SuShi Design Report

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Abstract
In the framework of a collaboration between CERN and MTA Wigner Research Centre for Physics (Budapest) a prototype of a superconducting septum magnet is being developed for the Future Circular Collider. This device uses a novel concept, the combination of a passive superconducting shield and a canted cosine theta-like superconducting magnet. The project is described in [1]. This document is the deliverable 'WRCP-hh-6.1/Document' of the collaboration agreement, the design report of the superconducting magnet.
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1 TODO
   - mention ramp rate
   - thermal contraction of MgB2

2 Introduction
The Future Circular Collider (FCC) study was launched in 2014 to identify the key challenges of the next-generation particle accelerators after the Large Hadron Collider (LHC). One of the key challenges of the FCC-hh is the high beam rigidity and strong magnetic fields required to manipulate this beam. The beam extraction system uses the so-called septum magnets which create a zero field at the position of the circulating beam and a high field region in close proximity for the extracted beam kicked off-orbit by upstream kicker magnets. The beam rigidity puts serious requirements on these magnets as well. A magnetic field of at least 3 T is desired in order to keep the total length of the septa within limits, which is about two times higher than achievable with the current technology.

One of the possible solutions for these challenges uses a superconducting shield placed inside a superconducting magnet. Hereinafter, this device will be denoted as SuShi (for superconducting shield) septum.

The external magnet of the SuShi septum would use the so-called canted cosine theta-like (CCT) technology. The advantages of the CCT configuration are as follows:

- Simple design and manufacturing, very few parts, easy to wind
- No complicated coil ends
- Mechanical stability; the Lorentz forces are intercepted by the support structure and do not accumulate to produce excessive stress in the conductors and impregnation.
- As a consequence excellent stability and quench performance
- Inherent quench protection: the aluminium formers act as a tightly coupled secondary winding, dissipating part of the stored magnetic energy due to the induced eddy currents during a quench. Being in a tight thermal contact with the superconducting windings, they also act as a quench-back system. Even if these features do not fully protect the magnet, the protection system can be made simple.

The CCT concept has the following drawbacks:

- It uses more conductor than the cosine-theta design for a given field. However with fields as moderate as 3 T one can use commercial standard NbTi conductors which are nowadays cheap and easily available and constitute only a small fraction of the cost of the device.
- The longitudinal field component between the two coils increases the peak field within the superconductors, lowering their critical current.

The well defined goals of the FCC-hh project and the coordinated research efforts with the participation of experts of different fields from around the world are an excellent framework for the development of new concepts and technologies for accelerators. Achieved results will certainly find application outside of the scope of the project itself. The development of high-field septum magnets with a magnetic field more than twice the limit of the current technology might enable the construction of more compact and more cost-efficient accelerators not only in the high-energy physics domain but also in the laboratory-scale, industrial or medical area.

3 Choice of parameters and 3D design

3.1 Basic parameters

The choice of parameters for a full-size device which would be used in the FCC-hh ring was described in [2]. This document describes the design of a small-scale prototype. A major goal during the design of this prototype was to profit from the existing design and already available hardware of the high-luminosity LHC CCT corrector magnet project [3] (referred to as HL-CCT in the following) as much as possible. Experience acquired during that project indicated that machining grooves into the formers with the width of a single wire, and a depth for several (5) wires is difficult. Instead, a groove with a width of $W_g = 2.1$ mm and depth of $H_g = 5.1$ mm for $n_1 \times n_2 = 2 \times 5$ wires was chosen. The same parameters were adopted for this project.

Since the manufacturing of a half-moon shaped MgB$_2$ shield is much simpler and faster than the design and construction of a special CCT magnet, the project’s strategy was to test an MgB$_2$ shield in the available 0.5 m long HL-CCT prototype, in order to gain experience before the construction of the magnet. This shield can then be tested in the special CCT magnet, once it is available. This strategy implies the choice of the same aperture of the magnet, i.e. $\varnothing 105.35$ mm. The geometry shown in Fig. [2] was chosen to have (i) $\varnothing 18$ mm hole in the shield to insert a set of Hall sensors mounted to a $\varnothing 15$ mm G10 rod, (ii) 15 mm shield thickness on both sides of this hole, which should be sufficient to shield 3.2 T field both with an MgB$_2$ and a NbTi/Cu multilayer shield, (iii) a flexible mechanical support holding the shield within the bore of the magnet, containing a $\varnothing 32$ mm hole for a $\varnothing 29$ mm rotating coil, to measure the field quality in the high-field zone. The 18 mm diameter in the shield is significantly smaller than the realistic aperture requirements for the FCC (58 mm diameter hole in the shield [2]). The goal of this project is to construct a small prototype which can demonstrate the feasibility of the concept, and the achievable field quality. It can then be scaled up without any difficulty to real size. Parameters of a realistically sized device for application in the FCC are given in reference [2].
### Table 1: Parameters of the device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>HL-LHC Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture diameter</td>
<td>$D_a$</td>
<td>105.35</td>
<td>mm</td>
<td>105.35</td>
<td>mm</td>
</tr>
<tr>
<td>Spar thickness</td>
<td>$T_{spar}$</td>
<td>3</td>
<td>mm</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Groove width</td>
<td>$W_g$</td>
<td>2.1</td>
<td>mm</td>
<td>2.1</td>
<td>mm</td>
</tr>
<tr>
<td>Groove depth</td>
<td>$H_g$</td>
<td>5.1</td>
<td>mm</td>
<td>5.1</td>
<td>mm</td>
</tr>
<tr>
<td>Radial gap between formers and support tube</td>
<td>$G_{former}$</td>
<td>0.725</td>
<td>mm</td>
<td>0.725</td>
<td>mm</td>
</tr>
<tr>
<td>Support tube wall thickness</td>
<td>$T_{support}$</td>
<td>12</td>
<td>mm</td>
<td>9.9</td>
<td>mm</td>
</tr>
<tr>
<td>Pitch</td>
<td>$P$</td>
<td>5.04</td>
<td>mm</td>
<td>5.22</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum rib thickness</td>
<td>$T_{rib,min}$</td>
<td>0.35</td>
<td>mm</td>
<td>0.33</td>
<td>mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$n$</td>
<td>102</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield length</td>
<td>$L_{shield}$</td>
<td>800</td>
<td>mm</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Yoke lamination thickness</td>
<td>$T_{yoke}$</td>
<td>5.8</td>
<td>mm</td>
<td>5.8</td>
<td>mm</td>
</tr>
<tr>
<td>Transfer function</td>
<td>$T$</td>
<td>0.0069</td>
<td>T/A</td>
<td>0.006 [4]</td>
<td>T/A</td>
</tr>
<tr>
<td>Nominal field</td>
<td>$B_0$</td>
<td>3.2</td>
<td>T</td>
<td>2.6</td>
<td>T</td>
</tr>
<tr>
<td>Nominal current</td>
<td>$I_0$</td>
<td>464</td>
<td>A</td>
<td>435</td>
<td>A</td>
</tr>
<tr>
<td>Magnet inductance</td>
<td>$I_0/short-sample-I_c$</td>
<td>146</td>
<td>103/820</td>
<td>mH</td>
<td></td>
</tr>
<tr>
<td>Yoke inner diameter</td>
<td>$D_{y1}$</td>
<td>168</td>
<td>mm</td>
<td>167</td>
<td>mm</td>
</tr>
<tr>
<td>Yoke outer diameter</td>
<td>$D_{y2}$</td>
<td>380</td>
<td>mm</td>
<td>614 (double-aperture)</td>
<td>mm</td>
</tr>
<tr>
<td>Shield fillet radius</td>
<td>$R_{fillet}$</td>
<td>8</td>
<td>mm</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Good field region center</td>
<td>$P_{grf}$</td>
<td>25.5</td>
<td>mm</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Good field region</td>
<td>$W_{grf}$</td>
<td>±15</td>
<td>mm</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Beam hole diameter in shield</td>
<td>$D_{beam}$</td>
<td>18</td>
<td>mm</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Circulating beam position</td>
<td>$P_{beam}$</td>
<td>-19.5</td>
<td>NA</td>
<td>NA</td>
<td>mm</td>
</tr>
<tr>
<td>Average length of turn (former 1)</td>
<td>$L_1$</td>
<td>529</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average length of turn (former 2)</td>
<td>$L_2$</td>
<td>629</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Winding geometry

