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Overview of Possible LHC IR Upgrade Layouts

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Abstract

An upgrade of the LHC interaction regions could potentially increase the luminosity by a factor of two or more. Several IR layouts are presented. The challenges and open questions related to the optics design, energy deposition and magnet design are discussed.

I. LHC Luminosity Upgrade

The initial luminosity goal in the LHC is an ambitious 10^{34} cm^{-2} sec^{-1}. The present plan is to achieve 10% of this luminosity in the first year of running, 30% in the second year and full luminosity in the fourth year [1]. After running at full luminosity for a few years, the need to reduce the statistical errors in the experimental data will require an upgrade in luminosity. This error is inversely proportional to the square root of the integrated luminosity and falls rapidly while the luminosity is increasing but falls very gradually once the luminosity plateaus.

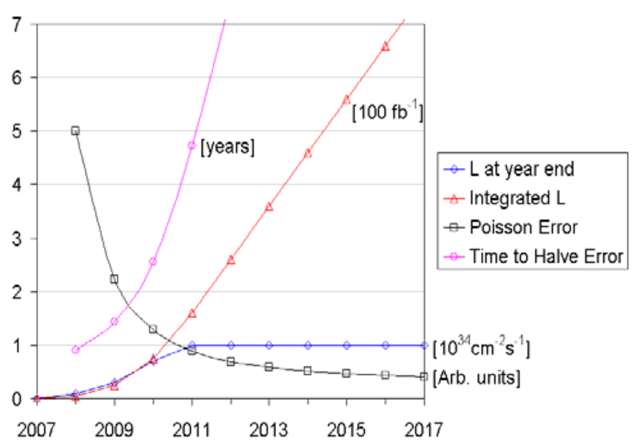

Figure 1: Evolution of the luminosity, integrated luminosity, the Poisson error in arbitrary units and the time in years to halve this error.

Figure 1 illustrates the time evolution of the luminosity, the integrated luminosity, the Poisson error and the time to halve this error. Assuming that the luminosity evolves as predicted, by the year 2012 it will take more than 7 years of running at the same luminosity to reduce the errors by a factor of two. By the middle of the next decade, the interaction region quadrupoles will be nearing the end of their expected radiation lifetime of 600-700 fb^{-1}, after having absorbed all the debris power from the collisions [2]. For these separate reasons, keeping the LHC physics program productive and the need to replace major components, we expect that an upgrade will be required in the years between 2012-2015. Of course the benefits of increasing the luminosity extend far beyond reducing the statistical errors. The increased physics potential includes extending the reach of electro-weak physics, the ability to study coupled vector gauge boson interactions, searching for new modes in super-symmetric theories (SUSY) and also searching for new massive objects, some of which could be manifestations of extra dimensions [3].

Increasing the luminosity by an order of magnitude to10^{35} cm^{-2} sec^{-1}will be very challenging. No single path for success is guaranteed and we need to consider several ways to achieve this goal. Upgrading the IRs will almost certainly be one of the options taken. It is likely that a new class of superconducting magnets will be required and considerable R&D is necessary to demonstrate that these can be built. From past experience we know that this takes several years, and therefore the R&D is starting now.

II. IR Upgrades

Luminosity can be increased directly by lowering the β* at the IPs – this will require an upgrade of the IRs. Furthermore if the long-range beam-beam interactions are observed to severely impact beam lifetime during the first phase of the LHC, then the IR layout can be changed to reduce the number of these interactions. An upgrade of the IR optics could feasibly reduce β* by 2-3 times, therefore a 10-fold increase in luminosity will also require an upgrade of beam parameters such as intensities and emittances. The IR layout must be equipped to deal with the resulting challenges of higher beam current and the 10-fold increase in power from the collision debris. The technical challenges associated with increased focusing in the IR are well known. The larger β^{max} values in the IR magnets imply that excellent field quality and precise alignment of these magnets will be even more critical. However the principal challenge will arise from the energy deposited by the collision byproducts in these magnets. The power in these debris particles increases linearly with luminosity - an estimated 9kW per beam must be safely absorbed at a luminosity of 10^{35} cm^{-2} sec^{-1}. This directly impacts the quench stability of the magnets due to the increase in local peak power density, increases the heat load on the cryogenic system and increases the radiation damage of components [2]. These challenges must be met by improved optics designs, detailed energy deposition calculations and new engineering designs for the magnets.

