20 T Hybrid Design: Common Coil

Leaping to a New Design Space: Facing the Kodak Moment

Ramesh Gupta

USMDP Annual Collaboration Meeting 2022
Content

- Explanation of why common coil design uses less conductor in the MDP dipole - 20 T plus margin? The difference is larger for the expensive HTS.

- Why common coil becomes more attractive for very high field collider dipoles
  - Lorentz forces, more cable options, more technology options, costs

- Comparing the cost of R&D dipole
  - Compare two apertures in common coil to single aperture in other designs

- R&D vision based on the common coil geometry
  - Rapid-turn-around and low-cost, change or study one parameter at a time, systematic and innovative R&D (we have a Proof-of-Principle 10 T dipole)

- Summary
Common Coil Design for Collider Magnets

Main Coils of the Common Coil Design

- Coil #1
- Coil #2

SLAC-R-591
Fermilab-TM-2149
June 4, 2001

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Lawrence Berkeley National Laboratory
SLAC National Accelerator Laboratory
Stanford University, Stanford, CA 94309

Work performed in part by the Department of Energy contract DE-AC03-76SF00515.
Comparative studies of 20 T designs (as presented at MT) revealed that the common coil design uses significantly less conductor than the other designs. Small differences in relative margin doesn’t explain that.

This finding is opposite to that expected from the conventional wisdom. Why? Back to the drawing board…

Explanation comes from the basic design principles. As the design field gets higher, relative ratio between the bore area and the coil area changes significantly. That changes the optimization and the outcome.

The difference is likely to grow for field quality magnets and particularly on the use of the expensive HTS.
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.

**Design guidelines from the first principle:**

- In a cos (θ) design, coil must extend to 60° (or more with wedges but limited to 90°) for $b_3=0$
- $B$ is proportional to the width * (current density)
- Conductor area needed to create the dipole field increases linearly with the radius of each layer
- In low field block coil designs, extending coil vertically (with no limit) for field quality or to reduce number of layers is not effective
- At low fields, block coil designs appear less efficient and less elegant. They have not been used in any major conductor dominated design.
In high field magnets, the ratio between the “Bore Area” and “Coil Area” becomes much higher and things change.
Another Observation: Coil Thickness

The coil width (number of layers) is primarily determined by the design field both (a) in cosine theta and (b) in canted cosine theta designs. However, a large flexibility in *coil width* to create the same field was found in the common coil design. Interestingly the *coil width* didn’t impact the conductor requirement much.

- **HTS:** 1 layer + pole blocks
  - 74 turns in ½ bore
- **LTS:** 5 layers
  - 198 turns in ½ bore
- **Total turns:** 272

- **HTS:** 1 layer + pole blocks
  - 80 turns in ½ bore
- **LTS:** 4 layers
  - 188 turns in ½ bore
- **Total turns:** 268

- **HTS:** 1 layer + pole blocks
  - 82 turns in ½ bore
- **LTS:** 5 layers
  - 180 turns in ½ bore
- **Total turns:** 262

Lowest cost design: 4-layer
Optimization of 20 T Design – max area & max field
(coil area much larger than the bore area)

Need six layers (of which 2 to 4 layers must be of HTS)

• In cos θ and canted cosine theta, certain coil thickness or # of layers, are needed to create field.
• The same thickness (#of layers) must continue to the pole (60 to 80 degrees), the fill in between is determined by the cosine theta optimization.
• The field remains high at pole for many layers, means may need HTS, depending on the angle.
• Outer layers of current cosine theta designs, need to be extended to larger angle for field quality, which will use more conductor without creating much field.
• Furthermore, since the field will be higher there, the need for HTS and more layers of HTS will grow.

