INSTALLATION STRATEGY FOR THE LHC MAIN DIPOLES

Stéphane Fartoukh, CERN, Geneva, Switzerland

MOTIVATIONS AND LIMITATIONS

From the point of view of the machine performance, the installation strategy of the LHC main dipoles must pursue the two following goals: **1)** whenever possible, installing out-of-tolerance magnets at suitable positions in the ring; **2)** to some extent, sorting the magnets in order to control or optimise several beam dynamics related quality criteria. The LHC is made of 8 different sectors. Each sector contains 46 arc cells (half FODO cells from Q11.R to Q34 to Q11.L) and two dispersion suppressors (DS), each made of 4 cells (from Q7 to Q11). With two main dipoles (MB) in the DS cells and three per arc cell, this makes a total number of 1232 MB's. In practice, it will not be possible to perform a global sorting knowing that magnet production, cold tests and installation will run in parallel up to 2007, and that the dipoles are hardly interchangeable from sector to sector or within a given sector due to four different types of hardware assemblies: the types AL, BL, AR and BR for the cryo-dipoles installed in a sector where the clock-wise rotating beam travels in the external or internal aperture of the ring (type L or R for the diode mounting), and for the magnets equipped with or without a b_4/b_5 spool-piece (dipoles type MBA and MBB installed in alternance in the machine). A less ambitious but much more realistic approach therefore consists in:

a) establishing priorities and acceptability thresholds both based on geometry and field quality to classify and/or flag accordingly the LHC main dipoles.

b) defining a general but flexible installation algorithm which can cope with all machine sectors while satisfying different kinds of practical constraints, such as a finite storage capacity or an installation sequence which differs from sector to sector, starting from mid-arc or from the DS.

The proposed algorithm is constructed on the basic rule to install the magnets by pairs such that deviations from average b_3 are partially but locally compensated (see e.g. Ref. [1] for the LHC and [2] for the SSC). This background activity will then be interrupted, in order of priority, by:

1. the requirement to install as soon as possible magnets which are out of geometrical tolerances,

2. to keep in stock some of the magnets with best geometry, for later installation at critical locations in the DS's.

3. not to install end to end more than three magnets with an out-of-tolerance b_1 (transfer function) and/or a_1 (field direction) error.

This priority list stems from how local the action shall be. The geometry issues have to be solved at the magnet level to maximise the mechanical aperture of the ring; the b_1/a_1 issues must be sorted out at the cell level to warrant a full correctability of the closed orbit up to 7 TeV; the impacts on beam dynamics of the non-linear field errors can be controlled at the sector or ring level to minimise more or less globally the induced detuning and resonance driving terms.

GEOMETRY

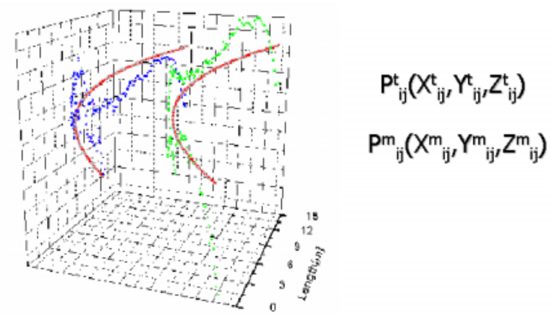

Figure 1: Mechanical axis of a two-in-one LHC dipole and best fit in 3D with the geometrical axis (courtesy of M. Bajko).

