Optimizing the global coupling knobs for the LHC

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Summary

This paper reviews the design of orthogonal knobs for the correction of transverse coupling. These knobs are typically used on-line in the CCC to minimize the $|C^-|$ in an iterative fashion. For their optimum performance they should be as orthogonal as possible using the minimum possible skew quadrupolar strength. To conclude it is proposed to modify the existing Beam 2 knobs for 2012 to achieve the best possible performance.

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# 1 Introduction

In LHC it is fundamental to ensure a closest tune approach, $\Delta Q_{\text{min}}$, well below 0.01 to avoid disturbing the tune feedback and to maximize the accessible tune space for the colliding beams. In the following a very brief theoretical introduction is given, followed by the initial plan for the coupling correction in the LHC [1]. This plan was unfortunately truncated by the 2008 accident, which destroyed the skew quadrupoles in the arc between IP3 and IP4. The current approaches for the coupling correction and the observed limitations are also described in this section. Section 2 describes the optimization of the global coupling knobs.

## 1.1 Theory

$\Delta Q_{\text{min}}$ can be approximated as a function of the difference resonance driving term $f_{1001}$ by the following equation,

$$\Delta Q_{\text{min}} \approx 4|\left(Q_y - Q_x\right) f_{1001}|,$$

where $Q_{x,y}$ represent the fractional transverse tunes. $f_{1001}$ is a complex quantity which is expressed as a function of the skew quadrupolar components as follows,

$$f_{1001}(s) = \frac{1}{1 - e^{-2\pi i (Q_x - Q_y)}} \sum_j \frac{1}{4} \sqrt{\beta_{xj} \beta_{yj}} K_{sj} e^{i \left(\Delta \phi_{xj} - \Delta \phi_{yj}\right)} ,$$

where $K_{sj}$, $\beta_{xj,yj}$, and $\phi_{xj,yj}^{\text{s}}$ correspond to the strength, beta functions and phase advances for the $j^{th}$ skew quadrupolar source, respectively. Note that the origin of phases is $s$ causing $|f_{1001}|$ to vary abruptly at the location of a skew quadrupole and remaining constant in the sections free of coupling sources. The relative variations of $|f_{1001}|$ tend to vanish as the tunes approach the difference coupling resonance. Therefore assuming that the machine tunes are close enough to this resonance and that the strong sources have been locally compensated it should be possible to control $\Delta Q_{\text{min}}$ by two orthogonal skew quadrupolar knobs that would act on the real and imaginary parts of $f_{1001}$ at a certain longitudinal location.

## 1.2 Initial plans for coupling correction in the LHC

LHC is equipped with skew quadrupoles in the triplets and in the arcs. One common skew quadrupole for Beam 1 and Beam 2 in the middle of every triplet is installed at both sides of the four experimental IPs. This gives a total of 8 skew quadrupoles to cancel the local coupling at these interaction regions. These quadrupoles are regularly used since mid 2010 based on beam-based measurements and the segment-by-segment technique [2, 3].

Every arc was initially equipped with 4 skew quadrupoles around its middle point. Their powering was chosen as a compromise between the number of cables and the locality of the correction to allow robust local corrections within every 2 neighboring arcs [1]. The unfortunate accident in 2008 caused the loss of the skew quadrupoles within arc 34 rendering this approach impractical.

Further improvements to the measurement of coupling and chromatic coupling are presented in [4, 5].

## 1.3 Current coupling correction approaches in the LHC

Currently three different approaches for the coupling correction are used in the LHC:

1. Local IR correction using triplet skew quadrupoles
Table 1: Current LHC coupling knobs designed to orthogonally control the real and imaginary parts of \( f_{1001} \) at IP1, normalized to a \( \Delta Q_{\text{min}} = 1 \) (typical corrections aim at a \( \Delta Q_{\text{min}} \leq 0.01 \)).

2. Measurement of \( f_{1001} \) at every BPM followed by an inverse response matrix approach to minimize \( f_{1001} \) everywhere using all available arc skew quadrupole correctors.

3. Iteration of two precomputed global and orthogonal knobs to minimize the difference resonance as measured locally at IR4 by the BBQ system [6].

The global coupling knobs are constructed using all available arc skew quadrupolar circuits. A MADX routine [7] matches two combinations of skew quadrupolar circuits giving \( f_{1001} = 0.001 \) (real) and \( f_{1001} = 0.001 \) (imaginary) at a given location. As discussed in Eq. (2) the \( f_{1001} \) features abrupt jumps at the location of the skew quadrupoles, therefore the choice of the evaluation location for the knobs plays an important role in the optimization process.