The multipole composition of the 2D current distribution was optimized using the method described in [2], for the 2D geometry shown in Fig. 2. The values of the current multipole coefficients are quoted in tables 2.

The conductors’ 3D path can be parametrized as $x(\vartheta), y(\vartheta)$ and $z(\vartheta)$, where $\vartheta$ is the azimuthal angle. For the angle $\alpha(\vartheta)$ between the winding’s tangential and the $z$ axis (see Fig. 1) we find

$$\frac{1}{\tan[\alpha(\vartheta)]} = \frac{1}{R} \frac{dz}{d\vartheta}$$

(1)

where $R$ is the winding’s radius. In the following we assume that the superconducting wires are arranged in a tight regular $n_1 \times n_2$ pattern, aligned to the bottom of the
Fig. 1: Schematic illustration of the coils and the shield, and the geometric parameters

<table>
<thead>
<tr>
<th></th>
<th>( J_1^{(1)} )</th>
<th>( J_2^{(1)} )</th>
<th>( J_3^{(1)} )</th>
<th>( J_4^{(1)} )</th>
<th>( J_5^{(1)} )</th>
<th>( J_6^{(1)} )</th>
<th>( J_1^{(2)} )</th>
<th>( J_2^{(2)} )</th>
<th>( J_3^{(2)} )</th>
<th>( J_4^{(2)} )</th>
<th>( J_5^{(2)} )</th>
<th>( J_6^{(2)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 8.04726 \times 10^7 )</td>
<td>( 4.16054 \times 10^7 )</td>
<td>( -1.18537 \times 10^7 )</td>
<td>( 2.92985 \times 10^6 )</td>
<td>( -1.73654 \times 10^7 )</td>
<td>( 6.71827 \times 10^6 )</td>
<td>( 8.60453 \times 10^7 )</td>
<td>( 3.97513 \times 10^7 )</td>
<td>( -1.60064 \times 10^7 )</td>
<td>( 3.78088 \times 10^6 )</td>
<td>( -1.87853 \times 10^7 )</td>
<td>( 7.72138 \times 10^6 )</td>
</tr>
</tbody>
</table>

Table 2: Values of the \( J_n^{(1)} \) current multipole coefficients of the 2D optimization, measured in A/(m\(^2\)·T).

The average current density in a single layer of winding (i.e. a cylindrical shell of thickness \( D_w \), where \( D_w \) is the diameter of the wire) is then:

\[
J(\vartheta) = \frac{I_0 n_1}{D_w a(\vartheta)}
\]  

where \( I_0 \) is the magnet current, \( n_1 \) is the number of parallel wires in a layer, \( a(\vartheta) = P \sin[\alpha(\vartheta)] \) is the distance between neighbouring grooves in the direction perpendicular to their tangential, and \( P \) is the winding’s pitch. The axial and azimuthal current density components are

\[
J_z = J \cos(\alpha) = \frac{I_0 n_1}{D_w P \tan(\alpha)} = \frac{I_0 n_1}{D_w P R \, d\vartheta}
\]  

\[
J_\varphi = \frac{1}{D_w P} \frac{1}{\tan(\alpha)} \frac{dJ_z}{d\vartheta} = \frac{I_0 n_1}{D_w P R} \, dz
\]
Fig. 2: 2D cross section of the SuShi septum prototype with dimensions. Diameters are associated to the inner surfaces of the formers. Show dimensions of the lifting features on the yoke.

\[ J_\theta = J \sin(\alpha) = \frac{I_0 n_1}{D_w P} \]

Since \( J_\theta \) only depends on the pitch \( P \), it is natural (also for other reasons) to choose the same pitch for the inner and outer windings. The two counter-rotating azimuthal currents in the inner and outer windings will therefore be equal and they will create an axial field \( B_z = \mu_0 \int J_\theta \, dr = \mu_0 I_0 n_1 n_2 / P \) between the two windings if the magnet is long enough, where the integral is running through the thickness of one of the coils. This magnetic field component is (i) parallel to the beam and (ii) does not spatially overlap with it, and will therefore be ignored in the following discussion. This component can not be neglected however when calculating the peak field in the coils. This is the major contribution to the large \( B_{\text{peak}} / B_0 \) ratio with small transfer.
functions, as will be demonstrated later.