The baseline IR has quadrupoles placed as close as possible to the IP. This layout has the advantages of minimizing β^{max} in the magnets for a given β*, and modest peak power deposition in the magnets because quadrupoles are relatively inefficient at sweeping charged particles. The disadvantages are a significant number of parasitic interactions between the beams, and a common correction system within the IR that must act on both beams simultaneously.

Several layouts for an IR upgrade were proposed in Reference [1]. These designs assume that pole tip fields in the neighborhood of 13T, with 15-20% operating margin, will be achievable with the use of Nb_3Sn superconductor. Figure 2 shows the two most straightforward designs – one with quadrupoles first as in the baseline IR and the other with dipoles first. In both these designs, the crossing angle increases with 1/√ β* from the baseline optics. Magnets in both layouts start at 23m from the IP – as in the baseline. TAS absorbers are placed before the magnets in both designs. In the first layout, the quadrupoles have the same gradient but larger coil aperture, 110mm, rather than the 70mm aperture in the baseline.

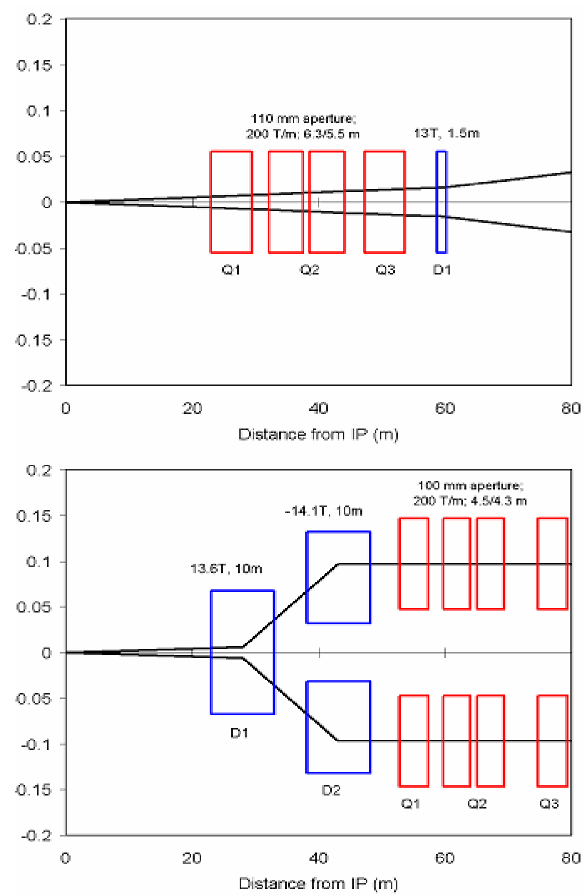

Figure 2: Straightforward IR upgrade layouts. Top (a): quadrupoles first, Bottom (b): dipoles first.

This aperture is the largest feasible for the desired gradient. The magnet aperture sets an upper limit on the allowed β^{max} – as remarked earlier, placing the quadrupoles closest to the IP leads to the smallest β^* for this allowed β^{max}. The first separation dipole D1 in this dipole is made as short as possible to minimize the amount of power deposited at the end of the dipole furthest from the IP. In the second layout, the beams are separated early with 10 m long dipoles D1 and D2. Space has been left for 5m

