0.27	−0.52	−1.24

Shim Coil Geometry

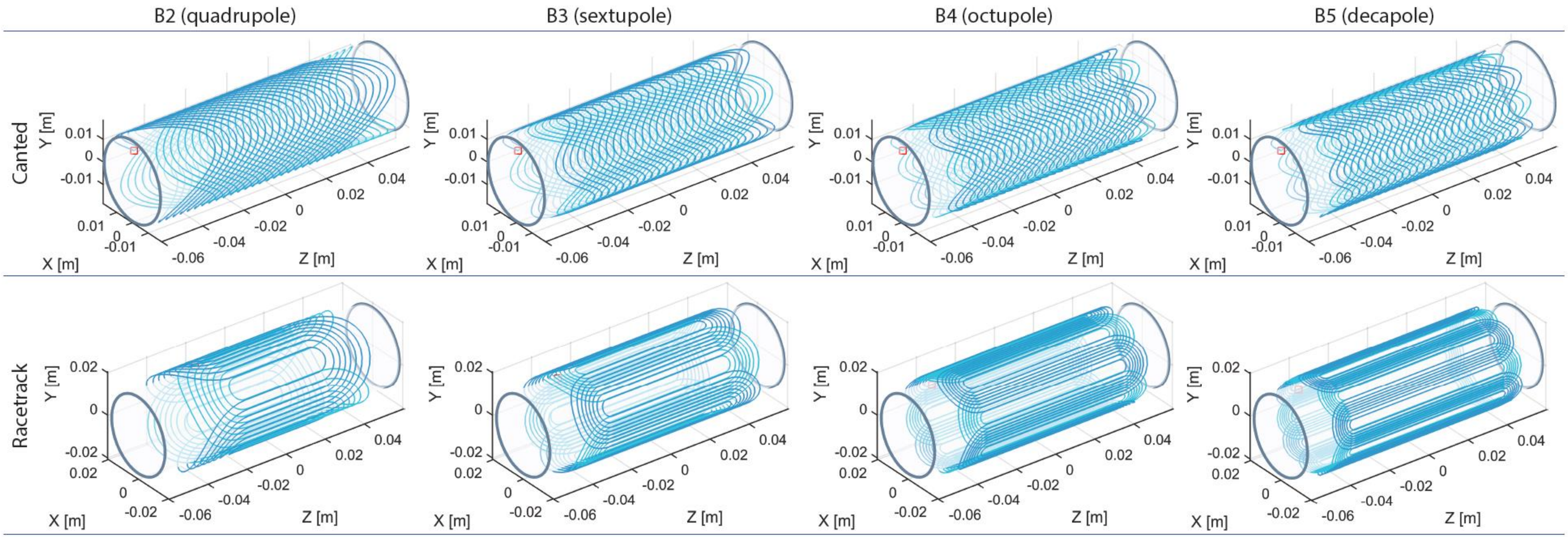


Fig. 1. Coil shape for each of the the first three coil harmonics with both racetrack and canted winding variations. Both variations consist of two separate layers represented by the light and dark blue lines respectively. A semi-transparent white cylinder was added inside the coils for viewing purposes.

HELICAL GEOMETRY

- The helical geometry is very suited for the shim coils since there are no end effects
- A simple equation represents the geometry
- The maximum harmonic a shim can be predicted analytically from the critical current Ic(B)
- Already some experience from the orbital corrector

$$\vec{x} = \vec{e}_x R_0 \cos(\theta) + \vec{e}_y R_0 \sin(\theta) + \vec{e}_z \left[\frac{R_0 \sin(n\theta)}{n \tan(\alpha)} + \frac{\omega\theta}{2\pi} \right], \quad (1)$$

$$B_n = \left[\frac{r_0}{R_0} \right]^{n-1} \frac{\mu_0 I_0 \cot(\alpha)}{2}$$

TABLE I

PARAMETERS DEFINING THE SHIMS IN THE NUMERICAL EVALUATION.

