Open Midplane Magnets

Part 2 - Magnet Design

(Part 1 was presented by Brett Parker)

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• **Open Midplane Dipole Design**
  – Basic design concept and advantages
  – Progress in high field and high field quality magnet designs (LARP work)

  ✓ Relevance to $\mu^+\mu^-$ collider: Large energy deposition at midplane from decay particles

• **RIA HTS Quadrupole**
  – HTS coils to withstand and economically remove extremely large heat loads
  – Magnet construction and test results
    ➢ including critical energy deposition experiments

  ✓ Relevance to $\mu^+\mu^-$ collider: HTS can create high fields and withstand large heat loads

• **Combined Function Magnet Designs**
  – A brief review of the previous work on neutrino factory combined function magnet design (dipole with skew quad) for a compact machine (B. Parker)

• **Summary**
Progress in Open Midplane Dipole Design
(work performed under the auspices of LARP)
A True Open Midplane Design

By open midplane, we mean truly open midplane:

- Particle spray from IP (mostly at midplane), passes through an open region to a warm (~80 K) absorber sufficiently away from the coil without hitting superconducting coils or any structure near it.

- In earlier “open midplane designs”, although there was “no conductor” at the midplane, but there was some “other structure” between the upper and lower halves of the coil. Secondary showers from that other structure deposited a large amount of energy on the superconducting (s.c.) coils.

- Earlier designs, therefore, did not work so well in protecting s.c. coils against energy deposition.
Open Midplane Dipole Design

Challenges

#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.

=> Could there be a solution that can overcome above?

→ With such basic challenges in place, don’t expect the design to look like what we are used to seeing in conventional cosine theta magnets.
**Challenge #1: Lorentz Forces between coils**

A new and major consideration in design optimization

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.

Original Design

New Design

Concept to navigate Lorentz forces

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.
Challenge #2: Peak Field

Several designs have been optimized with a small peak enhancement: \( \sim 7\% \) over \( B_0 \).

Relative field enhancement in coil over the central field.

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

Quench Field: \( \sim 15.8 \text{ T with } J_c = 3000 \text{ A/mm}^2, \text{ Cu/Non-cu} = 1.0 \)
**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°)

**Conventional cosine theta**

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!

**Open midplane design**

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:

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

**Geometric Field Harmonics:**

- 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.

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

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<tr>
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<td>Length</td>
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<td>A/m²</td>
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<td>Mass</td>
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Homogeneity of B/MOD w.r.t. value 1.57040153495193 at (0,0,0,0)
SUMMARY

- The open midplane dipole is very attractive option for the LARP dipole-first IR at $L = 10^{35}$. The design accommodates large vertical forces, has desired field quality of $10^{-4}$ along the beam path and is technology independent.

- After several iterations with the BNL group over last two years, we have arrived at the design that – being more compact than original designs – satisfies magnetic field, mechanical and energy deposition constraints.

- We propose to split the dipole in two pieces, 1.5-m D1A and 8.5-m D1B, with a 1.5-m long TAS2 absorber in between.

- With such a design, peak power density in SC coils is below the quench limit with a safety margin, heat load to D1 is drastically reduced, and other radiation issues are mitigated. This is a natural two-stage way for the dipole design and manufacturing.
## Summary of Optimized Open Midplane Nb$_3$Sn Dipole Designs for LARP

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<th>C</th>
<th>D</th>
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<td>13.6</td>
<td>13.6</td>
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<td>$B_{ss}$(T)</td>
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For more information (publications + talks):  http://www.bnl.gov/magnets/Staff/Gupta/
Open Midplane Designs With HTS (High Temperature Superconductors)

- HTS magnets could be designed to operate at very high fields (16 Tesla and above).
- HTS may be used in a hybrid design with Nb$_3$Sn coils.
- A significant advantage of HTS is that they could tolerate a large amount of energy deposition.
RIA HTS QUAD

Experience with construction and test of HTS magnet
Up to 400 kW of beam power hits the target producing a variety of isotopes.

