High Field Hybrid Dipoles for FCC

Ramesh Gupta
Brookhaven National Laboratory
Overview

- Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes
  - This could be a game changer for ReBCO

- Common Coil Dipole (Nb$_3$Sn and hybrid)
  - Additional options and requirements related to Nb$_3$Sn

- Open Midplane Dipole (Nb$_3$Sn and hybrid)
  - Relaxation in temperature margin and PoP model
• Issue:
  – ReBCO is primarily available in tape form
  – Magnetization is large in cosine theta or common coil designs
    ➢ related to tape width: 12 mm for high current conductors
• Solution #1: conductor design
  – Round wire
  – Striated tape
• Solution #2: coil design
  – See what we can do to use and enhance the strengths of the conductor

Next few slides on the technique
• Conductor magnetization and hence the persistent-current induced harmonics are related to the width of the conductor (wire or tape) “perpendicular to the field”

• In most Nb-Ti magnets, the filament size is ~ 6 μm
  – higher in Nb₃Sn, but usually <100 μm
• In ReBCO it is considered to be ~12 mm for high current tapes

Design Technique to Reduce Magnetization Effects:
• Align the tape conductor (thickness few μm) such that primarily the “narrow side sees the perpendicular field”
• It’s possible to align HTS tape to a good extent in hybrid magnets by carefully designing the coil

Effective filament size 12 mm ➞ a few μm in an ideal design ➞ small in a real design, depending on the optimization
Comparing Designs for Magnetization

For Single Figure of Merit:
- Persistent current induced harmonics

- **Bad** designs for HTS tape
  - large area covered by the perpendicular component of the field

- **Good** designs for tape (small area curved by the perpendicular component of the field)

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**Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes**

R. Gupta$^1$, A. Ghosh$^1$, R. Scanlan$^2$ and R. Weggel$^2$

$^1$Brookhaven National Laboratory, Upton, NY 11973 USA

$^2$Particle Beam Lasers, Inc., 18925 Dearborn Street, Northridge, CA 91324 USA

BNL Magnet Division Note: MDN-676-41

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Part of PBL/BNL Provisional Patent Application
Other Benefits of Aligned Tape Design (conductor efficiency)

Survey of 20 T Magnet design possibilities

One of many such plots and 1000’s of magnet x section designs in total

Courtesy: J. Van Nugteren
Other Benefits of Such Designs

• Lorentz forces are primarily on the wide face of conductor
  ➢ ReBCO can tolerate large stresses on wide side
• Blocks are easy to segment
  ➢ Between HTS and LTS
  ➢ Stress management
High Field Hybrid Dipoles for FCC

Ramesh Gupta
Feb. 16-18, 2015

Superconducting Magnet Division

**High Current Conductor/Cable**

**Success of this approach may impact the conductor optimization:**

- Attempt to increase isotropy should not sacrifice field parallel $I_c$
  - However, a broader peak (5-10 degrees) would simplify the magnet design
- Attempt to increase field parallel $I_c$ rather than field perpendicular $I_c$
- Present value of field parallel $I_c$ is over 3 kA for single tape
  - This is likely to increase as ReBCO thickness becomes ~1 μm to several μm
- Develop simple multi-tape (bonded, multi-ply, …) conductor
  - This increases kA value of conductor
  - This should make conductor more robust as current may bypass from one tape to another (as in “no-insulation”) in case of local defect or variation
- Develop wide multi-tape (say four, or more) with copper laminations on either side
  - Perform experiments on how effective such conductor is in magnet coils

*A dream conductor may be an optimized multi-tape configuration: 10-20 kA @ design*
Test of Principle in A Real Magnet
(measure and compare magnetization in two configurations)

Common Coil Dipole with a large open space
- Coils can be inserted without opening the magnet

A Hybrid HTS/LTS ...High-Field Accelerator Magnets
- Pending Phase II PBL/BNL STTR Application

Part of PBL/BNL Provisional Patent Application
Common Coil Dipole

- 15 T Design: Nb$_3$Sn or Nb$_3$Sn/NbTi (LTS only)
- 20 T Design: HTS/LTS Hybrid
In common coil design, a racetrack coil can move as a block, without straining the conductor in the ends and thus minimize quench or damage.