The current LHC coupling knobs have been computed at IP1, see Table 1. It is striking that the Beam 2 knobs require considerably stronger skew quadrupoles than for Beam 1. This asymmetry is suspected to have caused some troubles in the coupling correction only for Beam 2. On March 21, 2010, some Beam 2 skew quadrupoles were approaching their strength limits at 3.5 TeV after having corrected coupling with the global knobs. This happened before any IR local coupling cancellation or any dedicated response matrix correction. Moreover this problem triggered the need for a dedicated \( f_{1001} \) measurement at all BPMs followed by a correction based on a response matrix approach, resulting in much lower strengths in the skew quadrupoles. Figure 1 shows the strengths of the skew quadrupole circuits before and after the response matrix correction.

The following section focuses in the optimization of the coupling knobs profiting from the intrinsic longitudinal dependence of \( f_{1001} \).

## 2 Optimization of the LHC coupling knobs

A straightforward way to optimize the LHC coupling knobs consists in evaluating these knobs at different locations and choosing the best knobs. The performance of the knobs is given by their required skew quadrupole strengths and by the orthogonality of their contributions to the complex
Figure 1: Strengths of the Beam 2 skew quadrupole correctors after correcting the coupling via the orthogonal coupling knobs (red) and after a dedicated measurement and response matrix correction based on data from all BPMs (blue).

Figure 2: Quadratic sum of skew quadrupolar strengths of the real and imaginary knobs evaluated at the specified IP when separately generating a $\Delta Q_{\text{min}} = 0.001$.

The figure of merit for the strength of a pair of knobs is defined as

$$\sum_i K_{si}^2,$$  \hspace{1cm} (3)

where the sum runs over the skew quadrupole of both families when separately generating a $\Delta Q_{\text{min}}$ of 0.001. Figure 2 shows this figure of merit for 8 different evaluation locations of the knobs and for both beams. The locations correspond to the 8 IPs. It is evident that IP1 was the worst possible location to evaluate the Beam 2 coupling knobs. Instead for Beam 1 IP1 is among the best locations. For Beam 2 the knobs generated at IP2, IP3, IP4 and IP7 perform similarly.

The figure of merit for the orthogonality is defined as the ring average and rms angle ($\theta$) between the $f_{1001}$ terms from the real and the imaginary knobs. $\theta$ should be as close as possible to 90°. Figure 3 shows the $\theta - 90^\circ$ versus the specified evaluation location. Again Beam 2 shows the worst performance for IP1. Best locations for Beam 2 are IP8, IP7 and IP2. For Beam 1 the current choice,
2.1 Performance of the injection coupling knobs for the squeeze optics

There is a slight change of the lattice phase advance between injection and squeeze optics. The suitability of the knobs computed at injection should be verified for the squeeze optics. Figure 4 compares the orthogonality of the knobs at injection and with squeeze optics. Due to the fact that the tunes are closer to the difference resonance for the squeeze optics the longitudinal variations of $f_{1001}$ are reduced, hence reducing the rms values of $\theta$. The average $\theta$ remains similar to injection. This implies that knobs computed at injection are suitable for squeeze optics too.

It should still be answered whether generating dedicated knobs with squeeze optics could improve the coupling correction performance. Figure 5 compares the quadratic strength sum for knobs generated at injection and with squeeze optics. No relevant improvement is observed for the good evaluation locations.

3 Conclusion

The presented optimization of the coupling knobs has revealed that the current Beam 2 knobs feature the worst possible performance. On the contrary Beam 1 knobs are already very close to the optimum. These conclusions are in agreement with the LHC experience, where Beam 2 has consistently demonstrated to be more sensitivity to coupling. Therefore it is proposed to change the current Beam 2 coupling knobs for 2012. The best choices seem to be to generate these knobs either at IP7 or IP2. The corresponding skew quadrupole strengths are shown in Table 2.
Figure 4: Ring average and rms of the angle between the $f_{1001}$ produced by the real and the imaginary knobs evaluated at the specified IP when separately generating a $\Delta Q_{\text{min}} = 0.001$. All the knobs used for this plot are generated with injection optics.

Figure 5: Comparison of the required strength of the knobs when generated with injection or squeeze optics.
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Table 2: Proposed Beam 2 coupling knobs designed to orthogonally control the real and imaginary parts of \( f_{1001} \) at IP2 and IP7, normalized to a \( \Delta Q_{\text{min}} = 1 \) (typical corrections aim at a \( \Delta Q_{\text{min}} \leq 0.01 \)). These strengths are considerably lower than for the current knob as listed in Table 1.

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**References**