The ideal axial current distribution in the inner and outer windings is determined by a 2D optimization as described before, for 1 Tesla central field, in the form of the linear combination

$$J_z(c)(\vartheta, r) = \frac{R_i(c)}{r} \sum_{n=1}^{N} J_n^{(c)} \cdot \cos(n \vartheta)$$  \hspace{1cm} (5)

$$J_z^{(c)}(\vartheta) = J_z^i(c)(\vartheta, R_i^{(c)}) = \sum_{n=1}^{N} J_n^{(c)} \cdot \cos(n \vartheta)$$  \hspace{1cm} (6)

where \(c=1,2\) indexes the inner and outer coils, and the unit of \(J_z^{(c)}\) and \(J_n^{(c)}\) is \(\text{A}/(\text{m}^2 \cdot \text{T})\). This gives a zero net axial current when integrated over \(2\pi\). However, there is a net axial current in a spiral 3D winding due to its pitch, and the corresponding current density is the total current running in the \(n_1\) wires of a given layer, divided by the cross-sectional area of that layer:

$$J_P = \frac{I_0 n_1}{\pi [(R + D_w)^2 - R^2]} \approx \frac{I_0 n_1}{2\pi R D_w}$$  \hspace{1cm} (7)

\(J_P\) scales with \(1/R\) and is therefore different in the inner and outer coils. These two together create an azimuthal magnetic field between the two coils, which does not overlap with the extracted beam, and will be ignored.

The axial component of the 3D current pattern, eq. (3) must be equal to \(B_0 J_z + J_P\), where \(B_0\) is the desired central field of the real magnet. From this equation we get

$$x^{(c)}(\vartheta) = R^{(c)} \cos(\vartheta)$$  \hspace{1cm} (8a)

$$y^{(c)}(\vartheta) = R^{(c)} \sin(\vartheta)$$  \hspace{1cm} (8b)

$$z^{(c)}(\vartheta) = \mp \frac{TPRD_w}{n_1} \int_0^{\vartheta} \mathbb{J}_z^{(c)}(\vartheta') d\vartheta' - P \frac{\vartheta}{2\pi}$$

$$= \mp \frac{TPRD_w}{n_1} \sum_{n=1}^{N} \frac{J_n^{(c)}}{n} \sin(n \vartheta) - P \frac{\vartheta}{2\pi}$$  \hspace{1cm} (8c)

for the 3D path of the bottom of the groove, where \(T = B_0/I_0\) is the magnet’s transfer function, and the \(\mp\) sign was introduced to account for the different tilts of the inner and outer windings (negative and positive signs, respectively). The negative sign of the second terms in eq. (8c) results in a left-handed spiral. The scale factor \(T \cdot P\) defines the tilt angle of the windings.

Among the parameters which determine the geometry, \(R\) is determined by the choice of aperture diameter and spar thickness. \(D_w\) is 1 mm, the typical diameter of the commercially available superconducting wires; \(n_1\) is 2 due to practical
reasons, as explained above. The only remaining factors which determine the coils’ geometry are the transfer function $T$ and pitch $P$. However, the latter can be fixed at its smallest possible value at a given $T$, as it will be shown below, and then only $T$ remains as a free parameter, which drives the geometry of the windings.

The groove-to-groove period $a$ (see Fig. 1) can be written as

$$a = P \sin(\alpha) = \frac{P}{\sqrt{P^2 \left( \mp \frac{T D_{w1} J_z}{n_1} - \frac{1}{2\pi R} \right)^2 + 1}}$$

from which the pitch can be expressed as

$$P = a \left[ 1 - a^2 \left( \mp \frac{T D_{w1} J_z}{n_1} - \frac{1}{2\pi R} \right)^2 \right]^{-1/2}$$

The rib thickness is calculated as

$$T_{rib} = a - W_g$$

where the second term is the width of the groove. The HL-LHC magnets have a minimum rib thickness of 0.33 mm (at the bottom of the groove). Choosing $T_{rib,min}=0.35$ mm for the minimum rib thickness of the SuShi magnet, the minimum possible pitch is determined as

$$P_{min} = \max \left\{ a_{min} \left[ 1 - a_{min}^2 \left( \mp \frac{T D_{w1} J_z}{n_1} - \frac{1}{2\pi R} \right)^2 \right]^{-1/2} \bigg| 0 < \vartheta < 2\pi \right\}$$

$$a_{min} = T_{rib,min} + W_g$$

Since the 3D path of the grooves is calculated at their bottom where the rib thickness is the smallest, the required minimum rib thickness is respected everywhere. In order to reach the highest transfer function $T$ for the tilt angle driven by the product $T \cdot P$, the pitch $P$ must be chosen at its minimum possible value, which is done numerically using eq. (12) for each value of $T$. This choice leaves $T$ as the single parameter which determines the coils’ geometry.

Figure 3 illustrates that the coil shape is more complex than for simple dipole or quadrupole CCT magnets. The unusual shape at the backface of the shield serves to minimize the magnetic field at the equator, and thereby the leakage field inside the shield, in case the shield is bent from a NbTi/Cu multilayer shield with a cut at this point [2].

4 Simulation models

Different finite-element models were created in COMSOL to simulate the magnetic field, the electromagnetic forces and elastic distortion of the magnet.
4.1 Block-coil model

The real geometry of a CCT magnet is difficult to simulate due to the presence of features with very different scales. The minimum rib thickness is as small as 0.35 mm, whereas the windings, the shield etc are on the scale of several 10 cm. In order to describe the global magnetic field pattern of the complete device in 3D, the “block-coil” model was developed, where the two windings are modelled as a contiguous block, as shown in Fig. 4. The boundaries of the winding block are described by the parametric surfaces

\[ P_{\text{no pitch}}(\vartheta) + r \cdot \hat{r}(\vartheta) \pm \frac{L_{\text{coil}}}{2} \cdot \hat{z} \quad 0 < \vartheta < 2\pi, 0 < r < n_2 \cdot D_w \]

(front faces of the coil block)

\[ P_{\text{no pitch}}(\vartheta) + z \cdot \hat{z} \quad 0 < \vartheta < 2\pi, -\frac{L_{\text{coil}}}{2} < z < \frac{L_{\text{coil}}}{2} \]

