BROOKHAVEN
NATIONAL LABORATORY

BNL-76894-2006-CP

RACETRACK MAGNET DESIGNS AND TECHNOLOGIES

Ramesh Gupta

Presented at the Workshop on Accelerator Magnet Design and Optimization (WAMDO 2006)
Geneva, Switzerland
April 3-6, 2006

April 2006

Magnet Division
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

Presented at the Workshop on Accelerator Magnet Design and Optimization (WAMDO 2006) at CERN, Geneva, 3 - 6 April 2006.

RACETRACK MAGNET DESIGNS AND TECHNOLOGIES*

Ramesh Gupta
Brookhaven National Laboratory, Upton, NY 11786 USA

Abstract
This paper presents a review of racetrack coil magnet designs and technologies for high field magnets that can be used in LHC upgrade. The designs presented here allow both "Wind & React" and "React & Wind" technologies as they are based on flat racetrack coils with large bend radii. Test results of the BNL 10.3 T "React & Wind" common coil magnet are also presented. A possible use of High Temperature Superconductors (HTS) in future high field accelerator magnets is examined.

1. INTRODUCTION

All conductor dominated accelerator magnets are currently based on the conventional "cosine theta" designs. Magnets based on flat racetrack coils offer an alternative to these "cosine theta" designs. "Racetrack coil designs" are particularly attractive for "high field magnets" with "brittle conductors" (a) because of the way large Lorenz forces can be resolved in a magnet structure and (b) because of the simple flat racetrack coil geometry that minimizes the stress and strain degradation on brittle conductors. A number of designs have been developed with large bend radii that permit the use of both "Wind & React" and "React & Wind" technology and are also attractive for using HTS in accelerator magnets. These designs include the "common coil design" for "energy upgrade", the "open midplane dipole design" for "dipole first optics" and the "modular quadrupole design" for "luminosity upgrade". As shown in the following sections, these designs produce field quality that satisfies the requirements of accelerator magnets and is as good as that produced in conventional "cosine theta" designs. It is shown that commercially available HTS starts becoming competitive in performance with the Nb_3Sn superconductor currently specified for LARP (LHC Accelerator Research Program) interaction region magnets at an operating field of ~14 T or above.

2. MAGNET DESIGNS

2.1 Common Coil Design

The common coil magnet design has been proposed [1,2] for 2-in-1 dipoles where the apertures are over and under with the desired beam spacing in the vertical direction. In the basic design (see Fig. 1), the main coils are common to both apertures. This allows the use of flat racetrack coils with large radii. The basic concept was later extended to a 4-in-1 dipole [3] to allow the injector to be included in the same cryostat and magnet system. As shown in Fig. 2 and Fig. 3, it is possible to design such racetrack coil magnets that produce good field quality in both body and end regions [4]. The common coil magnet design can be used for an LHC energy upgrade. The proposed 4-in-1 magnet will incorporate a lower energy injector in the same cryostat to fit within the present LHC tunnel. The common coil design also offers a cost-effective and rapid turn around approach for carrying out a systematic magnet R&D program [1,4].

* This manuscript has been authored by Brookhaven Science Associates, LLC under US DOE contract DE-AC02-98CH1-886. The US government retains, and the publisher, by accepting the article for publication, acknowledges, a world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes.

