Phase 1 Optics: Merits and Challenges *

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Abstract

Low gradient optics have been proposed for an upgrade of the LHC interaction region. Using lower gradient, larger aperture and longer NbTi quadrupoles with respect to the nominal layout, it is possible to achieve $\beta = 25\,\mathrm{cm}$ with additional aperture margins and better dynamic aperture. The main drawbacks are an increase of the number of the long range interactions and limitations in the downstream matching section. Four layouts and optics, which span the parameter space and modularity for NbTi technology, are proposed and studied extensively in order identify and quantify the merits and challenges.

INTRODUCTION

Phase I upgrade aims at reducing β^* from $55\,\mathrm{cm}$ to $25\,\mathrm{cm}$ while keeping as small as possible changes in the LHC interaction region layout. The new layout should also:

- limit the beam size in the focusing system for reducing chromatic aberrations and errors sensitivities,
- maximize the aperture margins in the focusing system for reducing the heat load, radiation damage and increasing operational margins
- make the final focusing system as short as possible for reducing the number of long range beam beam interaction, reducing the field of D1/D2 and reducing overall the cost.

The nominal LHC layout cannot fulfill the Phase 1 targets because the triplet magnets have aperture limitations.

A study has been performed to identify the possibilities for a replacement of the nominal triplet (see [1]). Four different layouts has been proposed (see [2] and [3]) in order to explore the parameter space and identify the benefits and limitations of several design criteria.

TRIPLET OPTIMIZATION

A simplified model has been used to study the parameter space of final focus system.

The model consists piecewise constant gradient point to parallel focusing systems (see Fig. 1). Using this model it is possible to reduce the parameter space to three quantities: the normalized gradient k, the distance of the first quadrupole from the IP (L^*) and the beta function at the IP (β^*). Using the fact that the phase advance in the triplet is negligible, it is possible to find the parameters of all possible piecewise constant gradient point to parallel focusing systems with the help of a set of univariate numerical functions (see Fig. 2). For more details refer to [1].

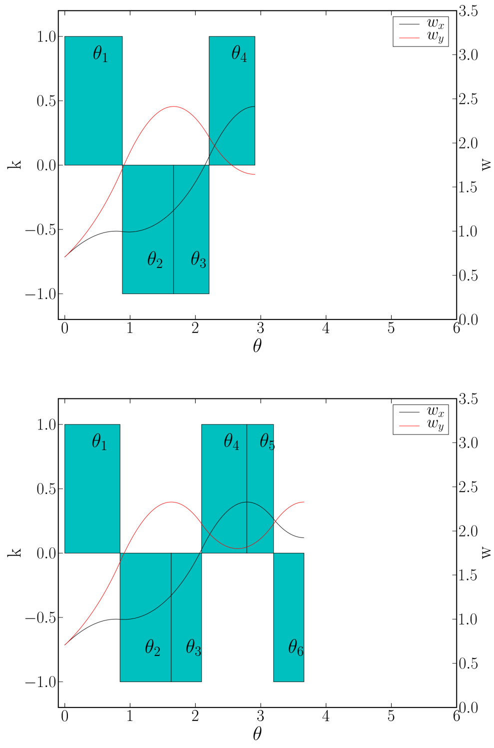

Figure 1: Point to parallel triplet and quadruplet focusing system.

Using these functions, it is possible to plot the maximum beam size of the beam in the triplet as a function of the gradient using the simplified models. This function divides the plane in a region where the focusing systems that have a negative focal length (above the black line in Fig. 3) and the one having positive focal length.

In the same plot it is possible to draw the region of the parameters of the quadrupoles compatible with NbTi (red region) using the peak field of $8\,\mathrm{T}$ and the edge of the beam region diameter a defined by $a = 33\sigma + 22\,\mathrm{mm}$.

Figure 3 shows that, when the gradient decrease, the aperture required by the beam increase slower than the aperture compatible with a given peak field. It implies that smaller is the gradient, larger will be the aperture margins. The clear advantage of low gradient quadrupole magnets is limited by the fact that the quadrupoles needs to be longer, the beta functions become larger and the chromatic aberrations increase. Another disadvantage is that the number of long range interaction increases as well.