(inner surface)

Fig. 3: 3D coil shape around the shield, with three times the pitch for better illustration.
Fig. 4: 3D magnetic field in the block-coil model.

\[
P_{\text{no pitch}}(\vartheta) + n_2 D_w \cdot \hat{r}(\vartheta) + z \cdot \hat{z} \quad 0 < \vartheta < 2\pi, -L_{\text{coil}}/2 < z < L_{\text{coil}}/2
\]

outer surface

(16)

(17)

\[
\hat{r}(\vartheta) = \begin{pmatrix} \cos(\vartheta) \\ \sin(\vartheta) \\ 0 \end{pmatrix} \quad \text{(local radial unit vector)}
\]

(18)

\[
\hat{z} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}
\]

(19)

\[
P_{\text{no pitch}}(\vartheta) = \begin{pmatrix} x(\vartheta) \\ y(\vartheta) \\ z_{\text{no pitch}}(\vartheta) \end{pmatrix}
\]

(20)

where \( z_{\text{no pitch}} \) is the same as eq. (8c) but without the last term describing the pitch.

The current densities in the coil blocks are

\[
J_{x}^{(c)}(\vartheta) = \pm B_0 \sin(\vartheta) \frac{I_0 n_1}{D_w P}
\]

(21)
\[ J_y^{(c)}(\vartheta) = \mp B_0 \cos(\vartheta) \frac{I_0 n_1}{D_w \rho} \quad (22) \]
\[ J_z^{(c)}(\vartheta) = B_0 J_z^{(c)}(\vartheta) \quad (23) \]

where \((c)\) indexes the two coils, and the upper/lower signs are for the inner/outer coils, respectively, and \(B_0\) is the desired central field of the device. The different signs describe the opposite azimuthal direction of the currents in the two windings. The superconducting shield was approximated as a bulk diamagnet with a relative permeability of \(\mu_r = 10^{-4}\).

4.2 2D models

For the construction of the 2D model, first only the coils were modeled in 3D using a simplified geometry, as shown in Fig. 5a, and their 3D current pattern was calculated (this step requires the meshing of the coil volume only, and is therefore feasible). The 2D model of the coils was then generated by taking the 3D model’s cross section at \(z=0\), and using the \(z\)-component of the previously calculated 3D current distribution. All of the other parts of the magnet, like the formers and the shield were built only in 2D, around the cross section of the winding. Figure 5b shows the resulting 2D geometry.

Fig. 5: (a) 3D shape of the coils. (b) 2D cross section of the magnet
5 Transfer function, coil length and superconductor operating parameters

5.1 Operating temperature

Two superconducting shield materials were successfully tested before. A shield made of 4 layers of a multilayer NbTi/Nb/Cu sheet \([5]\) was very stable against flux jumps at \(T=4.2\) K. At 1.9 K its shielding performance was better, but it suffered from flux jumps. A tube made of MgB\(_2\) using the reactive liquid infiltration technique \([6]\) was stable against flux jumps on the virgin curve at \(T=4.2\) K, but showed flux jumps in later magnetization cycles. The shield was not tested at 1.9 K. The operating temperature of the SuShi septum magnet therefore is chosen to be 4.2 K.

5.2 Choice of the transfer function, coil length and superconducting wire

The primary figure of merit of a geometry optimization of a real device aimed for the FCC is the average field of the device:

\[
\bar{B} = \frac{1}{L} \int_{-L/2}^{L/2} B_y(z) \, dz
\]  

(24)

where \(L\) is the physical length of a module, including vacuum tank, flanges, etc.

For a demonstrator prototype our goal was to choose parameters such that the device is simple and cheap to construct, and has at least 10 cm flat-top region where the field homogeneity can be measured.

Superconductors are optimally used if they run at their performance limits with the required safety margins at the nominal working conditions. The CCT-SuShi septum contains two classes of superconductors: (i) the superconducting magnet’s windings, and (ii) the passive superconducting shield. In an optimal geometry both of these are operating at their safe limit simultaneously. Otherwise the device performance would be limited by one of the two classes, leaving the material of the other class not fully exploited. Since the transverse geometry and the thickness of the shield was chosen such that a 3.2 T field can be safely shielded, the windings must be optimized for this operating field, with no more performance margin than needed. A larger transfer function results in a smaller operating current for the same magnetic field, and a larger tilt of the windings and thereby a longer device. Therefore the smallest transfer function must be chosen which still gives sufficient safety margin for the conductors, and the device length must be chosen to have the required length for the flat-top region.

Adequate conditions were found for a shield length of \(L=800\) mm. Figure 6a shows the peak field in the coils as a function of the transfer function, for a central field of \(B_0=3.2\) T, evaluated in the block coil model. The significant increase of the peak field towards low values of the transfer function are attributed to the axial
Fig. 6: (a) Peak field in the coils as a function of transfer function, with a central field of $B_0=3.2$ T. (b) $I_c(B)$ curves of three commercial superconducting wires with about 0.85 mm diameter (symbols: measurement; lines: linear fit). The large symbols show the $(B_{\text{peak}}, I_0)$ value pairs of the magnet for different transfer functions at $B_0=3.2$ T. The value within parentheses in the legend indicates $I_0/I_c(B_{\text{peak}})$.

Fig. 7: (a) Axial magnetic field component $B_z$ as a function of the transverse position $x$ at $z=0$, $y=0$ at different transfer functions, for a central field of $B_0=3.2$ T. (b) $B_z$ evaluated halfway between the two coils ($x=62.6$ mm) as a function of the transfer function, for a central field of $B_0=3.2$ T. As demonstrated in Fig. 7, this field component is steeply rising when the transfer function is decreased, and the central field is kept constant. This is due to (i) the increasing operating current required to reach the same nominal field, and (ii) the decreasing tilt of the windings, resulting in the increasing relative azimuthal component of the currents.