During the fiducialisation process taking place after the cold test, the mechanical center of the cold bore tube, or mechanical axis, is measured along the two apertures of the magnet and fitted (in the r.m.s. sens) by two arcs of a circle with the nominal radius of curvature and the nominal beam separation. This defines the so-called "geometrical axis" (GA) of the dipole (see Fig. 1). In order to optimize the mechanical acceptance of the LHC arcs, the base line is to install the magnets in such a way that the geometrical axis of the two apertures coincides with the machine axis, i.e. the reference trajectories of the two beams defined by the survey network in the tunnel. Requesting an H and V beam clearance of 8.5σ (corresponding to 10σ at $45°$ with the aspect ratio of the race-track LHC beam-screens), the main dipoles can be sorted into 3 different classes, the **golden**, **silver** and **mid-cell** classes. The corresponding mechanical tolerances are shown in Fig. 2 and are applied respectively depending on whether the dipole is suitable for machine slots very demanding in terms of aperture (i.e. in the DS up to Q13 where the optics matching to the arcs is not yet completed), close to a quadrupole of the regular arc (where, due to the Ring1/2 optics antisymmetry, the sizes of the two beams are maximal in one of the two transverse planes) or at mid-cell (where the aperture margin is improved due to the simultaneous reduction of the β's and dispersion in the two magnet bores). With the exception of the magnets which need to be aligned by their extremities (see [6] for more detail), these tolerances stand for the maximum deviations of the magnet mechanical axis with respect to its geometrical axis as defined on the fiducialisation bench. They leave a budget of 1.2 mm (H) $\times$ 0.9 mm (V) for any additional error taking place after fiducialisation, essentially ground motion effects after one year of operation.

FIELD QUALITY

With the latest cross-section 3 [3], the *systematic multipole components* of the main dipoles meet the field quality

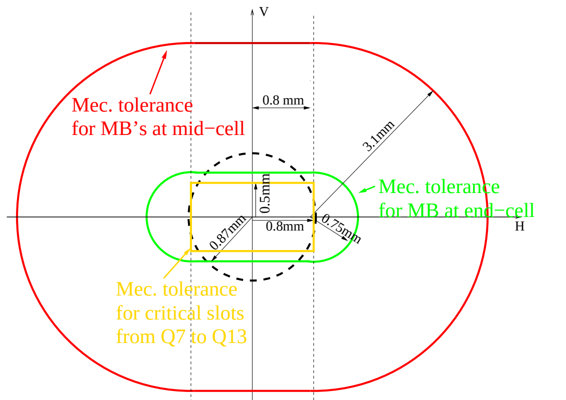

Figure 2: Mechanical tolerances for the dipole extremities (dashed line) and the magnet body (solid lines).

specifications given in Ref. [4], except for the systematic b_7 but with a small signature on the dynamic aperture at injection (0.5σ loss). This clearly cannot be solved by any dedicated sorting scheme, but with a fine tuning of the LHC working point ($Q_{x,y}$=.28/.31 very close to the (7,0) resonance) allowing to recover a target DA of 12σ at injection. The situation is quite different concerning the *random multipole harmonics* varying from dipole to dipole for which a careful ordering of the magnets at installation can allow relaxing some tolerances. Warm and cold magnetic measurements performed on the first $\sim$ 100 cryodipoles and $\sim$400 collared coils, indicate that the random b_1, a_1 and b_3 must be treated with special care, the other random multipoles being within or well within the specifications [4]. Finally both for a_1, b_1 and b_3, the good correlation between apertures (see case of b_3 in Fig. 3) implies that any sorting scheme, if well suited for one beam, will automatically be beneficial for the other beam.

Transfer function and field direction

The field direction (FD) can be interpreted as the magnet transfer function (TF) in the vertical plane with exactly the same importance on the beam control and, therefore, the same tolerance with the conversion rule FD $=$ 1 mrad $\leftrightarrow$ $b_1 = 10$ units (with 1 units corresponding to a relative field error of 10^{-4}). This tolerance is related to the strength limit at 7 TeV of the orbit corrector magnets (MCB) (max. kick of $\Theta_{\max} = 80.8\,\mu$rad). Since both the quadrupole misalignments and the dipoles contribute to the closed orbit in the LHC arcs, the budget has been split such that not more than 30% to 40% of the nominal MCB strength can be used to correct locally (i.e. from cell to cell) the a_1 and b_1 imperfections of the main dipoles. A tolerance of 10 units on the a_1 and b_1 harmonics is materialised with a TF_0 and FD_0 flag assigned to the magnet and is compatible with a blind installation without requiring more than 30% of the MCB strength to correct locally the induced closed orbit at 7 TeV. In between $\pm$10 and $\pm$15 units, the dipoles carry a $\mathrm{TF}_\pm$ and/or $\mathrm{FD}_\pm$ flag. Requesting that at most three consecutive dipoles can carry the same symbol "+" or "-" on their TF and FD flag, only in some worst cases, 40% of the MCB strength will be needed to correct the effect at 7 TeV. Beyond the threshold of 15 units, a dedicated sorting