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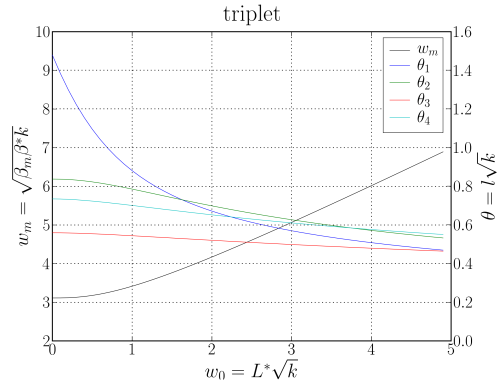

Figure 2: Parameters for all constant gradient point to parallel triplet focusing system.

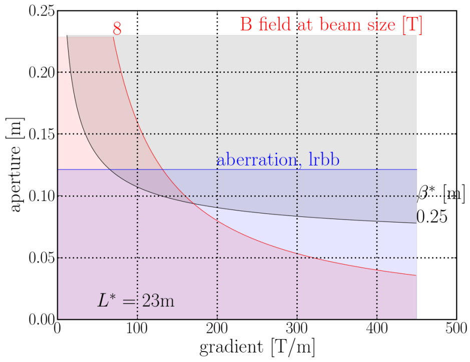

Figure 3: Triplet parameters space for the LHC upgrade.

The simplified model gives an indication of the parameters of possible focusing systems, however a realistic implementation is necessary to test the hypothesis and identify further limitations.

REALISTIC IMPLEMENTATIONS

In order to design a realistic focusing system, once the gradient is fixed, is necessary to introduce gaps between the quadrupoles in order to make room for coil ends that do not contribute to the field and interconnections. Additional room can be reserved for corrector packages.

The optimal quadrupole lengths are in general different for the every unit, one has to trade the aperture margins and the overall lengths with the possibility of using equal sized modules that reduce the cost of the equipment in terms of R&D and spare policy. It is worth noting that the first quadrupole unit requires always a smaller aperture, therefore it is possible to use a stronger quadrupole with the same peak field of the other units which translates in a gain in overall length and beta peak. Also in this case it is possible to trade this optimization with the cost of the equipment. In addition the larger aperture margins of the first unit can be used to install thick shielding tubes for protecting the coil from the debris coming from the IP that presumably will be higher for the first elements.

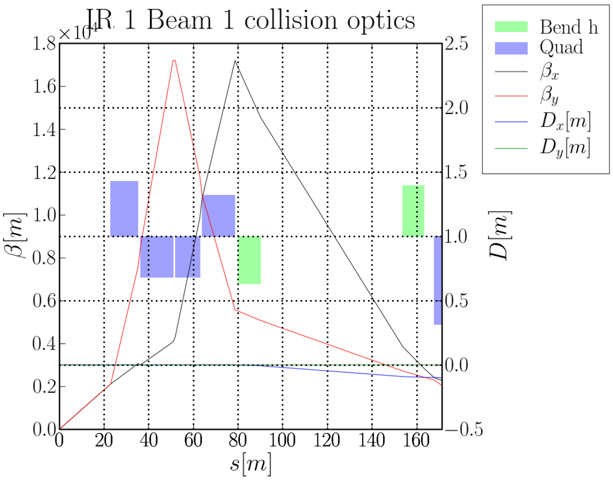

Figure 4: Upgraded IR layout: "Compact" (see [3]) .

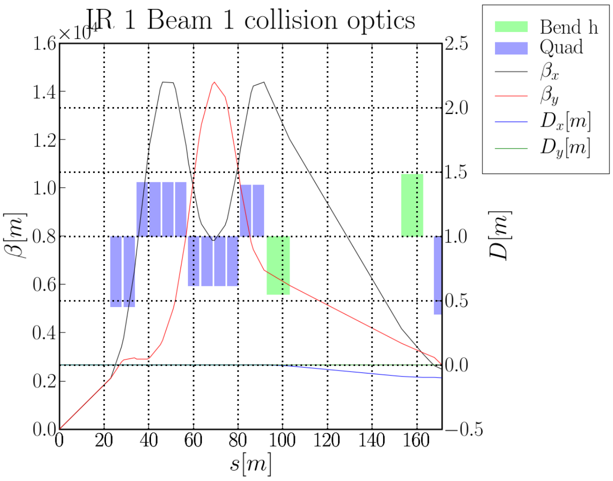

Figure 5: Upgraded IR layout: "Modular" (see [3]) .

