RAPID-CYCLING DIPOLE USING BLOCK-COIL GEOMETRY AND BRONZE-PROCESS Nb_3Sn SUPERCONDUCTOR *

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Abstract

The block coil geometry utilized in recent high-field dipole development has significant benefit for applications requiring rapid cycling, since it intrinsically suppresses coupling currents between strands. A conceptual design for a 6 Tesla dipole has been studied for such applications, in which the intra-strand losses are minimized by using bronze-process Nb_3Sn superconducting wire developed for ITER. That conductor provides isolated fine filaments and optimum matrix resistance between filaments. The block-coil geometry further accommodates placement of He cooling channels inside the coil, so that heat from radiation and from AC losses can be removed with minimum temperature rise in the coil. The design could be operated with supercritical helium cooling, and should make it possible to operate with a continuous ramp rate of 5-10 T/s.

INTRODUCTION

Several major accelerator projects have been proposed that would require rapid-cycling synchrotrons: a rapid-cycling upgrade of the injector chain for LHC [1], and the high-energy ring SIS300 for GSI [2]. The performance that is desired is typically a peak field ~5-6 T and a cycle time of <10 s. Several dipole magnet designs have been explored for these applications, typically based upon a cos θ coil geometry and NbTi superconductor. Attaining the desired performance with such designs is made challenging by the ac losses that are produced during the current ramp, and by the multipole fields produced by the persistent-current magnetization at injection field.

The Texas A&M group is developing a high-field dipole technology for future colliders, with a near-term goal of 16 T using Nb_3Sn windings [3] and a long-term goal of 25 T using Bi-2212 windings [4]. The design uses a block-coil geometry to convey several key benefits: facilitation of stress management within windings, natural suppression of persistent-current magnetization, modular construction of coils, and expansion-bladder preload.

AC losses arise during the current ramp of a dipole, both from current transfer among strands of the Rutherford cable and from current transfer among the subelements within each strand. *Extrinsic losses* arise from current transfer between adjacent strands in the cable, and also from current transfer through cross-over points in the cable,

Intrinsic losses arise within each strand, from magnetization hysteresis within each superconducting sub-element and also from current transfer between sub-elements through the matrix metal.

The block-coil geometry naturally suppresses extrinsic losses, which typically constitute ~half of all ac losses. The mechanism is illustrated in Figure 1. The loops of current that are induced by coupling and cross-over are driven by the time-changing flux through the loops formed by adjacent strands and by the diamonds formed by cross-over. In a cos θ dipole the cable elements are oriented roughly face-on to the magnetic flux that penetrates the windings, so that a maximum flux couples through each cable. In a block-coil dipole, however, the cable elements are oriented edge-on to the flux, so that the flux coupled through each cable is minimized. Since the extrinsic ac losses scale with this coupling, extrinsic losses are naturally reduced in the block-coil geometry by the aspect ratio of the cable, typically ~10:1.

The suppression of ac losses was evident in the testing of the model dipole TAMU2 [5]. This model Nb_3Sn dipole attained short-sample field on its first quench, and 85% of short-sample field even at a ramp rate of 4 T/s! The robustness of the block-coil geometry encouraged us to develop a design specifically optimized for rapid-cycling performance.

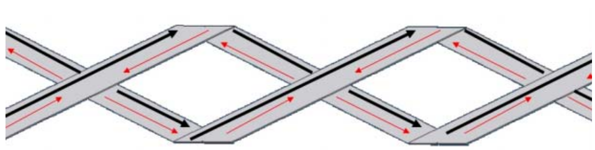

Figure 1: Induced coupling currents between adjacent strands when cable is face-on to flux (e.g. cos θ).