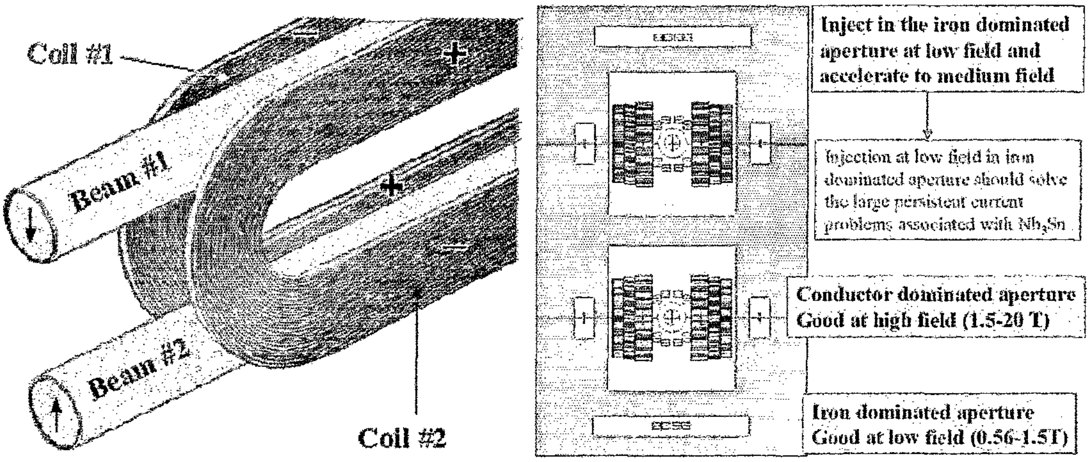


Fig. 1: Common coil design concept for 2-in-1 magnet (left) and for 4-in-1 magnet (right).

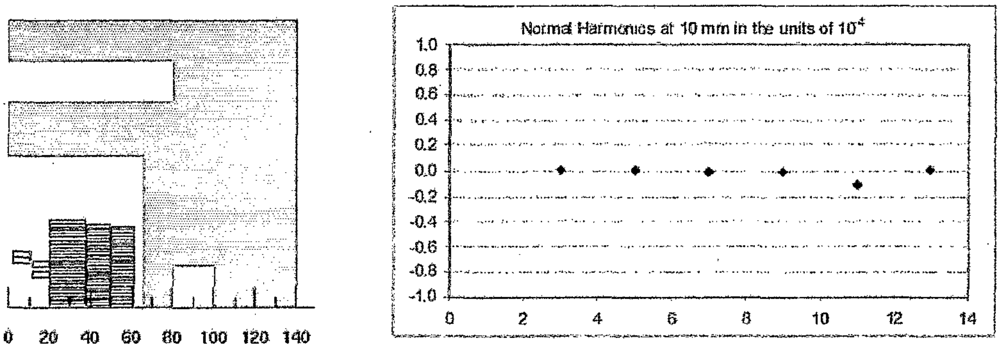
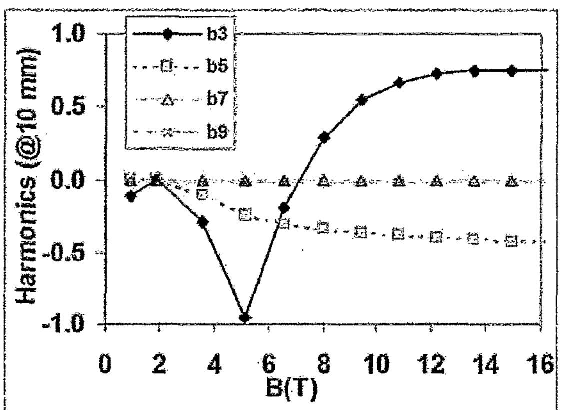


Fig. 2: Field harmonics in a 40 mm aperture common coil magnet design (left) at a 10 mm radius (right). The geometric harmonics are better than 1 part in 10^5 which satisfies the requirements of most particle accelerators.



End Harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Fig. 3: Saturation induced (left) and end-harmonics at a 10 mm radius in a 40 mm aperture common coil dipole. 2-d and 3-d optimization of above common coil design was carried out with ROXIE [5].

2.2 Open Midplane Dipole Design

The dipoles on the either side of the interaction regions in the "dipole first optics" of the LHC IR upgrade are subjected to a large spray of particles from the interaction point. Energy deposition from these particles gets highly concentrated on the midplane and may limit the lifetime and quench performance of these magnets. Moreover, the cost of removing this energy at 4 K will be very high. To overcome these challenges, an open midplane dipole design is proposed where most of the heat load is removed at ~80 K. The design concept is shown in Fig. 4. It has been discussed in more detail elsewhere [6]. The magnetic design can be optimized such that it produces the desired field quality (relative field error a few parts in 10^{-5} on midplane, see Fig. 4). Moreover, the design can be developed in such a way that the blocks closer to midplane experience the Lorentz forces away from midplane and thus requiring a little structure between the upper and lower halves of the coils at midplane. Energy deposition calculations by Mokhov [7] show that these designs significantly reduce the heat load on the coils and allow a safe operation of the magnet for over ten years.

