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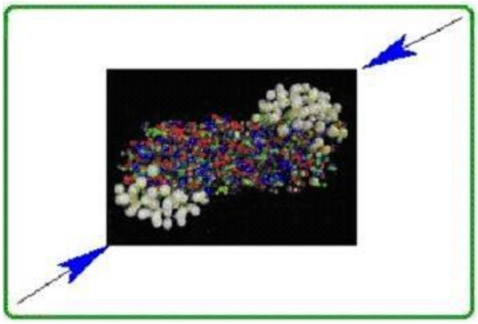

High Energy

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Hadron Beams

Low Gradient, Large Aperture IR Upgrade Options for the LHC compatible with NB-Ti Magnet Tecnology

Olivier Brüning, Riccardo De Maria, Ranko Ostojic

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Abstract

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Acknowledgements

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Large Hadron Collider Project **LHC Project Report XX**

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The paper presents three different layout and optics solutions for the upgrade of LHC insertions using Nb-Ti superconducting quadrupoles. Each solution is the outcome of different driving design criteria: a) a compact triplet using low gradient quadrupoles; b) a triplet using low gradient quadrupoles of modular design, and c) a layout minimizing the β-max while using modular magnets. The paper discusses the different strategies and design criteria for the three solutions. It also discusses their relative advantages and disadvantages and identifies outstanding studies that need to be addressed in order to develop the solutions further. All cases assume that the first quadrupole magnet requires a smaller minimum aperture and therefore, can feature a slightly larger gradient than the remaining final focus quadrupole magnets.

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1 Introduction

The option and performance reach of Nb-Ti based LHC IR upgrade was first discussed in [1]. The studies in [1] showed that the mechanical aperture of the final focus quadrupole magnets can not be increased far beyond that of the nominal LHC triplet magnets if the nominal quadrupole gradients are maintained. The technical feasibility of special, low gradient - large aperture, Nb-Ti based IR magnets and related IR layout and optic solutions was subsequently explored in [2] - [4]. More detailed layout options and optics solutions for a low gradient, large aperture, Nb-Ti based IR upgrade have been developed in a second CARE HHH workshop [5]. The discussions in [2] and [3] focused mainly on justifying the feasibility of Nb-Ti technology for a future LHC IR upgrade and building up momentum for future R&D activities related to Nb-Ti magnet technology. The discussions motivated two detailed optics case studies for an IR upgrade that are compatible with Nb-Ti magnet technology and could offer significant aperture margins that would help in coping with the heat and radiation issues inside these magnets and would provide additional margins for the beam-beam separation and the collimator jaw opening [6]. Both case studies in [6] have been developed for $L^* = 19.45$m, where L^* denotes the distance of the front face of the first quadrupole from the Interaction Point (IP). The value of $L^* = 19.45$m was chosen as the recommended reference value for a direct comparison of different IR layout options [5]. The choice in [5] was based on the assumption that any IR upgrade will also imply modifications to the LHC detector regions. Following the new proposal of a staged LHC IR upgrade with the goal of leaving the detector area and thus L^* unchanged with respect to the nominal LHC IR layout we present new versions of these two case studies with $L^* = 23$m. The re-matching for the new L^* values was done using small modifications in the magnet module length and locations in order to maintain the same peak β-functions inside the final focus magnets as for the $L^* = 19.45$ solutions in [6]. Both case studies result for $\beta^* = 0.25$m in maximum β-function values between 12km and 17km inside the final focusing quadrupole magnets, which is approximately 50% larger than the peak values in the reference upgrade option based on Nb_3Sn technology [7]. A first analysis of the chromatic aberrations and the effect of field imperfections on the dynamic aperture for such large maximum β-functions indicate that the performance degradation with respect to a compact, high gradient layout is only of the order of 20% to 35% [6], suggesting that an upgrade based on Nb-Ti magnet technology should be feasible from the optics and beam dynamics point of view. A general analysis of scaling laws for β^* values in the LHC interaction regions further underlined the feasibility of low gradient large aperture Nb-Ti magnets for an upgrade with $\beta^* = 0.25$m (e.g. half the nominal β^* value of the LHC) [8]. The discussions in [6] initiated the development of a third case study that trades the aperture margins for a minimization of the peak β-functions while keeping a modular final focus layout and a simple magnet powering scheme. The following paper summarizes the main aspects of these three Nb-Ti case studies that have been developed within the framework of the CARE HHH network activities. Each solution is the outcome of different driving design criteria: a) compact low gradient triplet upgrade; b) modular low gradient and c) low β-max optimized modular. The paper discusses the different strategies and design criteria for the three solutions and their relative advantage and disadvantages and indicates outstanding studies that need to be addressed in order to develop the solutions further. The presented solutions are meant to be reference cases for identifying the most important design criteria that should be used for the design of a Phase 1 upgrade of the LHC interaction regions based on Nb-Ti technology.

2 General considerations

Most triplet designs aim at the highest possible magnet gradients in order to maximize the triplet performance. However, the maximum obtainable gradient inside the triplet quadrupole magnets is ultimately limited by the maximum acceptable peak field in the magnet coils and the required minimum magnet aperture. In the following we present three different final focus design options that are based on a different design strategy: minimization of the quadrupole gradients in order to provide the maximum possible aperture for a given limit of the peak field in the magnet coils. The added margins in the magnet aperture can be used for any of the following benefits [6]:

- Enlarged collimator jaw openings.
- Reduced peak heat deposition for a given luminosity.
- Aperture margins for the installation of dedicated absorber material for a heat and radiation protection of the magnet coils.
- Larger beam-beam separations.
- Smaller β^* values.

All design cases discussed in the following assume that the first quadrupole magnet requires a smaller minimum aperture and therefore, can feature a slightly larger gradient than the remaining final focus quadrupole magnets.

2.1 Required minimum magnet aperture

The required minimum magnet aperture depends directly on the required beam separation and RMS beam size inside the triplet magnets. I the following we assume a required minimum beam separation of the two beams inside the common triplet aperture of 10σ and a required minimum beam clearance of 10σ for each beam from the beam centre to the magnet aperture, where σ denotes the RMS beam size. Adding furthermore additional margins for:

- 20% β-beat.
- 4mm closed orbit (CO) errors.
- 3mm for alignment errors of the magnets and the beam screens.
- 5mm for spurious dispersion effects,

the minimum required aperture inside the final focus magnets can be estimated by:

$$A \geq 33 \cdot \sigma + 12mm \qquad (1)$$

where the RMS beam size is given by

$$\sigma(s) = \sqrt{\beta(s) \cdot \varepsilon}, \qquad (2)$$

(ε is the beam emittance [ε = 3.75 10-6 m/ 7400 for the nominal LHC beam at 7 TeV]). For the margins of the spurious dispersion we assume a 30% perturbation of the arc dispersion and scale the dispersion function with the square root of β from the peak arc value β = 180m to β = 18km and assume a maximum momentum deviation of δp/p = 0.84 10^{-3} (three times the RMS momentum spread within the bunch plus as additional shift of $\Delta p/p = 0.5\ 10^{-3}$ for chromaticity measurements). This estimate is rather conservative and could be relaxed for optics solutions with β_{max} < 18km and if one does not foresee to perform chromaticity measurements with the full crossing angle being turned on. The maximum β-function (and therefore the maximum RMS beam size) inside the triplet magnets can now be estimated using a thin lens model for the triplet assembly and assuming that the slope of the β-function changes by twice its value at the entrance of the first quadrupole magnet [6]. Figure 1 shows the resulting increase of the peak β-function for the nominal LHC triplet layout with $L^* = 23$m as a function of the distance between the first and second triplet quadrupole magnet.

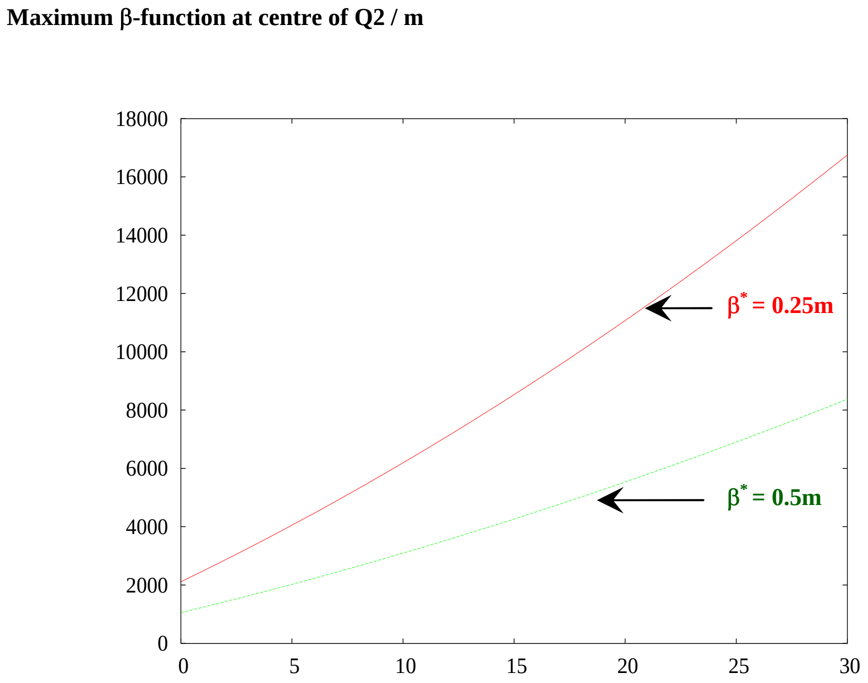

Figure 1: Maximum β-function at the centre of Q2 as a function of the distance of the centre of Q2 from the front face of Q1 for L* = 23m.

(Center of Q2 – L*) / m

For the nominal LHC triplet layout the first quadrupole magnet is placed 23 m away from the IP (denoted as L^*) and the distance between the first and second triplet quadrupole magnets is approximately 15.5m (front face of Q1 to the centre of Q2)[9]. According to Figure 1 this layout implies peak β-function values of 4.2km and 8.4km for $\beta^* = 0.5$ m and $\beta^* = 0.25$ m respectively. These values agree within 10% with the values obtained by exact, thick lens optics calculations [9].

Using Equations (1) and (2) Figure 2 shows the resulting required magnet aperture for L* = 23m as a function of the distance between the first and second triplet quadrupole magnets. For the nominal distance of ca. 15.5 m between Q1 and the centre of Q2 Figure 2 indicates a required triplet aperture of ca. 55 mm for β* = 0.5m which correspond within 10% to the nominal triplet aperture. The nominal LHC inner coil diameter of the triplet magnets is 70mm allowing 63mm for the inner diameter of the cold bore and approximately 60mm aperture with the beam screen. The nominal LHC triplet inner coil diameter is therefore ca. 10mm larger than the aperture available for the beams. In the following discussions we apply the same margins for a new final focus magnet. For β* = 0.25m Figure 2 indicates for the nominal IR layout a minimum required triplet aperture of 75mm. Applying an additional 10% margin for the inaccuracy of the thin lens estimate and the same 10mm margin between aperture and inner coil diameter as for the nominal triplet magnet layout this corresponds to a required minimum inner coil diameter of 92.5mm for β* = 0.25m. Assuming the same magnet gradient as for the nominal LHC triplet configuration (ca. 215 T/m design and 205 T/m operational) this implies a peak field at the coils of more of more than 9T which is at the limit of Nb-Ti magnet technology. An upgrade of the LHC IR that is compatible with $\beta^* = 0.25$ m therefore either requires the use of new magnet technologies that are capable of sustaining peak coil fields of 10T (e.g. Nb_3Sn) or the use of low gradient final focus configurations. In the following we will discuss the second option.

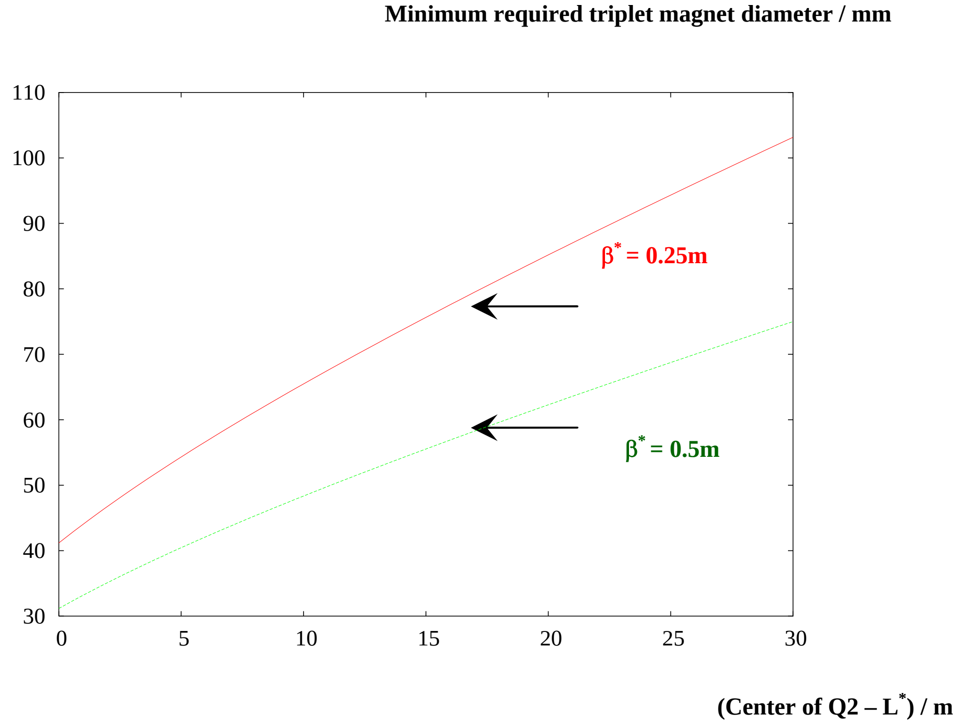

Figure 2: Required magnet apertures as a function of the distance between the centre of Q2 from the front face of Q1 for L* = 23m.

