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SORTING STRATEGIES FOR THE ARC QUADRUPOLES OF THE LHC

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The variation in the field gradient of the LHC arc quadrupoles can not be corrected by the dedicated trim quadrupole circuits. This may result to a beta function beating larger than the one accepted by the machine budget. In this respect, sorting strategies for the installation of these magnets were implemented in order to eliminate this effect, as locally as possible. Special care was taken for quadrupoles whose warm measurements showed large gradient errors due to an excessive magnetic permeability. The figures of merit used in the sorting and the results obtained for all 8 sectors of the LHC are detailed. The global optics function beating foreseen, as computed by analytical estimates are finally presented.

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The variation in the field gradient of the LHC arc quadrupoles can not be corrected by the dedicated trim quadrupole circuits. This may result to a beta function beating larger than the one accepted by the machine budget. In this respect, sorting strategies for the installation of these magnets were implemented in order to eliminate this effect, as locally as possible. Special care was taken for quadrupoles whose warm measurements showed large gradient errors due to an excessive magnetic permeability. The figures of merit used in the sorting and the results obtained for all 8 sectors of the LHC are detailed. The global optics function beating foreseen, as computed by analytical estimates are finally presented.

INTRODUCTION

Each of the 8 Large Hadron Collider (LHC) arcs contains 47 FODO half-cells (from Q11 right of one Interaction Region (IR) to Q11 left of the next IR), with 23 (or 24) focusing (or defocusing) (F/D) main quadrupoles (MQs) in both apertures (denoted V1 or V2) [1]. At each arc, quadrupoles of the same polarity (e.g. with V1F/V2D) are connected in series, for both beams. Two additional families of 8 tuning quadrupoles (QTF, QTD) per ring and arc allow the independent tuning of the phase advance for each ring and compensate systematic deviations from the nominal quadrupole field. Nevertheless, especially during the LHC injection plateau, a random b_2 error in the MQs induces linear optics function distortions and in particular beta variations (“beating”), which cannot be corrected. The different potential sources of β -beating have been identified and a budget has been allocated for each of the contributions, establishing that a beta-beating corresponding to a random (one standard deviation) b_2 of 10 units (10^{-4} of the main field at 17 mm of reference radius) can be tolerated in the LHC machine [2]. All MQs were measured at room temperature and a limited number at cold, based on which a warm to cold extrapolation model was established [3]. The extrapolated b_2 was exceeding by 30% the tolerance, without taking into account magnetic measurement uncertainties (~ 5 units rms [4]). It appeared thus necessary to “sort” the MQs, i.e. assign them to specific slots in the machine in order to minimise the β -beating. In addition, after measuring a sample of 90 MQs, anomalies in the focusing strength were noticed and attributed to a high permeability (HP) value of the stainless steel collars [4]. Even if cold measurements in a small number of them suggest that the effect should disappear at cold, the HP MQs necessitated special treatment.

SORTING STRATEGY AND TARGETS

Every MQ is assembled into a “cold mass” in industry (ACCEL), with a variety of correctors and components

for vacuum and cryogenics, making a total of 40 variants. These cold-mass families correspond to a limited number of slots in the LHC, ranging from 30 to only 2 members per family. A further restriction is imposed if the magnet is already put into a cryostat and for this reason the allocation for all sectors was done before the cryostating of cold masses. An additional effort was made to assemble together problematic HP collared coils in the two apertures of the same MQ and pre-assign them in well chosen cold masses for sorting purposes.

The beta-beating $\Delta\beta/\beta$ at location s , due to gradient errors ΔK distributed at locations s' around the ring is [5]

$$\frac{\Delta\beta}{\beta}(s) = \pm \frac{\int_{-C}^{+C} \beta(s') \Delta K(s') \cos(2\pi Q - 2|\mu(s) - \mu(s')|) ds'}{2 \sin(2\pi Q)} \quad (1),$$

where μ is the phase advance and Q the tune. This implies that two identical quadrupole field perturbations acting at a phase advance of $\pi/2$ apart would cancel. Taking advantage of the phase advance of roughly $\pi/2$ in an LHC cell, consecutive F (and D) quadrupoles in each aperture can be matched with respect to their gradient error, so that the beta-beating effect is reduced.

