LHC Luminosity Upgrades Using Close-In Magnets

Peter J. Limon, CERN, Geneva, Switzerland and Fermilab, Batavia, IL, USA

***Abstract*—Among luminosity upgrades presently being considered for the LHC are those that require changes to the insertion optics and magnet systems; changes to the existing inner triplets, quadrupoles placed closer to the detectors, and beam-splitting dipoles placed very close to and even inside the experiments at the high-luminosity interaction regions. The modifications of these magnet systems create challenges for both the experiments and for the magnets themselves. In this paper, we will discuss some of those issues and possible solutions and R&D paths.**

I. INTRODUCTION

EVEN though the LHC is yet to operate, a number of luminosity upgrades are being considered in order to understand the design options and issues and to provide guidance for the R&D that must be started long before the actual upgrades are installed. In this paper, we will consider upgrades that involve modifications to the insertion optics and magnets, including installing magnets close to the high-luminosity interaction points at ATLAS and CMS. These upgrades fall into three general categories:

- Modifications to the inner triplets aperture, strength and position
- Inserting additional close-in quadrupoles between the inner triplet and the interaction point [1]
- Inserting a beam-splitting dipole very close to the interaction point [2]

The purpose of either type of modification to the quadrupoles is to reduce β^* while limiting the growth in β_{max}. The purpose of the close-in splitting dipole is to reduce the crossing angle while controlling the long-range beam-beam effect. This strategy reduces the geometric effect that limits the effectiveness of making β^* smaller. We will concentrate on the quadrupole-based proposals, but will touch briefly on the unique issues of the dipole.

Each of these possibilities raises difficulties for the experiments and the magnetic insertions. For the experiments, the major issues are:

- Displacement of possible important parts of the experiments, particularly in the forward cone,
- Increased backscattering that contributes to backgrounds and track density, especially in the muon systems.

For the magnets, the major challenges are:

- Designing magnets that will meet the requirements of field strength and quality, aperture, radiation hardness and reliability in the high radiation area,

