MICROBORE DIPOLE FOR FUTURE HADRON COLLIDERS*

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Abstract

An important conclusion from the working groups on accelerator physics and superconducting magnets was that the physical aperture for an ultimate-energy hadron collider is ~3 cm horizontal, 2 cm vertical. We have designed a 11.4 Tesla dipole that meets this requirement while reducing dramatically the amount of superconductor compared to designs presently under development. It features block-coil construction, stress management, conductor optimization, and integration of a flux plate to suppress persistent-current multipoles. The total cross-section of Nb_3Sn superconductor is 8.6 cm^2, about one-third of that required in present cos θ and common-coil designs.

1 APERTURE REQUIREMENT

One important event during the 2001 Snowmass Conference was a set of joint sessions between the accelerator physics and superconducting magnet working groups. During those sessions there was an effort to identify and analyze the various issues that contribute to the requirements for physical aperture. It is of course realized that, in general, the cost of a superconducting dipole scales faster than linearly with aperture, but no one had yet explored the matter quantitatively for apertures smaller than a radius r ~ 4 cm.

Several recent developments make small aperture potentially tenable for a very high energy hadron collider. First, from the Workshop on Instabilities in Hadron Colliders, it has emerged that feedback can be used to control single-beam instabilities (whose amplitude scales with r^3) for beam tubes down to at least r ~ 1 cm. Second, it has been realized that photon stops can be used to absorb synchrotron radiation at the end of each dipole (as is done at synchrotron light sources), with much smaller dipole aperture than is typically needed for beam screens. Taking these new developments into account, it was concluded that a total physical aperture of 3 cm horizontal and 2 cm vertical should be sufficient for all issues that could be identified.

2 MAGNETIC DESIGN AND MECHANICS

The Texas A&M group is developing a block-coil technology for Nb_3Sn dipoles for future hadron colliders [1]. Inspired by the new relevance of small-aperture designs to collider needs, we set out to design a high-field dipole having this reduced aperture. Figure 1 shows the arrangement of the coil and the mechanical structure of the design.

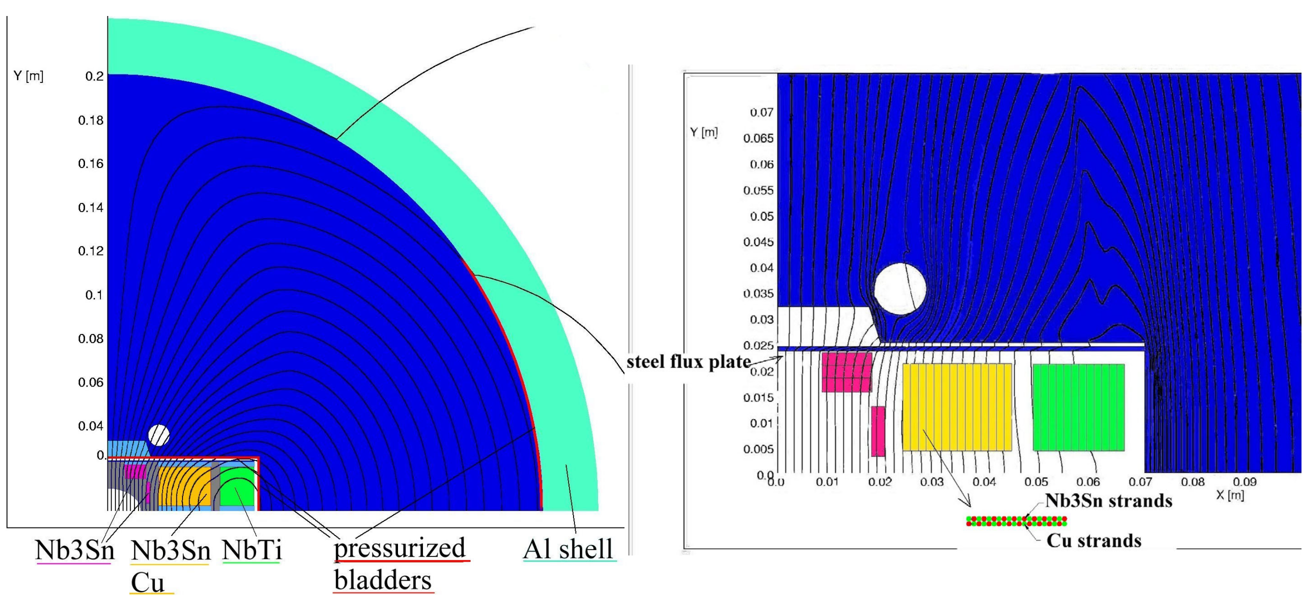


Figure 1. Quadrant of microbore dipole, showing coil assembly, flux return, pressurized bladders, and aluminum compression tube.