Fragment separator then select one isotope to transport out; but must deal with a large number of unwanted one.

Quad triplet in the fragment separator is exposed to very high level of radiation and heat loads.

~15 kW of the above is deposited in the first quadrupole itself.

Quads in the fragment separator region will live in an environment that was never experienced before by magnets in any accelerator or beam-line.

Basically, RIA needs “Radiation resistant” magnets that can withstand these extremely large radiation and heat loads and can also operate economically.
Advantages of using HTS in RIA/FRIIB

- Removing these large heat loads (~400 kW in target, ~15 kW in first quad) at ~30 K instead of ~4K is over an order of magnitude more efficient.

- HTS can tolerate a large local increase in temperature in superconducting coils caused by the non-uniform energy deposition.

- Moreover, in HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that for the present low temperature superconducting magnets (few kelvin rather than a few tenth of a kelvin). This simplifies the design and reduces cost of the cryogenic system.

- Therefore, HTS would facilitate a magnet system for fragment separator that will be robust and economical to operate.
RIA HTS Model Quadrupoles

Warm iron R&D quadrupole with twenty four coils in two cryostats
RIA coils are co-wound with HTS tape and S.S. tape. In RIA, S.S. tape is used as radiation resistant insulator.

In high field solenoid S.S. tape is used as high strength material (e.g. Muons, Inc./Palmer’s proposal and a coil earlier wound by Sampson under an LDRD).

RIA quad is made with 24 coils with each using ~200 meter of commercially available HTS wire (tape).

This gives a good opportunity to examine the reproducibility and reliability in performance of number of coils (number grows every year).
LN$_2$ (77 K) Test of 25 BSCCO 2223 Coils

13 Coils made earlier tape
(Nominal 175 turns with 220 meters)

12 Coils made with newer tape
(150 turns with 180 meters)

Coil performance generally tracked the conductor performance very well.

Note: A uniformity in performance of a large number of HTS coils made with commercially available superconductor (ASC).

It shows that the HTS technology is now maturing!
A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

More coils create more field and hence would have lower current carrying capacity.
Energy Deposition and Cryogenic Cooling Experiments (Direct Vs. Conduction)

Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- In conduction cooling mode, helium flows through top and bottom plates only.
- In direct cooling mode, helium goes in all places between the top and bottom plates and comes in direct contact with coils.

Stainless steel tape heaters for energy deposition experiments
Goal was to demonstrate that the magnet can operate in a stable fashion at the expected heat loads (5mW/cm³ or 5kW/m³ or 25 W on 12 short HTS coils) at the design temperature (~30 K) with some margin on current (@140 A, design current is 125 A).

Temperature differences may be partly real and partly calibration mis-match. As such HTS can tolerate such temp variations with small margin.

Stable operation for ~40 minutes

- We use 0.1 \( \mu \text{V/cm} \) as the definition of \( I_c \).
- Temperature differences may be partly real and partly calibration mis-match.
- Voltage spikes are related to the noise.
The goal is to move to 2\textsuperscript{nd} generation wire because:

- 2G is expected to allow operation at 50 K (or above), which would provide even more saving in operation.
- 2G is expected to be less expensive.

**Near Future (04/07-03/08)**
- Make 3 coils each with \(\sim\)100 m of 2\textsuperscript{nd} generation wire
  - Two coils with wire from ASC wire and one from SuperPower
- Continue experimental studies on radiation damage on YBCO and BSCCO to determine if one is significantly better than the other.

**Intermediate Future:**
- Develop design, build and test full length quad based on whichever conductor is better
- Study other critical magnets
$I_c$ vs. $T$ Over a Large Range of Temperature in RIA Coils Made with YBCO and Bi2223

BSSCO and YBCO Tapes from ASC

Note: YBCO is already better than BSCCO. And there is still a significant potential for improvements.
A Few HTS Magnet Topics Directly Related to Muon Collider and/or Neutrino Factory
HTS for High Field Magnets with Rutherford Cable

- Cable made at LBL, reacted at Showa, tested at BNL
- HTS coil wound & tested in a common coil magnet at BNL

HTS cables, coils & magnets can carry a significant current.