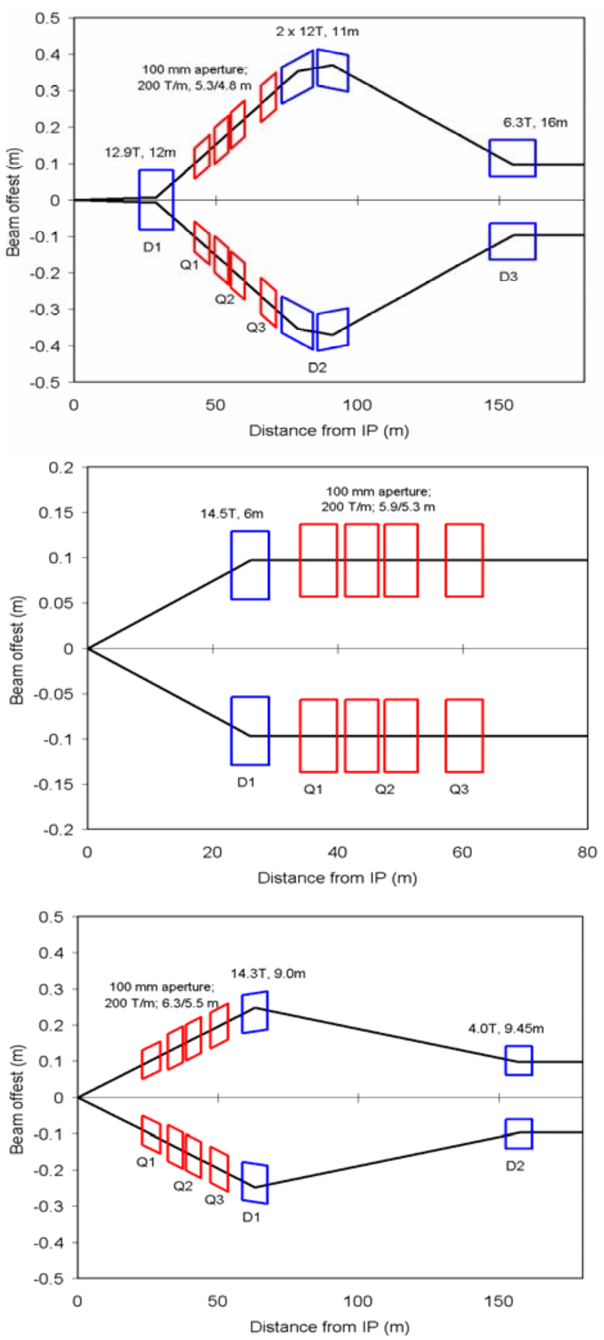

Figure 3: Alternate designs for an IR upgrade. Top (a): IR with quads between the separation dipoles, Middle (b): Dipole-first IR with large crossing angle. Bottom (c): Quadrupole-first IR with large crossing angle.

long neutral absorbers before and after the D2 dipoles. These components increase the distance from the IP to the first quadrupole Q1 to nearly 53m. The 100mm aperture of the quadrupoles is as large as possible without the coils touching in these twin aperture magnets; the center-to-center distance is 194mm. The reduced number of long-range interactions and the possibility of independent correction systems for the two beams are clear advantages of this design. The major challenges will be designing twin aperture dipoles and quadrupoles with the required field quality, and dealing with the power deposited in the dipoles.

Three alternate designs are shown in Figure 3. The first of these places quadrupoles as early as possible after the beams are separated. This has the advantage of a lower β^{max} compared to the dipoles first design, and fewer long-range interactions compared to the quadrupoles first design shown in Figure 2. The major challenge will be to design novel twin aperture dipoles and quadrupoles with non-parallel axes. The last two layouts in Figure 3 show very large crossing angles ~8 mrad – in the event that such large crossing angles help increase the luminosity while operating at the beam-beam limit [4].

Table 1 shows the basic IR parameters of the baseline optics and the five options for the upgrade.