Table 1. Main parameters of the coils in the microbore dipole.

	Outer winding	Center winding	Inner winding	
Material	NbTi (56% Cu)	A: Nb_3Sn (48% Cu) B: OFHC Cu	Nb_3Sn (48% Cu)	
# turns	12	14	3+1	
# strands	48	48	12	
Strand diameter	0.68	0.65	1.35	mm
max field	6.3	11.2	12.2	T
J_{sc}	2200	3024	1846	A/mm^2
J_{Cu} during quench	1700	1600	2000	A/mm^2
maximum stress	5	90	70	MPa

Figure 1 shows a cross-section of one quadrant of the dipole. All windings are driven in series (16.5 kA @ 11.4 T). The upper and lower windings of each of the three coil regions are wound from a single length of cable. The entire dipole contains only two splice joints. The windings are bent up through a 90^o arc at each end to form a saddle to accommodate the beam tube. This approach eliminates axial forces at the ends, thereby simplifying mechanical support. The coil configuration has been optimized to provide collider-quality field over a 20:1 dynamic range: $b_n < 10^{-4}$cm^{-n}.

A more severe challenge for Nb_3Sn dipoles is suppression of persistent-current (p.c.) multipoles. Filament magnetization scales with filament diameter d. p.c. fields are already difficult at LHC, which uses high-quality NbTi strand (d < 10 µm). In high-the performance Nb_3Sn strand needed for the inner windings of the microbore dipole, d > 50 µm, so that the p.c. fields would be problematic for injection of beams. We address this challenge by locating horizontal steel flux plates [2] just above and below the beam tube, as shown in Figure 1. At injection, the flux plates present a strong, unsaturated dipole boundary condition which suppresses sextupole and higher fields. The effect can be seen clearly in Figure 1b, where the lines of force rearrange laterally as they pass through the flux plate. Numerical simulation shows that a suppression of ~12 X is achieved, yielding the same level of p.c. fields with Nb_3Sn as LHC will experience with NbTi.

3 CONDUCTOR OPTIMIZATION

The coil consists of three windings, each containing Rutherford cables oriented as shown. The cable in succeeding layers is graded using a conductor optimization strategy [2] to minimize the amount of Nb_3Sn strand that is needed in the coil. The cable in the outer winding sees a maximum background field of 6.3 Tesla, so it can be made using (relatively) inexpensive NbTi strands.

The cable of the center winding sees a maximum background field of 11.2 T, so it must utilize Nb_3Sn strands. Sufficient copper must be added so that during a quench there is adequate time for the quench to propagate. Conventionally this is achieved by incorporating the necessary amount of copper into the superconducting strands. But one pays by the kg for superconducting strand, independent of how much or little copper it contains.

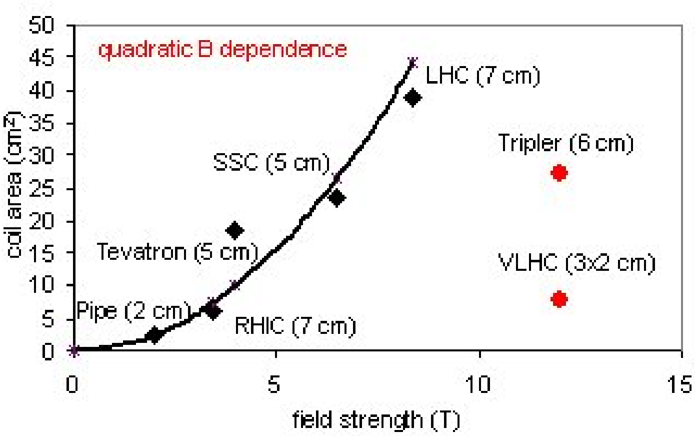


Figure 2. Coil cross-section *vs*. field strength for various dipole designs.

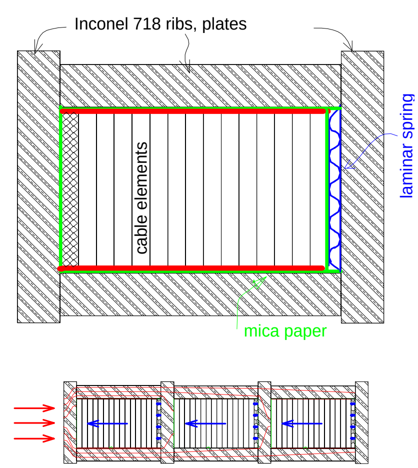


Figure 3. Detail of stress management within a coil.