Four different layouts (see Fig. 4, 5, 6, 7) were designed and studied using different gradients and modularity.

These options were extensivily studied and further infomartion will be available in [4].

Compact

This option (see Fig. 4,) uses a triplet layout and the lowest possible gradient compatible with tolerable aberrations. The overall length is minimized (the name comes from there) using an optimized gradient for Q1 and optimized lengths for Q1, Q2 and Q3. The gap between the quadrupoles is $1\,\mathrm{m}$ for the interconnection (a recent study REF established that the minimum distance between quadrupoles in two different cryostats is $1.3\,\mathrm{m}$ but smaller in case they are in the same cryostats). In order to find a

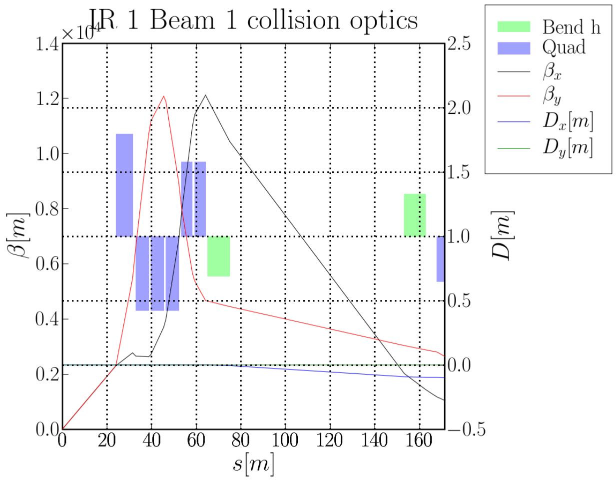

Figure 6: Upgraded IR layout: "Lowbetamax" (see [3]) .

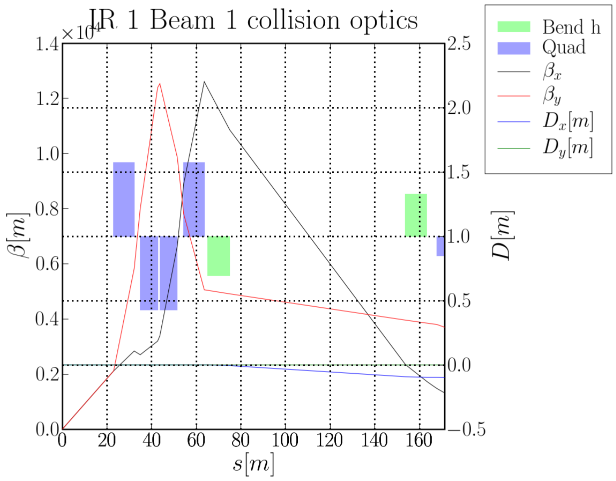

Figure 7: Upgraded IR layout: "Symmetric" (see [2]) .

suitable collision optics an additional Q6 module has been installed. This layout has been proposed in [3].

Modular

This option (see Fig. 5,) uses a quadruplet design with an intermediate gradient. All the modules have the same length (the name comes from there) but the first two have a larger gradient implying or a reduced aperture for the first two modules or reduced aperture margins in the other modules. The gap between the quadrupoles is 1 m. An advantage of this option is the large set of gaps that can be used for mask absorbers or corrector magnets. In order to find a suitable collision optics an additional Q6 module has been installed. This layout has been proposed in [3].

Lowbetamax

This option (see Fig. 6,) uses a triplet layout and the highest gradient compatible with some additional aperture margin in the triplet. The first element uses a reduced aperture and modules of three different lengths. These choices limits the peak of the beta function in the triplet (the name comes from there). No additional quadrupole modules are installed. This layout has been proposed in [3].

Symmetric

This option (see Fig. 6,) uses a triplet layout and the highest gradient compatible with some additional aperture margin in the triplet. This option uses only two different modules of different length but same aperture and gradient. The modules are arranged almost symmetrically with respect to the center of the triplet assembly (the name comes from there). The gaps are the same w.r.t the nominal layout. The triplet layout first presented in [2].