The 2nd order resonance driving terms are the chosen quality factors to be minimised in each arc (4 coefficients, one for each resonance and aperture),

$$QF = \frac{\sum_{j=1}^{45} \beta_j \bar{k}_j b_{2j} e^{2i\mu}}{\beta_{\max} \bar{k}} \quad (2),$$

where \bar{k} is the integrated gradient. The efficiency of the sorting can be checked, by a comparison with the rms coefficient issued by a random distribution of N quadrupoles

$$QF_{rms} \approx \frac{\sqrt{N}}{2} (b_2)_{rms} \quad (3).$$

In the case of the LHC arc $N=45$ (excluding the two Q11 equipped with individual trim windings), and for rms quadrupole errors of 10 units, this coefficient is equal to 34. It corresponds to an rms β -beating per arc of around 0.9 %, which is 1/3 of the peak value.

All arcs contain 10 out of the 40 cold mass variants, following a repeated pattern. Even after fixing the 45 cold mass candidates to be allocated, the number of possible combinations is too large (around 10^{13}) in order to evaluate the quality factors in all possible sequences and choose the best. A semi-automatic algorithm was constructed which matched neighbouring cold masses with respect to their gradient error and then applied permutations to each pair until a minimum in the quality factors was achieved. If a certain number of cold masses were not assembled during the sorting procedure, there was the possibility to choose from a pool of bare MQs,

allowing for more flexibility. As this choice imposes restrictions in the logistics of the MQ fabrication, a continuous communication with ACCEL [6] was necessary for steering the assembly process, verifying and correcting the sorting until the pre-allocation of each sector was considered final. For the compensation to be as local as possible, and apart from the best pairing between neighbouring F/D quads, the magnets with abnormal permeability and large b_2 were treated individually, and in priority, in all sectors. An example of the pairing between both apertures in the MQs of sector 2-3 is presented in Fig. 1, where the pattern of matching between neighbouring F/D quads is apparent, for the “cold” b_2 data. At the same time, and in order to reduce the effect of measurement uncertainty, a global minimisation of 4+4 coefficients was performed corresponding to two b_2 distributions based on the warm and the extrapolated cold measurements.

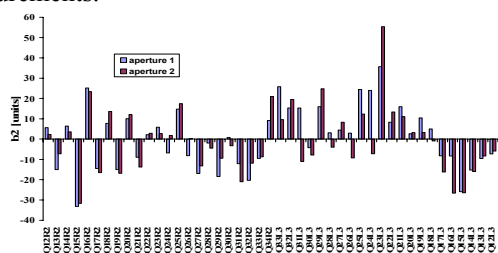


Figure 1: b_2 evolution in the MQs of Sector 2-3 after sorting, in the extrapolated cold scenario.

The necessary optics function components for the estimation of the quality factors are taken from a simulation with MADX [7] using the LHC optics version 6.5. The 8 coefficients are minimised in the least square sense, assigning weights to the realistic case of extrapolated cold b_2 values. The locality of the correction is further ensured by monitoring the local beta beating (1) within the sector in both scenarios. In Fig. 2, an example from sector 2-3 is presented. For both raw and extrapolated data, the maximum beta function is less than 2%, and in the grand majority of the arcs it is smaller than the maximum allowed 2.7 %, for the contribution of the arc to itself. However, it is difficult to anticipate its location with respect to the MQ sequence due to the contribution of the totality of the quadrupoles.

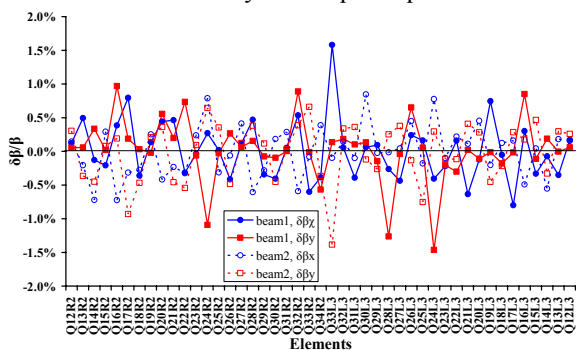


Figure 2: Horizontal (blue) and vertical (red) β -beating for both beams along the Sector 2-3 based on extrapolated cold b_2 data.