2.2 Chromatic aberrations

According to Figure 1 an increase in magnet length implies an approximately proportional increase in the peak β-function inside the triplet assembly. Assuming further that the chromatic aberrations of a triplet focusing system are proportional to the maximum β-function inside the focusing quadrupole magnets one expects on the basis of this simple scaling an increase of the chromatic aberrations that is proportional to the total triplet length. However, the simple scaling of the peak β-functions and the Chromatic aberrations are not correct if the triplet assembly becomes too long. Instead one needs to rely on the exact integral relations that include the β-function evolution over the final focus length. The Chromatic aberrations of a quadrupole magnet are proportional to the integral relation [10]:

$$I_z = \int_{IR} k_1(s) \cdot \beta_z(s) ds \tag{3}$$

The off momentum β-beat is proportional to

$$\frac{\partial \beta_z}{\partial p}\cdot\frac{1}{\beta_{z,0}} \propto I_z \cdot \cos(\Delta\mu_z^{15})\cdot\cos(|\,2\Delta\mu_z^{15}\,| - 2\pi Q_z) \tag{4}$$

and the second order chromaticity term is given by [10]:

$$Q_z'' \propto I_z^2 \cdot \cos(\Delta\mu_z^{15})\cdot\cos(|\,2\Delta\mu_z^{15}\,| - 2\pi Q_z) \tag{5}$$

where $\Delta\mu_z^{15}$ is the phase advance between IP1 and IP5.

2.3 Technological reach for Nb-Ti magnets

As the quadrupole aperture increases, the operating gradient decreases by 20 T/m for every 10mm of coil aperture [11]. In order to get a larger aperture magnet for a given integrated quadrupole one therefore needs to increase the overall quadrupole length accordingly (20-30% for the first 10mm aperture increase). The Nb-Ti technology has been proven for a quadrupole length of up to 12 m which is a factor 2 to 3 longer than the current triplet magnet modules. Figure 3 shows obtained operating gradients as a function of coil aperture for various Nb-Ti prototype magnets for an operation at 80% of the conductor limit [5].

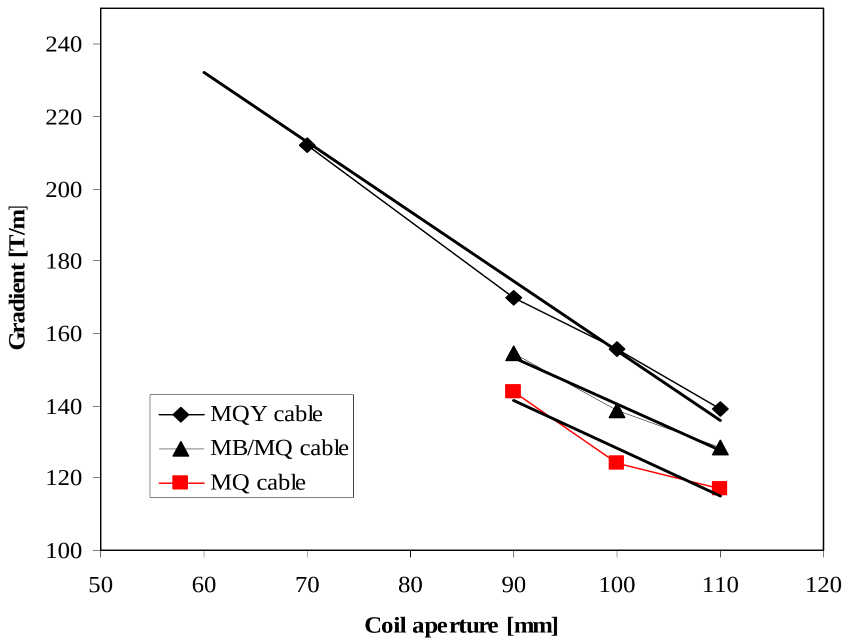

Figure 3: Obtainable quadrupole operating gradient as a function of coil aperture for various Nb-Ti prototype magnets for an operation at 80% of the conductor limit.

One clearly recognizes that by using the cable of the main LHC quadrupoles magnets, magnet apertures of 120mm are within reach of existing Nb-Ti magnet technology provided the magnet gradient remains below 100 T/m. Furthermore, there are still substantial potential improvements for the cooling capacities of the superconducting coils and the acceptable peak magnetic field inside the coils [11]. For example, Figure 4 shows the temperature increase inside the superconducting coils as a function of the deposited heat for various insulation materials [12]. One clearly recognizes that the choice in the insulating Kapton foil can increase the maximum acceptable power deposition by almost 100% with respect to the nominal LHC dipole magnet insulation without increasing the temperature inside the superconducting coils.

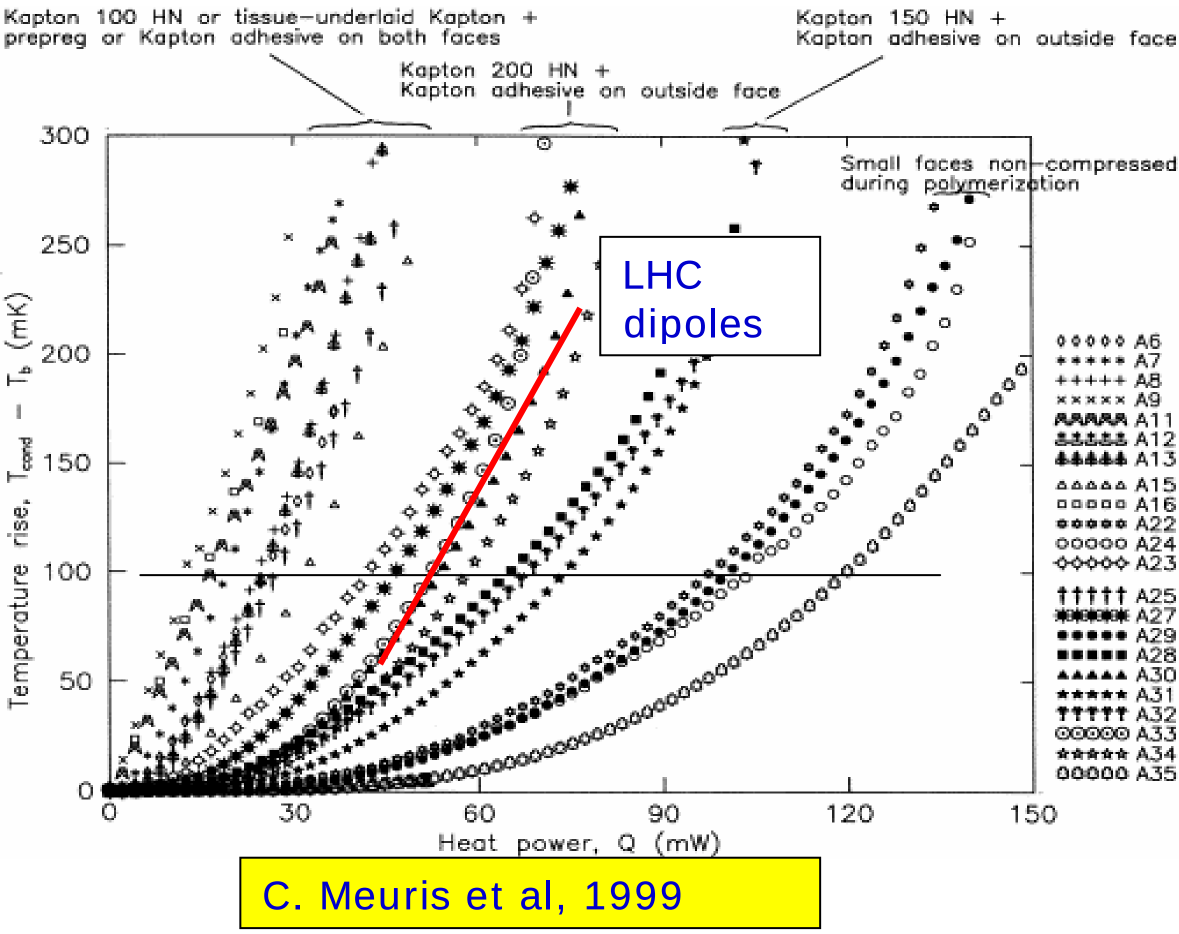

Figure 4: The temperature increase inside the superconducting coils as a function of the heat deposition for various Kapton insulation choices [12].

The KEK built LHC triplet quadrupole magnets have a peak field of 8.6 T at the superconducting coils. The nominal LHC arc and insertion quadrupole magnets have peak fields of the order of 6 T at the magnet coils [9]. However larger peak fields are in principle possible. Figure 5 gives an example for a Nb-Ti magnet with an aperture of 88mm and a peak field of 10T at the superconducting coils [13]. Recent scaling laws [15] show that for apertures from 35mm and 250mm the pole field can be between 6.6T and 8.4T with 80% operational margin at 1.9K. However, in the following analysis of the feasible magnet aperture we take a conservative approach and assume an acceptable pole field of 6.5T inside the magnet coils.

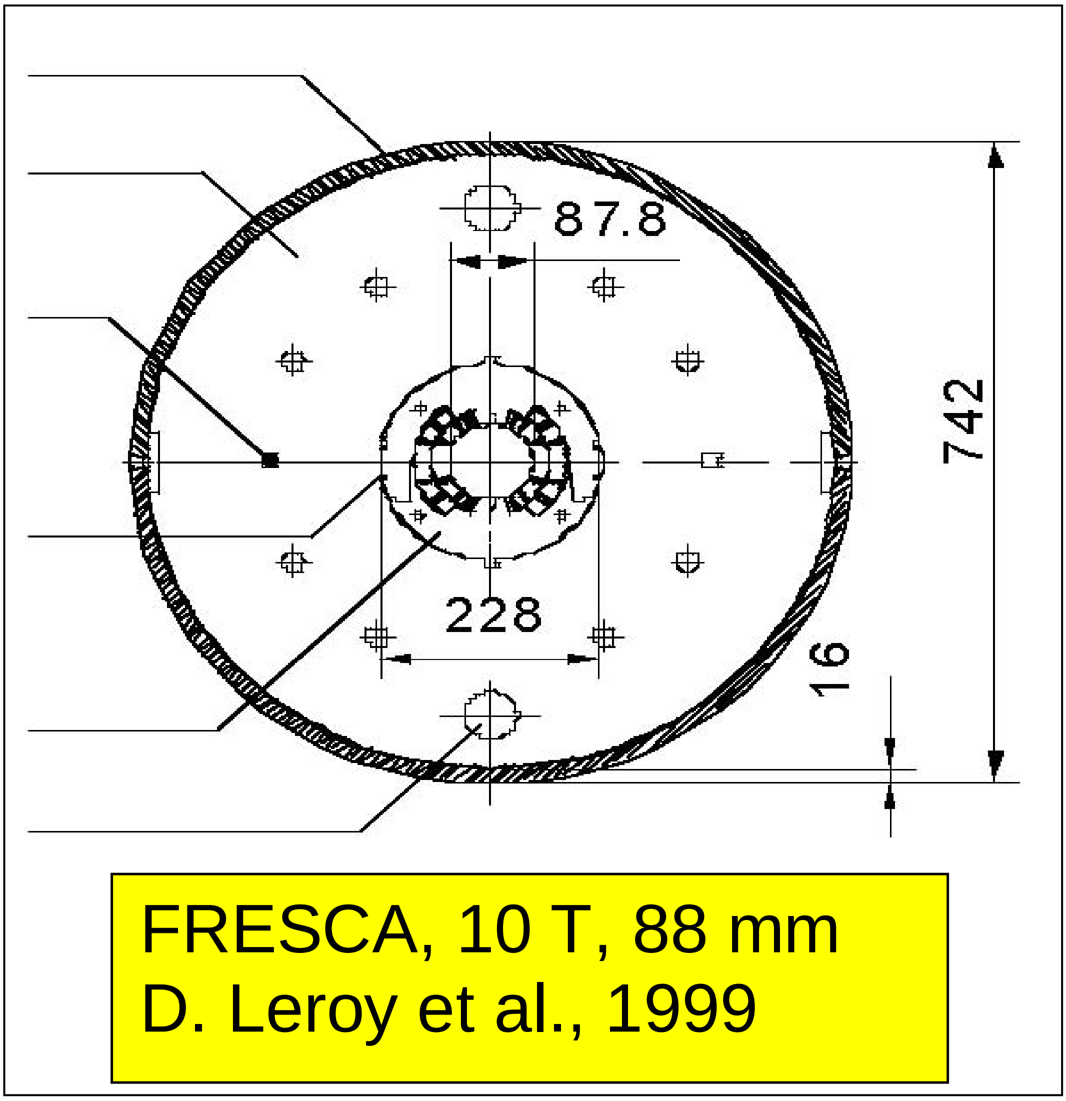

Figure 5: Example for Nb-Ti dipole magnet with an aperture of 88mm and a peak field of 10T at the superconducting coils [13]. Quadrupole magnets should be able to attain a similar performance.