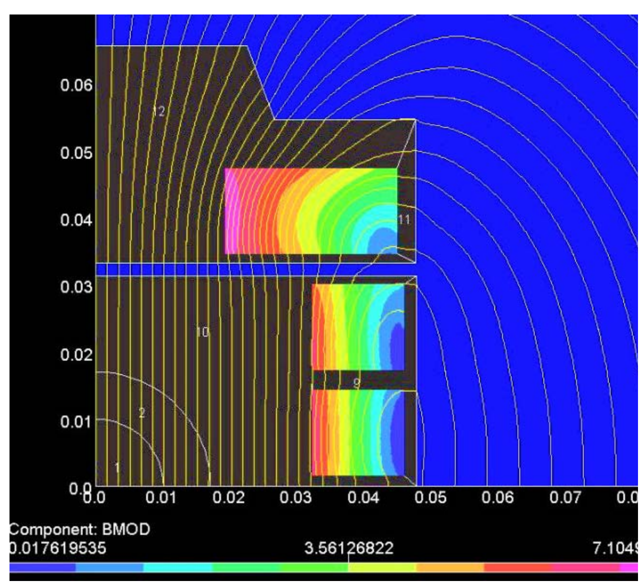

Figure 2: Field distribution in rapid-cycling block-coil dipole. B_{mod} is shown in coil blocks.

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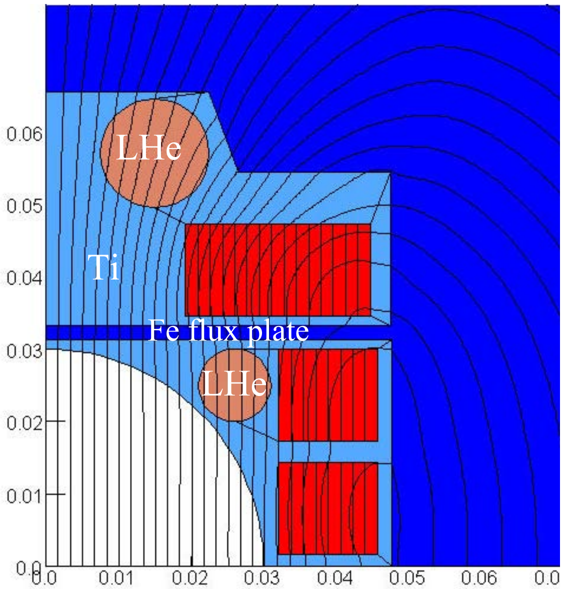

Figure 3: Structural design of rapid-cycling dipole.

The design parameters are taken as 7 T maximum field and 60 mm bore diameter (appropriate for the LHC injector requirements). The magnetic design of the dipole is shown in Figure 2; its structural elements are shown in Figure 3. It utilizes NbTi superconductor with LHC parameters. Note that the block-coil geometry accommodates placement of LHe flow channels close to the inner bounds of the coil elements, an important consideration for heat transfer.

A detailed estimation of the above loss mechanisms was made for the benchmark cases of the RHIC-type cos θ rapid-cycling dipole developed for GSI [2], the larger-aperture cos θ dipole design by Tkachenko [6], a simple block-coil equivalent with the same bore diameter, and the optimized block-coil dipole of the present study. The calculations follow closely the work of Wilson [7]. Table 1 presents the calculated ac losses for each design for a 1 T/s ramp rate. Hysteresis loss in iron is not included.

Table 1: AC losses in NbTi dipole designs at 1 T/s ramp

Dipole design	B_{max} (T)	A_{sc} (cm^2)	Bore dia. (mm)	AC loss (J/m/cycle
RHIC-type cos θ	4	55	80	58
Tkachenko cos θ	6	43	100	67
Simple block-coil	6	13	100	47
TAMU block-coil	6	19	60	23

The effect of suppression of extrinsic ac losses in the block-coil geometry is evident. Another interesting result is that the simple equivalent block-coil design requires 20% less superconductor than the cos θ design of the same aperture and field strength. These benefits, together with the potential for enhanced heat transfer, encouraged us to think more broadly about how to continue the optimization to minimize intrinsic losses.