	Base-line	Fig. 2a	Fig. 2b	Fig. 3a	Fig. 3b	Fig. 3c
IP to Q1 (m)	23	23	52.8	42.5	34	23
D_{quad} (mm)	70	110	100	100	100	100
β^*_{min} (cm)	50	16	26	19	15	10
β_{max} (km)	5	15	23	23	23	23
B_{D1} (T)	2.75	15.3	15	14.6	14.5	14.3
L_{D1} (m)	9.45	1.5	10	12	6	9
D_{D1} (mm)	80	110	135	165	75	105

Table 1: IR Parameters

III. Quadrupoles First Design Issues

An IR upgrade will be feasible only if the enormous amount of energy deposited in the IR can be safely absorbed. The optics design determines the distribution of the debris power along the IR. In the quadrupole first design, the energy deposited in a magnet increases with the quadrupole length and decreases with aperture. Figure 4, taken from [5], shows the peak energy deposited and the dynamic heat load, as calculated with the MARS code [6], along the four quadrupoles of the triplet at different radial distances for a luminosity of 2.5×10^{34} cm^{-2}sec^{-1}. The case shown uses a 90 mm aperture quadrupole design (Fig 5.) At a luminosity of 10^{35} cm^{-2}sec^{-1}, the maximum energy deposited would exceed 4 mW/g in Q2B, well above the quench limit. The heat load to the cryogenics would be greater than 120W/m and a total of 1.6kW would be deposited in the triplet.

With this radiation dose the expected lifetime of G11CR, if used for spacing coils at the magnet ends, would be less than 6 months. Extensive R&D is required for more radiation hard materials. The dynamic heat load is largest in Q1 with electromagnetic showers contributing about 90% of this amount. The dynamic heat load could be reduced with a separate cooling system for an internal absorber inside the Q1.

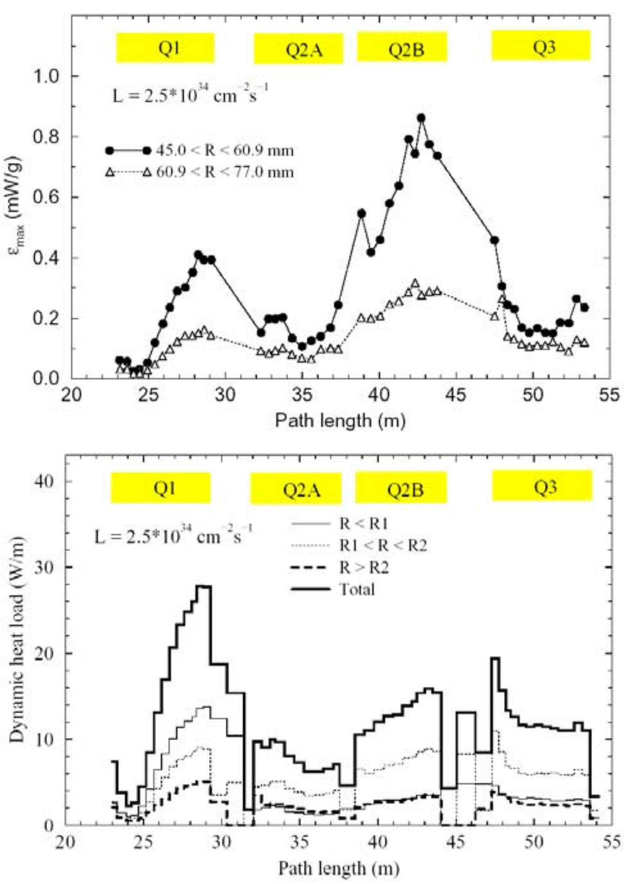

Figure 4: Energy deposition in the triplet quadrupoles at a luminosity 2.5×10^{34} cm^{-2} sec^{-1}, taken from Reference [5]. Top: peak power deposited, Bottom: dynamic heat load

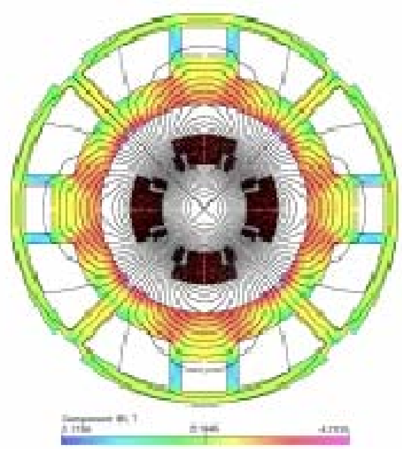

Figure 5: Optimized cross-section of a 90 mm aperture Nb_3Sn quadrupole, taken from Reference [7].