All these options do not cover all the possibilities and should be considered working hypothesis for identifying merits and limitations for the several options in terms of gradient and modularity.

Layout parameter

The layout data can be summarized in Table 1:

For these layouts collision optics with crossing schemes for the entire LHC has been developed.

APERTURE BOTTLENECKS

The quantity n_1 (see [7]) has been used for evaluating the aperture margins in the interaction region. The aperture model is indicated for the new elements in Table 1. For the rest of the elements the aperture model is the same as the one of the official LHC optics V6.501 with few exceptions for D2 Q4 and Q5. The aperture of these elements has been optimized for the injection optics with a particular orientation of the beam screen. In case of the upgraded optics the beta functions and as a consequence the crossing scheme pose tighter constraints at collision. The beam screens are consequently rotated in the locations where it is possible to increase aperture margins.

The apertures are computed using closed orbit tolerances of 3 mm, energy spread of $\delta = 0.00086$ and nominal aperture tolerances. Additional informations are given in [6].

The results are summarized in Tab. 2.

CHROMATIC EFFECTS

The upgrade optics present stronger chromatic effects due the reduction of β^* which implies a stronger impact of quadrupole errors in the final focusing system.

Table 3 shows the values for the required strengths of the arc sextupoles for compensating the first order chromaticity and the off momentum beta beating for two different energy error.

	Compact	Modular	Lowbetamax	Symmetric
L* [m]	23	23	24	23
Gradient [T/m]	91,68	115,88,82,84	168,122	122
Module L [m]	12.2,14.6,11	4.8	7.4,5.7,4.9	9.2,7.8
Total L [m]	55	68	40	41
LRBB	23	26	19	19
Aper. MQX [mm]	170,220	130,170	90,130	130
B.S. MQX [mm]	74,79;99,104	54,59;99,104	34,39;54,59	54,59
B.S. D1 [mm]	50,64;45,64	50,64;45,64	50,64;45,64	50,64;45,64

Table 1: Layout parameters for different LHC interaction region layouts. The beam screen apertures are given in term of half gap and radius and for the MQX the two couple refers to the twos aperture. The quadrupole apertures were proposed in [5]. The D1 apertures were proposed in [6].

	Compact	Modular	Lowbetamax	Symmetric	LHC
MQX, ap 1	20.026	14.141	7.821	15.466	7.215
MQX, ap 2	16.953	12.633	8.830	8.438	6.845
D1	5.303	6.379	7.607	7.323	7.431
D2	5.372	4.271	7.959	6.518	15.152
Q4	7.387	6.432	8.685	7.184	15.615
Q5	4.701	3.859	10.425	7.028	16.871

Table 2: Aperture bottlenecks for the upgrade optics and the nominal LHC in terms of n_1

The results show that while the natural chromaticity is still correctable by the arc sextupoles, the off momentum beta beat increases by a factor of 3 to 5 with respect to the nominal values. It is not clear whether the rest of the LHC subsystems can cope with such a large beating or if this effect can be corrected while keeping acceptable flexibility in the machine.

Dynamic aperture

In collision the dynamics aperture (DA) is dominated by the non linear fields in the interaction region. The larger contribution to the reduction of DA is the "other" beam which should reduce the DA to 6σ. For additional informations refer to [8].

Another important contribution comes from the field imperfections in large beta area (i.e. triplets, D1, D2 and the first elements of the matching section). For the LHC it has been estimated that for preserving the DA to 6σ with beam beam, the minimum DA over 60 seeds without beam beam effect should be larger than 12σ (see [7]).

In case of the upgrade is important to design magnets with a field quality that preserves a DA of 12σ. Estimates for the field quality of new magnets can be found using the scaling laws presented in [2] and the present production.

Table 4 shows the results for the four upgrade optics and the LHC. Designs with larger aperture margins present larger DA when only triplets error are included. In case of aperture bottlenecks in the matching section, the field quality of those elements starts to be dominant. These two facts explain the large differences between the Compact and Modular design with respect to the Lowbetamax and Symmetric. The differences between the Symmetric and Lowbetamax, very similar in terms of field quality, could be explained by the averaging effect of a different number of modules and the uncertainty of the method (for additional information refer to [9]).