Situation is very different in the common coil design.
• Horizontal and vertical sizes are decoupled. This provides flexibility and saving on the conductor.
• Moreover, the separation between the very high field and medium field region is good between the layers.
• This means that the HTS is needed only in one layer!
Field Quality in Common Coil Geometries
(all designs presented at MT27 had $10^{-4}$ harmonics)
Benefits of the Common Coil Design
All Nb$_3$Sn Coils Can be Made Identical

Such prospects can't be imagined in the CT/SMCT or CCT designs

- While HTS coils/layers will need separate tooling, all Nb$_3$Sn coils will need only one set for winding, reaction and impregnation
- Nb$_3$Sn coils for CT/SMCT or CCT designs will need tooling for at least four layers (all with more complex geometries)
- Need less practice & less spare coils
- Can sort/switch coils between layers, e.g., based on the performance

Question: Will the above savings in cost and time, overcome the cost of extra conductor for the 2$^{nd}$ aperture, at least in the R&D magnets where the relative cost of design and tooling are large?
Summary of Design with Identical Nb$_3$Sn Coils

(still good field quality and matched margins)

Geometric harmonics < 0.5 $10^{-4}$

<table>
<thead>
<tr>
<th>I(kA)</th>
<th>Bo (T)</th>
<th>Bpk(HTS)</th>
<th>Bpk(LTS)</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.50</td>
<td>20.00</td>
<td>20.75</td>
<td>13.60</td>
<td></td>
</tr>
<tr>
<td>15.73</td>
<td>23.00</td>
<td>23.88</td>
<td>15.68</td>
<td></td>
</tr>
<tr>
<td>15.80</td>
<td>23.10</td>
<td>23.98</td>
<td>15.74</td>
<td>15.5%</td>
</tr>
<tr>
<td>15.77</td>
<td>23.06</td>
<td>23.94</td>
<td>15.72</td>
<td>15.3%</td>
</tr>
</tbody>
</table>
Dealing with the large Lorentz Forces in the Common Coil Design

• Discussion in next few slides show the benefits of the common coil geometry in dealing with the large Lorentz forces at high fields

• Initial studies (just started) show that a solution can be found for keeping stresses both in Bi2212 coils and in Nb₃Sn coils below the desired limit
Lorentz Forces in the Common Coil

- Horizontal forces much larger than vertical (maximum vertical is 1/3 of horizontal)
- Large horizontal deflection can be tolerated since coils move as a unit - without causing much strain in the end or transition regions
- BNL common coil had 200 µm horizontal deflections and low vertical pre-stress
- Small forces on pole (mostly horizontal)
Stress in Nb3Sn coils are already below the maximum specified (180 MPa). The maximum value in Bi2212 coils needs to be reduced a bit (below 120 MPa). Peak value in Bi2212 coils seems to be about 150 MPa. Magnetic, mechanical & assembly designs will be iterated together (i.e., with feedback from one to other).
Impact of More Space for Structure
(to be iterated with mechanical analysis)

Modest 6% increase in conductor for providing 
~3-6 mm vertical and 6 mm horizontal space 
(space for structure is like that used in SMCT). 
We are unlikely to need so much.

Geometric harmonics < 0.4 \times 10^{-4}
Maximum peak stresses at 20 T are: 105 MPa (well below 180 MPa) in Nb$_3$Sn.

However, the peak stress on Bi2212 coil is 154 MPa (barring singularities), over 120 MPa desired.

Maximum stress in Bi2212 coil can be reduced by increasing the SS plate thickness (next slide).
Study of adding horizontal structure: Stress in Bi2212 coils reduced to 104 MPa (<120 MPa)

ANSYS analysis prove working concepts of structures to keep stresses within limit.

Next step: Iterate the magnetic and mechanical design to produce good field quality with acceptable stresses.
Benefit of Common Coil: Interfaces

• Interfaces are going to be a major issues in very high field magnets where we must deal with large Lorentz forces.

• Both Canted Cosine Theta (CCT) and Stress Managed Cosine Theta (SMTC) are going to have many interfaces.

• Gaps must be left for expanding cable in reaction and they should be filled with the epoxy. Since epoxy is not a strong material. It shouldn’t be too thick to minimize cracking (can that be avoided in complex structures where it will be difficult to fill in the gaps).