A preliminary design of large aperture quadrupoles using Nb_3Sn with the required field gradient was discussed in Reference [7]. A sketch of the cross-section of a magnet with 2 layer coils and 90mm aperture is seen in Figure 5. This design achieves a field gradient of 205 T/m at a current of 14.1 kA operating at 1.95K. The temperature margin is 2-3 times greater than with NbTi. A major challenge will be to efficiently remove the heat deposited by the beam from the magnet. The eight large wedge shaped holes seen in the cross-section are used to transport superfluid He through the length of the magnet to He tanks outside. Magnets with larger apertures of 100-110 mm would require the use of 4 layer superconductor coils[8]. There are several additional design challenges to be addressed for these magnets [7]. For example, the stresses due to Lorentz forces exceed 100 MPa, which will require a strong support structure for the coils.

IV. Dipoles First Design Issues

Dipoles are very efficient at sweeping the charged particle debris from the IP into the magnet due to the large on-axis field. Consequently, the energy deposition issues are more severe for the dipole first IR. Figure 6 shows the distribution of energy deposited on the cross-section of two different magnets: a standard cos θ design and a novel open mid-plane design.

The peak power density with a horizontal crossing angle is in the horizontal plane and skewed in the direction of the outgoing beam. At a luminosity of 10^{35} $cm^{-2}sec^{-1}$, the peak power density in the horizontal plane in the cos θ design is 50mW/g, about two orders of magnitude larger than the peak power density in the baseline optics. Out of the total power of 9kW from the IP, about 3.5 kW is deposited in the first dipole. The need to minimize the beam power in the superconducting coils has spurred the design of an open mid-plane dipole magnet [10]. Recent refinements have further reduced the amount of energy deposited in the coils [11].

Figure 7 shows particle tracks in a possible layout with an open mid-plane dipole D1 first and absorbers TAS and TAN on either side. The tracks shown originate from a single pp event at the IP and only particles with energies > 10 GeV are shown. TAS just before the D1 absorbs the majority of these particles, and only the most energetic particles propagate to the back end of D1 and the TAN absorber downstream of it. Tungsten rods at liquid nitrogen temperatures are placed in the mid-plane to absorb much of this radiation [11].

Figure 8 shows the power distribution with this design. The peak power density in the coils is significantly reduced by about two orders of magnitude from the cos θ design. However the magnet design itself is quite complex and considerable R&D is required to prove that such a magnet can be built.

V. NbTi Magnets for IR upgrades

It is widely accepted that the road to building accelerator quality magnets with Nb_3Sn will be long and hard. It therefore makes sense to

