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CONSIDERATIONS CONCERNING THE USE OF HTS CONDUCTOR FOR ACCELERATOR DIPOLES WITH INDUCTIONS ABOVE 15 T*

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Abstract

The use of high temperature superconductors for accelerator dipole has been discussed for about twenty years and maybe a little more. Conductors that can potentially be used for accelerator magnets have been available for about fifteen years. These conductors a REBCO tape conductors that can be wound into coils with no reaction after winding and BISSCO cable conductors that require reaction after winding and insulation after reaction in a process similar to Nb3Sn cables. Both conductors are expensive and the process after reacting is expensive. Some unknown factors that remain: Will either conductor degrade in current carrying capacity with repeated cycling like Nb3Sn cables do? The other two issues are problems for both types of HTS conductors and they are; 1) quench protection in the event of a nor-mal region run-away and 2) dealing with the superconducting magnetization inherent with HTS cables and tapes. This paper will discuss the last two issues and maybe will provide a partial solution to these problems.

INTRODUCTION

In the last several years there has been serious discussion about whether HTS conductors in high field accelerator magnets. One approach uses a pure HTS dipole [1], and a second approach is a hybrid magnet with either a low temperature superconductor outer coil with an HTS insert [2]. The outer coil could be niobium titanium at 1.8 K. The first accelerator dipole magnet to reach a central in induction above 13 T was hybrid niobium tin and niobium tita-nium magnet. The LBL magnet reached 13.2 T at 1.8 K and 12.5 T at 4.4 K in 1997 [3]. During the testing magnetic field measurements were done [4]. This magnet had field quality close to what is needed for an accelerator dipole. LBL built a series of block dipole using only Nb3Sn. Some of these magnets reached bore inductions of 16 T with poor field quality. The final magnet could go to 15 T, but the acceptable field quality was between 6 T and 13 T [5, 6]. At low fields, magnetization is an issue, but it is controllable.

LBL produced and tested the first Rutherford cable made from Bi2212 multifilament strands [7]. This conductor must be wound and then reacted in an oxygen atmosphere. As a result, the conductor contains no copper. LBL has fabricated and test a block dipole coil that could carry 8 kA [8]. In the authors opinion, the advantage of block coils is that the stress in the coils can be controlled using strong high modulus metal structures that can take up the stress and hold the coils.

High current tapes made from RECBO tapes, that can carry current at high overall currents densities [9]. HTS tape conductors can have insulation applied to the conductors before winding. Since the conductors can only be bent in the across the thin dimension of the tape (~20 mm radius bends), some have argued that the ends must avoid some kinds of bends, which may make magnet ends more complex [10]. A big issue with REBCO tape conductors is magnetization currents due to the changing field perpendicular to the tape. These currents affect field quality and they can induce large stresses in the coil conductor that damage the coil [11].

This paper proposes a design based on a window frame dipole. Panofsky used a similar design for quadrupoles and combined function magnets [12]. For dipoles wound with flat cables and tapes, one must control conductor magnetization due to fields perpendicular to the conductor flat face.

The negative effects of conductor magnetization in dipoles and quadrupoles have been known since the 1970s [13]. These effects can be troublesome in dipoles and quadrupoles fabricated with flat cables and tapes. In Nb-Ti dipoles these effects can be corrected for [14]. In Nb3Sn and HTS dipoles these effects are much harder to control especially at low fields in cosine dipoles. In symmetrical quadrupoles, magnetization is less of a problem. In a symmetrical dipole, sextupole (N = 3) and decapole (N = 5) are the multi-poles that cause magnetization problems [15, 16].