➢ By contrast, the common coil structure, as it appears to be developing now, should have fewer and simpler interfaces!
Common Coil: Conductor friendly design with large bend radii (order of magnitude more than others)

- Conductor degradation (both in Nb$_3$Sn and in HTS) is a major issue in high field magnets
- Larger degradation expected in coil ends with relatively complex geometries with small bend radii
- Smaller degradation is expected in the common coil designs with simpler ends and large bending radii.

React & Wind Bi2212 Rutherford cable coil built and tested

Cables must be bent in much smaller radii in CT/SMCT/CCT as compared to that in CC

- Many cables, including those that developed for the fusion (where a lot of investment is being made), can’t be used in Cos theta or CCT since many of them can’t be bent in small radii. However, they can be used in the common coil because of larger radii.
- Performance, reliability and cost of many cables can be reduced if they don’t have to be bent so tightly
Common Coil: Allowing More Technology Options

- Common coil design offers the opportunity for “React & Wind” technology, in addition to the “Wind & React”.
- “R&W” technology is attractive for large scale production in industry.
- BNL common coil dipole was wound using the “R&W” technology and reached short sample with strain (David - magnet can’t perform better than the conductor).
- Many insulation and coil material options become available as coil doesn’t have to go through the high temperature reaction.
What is the most critical thing that must be proven for the common coil design?

- Although several common coil designs have been designed with a variety of conductor (NbTi, Nb$_3$Sn, Bi2212, Bi2223, ReBCO), all have been made with the main coil only.
- The most efficient design to obtain good field is the one with the pole coils.
- We need to demonstrate a proof-of-principle design for pole coils that clear the bore tube. Many geometry considered but none demonstrated.

- Pole coils can be built, integrated and tested with the main coils in the BNL common coil dipole DCC017. Attempt to do that demo took off three times with SBIR Phase I (see next slide). However, none could be carried out as no Phase II was funded despite the productive work in Phase I.
- Proof-of-principle demo of the pole coils should be a high priority for MDP. It can be done in a short period and at a low cost for coil made by any lab.
A Few Possible Layouts of Pole Coils Clearing the Bore (other geometries discussed elsewhere)

Practice pole coil windings and preliminary designs performed under “three” SBIR Phase I. They can be built and tested at $10^+\,\text{T}$ field as a part of common coil dipole DCC017 under MDP.

CERN is also working on this design

CERN (Glyn Kirby) has shown strong interest in collaborating
BNL common coil design experience has been very productive for low, cost rapid-turn around R&D for a variety of purpose.

Identical design may not work for high fields, but a similar approach may.

For example, fully open space may be replaced by removable insert, or allow disassembly.
Recap: Benefits of the Common Coil Design

- Simple 2-d coil geometry for collider dipoles
- Conductor friendly design with large bend radii (determined by the spacing between two apertures). Less sensitive to conductor degradation.
- 20 T dipole uses significantly less conductor than used in other designs
- Efficient segmentation between LTS and HTS coils for HTS/LTS hybrid dipoles
- Mechanically handles well the large Lorentz forces associated with the high fields, creating lower internal strain on conductor despite large deflections
- Fewer coils (half) as the same coils are common between the two apertures
- Simple magnet geometry and simple tooling, expect lower costs
- Identical design can be used for all Nb₃Sn coils
- Allows both React & Wind and Wind & React options
- Allows more technology options for insulation, etc.
- Allows rapid-turn-around, low-cost R&D for systematic and innovative studies
- ...
We are in an era where the next hadron collider may be decades away.

Conductor, technologies and designs are evolving, and they may change the equation.

For long term R&D projects like this, we must re-evaluate our direction every five years so.

Potential benefits of the common coil geometry are becoming apparent.

Include common coil design at the top-level discussion, while overviewing the options.

Compare all designs methodically for their potential advantages and challenges.