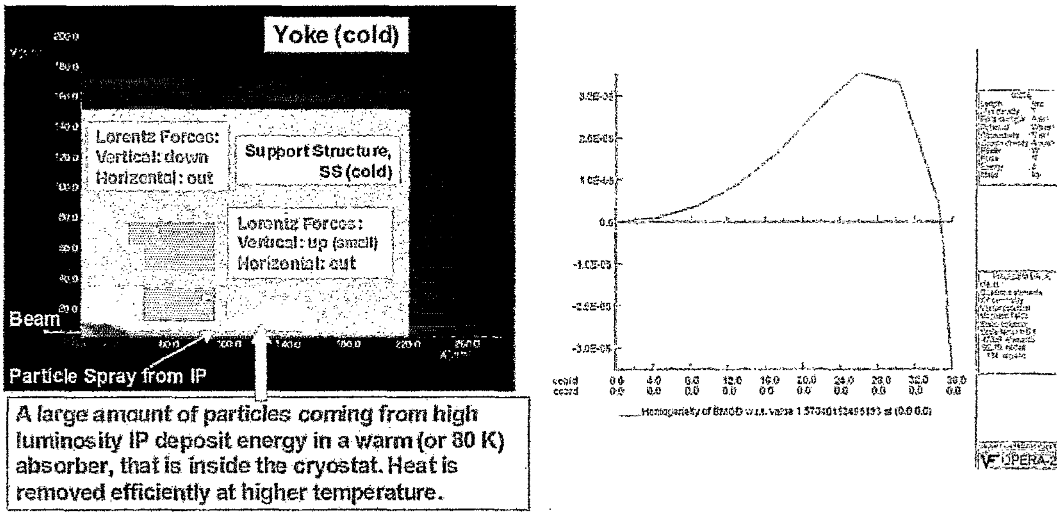


Fig. 4: Open midplane dipole design concept (left) and relative field errors on the midplane in an optimized design (right). The magnet design was optimized with RACE2dOPT [8].

2.3 Modular Quadrupole Design

The magnetic design of quadrupoles differs significantly from that of dipoles because, unlike the dipole, the strength of a quadrupole does not increase linearly as a function of conductor width. Moreover, for a high gradient design, the conductor must be at or very close to the aperture (radius) and at the midplane. However, most quadrupole designs with flat racetrack coils tend to put conductors near the aperture (radius) at or near the pole and away from the midplane. Thus, for the same conductor (same critical current), those type of quadrupole designs with flat racetrack coils have significantly lower maximum gradients irrespective of the amount of conductor used. A modular quadrupole design with flat racetrack coil and large bend radii (see two versions in Fig. 5) has been proposed [9] to overcome this disadvantage. This design creates a gradient in flat racetrack coils quadrupoles that is close to the gradient in cosine theta quadrupoles by allowing conductors to be placed at a radius similar to the midplane radius of cosine theta quadrupoles. The design uses twice as much conductor as a conventional design. Therefore, such a design is attractive where only a few magnets are needed and a higher conductor cost can be tolerated in favor of high performance or where the use of flat racetrack coils with large bend radii is critical. As shown in Fig. 6, it is possible to obtain good field quality. The design allows flexible, cost-effective and systematic R&D - a feature that has been found useful in various R&D magnet programs based on flat racetrack coils.