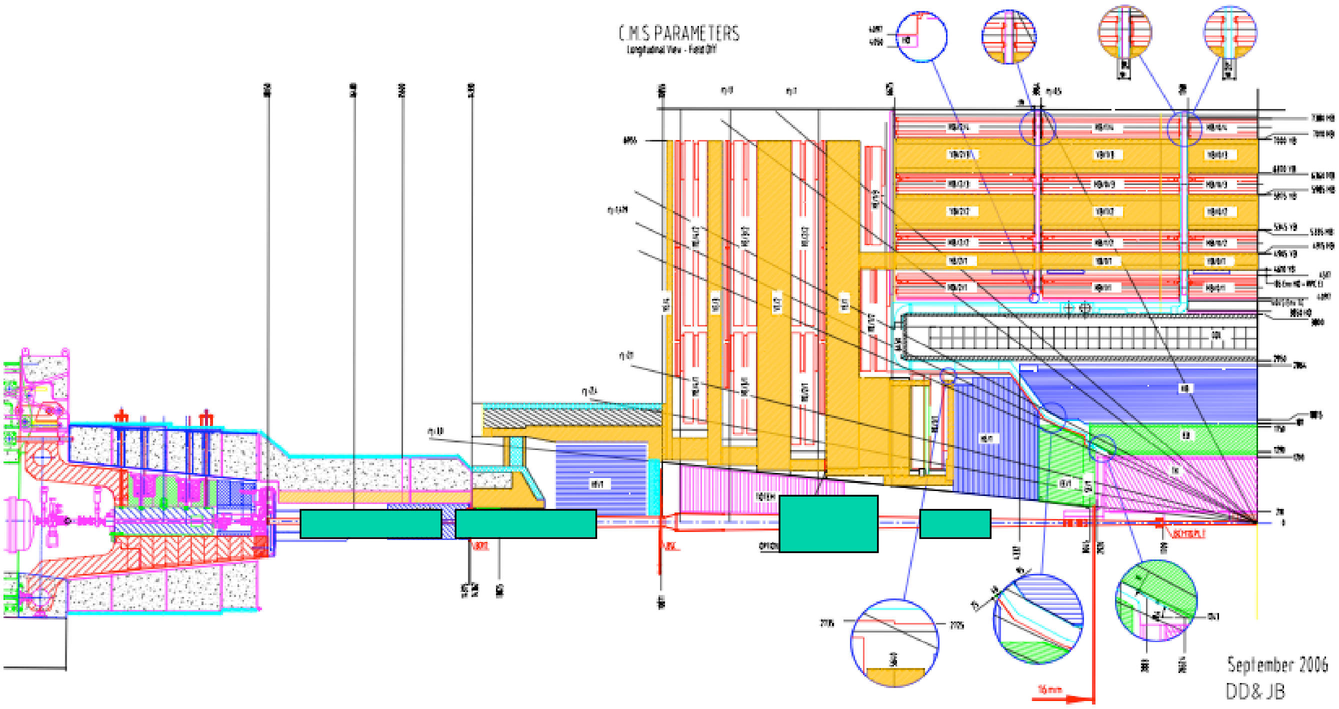

Fig. 1: The CMS detector illustrating possible placement of the slim magnets Q0 (two rectangles along the beam line on the left), and D0 (two rectangles on the right). These are merely examples; the magnets are not to scale. The arrangement for ATLAS will be

- Removing the heat generated by the interaction debris

In addition, there are at least three major issues in common:

- Judging the effects of the modifications on the parameters and performance of the LHC.
- Designs that permit the detectors to open for service,
- Implementing a stable mechanical support and cryogenic and electrical services for the magnets in the midst of the detectors.

II. A DISCUSSION OF THE POSSIBLE OPTIONS

A. Modification to the inner triplet magnets

Modifications to the existing inner triplets create the fewest problems for the experiments because it preserves the decoupling of the detector and LHC spaces. Of course, an increase in the luminosity, by itself, may require more shielding between the detector and the TAS shield in front of the triplet. The purpose of the TAS, essentially a copper or tungsten block with a hole for the beams, is to reduce the amount of beam debris that hits the magnets. This beam debris showers in the magnet structure, heating the coils and cryogens and reducing magnet performance. Unfortunately, scattering and albedo from the TAS is a source of background for the detectors. Hence, the TAS, which is itself a shield for the magnets, must have a massive shield around it to reduce the background that it causes in the detectors.

The major goal for the changes to the inner triplets is to increase the magnet aperture. This has a number of beneficial results, including permitting a larger crossing angle for the beams, thus reducing the long-range beam-beam effects, permitting larger gaps in the collimator jaws around the ring, thus reducing the possibility of instabilities, and permitting larger β_{max} and, hence, a smaller β^*, which leads to higher luminosity. Larger β_{max} also will contribute to larger chromaticity, which has to be corrected with sextupole trim magnets around the ring. The extent of such corrections is limited and has to be taken into account in the optical design. If the magnets are made with NbTi conductor, they will have to be longer than the existing magnets. There appears to be sufficient longitudinal space in the insertions at CMS and ATLAS to permit an inner triplet of about one-half the present gradient and a new splitting magnet, D1. In this case, β_{max} will be greater, which will increase the chromaticity and require more correction. As we discuss further on, the actual limit to the use of NbTi is most likely to be the small temperature margin of the material which may not be able to function well in an environment of high radiation.

B. Moving existing or modified inner triplets closer to the interaction point

It is, in principle, possible to move the inner triplet closer to the interaction point. If the focusing strength of the triplet is increased, such a move will permit a smaller β^* and greater luminosity with less growth in β_{max} and chromaticity. Magnets closer to the IP will certainly suffer more from beam debris and will generate more background in the experiments. In addition, the present inner triplet magnets are very massive and it is likely that they cannot be well-supported if they are moved more than a few meters toward the interaction region, where they will be hanging out in space, far from the cavern floor. Such a small move would not significantly increase the luminosity. Redesigning the inner triplet magnets will be a change as extensive as the one discussed in section C, below.

