HYBRID DIPOLES FOR FUTURE HADRON COLLIDERS*

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The design of high-field dipoles has been optimized using a block coil geometry. The object of the optimization is to produce the highest possible field strength with the least superconductor, while managing the challenges of Lorentz stress, field uniformity, and quench stability and protection. The optimization includes strategies for stress management, mixed-strand cables, and flux plate suppression of magnetization multipoles. We have recently developed a further step in this optimization: a hybrid coil geometry containing inner windings of Bi-2212 and outer windings of Nb$_3$Sn. We have used this approach to design a 24 Tesla dual dipole that should be suitable for an upgrade of the Large Hadron Collider, tripling its beam energy. Issues of fabrication technology and synchrotron radiation control are discussed. With this approach there is no obvious limit to the field that could be attained in the dipoles of future hadron colliders. The impact upon potential for discovery in high energy physics is discussed.

1. Superconducting magnet technology → discovery in particle physics

For 25 years hadron colliders have provided the primary tool for discovery of new particles in high energy physics: the weak bosons at CERN SPS [1], the top quark at the Fermilab Tevatron [2], and now the search for the Higgs boson and the particles of supersymmetry at the Tevatron and soon at the Large Hadron Collider (LHC) being built at CERN. The progression of discovery was paced by the development of superconducting magnets capable of reaching ever higher beam energy within a given tunnel circumference: from the copper-conductor dipoles of SPS (1.5 Tesla) to the NbTi cos $\theta$ dipoles of the Tevatron (4 Tesla), and now the super-cooled NbTi dipoles of LHC (8.36 Tesla) [3].

LHC will produce collisions of protons on protons with a center-of-mass energy $\sqrt{s} = 14$ TeV and a luminosity $\mathcal{L} \sim 10^{34}$ cm$^{-2}$s$^{-1}$. This performance should suffice to access signals from particles conjectured in current models of the Higgs field and minimal supergravity. Even as LHC is being built, however, there have been spectacular discoveries of the past few years in astrophysics - dark matter and dark energy [4]. Among current efforts to connect these discoveries with physics at the microscale, it appears that the ~TeV mass reach of

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the LHC could prove insufficient for accessing many of these states [5]. It is timely to ask: ‘Is it feasible to extend LHC’s mass reach by better technology?’

During the past decade a series of workshops have been held at Erice, fostering a dialog among those who are developing superconductors, superconducting magnets, and accelerator physics, aimed at finding the best path towards ultimate-energy hadron colliders. This paper presents a conceptual design for a superconducting magnet technology that could enable a tripling of LHC’s energy by installing a second ring of magnets in the same tunnel, as shown in Figure 1. The ideas embodied in this concept had their origins in the dialogs of the Erice workshops.

The design of the Tripler dipoles is shown in Figure 2 and the hybrid coil geometry is shown in Figure 3. The Tripler dipoles would operate at 24 Tesla field strength, utilizing a hybrid coil containing Nb3Sn outer windings and Bi-2212 inner cables. The concept for a coil containing these two very dissimilar superconductors is a departure from conventional design methodology. It builds upon a decade of development of these superconductors [6] and of new methods to accommodate the stresses [7] and magnetic effects [8] that arise at very high field strength. With continued development it should be possible to develop a practical hybrid-coil magnet for hadron colliders within another decade, just in time to be available to upgrade LHC after its first long runs if the added mass reach appears desirable.
Figure 2. Hybrid dual dipole, showing coil assemblies, steel flux return, and NbTi outer windings.

Figure 3. Detail of coil assembly in upper half of one bore. Bi-2212 windings are shown in light gray; Nb$_3$Sn windings are shown in gray and black.
Also presented are first considerations for several of the most important accelerator issues that must be take into account in tripling LHC’s energy. One such issue is synchrotron radiation, which increases as $E^4$ and is already a dominant cryogenic load in LHC. Because the spectrum of synchrotron radiation hardens as $E^3$, the peak photon energy shifts from ultraviolet to soft X-rays and can be absorbed on liquid-nitrogen-cooled photon stops at a few locations along each dipole. The a.c. power required to refrigerate this heat should be comparable to that of LHC, even though the radiated power increases 100-fold! Indeed the increased synchrotron radiation has a collateral benefit: it damps the beam emittance of the stored beam with a damping time $\sim$1 hour, which should provide a means to enhance and maintain luminosity during each store.

