

CONSTRUCTION AND PERFORMANCE OF IP OPTICS TUNING KNOBS IN THE LHC

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Abstract

During the first years of operation of the LHC unknown field errors or misalignments could lead to unmatched optics and discrepancies with respect to the model. This could affect some critical parameters such as the luminosity or the lifetime. It is therefore desirable to implement tools which allow for fine tuning of the IP optics and could be used during the commissioning phase of the LHC. In this paper we report on the implementation the performances and the limitations of these commissioning tools.

INTRODUCTION

When two proton bunches collide particles of one bunch will experience a localised defocusing force from the other bunch. This field, commonly called the beam-beam force, becomes strongly non-linear for particles with a large amplitude and produces a spread of the tunes and an excitation of non-linear resonances. We can therefore expect all effects that are known from resonance and non-linear theory such as unstable motion and beam blow-up or bad lifetime. The destructive effect of the beam-beam force is stronger for beams with unequal sizes as demonstrated in [1]. In addition, the luminosity for Gaussian beams in the case of head-on collisions without crossing angle is expressed as:

$$\mathcal{L}_0 = \frac{N_1 N_2 f N_b}{2\pi \sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} \quad (1)$$

where N_1 and N_2 are the bunch intensities, f the revolution frequency, N_b the number of bunches per beam and $\sigma_{ix, iy}$ the effective transverse beam sizes. Any increase of the beam sizes would then result in a loss of luminosity. Tools which allow for fine tuning of the beam sizes can therefore become very valuable in the LHC. The beam size at the IP where the dispersion is assumed to be equal to zero can be expressed as:

$$\sigma^* = \sqrt{\beta^* \varepsilon} \quad (2)$$

where σ^* and β^* are the beam size and the β -function at the IP and ε is the emittance. The only parameter left for adjustment of the beam size is β^* . β^* adjustments are done by changing the strengths of the main insertion quadrupoles via a knob.

IMPLEMENTATION

In the LHC the beams collide in four experimental regions with similar layouts [2]. The final focusing is performed with triplets which are common for the two rings.

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The other insertion quadrupoles (from Q4 to Q13) will drive the beams independently. For our purpose it is necessary to be able to control the beams independently, the triplets can therefore not be used. In addition, the optics changes should be as much localized as possible to the interaction region and parameters other than the β^* should remain constant. These changes were kept small by using all the insertion quadrupoles to compute the knobs.

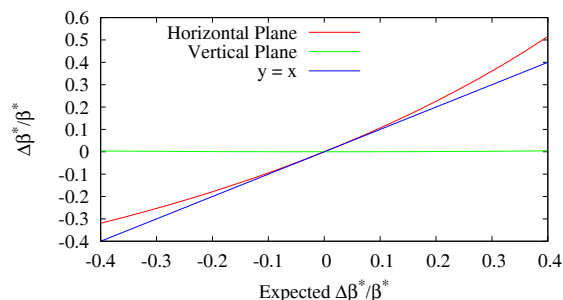


Figure 1: Evolution of tune and β^* as function of the expected change in β^* . Example of IP1 at injection optics.

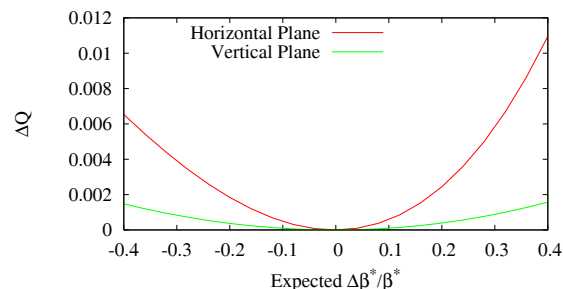


Figure 2: Evolution of tune as function of the expected change in β^* . Example of IP1 at injection optics.

The main criteria for a knob to be easily implemented and used in operation is the linearity. This is of course not the case when changing the strength in a quadrupole, however, if these changes remain small a linear approximation can be justified. This is illustrated Figure 1 and 2 where the changes of β^* are only seen in the adjusted plane and almost linear within a range of $\pm 20\%$. The tune changes are of the order of a few 10^{-3} .

β^* MEASUREMENTS AT 3.5 TEV

Table 1 summarizes the β^* measurements for injection optics at 3.5 TeV for which the β -beat was close to specifications (20%). The nominal values are 11 m for IP1 and IP5 and 10 m for IP2 and IP8 in both planes.

Table 1: β^* measurements at 3.5 TeV [3].