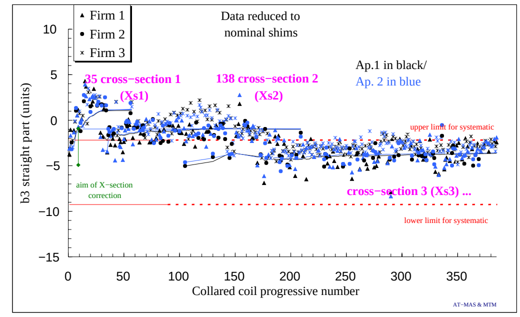

Figure 3: Evolution of the b_3 harmonics in the collared coils of LHC dipoles (courtesy of E. Todesco).

is needed based on a case by case analysis.

Random b_3

In order to preserve the LHC dynamic aperture and control the detunings at injection, the random b_3 has been specified to 1.4 units r.m.s. in the LHC main dipoles [4]. Due to the use of non-nominal shims in the early part of the production and the mixing of cross-sections in a given sector (Xs1/Xs2 and Xs2/Xs3 in sector 7-8 and 8-1, with a net shift of b_3 by -3.5 units at each change of cross-section, see Fig. 3), the overall spread of b_3 should be around 2 and 1.7 units r.m.s. in the first two sectors to be installed, and is then expected to lie on the border of its specification for the 6 remaining machine sectors. The normal sextupole b_3 is however the first allowed multipole in the dipole magnets, and, from experience, is liable to change. It is found to be the first significant multipole which impacts on the LHC dynamic aperture at injection. Finally, the third order resonances are the first low-order resonances close to the LHC working point. Since the calculation of the beam lifetime is presently out of reach of tracking studies, it is advisable to minimize their influence also in case no significant impact on dynamic aperture is found in simulations.

In order to estimate the impact of the random b_3 on the LHC dynamic aperture and to analyse possible remedies by a proper installation scheme, tracking studies have been performed in the four following cases:

- **Case I,II and III**. Random installation, field errors in the main quadrupoles (error table 9901, see e.g. [4, p.64]) and in the main dipoles (assuming MB's with Xs2 [5]), but random b_3 respectively set to zero, 1.4 (as specified in [4]) and 2.4 units r.m.s. (which is pessimistic for the full LHC ring but just covers the situation expected for sector 7-8).
- **Case IV**. Same as case III but requesting a pairing of the MB's such that their b_3 harmonics at injection lies below and above the average b_3[1] ("flip-flop scheme"). Due to the small random component of the b_3 decay (0.5 units r.m.s.) and the good correlation between aperture, this ordering is based on the b_3 component averaged over the two magnet bores and taken at the beginning of the injection plateau.

As illustrated in Fig. 4, an increase of the random b_3 by 1 unit causes a dynamic aperture loss of 1.5σ, bringing it

[1] For chromaticity compensation, b_3 is compensated in average in each sector of the machine by the dedicated b_3 spool-piece corrector circuits.

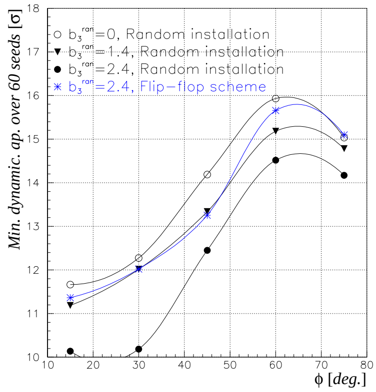

Figure 4: 100'000 turns LHC dynamic aperture $[\sigma]$ at injection as a function of the phase space angle $\phi = \arctan(A_x/A_y)$.