The main parameters of the Tripler dipole and the Tripler itself are summarized in Table 1.

Table 1. Main parameters of the hybrid dipoles for the LHC Tripler.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Dipole field strength:</td>
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</tr>
<tr>
<td>injection</td>
<td>1-4 Tesla</td>
</tr>
<tr>
<td>collision</td>
<td>24 Tesla</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.5 K</td>
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<td>Coil current</td>
<td>33 KA</td>
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<td>Coil windings:</td>
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<tr>
<td>B$_{12212}$:</td>
<td></td>
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<tr>
<td>Number of windings/bore</td>
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<tr>
<td>Total # turns/bore</td>
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<tr>
<td>Total cross-sectional area/bore</td>
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<tr>
<td>Current density in strand (24 T)</td>
<td>850 A/mm$^2$</td>
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<tr>
<td>Nb$_3$Sn:</td>
<td></td>
</tr>
<tr>
<td>Number of windings/bore</td>
<td>10</td>
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<tr>
<td>Total # turns/bore</td>
<td>76</td>
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<tr>
<td>Total cross-sectional area/bore</td>
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<tr>
<td>Current density in superconductor (12 T)</td>
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<td>Maximum stress in superconducting coils</td>
<td>150 MPa</td>
</tr>
<tr>
<td>Stored energy/bore</td>
<td>4.8 MJ/m</td>
</tr>
<tr>
<td>Total horizontal Lorentz force</td>
<td>40 MN/m</td>
</tr>
<tr>
<td>Multipoles $b_n$ (preliminary field design)</td>
<td>$&lt;5 \times 10^{-4}$ cm$^4$</td>
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</table>
1.1. Discovery reach for new particles

In order to assess the potential of the Tripler for the discovery of new particles, Dutta [9] has calculated parton luminosities with which the constituents of colliding hadrons interact. Parton luminosities [10] are calculated for gluon-gluon scattering for the cases of the Tevatron, LHC, and the Tripler. The calculations use the CTEQ4 parton distributions [11]. The results are presented in Figure 4 as a function of $\sqrt{s}$, the c.m. energy for the colliding partons. The arrows indicate the requirement to double the mass reach at any given mass scale. Because production cross-sections scale geometrically ($\propto s$), increasing the mass scale by a factor 2 would require 4 times the luminosity in the gluon-gluon initial state. On the other hand beams in a collider damp adiabatically as the beam energy is increased, so that the same circulating current and same invariant emittance as LHC would yield 3 times greater luminosity in a Tripler. The arrows indicate an increase of a factor of 2 in mass scale and a factor of 4/3 in cross-section. It is seen that the Tripler would roughly double the mass reach of LHC for discovery of new particles.

To understand the significance of this factor of 2 in mass reach, one must have a model for the particle states that would result from new gauge fields. One model of current significance is the minimal supersymmetric extension of the Standard Model (MSSM). Ellis et al. [12] have calculated the masses of the lightest sparticles in MSSM, applying constraints on the range of model parameters arising from recent results from astrophysics and cosmology (CMSSM). They have mapped the parameter space of CMSSM within those constraints under variations of $m_{0}$, $m_{1/2}$, $A_{0}$, $\tan \beta$, and $\mu$. The results are plotted in Figure 5 for the constrained range of these parameters in order to illustrate the range of sensitivity ($\sigma > 10^{-8}$ pb) provided by underground WIMP searches (light gray dots in lower left), LHC (those plus gray crosses in center region), and the Tripler (all the previous plus square boxes in upper right). Only with the Tripler is it possible to cover the upper third of the CMSSM parameter space.
Figure 4. Gluon-gluon luminosity vs. \( \sqrt{s} \) for the Tevatron, LHC, and LHC Tripler. Arrows indicate an increase of a factor 2 in mass reach.

Figure 5. Masses of the first two visible sparticles, plotted for the range of SUSY parameters constrained by experiments and cosmological bounds.
2. The Hybrid-Coil Dipole

The mass reach of a hadron collider is determined by the field strength and field quality of its superconducting magnets. The beam momentum $p$ in the collider is determined by the bend radius $\rho$ and the field strength $B$:

$$p[\text{TeV}] = 0.3 B[\text{T}] \rho[\text{km}]$$  \hspace{1cm} (1)

In turn the uniformity of the magnetic fields in the dipoles is key to sustaining the luminosity of collisions during a store for hours or days. Multipole components as small as $b_n \sim 10^{-4}$ cm$^{-n}$ in the dipoles can drive the growth of non-linear instabilities through the beam-beam interaction, which would cause beam growth and loss of luminosity through the duration of a collision cycle.