Figure 6b shows the $I_c(B)$ curve of some commercial superconducting wires, to-
Fig. 8: $B_y$ along the longitudinal sampling line at the center of the good field region, for a shield length of $L=800$ mm and different transfer functions. Figure (b) is a zoom to the flat-top region of figure (a). Together with the $(B_{\text{peak}}, I_0)$ values of the magnet at different transfer functions and a central field of 3.2 T. The value in parentheses in the legend indicates the $I_{\text{peak}}/I_c (B_{\text{peak}}$ value for the given wire. As is visible, all of these wires have a large safety margin at the operating parameters. The CERN wire is the one used to wind the HL-CCT magnets, and is still available in the CERN stocks (7). This wire has a Cu:SC ratio of 1.9 and an RRR of 250 due to the extra heat treatment applied to bond a second layer of wire insulation. The two other commercial wires have higher critical currents and thereby a larger safety margin, but a smaller Cu:SC ratio, and would need to be procured externally.

Figure 8 shows the magnetic field component $B_y$ along the longitudinal sampling line at the center of the good field region, for different transfer functions and a shield length of 800 mm. For a transfer function of 0.0069 T/A, the variation of the field is about 3‰ in a 20 cm long range. This long flat-top region gives the possibility to measure the field quality with a rotating coil, and this value has been chosen for the transfer function.
6 Simulations

6.1 Magnetic simulations

In the magnetic simulations the \textit{mf} module of COMSOL was used, which uses the A-formulation of Maxwell’s equations. The superconducting shield was modeled as a real superconductor with Campbell’s model \cite{7}. The $J_c(B)$ curve was taken from \cite{8} (350 °C x 672 h heat treatment, transport current normal to the rolling direction). For the iron yoke the standard B-H curve of the LHC magnets \cite{9} was used. Figure 9 shows the magnetic field in the 2D geometry at a magnet current of 475 A. The magnitude of the magnetic field on the $y=0$ line is shown in Fig. 10. The penetration depth is $\approx 3$ mm, and the field inhomogeneity is $\approx 0.25\%$.

![Magnetic field simulation results](image)

(a) Result in the full geometry

(b) Solution inside the bore

Fig. 9: Result of the magnetic simulation

![Magnetic field amplitude](image)

(a) Full range

(b) Shield’s surface

(c) Good field region

Fig. 10: Amplitude of the magnetic field along the $y = 0$ line. (a) full range, (b) at the shield’s surface, (c) in the good field region.

Figure 11 shows the homogeneity $(B_{\text{max}} - B_{\text{min}})/B_{\text{aver}}$ and the deviation of the average magnetic field in the good field region from the linear behaviour, as a function...
Fig. 11: (a) Homogeneity \((B_{\text{max}} - B_{\text{min}})/B_{\text{aver}}\), and (b) deviation of the average magnetic field in the good field region from the linear behaviour, as a function of magnet current.

of the magnet current. As it is visible, MgB\(_2\) and NbTi have similar performances at lower fields, and MgB\(_2\) has a running-away inhomogeneity and nonlinearity at the highest value, the former still being within the required ±1.5%.

6.2 Mechanical simulations

In contrast to the magnetic simulation, the mechanical 2D model was finalized by the Form Assembly node of comsol, to make it possible to model the separate movement of distinct parts. Also, the shield’s support structure was modelled with all of its features, which provide elasticity during the differential thermal contraction of the constituents.

Figures 12a and 12b show the boundary pairs with continuity and contact conditions, respectively. Continuity condition sticks the boundaries together, they can not separate, while the contact condition allows the movement and separation of the boundary pairs. The contact conditions at the inner surfaces of former 2 and the support tube are motivated by the fact that these surfaces will receive an epoxy-repellent coating, in order to stop the propagation/initiation of cracks in the epoxy at these interfaces. The Lorentz forces calculated by the magnetic simulation were applied in the coil cross-sections and in the shield. Figure 13 shows the deformation of the device under the effect of the Lorentz forces. The maximal deformation due to the Lorentz forces is around 30 \(\mu\) with respect to the device centre, which is negligible compared to the thermal expansion, which is approximately in the order of a mm. The forces acting on the shield can be calculated as

\[
F_x = - \int_{\text{shield}} B_y \cdot J_z \, d^2r = -1.23 \cdot 10^5 \, \text{N/m} \tag{25}
\]
Fig. 12: Boundary conditions in the 2D mechanical simulation.

Fig. 13: Deformation of the magnet due to the Lorentz forces

\[ F_y = \int_{\text{shield}} B_y \cdot J_z \, d^2r = -296 \text{ N/m} \]  \hspace{1cm} (26)

Since the device has an approximative symmetry through the \(x - z\) plane (which
is broken by the fact that the two coils with opposite tilts have different radii), the force component $F_y$ should be approximately zero, which holds.

### 6.3 Sensitivity studies

The effects of misalignments of the components on the field quality and the mechanical structure of the device are evaluated for two special cases: the azimuthal misalignment of the shield compared to the magnet, and the azimuthal misalignment of the outer former compared to the inner former. Figure 14 shows the torque, calculated as

$$\tau_z = \int_{\text{shield}} (y \cdot F_x - x \cdot F_y) \, d^2r \quad (27)$$

acting on the shield as a function of misalignments. The nominal alignment of the shield within the magnet is a stable equilibrium position, a negative torque is acting on the shield when it is misaligned by a positive angle (Fig. 14a). The misalignment of the shield has a larger effect than the misalignment of the outer former. The stabilizing torque on the shield is about -240 Nm for a unit length of the shield for a large misalignment of 1° of the shield, which corresponds to about 0.9 mm circumferencial displacement on the inner surface of the inner former. The torque due to the same misalignment of the former is smaller, and has an opposite sign, meaning that the equilibrium orientation of the shield moves in the same direction as the misalignment of the outer former. As demonstrated later, the concept of supporting the shield inside the magnet allows for a rotational movement of the shield without damage to the device (even if any such movement might quench the magnet).

![Figure 14: Torque caused by the misalignment of the shield or former](image-url)
direction of the dipole field (which can be compensated by offsetting the magnet orientation), it can also compromise field quality. For the quantification of this effect, a multipole analysis has been performed on the simulation results. The radial component of the magnetic field was sampled on a circle with $D_{GFR}$ diameter, around the center of the extracted beam-pipe, and then Fourier transformed. The result of the Fourier-transform was normalized to the dipole-component. Figure 16 shows the magnitude of the first 7 Fourier components.