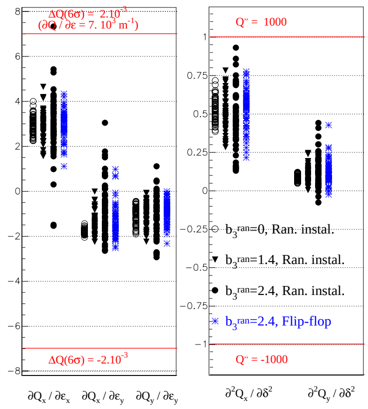

Figure 5: Anharmonicity coefficients $\partial Q_{x,y}/\partial\epsilon_{x,y}$ $[10^3\,\mathrm{m}^{-1}]$ and second order chromaticity $Q''_{x,y}$ $[10^3]$ due to a_3, b_3 and b_4 in MQ's and MB's at injection. Statistics performed over 60 seeds.

below 10σ at injection. This loss is fully recovered with the "flip-flop" installation scheme. As shown in Fig. 5, the non-linear chromaticities $Q''_{x,y}$ and anharmonicity coefficients $\partial Q_{x,y}/\partial\epsilon_{x,y}$ (varying quadratically with b_3) are put back well within target with the proposed scheme.

INSTALLATION ALGORITHM

At any time, the stock of available magnets is divided into two sub-stocks corresponding to the diode mounting of the sector(s) being installed. Prior to any classification, the magnets are attributed with a TF and FD flag as previously defined. Each sub-stock is then split into four classes, i.e. the silver class further divided according to b_3 into the **b_3-up** and **b_3-down** classes, the **mid-cell** and **golden** classes (class 1, 2, 3 and 4, respectively). Each class is finally split into two sub-classes as required by the two variants of cryo-assemblies (type A and B dipoles) which can be considered as equivalence classes in which the magnets can be swapped with a minimum impact on the performance of the machine. Finally the magnets exhibiting strong anomalies related to geometry and/or field quality are concentrated into the so-called **blue class**, and are processed on a case by case basis (see [6] for typical example).

For any installation sequence specified by the engineers in charge, the basic principle consists in proceeding in steps of two consecutive slots. Two magnets belonging to the classes 1,2, 3 or 4 are selected to fulfill the following neighborhood conditions (listed by order of priority):

1. the magnets already assigned to the slots $i-2$ and $i-1$, and selected for the actual slots i and $i+1$ do not carry the same symbol "+" or "-" attached to their TF and FD flags.

2. the magnets selected for the slots i and $i+1$ form a "flip-flop" pair according to b_3.

The demand in terms of geometry triggers the choice of the first magnet, selected in class 4 for the critical slots in the DS up to Q13, or in class 3 (class 1 or 2 if class 3 empty) for the mid-cell slots of the regular arc. The second magnet is then selected in class 1 or 2 in order to satisfy the above conditions. Exceptional violations of the neighborhood condition are allowed without dramatic consequences for the machine performance but some configurations are clearly excluded (e.g. several Xs1 dipoles with a large b_3 installed consecutively in sector 7-8). This activity is interrupted in priority, as soon as "blue magnets" are inserted in the installation sequence and extended neighborhood conditions are defined in that case (see [6] for typical examples), modifying for a while the philosophy of assignment of the few forthcoming slots.

From experience, this strategy allows to follow the LHC installation sequence without holes provided the LHC dipoles are discussed by pool of about 10 magnets at each session of the CERN Magnet Evaluation Board.

CONCLUSIONS

This strategy should allow to preserve or even optimize the machine performance in the presence of dipoles which may not fit with the beam dynamics requirements in terms of geometry or field quality. Being both general and rather flexible, this algorithm should be able to deal with the 8 sectors of the machine without significant interferences with the installation process. Furthermore, in the present context of a reduced cold measurement program, the quality of the warm-cold correlations is considered robust enough for a safe classification and installation of the LHC main dipoles[7].

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