The LHC dipole reaches the highest performance that is possible with the classic technology of NbTi superconductor and cos $\theta$ 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 requires new superconducting material and a new coil geometry.

2.1. Superconductor optimization for high-field dipoles

The current in a superconducting coil produces the magnetic field that is used to guide the beams in a collider. This same magnetic field acts back upon the superconductor itself, however, in two key ways. With any given superconducting material, the current density that can be carried in a wire is proportional to the density of Cooper-paired electrons in the metal. Each superconducting material has an upper critical field $B_{c2}$ at which the last Cooper pair is dissociated. The macroscopic magnetic field exerts a shear force upon the Cooper pairs within the wires, so that the density of Cooper pairs (and hence the transport current density $j_c$ that can be carried) is described by the Kramer phenomenology:

$$j_c^{1/2} B^{1/4} \propto \left(1 - B / B_{c2}\right)$$  \hspace{1cm} (2)

Figure 6 illustrates this dependence for the superconductors NbTi, Nb$_3$Sn, and Bi-2212 [13]. The range of practical field for each conductor is up to 9 T for NbTi, up to \~17 T for Nb$_3$Sn, and virtually unlimited for Bi-2212. Allowing for the distribution of field in a collider dipole, in which the maximum field strength actually occurs in the coil and is \~10% greater than that in the bore tube, the greatest bending field attainable for dipoles is thus \~8 T for a NbTi dipole and \~16 T for a Nb$_3$Sn dipole. To build a 24 T dipole for a Tripler one...
must utilize Nb$_3$Sn in the regions where B < 17 T, and Bi-2212 in the regions where B > 17 T. The technology for high-performance multifilament strand, Rutherford cables, coil winding, and heat treat and impregnation have all been matured for both Nb$_3$Sn [7] and Bi-2212 [14]. The heat treat requirements are radically different for the two materials, however. We have devised a fabrication procedure that makes it possible to perform optimum heat treatments for each set of windings in succession, as will be described below.

2.2. Stress management

The second effect of the magnetic field on the superconducting coil is the Lorentz force $F/\ell = I \times B$. Since the current required to produce a given field strength increases at least linearly, the force acting on the coils increases at least as $B^2$. This force acts as a lateral piston pushing the dipole open horizontally. The forces are immense at high field, and for $B \geq 12$ T approach the limit of degradation of the superconducting materials. Degradation is particularly troublesome with the high-field superconductors Nb$_3$Sn and Bi-2212, since they are brittle materials that must be formed in their superconducting phase in a high-temperature heat-treat of the final dipole after all coils are wound.
The Lorentz stress accumulates through the thickness of a superconducting coil. The field acts upon each conductor in turn and the forces add up as they are passed to the outside structure. This is unavoidable in coils that utilize cos $\theta$ of optimum geometry because the entire coil is one mechanical assembly.

For managing stress in high-field dipoles, we adopt the same simple approach that is used in a multi-story building. There gravity acts on people and objects on each floor, and if there were no support structure the forces would accumulate as each occupant was pressed upon the ones below. In a building the floors intercept the forces acting on each floor, and the walls bypass those forces past the occupants in floors below. We have developed a similar structure to manage Lorentz stresses in high-field dipoles [15]. The coils are configured in a rectangular block configuration and a support matrix of ribs and plates made of the high-strength alloy Inconel 718.

The support matrix is integrated within the coil to intercept the forces acting on inner windings and bypass them past outer windings to the flux return. The strategy is summarized in Figure 7a. 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, the only alloy we know that can retain a spring temper through a sustained 850 C bake.
In this way, 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 technique pioneered by Taylor [16]. A pattern of thin bladders is located on the four flat interfaces between the coil assembly and the flux return (Figure 7b); a pair of curved bladders are located between the flux return and the outer aluminum stress tube. After final assembly of the dipole, the entire dipole is heater to ~90°C and the bladders are evacuated and then filled hydraulically with molten Wood’s metal [17]. The molten metal is filled to a pressure corresponding to the desired preload and 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 8 shows a design for a 14 Tesla dipole that uses Nb3Sn superconductor and incorporates stress management [18]. We are currently building a succession of model dipoles with this design as the ultimate goal. Already LBNL’s Supercon group has successfully tested a proof-of-principle dipole (of
similar design but without a central beam tube) that reached its 16 Tesla short-sample field [19].

