ON THE FEASIBILITY OF A TRIPLER UPGRADE FOR LHC*

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Abstract

The design of high-field dipoles has been optimized using a block-coil geometry. The optimization includes stress management and flux plate suppression of multipoles from snap-back. The design has been extended to higher field by devising a hybrid coil geometry containing inner windings of Bi-2212 and outer windings of Nb_3Sn. A 24 Tesla dual dipole using this design offers the possibility of an LHC tripler. Issues of fabrication technology and synchrotron radiation control are discussed. There is no obvious upper limit to the field that could be attained for the dipoles of future hadron colliders.

THE HYBRID DIPOLE

The LHC dipole reaches the highest performance that is possible with the classic technology of NbTi superconductor and cos θ coil geometry. That methodology was first used in the Fermilab Tevatron, later in HERA and in RHIC, and now ultimately in LHC. Tripling the LHC field strength requires a new superconducting material and a new coil geometry.

The critical current density j_c in a BCS superconductor decreases with field according to the Kramer relation, reaching about 20% of its low-field value at a field of ~60% of H_{c2}. In practical terms that is about the limit for using a superconductor in magnet coils: ~8 T for NbTi, and ~16 T for Nb_3Sn. For winding fields beyond 16 T the high-temperature superconductor Bi-2212 has now been matured to a high-performance multi-filament round wire. Its j_c is substantially field-independent to at least 35 Tesla.

This suggests a hybrid dipole strategy for extending dipole design to ever-higher field strength: use Bi-2212 cable for the inner windings where $B > 16T$, and Nb_3Sn for the outer windings where $B < 16$ T. The strategy is embodied in the 24 T dual dipole shown in Figure 1.

STRESS MANAGEMENT

To be successful such a strategy must also cope with the strain sensitivity of both materials. As field increases, Lorentz stress increases $\propto B^2$. But Nb_3Sn undergoes reversible degradation for stress $\sigma > 150$ MPa, and Bi-2212 undergoes irreversible degradation for strain $\varepsilon > 0.6\%$.

Lorentz stress accumulates through the thickness of a superconducting coil. The field acts upon each cable element in turn and the forces add up as they are passed to the outside structure. This accumulation is unavoidable in coils of cos θ geometry because the entire coil is one mechanical assembly.

A new generation of Nb_3Sn dipoles has been under development, using a block-coil geometry of racetrack windings. The current record dipole field of 16 T was produced in this geometry by the LBNL group [1]. The Texas A&M group is developing a further refinement in which a support matrix of ribs and plates made of high-strength Inconel 718 is integrated within the windings [2].

The support matrix intercepts the forces acting on inner windings and bypass them past outer windings to the flux return. The strategy is summarized in Figure 2. Three windings in a horizontal section are shown, with ribs and plates of high-strength Inconel providing the support matrix. A preload is applied to the structure from the left, and Lorentz forces push from the right. A laminar spring is located at the inner end of each winding to enforce the decoupling of stress from one winding to the next. The laminar spring is made of tempered Inconel X-750, which retains a spring temper through a sustained 850 C bake.

Shear is released by lining all windings with mica paper. Even when the overall Lorentz stress exceeds 300 MPa, the stress in the windings never exceeds ~150 MPa.

Stress management is also provided for the preload of the coil assembly using a pattern of expansion bladders. Thin stainless steel bladders are inserted along the four flat interface between the coil assembly and the flux return. A pair of curved bladders is located between the flux return and the outer aluminum stress tube. After final assembly of the dipole, the entire dipole is heated to ~90 C and the bladders are evacuated and then filled with molten Wood's metal. The molten metal is pumped to a pressure corresponding to the desired preload and then the magnet is cooled while maintaining hydraulic pressure on the bladders. The Wood's metal alloy is selected to have net zero expansion over the cycle from melt temperature to 4 K, so preload is preserved in the operating dipole. This has the remarkable result that a totally uniform preload is delivered throughout the interfaces.

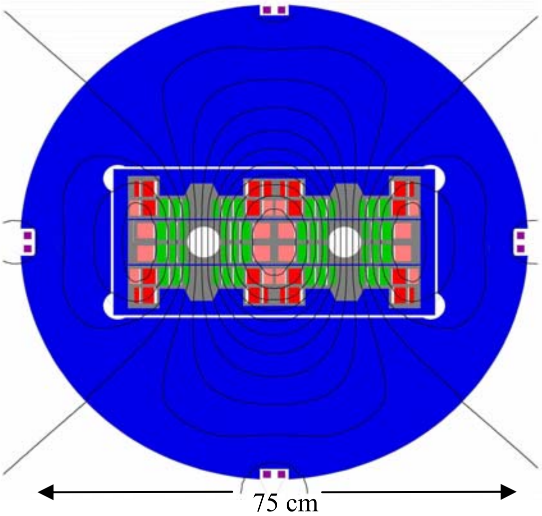

Figure 1. 24 Tesla hybrid dipole for LHC tripler.