In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.
Demonstration of Good Field Quality
(Geometric Harmonics)

Typical Requirements:
~ part in $10^4$, we have part in $10^5$

Horizontal coil aperture: 40 mm

MAIN FIELD: -1.86463 (IRON AND AIR):

b 1: 10000.000   b 2: 0.00000   b 3: 0.00308
b 4: 0.00000    b 5: 0.00075   b 6: 0.00000
b 7: -0.00099  b 8: 0.00000   b 9: -0.01684
b10: 0.00000  b11: -0.11428  b12: 0.00000
b13: 0.00932  b14: 0.00000  b15: 0.00140
b16: 0.00000  b17: -0.00049  b18: 0.00000

(from 1/4 model)
Demonstration of Good Field Quality
(Saturation-induced Harmonics)

Maximum change in entire range: ~ part in $10^4$
(satisfies general accelerator requirement)

Use cutouts at strategic places in yoke iron to control the saturation

Low saturation-induced harmonics (within 1 unit)
Demonstration of Good Field Quality (End Harmonics)

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

Contribution to integral \((a_n, b_n)\) in a 14 m long dipole (<10^-6)

(Very small)

End harmonics in Unit-m

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BNL Nb$_3$Sn React & Wind
Common Coil Dipole DCC017

Large vertical open space for insert coil testing
Superconducting Magnet Division

Performance of React & Wind Common Coil Dipole (despite large deflections)

- Magnet reached short sample after a number of quenches
  - √ Reasonable for the first technology magnet
- The geometry can tolerate large horizontal forces and deflections
  - important for high field magnets
  - computed horizontal deflection/movement of the coil as a whole ~200 μm

I_c = 10.8 kA
B_{pk} = 10.7 T
B_{ss} = 10.2 T

- Slightly exceeded the computed short sample
- Practically no vertical or horizontal pre-load

\[ I_c = 10.8 \text{ kA} \]
\[ B_{pk} = 10.7 \text{ T} \]
\[ B_{ss} = 10.2 \text{ T} \]
Large bend radius in common coil design also allows the alternate “React & Wind” Approach. “React & Wind” offers the following:

- Allows a larger choices for insulation and other coil material as the coil doesn’t have to go through the high temperature reaction process.
- Surprises during scale-up to longer length should be much less of a concern than that in the “Wind & React” approach
- Another minor advantage (though only for a short time scale) that it requires much less expensive tooling to start the R&D magnet production (short or long) as many steps and care involved in coil reaction process are not applicable.
- The “React & Wind” design puts extra consideration on the conductor development. Even though common coil design allows a larger bending radius, the strain dependence degradation should be minimized for high field applications.
Open Midplane Dipole

- 15 T Design: Nb$_3$Sn or Nb$_3$Sn/NbTi (LTS only)
- 20 T Design: HTS/LTS Hybrid
• In a true open midplane dipole, synchrotron radiations deposit most energy in a warm absorber that is sufficiently away from the superconducting coils or cold structure.

• In a “partial open midplane design”, although there are “no conductors” at the midplane, there is “structure” between the upper and lower coils. That structure helps in dealing with the Lorentz forces but it also absorbs energy at 4 K and creates secondary showers which then deposit additional energy at 4 K.

• Therefore, a “true open midplane dipole” is preferred, provided a viable design can be proven.
SYNCHROTRON RADIATION

In 100 TeV p-p collider (CERN FCC-hh) 0.5 amp 16 T:

- Total SR power = 4.8 MW
- If on magnet bore: wall power to cool is crazy
- Requires beam screen at 50 K
- If screen inside beam pipe: uses valuable space
- If screen in beam tube: Emits electrons \( \rightarrow \) electron cloud
- If deposited away from beam tube, as in e+e- ring colliders, BOTH PROBLEMS SOLVED

Courtesy: Bob Palmer, BNL
Challenges associated with the “Ideal” or “True” Open Midplane Dipole Design

#1 In usual cosine theta or block coil designs, there are large attractive forces between upper and lower coils. How can these coils hang in air with no structure in between?

#2 The ratio of peak field in the coil to the design field appears to become large for large midplane gaps.

#3 The large gap at midplane appears to make obtaining good field quality a challenging task. Gap requirements are such that a significant portion of the cosine theta, which normally plays a major role in generating field and field quality, must be taken out from the coil structure.

Several innovative design solutions were developed to overcome above challenges (please see extra slides) with significant funding from LARP. The R&D was terminated before those solutions could be demonstrated.

We get another chance now – either through SBIR and/or direct funding
A Proof of Principle Demonstration of A True Open Midplane Dipole

A 20 T Hybrid Design (HTS & LTS well separated)

Can one have coils energized with no structure between upper and lower halves at midplane?