For the Tripler dipole we have extended this methodology to a succession of block-coil windings: Bi-2212 windings near the beam tube, and Nb$_3$Sn windings in the outer region. The design is shown in Figure 9. Note that all Bi-2212 windings for each dipole are wound from a single length of cable, with the transition from one winding to the next occurring in the end turns (Figure 9c), and similarly the Nb$_3$Sn windings for each dipole are wound from two lengths of cable (the outermost Nb$_3$Sn windings utilize mixed-strand cable containing pure copper stands interspersed with the superconducting strands). Thus although there are 44 ‘windings’, they contain only 3 lengths of cable and 4 splices.

Figure 10a shows the von Mises stress and strain distributions in the hybrid dipole when it is excited to 23 Tesla, as calculated using ALGOR [20]. Maximum stress in the coils is ~150 MPa; maximum stress in the Inconel support matrix is ~800 MPa, within the limit for yield at cryogenic temperature. Figure 10b shows the von Mises strain distribution. Maximum strain in the superconductor is ~0.4%, below the threshold for strain degradation of either superconductor.
Figure 8. 14 Tesla block-coil dipole under development at Texas A&M University: a) cutaway view showing windings and structure; b) field distribution in coil package, calculated using PE2D [21]; c) stress management structural elements being installed on inner winding; d) TAMU2: single-pancake model test for the 14 Tesla dipole design.
Figure 9. Detail of Tripler dipole structure: a) half of dual dipole cold mass; b) blow-up of one coil assembly; c) detail of coil ends. Note that all Bi-2212 windings (light gray) are wound from a single cable; and all Nb3Sn windings are wound from a single cable (dark gray).
Figure 10. Stress and strain in the hybrid dipole of Figure 9 at 23 Tesla central field: a) von Mises strain distribution (contours in MPa); b) strain distribution (contours in %).
2.3. Flux plate suppression of persistent-current magnetization, snap-back

The dipole designs shown in Figure 8a for our 14 Tesla Nb$_3$Sn dipole and in Figure 9 for the Tripler also incorporate a new strategy for suppressing the magnetic multipoles that are induced by persistent currents within each strand of superconductor. When the dipole is ramped from high field (collision energy) to low field (injection of fresh beams), loops of supercurrents are induced within the filaments of each strand. Since the filament is superconducting, these induced current loops persist for a long time (hours to weeks). The magnetization from persistent currents produces its own contribution to the magnetic field distribution in the beam tube. The sextupole component of this distribution can disrupt the beam at injection. The effect is further exacerbated by the 'snap-back' phenomenon [8] that occurs when the current ramp is applied as the beam is accelerated. The snap-back produces a step-change in chromaticity. It is already a problem to be managed at LHC, and would be much worse for the larger filaments of presently available high-field superconducting strand.

To suppress snap-back multipoles we utilize a flux plate [22] as shown in Figure 8b. The flux plates are a simple planar sheets of steel, located between winding layers just above and below the beam tube. If the injection field is below the saturation of steel (1.7 T) the plates are unsaturated and produce a strong dipole boundary condition closely coupled to the beam tube region. This boundary condition suppresses multipoles from persistent magnetization in the coils, and does so dynamically during snap-back by Lenz’ Law. By this means it should be possible to control magnetization effects to a level comparable to that in LHC.

2.4. Heat treatment for in situ formation of high-field superconductors

Both Nb$_3$Sn and Bi-2212 are brittle materials. If the multi-filament strands in each cable were fabricated with the final superconducting filaments within, the filaments would fracture under the bending stress of cabling and of coil winding. Over the past decade techniques have been developed to overcome this problem. The strand is fabricated as a heterogeneous composite in which each filament contains the right stoichiometry of mixed-phase materials. The coil is then heat treated to form the superconducting phase once all cabling and coil winding are finished.

This technique has been perfected for Nb$_3$Sn [7], for which the necessary heat treat is at ~ 650 C in an argon atmosphere. Figure 11a shows a completed Nb$_3$Sn coil being prepared for heat treat in a gas-purge furnace. Note the connections for purging inert gas through a manifold; the purge flow removes con-
taminant vapors from decomposition of insulation sizing so that the cable insulation is not compromised.