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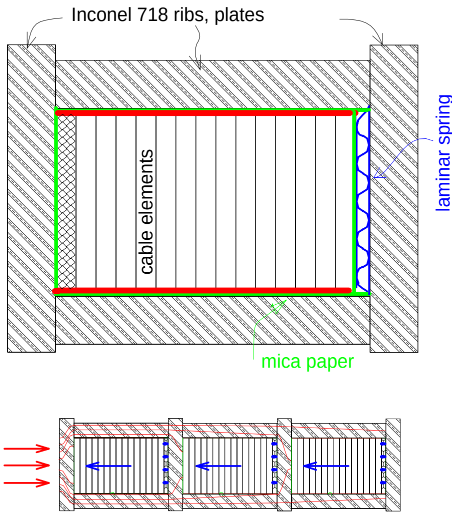

Figure 2. Stress management in a block coil geometry.

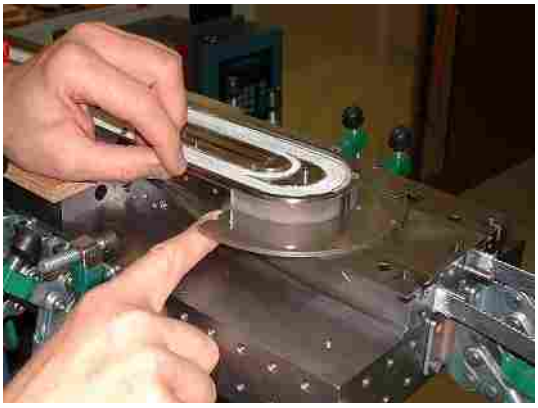

Figure 3. Applying laminar springs, ribs and plates to inner winding of Nb_3Sn.

Figure 3 shows the actual fabrication of a winding embodying stress management. The innermost winding is complete, and a laminar spring is being installed on a support rib preparatory to winding the second winding.

Figure 4a shows a detail of the winding assembly for the 24 T hybrid dual dipole. Figure 4b illustrates the use of a flux plate [3] to suppress multipoles from persistent currents and snap-back [4] at injection field. The flux plate is a horizontal steel sheet located between the upper and lower rows of windings. At injection field (1.25 T corresponds to 1 TeV for an LHC tripler) this sheet is unsaturated and imposes a dipole boundary condition that suppresses all higher multipoles in the beam tube region. Simulations of this feature indicate a reduction of sextupole by a factor of 5. The suppression offsets the increase in magnetization that would result from the larger subelements in Nb_3Sn and Bi-2212 strands compared to NbTi.

A set of NbTi windings are located in notches in the outside surface of the steel as shown in Figure 4b. These windings are used to contain return flux within the steel.

HEAT TREATMENT OF Nb_3Sn, Bi-2212

Both Nb_3Sn and Bi-2212 windings must be heat treated in a wind-and-react process to form the superconducting phase. This technique has been perfected for Nb_3Sn [5], for which the necessary heat treat is at ~650 C in an argon atmosphere. The optimum heat treatment for Bi-2212 is very different, however [5]. The winding must be heated to ~850 C in an oxygen-rich atmosphere (to push the stoichiometry of the superconducting phase). The heat treatment culminates in a brief excursion into partial melt of the 2212 phase at ~870 C for only ~5 minutes. Until recently this the peak temperature during this excursion had to be controlled to a tolerance of ±2 C to achieve optimum j_c in the final wire. Such temperature control would be problematic in large coils.