A VOBLY DIPOLE BASED DIPOLE

From 1990 to 1999, I worked on compact 1.5 GeV electron synchrotron for UCLA. In June 1992, I travelled to Russia, to visit what is now the Budker Institute of Nuclear Physics (BINP) in Novosibirsk Siberia [17]. This laboratory had been working on compact light sources since the 1970s [18]. I met with Pavel Vobly who was a major force there in magnet design for many years. Our discussions [19] were about a short 7.2 T superconducting dipole for making bends of 30 to 45 degrees. These magnets must have a uniform field across a broad pole width to accommodate the beam bend. These magnets were also designed to have a rapid field drop-off at the magnet ends similar to conventional iron-dominated dipoles.

LBL developed a magnet design that could be used for a variety of machines.

We did a detailed 2D and 3D analysis on 380 mm long 7.2 T dipole that was suitable for the UCLA machine [20, 21]. The pole vertical aper-ture is 40 mm and the open hor-izontal aperture is up to 180 mm. The horizontal aperture allowed for the Sagitta of a 45-deg. bend of 1.5 GeV electrons. Figure 1 shows the magnet cross-section.

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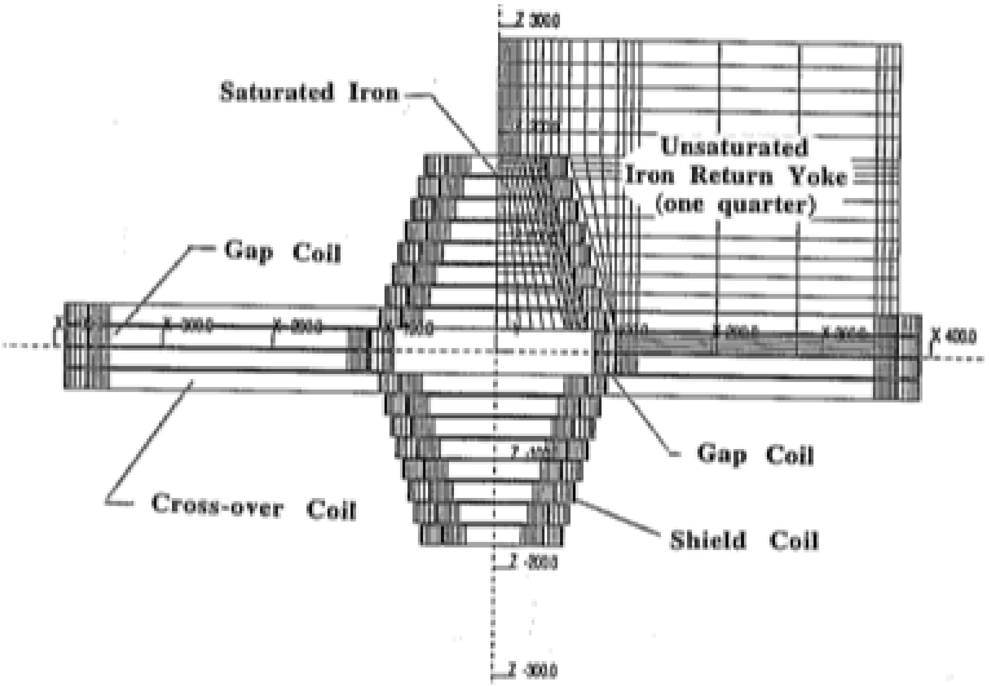

Figure 1: A short 7.2 T Vobly dipole that could be used in a compact storage ring for bends of 30 to 45 degrees [21]. This type of magnet consists of three types of coils, the gap coils which are in the gap, the crossover coils that produce a sharp magnetic field change at the magnet ends, and the shield coils that shields saturated iron from the unsaturated iron return yoke. The gap coils and the cross-over coils are connected in series. When the field in the gap is greater than the iron saturation field, there must be current in the shield coils (see Fig. 2).

Figure 2 shows the current density in the two coils sets for a Vobly dipole. The slope of the two-current density versus B in the gap is the same for both coil types.