Be ready to adjust directions, specific goals, and milestones, if necessary.
You are invited to join the white paper

Common Coil Dipole for High Field Magnet Design and R&D

Proponents: Ramesh Gupta, Kathleen Ann, Michael Ansell, Anis Ben Yahia, John Cozzolini, Piyush Joshi, Jess Schmalzle (BNL), Ronald Scanlan, Robert Weggell, Erich Willen (PBL), Qingxin Xu (IHEP), Fernando Toral (CIMET), Gianluca Sbabi, Steve Gourlay (BNL), Danilo van der Laan and Jeremy Weiss (ACT)

REFERENCES

You are invited to join the white paper

Common Coil Dipole for High Field Magnet Design and R&D

Proponents: Ramesh Gupta, Kathleen Ann, Michael Ansell, Anis Ben Yahia, John Cozzolini, Piyush Joshi, Jess Schmalzle (BNL), Ronald Scanlan, Robert Weggell, Erich Willen (PBL), Qingxin Xu (IHEP), Fernando Toral (CIMET), Gianluca Sbabi, Steve Gourlay (BNL), Danilo van der Laan and Jeremy Weiss (ACT)

The principle threat of magnet R&D for the next generation high energy collider is developing and demonstrating magnet designs for building high field magnets in large volume in industry at a low cost. Many current studies at date have been built on the strength of the costs these magnet designs using MHT and, more recently, Multi-Heat Temperature Superconductors (MHTS). These magnet designs are being extended to reach higher fields based on a significant 20% reduction in Nb3Sn conductor cost. Additional research is needed in the understanding of high fields both in terms of budget and turn-around time can be estimated. With the colliding several decades away, a rate can be made that this time should be used to demonstrate alternative designs that have the potential to produce high field magnets in industry at a lower cost while meeting the field qualification requirements of high energy colliders. There is also a need to include a strong R&D component in the program which facilitates testing and demonstration of new components and technologies as a relatively short time frame and at a cost much smaller than building a magnet.

The common coil design is a conductor-friendly block coil design with simple edges that have a large bend radius. The bend radius is determined by the separation between the two apertures of the colliders rather than the aperture itself. The common coil design readily accommodates high field, high power conductors, or conductors that require large bend radii. The large bend radii in the common coil geometry allows both the "Wind & React" and "React & Wind" technologies. The common coil design is a technically superior solution for high field magnets because the coils are primarily stacked vertically and move as a unit against the large longitudinal Lorentz force. This largely eliminates the internal strain on the conductor at or near the end region of the superconducting coil when the two sides of the coil move apart under Lorentz forces — a very different situation as compared to that in the conventional block coil or coupler type dipole designs. As a common coil design, the common coil block coil design eliminates almost all of the hard bandways (or ends requiring long weight). The only remaining hard bandways are on the multiple coils and some design practices eliminate the hard bandways in those as well.

The common coil design facilitates a modular geometry which is particularly attractive for superconducting hybrid (HTS/HTS) magnets which require matching coil and different types of conductors. In addition, the common coil design also offers sideband segmentation that is easily suitable for hybrid coil dipole design. Such magnets use one conductor made with material conductors (NbTi and Nb3Sn) in addition to the common coil design, the common coil block coil design eliminates almost all hard bandways (or ends requiring long weight). The only remaining hard bandways are on the multiple coils and some design practices eliminate the hard bandways in those as well.

The common coil design facilitates a modular geometry which is particularly advantageous for superconducting hybrid (HTS/HTS) magnets which require matching coil and different types of conductors. In addition, the common coil design also offers sideband segmentation that is suitable suitable for hybrid coil dipole design. Such magnets use one conductor made with material conductors (NbTi and Nb3Sn). In addition to the common coil design, the common coil block coil design eliminates almost all of the hard bandways (or ends requiring long weight). The only remaining hard bandways are on the multiple coils and some design practices eliminate the hard bandways in those as well.

In addition to allowing versatility in conductors and technologies, the common coil design is also one of the most likely candidates to provide lower cost large scale production of high field 2-in-1 coil dipole with good technical performance. Lower cost in large volume industrial manufacturing is expected because the common coil design would allow less expensive and more rapid production techniques due to its simpler racetrack coil geometry. Half the number of coils required (as the same coils are shared between two quads) reduces the overall cost of the coil units by a factor of two in structural material.