Figure 11b shows the same coil as it is about to be vacuum-impregnated with epoxy to mechanically stabilize the reacted coil. The same pattern of purge channels is again used to provide epoxy flow during the epoxy impregnation.

The optimum heat treatment for Bi-2212 is radically different, however [13]. The winding must be heated in an oxygen-rich atmosphere (to push the stoichiometry of the superconducting phase), and the heat treatment culminates in a brief excursion (only ~5 minutes!) into partial melt of the 2212 phase at ~870 C.

The challenge for a hybrid coil is that one must accomplish both of these heat treats, one for each set of windings, in the same hybrid coil. At high temperature oxygen would ruin the stabilizing copper sheath on Nb$_3$Sn, but a lack of oxygen would deplete the stoichiometry of the Bi-2212 and ruin its superconducting performance.

We have devised a means to accomplish both processes. We will first complete all of the inner Bi-2212 windings, support that portion of the coil assembly in its final shape, and perform its heat treat. During the heat treat oxygen will be purged through the coil as shown in Figure 12a. We will then wind the Nb$_3$Sn windings, using the completed Bi-2212 subassembly as the mandrel. The reaction bake for the Nb$_3$Sn windings will be performed while maintaining an oxygen purge on the Bi-2212 windings and Ar purge on the Nb$_3$Sn windings, as shown in Figure 12b. 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. During the Nb$_3$Sn heat treat, the oxygen purge in the inner Bi-2212 windings during that heat treat should maintain optimum stoichiometry in the already-prepared Bi-2212 windings so that its superconducting properties are not degraded.

There remains a very significant challenge: how to bring the entire Bi-2212 subassembly into partial melt in precise simultaneity, and for a duration of only ~5 minutes! The heat treat sequence calls for a slow heating in multiple stages to ~850 C, followed by rapid heating to partial melt at ~870 C, then a rapid return to ~850 C and then a slow anneal during cooldown. The large thermal mass of the coil assembly and the small thermal conductivity through the many layers of cable insulation make it improbable that the excursion into partial melt could be accomplished so quickly.
We have devised two possible solutions to this difficulty. The first solution is ohmic heating: a current can be driven through the Bi-2212 windings (all in series) in order to ohmically heat them for the 20°C step. This heating is volumetric within the entire winding, so the temperature increase should be rapid and uniform throughout the winding. The decrease rate will be determined by the dynamics of radiative transfer: if the furnace heating elements are turned off at the same time the ohmic heating is applied, it should be possible to attain the necessary decreasing ramp once the ohmic current is turned off.

The second solution is isothermal melt processing. Holesinger has shown [23] that the transition into partial melt can be induced by changing the partial pressure of oxygen (pO₂) in the purge gas instead of changing the temperature. By providing parallel manifolding to the assembly of Bi-2212 windings (Figure 12a) we will be able to make a step change in pO₂ with a time constant of ~minute.

This multi-step reaction bake process will require considerable process development, and may involve a combination of both of the above approaches.
2.5. *Quench protection*

Quench protection takes on a very different character with Bi-2212 windings. Figure 13 shows the temperature dependence of $j_c$ in Bi-2212 [24]. A strand must be heated to $\sim 50$ K (more than twice the same threshold for Nb$_3$Sn) before the critical current decreases sufficiently to insure quench. Since the heat capacity increases as $T^3$, this means that quench heaters will require $\sim 20$ times more pulse power in order to force the distribution of a quench. Our experience with quench heaters indicates that this margin is feasible.

A related challenge comes from the electrical insulation that must be used with Bi-2212. The only currently available insulating fabric that survives the 850 C reaction bake is ceramic cloth (e.g. Nextel [25]). Unfortunately such fabric is currently available only with a layer thickness of $\sim 500 \mu$m, three times that of S-glass fabric. While Nextel provides excellent electrical insulation, it also provides far too much thermal insulation in order for quench heaters to deliver their heat pulse with $\sim$ms time constant. It will be necessary to develop a solution to this problem, perhaps by excising the Nextel insulation after reaction bake at the interface locations where a quench heater is to be placed and replace it locally with S-glass fabric.
3. Synchrotron radiation and damping

Perhaps the most obvious challenge that arises for a concept of an LHC Tripler is the strong dependence of synchrotron radiation upon beam energy. The power per unit length $\tilde{P}$ that is radiated in a proton beam of energy $E$, current $I$ and curvature radius $\rho$ is

$$\tilde{P} \propto IE^4 / \rho^2$$

Tripling the energy while keeping $I$ and $\rho$ constant increases the radiated power from 0.22 W/m (LHC) to 14 W/m! Already in LHC absorbing the synchrotron radiation is a major challenge, requiring an intermediate-temperature heat shield within the beam tube. It would seem at first that this dramatic increase in $\tilde{P}$ would make a Tripler untenable.