As a conclusion, azimuthal alignments better than about 1° seem to be sufficient. This corresponds to circumferential displacements between the components on the order of 1 mm. Feasible machining and assembly tolerances of a few-100 microns on the azimuthal alignment features can therefore be accepted.

7 Quench protection

Although there exist quench simulation tools for CCT magnets (add further references), the adaptation of these for the CCT-SuShi magnet is not straightforward. Therefore the development of a general quench simulation framework is in progress at Wigner Research Centre for Physics. This software is based entirely on COMSOL and it can describe an arbitrary coil shape using the multipole parameterization eqs. (8). It will include the effect of eddy currents in the formers, quench-back, transverse heat propagation in the coil pack and thereby strand-to-strand coupling.
Fig. 16: Multipole components of the magnetic field in the high-field region for different azimuthal misalignments of the shield and outer former with respect to the inner former

longitudinal quench propagation in the strands, and will be able to directly obtain the hotspot temperature and the temperature profile along individual strands.

For the time being the quench behaviour of the magnet is estimated using standard methods.

7.1 Magnet inductance

The inductance of the magnet is calculated from the static magnetic field pattern of the block coil model using the formula $L = \frac{1}{i} \int BH \, d^3x$ giving 146 mH, which is between the 103 mH [4] and 820 mH [10] inductances of the 0.5 m and 2.2 m long HL-CCT magnets, respectively. Since the coil packs have identical geometries and parameters, the same quench protection system (the application of an external damp resistor) seems adequate at first sight.

7.2 Adiabatic hot spot temperature

A pessimistic back-of-the-envelope estimate can be made assuming that the quench protection system described in [10] is used, and that the protection system is triggered similarly 17 ms after the onset of the quench. The magnet is first discharged through a 50 mΩ crowbar for 10 ms, then through a damp resistor of 700 mΩ. Neglecting the resistance of the strands and the mutual inductances to the eddy currents in the formers, the magnet current is approximated to decay exponentially as shown by the green line in Fig. 17a, and the full quench integral is calculated to be...
Fig. 17: Calculated MIITS curve for a superconducting wire with a Cu:SC ratio of 1.35, and bare wire diameter of 0.85 mm, assuming RRR=200 for the copper.

\[ Q_1 = \int I^2(t) \, dt = 28105 \, A^2s. \] If we allow a maximum voltage of 400 V, the dump resistance can be increased to 862 mΩ, giving a quench integral of \( Q_2 = 23914 \, A^2s. \)

Figure 17b shows the calculated adiabatic hot spot temperature of a superconducting wire with a copper RRR of 200 (a more pressimistic value than RRR=250 used in [10]) in an external magnetic field of 4 T, indicating the hot-spot temperatures corresponding to the two values of the quench integral shown above by squares.

This approach of course neglects that for similar magnets, about 28% of the stored energy is dissipated in the formers [10]; cooling of the hot-spot by its environment; cooling of the magnet by the helium bath; resistance of the quenched parts of the strands, and quench-back.

A more detailed simulation was made using a lumped element model of four coupled LR circuits: (i) the magnet coil shorted via the external resistors, and (ii-iv) the eddy current loops in the two formers and the support tube. These LR circuits are described by the equivalent lumped element parameters \( L_i \) and \( R_i \) (inductance and resistance), and time-dependent currents. The eddy currents are assumed to have a time-invariant 3D pattern, and only change in magnitude over time. The equations of this system are as follows:

\[
\frac{dI}{dt} = L^{-1}U = L^{-1}R(t) \cdot I \tag{28}
\]

\[
R(t) = \text{diag} (R_i(t)) | i = \text{coil, former1, former2, support} \tag{29}
\]

The diagonal elements of the inductance matrix \( L \) are the self-inductances of the current loops, the off-diagonal elements are the mutual inductances. The equivalent circuit is shown schematically in Fig. 18.
The lumped element parameters are calculated using the 3D block coil model in the following way. Due to the nature of the eddy current loops (they flow through the $z=0$ symmetry plane), the equivalent loop currents are defined as

$$I = \frac{1}{2} \int_{z=0} dxdy |J_z(x, y, 0)|$$

(30)

The magnet current was forced to have a linear ramp for a long-enough time so that the eddy currents reach a steady state in the formers, when the resistive voltages counteract the driving inductive electromotive force. Inductances of the eddy current loops and the magnet coil are defined using the formula

$$\frac{1}{2} L_i I^2 = E_i = \frac{1}{2} \int B_i \cdot H_i \, d^3x$$

(31)

in separate static simulation runs for the four LR circuits, where the current pattern (calculated from the time-dependent inductive problem) was prescribed only in the corresponding component $i$, and in all others it was set to zero. Here $B_i$ and $H_i$ are the magnetic induction and field solutions when only the current in the given component is excited, and $E_i$ is the stored magnetic energy.

The mutual inductances and coupling factors between any two components $i$ and $j$ can be calculated using the field solutions $B_{ij}$ and $H_{ij}$, when the current in these two components is excited. $B_{ij}$ and $H_{ij}$ were not simulated separately, but rather obtained as the sum of $B_i$ and $B_j$, assuming a linear system. The stored energy is then

$$E_{ij} = \frac{1}{2} \int (B_i + B_j) \cdot (H_i + H_j) \, d^3x$$

(32)
Table 3: Lumped-element equivalent inductance matrix

<table>
<thead>
<tr>
<th>Self and mutual inductances [mH]</th>
<th>Coil</th>
<th>Inner former</th>
<th>Outer former</th>
<th>Support tube</th>
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<td>0.166</td>
<td>0.192</td>
<td>0.177</td>
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<td>Inner former</td>
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<td>2.36e-4</td>
<td>2e-4</td>
<td></td>
</tr>
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<td>2.95e-4</td>
<td>2.49e-4</td>
<td></td>
</tr>
<tr>
<td>Support tube</td>
<td></td>
<td></td>
<td></td>
<td>2.82e-4</td>
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Table 4: Lumped element equivalent coupling factors

<table>
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<th>Inner former</th>
<th>Outer former</th>
<th>Support tube</th>
</tr>
</thead>
<tbody>
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<td>0.922</td>
<td>0.873</td>
</tr>
<tr>
<td>Inner former</td>
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<td>0.855</td>
<td>0.742</td>
</tr>
<tr>
<td>Outer former</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0.863</td>
</tr>
<tr>
<td>Support tube</td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

and the coupling factor and mutual inductance between the two inductors is

\[
\begin{align*}
    k_{ij} &= \frac{E_{ij} - E_i - E_j}{2\sqrt{E_i E_j}} \\
    L_{ij} &= k_{ij} \sqrt{L_i L_j}
\end{align*}
\]  

(33)  

(34)

The lumped-element equivalent resistance of the LR circuits is calculated when the eddy currents in the formers reach a steady state, after a long-enough linear ramp of the magnet current, from the steady-state transformer equation

\[
L_{\text{coil}_i} \frac{dI_{\text{coil}_i}}{dt} = R_i I_i
\]

(35)

where \( L_{\text{coil}_i} \) is the mutual inductance between the magnet coil and the given eddy current loop, calculated as described above. The values of these parameters are summarized in Tables 3, 4 and 5.