As the dispersion beating

$$\frac{\Delta D}{\sqrt{\beta}}(s) = -\frac{\int \sqrt{\beta(s')} \Delta K(s') D(s') \cos(\pi Q - |\mu(s) - \mu(s')|) ds'}{2 \sin(\pi Q)}$$

is not minimised by the process, its evolution is also controlled during the sorting. The budget for the relative horizontal parasitic dispersion is given by

$$\frac{\Delta D_x}{D_x} \frac{\sqrt{\beta_x^{\max}}}{\sqrt{\beta_x}} \approx 27\% [8] \text{ with } \beta_x^{\max}, D_x^{\max} \text{ the maximum beta}$$

and dispersion in the LHC arcs (181 m and 2.1 m, respectively). The rms budget attributed to all the MQs is 3 %, i.e. 1.1 % per arc [2]. The evolution of the parasitic dispersion for sector 2-3 is shown in Fig. 3, where the typical beating over π is apparent. The maximum horizontal parasitic dispersion beating is around 2.5 %, always less than the specified, for both warm and “cold” errors.

Finally, because of the individual powering scheme of the MQs, the tune-split between the two rings induced by the quadrupole errors $\delta \Delta Q = |\Delta Q^{\text{ring1}} - \Delta Q^{\text{ring2}}|$ with

$$\Delta Q_{\text{arc}} = \pm \frac{1}{4\pi} \sum_{j=1}^{45} \beta_j \bar{k}_j b_{2j}$$

was estimated during the sorting. The rms value attributed to MQs is 2×10^{-3} per arc, for both planes [2]. An example from sector 2-3 is shown in Fig. 4. In all sectors, the induced tune-split is well within tolerances, a few orders of magnitude below the specified.

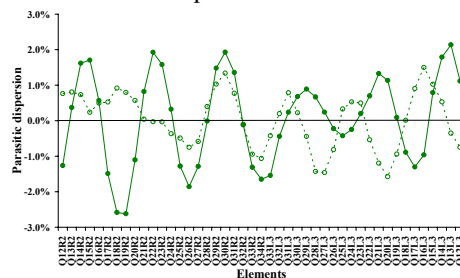


Figure 3: Horizontal parasitic dispersion for both beams along the Sector 2-3 based on “cold” b_2 .

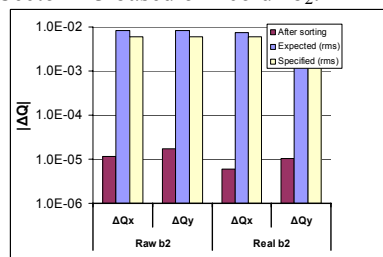


Figure 4: Horizontal and vertical tune split between the two rings for warm (raw) and cold (real) b_2 in Sector 2-3.

SORTING PERFORMANCE

The sorting procedure followed the installation starting from Sector 7-8 and continued with sectors 8-1, 4-5 and 3-4. At that stage, a decision was taken to sort all the MQs in the rest of the machine, in order to facilitate the magnet evaluation and installation process. For the first three sectors, the sorting was done based on warm measurements, including very few cases measured at cold. In Fig.4, the rms b_2 values per beam and sector are

illustrated. In the case of warm measurements, the b_2 ranges from 12 up to 30 units in sector 5-6 where most of the HP magnets were pre-assigned. When the HP effect disappears, the error ranges from 10 to 15 units.

The horizontal and vertical rms β -beating achieved after sorting, as estimated by the quality factor (2), for all the sectors of the LHC and both beams is presented in Fig.6. On the top, we plot the performance of the sorting based on the raw warm measurements and, on the bottom,

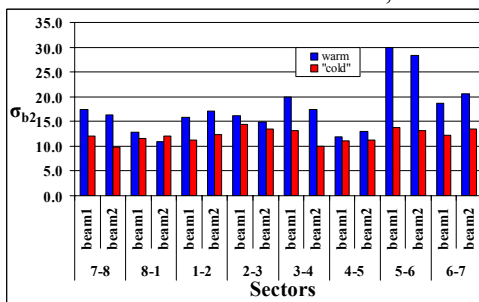


Figure 5: RMS b_2 values per LHC sector and ring.

