LHC Insertion Upgrade Combining Nb_3Sn and Nb-Ti Magnets

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Abstract

Superconducting magnet technology based on Nb-Ti cable cooled at 1.9 K has provided the present generation of LHC magnets. Magnetic fields above 10 T that will be required in future accelerators, including the upgrade of the LHC, call for the use of brittle conductors, such as Nb_3Sn or Nb_3Al. However, these conductors are proving difficult to use, and while the development of accelerator-type magnets (dipoles and quadrupoles) is advancing, it is likely to be some time before we will be confident enough to replace sections of the LHC (for example the magnets of the inner triplets) using the new technology. It is shown that Nb-Ti superconducting magnets operating at 1.9 K could provide a viable intermediate step for the upgrade of the LHC insertions, taking advantage of the established technology, and including improvements that could be reasonably applied to a small-scale magnet production. Moreover, by incorporating one (or two) relatively short Nb_3Sn quadrupoles in each triplet, the optical and heat load performance could be tailored to approach that of triplets made entirely from Nb_3Sn magnets and allow us to consider an early upgrade with larger aperture magnets but having only limited reliance on Nb_3Sn technology.

INTRODUCTION

Superconducting magnets based on Nb-Ti Rutherford-type superconducting cables have been at the forefront of the accelerator magnet science since the Tevatron construction (1980) and well into the 1990s with the SSC and LHC development efforts. Impressive progress has been made in all segments of magnet design and construction (superconducting wire and cable development, coil design and fabrication techniques, understanding of the dynamics of current sharing and of quench propagation through better modelling and measurement techniques, etc.) All these factors have contributed to the overall maturity of the field. As from the mid-90s, progress in magnet performance slowed down as attention turned to guaranteeing performance rather than enhancing it, which is an essential element of a full-scale and affordable industrial production. It is therefore reasonable to say that Nb-Ti magnet technology has reached its full potential for large-scale production with the development of the LHC main dipoles.

In parallel with the construction of the LHC, the HEP accelerator community has continued to investigate the possibilities for the next generation of hadron colliders. It is generally accepted that a “Super LHC”, with substantially increased energy reach, will require a new generation of magnets capable of operating at well above 10 T. New magnet designs, based mostly on Nb_3Sn superconductors, have been proposed and discussed in conferences and networking events such as CARE workshops. The present R&D efforts in the US (LARP) and EU (NED) are focused on a demonstration of Nb_3Sn technology as defined by magnet parameters required for an LHC luminosity upgrade.

In this context, it may be unconventional to consider Nb-Ti magnets as major elements in an upgrade of LHC low-beta insertions, as suggested by the title of this talk. Although the basic superconductor performs inherently less well than Nb_3Sn, the Nb-Ti technology is sufficiently mastered that a number of magnet designs can be readily extrapolated from the LHC experience. Furthermore, it is not unreasonable to expect additional improvements in performance for purpose-built magnets. This flexibility opens certain alternatives that have not been fully exploited in the present LHC insertions. They deserve further attention should a change of some of the critical insertion magnets be desirable (to reduce complexity of operation, for example) sooner than it is possible to complete the Nb_3Sn magnet R&D and manufacture the series of at least 20 magnets that would be required to equip the two high luminosity insertions for ATLAS and CMS. In this report, we sketch some of the arguments why using Nb-Ti magnet technology could provide an interesting alternative for an early upgrade.

POSSIBLE UPGRADES OF THE LHC INSERTION MAGNETS

The present low-β insertions were originally designed in 1996 to allow for reducing β* down to 0.25 m. In the meantime beam screens have been introduced, to cope with the vacuum stability issues, and improved calculations of the long-range beam-beam effect have led to a doubling of the required beam crossing angle, so the magnet bore of 70 mm will probably not allow β* of less than 0.55 m. This is basically why we need to rethink the triplet magnets. As concerns the matching sections and dispersion suppressors, the present twin-aperture magnets should allow matching the optics to provide β* of down to 0.25 m (provided the triplets are changed). If the revised optics leads to increased demands on the matching quadrupoles there is a possibility of increasing their gradients by reducing the operation temperature from 4.5 K to 1.9 K. However, the separation dipoles, both of the normal-conducting and superconducting type, will also have to be changed to provide a larger aperture, and it may be advantageous to replace them with magnets of similar technology to that of the LHC main dipoles.