name	value	description
n	3,5,7 and/or 9	harmonic
α	35.0 deg	skew angle
d_r	1.00 mm	midplane rib thickness
d_w	0.60 mm	wire diameter
n_{tshort}	60	number of turns for the short shims
n_{multi}	40	number of turns per adjacent shim
n_{long}	210	number of turns for the long shim
n_{pt}	210	number of elements per turn
n_d	2	number of elements in wire width
n_h	2	number of elements in wire height

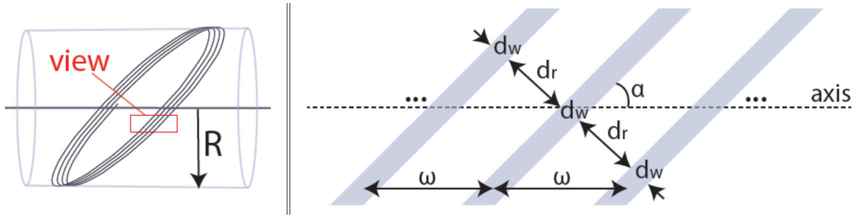
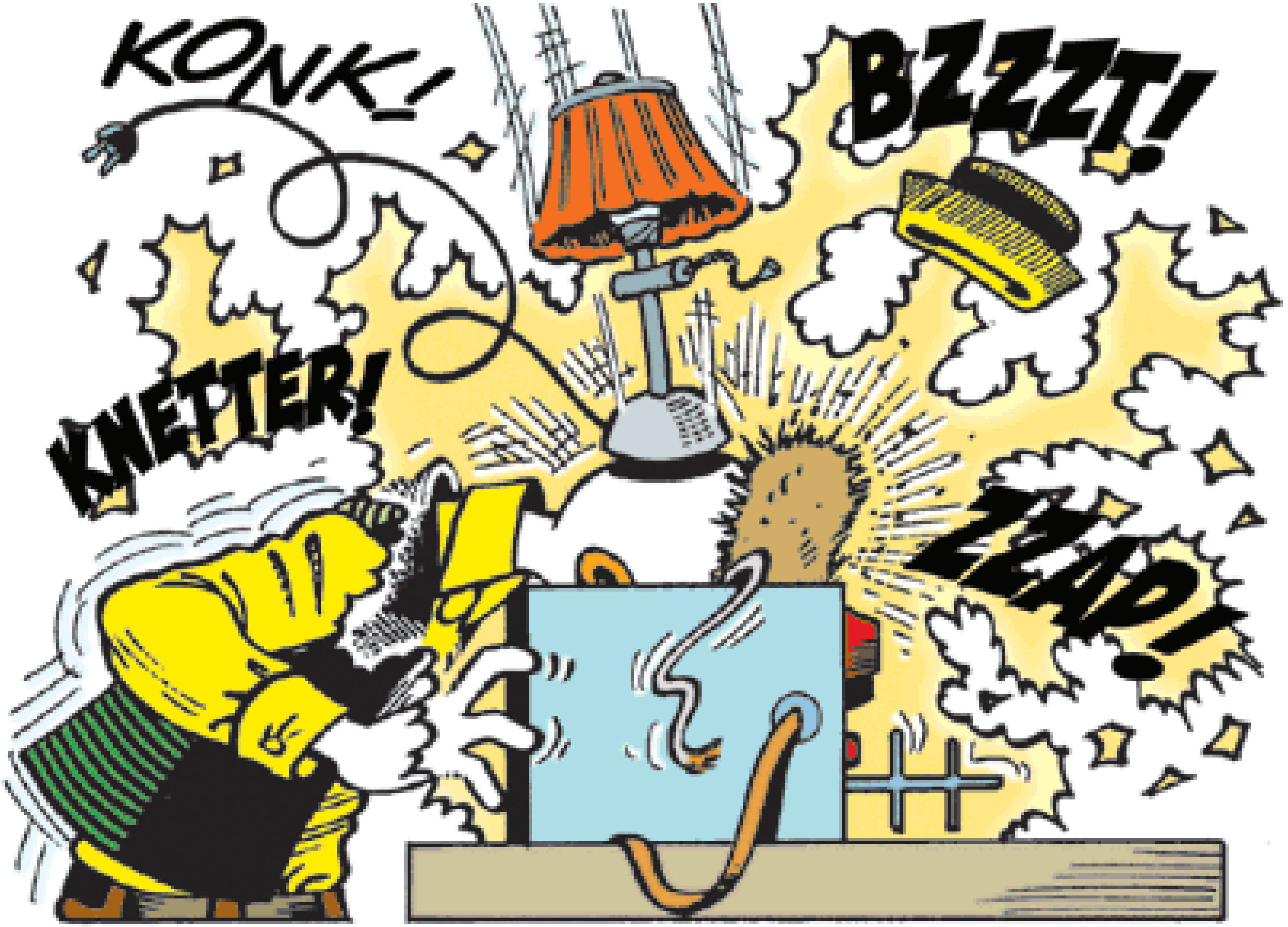