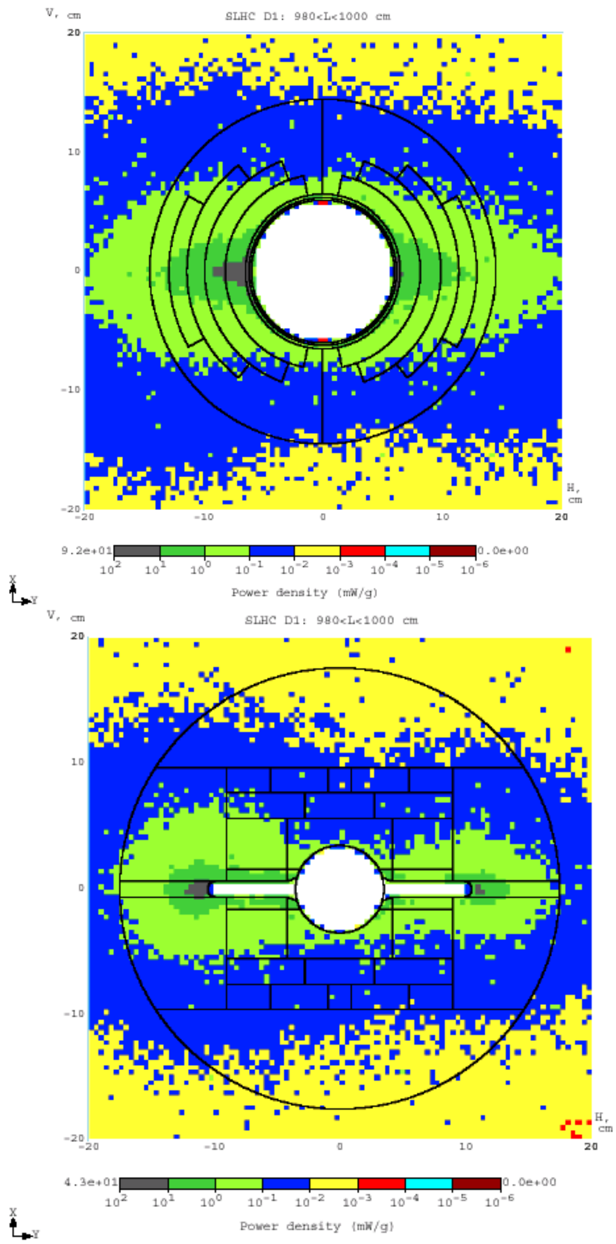

Figure 6: Energy deposition on dipole cross-sections, taken from [9]. Top: cos θ design, Bottom: Open mid-plane design

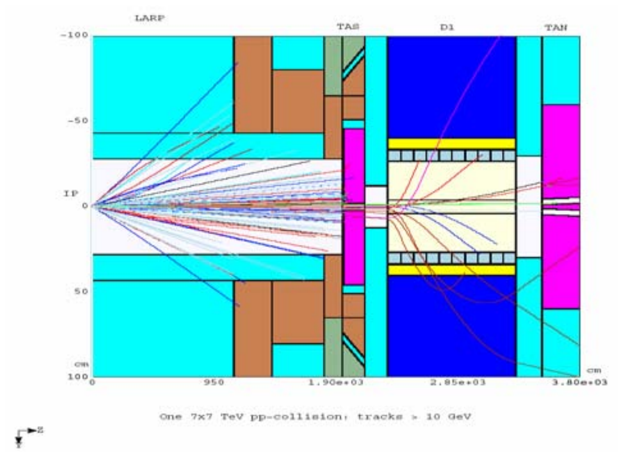

Figure 7: Particle tracks in the detector, absorbers and the dipole in a dipole first layout.

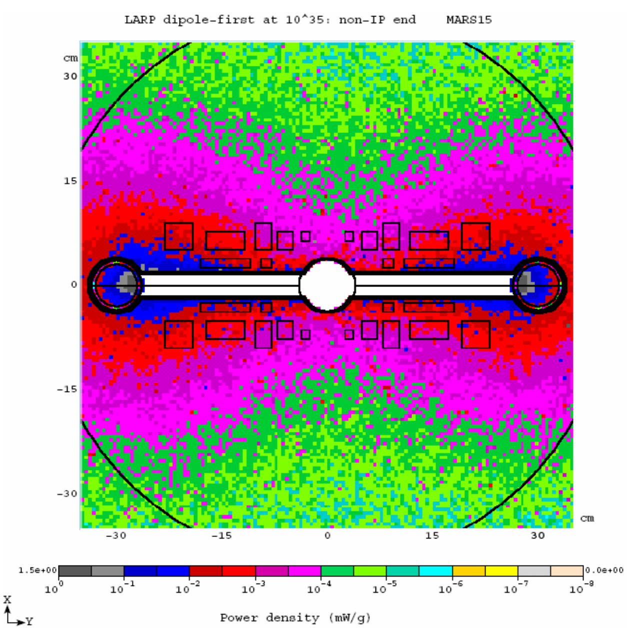

Figure 8: Peak energy deposition in an open midplane dipole with tungsten rods [11].

determine the potential of an upgrade with conventional NbTi superconductor [12]. This could be seen as possibly a first of a series of upgrades. It is clear that the dipole first design, which requires the highest possible field (~ 13-15 T) in order to separate the beams quickly and to bring the quadrupoles as close as possible to the IP, will only be possible with Nb_3Sn technology.

