

# THE PROBLEM

HTS Development, Dynamic Field Quality, Magnetization Currents



## HTS DEVELOPMENT



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

### DYNAMIC FIELD QUALITY Aligned Block design Cos theta design 30 30 25 25 3*8 6* 6 6 6 6 20 20 [ ⊑ 15 ≻ 15 10 10 . . . . . . . . . . . 5 5 0 20 30 20 30 10 40 10 40 50 0 50 X [mm] X [mm] -600 -400 -200 200 400 600 -400 -200 0 200 400 600 0 -600 Current Density [A/mm] Current Density [A/mm] 60 "b3, 60 unit's variation at low field Unit First simulation give b3, 3units at low reducing to < 20 units at high field. Cno field b5 and b7 we see ~ 10 units variation, Increasing at high field 20 T then converge to low values at high field."\*

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

## ARTWORK SHOWING MAGNETIZATION CURRENTS



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# 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.

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# THE CIRCUIT AND CONCEPT

- 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.

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Integrated harmonic content, at 18 mm radius, over the full length of the combined coil (shim + dipole).

| shim coils (with $R$ )        | b <sub>3</sub> [units] | b <sub>5</sub> [units] | b <sub>7</sub> [units] | b <sub>9</sub> [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                  |

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

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# Shim Coil Geometry



Fig. 1. Coil shape for each of 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 Ο
- Ο
- Ο
- Already some experience from the orbital Ο corrector



A simple equation represents the geometry  $\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{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(n\theta)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(\alpha)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(\alpha)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)} \right] + \vec{e}_z \left[ \frac{R_0 \sin(\alpha)}{n \tan(\alpha)} - \frac{1}{n \tan(\alpha)}$ DEFINING THE SHIMS IN THE NUMERICAL EVALUATION.

| name                | value             | description                         |
|---------------------|-------------------|-------------------------------------|
| n                   | 3,5,7 and/or 9    | harmonic                            |
| $\alpha$            | $35.0\deg$        | skew angle                          |
| $d_r$               | $1.00\mathrm{mm}$ | midplane rib thickness              |
| $d_w$               | $0.60\mathrm{mm}$ | wire diameter                       |
| n <sub>tshort</sub> | 60                | number of turns for the short shims |
| $n_{ m multi}$      | 40                | number of turns per adjacent shim   |
| $n_{\rm long}$      | 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.

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# 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
- $\circ$  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.

0.2

0.1

-0.1

-0.2

# PRELIMINARY QUENCH ANALYSIS

- Simple adiabatic quench model
- $\circ$  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  $0.8\,\mathrm{m}$  long sextupole shim coil operating at  $250\,\mathrm{A}$ , 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.

 TABLE III

 Sensitivity of the integrated harmonic content of the shim coils to random noise in the p-direction.

| coil a     | nd error des | cription   |       |       |       | stan  | dard dev | viation $\sigma$ | of the i | ntegrate | d harmo | nics in u | inits |       |       |       |
|------------|--------------|------------|-------|-------|-------|-------|----------|------------------|----------|----------|---------|-----------|-------|-------|-------|-------|
| 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       | $50\mu$    | 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       | $50\mu$    | 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  |
| $B_7 \log$ | rand-p       | $50\mu$    | 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 a     | nd error des | cor description standard deviation $\sigma$ 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       | $50\mu$  | 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       | $50\mu$  | 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       | $50\mu$  | 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       | $50\mu$  | 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            | $50\mu$  | 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            | $50\mu$  | 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           | $50\mu$  | 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 | $\theta$     | $0.5 \deg$   | 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 | $\alpha$     | $0.5 \deg$   | 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  |
|            |              |  |       |       |       |       |       |       |       |       |       |       |       |       |       |       |



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.