the more realistic case of the extrapolated data to “cold”. The purple bars correspond to the beating after sorting and the light blue to the expected rms beating without sorting. In the case of the warm data scenario, the β -beating ranges from almost 0.1 % to 2 %. It is always less than the expected beta-beating with the exception of sector 7-8, where it reaches its maximum. This effect is attributed to two high permeability magnets that were already produced and cryostated and their compensation was impossible during the sorting. Their effect indeed disappears in the case of cold values (bottom plot on the left) and all β -beating coefficients are well within the 0.9 % rms tolerance per beam and arc.

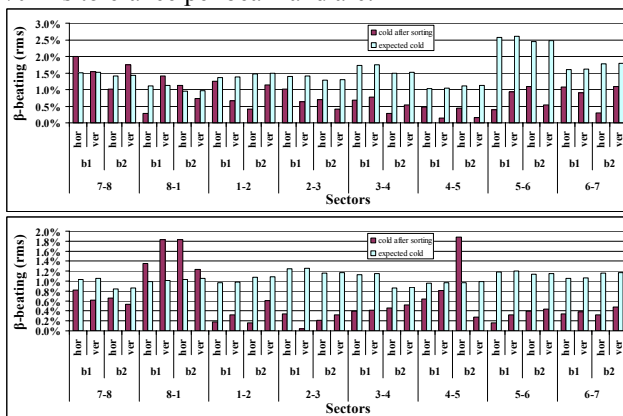


Figure 6: Horizontal and vertical rms β -beating results based on warm (top) or cold (bottom) b_2 data, for both beams in all sectors.

For all the rest of the sectors in the realistic scenario the beta-beating after sorting is small (below 0.6 %), with the exception of all the coefficients of sector 8-1 and the horizontal β -beating for beam 2 of sector 4-5. For both sectors, the minimization was done using only the warm measurements and this explains the poor sorting performance with the extrapolated data to cold. In particular for sector 8-1, two magnets were measured at cold after the sorting and a big difference was found

between the extrapolated and measured data (10 to 30 units), further deteriorating the performance of the “cold” data scenario. The best performance is observed on sector 2-3 (below 0.3%), where around 25% of the magnets distributed in 5 out of the 10 cold mass variants were not assembled, providing the largest flexibility for matching magnets with equivalent errors in both apertures.

In Fig. 7, we present the global performance of the peak horizontal and vertical β -beating (maximum value around the rings given by Eq. (2)), for both beams in the LHC machine. In the case of warm measurements, the beating ranges between 4 to 5 %, as compared to 13.5 % of the expected value without sorting. The gain with respect to the specified value of 8 % is a factor of 2. In the realistic scenario, the beating is well within the tolerances (3 to 4 %), as compared to 9 % of the expected value. In general, the sorting reduced the effect of beating at best by a factor of 3 with respect to the expected peak value from a random distribution (3σ) and a factor of 2 with respect to the specified budget. Indeed, this is a pessimistic estimate, taking into account that the distribution is not random over all the arc quads, as some of them can only go in only one slot. A more fair comparison, between simulations of the machine after sorting and models based on random distributions of cold mass variants is currently under way.

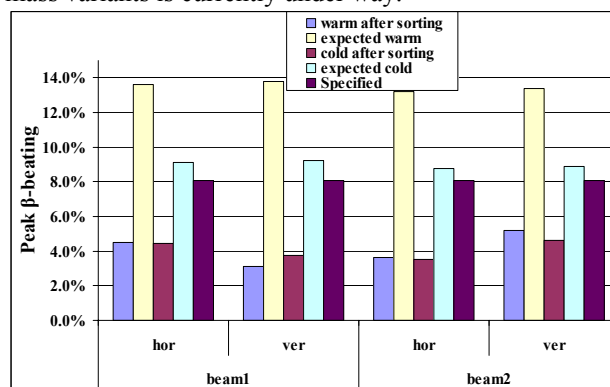


Figure 7: Horizontal and vertical peak β -beating for all beams and b_2 scenarios of the MQs in the LHC.

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