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 in LHC) to 1.2 keV (soft X-ray)! Figure 14 shows the energy spectrum for the photons from synchrotron light for the LHC and for a Tripler. The hard UV photons in the light in LHC have large cross-section for scattering from the surface layers of any-

Figure 13. Temperature dependence of $j_c$ in Bi-2212.
thing they hit and for degassing those surfaces [26]. By contrast the soft X-rays that carry most of the energy for light in the Tripler penetrate into the surfaces and stop within the first \( \sim 100 \) µm of the metal. Bauer [27] suggested that one could absorb the synchrotron light on photon stops located at discrete locations just after each dipole. The photon stop in turn could be maintained at room temperature so that there is no impact upon the refrigeration of the superconducting dipoles. That approach has been used successfully at some synchrotron light sources. A limitation of that approach is that with the 4.6 cm horizontal aperture of the Tripler dipole (adequate for all other requirements) the requirement to pass the entire sheet of synchrotron light out at the end each dipole would limit the allowable sagitta from the curving beam trajectory and therefore limit the length of each dipole to \( \sim 7 \) m.

We propose that the dipoles of a Tripler should be longer (not shorter) than those of the LHC, perhaps 30 m, in order to keep to a minimum the number of independent dipoles (and end regions where most failure modes occur). To decouple magnet length from the performance of the photon stop, we have designed a photon stop that could be actually integrated directly into the body of the dipole.

The design is shown in Figure 15. A total of three photon stops are provided for each 30 m dipole: two mounted at intervals along the dipole length and the third at the beam exit end of the dipole. 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 liquid nitrogen (LN\(_2\)) temperature. The photon stop consists of a blade supported on a stem which contains the supply and return LN\(_2\) refrigeration. The stem is mounted on a rotary feedthrough and can be rotated between two angular positions as shown in Figure 15c: in the out position it provides maximum clearance (\( \sim 1.8 \) cm) for injection of beams; in the in position it intercepts synchrotron light up to within a few mm of the beam. A clearing electrode is mounted along the opposite wall of the insertion to clear electrons and ions.

The radiant heat load from the photon stop insertion to the 4.2 K dipole cryogenics is very small in the overall heat budget. The a.c. power to remove heat at 77 K is \( \sim 11 \) W/W [28], compared to \( \sim 750 \) W/W at 10 K [29]. The improved efficiency offsets the increase in synchrotron radiation power for the Tripler compared to LHC, so the overall a.c. required for refrigeration should be comparable. Indeed one could intercept heat at an even higher temperature (e.g.
liquid Xe, 160 K) and further reduce the refrigeration power requirement consistent with acceptable radiant load to the 4.2 K dipole cryogenics.

The interaction of synchrotron light at the beam tube wall can liberate a significant fluence of soft electrons, which can be trapped in the circulating beam and also multipactor from the walls from acceleration in the charge distribution of the beam [30]. We provide a clearing electrode (Figure 15b) opposite to the photon stop in order to clear these electrons locally where they are produced.

![Figure 14. Synchrotron radiation spectrum emitted by protons: a) LHC; b) Tripler.](image1)

Figure 14. Synchrotron radiation spectrum emitted by protons: a) LHC; b) Tripler.

![Figure 15. Photon stop for Tripler: a) placement of 3 photon stops along a 30 m dipole suffices to intercept the full light fan; b) cutaway showing beam stop rotated into operating position; c) end view showing clearing electrode and photon stop in injection position and operating position.](image2)

Figure 15. Photon stop for Tripler: a) placement of 3 photon stops along a 30 m dipole suffices to intercept the full light fan; b) cutaway showing beam stop rotated into operating position; c) end view showing clearing electrode and photon stop in injection position and operating position.
Placing the photon stops within the dipole means that the coil and flux return must be penetrated by the 2.5 cm diameter vertical access tube. The coil placement in the block-coil geometry accommodates the insertion without a problem (Figure 9). The effect of the hole required in the flux return steel has been modeled using TOSCA [21]. The sextupole moment is plotted vs $z$ in the region of the insertion. The effect upon the integrated sextupole in the dipole is < $10^{-5}$ cm$^2$.