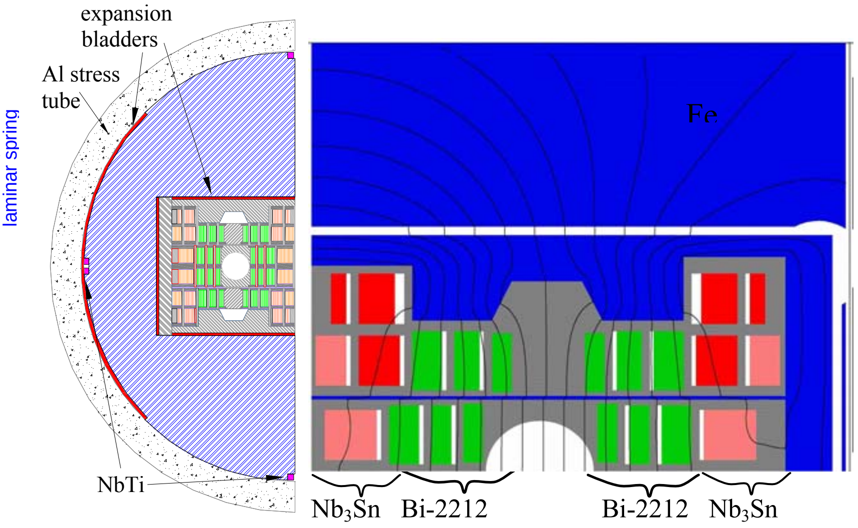

Figure 4. Elements of the hybrid coil dipole: a) half-section showing bladders; detail showing action of flux plate.

During the past year a major step towards feasibility of Bi-2212 for large-coil applications has been achieved by Marken *et al.*[6]. They have modified the core composition to increase j_c (see Figure 5) and at the same time to reduce the sensitivity to peak temperature (see Figure 6). This new material provides an engineering current density j_E = 400 A/mm^2 at 25 T, the full performance needed for the Tripler dipole. It also provides a ~12 C window for the peak temperature, which should accommodate realistic large-coil reaction strategies.

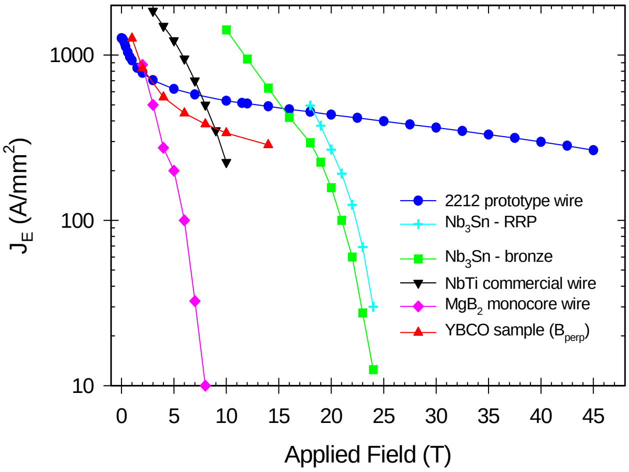

Figure 5. j_c vs. B for new Bi-2212 wire (from Ref. 6).

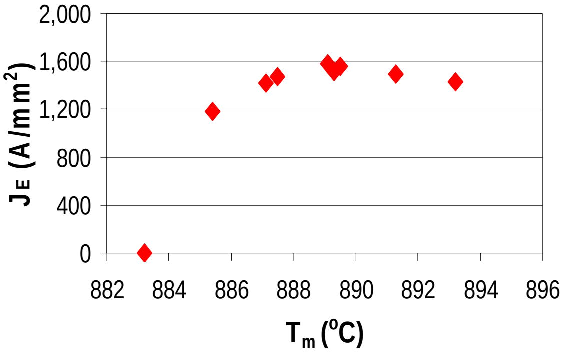

Figure 6. Dependence of j_E on peak reaction temperature for the Bi-2212 wire of Ref. 6.

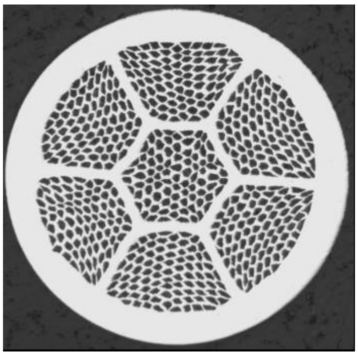

Figure 7. Cross-section of multi-filament Bi-2212 wire fabricated by Marken *et al.* [6]. Filament size is ~15 µm.

Table 1. Main parameters of the 24 T hybrid dipole.

Dipole dimensions:	length	30	m
	cold mass diameter	80	cm
Beam tube diameter		40	mm
Operating temperature		4.5	K
Coil current		33	KA
Windings per bore:	Nb_3Sn	4	
	Bi-2212	4	
Current density in strand:			
Nb_3Sn – j_{sc} @ 12 T, 4.2 K		3000	A/mm^2
Bi-2212 – j_E @ 25 T, 4.2 K		380	A/mm^2
Maximum stress in windings		150	MPa
Stored energy/bore		5	MJ/m
Total horizontal Lorentz force/bore		40	MN/m

The challenge for a hybrid coil is that one must accomplish both of these heat treats in the same hybrid coil. At high temperature oxygen would ruin the stabilizing copper sheath on Nb_3Sn, but a *lack* of oxygen would deplete the stoichiometry of the Bi-2212 and ruin its superconducting performance.