# 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

# DEVELOPMENT PLAN

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





## PAPER

## Paper ready for publication Ο

## Persistent current shim coils for accelerator magnets

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Introduces the avoid of periodic strikes the tops using here certific [2]. However its components of an autokense magnets for an autokense magnets for a low domain full distance in the strike strik and to correction come in order in the space with the magnetic field [1]. Although this suppresses the object, This implementation is the second considered conduct of the second constraints, each field he targets have the displant, therein the second constraints of the second constraints of the second constants of our hand, the second constant of our hand, the second constant of our hand, th

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| Fig. 1. Consider the mask of the first time constrained with both w<br>layous represented by the light and dark blue lines respectively. A soni-many   | reack and caread writing cardinate. Both caracteris carear of two adjurnal<br>areast white cylinder was added minde the only for viewing purposes.   |
|--|--|
| effects. Therefore in this paper the focus lies on the belied<br>type. The respective shapes for the first four higher order<br>harmonies are presented in Fig. 1. The centre-like defining the<br>shape of the correction cull is described using the equation<br>$\sum_{i=1}^{n} \frac{1}{i} \sum_{i=1}^{n} \frac{1}{$ | P. A.  |
| $x = e_{\alpha}R_{0} \cos(\theta) + e_{y}R_{0} \sin(\theta) + e_{\delta} \left[\frac{1}{n \sin(\alpha)} + \frac{1}{2\pi} \int_{(1)}^{1} \frac{1}{(1)} \sin(\alpha) + \frac{1}{2\pi} \int_{(1)}^{1} \frac{1}{(1)} \sin(\theta) \sin(\theta) d\theta + \sin(\theta) \sin(\theta) \sin(\theta) \sin(\theta) d\theta$<br>where R is the mid-plane (so called skew angle). In the number of points (n must be integer, b the rounting permetter running from $-n_{0}\pi/2$ to $n_{0}\pi/2$ , where $n_{0}$ is the camber of times. The number is $2\pi/n_{0}$ midma where $n_{0}$ is the number of the number of the second of the second of the second of the number of the n  | Fig. 2. Definition of the parameters that define the shape of the below cells. The part on the right is a view on the mol-place as induced on the left.<br>$\begin{array}{c} b_{1} & b_{2} \\ \hline \\ power supply \\ \hline \\ \hline \\ \hline \\ \hline \end{array} \underbrace{ b_{1} & b_{2} \\ b_{1} & b_{2} \\ \hline \\ b_{2} & b_{3} \\ \hline \\ b_{1} & b_{2} \\ \hline \\ b_{2} & b_{3} \\ \hline \\ b_{2} & b_{3} \\ \hline \\ b_{3} & b_{3} \\$ |
| teep use or $\delta = \delta_1 n_j n_j$ makes, where $n_{kl}$ is its bounder of<br>elements per turn. The axial while parameter $\omega$ is calculated<br>as $\omega = (\delta_i + \delta_{ij})/\sin(\alpha)$ , where $\delta_i$ is the spacing between<br>two turns on the mid-plane and $\delta_{ij}$ the diameter of the wire.<br>The magnetic length is then calculated as $\ell_{miny} = n_i \omega$ . For<br>the second layer the radius is slightly increased, depending or   | [powary  |
| the wire blickness, the running parameter is reversed and the<br>kew angle is agritive. The start and end of both largers are<br>located on top of one mother. The coils can be rotated around<br>the z-axis by $\pi/2$ read to create coils sensitive to the respective<br>skew harmonics A <sub>n</sub> . The strength of the harmonic, B <sub>n</sub> is [T1,<br>parentaed by each layer (1 coil consists of z least 2 layers),<br>at reference entities $\pi_0$ , is a classified analytically using [8]   | The shape of there shim colis is defined using the parameters<br>given in Table 1. The current in the shim colis is calculated by<br>approaching the system as a transformer (see fig 4), with the<br>dipole magnet and its power supply in the primary circuit and<br>the shim coli with a persistent joint is in the secondary circuit.<br>The (change of) current in the secondary circuit $I_2$ is then<br>calculated from the (change of) current in the primary circuit  |
| $B_n = \left[\frac{r_0}{R_0}\right]^{n-1} \frac{\mu_0 I_0 \cot(\alpha)}{2\omega},$ (2)   | $I_1 \text{ using}$<br>$\frac{dI_2}{dt} = \frac{M_{12}}{L_2} \frac{dI_1}{dt},$ (3)   |
| where $\mu_0$ is the permetability of vacuum and $I_0$ the induced<br>current in the coil. Using this equation the maximum strength<br>can be determined by replacing $I_0$ by the critical current $I_c$<br>calculated at the magnetic field located on the compensation<br>coils (thereby neglecting the self field).  | where M <sub>12</sub> is the motual inductance between the two circuits<br>and L <sub>2</sub> the soft inductance of the secondary circuit. The soft<br>and mutual inductances are calculated using a Biot-Stoart type<br>of appreach, where all coils are split into many short line<br>elements. All mutual interactions between all line elements in<br>the moments in the second part of the second inductances.   |