C. Inserting quadrupoles between the inner triplet and the interaction point

The purpose of inserting a “thin” quadrupole doublet (Q0) or singlet between the inner triplet and the IP is to reduce β^* at the IP while limiting the growth in β_{max}. The advantage over merely moving the inner triplet forward is that Q0 is not as strong nor as long as the inner triplet, and hence it will be easier to support mechanically while suspended or cantilevered out from the LHC tunnel. A robust support is necessary to allow stable alignment and reduce vibration. A possible arrangement of the thin quads in CMS is shown in Fig. 1. The arrangement for ATLAS is similar. The leading edge of a Q0 doublet would be about 13 m from the IP, with an aperture of at least 50 mm, length about 3 m to 3.5 m, and gradient about 165 T/m. Although the parameters do not appear at first glance to be challenging, they are not trivial in the context of the large amount of radiation heating. To reduce this heating, a new TAS should precede the Q0, which will be a source of background in the detector. Simulations have begun to understand the nature of the heating and background due to the beam debris scattering off the magnets and TAS in their new positions.

D. Inserting dipoles very close to the IP

A dipole close to the IP reduces or eliminates the crossing angle and so reduces the geometric effect that cripples the effectiveness of having smaller beam size at the collision point. The geometric effect is quite large. When β^* is reduced a factor of two, the luminosity increases only by about 50 percent due to the geometric effect. Without D0, however, one cannot reduce the crossing angle because of the long-range beam-beam effect that increases the tune spread in the beam. It is obvious that placing the D0 as close as possible to the IP so as to eliminate close encounters of the two beams outside of the IP is important. The closest that a D0 can be placed is about 3.5 m. This creates more background in both detectors and is particularly bothersome in CMS, as discussed later.

Another feature of D0 is that a reduced crossing angle, even if not exactly zero, may make the use of crab cavities more practical, since the rotation angle for effective head-on collisions will be smaller.

III. DESIGN CONSIDERATIONS

A. The TAS – its uses and effects

To reduce heating of the coils of the magnets, a shield called a TAS is placed in front of the magnets. The TAS is designed to absorb the energy of the beam debris, and to shadow the coils so that fewer particles hit them. It is obvious that from the point of view of protecting the magnets, the

TAS should have the smallest beam hole possible consistent with safe beam passage and alignment. The beam hole in the TAS in front of the existing triplets is 34 mm diameter, much smaller than the physical aperture of the magnets in the triplet, 70 mm.

The energy deposition from the beam debris is shown in Fig. 2. For nominal luminosity, it is expected to total about 200 W in the triplet.

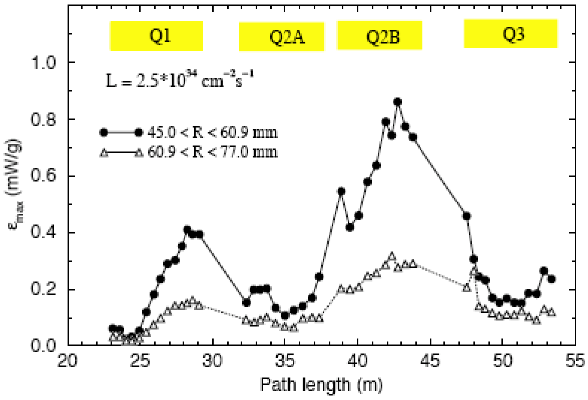

Fig. 2: The energy deposition along the length of the interaction region quadrupoles Q1 - Q3 due to the secondary particles coming from the interaction point. The energy deposition is divided radially to show the inner and outer coils separately. Note that this graph is for ultimate luminosity. The upgraded LHC may have luminosity five times greater. (From T. Sen, et al. [3])