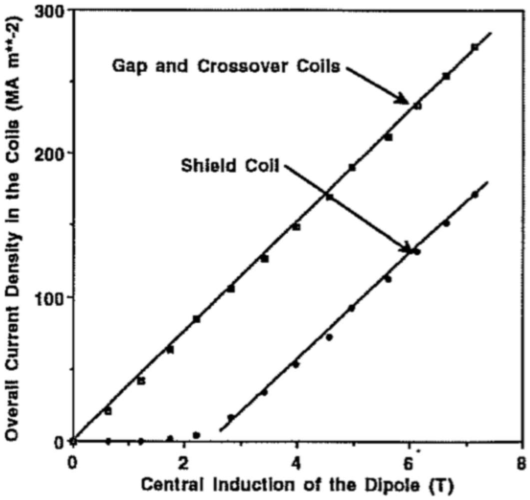

Figure 2: The coil current density for the gap and cross-over coils and the shield coils as a Function of B [20].

When one looks at Fig. 2, one can see the current density in the Gap and Cross-over coils and the current density in the shield coils that will produce a uniform dipole field within the gap between the coils for magnetic inductions between 0 and 7.5 T. When one looks at Fig. 3, one sees that the direction of the flux lines doesn't change radically until one gets close to the unsaturated iron in the return yoke. The field lines in the saturated iron within the shield coils is a continuation of the flux in the magnet gap.

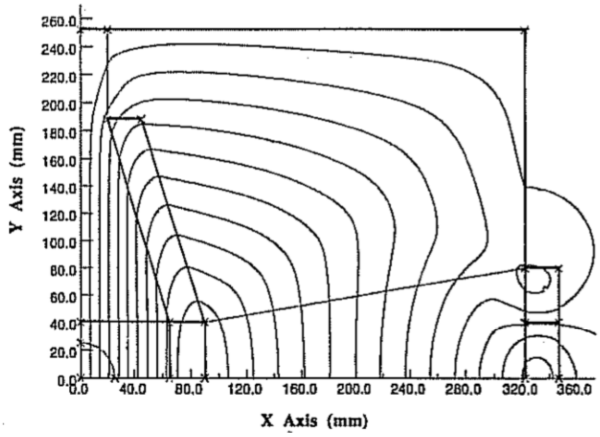

Figure 3: The magnetic flux lines within beam region and the saturated and unsaturated iron in a Vobly Dipole [20].

It appears that a long version of a block dipole magnet similar to the magnet in Fig. 1 could be used in a high field synchrotron with low magnetization field errors at injection could be wound with REBCO tapes with a bend radius in the thickness direction that is as small as 20 mm.

DIMENSIONS OF A 15 T REBCO DIPOLE FOR AN HIGH ENRGY ACCLERATOR

The width and height of the magnet gap is a function of the beam dimensions, allowances that be made for a quench protection system and magnetization effects at injection. Such magnets and their quench protection systems should be relatively easy to insulate and wind using commercial tapes. A long REBCO dipole that can be quench protected must be fully insulated turn-to-turn, turn-to-ground and turn to the quench protection system. It is assumed the magnet has cold iron and a cold bore.

The best quench protection system for REBCO magnets found by this author is shifting the coil current to an inductively to a closely coupled low resistance shorted secondary circuit [22, 23], while discharging the coil across a power varisitor [24] at voltages up to 2.5 kV. The quench protection system is assumed to be adiabatic with all of the stored energy from the magnet ending up in the coil packages. Details about the quench protection system will be in a future report.

The dimensions of the dipole are determined by the horizontal aperture needed for the beam W, the magnet gap G, the peak induction BP, and the peak coil package current NI = µ0BpG The peak coil current density JcoiL is determined by the REBCO coil current at (BP at 4.2 K), by the REBCO conductor area, the insulation area and the quench protection shorted secondary circuit area wound into the coil. The conductor selected for this study is SuperPower SC5-4030 AP [9]. This conductor appears to be stable at 4.2 K down ~3 T.