Fig. 2. Definition of the parameters that define the shape of the helical coils. The part on the right is a view on the mid-plane as indicated on the left.

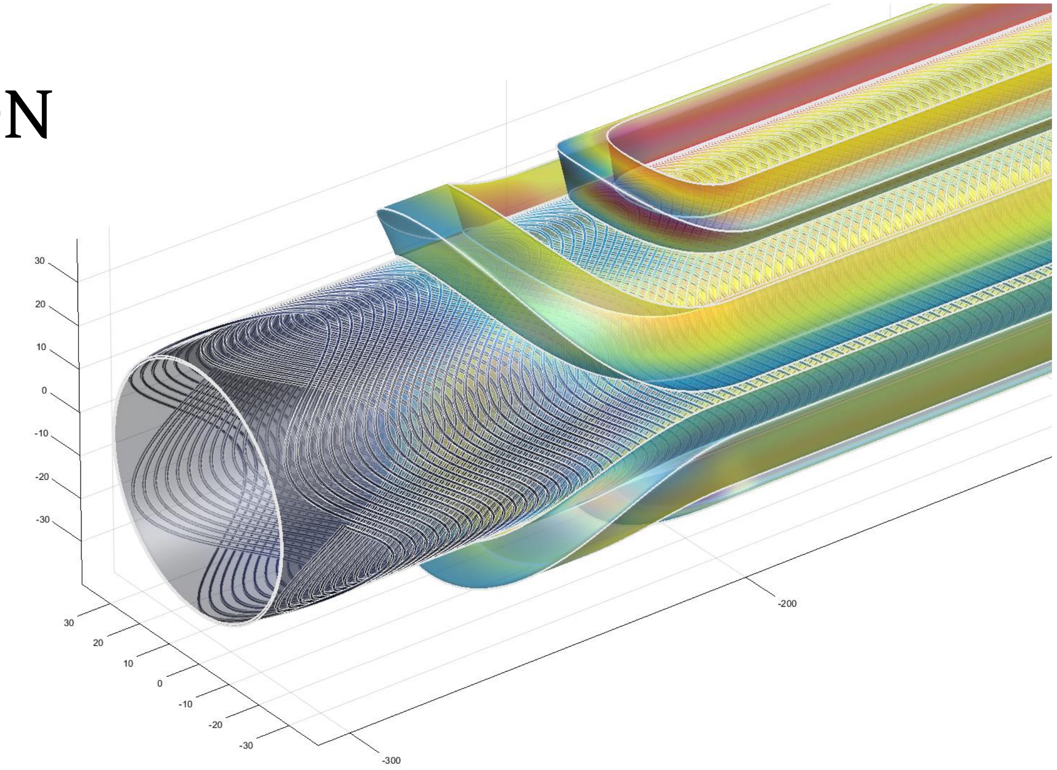
Further Analysis

Shim Length, Quench, Sensitivity, Manufacturing



SHIM COIL LENGTH AND CONFIGURATION

- In order to validate the concept an experiment will be performed.
- A numerical analysis is performed on the pseudo harmonics along the length of the magnet
- The shims work over their magnetic length
- Since the length and position of the measurement probe is likely different the result should be compared to the model.