BRONZE-PROCESS NB$_3$SN CONDUCTOR FOR RAPID-CYCLING

In 1994 a European workshop was devoted to considering issues that limited rapid-cycling dipole technology [8]. It identified the need to develop µm-filament NbTi strand to suppress matrix losses. But there actually *is* a superconducting strand with µm filaments that is available today – bronze-process Nb_3Sn. And thanks to the ITER program the fabrication technology has progressed to an impressive performance. As one example, Furukawa makes bronze-process wire (shown in Figure 4) for both NMR and fusion with Q_h <80 mJ/cc, j_{sc} >650 A/mm^2 @12 T, 4.2 K. A 0.8 mm diameter wire contains 9800 filaments with excellent bronze separation among filaments. It is interesting to see if this performance could be of benefit to further reduce the ac losses of a 7 T dipole.

A first important parameter is the engineering current density j_e at operating field. Figure 1 shows j_e at 6 T for the bronze-process wire of Figure 4 and for NbTi wire of LHC spec.

In a rapid-cycling dipole, the limit to ramp rate is ultimately determined by the ability to remove heat from ac losses. In pushing ramp rate to maximum it would be desirable to accommodate a temperature differential of ~2 K for heat transfer. That is clearly impossible with NbTi unless one operated with superfluid cooling.

As a first exploration of the significance of Nb_3Sn for ac losses we used the same model and simply replaced the NbTi windings with Nb_3Sn windings. That is certainly a worst-case estimate for Nb_3Sn, since the engineering current density is ~70% higher, so the winding package could be much thinner and more magnetically efficient.

For this Nb_3Sn version of the block-coil design of Figure 3, we obtain total losses of 11.4 J/m/cycle, an improvement of a factor 2 compared to the NbTi version of the same design. The hysteresis losses within subelements are much smaller (smaller filament size) and the bronze matrix has near-optimum resistivity.

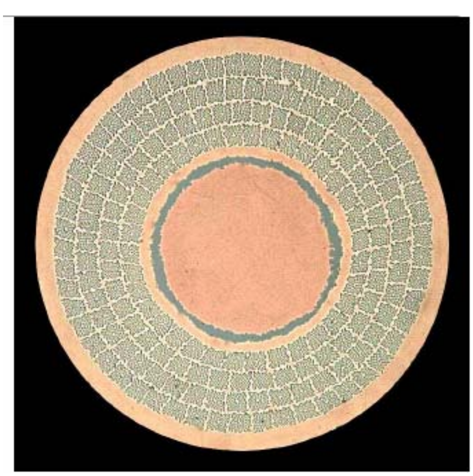

Figure 4: Cross-section micrograph of Furukawa bronze-process Nb_3Sn strand: 9800 filaments, 0.8 mm diameter.

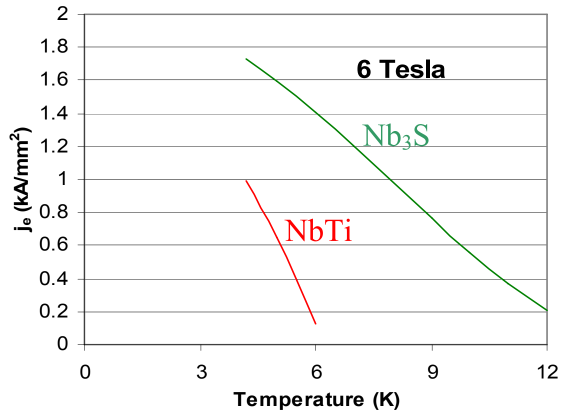

Figure 5: j_E *vs*. T for NbTi and N_3Sn.

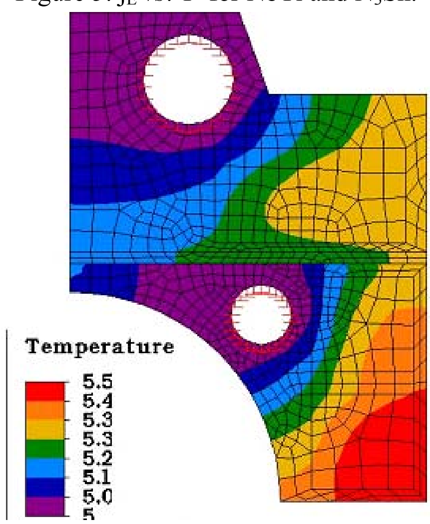

Figure 6: Temperature profile with supercritical cooling; the coil is dissipating 48 W/m at 9 T/s ramp rate.