In another respect the enhanced synchrotron radiation may provide a significant benefit. The proton beams are damped in all dimensions of phase space by the balance of synchrotron radiation and r.f. acceleration. The damping time depends strongly upon beam energy:

$$
\tau = \frac{2 \text{ years}}{E[\text{TeV}] B'[\text{T}]}
$$

Transverse damping in LHC has a damping time of ~1 day; transverse damping in the Tripler would have a damping time of ~1 hour! It could prove useful in controlling slow beam growth and sustaining luminosity, up to limits from beam depletion from collisions and beam-beam tune shift.

4. Integration of a Tripler with LHC

The Tripler could be located directly above the LHC ring in the existing tunnel. Space in this region is very limited and it is necessary to minimize the cross-section of the Tripler while maintaining compatibility for transfer of beams from LHC (its injector) and for beam collision.

The cross-section for a high-field dual dipole is largely determined by the condition to return magnetic flux within a steel flux return structure so that the minimum fringe field is produced in the tunnel and neighboring elements. For
the Tripler we have managed to reduce the size of flux return steel that would normally be required by utilizing a pattern of NbTi windings located on the outer surface of the flux return (see Figure 2) to cancel flux that would otherwise fringe beyond the steel boundary. In this way we can contain the flux of the Tripler within a cold mass of 80 cm diameter, comparable to that of LHC.

The transfer of beams from LHC to the Tripler could be done at an intermediate energy, ~1-4 TeV. Injection at 1.4 TeV would correspond to a dipole field at injection of ~1.7 T, just short of saturation so that the flux plate suppression of persistent multipoles would work. Alternatively injection at 4 TeV would correspond to a very modest dynamic range for the Tripler dipoles (6:1), far less than the 15:1 dynamic range required for the LHC dipoles.

The Tripler dipole has been designed to preserve the same beam tube spacing (19.6 cm) as that in LHC, so the crossing geometry would be similar. Of course it will be necessary to develop quadrupoles that attain the same ratio of performance to those in LHC, but in general the arc quadrupoles are less challenging to build than dipoles for a collider.

Special magnets are required in the crossing region to bring the beams to crossing and to achieve low-β focus. These magnets will be very challenging: the beams have higher stored energy and there is much greater synchrotron radiation power and greater losses from interacting protons.

5. R&D Requirements to develop the hybrid dipole

The hybrid dipole required for an LHC Tripler requires several developments beyond present state of the art:

- The design assumes an engineering current density (average over the cross-section of a multi-filament strand) in Bi-2212 strand of 850 A/mm². The short-sample limit for currently available strand is ~500 A/mm². In discussions with the present manufacturers (Oxford Superconducting Technology, Supramagnetics, and Showa Electric Wire) it appears that this higher performance could likely be achieved with a few years' time providing there is a significant market.

- The extension of superconducting magnet technology will require integration of the techniques for building, heat treating, and stabilizing windings of Nb₃Sn and Bi-2212 within a hybrid coil assembly. These techniques have been developed and proven separately, but they have never before integrated with one another.

- The preliminary design of the photon stop requires more detailed analysis, with simulation and beam line studies of scattering, desorption, and electron cloud formation. These issues will have to be evaluated for the light spectrum appropriate for the Tripler.
• Quench protection in the hybrid dipole presents a new challenge which must be evaluated and modeled in model dipole studies.

Conclusions

Thanks to developments in superconducting materials and magnet technology, it could become possible to build a Tripler for the LHC. Preliminary looks at issues of synchrotron radiation, beam transfer, and magnetic field requirements indicate that the Tripler could be feasible to operate with high luminosity. Calculation of the physics reach through gluon-gluon interactions indicates that a Tripler would provide a doubling of the mass reach for discovery of new particles of the gauge fields that have been conjectured.

A great deal of technology development will be required to develop hybrid-coil dipoles and to mature their technology from model coil studies to manufacturable collider magnets. Given vigorous and sustained R&D support, it should be feasible to arrive at that mature technology in about a decade, in time for it to be available when the results come from the first long physics runs of LHC and we begin to ask: 'Where do we go from here?'

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