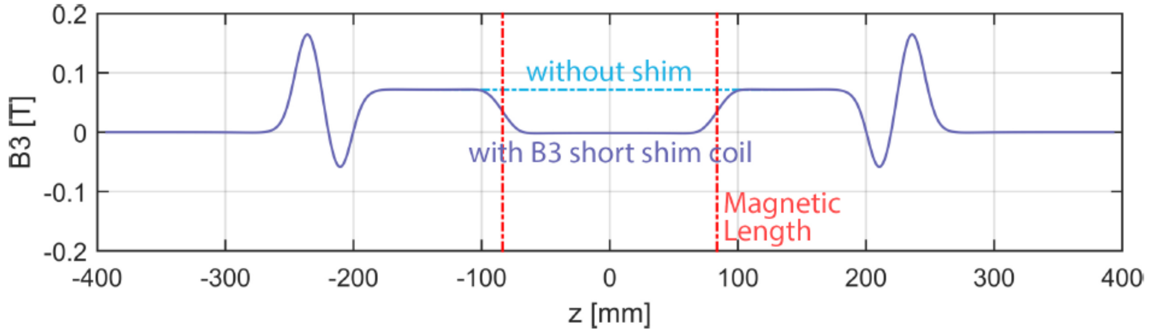


Fig. 5. The sextupole component at 18 mm as function of the axial position, with and without shim coil, for the case where a shim coil is covering only a short straight section of the coil.

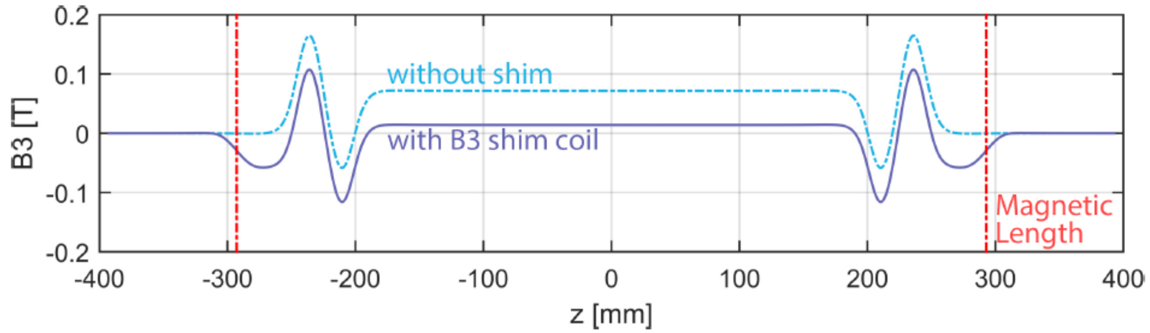


Fig. 7. The sextupole component at 18 mm as function of the axial position, with and without shim coil, for the case where a single shim coil is covering the full length of the dipole.

Preliminary Quench Analysis

- Simple adiabatic quench model
- For a meter long shim there is not enough stored energy to burn the coil.
- More analysis needed for longer coils