III. NOMERICAL EVALUATION for two coles are summed to calculate the numula inducation. For the stell inducation the same sproach is used set energy for To evaluate and demonstrate the effectiveness of the com- the interaction is a low effectiveness of the com- the interaction is a low effectiveness of the com- tain arbitrary dipole generacy that is no optimized or all for the inducations is estimal in doctaries of the an arbitrary dipole generacy that is no optimized or all for the inducation set and all quadity (or Fig. 21) is used for demonstration paperos. Lance Links that in this append the humanics content of the quadity of the set of the



the magnetic field in the aperture is not used. As a result it 60 A more result in 60

| is now possible to salely study the effect of the shirn coils  | E  |
|--|--|
| on the field quality. This is useful to determine the position   | g V whithdorshanded V  |
| and length/type of the measurement probe for experimental  | et1 Magnetic   |
| validation later on.   | 42 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4   |
| In this paper three cases are considered. The first case is  | 2 (mm)   |
| a shim coil shorter than the dipole it is inserted in. It is   | A DATA STRATEGY AND A REAL PROPERTY OF A DATA STRATEGY AND A   |
| observed that the integrated harmonic, corresponding to the  | Fig. 5. The acetapole component at 18 mm as function of the mial portion   |
| shim, is compensated perfectly over its magnetic length (see   | a dest desirie series of the call.   |
| Fig. 5). The second case involves multiple shorter shim coils  |  |
| that are adjacent to one another. Each of the shim zeros out the   | 8.7  |
| integrated harmonic over its magnetic length, thereby (more)   | at A stream A  |
| locally improving the field quality (see Fig.6). Note that in this   | E co Il contration of the cont |
| case, since the shim coils are of the same order, the mutual   | at a second s  |
| inductances between them have to be taken into account.  | 42 1 1 2 2 14 1 iprester   |
| Having multiple coils however comes at the cost of multiple  | -en -on -on -on -on -on -on -on  |
| persistent inints. In the third case a longer shim coil, covering  | That   |
| the ords of the menet is used. The macaretic field concrated   | Fig. 6. The sectupole component at 18 mm as function of the saial proting  |
| by the dipole is near zero outside of this length (possibly  | with and without shim coil, for the case where multiple shim coils are locate  |
| immand further by adding an iron water). The integrated  | adjacent to one another orvering different sections of the coil,   |
| harmonics are then commensated over the full length of the   | 12/  |
| manual (see Fig. 7). In all features the effect is shown for the   | at a starter a   |
| carturols component houses circiler much an attained for   | 6  |
| harmonics of different order. Multiple abirs coils of different  | a Wanataway  |
| interesting of university of the second seco | ent Wageste  |
| order can be nested argenter to submanifoldary inter manaple   | 4.2  |
| narmonics from the aperatic (see table if and Fig. 8). The   | irr(s  |
| shift cous do fat anect one another because the inductance   |  |
| between shims of different harmonics is zero (in essence the   | Fig. 7. The excluption component at 18 mm as function of the axial position<br>with and authorst chine will. For the case where a database database with a   |
| system of equations is near ontrogonal). The sequence in   | the full length of the dipole.   |
| which the coils are placed has a small effect on the result,   |  |
| in the numerical model the best results are obtained when  |  |
| the lower order couls are nearest to the aperture center. The  | dissipated in the wire only, no quench protection system i   |
| resulting field quality is very good: with deviations less than  | present. The resulting temperature evolution and current decay   |
| a unit. These deviations are likely caused by the numerical  | is presented in Fig. 9. It can be seen that the wire reaches :   |
| in-accuracy of the inductance calculations.  | peak temperature of 100 K. This is within acceptable bounds  |
|  | However for longer magnets further studies is recommended  |
| IV. PRELIMINARY OUENCH ANALYSIS  | Splitting the coils into multiple sections reduces the store   |
|  | energy and thus heles reduce the peak temperature. Also it   |
| Quenching and/or fast ramp-down of the main magnet is  | should be noted that it is likely that after a quench the shin   |
| not a concern because in this case the current in the shim   | coil needs to be neset with the build in heater, since sem   |
| is driven down. However the shims have a stored energy,  | persistent currents of the main marnet may be frozen in when   |
| therefore a preliminary analysis is performed. The long shim   | the shim is cooled down.   |
| coil with a self inductance of 0.33 mH and an operating  |  |
| current of 250 A is assumed (other parameters are the same as  | M. Deserve and Deserve and Annual   |
| given in Section III). The copper to superconductor fraction is  | V. PRELIMINARY SENSITIVITY ANALYSIS  |
| set at 1. The normal zone propagation velocity is calculated   | The effect of errors in the harmonics of the shim will   |
| analytically using a standard equation [10]. The energy is   | have an effect on the harmonics when the main coil i   |