2.4 *Field quality requirements for high β solutions*

Preliminary tracking studies for IR optics solutions with β-max values between 16km and 18km show that the expected dynamic aperture varies between 6σ and 12σ if one assumes an effective field quality (including corrections via dedicated corrector elements) that corresponds to approximately 10% of the relative multipole errors of MQXB [14]. Figure 6 shows the resulting scaled field error tolerances for a reference radius of 17mm. Smaller field error values or a more efficient correction mechanism that can result in effective field errors that are better than the estimates given in Figure 6 can, of course, further increase the dynamic aperture of the LHC.

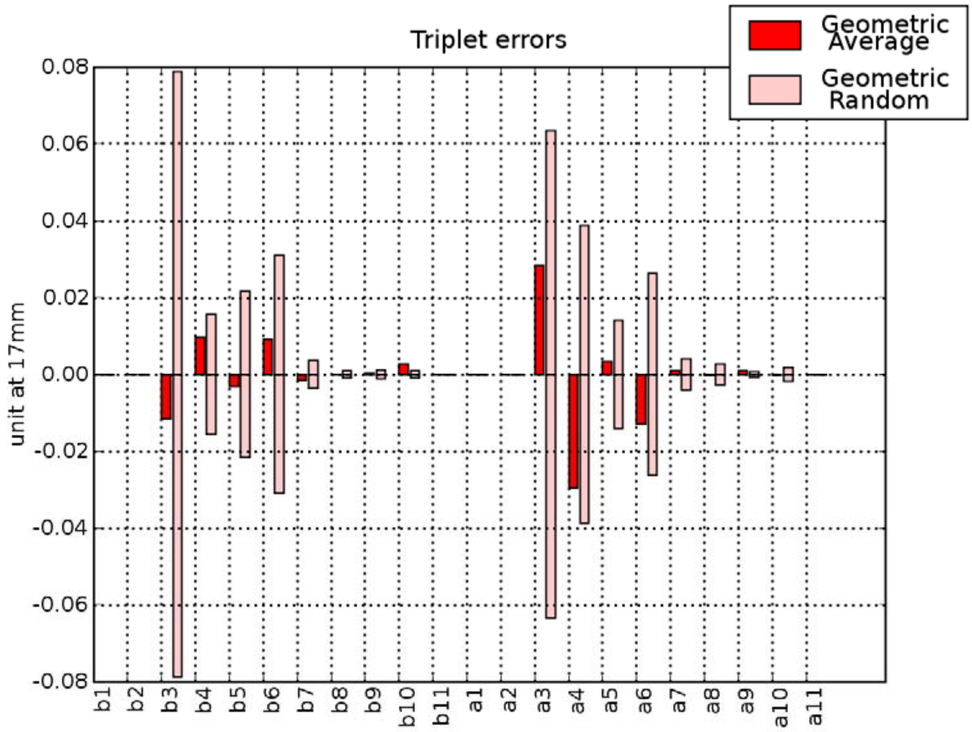

Figure 6: Field error tolerances for a reference radius of 17mm that are consistent with dynamic aperture values between 6σ and 12 σ [14]. The field errors correspond to approximately 10% of the uncorrected MQXB field errors of the nominal LHC triplet assembly.

2.5 General additional IR upgrade needs.

Any IR upgrade of the LHC experimental insertions implies additional modifications beyond the triplet quadrupole magnets. For example, the current TAS absorber and D1 dipole magnet apertures are optimized for the nominal triplet magnet apertures and $\beta^* = 0.5$m. Reducing β^* and changing the aperture of the final focus quadrupole magnets therefore implies also a modification of the TAS absorber and the D1 magnet units. Furthermore, an increase in the LHC triplet length implies ultimately a reduction in the separation of the D1 / D2 separation / recombination dipole magnets and therefore a re-evaluation of their strength and aperture requirements. Similar arguments apply to other equipment in the LHC. While this paper focuses on aspects related to the final focus quadrupole magnets, the following items will also be affected by an IR upgrade:

- TAS absorber (changed aperture).
- D1 dipole magnets (changed aperture and reduced separation between the D1 and D2 separation / recombination dipole magnets).
- D2 dipole magnets (reduced separation between the D1 and D2 separation / recombination dipole magnets)
- Some matching section quadrupole magnets need to be upgraded (aperture and / or strength) in addition to the triplet quadrupole magnets (Q5 and Q6).
- The triplet orbit corrector packages and the crossing angle bumps need to be re-evaluated.

- The coupling and nonlinear triplet corrector magnets need to be newly specified and redesigned.
- The cooling system for the final focus quadruple and D1 magnets needs to be redesigned.
- The tertiary collimators in front of the triplet magnets need to be redesigned and the impact on the collimation system and machine protection system need to be re-evaluated.

In the following case studies we assume therefore that the whole matching section of IR1 and IR5 can be modified without looking in detail into all the implications. Figure 7 shows a schematic overview over one half of the IR5 and Figure 8 shows a schematic overview of the nominal LHC triplet layout including the D1 magnets. In the following we assume further that L* (the distance of the first quadrupole magnet from the IP) remains unchanged from the nominal value 23m.This assumption differs from the assumption at the LUMI'05 and LUMI'06 workshops where it was assumed that the final focus quadrupole magnets could be moved closer to the IP (^{L*} = 19.45m).

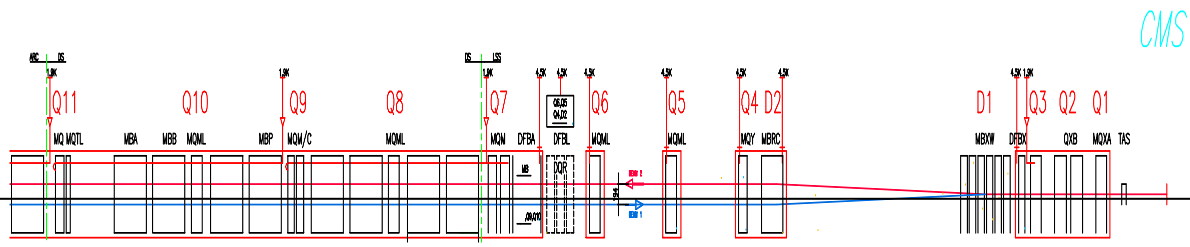

Figure 7: Schematic overview over the left side of IR5.

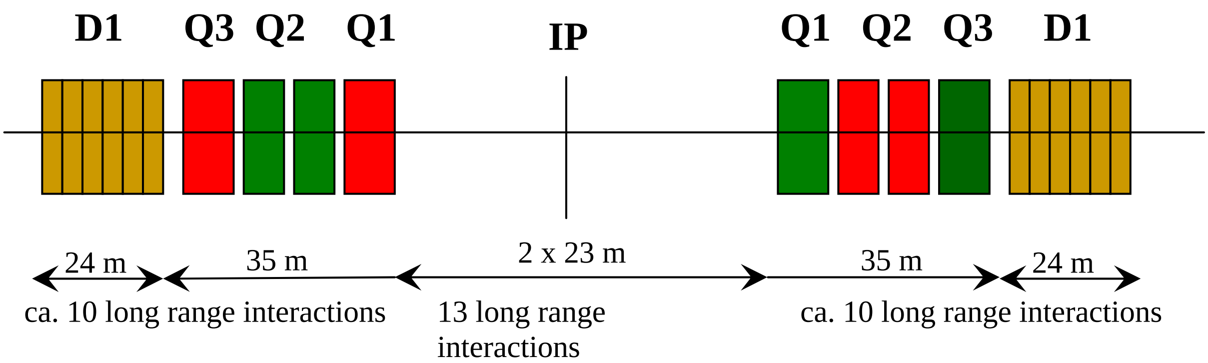

Figure 8: Schematic overview of the nominal LHC triplet layout with D1 magnets.

3 Three different driving design criteria

The three layout and optics options discussed in this paper share the design criterion of minimizing the peak β-functions inside the quadrupole magnets. However, apart from this common goal they are based on three different design criteria. All three solutions represent rather extreme study cases, highlighting the potential gains and drawbacks for each design criterion. For a final solution of the LHC IR upgrade it might still be necessary to evaluate either more moderate versions or even hybrid solution of any of the cases studies presented here. Since not all three cases feature a triplet layout (three different quadrupole units) but four different quadrupole units in one case we will not use the term 'Triplet' in the following and refer to the quadrupole magnets next to the experiments as the 'final focus' system. In this paper we look at the following three driving design criteria and associated case studies:

1. **Compact Low Gradient** final focus design: the design aims at low quadrupole gradients and maximum magnet apertures while keeping the final focus system as compact and modular as possible.
2. **Modular Low Gradient** final focus design: this design aims at low quadrupole gradients and maximum magnet apertures while providing a modular design concept that minimizes the need for different spare parts and offers a large set of slots for the installation of corrector magnets and absorber elements. The price to pay for this optimization goal is a smaller aperture margin.
3. **Small β-max Low Gradient** final focus design: this design aims at the smallest possible peak β-functions using intermediate quadrupole gradients and magnet apertures while still providing a modular design concept and equal powering of the main quadrupole magnet units. While this design criterion minimizes the chromatic aberrations and the constraints on the magnet field quality it further reduces the aperture margin of the magnets.

In all cases we assume a standard magnet separation of 1m. This space should be a sufficiently large place holder for the magnet interconnection and the installation of additional absorber material and corrector elements. The magnet spacing can be further optimized in a second iteration once the number and locations of required additional absorber and corrector elements has been identified.

3.1 Compact Low Gradient Final Focus System

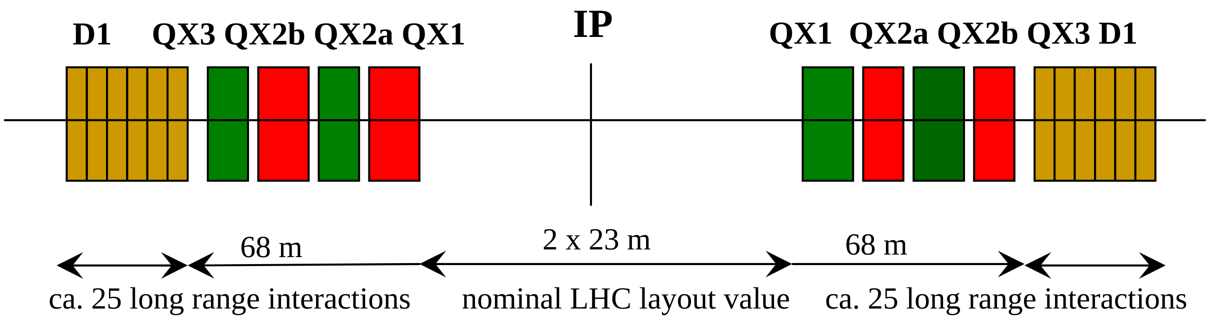

Figure 9: Schematic layout of a '*Compact Low Gradient'* final focus system.

First we look at a low gradient optics solution using a final focus layout based on a standard triplet layout (see Figure 8) with L^* = 23m. Figure 9 shows the schematic layout for this case. The optics solution in Figure 10 features a peak β-function of approximately 17.2km for β^* = 0.25m which yields an RMS beam size of σ =2.94mm for the nominal emittance value of the LHC. Using Equation (1) this implies a required minimum magnet aperture of 110mm. Applying a 10mm increase in the required aperture for the beam-screen and cold bore installation this implies a required minimum inner coil diameter of 120mm.

The solution requires the following magnet gradients and lengths:

- QX1: 12.24m long magnet with a gradient of 91.5 T/m, minimum coil aperture of 86.5mm.
- QX2a: 14.2m long and having a gradient of 68.3 T/m, minimum coil aperture of 111mm.

- QX2b: 11m long and having a gradient of 68.3 T/m, minimum coil aperture of 111mm.
- QX3: 14.75m long and a gradient of 68.3 T/m, minimum coil aperture of 111mm.