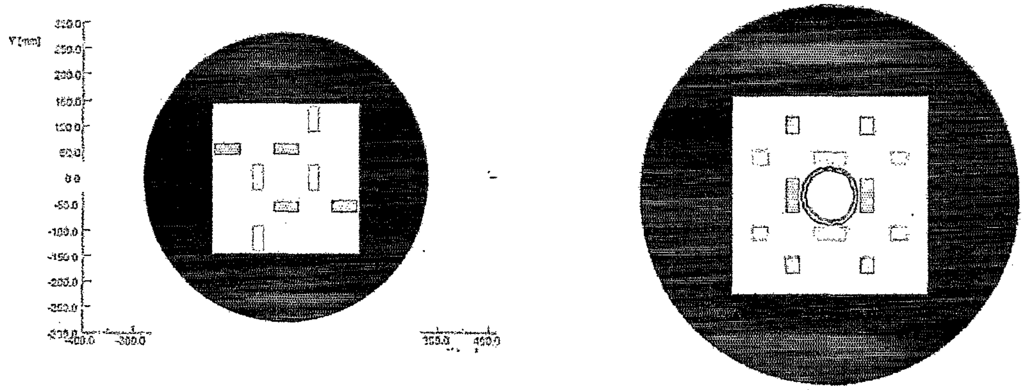
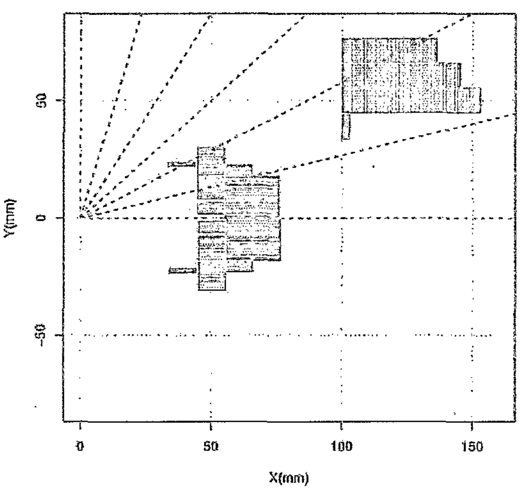


Fig. 5: Two versions of the modular quadrupole design. The one on the left is simpler and uses four sets of racetrack coils and one on the right is symmetric and uses eight sets of racetrack coils.



n	a_n	b_n
6	-0.0049	-0.0015
10	0.0006	0.0075
14	0.0018	0.0231
18	0.0000	0.0000

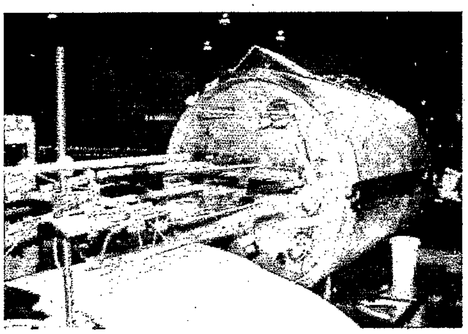
Fig. 6: A 90 mm aperture modular quadrupole design optimized for field quality. Harmonics are given at a reference radius of 30 mm (2/3 of coil radius). The magnet design was optimized with RACE2dOPT [8].

3. WIND & REACT AND REACT & WIND MAGNET TECHNOLOGIES

All known high field superconductors (such as Nb_3Sn, Nb_3Al and HTS) are brittle in nature. However, they are not brittle initially and become brittle only after the composite is reacted (heat treated) to turn them into a metallic compound that can become superconducting when cooled to low temperatures. There are two distinct approaches to make magnets with such conductors: "Wind & React" and "React & Wind". In the "Wind & React" approach, the coil is wound before the reaction when the conductor is still ductile. The entire coil package consisting of conductor, insulation, wedges, end-spacers, and other structures, is then heat treated at high temperatures. This puts limitations on the types of materials that can be used in the coil package. Moreover, one must also deal with the differential thermal expansion of various materials in the coil package to make sure that they do not put excessive strain on the conductor. In the "React & Wind" approach only the conductor is heat treated before winding the coil. In this case, the major challenge is to find design and manufacturing processes that do not put excessive strain on the coil during the construction of the magnet. The issues and comparisons (advantages and dis-advantages) between "React & Wind" and "Wind & React" are listed in Table 1. Most Nb_3Sn magnets to date have been built using the "Wind & React" approach as it offers a greater likelihood of success (at least in short R&D magnets) due to lower bending and handling degradation. However, the "React & Wind" approach is considered to be more scalable for long magnets provided one can develop magnet designs that are "conductor friendly" and demonstrate this technology in successful magnets. The "React & Wind" technology is particularly important for HTS magnets where the reaction temperature is very high (~880 K) and the allowance for variation in this is very low (~0.5 K).