ESTIMATED PERFORMANCE 0→6 T

We have done a first analysis of heat transfer in the dipole, assuming that the two He channels shown in Figure 3 carry supercritical helium operating on a thermodynamic cycle 4→5 K. Figure 6 shows the temperature profile in the dipole when the reservoir channels are at 5 K, the coil is at 5.5 K, and a total of 48 W/m is being deposited as ac losses in the coil. This would correspond to a ramp rate of 9 T/s, or a cycle time of 0.7 seconds to 6 T!

SUPPRESSION OF PERSISTENT CURRENT MAGNETIZATION, SNAP-BACK

A further challenge for rapid-cycling dipoles is the excitation of magnetization currents within the sub-elements, which produces magnetization multipoles at injection field. The magnetization current loops are mobile within a given sub-element. An horizontal force acts upon them due to the gradient of the field in the coil region, so that the magnetization moves to the outside region of each cable during injection flat-bottom. When the ramp for acceleration is applied, the magnetizations redistribute, producing a snap-back in magnetization. The orientation of the cable elements parallel to the flux within the winding serves to suppress the mobility of magnetization currents just as it suppresses extrinsic ac losses. Additionally a horizontal steel flux plate can be situated within the coil geometry, as shown in Figure 2. This plate is unsaturated at injection field and so presents a strong dipole boundary condition that is close-coupled to the beam tube region. Detailed simulations of magnetization response indicate that the flux plate should suppress the sextupole field due to persistent-current magnetization by a factor 5.

CONCLUSIONS

A block-coil geometry provides an optimized basis for design of rapid-cycling dipoles by suppressing intrinsic ac losses and magnetization multipoles. Fine-filament bronze-process Nb_3Sn conductor enables the suppression of intrinsic losses and makes possible a robust cryogenic system that should support ramp rates up to 9 T/s.

REFERENCES

[1] W. Scandale, 'LHC upgrade based on a high-intensity high-energy injector chain', Workshop LHC-LUMI-05, Arcidosso, Aug. 31, 2005.

[2] G. Moritz, 'SIS300 dipoles and R&D envisaged by GSI', Meeting on Superconducting Pulsed Dipoles for the LHC Injector Upgrade', CERN, Feb. 17, 2005.

[3] R. Blackburn *et al.*, 'Construction of block-coil high-field dipoles for future hadron colliders', IEEE Trans. Appl. Supercond. **13**, 2, 1355 (2003).

[4] P. McIntyre and A. Sattarov, 'On the feasibility of a tripler upgrade for LHC', Proc. PAC 2005, Knoxville, May 16, 2005.

[5] A.D. McInturff *et al.*, 'Test results of a Nb_3Sn wind/react block dipole', Proc. Appl. Superconduct. Conf., Seattle, WA, Aug. 27, 2006.
P. Noyes *et al.*, 'Construction of a mirror-configuration stress-managed Nb_3Sn block-coil dipole', IEEE Trans. Appl. Superconduct. **16,** 2, 391 (2006).

[6] L. Tkachenko *et al.*, 'Method for reducing cable losses in fast-cycling dipoles for the SIS300 ring', Proc. EPAC 2004, Lucerne, Switzerland.

[7] M.N. Wilson *et al.*, 'Cored Rutherford cables for the GSI fast ramping synchrotron', ASC-2002, Houston TX, August 4 2002.
M.N. Wilson, 'Review of cable loss formulae', MNW Report GSI 18 version 1, GSI Fast–Pulsed Synchrotron Project, Feb. 7, 2004.
M.N. Wilson *et al.*, 'Measured and calculated losses in model dipole for GSI's heavy ion synchrotron', Trans. Appl. Superconduct. **14**, 306 (2006).

[8] A. Ghosh, 'Cable design for fast ramped SC magnets (cos-θ design)', Workshop on Accelerator Magnet Superconductors, Archamps, March 22, 2004.

 1-4244-0917-9/07/$25.00