With regard to the triplets, experience with the present generation of the LHC dipoles and quadrupoles allows a fairly straightforward extrapolation to magnets of similar length or aperture. Analysis of the design details of superconducting magnets in the LHC reveals that not all magnets belong to the same generation, neither in terms of superconducting cable performance, nor in terms of thermal and radiation properties of the coils, and techniques of heat extraction. It is therefore natural to consider in the first instance whether the required performance for magnet upgrade could be achieved by using existing techniques (using the more porous insulation scheme of the main dipoles, for example, or even some enhanced version of it). The present LHC low-β quadrupoles were designed and built by Fermilab and KEK as part of the contribution of the US and Japan to the construction of the LHC. The magnets developed by these two laboratories differ in several important features [1], but they both fulfil the operational requirements of the LHC: they provide the necessary field strength and mechanical and dynamic aperture for the LHC circulating beams at 7 TeV and with a $\beta^*=0.55$ m at the collision points, corresponding to the nominal LHC luminosity of 10^{34} cm^{-2}s^{-1}. These quadrupoles also provide a safety margin of a factor of 3 with respect to the local peak power generated in the coils by the debris emanating from the *pp* collisions at nominal luminosity. The triplet cooling system enables extraction of 420 W at 1.9 K per triplet, which allows effective cooling of the magnet string up to three times the nominal luminosity. It is therefore not impossible that the present triplets could operate at the ultimate LHC luminosity of 2.3 10^{34} cm^{-2}s^{-1} (with a minimal margin). However, the aperture is tight and may give rise to operational difficulties that could add weight to demands for an early upgrade.

The lifetime of the inner triplets is estimated as 7 years at nominal luminosity and standard LHC operating scenario [2], which is comparable with the lifetime of the ATLAS and CMS inner trackers. In the running scenario for the first few years of LHC operation, priority will be given to achieving integrated luminosity by maximizing the effective data taking time. Availability of replacement equipment, including spare magnets, is therefore essential to guarantee immediate reaction to unforeseen failures and short maintenance periods. The arrangements with Fermilab and KEK for the supply of the triplets included one full spare triplet, in line with the available budget and with the expectation that work on second generation magnets would soon follow. Having one spare magnet of any kind is absolutely a bare minimum in view of the relatively long time needed for repair or to restart fabrication. Any proposal for the inner triplet upgrade must therefore also address the issue of spares and provide an appropriate solution, which may in turn reinforce the reasons for an early upgrade.

The present layout of the low-β triplet contains two 6.3 m long MQXA (KEK) and two 5.5 m long MQXB (Fermilab) quadrupoles, all with a coil aperture of 70 mm and operating at 205 T/m in an antisymmetric arrangement [1]. While fulfilling the optical requirements, the disposition does not optimize the aperture and length of the magnets. Alternative layouts are possible if the aperture and length of the quadrupoles are adapted to their position in the triplet, allowing better use of the potential of the superconductor. Furthermore, the use of quadrupoles providing a more moderate field gradient but having a larger aperture can be envisaged - at the expense of increasing the length of the magnets. Several designs of large aperture quadrupoles based on the existing LHC superconducting cables have been considered [3]. It has been shown that operating field gradients of 150 T/m may be achieved with coil apertures of 90-110 mm. Such an upgraded triplet requires 8-10 m long quadrupoles, with only a modest extension of existing technology.

A quadrupole aperture in the range of 100 mm opens the possibility of reducing β^* to 0.25 m, and hence increasing the luminosity of the LHC. However, as the product of the crossing angle and bunch length (Piwinski parameter) for the LHC beam parameters is already large, the luminosity (proportional to F/β^*, where F is a function of the Piwinski parameter), increases by only a factor of 1.5 when β^* is reduced from 0.55 m to 0.25 m. This is a regime of diminishing returns, and reducing β^* below 0.25 m leads to an ever smaller increase in luminosity at the expense of exponential rise of the quadrupole aperture. Possible remedies are to shorten the bunch length and/or reduce the crossing angle, thus reducing the Piwinski parameter, and these possibilities are also addressed in this workshop. Notwithstanding, it would seem that with the standard quadrupole triplet scheme a β^* of around 0.25 m remains a practical limit for an LHC upgrade (see Fig. 1). With this in mind, the increase of the coil aperture should be considered primarily as a means to accommodate larger beam size and crossing angle, as well as the large heat load, that are concomitant with the higher luminosity. Opening the aperture also tends to increase the efficiency of the quadrupole winding, and to improve the field quality of the magnets and possibly remove the need for higher-order multipole correctors. This leaves space for stronger orbit correctors and for local radiation absorbers. In this perspective, the reduction of β^* to 0.25 m can be seen as a measure that is complementary to other factors for increasing the luminosity, rather than its driving element.