Table 1: Comparison between "Wind & React" and "React & Wind" technologies.

Issues	Wind & React	React &Wind
Use of "Brittle Super-conductors"	Since one does not have to work with the brittle superconductor, the "Wind & React" is the safest and the most popular choice for the demonstration of successful R&D magnets. (+)	Biggest challenge for "React & Wind". Brittle superconductor must go through all steps of coil manufacturing. That's why it is the least popular for R&D magnets. Design and automate all aspects of tooling to minimize potential for conductor degradation. (-)
Insulation and use of other material in coil	Limited choices (insulation is generally thicker), as they must withstand high reaction temperatures. (-)	Can use a variety of insulation and other materials in the coil, as they do not go through high reaction temperature. (+)
Length scale-up issues	Biggest challenge for "Wind & React". Integrated build-up of material in the ends and in transition region as coil gets longer due to differential thermal contraction. (-)	A successful demonstration of technology in short magnet directly applies to long magnets, as the coil does not go through high reaction temperature. This is the biggest strength and argument for "React & Wind". (+)
Industrialization	More new technologies (-)	Fewer new technologies. (+)
Biggest challenge for future	Length scale-up issues, particularly in designs with complex ends. (-)	Magnet and conductor designs to minimize the bending strain. (+)



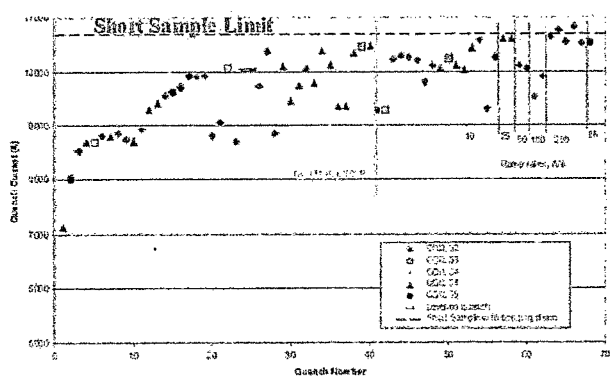


Fig. 7: React & Wind 32 mm aperture common coil dipole (left) that was recently built and tested at BNL. The magnet reached the computed short sample current (right).

4. TEST RESULTS OF REACT & WIND COMMON COIL DIPOLE AT BNL

Recently a "React & Wind" Nb_3Sn 32 mm aperture common coil dipole was built and tested at BNL. The detailed design of this magnet has been discussed elsewhere [10]. The magnet was made with a relatively lower performance MJR (modified Jelly Roll) conductor with J_c(12T,4K) below 2000 A/mm^2. The magnet reached the computed short sample current of 10.8 kA and field of 10.3 T. This is a significant result as it demonstrates that it is possible to design and built a magnet in the 10+ T range using "React & Wind" technology. The construction, analysis and test results of this magnet will be discussed in more detail elsewhere [11]. A conductor friendly design with flat racetrack coils with large bend radii and the development of tooling (such as a new winding machine) that minimized the degradation of conductor played a major role in the success of this magnet. An interesting feature of this magnet is that it has a large tall open space (32 mm X 240 mm) that can be used for testing one or more insert coils without disassembling the magnet.