The differential equation system describing the four coupled LR circuits contains temperature- and time-dependent resistances. For the formers, the equivalent resistance is defined as \( R \cdot \rho_{\text{Alu}}(T)/\rho_{\text{Alu}}(T_0) \), in which the time-dependent temperature of the formers is driven by the adiabatic formula

\[
\frac{dT(I, T, t)}{dt} = \left( \frac{I}{A} \right)^2 \frac{\rho(T)}{C(T)}
\]

(36)

where \( A \) is the cross section of the given former, and the current density and the temperature are assumed to be the same over the entire cross section of the formers.
This formulation still neglects heat transfer between the components, but it describes the energy dissipation in the formers. The effect of temperature-dependent former resistances is negligible.

Quench propagation in the strands is considered using the simple formulation of [11]. The length of the quenched section of the strand is continuously increased with the propagation velocity

\[ v = \frac{I}{AC(T_m)} \sqrt{\frac{\rho(T_m)k(T_m)}{T_c - T_0}} \]  

with \( T_m = (T_0 + T_c)/2 \), and the temperature profile of the quenched strand section is updated at discrete points using the calculated MIITS curve for the strand. The resistance of the cable is then calculated as \( R_{\text{strand}} = \int \rho(T_c)/A \). After the onset of the quench, the developing voltage in the strand is computed as a function of time, and compared against the threshold voltage of 100 mV, which was reached after 14.5 ms. After a validation time of 10 ms has elapsed, the current runs through the crowbar of 50 m\( \Omega \) for 10 ms, and then through the crowbar and the external damp resistor of 700 m\( \Omega \). The resulting quench integral was \( Q_3=2.1 \times 10^4 \) A\(^2\) s, giving a hot spot temperature of 162 K (red star in Fig. [17]).

The developing strand resistance has little effect on the evolution of the \( I_{\text{coil}}(t) \) curve, and thereby on the quench integral. Using a multiplication factor of 10 for the strand resistance in the lumped element transformer equations (i.e. assuming that all 10 strands in a groove have quenched initially), but using the unaltered value of the calculated strand resistance to check the triggering condition, the quench integral was decreased only by 4%. Setting the coupling factors to zero between the coil and the former current loops, the resulting quench integral was \( Q_4=2.8 \times 10^4 \) A\(^2\) s, in good agreement with the value of \( Q_1 \) above.

The lumped element simulation still neglects heat transfer between the components, i.e. the cooling of the hot spot by its environment, and cooling of the complete magnet by the liquid helium bath. Cooling decreases the hot spot temperature, but at the same time it can lead to a longer decay time due to the lowered strand resistance. Since the resistance of the quenched section of the strand has a very small effect, the net effect will be a lower hot spot temperature. This simulation also neglects the quench-back effect, which brings the entire coil to the normal conducting state after
some time, lowering the value of the quench integral. The above value of the hot spot temperature is therefore a conservative estimate.

As a conclusion: simple estimates indicate that the quench protection system used for the HL-CCT magnets with the same parameters can safely protect the magnet. By the time the magnet is manufactured and assembled, the quench behaviour of the magnet will be studied in more detail by the software under development.

8 Mechanical design

The mechanical design is based on the design of the HL-CCT magnets, in particular on the LHCMCBRD magnet design. Most of the parameters (see table 1) were adapted without change. Features and design concepts which are different from those in the reference design were motivated by the experience acquired during the participation of D. Barna and M. Novák in the assembly and impregnation of the magnet (3 weeks in September 2019, and 3 days in October 2019), and will be described in detail in each case. Features which are not described below are conceptually the same as in the reference design.

Illustrations below were made using a simplified 3D CAD model where the large number of turns was suppressed for a faster response of the software, keeping only a few turns at the extremities.

8.1 General design goals

Since openings and the associated seals on the mold are potential failure points during impregnation, their number was minimized.

Bolt holes within the impregnated volume have venting holes to avoid trapped volumes behind the bolts, where the epoxy can not easily penetrate.

8.2 Tolerances

The field quality requirements of this magnet are much looser than for the HL-CCT magnets, and do not necessitate tighter tolerances. The azimuthal alignment of the shield and the formers does not require any special measures beyond standard tolerances either, as it was demonstrated in section 6.3. The machining tolerances are therefore adopted from the HL-CCT design, which ensure proper matching of the components.

8.3 Magnet assembly and layout

Similarly to the recent HL-LHC designs, the transition of the superconducting wires from the inner former to the outer former is made without splices, at one end of the magnet. The 10 strands are spliced in series, and to the current leads, at the other end, utilizing a “connection box” to support and isolate the splices, where the
support tube has a rim, which is clamped between the thick yoke end plate and the first lamination. This end is therefore called the “fix end”. The other end is left loose so that the different thermal expansion of the aluminium formers and the iron yoke do not lead to the damage of the winding. The winding is supported transversally within the yoke using 4 keys, similarly to the HL-LHC magnets.

8.4 Connection box
The connection box (Fig. 20) is a comb-like supporting structure made of Ultem or peek, which provides insulation and mechanical separation between the splices of the individual strands. The design is very similar to that of the HL-LHC magnets. One exception is the clearing in former 1 (indicated in Fig. 20), which provides room for the wires while former 2 is slid onto former 1 from this direction.