Compared to the L* = 19.45m layout in [6] the new solution offers identical quadrupole gradients in QX2a, QX2b and QX3 which significantly simplifies the magnet production aspects. The required minimum coil aperture of 120mm and gradient of 68.3T/m is well inside the range of the Nb-Ti magnet technology indicated in Figure 3. Assuming an acceptable peak field in the magnet coils of 9T (the peak field in the coils of the nominal LHC triplet quadrupole magnets is 8.6T for the KEK built magnets [9]) and maintaining a 10% operation margin the required magnet gradients could allow magnet apertures of up to 235mm diameter. Assuming a more conservative peak field of 6.5T in the magnet coils (the peak field of the LHC insertion quadrupole magnets is just above 6T [9]) the required magnet gradients would still allow a magnet aperture of up to 190mm which still provides a significant aperture margin that could either be used for larger beam-beam separations, increased collimator jaw openings, smaller β^* values or aperture margins for the installation of dedicated absorber material for a heat and radiation protection of the magnet coils. Assuming a module spacing of 1m the total final focus length increases from the nominal 30.67m to ca. 60m. Increasing the overall length of the final focus system implies a reduction of the D1 – D2 separation by approximately 30m leaving a maximum space of 75m for the D1 – D2 separation-recombination magnets (the available space in the nominal LHC IR layout is 103.4m [9]). Placing the D1-D2 magnets at the extremities of the available space between the final focus system and Q4 and assuming that half of the available space will be used up by the dipole magnets implies a required deflection angle of ca. 1.9mrad which is compatible with a 34m long, 1.3T strong warm D1 magnet and a 11m long, 4T strong superconducting D2 magnet.

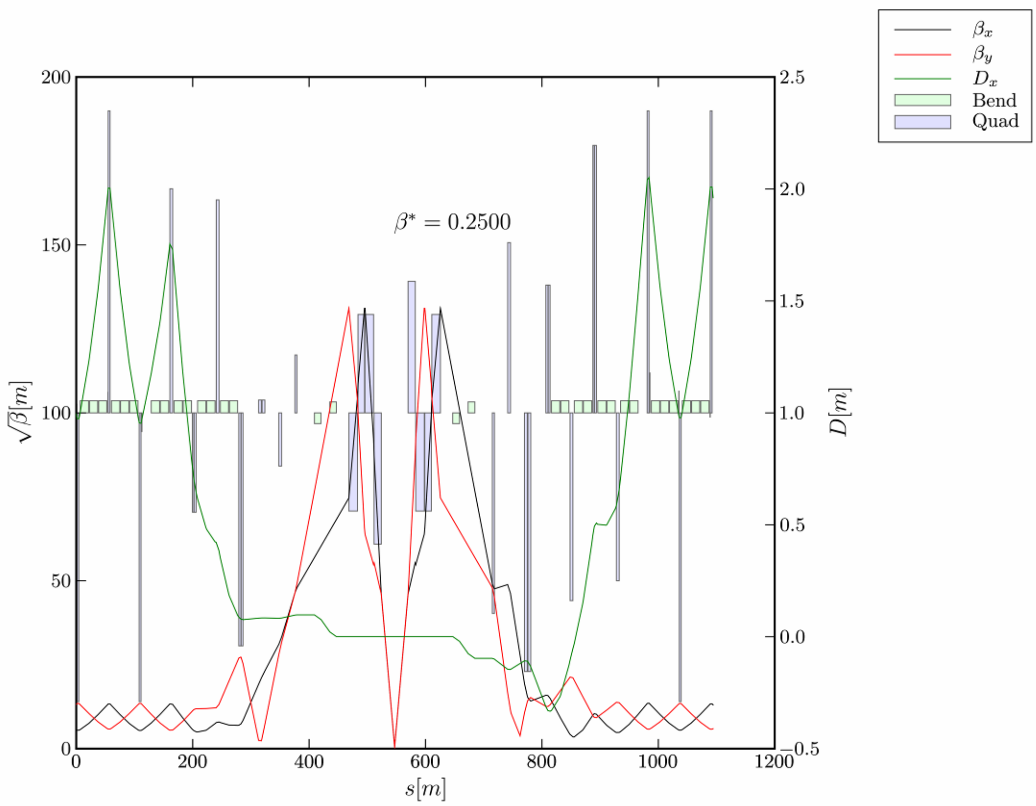

Figure 10: The horizontal dispersion and the square root of the Beam1 β-functions of the matched solution over the IR5 for the '*Compact Low Gradient*' final focus system.

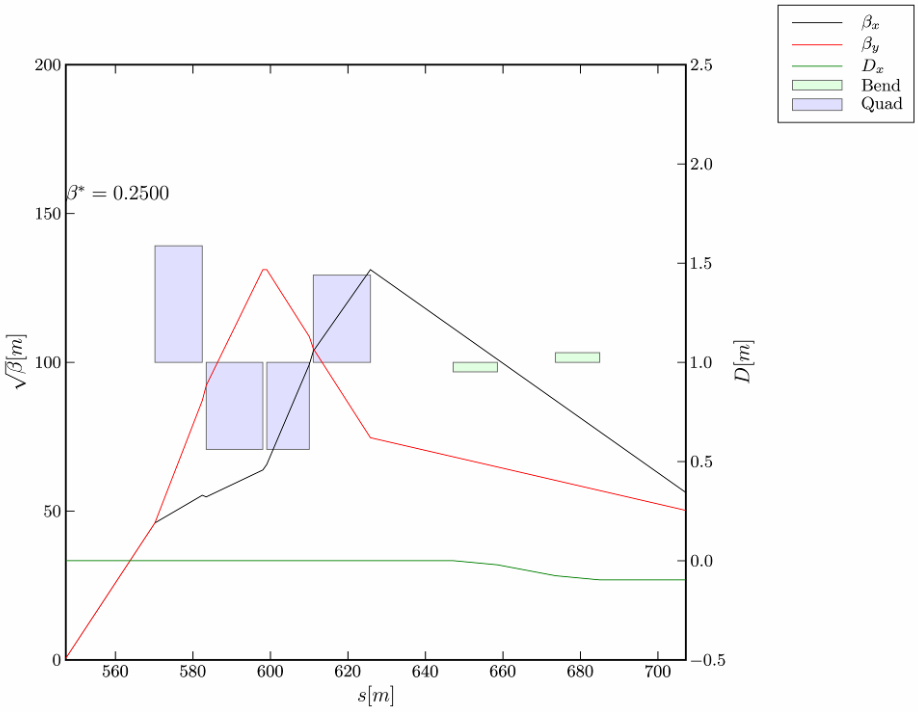

Figure 11: The horizontal dispersion and the square root of the Beam1 β-functions of the matched solution over the right hand side of the final focus system for the '*Compact Low Gradient'* final focus system.

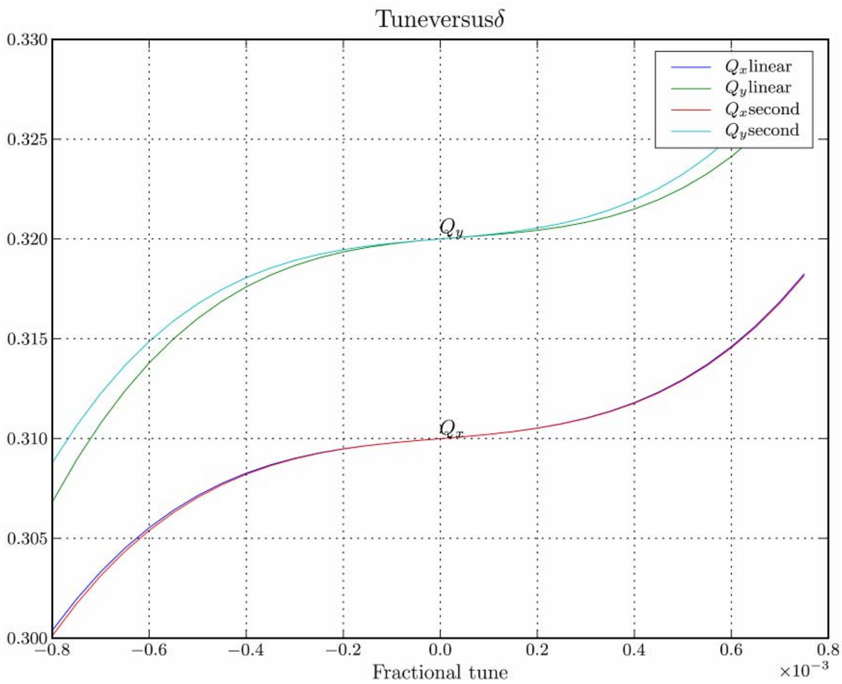

Figure 12: The tune variation for the *'Compact Low Gradient'* solution with corrected first and second order chromaticity terms.

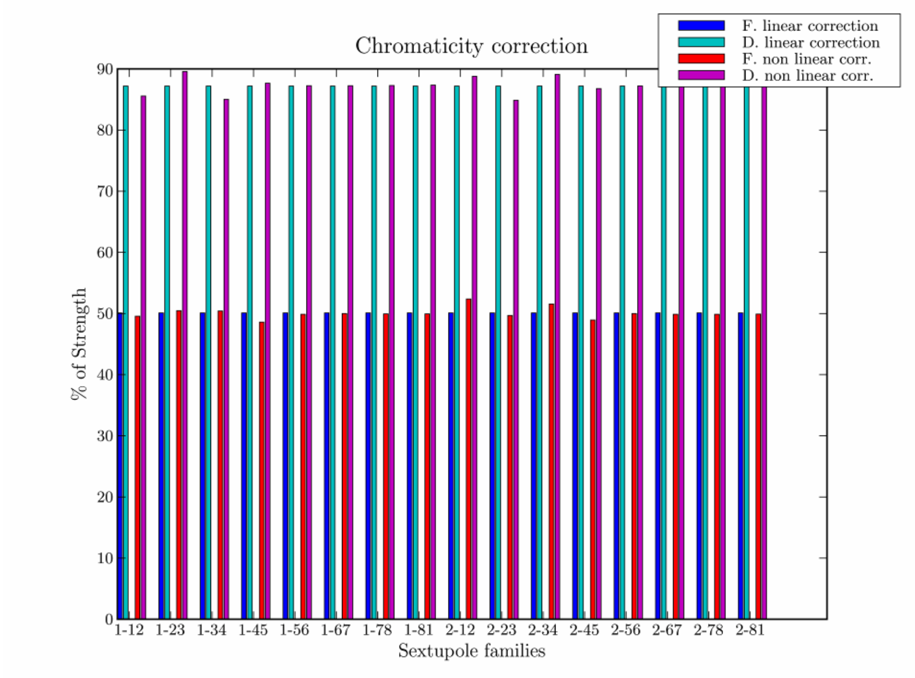

Figure 13: The required sextupole corrector strength in the lattice sextupole circuits for a correction of the first and second order chromaticity terms. While a correction is still possible for the *'Compact Low Gradient'* one clearly recognizes that it is at the limit of the available sextupole corrector strength.

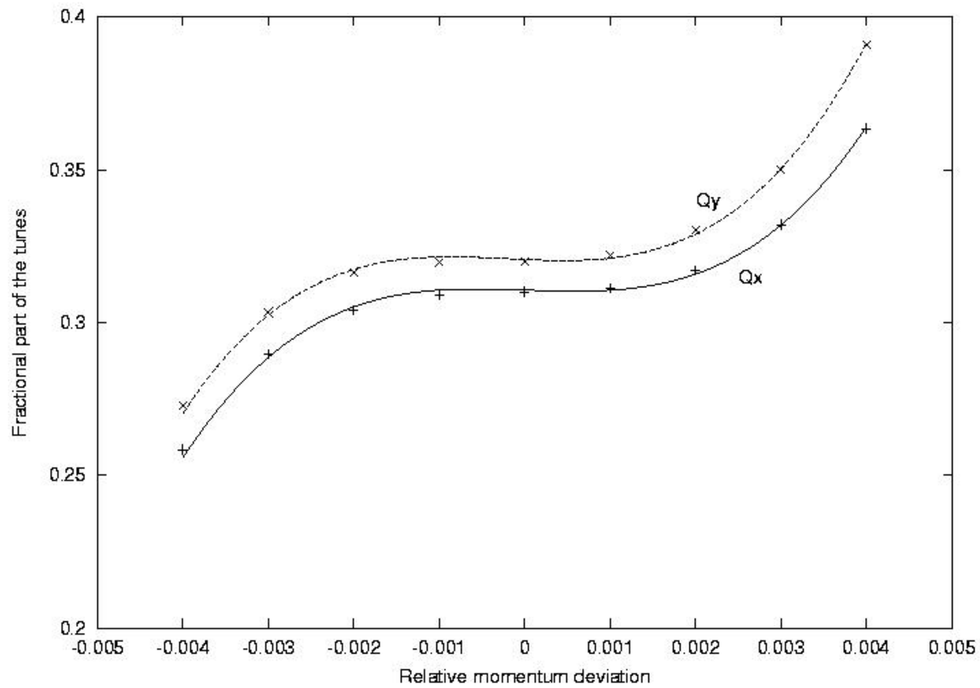

Figure 14: The tune variation for the nominal LHC collision optics with $\beta^{*} = 0.55$m with corrected first and second order chromaticity terms [9].