in the second

is performed separately for the x- and y-components, after which the integrated components are use nucleons the region where the field integral deviance into that 0.1% from the field integral on the

exaggenated error in the parallel direction is shown in Fig. 11. The adicianted standard deviations on the shirt's hummites are presented in Table III. To tetake the effect of flows errors are construined with the main magnet. The results of which are presented in Table IV. The standard orisiding the supercise hummotic of the shirt cells is clearly the dominant term. This because the current induced (or the total energy of the shirt). TABLE 1 NUMBER OF REPORTED AND DECOMPOSITION name veloe description v 3.5,7 and/or 9 harmonic skew angle midplane s (b fikines) who dismose number of tens for the short shire number of tens per adjacent shire number of rans for the long shire number of elements per ten eans that the shim no longer able to fully compensate e harmonic it is sensitive to. For random errors applied it is adjustion the the results are similar to the adjustion. this because the shim is no lenger co-axial with the axi on which the harmonics are calculated. A rotational error in the 6-direction generates the respective slave harmonic. The shine coils (with R) = 3x (units) = 6x (units) = 5x (units) = 5x (units) o error unbalances the solenoidal contribution between layers (not visible in the pseudo harmooida). Thirrfore part of the induced current in the shift in is used for the solenoid, resulting in non-full compensation. This then results in a error in the -419.9 8.29 8.20 8.29 -0.55 -0.19 -0.09 8.29 -24.5 -34.69 -0.22 -0.25 -0.27 -0.27 -0.27 -0.27 -281 -251 -251 -251 -251 -0.52 -0.53 -0.53 -0.52  $\begin{array}{c} B_1 \\ B_2 \cdot B_3 \\ B_3 \cdot B_3 \\ B_2 \cdot B_3 \cdot B_1 \\ B_2 \cdot B_3 \cdot B_1 \\ B_2 \cdot B_3 \cdot B_1 \\ B_3 \cdot B_3 \cdot B_1 \cdot B_2 \\ B_4 \cdot B_7 \cdot B_5 \cdot B_5 \end{array}$ combined with the shim. Different types of error can be considered (see Fig. 10). The errors are applied to the col-using a nunicon number generator (with different scole), after which a statistical analysis can be performed on the resulting harmenics. A method known as Monte Cafe. The errors are ornlied at 30 nodes per turn. The other deviation of the c windings of a sextupole call with an over

femat types of errors in m. as z-axis. On the bottom the view VI. PROTOTYPING AND MANUFACTURING 0 801 802 808 604 905 804 Time[t]

One of the challenges is the manufacturing of these per-sistent colls. Since the space in the aperture is valuable the (nested) colls should be as thin as possible. For a first prototype a Nb-Ti wire will be inserted in a shut (wire in Fig. 9. Additute quests analysis of a 0.8 m long aextensic shim a operating at 250 A, without quench protection system.