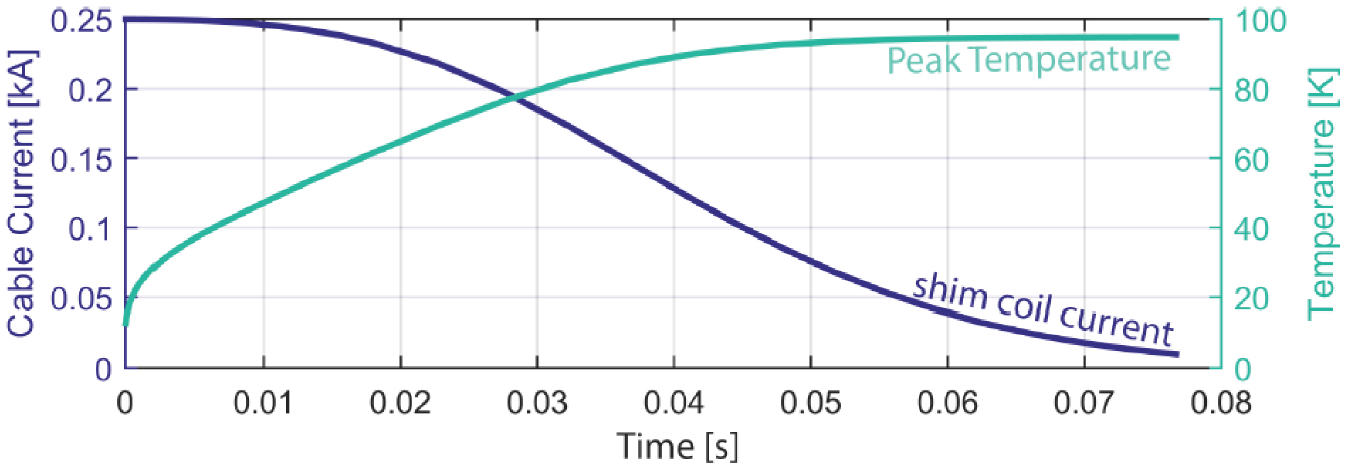


Fig. 9. Adiabatic quench analysis of a 0.8 m long sextupole shim coil operating at 250 A, without quench protection system.

Preliminary Sensitivity Analysis

- A statistical analysis is performed on different type of errors.
- When the shim coil generates harmonics that are not part of the intended field part of the energy or current is used in a different harmonic leading to under compensation
- For errors around 50 micron the standard deviations remain less than a unit.

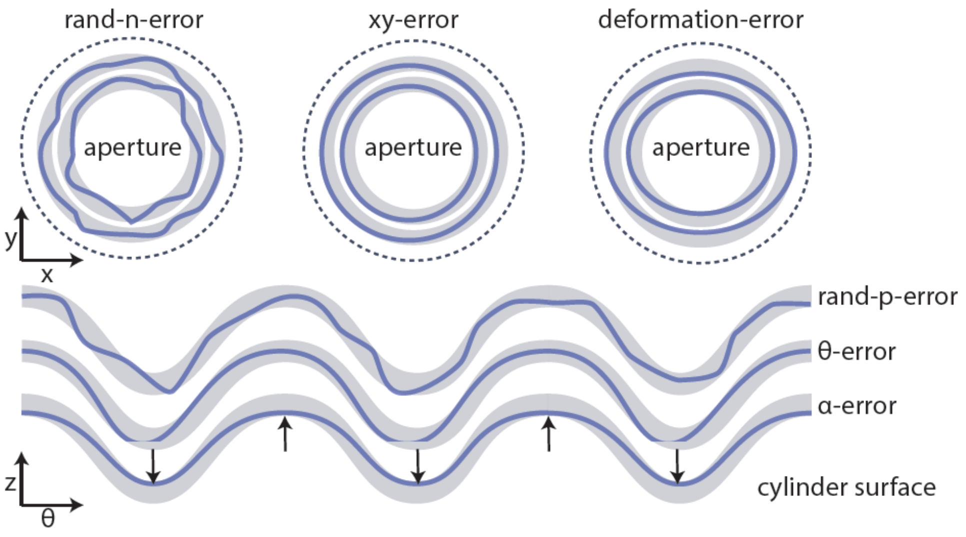


Fig. 10. Different types of errors on the wire position. On the top the view is along the z-axis. On the bottom the view is normal to the surface of the support cylinder looking directly at the slots.