We have devised a procedure that resolves this difficulty. All of the Bi-2212 windings will be completed and supported within their stress management structure, and the Bi-2212 heat treatment will be performed using the isothermal melt process. The Nb_3Sn windings will then be wound onto the completed Bi-2212 structure. The reaction bake for the Nb_3Sn windings will be performed while maintaining an oxygen-rich purge on the Bi-2212 windings and an Ar purge on the Nb_3Sn windings. The box-like support matrix that is provided for stress management has the useful double-purpose of providing internal isolation within the coil assembly between the two winding regions. Purge gas flow can be channeled separately through the two coil regions - oxygen through the inner Bi-2212 windings and argon through the outer Bi-2212 windings.

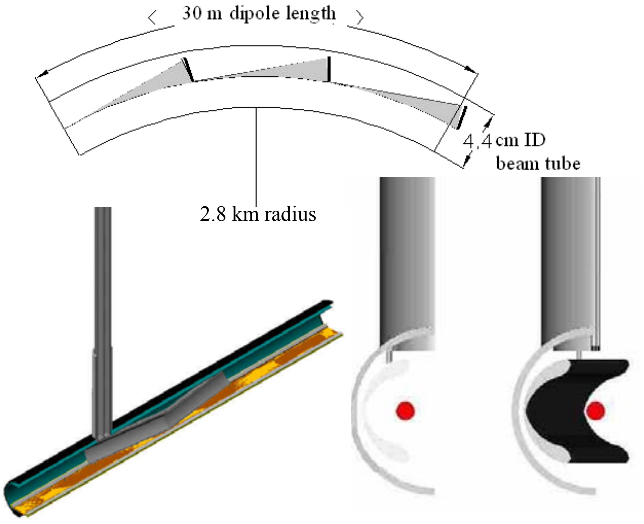

Figure 8. Photon stop in dipole: a) placement along dipole; b) cutaway view; end view at c) injection; d) collision.

Perhaps the most obvious challenge for an LHC Tripler is the strong dependence of synchrotron radiation upon beam energy. The power per unit length $\tilde{P}$ radiated by a proton beam of energy E, and curvature radius ρ is $\tilde{P} \propto E^4 / \rho^2$. Tripling the collision energy while keeping ρ constant increases $\tilde{P}$ from 0.22 W/m to 14 W/m.

But the spectrum of synchrotron light also hardens. The critical energy E_c is the peak of this spectrum: $E_c \propto E^3 / \rho$. Tripling the energy increases E_c from 44 eV (hard UV) to 1.2 keV (soft X-ray). The hard UV photons in LHC have significant cross-section for backscattering from the surface layers of the beam tube and photoionization [7]. By contrast soft X-rays in the Tripler penetrate into the surfaces and stop within the first ~100 µm.

A photon stop is proposed to absorb the synchrotron light fan from each dipole at several discrete locations along its length. The design is shown in Figure 8a. A total of 3 photon stops are provided for each 30 m dipole: two along the dipole length and the third at its end. A beam screen is installed along the length of the dipole to intercept specular reflections at a temperature of ~20 K.

Each photon stop within the dipole is mounted in a T insertion to the beam tube, supported within a 2.5 cm. diameter tube extending up through the entire structure of the dipole. The photon stop is maintained at 160 K by refrigeration with liquid xenon (LXe). The photon stop consists of a blade supported on a stem which contains the supply and return LXe flows. The stem is mounted on a rotary feedthrough and can be rotated between two angular positions (Figure 8a): in the out-position it provides maximum clearance (~1.8 cm) for injection of beams (Figure 8b); in the in-position it intercepts synchrotron light to within a few mm of the beam (Figure 8c). Preliminary calculations by F. Zimmermann indicate that, if a return foil is attached to the downstream edge of each photon stop to carry image current back to the beam screen, the effect on impedance is modest.

Each photon stop must intercept a photon power $P_\gamma = \widetilde{P}L = 100W$. The blade shown in Figure 8b has a length of 20 cm and LXe cooling lines in the top and bottom lips. The heat transfer in the cooling lines corresponds to a surface density of ~1 W/cm^2. The radiant heat load to the beam screen from each photon stop is ~0.1 W. The a.c. power to remove the heat of Tripler's synchrotron light at 160 K should be comparable to the presently installed capacity for LHC.