Horizontal		
	Beam 1	Beam 2
IP1	11.54±0.20	9.89±0.27
IP2	9.21±0.12	11.54±0.15
IP5	11.85±0.27	10.74±0.21
IP8	10.20±0.69	9.45±0.15
Vertical		
	Beam 1	Beam 2
IP1	12.74±0.45	12.70±0.15
IP2	8.92±0.30	12.04±0.07
IP5	10.73±0.47	11.15±0.40
IP8	11.35±1.24	9.19±0.05

From these measurements one can estimate the loss in luminosity with respect to the nominal values using Equation 1. Assuming round equal beams ($\epsilon_{ix} = \epsilon_{iy} = \epsilon$) to compute the losses IP5 and IP8 are almost at nominal values while IP1 and IP2 have a loss of about 6 % and 4 % respectively, which becomes non-negligible for high luminosity operation.

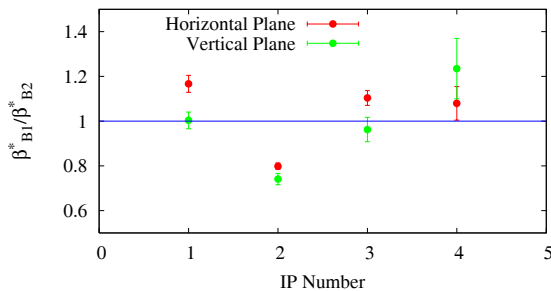


Figure 3: Ratio of the β^* at the four interaction points.

The ratio of the β^* between the two beams might also become an issue for lifetime once LHC will run with high bunch intensity. As shown in Figure 3, the difference between beam 1 and beam 2 can go up to more than 20 % and will probably require corrections in the presence of strong beam-beam.

β^* KNOB MEASUREMENTS

Measurements were performed at 3.5 TeV for injection optics. Only one knob was tested for IP5 beam 2 horizontal but the results should be similar for the other knobs as predicted by the model. The measurement consisted of a series of acquisitions with $\Delta\beta^*$ of 0% -20%, -10% and +20% and finally back to the initial situation to check for hysteresis effects. At each point the beam was excited using the AC dipole to measure the optics.

The results for the scanned plane agree within the error bars except for the point at -10% as shown in Figure 4. In the plane which is not trimmed the $\Delta\beta^*/\beta^*$ is consistent with zero for all points. It is also interesting to note that the starting point and the end point of the scan are consis-

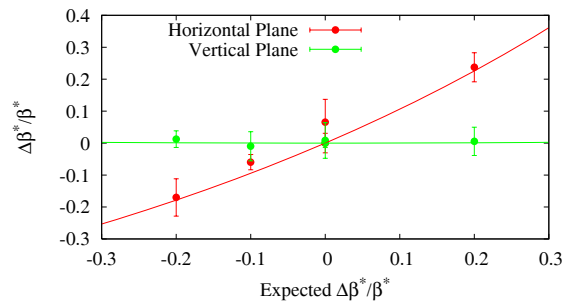


Figure 4: β^* scan at 3.5 TeV and injection optics. The plain lines represent the model.

tent with each other which demonstrates that in these conditions the hysteresis was small enough to leave the optics unchanged.

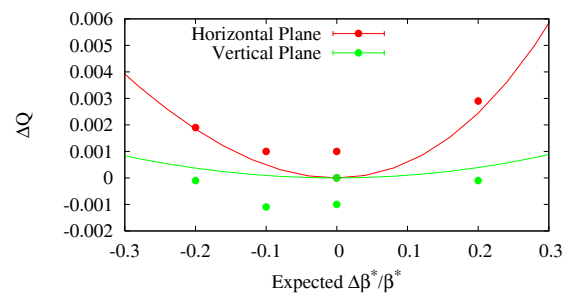


Figure 5: Tune changes during the scan. The plain lines represent the model.

The tune is another observable that can be measured with high precision. Figure 5 shows the changes in tune during the scan. The measurements show some small discrepancies with respect to the model and the initial tunes could not be recovered by going back to initial position. The differences are of the order of a few $\approx 10^{-3}$ which is a factor two larger than the natural tune jitter ($5 \cdot 10^{-4}$). This could be the sign of field errors or small hysteresis effects not seen on the β -functions which is a less precise measurement.

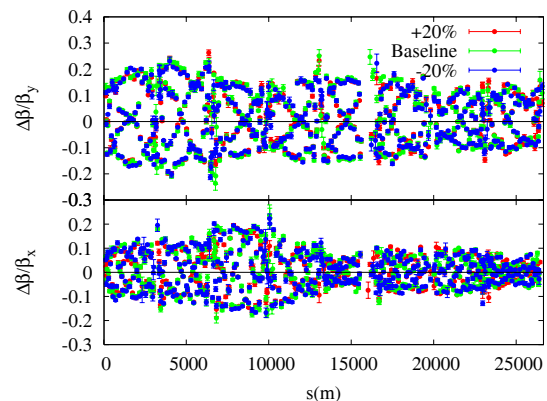


Figure 6: β -beat over the whole ring in the horizontal (bottom) and vertical (top) plane. The change in optics was taken into account in the model when β^* was trimmed.