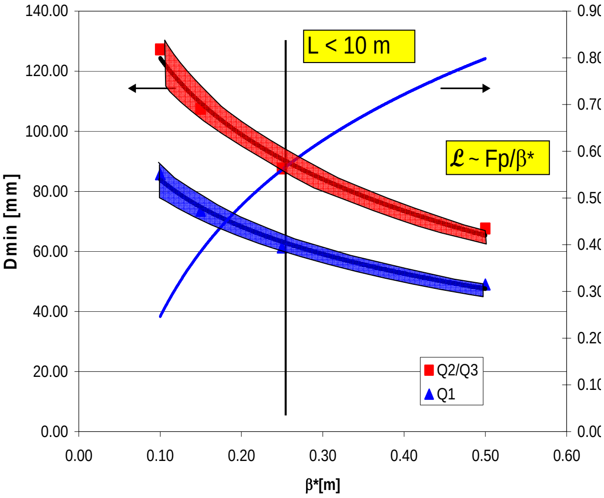

Figure 1: With this layout, for magnets of up to 10 m, increasing the bore D and decreasing the Piwinski factor Fp lead to a practical lower limit of β^* of 0.25 m.

Having in mind the present status of high-field magnet technology, Nb-Ti quadrupoles seem to provide an appropriate intermediate solution that could be installed before Nb_3Sn accelerator magnets have been developed up to the point where the manufacture of a series of about twenty 6 m long units can be confidently envisaged, including a reasonable guarantee that they can be brought up rapidly to full performance (implying extensive testing of prototypes). Although Nb-Ti technology is mature, a number of design details should still be improved in the framework of small-scale production. In particular, the cable insulation and the coil transparency for heat transport should be increased along the lines already studied for the LHC main dipoles [4]. The engineering of the magnet and its coupling to the 1.9 K heat exchanger would also benefit from further optimization. Some improvements in superconductor performance, or perhaps the use of ternary Nb-Ti(Ta) alloy are also possibilities. These improvements could realistically lead to at least a 3 to 4 times larger safety margin than that of the present triplets, and which would allow regular operation of the low-β triplets at above the ultimate LHC luminosity.

PROPOSED INSERTION LAYOUT WITH Nb_3Sn Q1 AND Nb-Ti Q2 AND Q3

Insertion layouts of the nature of those now being put into service, i.e. a quadrupole triplet, Q1, Q2 and Q3, with Q1 being closest magnet to the interaction point, share the common attribute of requiring a similar aperture for Q2 and Q3, and a smaller aperture for Q1. The aperture requirement through the present triplet with nominal optics and β* of 0.55 m is illustrated in Figs 2 and 3. In order to standardize magnet types in this first phase of the LHC, the aperture of Q1 is larger than is strictly necessary, but this has been put to good use by installing a thick beam tube that replaces an absorber that would otherwise be necessary between Q1 and Q2. Moreover, the length of Q1 was chosen to be the same as that of Q3, and Q2 was made up of 2 equal units of an appropriate (somewhat shorter) length. This was convenient because half of the magnets were to be supplied by Fermilab and half by KEK.

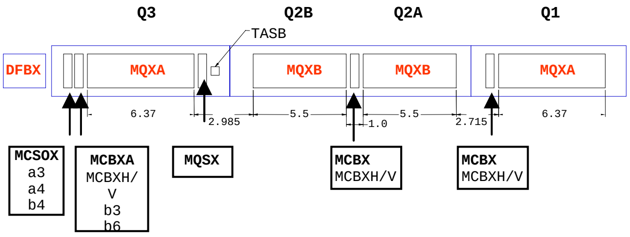

Figure 2: Layout of the present LHC low-β triplet.

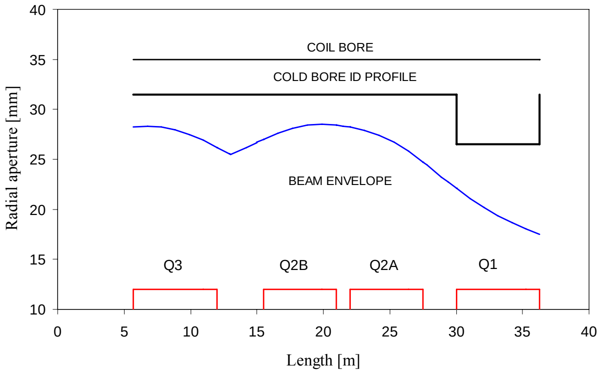

Figure 3: Physical aperture through the present triplet.