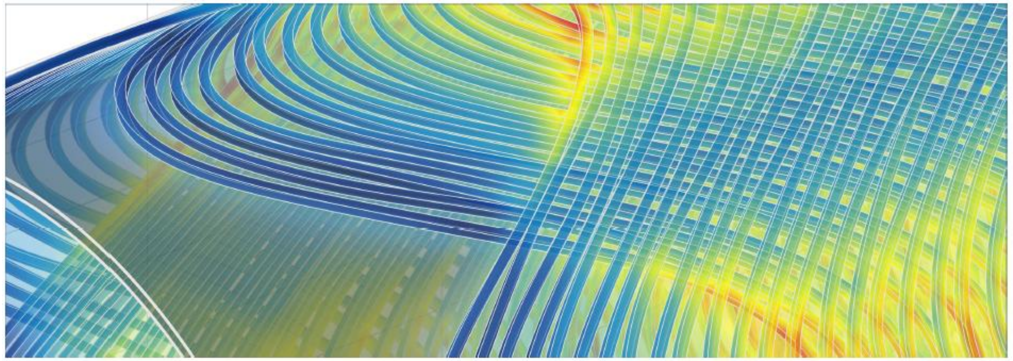


Fig. 11. Over exaggerated random positional errors added to the geometry of a sextupole shim coil in the direction parallel to the surface of the support cylinder.

TABLE III
SENSITIVITY OF THE INTEGRATED HARMONIC CONTENT OF THE SHIM COILS TO RANDOM NOISE IN THE P-DIRECTION.

coil and error description			standard deviation σ of the integrated harmonics in units													
coil type	err. type	err. ampl.	b_1	b_2	b_3	b_4	b_5	b_6	b_7	a_1	a_2	a_3	a_4	a_5	a_6	a_7
B_3 long	rand-p	50 μ	0.45	0.51	0.00	0.40	0.33	0.23	0.17	0.42	0.53	0.55	0.41	0.32	0.24	0.19
B_5 long	rand-p	50 μ	1.17	1.35	1.30	1.03	0.00	0.59	0.43	1.07	1.36	1.24	1.08	0.93	0.62	0.47
B_7 long	rand-p	50 μ	2.89	3.48	3.40	2.65	2.21	1.50	0.00	2.71	3.52	3.20	2.81	2.14	1.58	1.36

TABLE IV
SENSITIVITY OF THE INTEGRATED HARMONIC CONTENT OF THE SHIM COMBINED WITH THE MAIN DIPOLE. VALUES OF INTEREST ARE IN ORANGE.

coil and error description			standard deviation σ of the integrated harmonics in units													
coil type	err. type	err. ampl.	b_1	b_2	b_3	b_4	b_5	b_6	b_7	a_1	a_2	a_3	a_4	a_5	a_6	a_7
B_3 long	rand-p	50 μ	0.00	0.02	0.20	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.01	0.01	0.01	0.01
B_5 long	rand-p	50 μ	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B_7 long	rand-p	50 μ	0.00	0.01	0.01	0.01	0.00	0.00	0.06	0.01	0.01	0.01	0.01	0.00	0.00	0.00
B_3 long	rand-n	50 μ	0.00	0.01	0.12	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
B_3 long	x	50 μ	0.00	0.70	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B_3 long	y	50 μ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72	0.00	0.00	0.00	0.00	0.00
B_3 long	xy	50 μ	0.00	0.73	0.13	0.00	0.00	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.00
B_3 long	θ	0.5 deg	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	4.21	0.00	0.00	0.00	0.00
B_3 long	α	0.5 deg	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