5. HTS IN HIGH FIELD MAGNET DESIGNS

For a long time HTS has been considered as the conductor for future magnets either for achieving very high fields or operating at temperatures much higher than 4 K. However, recent test results at BNL in making several racetrack coils and an R&D magnet with HTS tape for the Rare Isotope Accelerator (RIA) [12] and 10-turn common coil R&D magnets with Rutherford cable [13] show that conductor, coil and magnet technology have now evolved to a stage that one can seriously consider HTS for accelerator magnets. The conductor is now available in long lengths. Moreover, as shown in Fig. 8, one can make a series of coils with a consistently good performance. Fig. 9 shows the measured critical current of two, four, six and twelve coils as a function of temperature in a magnetic structure. Thirteen coils were made with BSCCO 2223 tape and were tested in a warm and cold iron designs. In cold iron test set-up, two, four and six were tested in series, whereas in warm iron design (see Fig. 9) twelve coils were tested in series. Additional benefits of using HTS in magnets are that they can tolerate large energy deposition and that the temperature control of the cryogenic system can be relaxed to several degrees from a few tenths of a degree in conventional low temperature superconducting magnets.

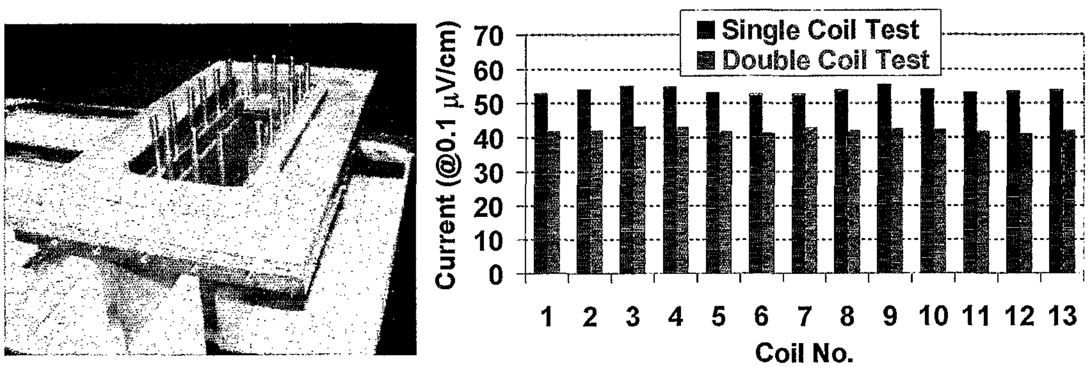


Fig. 8: Racetrack coils made with ~220 meter of HTS tape from American Superconductor Corporation (ASC). The performance of the 13 coils tested so far has been very uniform and consistent (right).

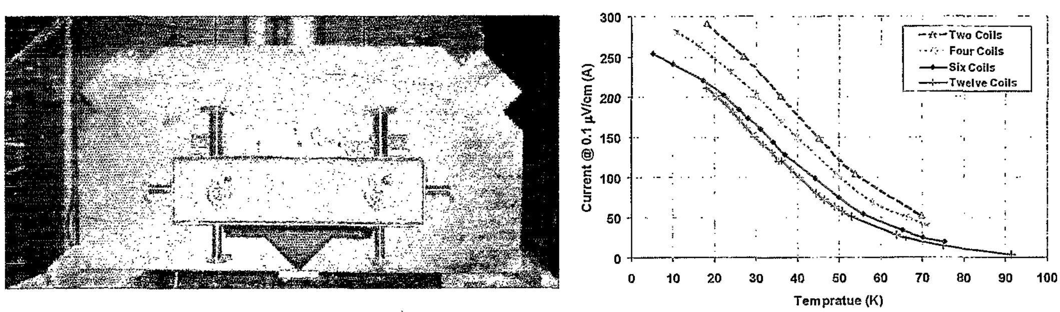


Fig. 9: Warm iron magnetic mirror HTS quadrupole for RIA's fragment separator region (left). Measured current carrying capacity of number coils (two, four, six and twelve) as a function temperature is shown on right.