The common coil dipole design was used in an earlier proposal for the Very Large Hadron Collider (VLC) in the US [2]. The common coil design has also been used [3] in the previous Large Hadron Collider (LHC) in Europe and in China and is one of the design under consideration for the proposed Future Circular Collider by CERN [4].

Several measurements including BNL [5], BNL [6], FNAL [7], CERN [8] and CERN collaboration on the conceptual design of the magnet. Magnets design on the common coil dipole design have been successfully built at BNL [9], FNAL [10] and BNL with Nb3Sn and HTS-RSSW (RBS) [11]. The very first test magnet based on this design at BNL (HTS) reached short sample with almost no quench [12]. There are several other magnets and magnet designs currently under various stages of development. A recent publication also showed that the change in stress causes no degradation in performance. A common coil Nb3 Sn dipole [13] built using the "Wind & React" technology reached 17 T at 4.5 K. At BNL a "React & Wind" Ni³Sn dipole [14] was built with essentially no vertical and horizontal stress and it reached over 14 T. It consisted of multiple Nb3Sn [17] and HTS [10] coils and coil designs. Coils [18] have been also built and tested on magnets based on this design. Despite many incarnations and even though FNAL built and tested an accelerator type field quality common coil dipole design [19], the common coil design has been shown to achieve a fully optimized high quality coil in a higher field regime. This common coil design has been demonstrated to have very good and field performance compared to classic designs.

Hybrid magnets based on the common coil design have also been built and tested. Some examples of hybrid common coil dipole include a 5.7 T dipole at BNL with NbTi and Nb3Sn [20] and Rutherford cables [21] at BNL at 14 T dipole at 4.5 K with NbTi and Nb3Sn coil [22]. Higher field hybrid common coil dipole is under construction includes 14-18 T Wells-1pole and 4 T RS-1pole dipole under a collaboration between the Advanced Research Technologies LLC and BNL [23], and HTS (RBS) [24] is in [25]. A common feature of all these coils is a very high field and improved approximately 10% between the common coil design and a different conductor.

The common coil dipole design offers significant improvements over conventional magnetic systems and is a novel approach that may offer a simpler and less expensive way to build large scale high field magnets. However, the common coil design is a cost-effective and robust design that may offer a viable alternative to conventional magnetic systems.
Kodak knew about the digital photography.
But chose to stay with the print...
Summary

- MDP comparative study revealed that for very high field dipoles (20 T), common coil design uses significantly less conductor than that used in other designs. The analysis presented here explains why?
- Common coil offers several advantages, some outlined in this presentation.
- A focused effort should now be made across the labs to develop this design in more detail (including 3-d design, quench protection, assembly, R&D plan, etc.).
- This is a different design and provides new opportunity. A good opportunity for new scientists and engineers (who come with less to NO pre-conceived notions and biases) for doing pioneering work.
- Suggest that we to do a full comparative study of all options in the next annual meeting and see if an update in direction is warranted.
Splices in Common Coil Design (between two single layer coil)

In common coil design, splice (even between two types of coils), can be easily made in the middle of the coil where the field is very low.

Perpendicular Nb-Ti splice in the low field region of BNL common coil dipole DCC017
Demonstration of Good Field Quality in Ends

End harmonics can be made small in a common coil design.

End harmonics in Unit-m (Very small)

<table>
<thead>
<tr>
<th>n</th>
<th>Bn</th>
<th>An</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>-0.03</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>-0.10</td>
</tr>
<tr>
<td>7</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
<td>-0.05</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
<td>-0.01</td>
</tr>
<tr>
<td>11</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>12</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>18</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Up-down asymmetry will give large skew harmonics, if done nothing.

However, it can be easily compensated with the end spacers. Integral $B_y$ 10 mm above & 10 mm below midplane.