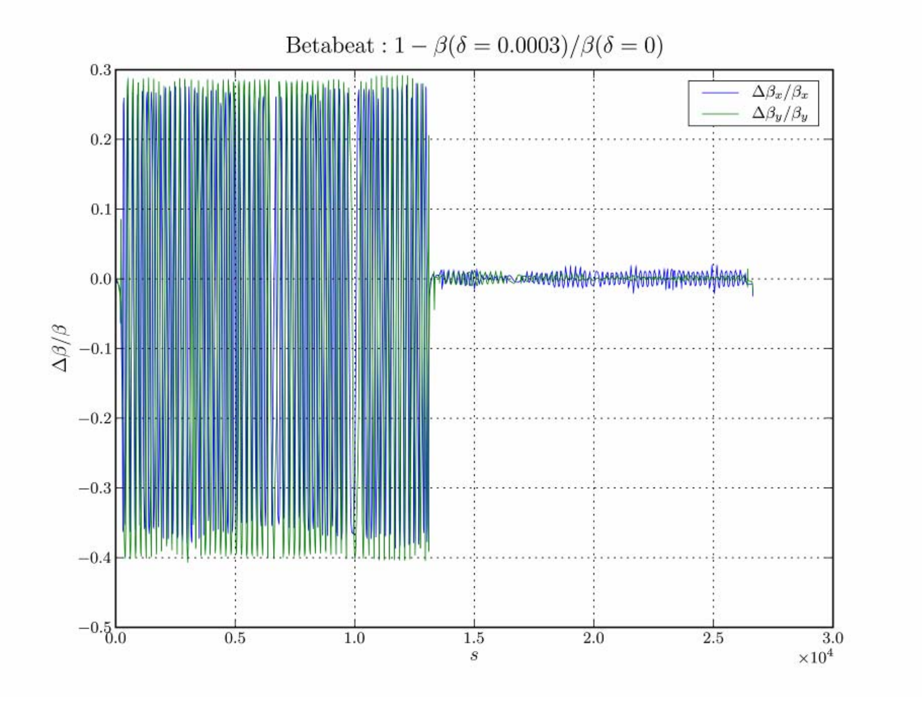

Figure 15: The off momentum β-beat along the LHC for the ‘Compact Low Gradient’ solution with corrected first and second order chromaticity terms.

Matching the dispersion for the L^* = 23m layout option of the ‘Compact Low Gradient’ system no longer requires an independent powering of the 2 Q2 magnet modules making the powering of the final focus system much simpler. However, the experience with the matching for L^* = 19.45 in [6] indicates that the low gradient final focus system becomes more flexible if a fourth magnetic unit is added to the standard triplet layout. Such a final focus system with four independent magnet parameters offers 4 parameters for the adjustment of the peak β-functions inside and the slopes of the β-functions at the exit of the final focus system. We will come back to this point in the following case study.

Figure 10 shows the square root of the corresponding β-functions of the matched solution for Beam1 over the full IR5. Figure 11 shows the same optics over the right hand side of the final focus system. The total chromatic aberration integral in Equation (3) becomes I_z = 1035 and the first and second order chromatic aberrations can still be corrected using the existing sextupole circuits of the LHC if the phase advance between IP1 and IP5 is adjusted for a minimization of the second order chromaticity [10]. In this study the phase advance between IP1 and IP5 was adjusted using the QF and QD arc circuits and re-matching the insertions optics for all IRs to the arcs. Figure 12 shows the tune variation as a function of the particle momentum for the corrected lattice (first order corrected to Q’= 2 and the second order chromaticities corrected to zero) and Figure 13 shows the required corrector strength. While a correction is still possible for the *‘Compact Low Gradient’* one clearly recognizes that it is at the limit of the available sextupole corrector strength and the correction requires an adjustment of the phase advance between IP1 and IP5 for a correction of the second order chromaticity. Figure 14 shows the tune variation as a function of the particle momentum for the corrected nominal LHC collision optics for comparison [9].

The nominal RMS momentum spread in the LHC bunches is $\sigma(\Delta p/p) = 0.113\ 10^{-3}$ [9]. Assuming a peak momentum offset of 3 σ and applying an additional shift of $0.5\ 10^{-3}$ for chromaticity measurements yields a maximum offset at collision of $(\Delta p/p)_{max} = 0.84\ 10^{-3}$.

Figure 15 shows the resulting off momentum β-beat along the LHC for $(\Delta p/p) = 0.3\ 10^{-3}$ (3 σ) IP1 is at the far left of the figure and IP5 in the middle.

The case study of a '*Compact Low Gradient Final Focus System*' demonstrated the following main points:

- It illustrated the feasibility of an LHC IR upgrade based on Nb-Ti magnet technology that is compatible with $\beta^* = 0.25$m.
- It illustrated that a compact Nb-Ti upgrade can be installed within the given space without changing the magnet positions of the matching section quadrupole magnets and with the use of existing magnet technology for the separation – recombination dipole magnets.
- It illustrated that a low gradient final focus design could provide significant aperture margins even if one assumes rather conservative values for the maximum acceptable peak field inside the quadrupole coils (23σ aperture margin for a peak coil field of 6.5T for $\beta^* = 0.25$m).
- It illustrated that the first and second order chromaticity terms can still be corrected with the existing nominal sextupole circuits in the LHC.
- It illustrated the feasibility of a low gradient Nb-Ti upgrade with a simple powering scheme.

The main drawbacks of the '*Compact Low Gradient Final Focus System*' study are:

- It requires two specialized cross sections for each final focus unit and therefore implies an expensive R&D and spare part policy. On the other hand the system is compatible with a single cross section at the cost of a smaller aperture margin.
- It requires two different gradients and therefore independent powering of each final focus module implying an expensive power converter installation and small tolerances against power converter ripple.
- It requires three different magnet lengths for the final focus magnets and therefore partially spoils a simple spare part policy as proposed for the '*Modular Low Gradient Final Focus System*'.
- It presents large aberrations which might not be compatible with a realistic field quality.

Open issues for future studies for the '*Compact Low Gradient Final Focus System*' studies include:

- One needs to specify the detailed magnetic field quality tolerances and the required corrector packages for the final focus assembly.
- One still needs to calculate the heat and radiation deposition inside the final focus magnets and evaluate means for protecting the final focus magnets (e.g. dedicated absorber masks and inserts) and cooling needs (e.g. can the heat be extracted from the final focus magnets?).
- One still needs to evaluate from the beam dynamics point of view the maximum acceptable chromatic aberrations.

3.2 Modular Low Gradient Final Focus System

Next we look at a ‘Modular Low Gradient’ final focus system with L^* = 23m. Based on the experience with the ‘Compact Low Gradient Final Focus System’ in [6] we introduce a fourth magnet unit in the final focus system in order to facilitate optics matching to the arc. The schematic layout is illustrated in Figure 16.

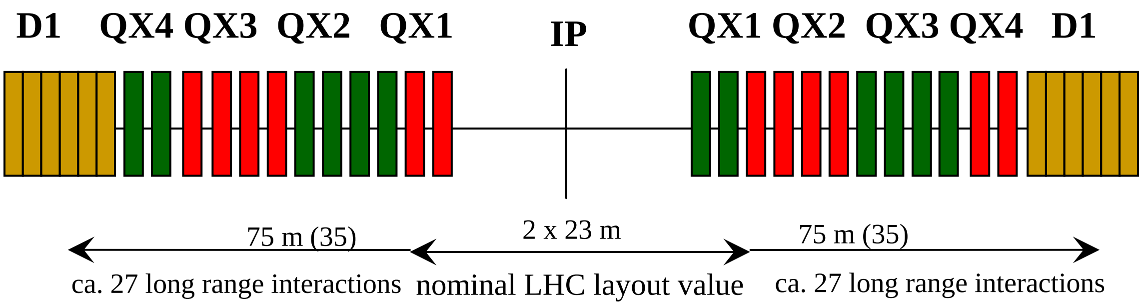

Figure 16: Schematic layout of a ‘*Modular Low Gradient’* final focus system.

Compared to the L* = 19.45m solution in [6] we introduced an additional magnet module in the QX3 unit and changed the magnet module length from 5.5m to 4.8m. Figure 17 shows the Beam1 optics solution over the full IR and Figure 18 over the right hand side of the final focus system. (The impact of the double β-function peak inside the final focus system due to the fourth quadrupole unit on the crossing angle generation still needs to be evaluated in more detail in a future study.) The optics solution in Figure 17 requires a peak gradient of 88.5 T/m in QX2 (116 T/m in QX1) and features a peak β-function of approximately 14.4km for β^* = 0.25m which yields an RMS beam size of 2.69mm for the nominal emittance value of the LHC. Using Equation (1) this implies a required minimum magnet aperture of 100mm. Providing a 10mm increase in the required aperture for the beam-screen and cold bore installation this implies a minimum inner coil diameter of 110mm. Assuming an acceptable peak field in the magnet coils of 9T (the peak field in the coils of the nominal LHC triplet quadrupole magnets is 8.6T for the KEK built magnets [9]) and maintaining a 10% operation margin the required magnet gradients could allow magnet apertures of up to 183mm diameter for the QX2, QX3 and QX4 magnet modules. Assuming a more conservative peak field of 6.5T in the magnet coils (the peak field of the LHC insertion quadrupole magnets is just above 6T [9]) the required magnet gradients would still allow a magnet aperture of up to 146mm which still provides an aperture margin of 13σ for β^* = 0.25m. The solution is based on 4.8m long identical magnet modules spaced by a separation of 1m for the magnet interconnections and the installation of eventual corrector magnets and / or absorber masks. The solution in Figure 17 requires the following number of magnet modules and gradients:

- QX1: 2 modules of 4.8m length (total length of 11.6m) with a gradient of 116 T/m, minimum coil aperture of 82mm.
- QX2: 4 modules of 4.8m length (total length of 23.2m) with a gradient of 88.5 T/m, minimum coil aperture of 110mm.
- QX3: 4 modules of 4.8m length (total length of 23.2m) with a gradient of 82 T/m, minimum coil aperture of 110mm.
- QX3: 2 modules of 4.8m length (total length of 11.6m) with a gradient of 84 T/m, minimum coil aperture of 110mm.

The total final focus length therefore increases from the nominal 30.67m to approximately 70m.The required minimum coil aperture of 110mm and gradient of 88.5T/m is well inside the range of the Nb-Ti magnet technology indicated in Figure 3. Increasing the overall length of the final focus system implies a reduction of the D1 – D2 separation by approximately 40m leaving a maximum space of 65m for the D1 – D2 separation (the available space in the nominal LHC IR layout is 103.4m [9]). Placing the D1-D2 magnets at the extremities of the available space between the final focus system and Q4 still leaves enough space for a separation-recombination scheme that does not require a change of the Q4 magnet position and is still compatible with a warm, 1.3T strong D1 and a cold, 4T strong D2 magnet design. However, the D1 and D2 magnets fill in this case the entire available space between the final focus system and the Q4 magnet.

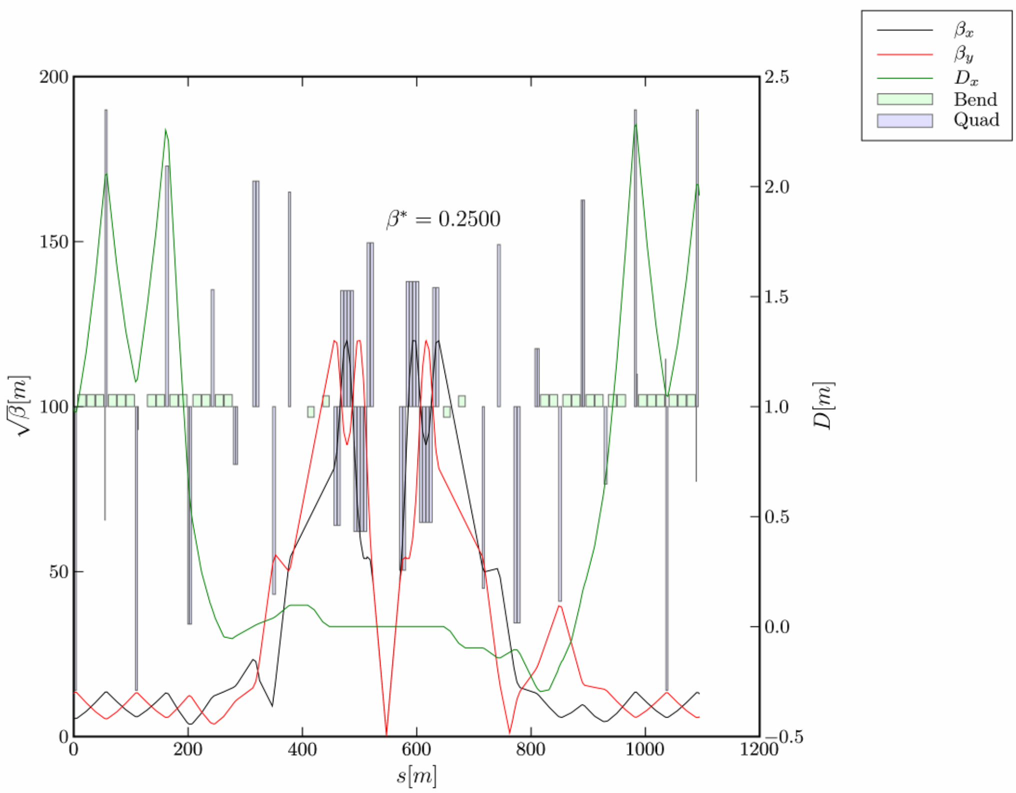

Figure 17: The Beam1 horizontal dispersion and the square root of the β-functions of the matched solution over the full IR5 for the ‘*Modular Low Gradient*’ final focus system.