8.5 Layer jump
The 3D path of the LHCMCBRD design has led to difficulties when winding the layer jump of the magnet. The path raises from former #1 to former #2 simultaneously to bending between the directions of the grooves of the two formers. Due to the path raising out of former #1, the grooves are no more supporting the wire pack, and it had the tendency to “fall apart”, making it very cumbersome to place the layer jump insert on top of it. In addition, the fiber glass tape wrap below the wire pack hindered it even more from entering the groove. The problem was mitigated by cutting the tape below the wires, leading to unsupported tape ends (see Fig. 21).

Since the field quality requirements for the CCT-SuShi magnet are much looser than for a ring-magnet, the current design has more freedom in choosing the 3D layer jump path of the winding. The path is first brought to parallel with the axis.
Fig. 20: Connection box. In the lower figure the cutout reveals the grooves in former #1.
of the device, having a few millimeter long straight section, and raises only then to former #2 in a plane containing the axis of the device (Fig. 22). The groove in the layer jump insert is open towards the outside and has enough room to accommodate the wire pack without cutting the fiber glass wrap below the wires. A small recess on the inner side of the layer jump insert ensures that its two branches will push down and fix the fiber glass tape at the two sides of the groove, when the tape is cut. The wire pack can be bent outwards through the layer jump insert, making the fiber glass wrap below the wires accessible by a scalpel. This space will be filled by fiber glass before impregnation. The end of the groove in former #1 is made 1 mm wider to accommodate the wire pack together with the cut ends of the fiber glass tapes.

Another difficulty with the LHCMCBRD design was the tight entrance size of the groove in former #2. Misalignments of the layer jump insert can push the wires against the groove’s edge, damaging the insulation. The entrance of the groove in former #2 has therefore a slight widening (up to 3.6 mm).

8.6 Azimuthal alignment of the formers

The two azimuthal alignment pins of the LHCMCBRD design are inserted from the side, penetrating through the support tube, kapton layers and former #2 into former #1. The opening on the side of the support tube must be sealed for impregnation, and the holes in the kapton layers had to be cut after the assembly of the magnet.

Azimuthal and longitudinal alignment in the current design is realized using lock rings at the two ends of the magnet, as shown in Fig. 23. The teeth of the lock ring enter into pockets machined into the formers. The radial gaps of 1 mm between the lock ring and former #1 and the support tube, and the axial gap between the lock ring and former #2 serve as a distribution channel for the epoxy, which enters through the sealing endcap (see later, Figs. 24, 25). The design ensures a path of closest
approach without intercepting kapton layers between any two aluminium parts of at least 4 mm everywhere, as a high-voltage safety clearance.

### 8.7 Epoxy impregnation mold

The impregnation mold volume is enclosed radially by the walls of former #1 and the support tube, which have no holes. The mold volume is closed axially using two viton O-rings, pushed against the end faces of former #1 and the support tube by an aluminium sealing endcap, as shown in Figs. 24 and 25. The O-rings are placed into appropriate grooves machined into the endcap (not visible in the figure).

The epoxy impregnation setup of the LHCMCBRD magnet features a long threaded steel shaft going through the two sealing endcaps, tightening them with nuts. In order to allow the differential thermal expansion of the shaft and the formers during the heating of the setup, a series of spring washers was used. The seal started to leak during impregnation when the pressure was raised slightly above 2 bar. In order to avoid the differential thermal expansion problem, the two sealing endcaps of the current design are bolted directly to the ends of the support tube. At the fixed end of the magnet it is bolted to the rim of the support tube, as shown in Fig. 24. At the lose end of the magnet a circular groove in the support tube, and two half collars are used to fix the endcap (Fig. 25).

The epoxy inlet and outlet are mounted into the sealing endcaps, using silicone seal-
Fig. 23: Azimuthal alignment of the formers and support tube using a lock ring

Fig. 24: Epoxy impregnation setup - fix end of the magnet
Fig. 25: Epoxy impregnation setup - lose end of the magnet.
ing rings. An axial gap of at least 1 mm between the lock ring and the sealing endcap allows the distribution of the epoxy along the full circumference. The surface of the endcap and the surface of the lock ring facing it will receive an epoxy repellent coating. The radial gap between the lock ring and former #1 and the support tube allows the penetration of the epoxy between the aluminium tubes. A matching hole in the lock rings also allows the direct penetration of the epoxy between the lock ring and former #2. Sealing around the wires is designed in a similar way to the HL-LHC magnets.

8.8 Miscellaneous features

The integrity of the insulation between any of the strands and the aluminium tubes must be tested at several stages during assembly (during winding of the individual layers, after the installation of each aluminium tube, and at the fully assembled stage). This requires features for electrical connections to the aluminium tubes. These are tapped holes and bolts in the aluminium tubes (similarly to the HL-LHC design), as shown in Fig. 26. These tapped holes must be protected during hard anodization to ensure the electrical contact between the bolts and the aluminium tubes.

9 Conclusions

To be written...
Fig. 26: Features for electrical connections to the aluminium tubes
Appendices
1 List of drawings in CDD

The equipment code for the CCT-SuShi device is FCCMSSUSHI.

<table>
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<th>Code</th>
<th>Description</th>
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</tr>
<tr>
<td>FCCMSSUSHI0002</td>
<td>CCT magnet with yoke (assembly)</td>
</tr>
<tr>
<td>FCCMSSUSHI0003</td>
<td>CCT magnet windings (assembly)</td>
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<td>FCCMSSUSHI0019</td>
<td>Spring pin (part)</td>
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<td>FCCMSSUSHI0020</td>
<td>Tie rod (part)</td>
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<td>Current lead guiding insert (part)</td>
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<td>Cover of current lead guiding insert (part)</td>
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<td>FCCMSSUSHI0023</td>
<td>Key (part)</td>
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<td>Dummy element for a general shield (part)</td>
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<td>Backface supporting element of the shield (part)</td>
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<td>Split shield clamp 1-1, supporting the shield in the aperture (part)</td>
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<td>Split shield clamp 1-2, supporting the shield in the aperture (part)</td>
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<td>Split shield clamp 2-1, supporting the shield in the aperture (part)</td>
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<td>FCCMSSUSHI0029</td>
<td>Split shield clamp 2-2, supporting the shield in the aperture (part)</td>
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Acknowledgements
References