The distribution is double-peaked. The front peak is due to penetration through the TAS. The rear peak is due to particles that are bent by the magnet into its own coils. The small aperture of the TAS shadows part of the magnet and causes the valley in the center. As discussed later, the small aperture of the TAS is a cause of much of the background in the detectors. Note also that the inner coil absorbs much more radiation than the outer, indicating that a thicker beam pipe might reduce the radiation heating in the coils. This result already assumes a beam pipe that is 5 mm thick in Q1.

Most of the magnet heating is caused by relatively high-energy particles, and absorbing these particles generates copious neutrons that exit from the TAS (and from anything else that they hit, such as calorimeters and beam pipes, etc.) as a plume, sometimes at large angles, degrade to a few MeV each in the TAS and in the surrounding shielding, and fill the cavern like a gas. These fast neutrons are the major background in the muon systems of the detectors. The number of neutrons emanating from the TAS depends on the total energy absorbed. As a rule of thumb, there is one inelastic collision for each GeV absorbed, and each of these interactions gives birth to a few fast neutrons.

Since the number of particles per unit pseudorapidity is roughly constant and pseudorapidity is a logarithmic function of the angle relative to the beam axis, the number of particles grows exponentially as the angle relative to the beam axis decreases. This dependence is even more pronounced when one considers the energy flow as a function of angle.

From these considerations, we have the following conflict: from the point of view of the magnets, one wants a TAS with the smallest aperture possible; from the point of view of the detector, one wants a TAS, or any other object close to the beam to have the largest aperture possible. Using magnets with large aperture permits a TAS with a generous beam opening while still effectively shielding the magnets, and removes the magnet coils themselves from the region with the most energetic and copious particles.

There are some differences between the two high-luminosity detectors when considering the effects of close-in magnets. It is interesting to note that the shielding philosophies of CMS and ATLAS are different, and are driven by the different designs of their forward calorimeters. The ATLAS forward calorimeter is in the end-cap. In order to be able to move the end-cap for access to the central detector, the ATLAS beam pipe is of constant diameter, which makes it a major source of background. The shielding around the beam pipe in ATLAS is rather massive to reduce this background. Putting magnets in place of the dense shielding may reduce the effectiveness of the shield.

The CMS forward calorimeter, on the other hand, is outside the detector, starting about 13 m from the interaction point. In order not to interfere with the forward calorimeter, the conical space in front of it projecting to the interaction point is kept free of material, and the beam pipe is also conically shaped. This eliminates the beam pipe as a source of background, but does not permit the installation of a close-in magnet such as a D0. If a D0 is put in its place close to the interaction point, the forward calorimeter must be placed in front of it to be effective. It is not known at this time whether a forward calorimeter will be needed for the physics done at very high luminosity.

IV. MAGNET DESIGNS

There are a number of magnet design issues that must be dealt with, the most challenging of which is to meet the field strength requirements in the presence of beam-debris heating.

A. *The preferred material to use in upgraded magnets*

What material should one use for the magnets? The Q0 and D0 will almost certainly require Nb_3Sn or other high-performance superconductor. The scattered beams will deposit more than 100 watts in only a few meters.

What will succeed for the modified inner triplet will depend on the goals one is trying to reach. If the LHC has some problem that does not permit beams of sufficient intensity, instabilities, for example, or problems in the injector chain, and one is trying to increase the luminosity by some small factor up to the nominal 10^{34} cm^{-2}s^{-1}, then it seems that NbTi quadrupoles of larger aperture might do the trick. If, on the other hand, one is trying to make a significant increase in luminosity, a factor of five or 10 beyond nominal, then NbTi will be severely challenged. The reason is simple: heating from beam debris. It is very likely that one will need to use Nb_3Sn, or HTS, if practical cable became available.