MANUFACTURING

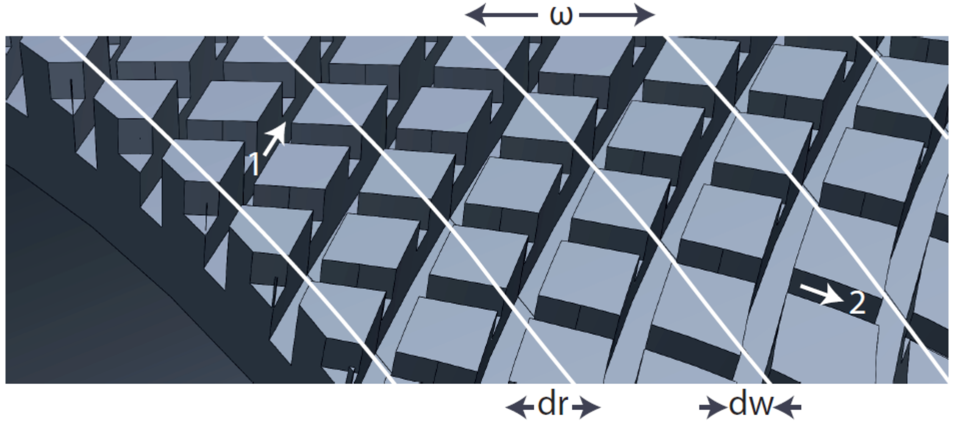


Fig. 13. Close-up showing a CAD drawing of the surface geometry of the support cylinder for a sextupole shim coil prototype. To allow the layers to be wound on top of one another the slots into which the wire is wound are of different depth.

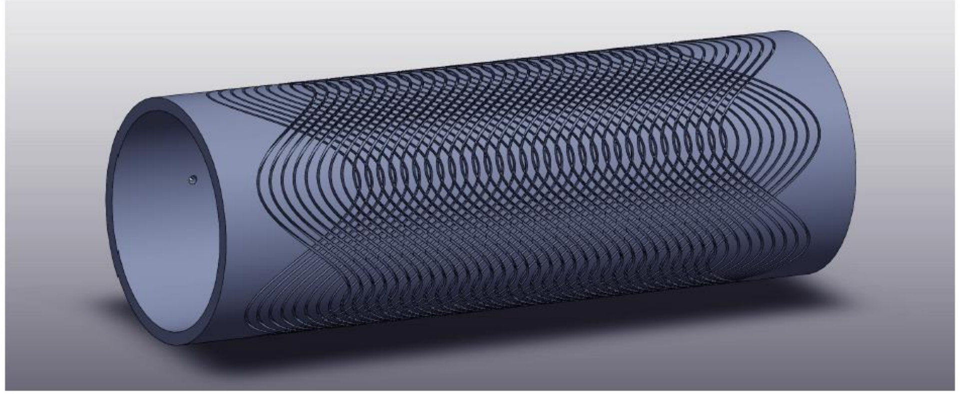


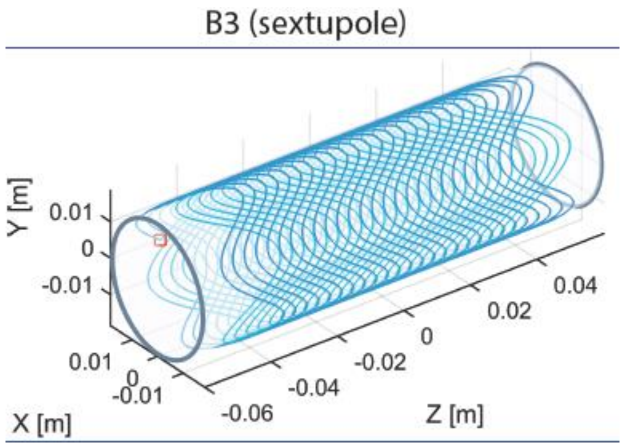
Fig. 12. CAD drawing of the support cylinder for a sextupole shim coil prototype.