A single dipole with G = 45 mm and W = 70 mm, there is ~600 kA in both gap coils at 15 T. At 15 T, a 43 µm thick conductor current density is 2580 A mm^{-2} with the field perpendicular to the flat face. If the gap coil current density is 170 A mm-2, the gap coil width WGC = ~40 mm. With the data given, on can determine the iron width WFE and the iron height HFE. See the equations below;

$$W_{FE} = \frac{B_P}{B_{SAT}}[W + W_{GC}] + (W + 2W_{GC}) \text{ and } (1)$$

$$H_{FE} = \frac{B_P}{B_{SAT}}[W + W_{GC}] + G \qquad (2)$$

Since the ramp time from injection to the final field is long, the value of BSAT can be as high as 2.2 T because the iron can be low electrical resistivity iron. The beam space is assumed to be 65 mm wide by 40 mm high. The magnet cross-section doesn't have to be rectangular as long as the return iron is unsaturated, but the iron must fit in the dimension given by Eqs. (1) and (2) above.

The stored energy EM per unit length can be calculated using the following expression [25];

$$E_M = \frac{1}{2\mu}\int B^2\, dV = \frac{1}{2\mu}\int \boldsymbol{\nabla} \times \boldsymbol{B} \cdot \boldsymbol{A}\, dV, \quad (3)$$

where **B** is the magnetic induction, µ is the permeability, **A** is the magnetic vector potential and V is volume. The most common method of doing the calculation in-volves the equation after the first equal sign. Most of the magnet stored energy is within the gap, the coils in the gap, the iron within the shield coil, and the coils between the saturated iron and unsaturated iron. The unsaturated iron, the parts of coils outside of the unsaturated iron contribute very little to the magnet stored-energy. Table 1 shows the parameters of a 15 T dipole magnet that allows one to orient the REBCO tape so that the field lines are parallel to the flat surface of the tape to minimize effects of conductor magnetization within the di-pole good field region.

Table 1: Parameters for a 15T REBCO Dipole

Parameter and (units)	**Value**
Design Induction B_P (T)	15.0
Maximum Iron Width W_{FE} (mm)	900
Maximum Iron Height H_{FE} (mm)	795
Radius of the Good Field Region (mm)	20
Gap between Iron Poles G (mm)	45
Pole Width between the Coils W (mm)	70
Gap Coil Height (mm)	44
Gap Coil Width (mm)	~40
Number of turns per Gap Coil	320
Gap Coil Current (A)	~938
Average Coil Current Density (A mm^{-2})	~170^
Stored Magnetic Energy (MJ m^{-1})	~2.6*

^based on the total coil package area.
*per meter dipole length

The magnet gap coils for the magnet in Table 1 can be wound with two double pancakes of REBCO tape that is 10-mm wide with 160 turns in each double pancake. The current at 15 T is ~80 percent of the critical current for a 10 mm wide tape with the field parallel to the tape along the load line. The quench protection uses an insulated shorted secondary would be wound between the insulated superconducting tapes to ensure close coupling between the primary and secondary circuits. This is essential for protecting the coil [23, 24, 26]. The design of the quench protection circuits will be a topic for a future paper. The shield coils can be wound with the same superconductor and insulated copper secondary as the gap and cross-over coils. Since much of the stored energy is in the saturated iron, the optimization of the shield coils is important.

There is an excellent chance that effects of conductor magnetization can be minimized because of the orientation of the magnetic field with respect to the REBCO tape is favourable for the HTS conductors that are closest to the beam. This is certainly true at gap inductions < 5 T.

CONCLUSION

A Vobly type of dipole could be well suited for use with a tape type of HTS conductor. It may also be useful for a dipole made with cable conductor made with Bi2212. A Vobly type of dipole must be optimized to reduce the amount of superconductor in the shield coils and the magnet stored energy while still retaining the flux directionality needed for low magnetization sextupole and decapole at low field for beam injection. Small changes in the shield coil current can be used to tune the magnetic field. This is an ongoing project for future papers.

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