This risk to NbTi is easily demonstrated. At nominal LHC peak luminosity, with an average coil density of 8 g/cm^3, the energy deposition corresponds to about 3 mW/cm^3 (see Fig.

2). One can see from the calculated result in Fig. 3 that there is about a factor of three in temperature margin for the initial LHC triplet configuration. It is thought that a margin this great is needed to assure reliable operation in the face of fluctuations in the instantaneous secondary beam flux. The upgraded peak luminosity could be as much as 10 times the nominal value, which places NbTi so far out of the operating range that even improved shielding would be unlikely to make it viable. If one uses Nb_3Sn the margin approaches zero at about 40 mW/cm^3, which would require even in this case, better collimation and shielding for reliable operation than presently exists. [5] Nevertheless, one is in a much better situation with the Nb3Sn than with NbTi. In addition, the higher gradient and larger aperture available if the quadrupoles use Nb_3Sn will make for a superior optical design, with lower β_{max}, and less required chromatic correction.

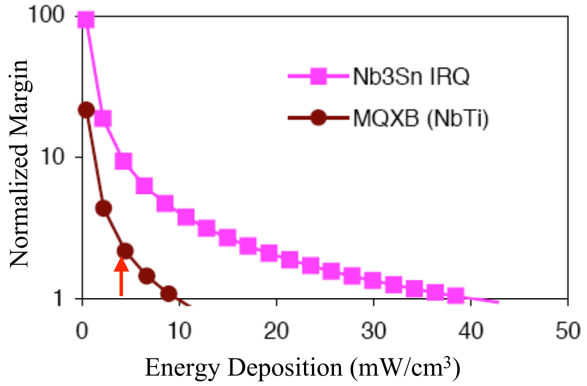

Fig. 3: A simulation result comparing the magnet operational temperature margin vs. the maximum energy deposition in the inner-layer midplane turn for a 70 mm NbTi quadrupole (MQXB) and for a 90 mm Nb_3Sn quadrupole. (From A. Zlobin, et al. [4])

B. *Progress in Nb_3Sn conductor and magnet R&D*

There has been considerable progress in recent years on both Nb_3Sn conductors and magnets. The progress in conductor performance started with the ITER R&D and has continued as shown in Fig. 4.

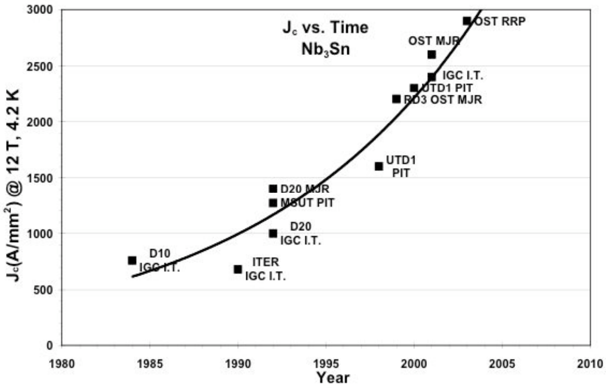

Fig. 4: The advances in critical current density of Nb_3Sn since 1983. The notations on each data point indicate the manufacturer and the fabrication technique. (Courtesy of E. Barzi)

Whereas the performance as recently as 1995 was not adequate for a practical inner triplet, it is now more than capable for that purpose. There remains a number of R&D issues for Nb_3Sn, such as reducing the magnetization for increased stability and low-current field quality, and, of course, improved manufacturing techniques for reliable performance and lower cost.

There has also been progress in magnet R&D. Figure 5 shows the performance of recent R&D dipoles at Fermilab. It is clear that the performance can be improved, particularly in terms of training and peak field. Nevertheless, the performance is as expected and is encouraging, especially that two essentially identical magnets behave in an identical fashion. The next steps, which are already well advanced, are to build a few examples of short (~1 m) quadrupoles, and, in parallel, demonstrate that long coils, about 4 m or greater, can be built and have good performance.