We cut in half the superconductor requirement in this center winding by providing most of the copper needed for quench protection in separate, pure-Cu strands, which are cabled 1:1 with the superconducting strands as shown in the detail in Figure 1.

The cable of the inner winding is made entirely from Nb_3Sn strands, since it operates in the highest background field (12.2 T).

An appropriate figure of merit for conductor cost is the total cross-section of Nb_3Sn strands in the coil. The microbore dipole contains only 8.6 cm^2 of Nb_3Sn strand, compared to ~23 cm^2 for most 12 Tesla designs currently under development. It is interesting to compare the conductor area with earlier dipoles, as shown in Figure 2.

The dramatic reduction in Nb_3Sn requirement is only possible because in the block-coil geometry the background field within the coil decreases smoothly from center out, so successive blocks can be graded to maximum advantage.

4 STRESS MANAGEMENT

The compressive stress in a superconducting coil accumulates from the inside out, reaching a value that is typically several times the Lorentz stress $S_0 = B^2/2\mu_0 = 60\text{MPa}$. A typical maximum stress in a 12 Tesla dipole with a homogenous coil assembly is ~150 MPa. In addition shear stress develops wherever there is convergence or divergence of magnetic flux within the coil. Nb_3Sn is a brittle material, and is further subject to stress concentration around voids that form within the strands during the formation heat treat that creates the superconducting A15 phase within the completed coil. The above stress levels are at the limit of strain degradation in Nb_3Sn.

For this reason we introduced the strategy of stress management within the coil. The principle is evident in Figure 1 and is detailed in Figure 3. A matrix of ribs and plates is assembled as the coil is wound, providing a means to bridge the stress produced in the inner winding past the center winding so that it cannot accumulate there. Shear stress is released by means of a mica paper lining that separates each winding from its neighboring ribs and plates. A laminar spring enforces the decoupling of stress between the inner and center windings. As seen in Table 1, the stress never accumulates to greater than 90 MPa anywhere in the coil. Stress management is a key strategy to achieve high-field dipoles that can utilize the full current-carrying potential of the Nb_3Sn strands without training.

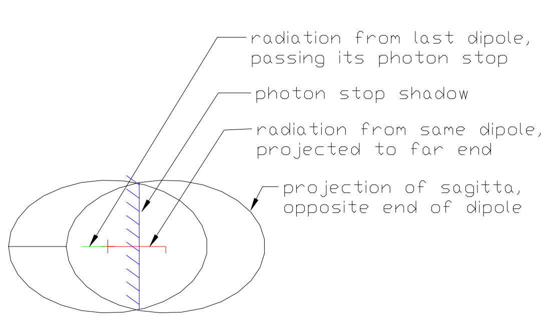
Transverse preload is provided within the body of the dipole using an arrangement of thin-wall bladders (see Figure 1), which are filled with Woods' metal during assembly and pressurized to provide adequate support of the coils by reacting against an outer aluminum support tube. This tube will further shrink during cooldown, assuring adequate support during dipole operation.

5 SYNCHROTRON LIGHT

Synchrotron light is a major issue in a high-field, multi-TeV collider. The emitted light power can be ~kW/dipole, and it is vital to intercept this power at the maximum temperature possible, since refrigeration power could dominate the total budget for the laboratory. Schemes involving liners, such as that used in LHC, are difficult to configure within a small-aperture dipole, and in any case the large heat loads are problematic for heat transport in liners.

We envisage locating a photon stop at the end of each dipole, shadowing the outer ~1 cm of horizontal aperture. The effect for a 22 m-long microbore dipole is shown in Figure 4. The entrance and exit ellipses of the beam tube are shown. The sweep in red is the end image of the fan of synchrotron light from that dipole (total sagitta 8.7 mm).

Figure 4. Photon stop geometry and fan shadowing.



The photon stop is shown in blue, while the remaining fan from the last dipole that passed within the beam opening is shown in green. A magnet length of 22 m is the maximum that can accommodate such a photon stop within the 3 cm horizontal aperture of the dipole.

REFERENCES

[1] R. Blackburn *et al.*, "12 Tesla hybrid block-coil dipole for future hadron colliders". Proc. Applied Superconductivity Conf., Virginia Beach, VA Sept. 17-22, 2000.

[2] C. Battle *et al.*, "Optimization of block-coil dipoles for hadron colliders", Proc. 1999 Particle Accelerator Conf., New York, NY, March 30-April 1, 1999.