| ori a                                | ad error des                       | standard decision e of the internet harmonics in units |                      |                            |                      |                            |                            |                            |                      |                      |                            |                            |                             |                      |                      |                      |
|--------------------------------------|------------------------------------|--|----------------------|----------------------------|----------------------|----------------------------|----------------------------|----------------------------|----------------------|----------------------|----------------------------|----------------------------|-----------------------------|----------------------|----------------------|----------------------|
| ol spe<br>9, log<br>9; log<br>9- log | en type<br>nod-p<br>nod-p<br>nod-p | 66, απρί<br>50 μ<br>50 μ                               | 0.45<br>1.17<br>2.89 | 65<br>0.51<br>1.35<br>3.48 | 6,00<br>1,50<br>3,40 | 84<br>0.40<br>1.03<br>2.65 | 53<br>0.33<br>0.80<br>2.21 | 61<br>0.23<br>0.89<br>1.30 | 6.17<br>6.43<br>6.08 | 0.42<br>1.00<br>2.71 | 69<br>0.53<br>1.35<br>3.57 | 95<br>0.55<br>1.24<br>3.20 | \$4<br>0.41<br>1.08<br>2.81 | 0.12<br>0.10<br>2.34 | 0.24<br>0.62<br>1.58 | 47<br>01<br>14<br>13 |
| ENSIT71                              | TY OF THE I                        | INTEGRATER   | 1148300              | NE 008                     | TENT O               | 1 176 4                    | TABLE<br>ID4 CO1           | I IV<br>DONED              | erra ta              | IE NAN               | 100016                     | VALUE                      | S OF IN                     |                      | IRE IN               | a Anic               |





ction III). The (p. 1). Over exaggential modern positional arrays added to the geometry or scorepoie stam, out in the direction pendlel in the surface of the surport.



channels, manihum of 20 primes in a solution part Pag. [25], by raide afformst applied for the data in the same systems. WHI. Directionics and the solution of the solution

|      | 1927         |              |        |  |        |         | TABLE  | 6 10    |       |       |       |          |      |       |
|------|--------------|--------------|--------|--|--------|---------|--------|---------|-------|-------|-------|----------|------|-------|
|      | SENSIT       | IVITY OF THE | TAUEOR | LATED H  | ADHON: | ic coxr | 231.05 | THE NO. | V COL | TORAS | BOH 3 | THE IN I | REF  | RECTR |
| on a | no arror ass | 211 10 203   |        | standard deviation or or the integrated harmonics in units |        |         |        |         |       |       |       |          |      |       |
| ope  | en ppe       | on, smpl.    | - 20   | 15   | - Ø2 - | - 14    | 62     | 15      | 07    | 121   | 09    | 03       | - 64 | 12.5  |
| 1002 | - mod-p-     | 50 0         | 0.45   | 0.51   | 0.00   | 0.40    | 0.33   | 0.23    | 6.17  | 0.42  | 0.53  | 0.55     | 0.41 | 0.52  |
|      | mnd-p        | 50 a         | 1.17   | 1.35   | 1.50   | 1.03    | 0.80   | 0.89    | 8.43  | 1.07  | 1.35  | 1.24     | 1.08 | 0.93  |
| 3000 | mrd.r.       | 50           | 2.89   | 3.45   | 3.40   | 2.65    | 2.21   | 1.30    | 8.08  | 2.71  | 3.52  | 3.20     | 2.81 | 2.34  |
| lang |              |              |        |  |        |         |        |         |       |       |       |          |      |       |
| part | ane /        |              |        |  |        |         |        |         |       |       |       |          |      |       |

rps, consisting of a wire wound into a slot on a cylind 11 T magnet at CERN. If the shim colls prove to , the preliminary studies presented in this paper shue panded. Also a investigation, on the Lorentz for

хах

A preliminary quench analysis showed that for short the stored energy is not sufficient to cause problems, could a preliminary sensitivity ands, an the effect of n errors in the position of the wires in the shim coil, i field quality uses performed. The resoluting standard less on the field errors, for relative error amplitudes,

than a unit. It is planned as a next step to test

avestigation, on the Lorentz for nical deformation of the cylinde

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nous, Semios Deposition of HTS on Cylin industry Work, Vol. 28, No. 7, August 2015

ring of a persistent joint between the two layer can consist of single turns continuously running



Fig. 13. Close-up showing a CAD drawing of the surface support optimizer for a sestapole skim coll prototype. To all be assessed using the prior one another the oldst into which the y hantel), machined or 3D printed in a eviloter (see Fig. 12

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