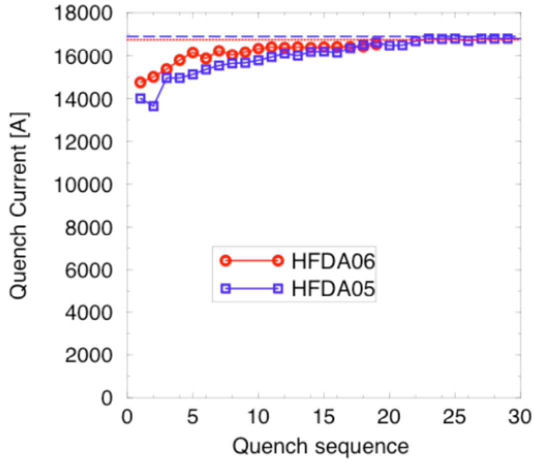

Fig. 5: Quench current training for Nb_3Sn cos(θ) dipoles HFDA05 & 06 both made from PIT conductor. The dashed line at about 17 kA is the short-sample limit for HFDA05; the dotted line is the SSL for HFDA06; they correspond to about 10 T peak field strength. (From S. Feher, et al. [6])

The design of magnets for either the inner triplet or, particularly, Q0 and D0, will be dominated by the need to remove the heat caused by the interaction debris interacting in the magnets, and to make the magnet relatively light and compact. We believe these goals can be achieved. Designs without iron, or with minimal warm iron appear to be feasible within the 300 mm to 400 mm limits on outer diameter. And with modern Nb_3Sn would certainly reach the required gradient of about 165 T/m at 90 mm aperture. The static heat leak of warm iron magnets is high, due to the necessarily short support structure, but that may not matter in magnets that absorb 100 watts or more from the scattered beam. A concept for such a design is shown in Fig. 6.

To remove the heat from the beam one might modify the coaxial heat exchanger of the Tevatron design to be made more efficient and larger in helium cross section. The pressure vessel surface that separates the single-phase superfluid from the boiling helium must have good heat exchange properties, yet be a poor electrical conductor because of eddy-current losses during ramping. A possible design could be a tube made from laminations of copper and stainless steel rollbonded together, much like a modern frying pan, stamped to shape and electron-beam welded. This would have the necessary strength and thermal conductivity, and avoid excessive eddy currents during ramping.

If a D0 is used in CMS, there are additional design challenges. Since a close-in D0 will be in the 4 T solenoid field of the detector, it will experience very large external forces. The force from the interaction of the two magnets is entirely at the ends of the magnet and is of the order of 50 tons or more. The torque from this couple must be supported on something, perhaps the detector muon steel, but the crushing force on the end-turns of the magnets, which are not geometrically good arches, will have to be supported internally. We do not know of any accelerator-type magnets that have successfully used internal support for the coils, although the reason for this lack of success is not known. This may be an additional subject for R&D.

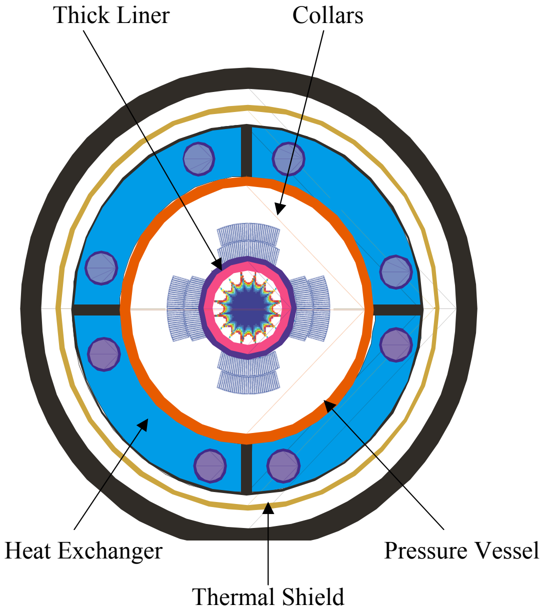

Fig. 6: A concept for slim quadrupole suitable for insertion inside the shielding for the detector. The overall diameter is less than 300 mm for an aperture of 90 mm. It has an annular space for helium to remove the beam-debris heating. (Courtesy of G. Kirby, private communication)