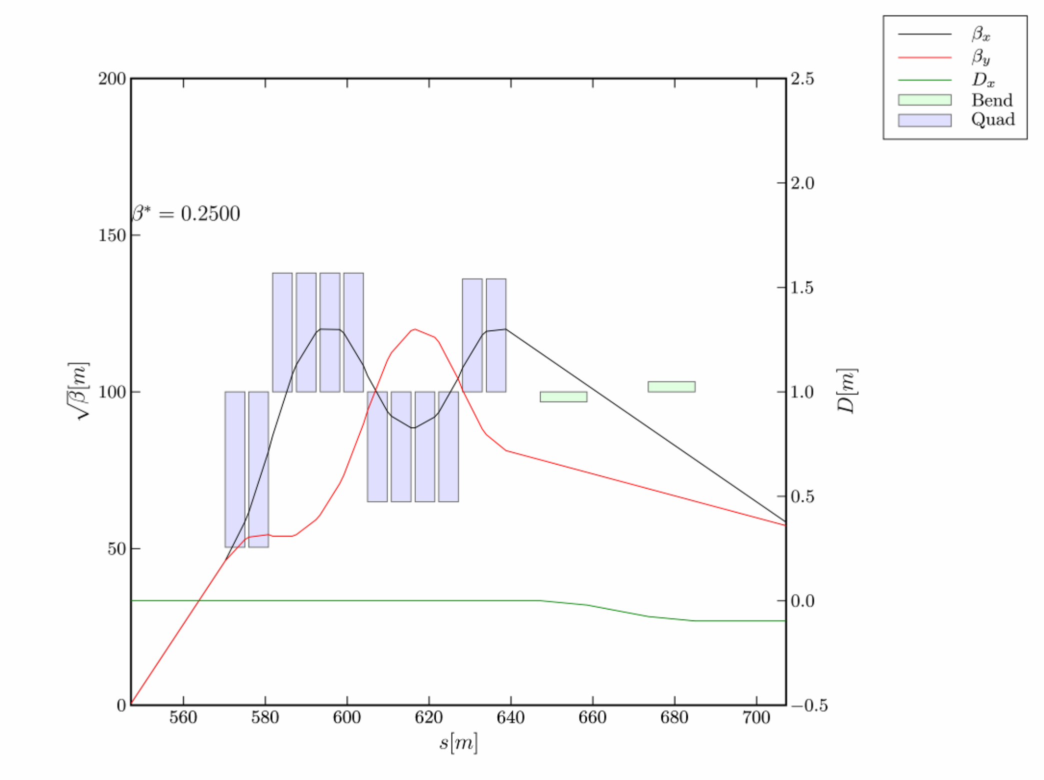

Figure 18: The Beam1 horizontal dispersion and the square root of the β-functions of the matched solution over the right hand side of the final focus system for the '*Modular Low Gradient'* final focus system.

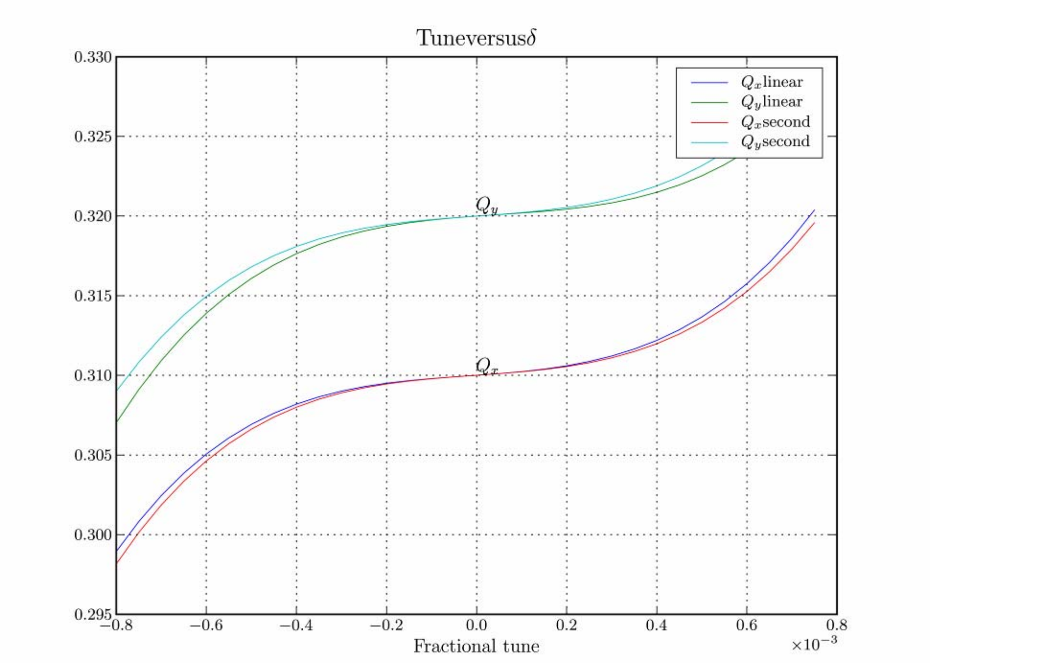

Figure 19: The tune variation for the '*Modular Low Gradient'* solution with corrected first and second order chromaticity terms.

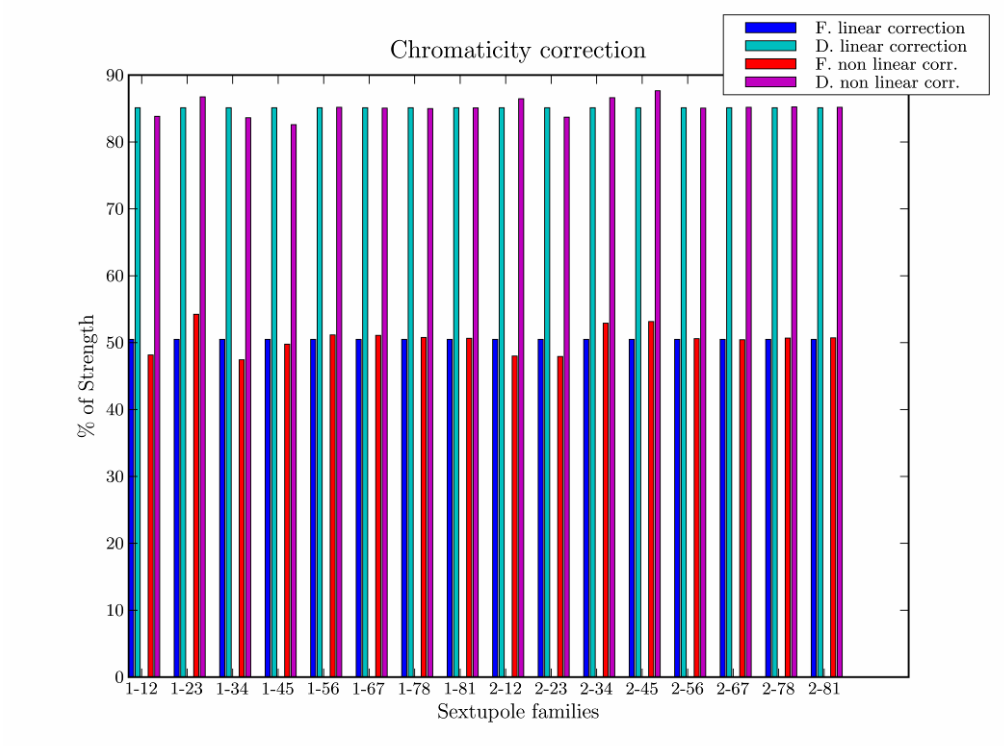

Figure 20: The required sextupole corrector strength in the lattice sextupole circuits for a correction of the first and second order chromaticity terms. While a correction is still possible for the '*Modular Low Gradient'* one clearly recognizes that it is at the limit of the available sextupole corrector strength.

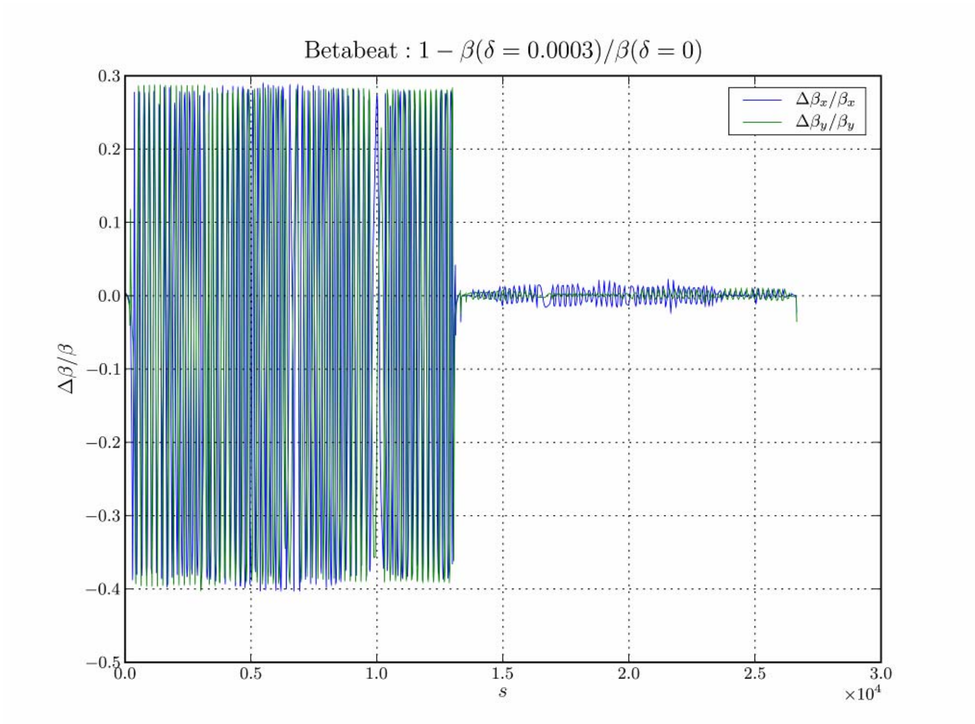

Figure 21: The off momentum β-beat along the LHC for the '*Modular Low Gradient*' solution with corrected first and second order chromaticity terms. The β-beat is comparable to that of the *'Compact Low Gradient'* solution.

Figure 17 shows the horizontal Beam1 dispersion function and the square root of the β-functions of the matched solution over the full IR. The total chromatic aberration integral in Equation (3) becomes I_z = 1010 for this solution. Figure 19 shows the tune variation as a function of the particle momentum for the corrected lattice (first order corrected to Q' = 2 and second order chromaticities corrected to zero) and Figure 20 shows the required corrector strength. While a correction is still possible for the '*Modular Low Gradient*' one clearly recognizes that it is at the limit of the available sextupole corrector strength and the correction requires an adjustment of the phase advance between IP1 and IP5 for a correction of the second order chromaticity. Figure 21 shows the corresponding off momentum β-beat along the LHC starting with IP1 one the left. The off momentum β-beat and the peak β-functions are comparable with the values of the '*Compact Low Gradient'* final focus.

The case study of a '*Modular Low Gradient'* final focus system demonstrated the following main points:

- It illustrated the feasibility of a modular LHC IR upgrade based on Nb-Ti magnet technology that is compatible with $\beta^* = 0.25$m.
- It illustrated that a modular Nb-Ti upgrade can be installed within the given space without changing the magnet positions of the matching section quadrupole magnets and with the use of existing magnet technology for the separation – recombination dipole magnets.
- It illustrated that a modular low gradient final focus design could still provide significant aperture margins even if one assumes rather conservative values for the maximum acceptable peak field inside the quadrupole coils (13σ margin for a peak coil field of 6.5T for $\beta^* = 0.25$m).
- It illustrated that a Nb-Ti upgrade with only two types of magnet of the same length (only one type if one is willing to accept a smaller aperture margin or an additional magnet module [6]) is feasible and thus provides a case study with a potentially simple magnet production and spare part policy.
- It offers a large number of potential installation slots for corrector magnets and absorber masks.