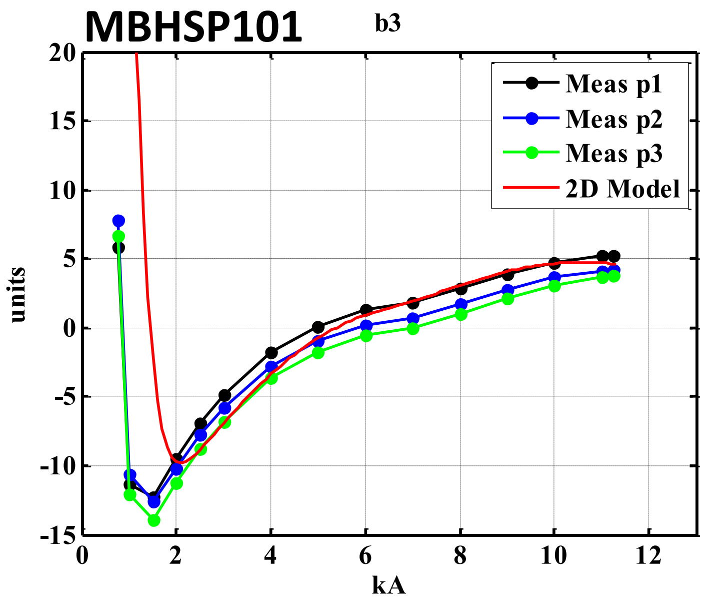
- Since valuable space in the aperture is used. The coils should be as thin as possible
- For a prototype however a wire in channel approach will be used
- Later vapour deposition of Nb_3Sn (as done for cavities at CERN) or YBCO (at 3CS UK) on a cylinder after which lanes are scribed using a laser can be considered

J. van Nugteren et al., FCC Dipole Layout Study, Magnet Technology Conference, 2015

Development Plan

- Build a Nb-Ti Magic magnet.
  - We have the Nb-Ti persistent joint technology, and switches.
  - CNC machine, or 3D print the magnet former in Ceramic, GRP, or Titanium.
  - We have the small filament wire 2 -3 um
- Test in a LHC development magnet (such as the 11T), new one every two months.
- Think how to get to high field for the HTS Magnets.
- High Luminosity orbit corrector could be a candidate for first implementation.
- Very fresh idea there is still lots to iron out.





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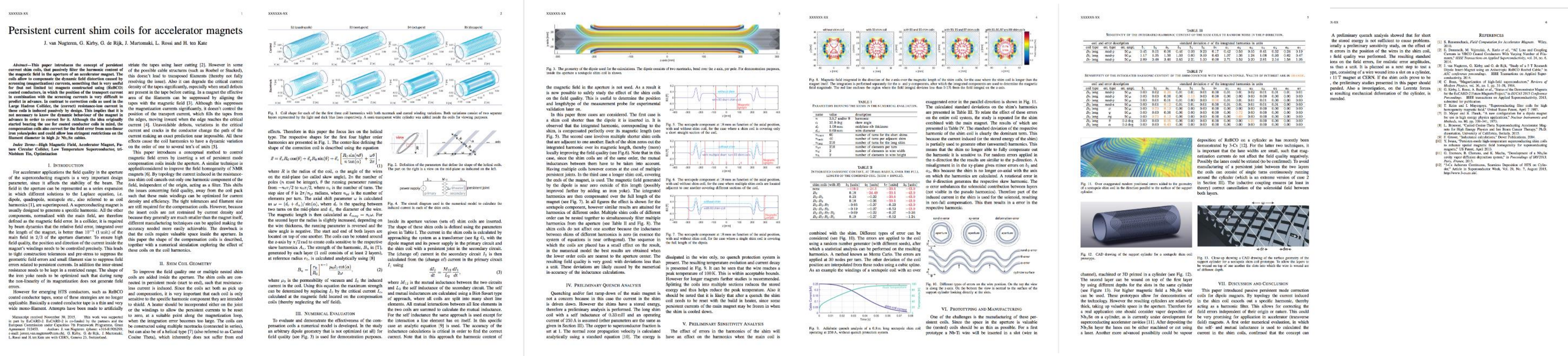
PAPER

- Paper ready for publication



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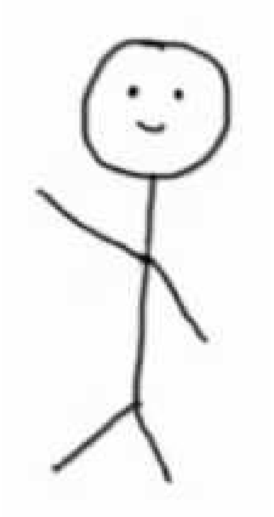

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