Earlier coils:
- <1 kA (~2001)

Later coils:
- 4.3 kA (10/03)

Self-field:
- <0.05 T
- ~ 1.85 T
• Roebel cable allows higher operating current and coupling between a number of wires (somewhat analogous to Rutherford cable with round wires)

• Roebel cable may make YBCO tape much more attractive for accelerator and other type of magnets
**Medium Field HTS Dipole for Super Neutrino Facility**  
**A Case Study for Cost of Ownership (capital+operation)**  
**Comparison between Copper and HTS Magnet**

### Copper Magnets:
- Better known costs (estimated: ~150k$ each for this magnet)
- Cost of individual components like coil, yoke, etc., is well understood
- High operating costs (estimated ~3 MW total)
- Low thermal conductivity water cooling plan
- Higher current (a few kA) power supply (higher cost)
- Maintenance issues (cost, downtime): water leak etc.

### HTS Magnets:
- Develop designs to reduce cost (goal: ~150k$/magnet for equivalent integral field)
- Cost of HTS: ~30 k$ (~1/5 of total magnet cost per present rate)
- Need to include cost of other components like iron (low and well understood), support structure, cryostat (major driver unless better designs developed)
- Lower operating costs (wall power of cryo-cooler? Is LN2 possible?)
- Cost of cryo-coolers (compare with infrastructure cost of Low Thermal Conductivity Power Plant)
- Lower current (a few hundred Amp) power supply (cheaper)
- Maintenance issues (cost, downtime): cryo-coolers

**Design Parameters:**
- $B = 1.55$ T
- $L = 3.73$ m
- Pole width = 153 mm
- Pole gap = 76 mm
HTS Solenoid for Electron Cooling

Larger coil: 15 X 12 turns
Smaller coil: 15 X 2 turns
Nominal current: 33.6 Amp

Test result of larger coil
Combined Function Magnet Design

Dipole and skew quadrupole optics for compact ring (Parker)
Design Principles and Requirements:

Decay products clear superconducting coils

Compact ring to minimize the environmental impact (the machine is tilted)

→ Need high field magnets and efficient machine design

Storage ring magnet design (simple racetrack coils with open midplane)
• Skew quadrupole needs **NO** conductor at midplane (B. Parker)

• In study 1 (50 GeV), ~1/3 space was taken by inter-connect regions


To first order, dipole becomes a skew quad, if the relative polarity of coils is changed.
Coil Layout for Obtaining A Variety of Magnet Configurations

New magnet system design makes a productive use of all space!

Shorter cells → smaller aperture, improved beam dynamics (Parker)

Reverse coils also cancel harmonic errors in the ends
A Possible Magnet Test Setup

Structure to test magnet performance in various configuration:

Magnet system layout in the proposed ν factory storage ring:

- One Coil D/2 & Q/2
- Normal Coils Dipole (D)
- Reverse Coils Skew Quad (Q)

Work carried out under a BNL LDRD
• The development of open midplane design is important to $\mu^+\mu^-$ colliders, as large magnitude of decay particles at the midplane may limit the performance of superconducting coils and increase the operating cost of the machine.

• The design concept has been significantly developed over last few years. Now, we can have a truly “Open Midplane” design with a way to deal with Lorentz forces and have a good field quality, as well.

• HTS is beneficial in a variety of magnets in $\mu^+\mu^-$ colliders. HTS can generate very high fields and can tolerate and economically remove large heat loads.

• It has been shown that HTS magnets can be designed, built and operated in presence of a large heat load environment.

• Second generation HTS makes HTS magnets even more attractive.

• Combined function magnet design with skew quadrupole offers an interesting possibility. Such magnets and lattice can be designed.

Of course, all of above still require a significant amount of work before magnets based on these designs could be inducted in an operating machine.