RAPID-CYCLING INJECTOR

There has been significant interest in the possibility of replacing the SPS with a rapid-cycling synchrotron to enhance beam delivery for injection for luminosity upgrade of LHC. It is interesting to note that the same block-coil geometry that makes it possible to integrate Bi-2212 windngs with Nb$_3$Sn windings in the Tripler dipole also makes possible a significant suppression of AC losses if it is used in the dipoles of a rapid-cycling injector synchrotron.

Figure 9 shows the field design of a block-coil dipole that could be a candidate for such a super-SPS injector. An important feature of this design is that the superconducting cables are oriented so that the magnetic field in the coil is parallel to the face of the cable. As the coil current is ramped, eddy currents are induced within the cable elements in two ways: as currents circulating among the subelements within a strand (intrinsic AC losses), and as currents circulating among the strands of a cable by passing through the strand crossings and by lateral contact between adjacent strands (extrinsic AC losses). The two loss mechanisms are typically comparable in importance for dipoles in which the cables are oriented face-on to the magnetic field as is typical of cos θ dipoles.

In the block-coil dipole the cable elements are oriented side-on to the magnetic field, so extrinsic losses are strongly suppressed.

Rapid cycling also produces magnetization multipoles, both at injection and during the ramp. In the block-coil dipoles such multipoles are strongly suppressed by the flux plate (horizontal steel divider shown in blue between the lower and upper windings in Figure 9).

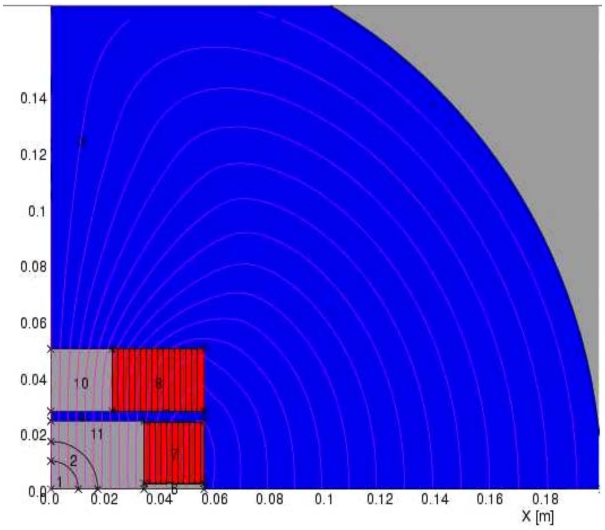

Figure 9. Block-coil design for a 6 T rapid-cycling dipole

CONCLUSIONS

A conceptual design for a 24 T hybrid dipole has been prepared. While much work will be required to develop the processes for heat treatment and splices, the design builds upon the techniques of stress management and magnetics that have been developed for Nb$_3$Sn dipoles. During the past year the current density in multifilament Bi-2212 wire needed for the hybrid design has been achieved, and the temperature margin for the reaction bake has been broadened so that it should be realistic for large-coil fabrication.

The hybrid dipole would make possible a Tripler upgrade for LHC. Studies of phenomenology of a Tripler upgrade suggests that it would double the mass reach for discovery of new gauge fields. With the proposed approach to stress management and synchrotron light; there appears to be no foreseeable limit to how high a magnetic field could be provided for future hadron colliders.

REFERENCES

[1] S. Mattafirri et al., 'Performance analysis of HD1: a 16 Tesla Nb3Sn dipole magnet', Proc. Appl. Superconductivity Conf., Jacksonville, FL, Oct. 1-6, 2004.

[2] N. Diaczenko *et al.*, 'Stress management in high-field dipoles', Proc. PAC1997.

[3] C. Battle et al., 'Optimization of block-coil dipoles for hadron colliders', Proc. PAC1999.

[4] S. Sanfilippo, 'Persistent and coupling current effects in the LHC superconducting dipoles', Proc. Appl. Superconductivity Conf., Houston, TX, August 4-9, 2002.

[5] R.M. Scanlan *et al.*, 'Fabrication and test results for coils fabricated with Bi-2212 Rutherford-type cable', *ibid.*

[6] K.R. Marken, H. Miao, M. Meinesz, B. Czabaj, S. Hong, 'Progress in Bi-2212 Wires for High Magnetic Field Applications', Proc. MT-19, 18th Int'l Conf. on Magnet Technology, Genova, Sept. 18-23, 2005.

[7] R. Cimino, I.R. Collins, and V. Baglin, Phys. Rev. Special Topics – Accelerators & Beams **2**, 063201 (1999).