Optimization of Common Coil Geometry and Relative Conductor Usage for a 20 T Design

Ramesh Gupta
January 25, 2022
- Comparative study – conductor usage in different designs
  - Why the conductor usage appears to be lower in the common coil design as compared to the other designs based on the initial design work on 20 T
- Updated design satisfying the 15% margin requirements and flexibilities
- Work ahead – mostly mechanical design and analysis
- Summary
Some Observations and Possible Explanation

- Comparative studies of 20 T designs revealed that in the common coil design, one can get away with fewer layers and it uses less conductor.
- This is opposite to what was the conventional wisdom. Small differences in margin can’t explain that.
- Any basic change in going from lower to higher fields?

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CT I</th>
<th>CT II</th>
<th>SMCT I</th>
<th>SMCT II</th>
<th>CCT</th>
<th>BL I</th>
<th>BL II</th>
<th>CC I</th>
<th>CC II</th>
<th>CC III</th>
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<tr>
<td>Ins. cable I width/thick.</td>
<td>mm</td>
<td>10.7/1.5</td>
<td>12.0/1.7</td>
<td>12.3/1.5</td>
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<td>18.7/1.9</td>
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<td>18.7/1.8</td>
<td>21.6/1.9</td>
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<td>mm</td>
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<td>14.2/2.1</td>
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<td>13.9/1.5</td>
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<td>17.1/2.1</td>
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<td>13.6/1.9</td>
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<td>-</td>
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<td>Current_op</td>
<td>kA</td>
<td>10.7</td>
<td>13.0</td>
<td>11.4</td>
<td>11.8</td>
<td>12.8</td>
<td>12.6</td>
<td>12.2</td>
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<td>B_bore_op</td>
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<td>20.1</td>
<td>20.0</td>
<td>20.0</td>
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<td>T</td>
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<td>20.3/16.1</td>
<td>20.6/13.6</td>
<td>20.6/16.0</td>
<td>20.2/15.2</td>
<td>20.6/15.1</td>
<td>20.9/15.2</td>
<td>20.4/13.8</td>
<td>20.2/13.7</td>
<td>21.0/17.0</td>
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<tr>
<td>B_bores as HTS/LTS</td>
<td>T</td>
<td>24.4</td>
<td>23.5</td>
<td>24.4</td>
<td>23.2</td>
<td>23.4</td>
<td>23.6</td>
<td>23.6</td>
<td>22.9</td>
<td>23</td>
<td>21.7</td>
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<tr>
<td>Load-line margin (%)</td>
<td></td>
<td>18 / 25</td>
<td>21 / 15</td>
<td>22 / 18</td>
<td>20 / 15</td>
<td>14 / 14</td>
<td>21 / 17</td>
<td>22 / 17</td>
<td>13 / 13</td>
<td>13 / 13</td>
<td>15 / 7</td>
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<tr>
<td>Area quad. ins. cable HTS</td>
<td>mm²</td>
<td>3241</td>
<td>1494</td>
<td>2091</td>
<td>1527</td>
<td>4490</td>
<td>1360</td>
<td>1290</td>
<td>1154</td>
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<td>mm²</td>
<td>2150</td>
<td>6106</td>
<td>3780</td>
<td>5148</td>
<td>4915</td>
<td>4740</td>
<td>6000</td>
<td>2226</td>
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<td>4191 &lt; Typo?</td>
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<td>Coil width*</td>
<td>mm²</td>
<td>105</td>
<td>129</td>
<td>144</td>
<td>149</td>
<td>135</td>
<td>80</td>
<td>112</td>
<td>70</td>
<td>104</td>
<td>106</td>
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<td>Coil inner radius*</td>
<td>mm</td>
<td>25</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>35</td>
<td>25</td>
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</table>
Observation: Multiple solutions

6-layer design
HTS: 1 layer + pole blocks
❖ 74 turns in ½ bore
LTS: 5 layers
❖ 198 turns in ½ bore
Total turns = 272

5-layer design
HTS: 1 layer + pole blocks
❖ 80 turns in ½ bore
LTS: 4 layers
❖ 188 turns in ½ bore
Total turns = 268

4-layer design
HTS: 1 layer + pole blocks
❖ 82 turns in ½ bore
LTS: 5 layers
❖ 180 turns in ½ bore
Total turns = 262

Only relatively small changes in the overall conductor uses despite a significant change between “height” Vs. “width”, while maintaining a good (10^-4) field quality
Accelerator magnets typically have circular bore. Therefore, a shell geometry is a natural choice. At low fields, the required width (and area) of conductor needed is much less than bore. One can design magnets with a single layer coil (RHIC). Block coil geometry will require many coils (layers) and may also use more conductor.

However, the situation changes when the required conductor width (and area) becomes larger than that of the bore (MDP).