TRANSITION TO INJECTION

An optics with $\beta^* > 5\,\mathrm{m}$ is required at injection where the transverse beam size is a four time larger. A set of transition optics should be found in order change the IR configuration from injection to collision. The quadrupole settings should smoothly change and the transition optics should keep the phase advance in order ease the procedure and accommodate the restriction in the power supply.

For the LHC the set of transition optics is hard to find because of the limitations in the maximum current of the magnets and limitations of mechanical aperture in the LSS. Without one these two limitations is very straightforward to find a solution because the number of parameters are larger than the number of constraints. In case of limitations of aperture, which translates in limitations of the maximum beta in some location, and limitations of quadrupole strengths, which translate in limitations of tunability (roughly proportional to the product βk), the parameters are not truly independent and the solution may or may not exist.

A preliminary study show that is possible to keep the phase advance of the insertion for a large range of β^* only for Lowbetamax and Symmetric.

	Compact	Modular	Lowbetamax	Symmetric	LHC
Sextupoles [%]	88,56	87,58	74,46	75,46	48,28
Beat. $\delta = 3 \cdot \cdot 10^{-4}$ [%]	40	40	30	30	10
Beat. $\delta = 8 \cdot \cdot 10^{-4}$ [%]	150	150	100	105	30

Table 3: Chromatic aberrations for the upgrade optics and the nominal LHC. The first row show the required strength of the arc sextupoles for compensating the first order chromaticity, while the last two rows present the off momentum beta beating for two different energy error.

	Compact	Modular	Lowbetamax	Symmetric	LHC
Full	16	11	14	12	12
Triplet only	22	17	14	12	
Triplet excluded	16	11	20	16	

Table 4: Minimum DA over 60 seeds without beam beam effect and field imperfections of D1 and D2. The second row and the third row show the DA excluding in addition all field imperfections but the triplet and the triplet respectively. The field quality for the triplets is estimated using the results showed in [2].

CROSSING SCHEME AND ANTISYMMETRY

The LHC optics present a certain degree of left-right symmetry with respect to the IP in the quadrupole polarity (opposite) and position. Nevertheless the quadrupole strengths don't follow the antisymmetry because the dispersion boundary conditions don't follow it. Anyway the nominal layout tries to force the antisymmetry, because it seems beneficial for finding smooth transitions (see [10]). In addition for the TOTEM experiment (see [11]) it is useful to have antisymmetric optics function up to Q6. In developing the optics for the upgrade, this strategy additional constraint, restrict the flexibility and the ability of finding optimized optics. It is not excluded that further optimization can recover the symmetry.

CONCLUSION

The development of four different optics showed he actual limitations and challenges for Phase 1 upgrade.

At this stage of the studies there are outstanding issues that need to be further investigated.

There are aperture bottleneck in D1, D2, Q4, Q5. The limitation in D1 is an avoidable and require a new design for the dipole. The limitations for D2, Q4, Q5 depends on the triplet layout. A further optimization can reduce the problem but on one hand the triplets have a limited number of free parameters to use and on the other hand the LSS is not flexible enough to accept all possible optics function that merely fulfill the aperture requirements. This limitation is more severe for the Compact and Modular options, while is presumably fixable for the symmetric option and barely acceptable for the Lowbetamax option.

The impact of the larger off momentum beta beat and the third order chromaticity need to studied. It is a global quantity and it may affect other LHC subsystem (e.g the collimation system).

The solution presented even though were designed to be as realistic as possible, represents an effort to study the possibilities and implication of several design criteria: gradient and aperture of the quadrupoles, number of modules, triplet or quadruplet design.

The analysis presented is not exhaustive. For a realistic design many refinements are need. In particular it is important to check whether the heat load and radiation damage levels are compatible with the new elements and redesign the final focus system for increasing the aperture margins and reserving the right locations for correctors and diagnostics (orbit corrector and BPM).

The results presented so far show that the Lowbetamax option show the best overall performance closely followed by the Symmetric option which offers a simpler tough less flexible design. Both options can be further optimized to gain aperture margins and represent an good starting point for the final design.

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