We have seen that a quadrupole first design with Nb_3Sn magnets of 110mm aperture and ~6 m length can achieve $\beta^* = 16$ cm. To achieve the same β^* with NbTi magnets which have a lower pole tip field would require magnets with lengths in the range 8-9m to have the same focusing strength. The increased length of magnets implies that β^{max} will be about 30% larger requiring apertures in the range 120-130 mm. Beams are separated further away from the IP implying an increase in the number of parasitic interactions by 15-20%. These accelerator physics issues could possibly be addressed by better correction systems. The smaller temperature margin of NbTi implies that these magnets will be very sensitive to beam heating. This problem could be addressed by placing adequate absorbers within these magnets at the cost of further increasing the aperture and therefore also the length and β^{max}. Radiation hard materials that can be used with NbTi also need to be developed to handle the increased radiation dose. This brief discussion suggests that NbTi quadrupoles may be suitable for a modest luminosity upgrade but probably not for the ultimate upgrade.

VI. Open questions, issues and challenges

The basic IR design concepts discussed here show that β^* can be reduced by factors of 2-5 with respect to the baseline design. However this alone does not increase the luminosity by the same factors. At smaller β^*, the crossing angles have to be increased to keep the same beam separations, which limits the increase in luminosity. Several options to recover this luminosity loss have been considered. Bunches could be shortened with higher frequency rf cavities; increased voltage with more cavities is likely not possible due to the lack of space. However even this option is expensive. Another option is to introduce crab cavities that make the beams collide head-on at the IPs. The estimated voltages are rather large, around 40 MV, and special care will be needed to keep cavity errors to a minimum to prevent emittance blow up.

KEK plans to install crab cavities in their B factory in late 2005 – much will be learned from this first experience with crab cavities in an operating machine. Finally one can also envisage increasing the beam current to the extent allowed by the injectors and potential instabilities in the LHC.

We list here some other accelerator physics questions specific to the IR optics design.

- Can IR magnet errors be adequately corrected given the very large β functions?
- Are the very large crossing angle schemes in any way feasible?
- Can dispersion suppressors be designed for quadrupoles with non-parallel axes?

Several magnet R&D challenges have to be met as well. All designs put a premium on achieving very high fields. In the case of quadrupoles first, this maximizes the aperture for a given gradient, while for dipoles this separates the beams quickly and brings quadrupoles in closer to the IP. The operating field is increased from 8T in the baseline optics to 13-15 T in the dipoles or at the pole tip of the quadrupoles. This field can only be achieved today with Nb_3Sn technology. All designs also put a premium on large apertures to allow a smaller β*. Quadrupole apertures as large as 110 mm may be required, while the need to accommodate both beams in the first dipole D1 require an aperture around 130 mm. The magnet design challenges with these large apertures have to be addressed. Perhaps the hardest will be to meet the various demands of coping with the immense energy deposited: issues of quench stability, heat load on the cryogenics, and developing radiation hard materials have to be addressed.

The first few years of operating the LHC at the nominal luminosity will help to determine the main factors that limit luminosity and will be essential in guiding the design of an upgrade. For example, if active beam-beam compensation is shown to work then the simpler quadrupole first design may be the more attractive option. The requirements of the experiments may also change for the upgrade. They may allow the magnets to move in closer to the IP in the quest for higher luminosity or alternatively the magnets may have to be pushed back if the Higgs can only be found in channels such as WZ scattering [3].

VII. Summary

We have reviewed some options for increasing the luminosity with an IR upgrade. There are two "simple" upgrade options with either quadrupoles first or dipoles first using Nb_3Sn technology that have the potential of reducing β* by factors of 2-3. More "exotic" layouts have also been presented that might reduce β* by up to a factor of 5. Energy deposition and radiation hardness will be the major challenges to address at 10^{35} cm^{-2} sec^{-1} luminosity. While a modest upgrade may be possible using magnets with NbTi technology, the ultimate luminosity goal seems feasible only with Nb_3Sn technology. However considerable R&D is required before this new technology is proven. Given the complex and disparate challenges on the road to higher luminosity, all promising options need to be pursued now to ensure success.

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