STUDY OF THE IMPACT OF FRINGE FIELDS OF THE LARGE APERTURE TRIPLETS ON THE LINEAR OPTICS OF THE HL-LHC*

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Abstract

High-luminosity hadron colliders such as the High Luminosity LHC (HL-LHC) project place demanding requirements on existing and new magnet technology. The very low β^* achieved by the Achromatic Telescopic Squeeze (ATS) optics scheme for the HL-LHC in particular, requires large apertures in the high gradient Nb_3Sn final focusing inner triplet triplet. Such magnets have extended fringe fields which perturb the optics. This paper presents studies into the linear optics of the LHC using a range of fringe field models, including realistic fringe fields from prototype magnets, and presents calculations of the resulting beta-beating. Furthermore a similar study is presented on the nominal LHC optics, which uses final focus quadrupoles of higher gradient but significantly smaller aperture.

INTRODUCTION

The High Luminosity LHC (HL-LHC) is a planned upgrade for the LHC, aimed at significantly increasing the instantaneous and integrated luminosity of the machine. Peak luminosity will be $\sim 10^{35}$ cm^{-2}s^{-1} with the goal of using so-called leveling schemes to produce a sustained luminosity of 5×10^{34} cm^{-2}s^{-1} for many hours [1].

To achieve this the Achromatic Telescopic Squeeze (ATS [2]) optics scheme is used to reduce the amplitude of the beam envelope at the point of collision, β^*, at IP1 and IP5, for the ATLAS and CMS experiments, from 0.55 m to 0.15 m. The ATS scheme is the only solution thus far which allows the necessary decrease in β^* while correcting first- and second-order chromaticity Q' and Q''.

The large β peaks in the inner triplets (ITs) of IP1 and IP5, along with the high focusing strength, means that sensitivity to errors is extremely high. The standard MADX [3] "hard-edge" linear model assumes quadrupole strength is a step function along the longitudinal beam axis, and real field falloff can cause significant mis-matching of optics. Figure 1 compares a hard-edge field to a more realistic falloff. This paper describes the work done to quantify these errors and qualify their impact on the HL-LHC optics.

The shape of the β-function around an interaction regions (IR) 1 and 5 is illustrated in Fig. 2. This shows the large peaks, increasing beam sensitivity and making it important to more accurately model fringe fields in these regions. This need is unique to the HL-LHC due to the challenges of achieving such high luminosities.

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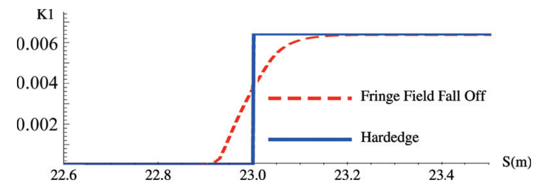

Figure 1: Hard-edge field compared to realistic falloff.

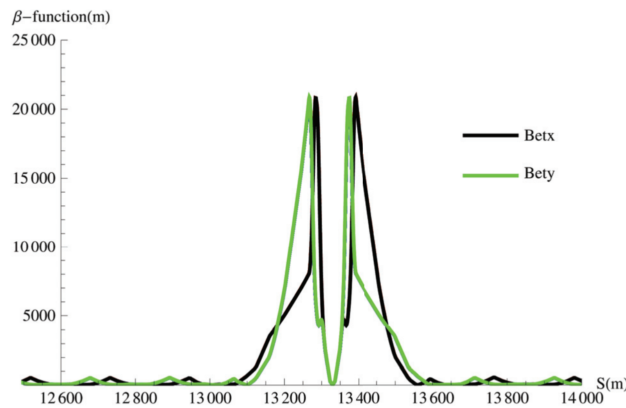

Figure 2: β-function in the HL-LHC optics in IR5 for $\beta^* =$ 15 cm.

This study quantifies fringe field effects by comparing the hard-edge model β function with that produced by the fringe-field model. This β-beat is calculated as $\Delta\beta/\beta$.

REPLACING MAGNETS

The hard-edge IT magnets at IP1 and IP5 are replaced in MADX with several shorter magnets of constant strength. A series of shorter magnets is added at the ends with progressively lower values of normalised magnetic strength k, where the gradient in Tesla per metre $g = kp/e$. These strengths are governed by analytic functions which model the real field falloff. As the field falloff may begin inside the hard-edge modelled magnetic length, the end slices begin before the hard-edge as shown in Fig. 3. The integrated strength, kL_h in the hard-edge model, must remain constant, as this quantity is ultimately what is applied to the machine optics. In the model described here, integrated strength is given by

$$\int k \, \mathrm{d}L = \sum k_i L_i \tag{1}$$

where k_i and L_i are the strengths and lengths of each slice.