The main drawbacks of the '*Compact Low Gradient'* final focus system are:

- It offers smaller aperture margins as compared to the '*Compact Low gradient'* final focus system.
- It requires four different gradients and therefore independent powering of each final focus module implying an expensive power converter installation and small tolerances against power converter ripple.

Open issues for future studies for the '*Compact Low Gradient'* final focus system studies include:

- One needs to specify the magnetic field quality tolerances and the required corrector packages for the final focus assembly.
- One still needs to calculate the heat and radiation deposition inside the final focus magnets and evaluate means for protecting the final focus magnets (e.g. dedicated absorber masks and inserts) and cooling needs (e.g. can the heat be extracted from the final focus magnets?).
- One still needs to evaluate from the beam dynamics point of view the maximum acceptable Chromatic aberrations.

3.3 *Small β-max Low Gradient Final Focus System*

Next we look at a '*Small β-max Low Gradient*' final focus system with L^* = 24m. The L^* value is slightly larger as compared to the nominal LHC layout in order to provide space for additional shielding following the TAS absorber. The basic layout is given in Figure 22 and corresponds to a basic triplet layout with three distinct magnet units. The layout uses two different magnet types: one for the QX1 unit and a second type for the QX2 and QX3 triplet units. The magnet blocks for the QX2 and QX3 units share the same aperture and operation gradient but require slightly different magnet lengths. Compared to the previous two cases the '*Small β-max Low Gradient*' system uses slightly increased quadrupole gradients and has therefore a slightly lower maximum aperture potential. On the other hand it generates also slightly lower peak β-functions and provides a simple powering scheme where the magnets with peak β-function values, QX2 and QX3, are powered in series by a single power supply. Such a powering scheme will partially compensate any modulation in the beam focusing due to power converter ripple and therefore reduce the constraints on the power converter system in terms of current stability.

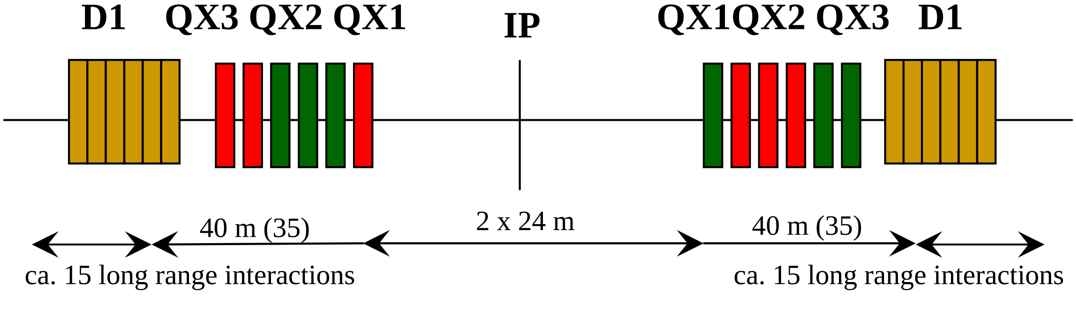

Figure 22: Schematic layout of a '*Small β-max Low Gradient'* final focus system.

Figure 23 shows the Beam1 optics solution over the full IR and Figure 24 over the right hand side of the final focus system. The optics solutions in Figure 23 and 24 feature a maximum gradient of 122 T/m in the QX2 and QX3 units (168 T/m in the MQX1 unit) and a peak β-function of approximately 12.2km for $\beta^* = 0.25$m which yields an RMS beam size of 2.47mm for the nominal emittance value of the LHC. Using Equation (1) this implies a required minimum magnet aperture of approximately 95mm. Providing a 10mm increase in the required aperture for the beam-screen and cold bore installation this implies a minimum inner coil diameter of 105mm. Assuming an acceptable peak field in the magnet coils of 9T (the peak field in the coils of the nominal LHC triplet quadrupole magnets is 8.6T for the KEK built magnets [9]) and maintaining a 10% operation margin the required magnet gradients could allow magnet apertures of up to 133mm diameter. Assuming a more conservative peak field of 6.5T in the magnet coils (the peak field of the LHC insertion quadrupole magnets is just above 6T [9]) the required magnet gradients would still allow a magnet aperture of up to 106mm which is feasible for the '*Small β-max Low Gradient*' layout but no longer provides an additional aperture margin for $\beta^* = 0.25$m. The solution in Figure 17 requires the following number of magnet modules and gradients:

- QX1: 1 module of 7.5m length with a gradient of 168 T/m, minimum coil aperture of 76mm.
- QX2: 3 modules of 5.75m length (total length of 19.25m) with a gradient of 122 T/m, minimum coil aperture of 105mm.
- QX3: 3 modules of 4.9m length (total length of 11m) with a gradient of 122 T/m, minimum coil aperture of 105mm.

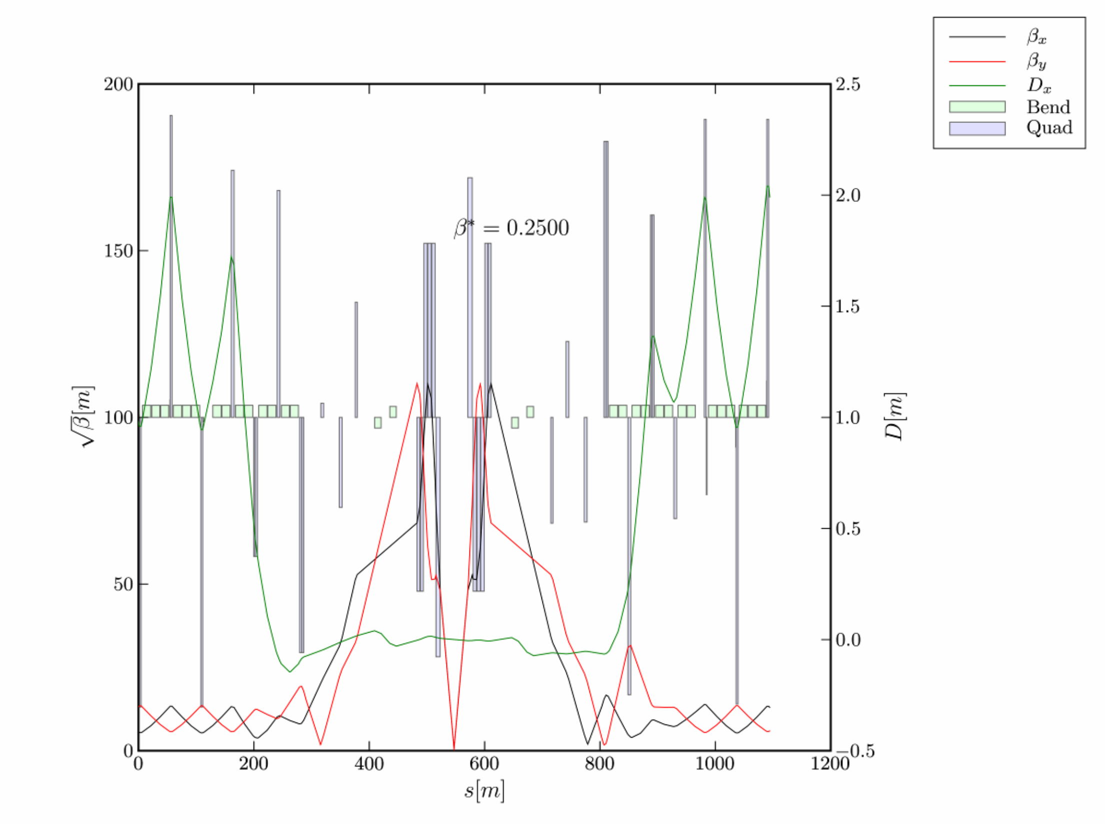

Figure 23: Beam1 optics solutions for the '*Small β-max Low Gradient*' final focus system over the full IR.

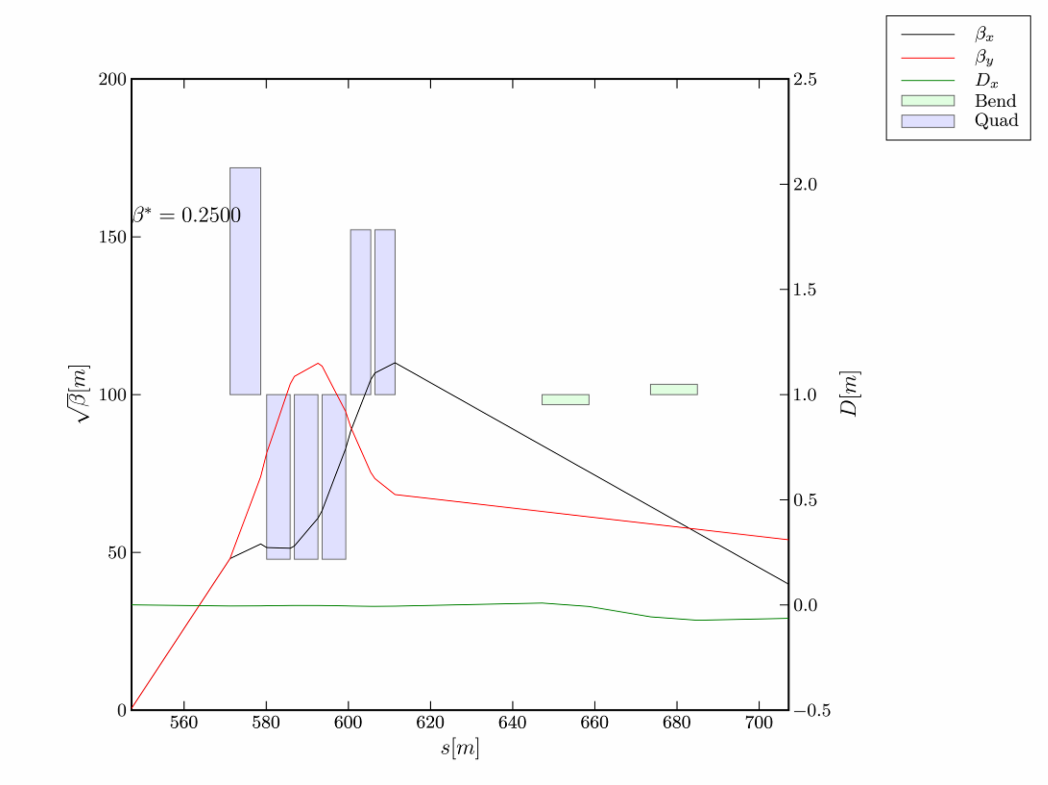

Figure 24: Beam1 optics solutions for the '*Small β-max Low Gradient*' final focus system over the right hand side of the final focus system.

The total final focus length increases from the nominal 30.67m to 39.75m.The required minimum coil aperture of 105mm and gradient of 122T/m is still inside the range of the Nb-Ti magnet technology indicated in Figure 3 but requires a slightly larger peak field in at the coil (B = 6.4T) as compared to the '*Compact Low Gradient*' and the '*Modular Low Gradient*' solutions. Increasing the overall length of the final focus system implies a reduction of the D1 – D2 separation by approximately 10m leaving still sufficient space for the D1 and D2 installation.

The total chromatic aberration integral in Equation (3) becomes $I_z = 827$ for this solution which corresponds approximately to the value of the compact Nb_3Sn reference layout with $\beta^* = 0.25$m [10] and the first and second order chromatic aberrations can therefore be corrected using the existing LHC sextupole lattice and spool piece circuits. Figure 25 shows the tune variation versus particle momentum for the corrected machine and Figure 26 the required sextupole corrector strength in the lattice sextupole circuits in percent of their nominal strength. One clearly recognizes that the chromatic aberrations of the '*Small β-max Low Gradient*' solution are smaller than the aberrations of the '*Compact Low Gradient*' and the '*Modular Low Gradient*' solutions and therefore still leave margins for the lattice corrector circuit settings. Figure 27 shows the resulting off-momentum β-beat between IP1 and IP5. With a peak perturbation of 22% at $\delta p/p = 3\ 10^{-4}$ the off-momentum β-beat is approximately 30% smaller compared to the case of the '*Compact Low Gradient*' solution in Figure 15.

The case study of a '*Small β-max Low Gradient*' final focus system demonstrated the following main points:

- It illustrated the feasibility of a modular Nb-Ti upgrade with a simple powering scheme.

- It illustrated the feasibility of a modular Nb-Ti upgrade with chromatic aberrations comparable to those of a compact Nb_3Sn triplet layout.

The main drawbacks of the '*Compact Low Gradient' final* focus system are:

- It offers smaller aperture margins as compared to the '*Compact Low gradient'* final focus system and no aperture margins for a peak coil field of 6.5 T.
- It requires 3 different magnet lengths and two different cross section for the final focus magnets and therefore partially spoils the simple spare part policy of the '*Modular Low Gradient'* final focus system.