For an LHC luminosity upgrade one would take advantage of the special high field characteristics of HTS. The RIA HTS quadrupole design is a super-ferric magnet design that is suitable for a lower field. At very high field, no superconductor carries as much current as HTS does. Traditionally, accelerator magnets have been built with Rutherford cable operating at several kilo-amperes or above. BNL has built and tested several coils and R&D magnets [13] made with BSCCO 2212 Rutherford cable (see left on Fig. 10). Fig. 10 (right) shows the improvements in performance of Rutherford cable over time. It should be possible to develop high field accelerator magnet technology with flat tape as well; in particular since the ramp rate requirements in high-energy machines are now much lower. Moreover, future YBCO tapes could be much wider and can carry several kilo-amperes current at any field. It may be pointed out that since the development of HTS technology has been funded primarily by the applications that do not necessarily need high current cable, a prudent approach would be to develop magnet designs and technology around the conductor.

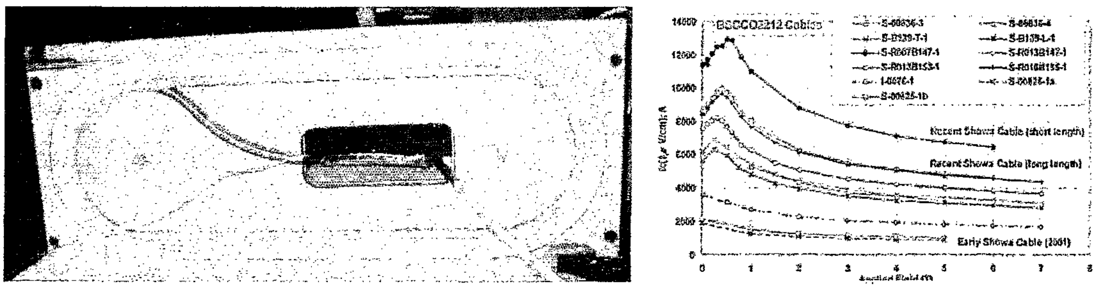


Fig. 10: The figure on the left shows an HTS coil made with Rutherford cable for a common coil dipole. The figure on the right shows the measured current carrying capacity at 4 K as a field for a number Rutherford cable tested between 2001 and 2003.

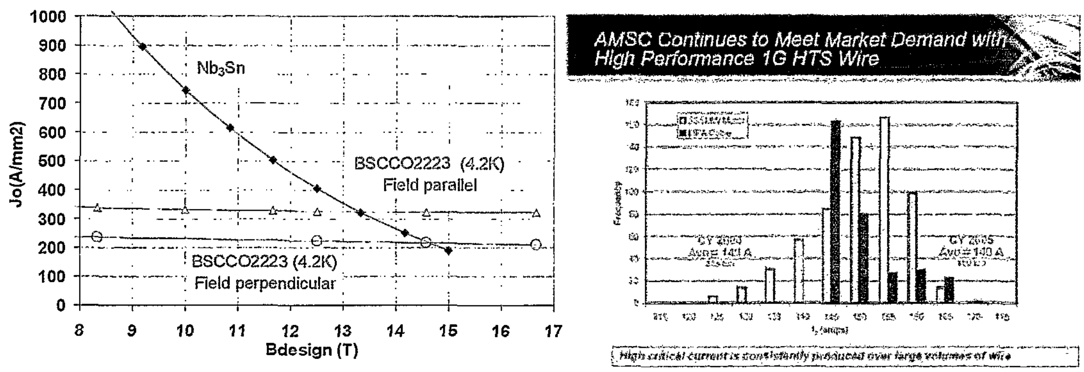


Fig. 11: The figure on the left shows the overall current density in coil as a function design field (including peak field and margin) for commercially available HTS tape (BSCCO2223) and Nb_3Sn Rutherford cable for designing LHC IR upgrade magnets. The figure on the right shows the measured critical current at 77 K (self field) in HTS tape produced by AMSC [14].