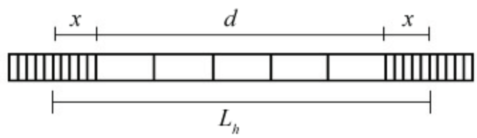

Figure 3: Example of one hard-edged magnet replaced by 5 central magnets and 10 "fringe" magnets, which are used to model a more accurate field falloff.

L_h is the hard-edge magnet length and x is the distance the field fall-off incurs into the magnet. The 5 central magnets do not need to be split up further as the magnetic strength remains unchanged over this range. The new inner length of the magnet d, over which k is constant, is simply $d = L_h - 2x$. The length of each fringe magnet is then

$$L_i = \frac{2x}{n}, \tag{2}$$

where n is the number of fringe magnets, effectively the resolution of the model. This is chosen appropriately in each case depending on the model. Above $n \approx 10$, results are sufficiently insensitive to n.

A script removes the existing magnets and replaces them with an assembly of shorter magnets according to the algorithm above. The new magnets are then assigned strengths that vary according to an analytical function, mapping the realistic fringe field.

FIELD MAP FORM

Analytic functions are fitted to the field map. In general, the field falloff is asymmetric about the physical edge of the magnet and the extent scales almost linearly with the aperture of the magnet. Three functions are used to replicate the field - one arctan function and two exponentials. These use the forms

$$\begin{aligned} k_{1,2}(s) &= a_{1,2}[\exp(b_{1,2}(s - c_{1,2})) + d_{1,2}] \\ k_3(s) &= a_3[\arctan(b_3(s - c_3)) + d_3] \end{aligned} \tag{3}$$

where s is the longitudinal coordinate and a, b, c, d are fitting parameters. The functions are combined in the form

$$k(s) = \begin{cases} k_1(s) & s_0 < s \leq s_1 \\ k_2(s) & s_1 < s \leq s_2 \\ k_3(s) & s_2 < s \leq s_3 \end{cases} \tag{4}$$

which is illustrated in Fig. 4.

Soft-edge models are then applied to the nominal LHC and two slightly different optics scenarios for the HL-LHC: SLHCV3.1b[4] and HL-LHCV1.0 [5].

HL-LHC UPGRADE

A realistic field map for a MQXF inner triplet quadrupole with an aperture of 150 mm and maximum gradient of 140 T/m [6] was applied to the SLHCV3.1b ATS optics. The fringe field begins to fall off 0.2 m inside the magnet and extends to 0.12 m outside. Three functions are fitted to the data points as discussed in section . The coefficients a, b and c are used as inputs to a MADX macro to implement the fringe field fall off for the inner triplet magnets at IP1 and IP5.

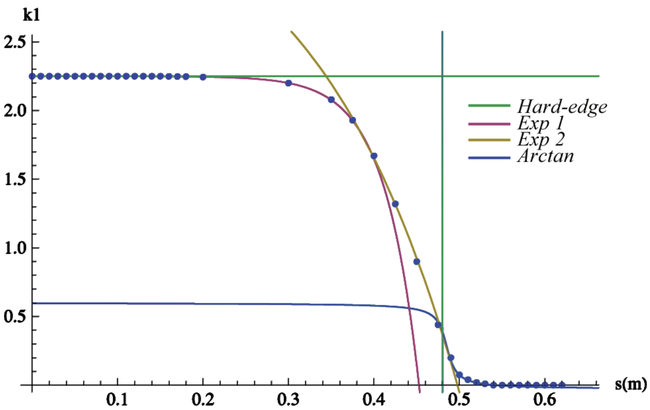

Figure 4: The exponential and arctan functions described in equation 3, combined as described in equation 4 and fitted to field data (circles).

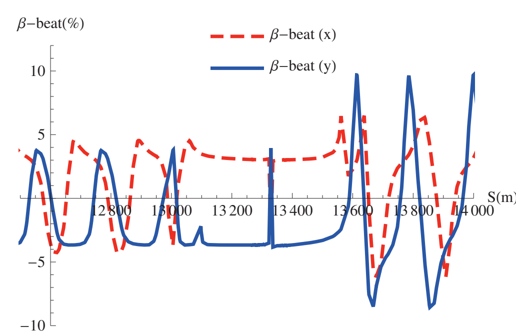

Figure 5: β-beat for SLHCV3.1b IR 5 optics with $\beta^* = 15$ cm.