The basic rules of the cos theta dipole design:

- B is proportional to the width * (current density)
- Conductor area needed to create the dipole field increases linearly with the radius of each layer (worse for fixing higher order multipoles)
- Coil must extend to 60° or more for \( b_3 = 0 \) (weighted average for multi-layer). These principles define the geometry and conductor area, with little freedom left

- Canted cosine theta design also faces similar geometrical issues on the required conductor
More Complications in Minimizing Expensive HTS in 20 T +15% margin HTS/LTS hybrid design

Need 2 to 4 layers of HTS. Blocks at higher pole angle need HTS (needed for field quality)

Common coil design naturally provides excellent field boundary for separating HTS and LTS layers
• Only one layer of HTS required, irrespective of the number Nb₃Sn layers in the MDP 20 T design
• Coils can be extended vertically up for good field quality without increasing the number of layers
• Only design to produce <10⁻⁴ harmonics
• Flexible for optimizing between the width (number of layers) and height. The two are locked in cosine theta and canted cosine theta

Both upper and lower layers need partly HTS (internal splice). Realistic design may need several layers
Specific Design Chosen for Jan 2022
(matched margins, fewer layers - some identical)

- All three Nb₃Sn coils (layers) are made identical
- Less tooling and spares required, important for reducing costs of R&D magnets
- HTS & LTS matched with a few tenth of a percent

Identical in size (and in total current) blocks (1,2,3,4); (7,9,11); (8,10,12)
Computation of Field Margins

<table>
<thead>
<tr>
<th>I(kA)</th>
<th>(Nb3Sn)</th>
<th>Je(HTS), A/mm²</th>
<th>Jo(HTS), A/mm²</th>
<th>Jc(Nb3Sn)</th>
<th>Jo(Nb3Sn)</th>
<th>Bo (T)</th>
<th>Bpk(HTS)</th>
<th>Bpk(Nb3Sn)</th>
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<tbody>
<tr>
<td>13.435</td>
<td>13435</td>
<td>483.83</td>
<td>397.578</td>
<td>634.16</td>
<td>522.252</td>
<td>20.000</td>
<td>20.161</td>
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<td>15.733</td>
<td>15733</td>
<td>564.07</td>
<td>463.512</td>
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<td>741.181</td>
<td>610.384</td>
<td>23.058</td>
<td>23.362</td>
<td>15.715</td>
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</table>

- Margins
  - 15.5%
  - 15.3%

- Bi2212: Jo(Jc/1.45)
- Bo (T)
- Bpk(HTS)

- Nb₃Sn: Jc (1.9K)
- Bo (T)
- Bpk(Nb3Sn)
Field Quality and Fields on the Conductors

Geometric harmonics < 0.5 $10^{-4}$ (not 5.0 $10^{-4}$)

Turns in ½ aperture
- HTS: 80
- LTS: 182
- Total: 262
Flexibility in design

• Apart from the number of layers, cases examined for the number of turns in each layer (no limit on vertical)
• Also examined 2 + 2 turns in pole coil
• In most cases, good solution found
Optimization in Various Geometries

Typical requirements in accelerator magnet is that field harmonics due to coil geometry remain within a few parts in $10^4$ (we demonstrated $<1$ parts in $10^4$)

Variable to optimize the cosine theta and the canted cosine theta designs

- Total coil width (radial extent – free to grow). However, more width means more layers for given cable
- Pole Angle (limited to 90° max. & 60° min. for $b_3=0$)
- For field quality wedges (may use for structure)
- Radial space between layers for structure element

Variable to optimize the block coil and the common coil designs

- Total coil width (horizontal width – free to grow). However, more width means more layers.
- Coil Height (vertical height – free to grow) – major difference from the cos $\theta$ or canted cosine theta
- For field quality spacer (also structure) & pole coils
- Horizontal space for structure elements
Work Ahead
(priority mechanical design and analysis)

➢ Perform a quick mechanical analysis of the 20 T design (just as performed for the 16 T dipole (include collars, yoke and SS shell)
➢ Provide feedback to magnetic design for the space needed for structure between layers and within layer
➢ Develop concepts for assembling the magnet
➢ Perform refined mechanical analysis with interacted structure
➢ Perform 3-d magnetic and mechanical analysis for a 20 T design
For such high fields, common coil design uses less conductor, particularly HTS (opposite to what people think) – is mystery solved?

Common coil allows easy and efficient segmentation between HTS and LTS

Based on DCC017, Common coil allows larger deflections without putting high strain on coils (to be shown with the mechanical analysis for this design also)

Simple geometry should facilitate more reliable and lower cost manufacturing. All Nb₃Sn coils are identical, saving costs in engineering for tooling and spare

Common coil design is appearing to look more and more attractive for high field (20 T) HTS/LTS hybrid dipoles – both R&D dipoles and collider dipoles

A lot of work is remaining to fully develop the design. A good opportunity for long term R&D for young scientists and engineers for pioneering work