The right side of Fig. 11 shows that the current carrying capacity of HTS decreases slowly as a function of field and therefore at high fields HTS has more critical current density than that in conventional low temperature superconductors (LTS). Here the design field at which coils made with commercially available HTS will have higher engineering (or overall) current density than the Nb_3Sn that is being used in designing LARP quadrupoles is estimated. It may be pointed out that the design field (the field that machine builder can use in designing an accelerator) is generally 20% lower than the limiting field on the superconductor due to peak field (field enhancement) and margin requirements. Overall current density includes copper (in case of Nb_3Sn) or silver (in case of HTS) and insulation. A current density of 2400 A/mm^2 (12T, 4.2K) is assumed for Nb_3Sn and a critical current of 155 A (77K, self field) for BSCCO2223. Both of these have been produced in higher performance versions, however, those improvements do not significantly change the relative cross-over (~13.5 T for field parallel and ~14.5 T for field perpendicular) between Nb_3Sn and HTS (see Fig. 11). Even though HTS is more expensive than Nb_3Sn, for a few magnets a higher-cost conductor should be acceptable in favor of performance, particular if the conductor costs are only a fraction of the overall magnet development cost.

6. SUMMARY

A number of racetrack coil magnet designs with good field quality have been presented that can potentially be used in an LHC luminosity and/or energy upgrade. These include: common coil dipole, open midplane dipole, modular high gradient quadrupole and common coil magnet system. Racetrack coil geometry offers a high likelihood of success in making magnets with brittle conductors due to its simple, 2-d geometry. Because of large bend radii, these designs allow the use of both "Wind & React" and "React & Wind" technology. The "React & Wind" approach with racetrack coil geometry offers an attractive option for making "long" magnets with brittle superconductors. Test results of the BNL common coil dipole shows that one can successfully build magnets using "React & Wind" technology. Present day HTS provides higher engineering or overall current density in coils, compared to Nb_3Sn in magnets that must operate above ~14 T.

The brief summary presented here is complementary to the presentation made at the workshop [15].

REFERENCES

[1] R.C. Gupta, "A Common Coil Design for High Field 2-in-1 Accelerator Magnets," Presented at the 1997 Particle Accelerator Conference in Vancouver, Canada (1997).

[2] G. Danby, et al., "Proceedings of the 12th International Conference on High Energy Accelerators", Fermilab, Aug. 1983

[3] R.C. Gupta, "Common Coil Magnet System for VLHC," Presented at the 1999 Particle Accelerator Conference at New York City, NY (1999).

[4] R. Gupta, et al., "Common Coil Magnet Program at BNL," Presented at the Applied Superconductivity Conference at Virginia Beach, USA (2000).

[5] S. Russenschuck, "ROXIE – A Computer Code for the Integrated Design of Accelerator Magnets," Sixth European Particle Accelerator Conference, Stockholm, Sweden, June 1998.

[6] R. Gupta, et. al, "Optimization of Open Midplane Dipole Design for LHC IR Upgrade," Presented at the 2005 Particle Accelerator Conference, Knoxville, TN, USA (2005).

[7] N.V. Mokhov, et al., "Energy Deposition Limits in A Nb_3Sn Separation Dipole in Front of the LHC High-Luminosity Inner Triple," PAC, Portland, USA (2003).

[8] P. Thomson, "RACE2dOPT and a series of other codes developed to optimize accelerator magnets", Private communications.

[9] R. Gupta, "Modular Design and Modular Program for High Gradient Quadrupoles", To be presented at ASC 2006, August 27 – September 1, 2006 in Seattle, USA.

[10] J. Cozzolino, et. al., "Magnet Engineering and Test Results of the High Field Magnet R&D Program at BNL", Presented at the Applied Superconductivity Conference at Houston, TX, USA (2002).

[11] R. Gupta, et al., “Common Coil Magnet Program at BNL,” To be presented at ASC 2006, August 27 – September 1, 2006 in Seattle, USA.

[12] R. Gupta, et. al, "Test Results of HTS Coils and An R&D Magnet for RIA," Presented at the 2005 Particle Accelerator Conference, Knoxville, TN, USA (2005).

[13] R. Gupta, et al., “Status of High Temperature Superconductor Magnet R&D at BNL,” International Conference on Magnet Technology (MT-18) at Morioka City, Japan (2003).

[14] G. Ferguson, American Superconductor Corporation, “Private communications,” http://www.amsuper.com/.

[15] http://www.bnl.gov/magnets/Staff/Gupta/Talks/wamdo2006/gupta-wamdo2006.pdf