Open issues for future studies for the '*Small β-max Low Gradient'* final focus system studies include:

- One needs to specify the magnetic field quality tolerances and the required corrector packages for the final focus assembly.
- One still needs to calculate the heat and radiation deposition inside the final focus magnets and evaluate means for protecting the final focus magnets (e.g. dedicated absorber masks and inserts) and cooling needs (e.g. can the heat be extracted from the final focus magnets?).

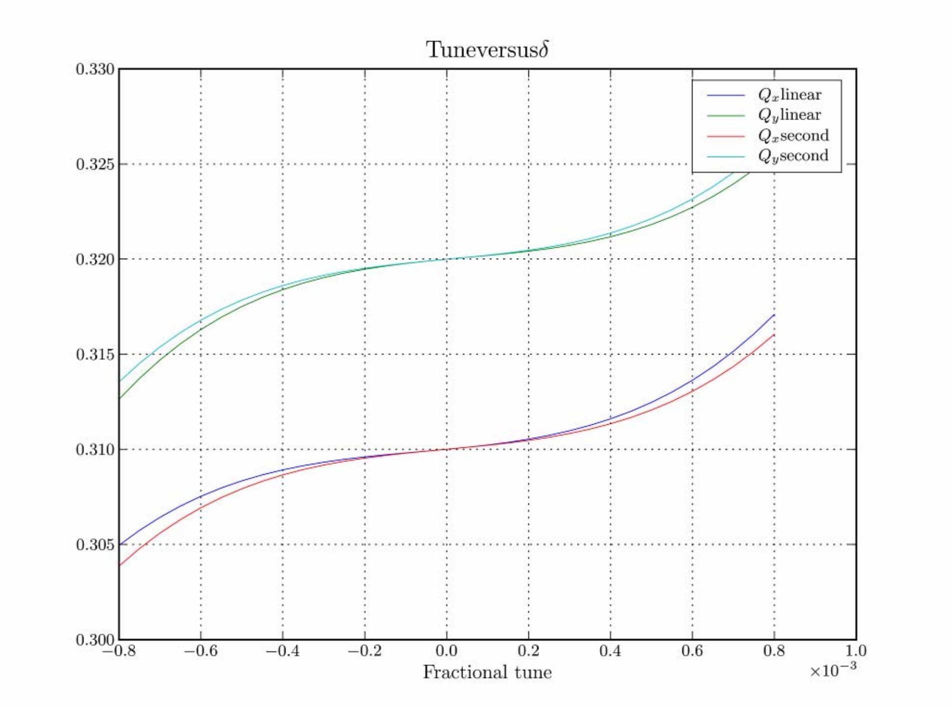

Figure 25: The tune variation for the *'Small β-max Low Gradient'* solution with corrected first and second order chromaticity terms.

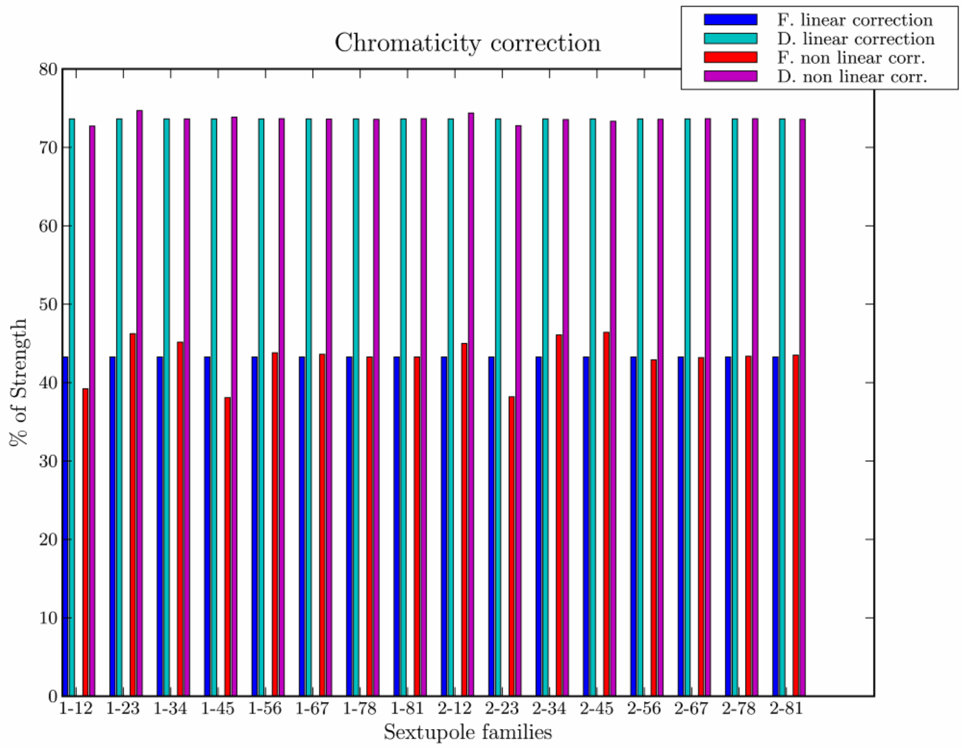

Figure 26: The required sextupole corrector strength in the lattice sextupole circuits in percent of their nominal strength for a correction of the first and second order chromaticity terms for the *'Small β-max Low Gradient'* solution.

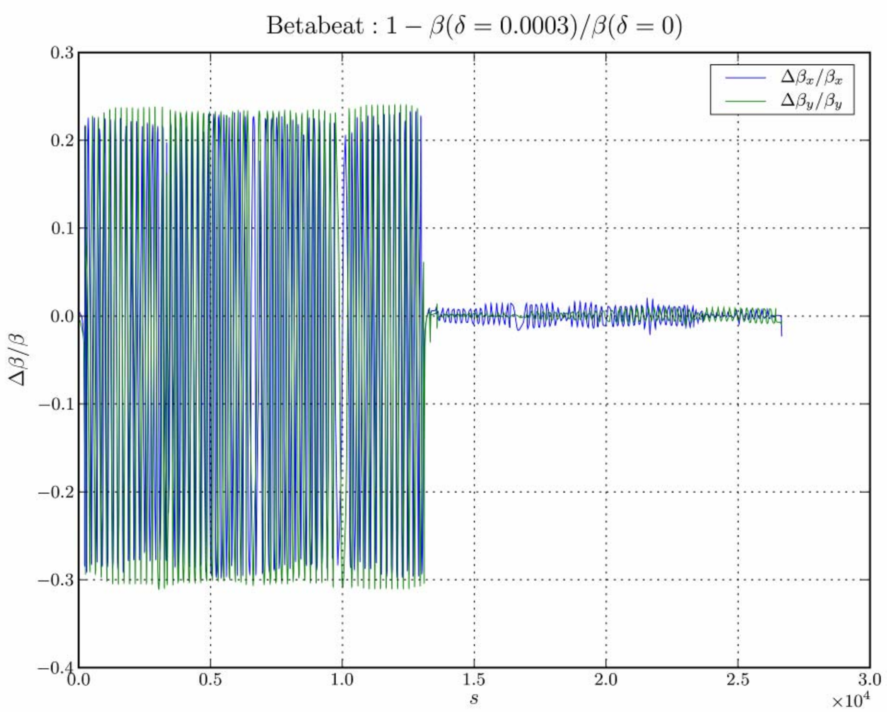

Figure 27: The off momentum β-beat along the LHC for the *'Small β-max Low Gradient'* solution with corrected first and second order chromaticity terms.

4 Summary

All case discussed in this paper assume a simplified separation for the individual magnet modules. For a first discussion we assumed a 1m separation between all magnet modules that should be sufficient for the installation of either dedicated corrector magnet packages or dedicated collimators for protection of the magnets. A more realistic inter module spacing depends on simulation studies for the expected loss patterns due to debris leaving the IP and the required corrector magnet packages and strength. Heat deposition simulations and studies on the feasibility of extracting the deposited heat from the magnet cryostats and more detailed simulation studies on the dynamic aperture with field errors and dedicated corrector packages should therefore take a high priority for the next studies. The first two case studies require an upgrade of the Q6 MQM module (e.g. installation of a second MQM module) in addition to the new final focus magnets. However, while the additional Q6 strength provides more flexibility of the optics, this requirement might be resolved by further optics study. All cases require new separation and recombination dipoles and a modification of the existing TAS absorber (change in the RMS beam size and beam separation inside the TAS and change in the cold bore aperture of the final focus magnets). The aperture margins are estimated using a conservative peak field of 6.5T. Recent results [15] show that it can be assumed larger for large aperture quadrupole magnets allowing larger aperture margins for all the presented options. Table 1 compares key performance indicators for the three Nb-Ti cases.

The '*Compact Low Gradient*' layout solution offers substantial aperture margins that could be used either for increasing the beam-beam separations in the common beam pipes, for installing dedicated absorber materials and thus reducing the heat and radiation deposition inside the magnet coils, increased collimator jaw openings (and thus a reduced impedance) or a further reduction of the β^* value. It features identical gradients inside the magnets with the larger β-function values and offers therefore a simple and robust powering scheme. It also offers a semi modular layout with only two magnet types but one type requiring different magnet lengths for each final focus element. The main draw back of this layout is the need for special magnet module length for each final focus element and therefore a slightly more cumbersome magnet production and a more demanding spare magnet policy as compared to the other case studies.

The '*Modular Low Gradient*' layout solution emphasizes the benefits of a simplified magnet production and spare part policy. The proposed IR layout features only one magnet type (different magnet gradients but identical apertures and magnet module lengths). The price to pay for this simplification is a slightly larger peak β-function and therefore slightly larger chromatic aberrations and reduced aperture margins.

The '*Small β-max Low Gradient*' final focus system aims to minimize of the peak β-functions in the final focus system and thus to reduce the chromatic aberrations. This solution offers a simple powering layout of the final focus magnets and thus an internal partial compensation of the tune modulation due to power converter ripple. Like the 'Compact Low Gradient' layout it features a semi-modular final focus system with only two magnet types. The main draw back of this layout is a reduced aperture margin and the need for special magnet module lengths for each final focus element and therefore a slightly more cumbersome magnet production and a more demanding spare magnet policy as compared to the modular layout and reduced aperture margins as compared to the other case studies. The presented solution offers therefore no aperture margins and implies a peak field at the coil of slightly more than 6 T.

In order to choose the best design criteria for an LHC IR upgrade one needs to identify next:

- Hard limits for the maximum peak β-functions (field error tolerances and required corrector packages require detailed dynamic aperture simulations).
- Identification of the maximum acceptable chromatic aberration (off momentum β-beat and experimental background conditions and impact on the LH collimation system).
- Identification of locations for dedicated absorber masks inside the final focus magnets (requires simulation studies for the location of the highest radiation levels due to debris leaving the IP).
- Identification of the required aperture margins for installing internal absorber materials inside the magnets and coping with the heat deposition (cooling capacity and efficiency of heat extraction).
- Identification of the feasible maximum peak field inside the magnet coils for the Phase 1 upgrade (this determines the maximum potential aperture reach for each design study).

	Min required Aperture QX1 & QX2, QX3, QX4	Maxim Aperture for 6.5T peak field at coil for QX1 and QX2 gradients	Aperture margin in σ in addition to the minimum aperture requirement in Equation (1) assuming the QX2 gradients	Maximum Gradient (Q1 and Q2 / Q3)	Total final focus length	β_{max} and RMS beam size for $\beta^* = 0.25$m	Chromatic aberrations measured by $I_z = I_{zL}+I_{zR}$	Powering	complexity
Compact	86mm & 120mm	142mm & 190mm	23 σ	91.5 T/m & 68.3 T/m	60m	16km 2.94mm	1035	Partial serial: 2 PC units per IP side	Medium: two or one magnet design but one with 3 lengths variations
Modular	82mm & 110mm	112mm & 146mm	13 σ	116 T/m & 88.5 T/m	70m	14.4km 2.68mm	1010	Individual 4 PC units per IP side.	Simple: two or one magnet design for all final focus modules + additional Q6 module (MQM)
Small β-max	77mm	77mm	0 σ	168 T/m	39.75m	12.2km 2.47mm	827	Partial serial: 2	Medium: two

	& 105mm	& 106mm		& 122 T/m				PC units per IP side	magnet designs but one with 2 lengths variations; no additional Q6 module required

Table1: Comparison of key performance indicators for the three Nb-Ti case studies. The 'Compact' solution clearly maximises the aperture margins. All studied Nb-Ti cases have at most 30% higher Chromatic aberration for $\beta^* = 0.25$ when compared to the most compact Nb_3Sn solution ($I_z = 700$ for $\beta^* = 0.25$ [10]). The values for the Chromatic aberrations refer to the sum of the integral in Equation (1) over the left and right triplet sides.

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