Proof of Principle Demonstration with HTS Coils at 77 K (proposed in Phase I itself)

(HTS demo magnets can be cheap to build and test – custom made for graduate research)

Novel High Field Hybrid Open Mid-Plane Dipole Coil

- Phase I E2P/BNL SBIR Application

Lorentz forces in upper-right quadrant
Tolerate some perturbation in the ends where turns go from one aperture to another.

- \( \text{Nb}_3\text{Sn} \) coil go from upper aperture to lower aperture (as in common coil) but HTS coil within the same while clearing the bore (developed for LHC magnets - ASC2002).

- Such windings allows wide side of the HTS tape align parallel to the field.

From Phase I proposal
Novel High Field Hybrid Open Mid-Plane Dipole Coil
SUMMARY

High field hybrid magnet designs can be developed in such a way that the conductor magnetization (persistent current induced harmonics) become significantly less, overcoming a major technical issue associated with the tape.

It may be possible to design the high field hybrid magnets with ReBCO tape configuration carrying over 10 kA current.

Such designs can handle large stresses, as present in high field magnets, as they are against the wider side of the tape.

Requirements of expensive conductor are significantly reduced because of the field orientation (previous design work at CERN).

Degree of above benefits need to be determined by model calculations and demonstration. A cost effective systematic R&D could be carried out with a unique background field common coil magnet available for testing at BNL.

Common coil dipole (either “Nb$_3$Sn” or “Hybrid” and either “React & Wind” or “Wind & React”) could handle large forces.

Open midplane dipole allows the significant reduction of the heat load on the superconducting coils and on cryogenic system.
Extra Slides
Common Coil Design

- **Simple 2-d geometry** with large bend radius (no complex 3-d ends)
- **Conductor friendly** (suitable for brittle materials – can do both Wind & React and React & Wind with LTS and HTS)
- **Compact** (compared to single aperture LBL’s D20 magnet, half the yoke size for two apertures)
- **Special coil geometry** (suitable for large Lorentz forces at high fields)
- **Efficient and methodical R&D** due to simple & modular design
- **Minimum requirements** on expensive tooling and labor
- **Successfully built** at LBL, BNL & FNAL
- **Lower cost magnets** expected

Main Coils of the Common Coil Design
In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils. Structure generates large heat loads and the goal is to minimize them.

Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.
Net upward vertical force on lower double pancake coil

Downward vertical force on upper double pancake coil is taken by the support structure between two double pancake coils

Net Force per quadrant:
Horizontal = 11 MN/m; Vertical = -5.4 MN/m
In a more optimized design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron).

Above deflections are at design field (13.6 T). They are ~1-2 mil higher at 15 T.
Several designs have been optimized with a small peak enhancement: ~7% over $B_0$

Relative field enhancement in coil (peak field) over the central field

Quench Field: $\sim 16\, T$ with $J_c = 3000\, \text{A/mm}^2$, Cu/Non-cu = 0.85

Quench Field: $\sim 15.8\, T$ with $J_c = 3000\, \text{A/mm}^2$, Cu/Non-cu = 1.0
**Challenge #3: Field Quality**

Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

⇒ Vertical gap is > 42% of horizontal aperture

(midplane angle: 23°)

What part of cosine(θ) is left in that famous cosine(θ) current distribution now?

This makes obtaining high field and high field quality a challenging task!

We did not let prejudices come in our way of optimizing coil - e.g. that the coil must create some thing like cosine theta current distribution!
Field Harmonics and Relative Field Errors in an Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:

Area where field error is $<10^{-4}$

(Bean @ x=+/− 36 mm at far end)
(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

Harmonics optimized by RACE2dOPT

Field errors should be minimized for actual beam trajectory & beam size. It was sort of done when the design concept was being optimized by hand. Optimization programs are being modified to include various scenarios. Waiting for feedback from Beam Physicists on how best to optimize. However, the design as such looks good and should be adequate.
Field Uniformity in an Optimized 15 T Open Midplane Dipole Design

Proof that good field quality can be obtained in such a wide open midplane dipole design:

The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

The actual field errors in these magnets will now be determined by construction, persistent currents, etc.; i.e., they are not limited by the design geometry.

Note: The scale is a few parts in $10^{-5}$. 

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PROBLEM DATA
- Test Case
- Quadratic elements
- XY symmetry
- Vector potential
- Magnetic fields
- Static solution
- Scale factor = 0.1
- 47309 elements
- 95210 nodes
- 134 regions

Homogeneity of BMOD w.r.t. value 1.57040153495193 at (0,0,0.0)