For the upgrade we propose a different distribution of magnet types. For a given β* the peak value of β in Q2 and Q3 depends on the distance of these magnets from the interaction point (IP), so besides the obvious interest in bringing the triplet as close as possible to the IP, there is an interest in making Q1 as short as possible. We therefore propose to make Q1 using Nb_3Sn conductor. Taking advantage of the fact that we can also choose a smaller aperture for this magnet (and therefore increase its gradient) it is found that a length of about 4 m and a coil bore of 60 mm should be sufficient [3]. It is further proposed that quadrupoles Q3 and Q2b should have the same coil bore of diameter 100 mm and both be 8 m long. The Q2a quadrupole would be a separate cryogenic unit, again adapted in length and coil bore to the requirements of physical aperture. The matched layout is shown in Fig. 4, which also illustrates suggested locations for absorbers and correction magnets. This triplet should provide the possibility of running with β* of 0.25 m. Should, the development of Nb_3Sn magnets prove to be more difficult than expected, a backup possibility would be to replace Q1 with a Nb-Ti magnet of similar coil bore. As it would be longer by about 30 % than its Nb_3Sn counterpart, it would require pushing back Q2 and Q3, and lead to a slightly increased β* for the same peak values of β in Q2 and Q3. Conversely, if the development advances more rapidly, both Q1 and Q2a could be built using Nb_3Sn conductor and be shorter, to improve the performance of the insertion.

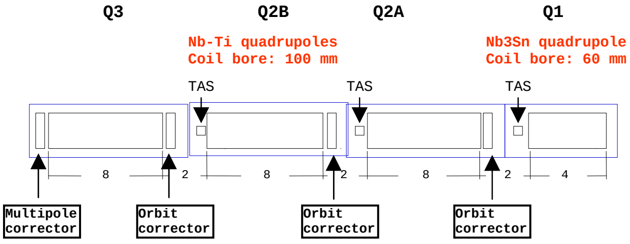

Figure 4: Possible layout of the low-β triplet for an intermediate upgrade of the LHC.

SOME PRACTICAL CONSIDERATIONS

Whereas this approach of using Nb-Ti technology does not require the same level of resource allocation as the Nb_3Sn magnet development, it would nevertheless be advisable to follow up with some essential studies. This work will in any case have to be engaged upon for any new insertion with larger aperture quadrupoles, regardless of the chosen technology.

Space

In the present triplet the front end of Q1 is located at 23 m from the IP. If this distance could be reduced the whole triplet could be moved towards the IP with a corresponding improvement in its performance. In fact, there is reason to believe that some space could be saved in between the experiment and the triplet. Once this is done, one should return to the process of matching to re-define magnet lengths and spacing. The final refinement of the parameters will depend on input from the experience of the first year or two of operation, but to arrive at the optimum via a series of intermediate studies would be more effective than waiting for the results of operational experience before starting the work. This is because of its potential to reveal other possible roadblocks at an early date.

Transverse space in the LHC tunnel is limited, especially in the vicinity of the inner triplets, and the large aperture quadrupoles will need to be designed taking this into account. It would be preferable if the magnets and associated cryogenic heat exchanger system could be made to fit into the same envelopes as the present system, and a first appraisal indicates that this should indeed be possible. The approach would be to increase the radial extent of the non-magnetic collars and to decrease the radial thickness of the iron flux return/magnetic shield. The broader collars also serve to minimize motion due to Lorentz forces, and though the iron yoke would participate less in the generation of gradient, the temperature margin would be virtually unchanged, as the conductor would operate at a higher current in a lower magnetic field.

CONCLUSIONS

Superconducting magnet technology based on Nb-Ti cable cooled at 1.9 K has reached a high degree of maturity with the LHC magnets. Extensive experience exists in building magnets of different aperture and length, and extensions beyond existing designs seem relatively straightforward. Alternatives are necessary in case the development of the next generation of high-field magnets (Nb_3Sn) proves to be more time-consuming than presently expected. For a layout similar to the present LHC low-β triplet, options exist that would allow increasing the acceptance by optimizing the length, aperture and technology of each quadrupole. A number of design features of Nb-Ti magnets could still be improved, in particular the coil insulation, to provide for regular operation of the triplet at above the ultimate LHC luminosity. The incorporation of a limited number of Nb_3Sn quadrupoles would improve the performance of the triplet and provide a useful intermediate goal and test bed for this new generation of magnets, in anticipation of their use on a wider scale. However, should the development of the new technology not be mature before pressure builds up for providing the upgrade, a layout based entirely on the use of large Nb-Ti quadrupoles could in the meantime provide a somewhat lower β^* combined with a reduction in the complexity of operation due to the increase in aperture.

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