The β-beat is generated by the triplet and propagates to the arc, maintaining a constant amplitude of $+10\% \rightarrow -8\%$ around the ring as shown in Fig. 5. These figures, representing an upper limit, are rough averages of the beating amplitudes in whichever plane exhibits most beating. In this case it is asymmetric, and the larger figure on the right is taken.

HL-LHCV1.0 is the current optics design for the LHC upgrade and is therefore the most important optics to consider for sources of β-beat in this context. Compared to SLHCV3.1b, Q1 and Q3 are now split into two magnets, analogously to Q2 in previous optics. The IT quadrupole apertures are increased to 150 mm and maximum gradient to 140 Tm^{-1}. The field map used in the case above is applied directly here, without scaling for aperture. This results in a β-beat around the ring of $+8\% \rightarrow -7\%$, as shown in Fig. 6.

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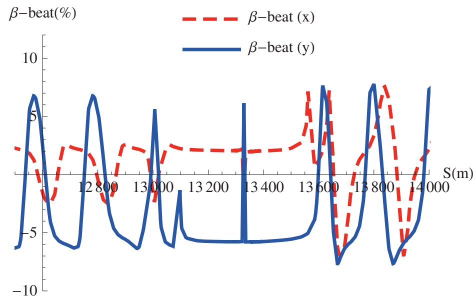

Figure 6: β-beat for HLLHCV1.0 IR 5 optics with $\beta^* = 15$ cm.

NOMINAL LHC

To extend this study, the same techniques were applied to the nominal LHC optics with $\beta^* = 55$ cm. The last measured beta-beating in the LHC after correction is $7 \pm 4\%$ [8] with sources like triplet misalignments and fringe fields not taken into account in the compensation strategy. A field map measured from the current LHC 70 mm aperture triplet quadrupole design [7] was used as above, fitting analytic functions to the field to replicate the falloff in MADX.

Unlike the ATS quadrupoles, the fringe field in these magnets is roughly centred about the hard edge of the magnet; i.e. the extension of the fringe field outside the magnet was roughly equal to the incursion into the magnet. Using this field map, β-beat was found to be $+2\% \rightarrow -2\%$ around the ring, as shown in Fig. 7.

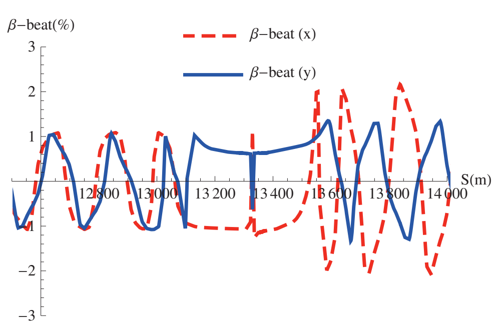

Figure 7: β-beat for IR 5 nominal optics with $\beta^* = 55$ cm.

DISCUSSION

Table 1 shows a comparison of results of the maximum β-beating including combined effect of both IRs. The differences between the scenarios depend on β^*, the triplet gradients and the phase advance between IP1 and IP5.

HL-LHC

The measured field maps provided show an asymmetric fringe field fall off around the physical edge of the magnet.

Table 1: Summary Table of β-beat for all Optics Concerned

Optics	β^* **[cm]**	β**-beat** (%)
SLHCV3.1b	15	$+11 \rightarrow -8$
HLLHCV1.0	15	$+8 \rightarrow -7$
Nominal	55	$+2 \rightarrow -2$

The β-beat plot in Fig. 6 also displays a left-right asymmetry in the form of the β-beat around the IR, due to the imperfections located around IP1 and affecting IR5. A similar form is seen around IR1. The effect is more extreme for the x-axis β-beat in the HLLHCV1.0 compared with the SLHCV3.1b due to the different optics.

The β-beat calculated for the HLLHCV1.0 is low enough that rematching is feasible. A new optics will be matched using these scripts to minimise the errors caused by magnetic fringe fields. However this β-beat consumes nearly half of the allowed 20% tolerance in the LHC accelerator, and so would have significant impact on the continued safety and efficiency of the machine if left uncorrected.

Nominal

As it stands the best estimate for the fringe field induced β-beat in the nominal optics, generated at IP1 and IP5, is $\pm 2\%$. This is sufficiently low as to not dramatically effect the operation of the nominal optics, and could be one of the contributing factors of the residual observed β-beat in the LHC. To gain further confidence in this result, the nominal study was repeated using the field map for the 150 mm triplet was used, with extent scaled linearly by $\frac{70}{150}$ for 70 mm aperture. Minimal differences were seen, indicating that the effects are relatively insensitive to field map inaccuracies. This suggests that these results closely model the behaviour of the LHC.

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