Looking at the β -beat over the whole ring allows to check whether unwanted optics errors were induced by changing the β^* . In Figure 6 the β -beat was calculated with respect to a model including the knob. Differences are observed with respect to the baseline optics but the overall and peak β -beat remain within the specification of 20%. Looking closer at IR5 as illustrated Figure 7, where the β -beat was calculated using the nominal optics as a reference (i.e. not including the changes from the knob), we can clearly see the changes around the IP for the different trims. The optics changes are localized to the region around the IP and the β -beat is back to the initial one in the arcs. β^* being too small compared to nominal optics for the baseline solution the trim to +20% improved the situation even if going further than the nominal β^* of 11 m. This is illustrated Figure 8 where a clear improvement is seen in IR1 but also a slight overall improvement all around the ring.

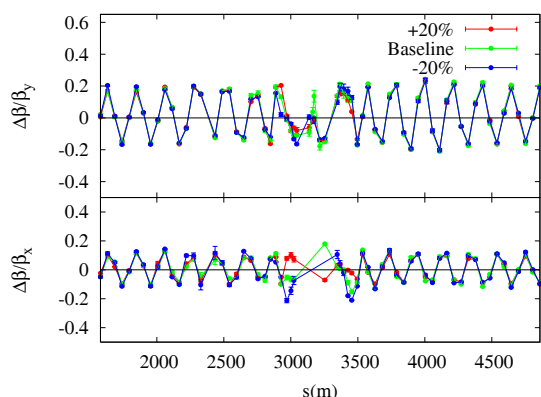


Figure 7: β -beat in IR5 in the horizontal (bottom) and vertical (top) plane. The β -beat was calculated with respect to the nominal optics for all cases.

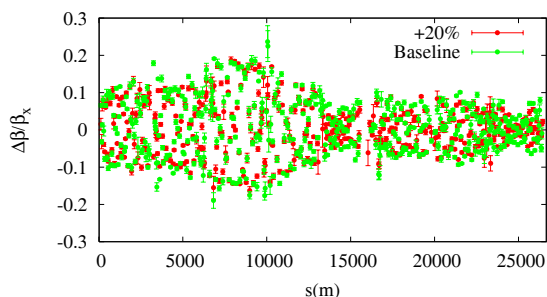


Figure 8: β -beat for the whole ring for the baseline and +20% β^* with respect to nominal optics.

OUTLOOK FOR SQUEEZED OPTICS

In order to reach the LHC nominal luminosity β^* has to be reduced down to 0.55 m. Decreasing β^* increases the β -function in the triplets which considerably reduces the aperture margin compared to injection optics. As a consequence the tertiary collimators, situated in the triplet region, have to be set closer to the beam. Similarly to the

squeeze process correcting β^* using a knob changes the β -functions in the triplet and at the tertiary collimators. One should therefore be very careful not to hit the aperture. In addition, the squeezed optics is reached by decreasing the current in the insertion quadrupoles. Operating at lower currents could lead to non-negligible hysteresis effects when trimming the β^* . For its first two years of operation the LHC will run with β^* larger or equal to 2 m. As illustrated Figure 9 it is more difficult for the 2 m optics to keep the β^* constant in the other plane, a change of 20% in one plane would result in a change of about 1.5% in the other plane. Furthermore, when trimming the β^* by -20% the minimum n_1 [4], which describes the aperture, is reduced by about 1.2σ which represents a non negligible loss.

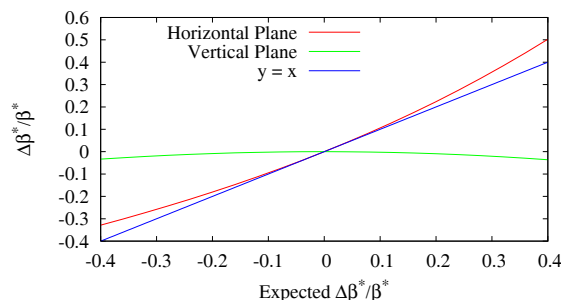


Figure 9: Evolution of tune and β^* as function of the expected change in β^* . Example of IP1 for 2 m optics.

CONCLUSION

The β^* knobs were successfully implemented and tested for injection optics at 3.5 TeV. The measurements results are in good agreement with the simulations and no significant optics errors was observed. The tune measurements showed possible small hysteresis effects. In order to include these tools as part of routine operation a systematic check of all IPs separately and together needs to be performed in case these small effects add up to build larger errors. In the case of squeezed optics the situation becomes more complicated and a detailed study is required to assess the real effects and the impact on machine protection.

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