Contribution to integral ($a_n b_n$) in a 14 m long dipole ($\leq 10^{-5}$)

<table>
<thead>
<tr>
<th>n</th>
<th>Bn</th>
<th>An</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>3</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
<td>-0.005</td>
</tr>
<tr>
<td>5</td>
<td>0.019</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>-0.014</td>
</tr>
<tr>
<td>7</td>
<td>0.025</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
<td>-0.008</td>
</tr>
<tr>
<td>9</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
<td>-0.001</td>
</tr>
<tr>
<td>11</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Delta-Integral

$B_y$ 10 mm above and below midplane on magnet axis (ends optimized with one spacer to match integral)
Situations change for high field designs when the coil width (area) becomes much larger than the bore (aperture). One must re-evaluate the impact on geometry and other constraints.

Variables and constraints to optimize the cosine theta and the canted cosine theta designs:

- Total coil width (radial width – free to grow)
- Pole Angle (limited to 90° max., 60° min. for $b_3=0$)
- Field quality: use wedges (may be used for structure)
- Radial space between layers for structure element

Variables and constraints to optimize the block coil and the common coil designs:

- Total coil width (horizontal width – free to grow)
- Coil Height (vertical height – free to grow) – major difference from the cos θ or canted cosine theta
- Field quality: use spacer (structure) & pole coils
- Horizontal space for structure elements
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?

### Cosθ without and “with stress management”

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Ins. cable I width/thick.</td>
<td>mm</td>
<td>10.7</td>
<td>12.0</td>
<td>12.3</td>
<td>12.3/1.5</td>
<td>18.7/1.9</td>
<td>17.1/2.1</td>
<td>17.1/2.1</td>
<td>18.7/1.8</td>
<td>18.7/1.8</td>
<td>7.5/7.5</td>
</tr>
<tr>
<td>Ins. cable II width/thick.</td>
<td>mm</td>
<td>9.4/1.5</td>
<td>14.2/2.1</td>
<td>10.7/1.5</td>
<td>13.9/1.5</td>
<td>-</td>
<td>17.1/2.1</td>
<td>17.1/2.1</td>
<td>13.6/1.9</td>
<td>13.6/1.9</td>
<td>21.6/1.9</td>
</tr>
<tr>
<td>Ins. cable III width/thick.</td>
<td>mm</td>
<td>9.3/1.5</td>
<td>7.9/1.5</td>
<td>9.1/1.5</td>
<td>9.1/1.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<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>
<td>14</td>
<td>13.9</td>
<td>17.8</td>
</tr>
<tr>
<td>B_bore_op</td>
<td>T</td>
<td>20.0</td>
<td>20.0</td>
<td>20.1</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>B_bore_op HTS/LTS</td>
<td>T</td>
<td>20.5/12.7</td>
<td>20.3/16.1</td>
<td>20.6/13.6</td>
<td>20.6/16.0</td>
<td>20.2/13.2</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>
</tr>
<tr>
<td>B_bore_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>
</tr>
<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>
</tr>
<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>1500</td>
<td>1290</td>
<td>1154</td>
<td>1012</td>
</tr>
<tr>
<td>Area quad. ins. cable LTS</td>
<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>2326</td>
<td>2588</td>
<td>4191</td>
</tr>
<tr>
<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>
</tr>
<tr>
<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>35</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Cosθ without and “with stress management”

**Typo?**

P. Ferracin, "Towards 20 T hybrid accelerator dipole magnets" - Ramesh Gupta, BNL
➢ Mechanical analysis of the 20 T HTS/LTS hybrid design (work just started).
➢ Provide feedback to magnetic design for the space needed for the structure between layers and within layer. Iterate magnetic and mechanical designs.
➢ Develop concepts for assembling the magnet.
➢ Perform 3-d magnetic and mechanical analysis for a 20 T design.
➢ Perform refined mechanical analysis for practical 3-d structures.
➢ Perform quench protection analysis.
➢ Several common coil dipoles with main coils have been built and tested; however, none with the pole coils necessary for the field quality. Build pole coils and demonstrate them in a proof-of-principle magnet (e.g. in DCC017).
➢ Perform cost estimates of R&D dipoles and for large scale series production.