V. PRIMARY GOALS FOR FURTHER R&D

It cannot be emphasized strongly enough that the most important issues are as bulleted in the introduction. In terms of magnet R&D, the primary goal should be to make a working Nb_3Sn high-gradient quadrupole of large aperture, about 90 mm or perhaps slightly more, and reasonable length, about 6 m long. This work is proceeding in the U.S., but must be augmented by additional work elsewhere, if it is to succeed for the LHC luminosity upgrades. Since this is an upgrade for the LHC it seems logical that CERN, at least, should start an aggressive R&D program on Nb_3Sn magnets. In addition, it is not too early to begin to understand the consequences of integration of new insertion magnets such as Q0 and D0 into the detectors. This involves issues of space, support, mobility, cryogenics and perhaps most important, the effects of backscattering and albedo on detector operation.

VI. CONCLUSIONS

There are a number of paths to luminosity upgrades for the LHC. Large increases in the beam current are not desired, both because of the dangers of huge stored energy in the beam and because of the uncertainties of being able to achieve large increases. The most straightforward, and with the least R&D is to make new NbTi quadrupoles of large aperture using NbTi conductor. This upgrade, however, will only provide a small increase in luminosity, less than a factor of two. Nevertheless, it could still be useful if the LHC is struggling to reach its initial design goals.

In the absence of much-increased beam intensity, more significant luminosity increases, approaching 10^{35} $cm^{-2}s^{-1}$, will very likely require some magnets inserted close to or even inside the detectors. These insertions present many challenges, including large forces on the magnets due to the detector magnetic fields, back scattering and albedo from the close-in insertions that will increase background in the detectors, and the difficulty of operating high-performance magnets in an environment of high levels of beam debris.

These close-in insertions and replacements for the present inner triplet magnets will almost certainly have to be built using Nb_3Sn or another high-performance conductor in order to operate in that high-radiation environment. Although no practical Nb_3Sn magnets have yet been built and operated in accelerators, there has been great progress in both materials and model magnets in recent years, and, with continued investment in R&D it is very likely that practical magnets will be proven in the next few years.

ACKNOWLEDGMENTS

The author would like to thank G. Kirby, R. Ostojic, G. Sterbini, E. Laface, W. Scandale and J.-P. Koutchouk for useful discussions.

REFERENCES

[1] E. Laface, et al., “Interaction region with slim quadrupoles”, EPAC 2006, Edinburgh, UK, June 26-30 2006, to be published
[2] J.-P. Koutchouk, G. Sterbini, “An early separation scheme for the LHC luminosity upgrade”, EPAC 2006, Edinburgh, UK, June 26-30, 2006, to be published.
[3] T. Sen et al., “Beam physics issues for a possible 2nd generation LHC IR”, EPAC2002, Paris, June 3-7 2002, p.371.
[4] A.V. Zlobin et al., “Large-Aperture Nb_3Sn Quadrupoles for 2nd generation LHC IRs”, EPAC2002, Paris, June 3-7, 2002, p.2451
[5] N.V. Mokhov & I.L. Rakhno, “Mitigating radiation loads in Nb_3Sn quadrupoles for the CERN Large Hadron Collider upgrades”, Phys. Rev. ST – Accel. & Beams, 9, 101001 (2006)
[6] S. Feher, et al.,”Development and Test of Nb_3Sn Cos-Theta Magnets Based on RRP and PIT Strands”, MT-19, Genoa, IT, Sept. 19-23, 2005.