ESTIMATES OF THE LHC MAGNETIC OPTICS VERSUS REQUIREMENTS

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Abstract

The expected field quality of the main magnets of the LHC based on the measurements carried out over a significant fraction of the production is given. Main dipoles, main quadrupoles and insertion quadrupoles are analysed. The more critical parameters and cases of field components out of targets are pointed out, and the implications on the beam optics are outlined. Corrective actions that could still be taken to improve the field quality at this advanced stage of production are discussed.

INTRODUCTION

The production of the magnets of the Large Hadron Collider is well advanced, and has reached half of the quantities for most of the components [1, 2]. All magnets are magnetically measured at room temperature and a fraction of them will be measured in operational conditions at 1.9 K [3]. At the present stage of the production, data are being collected, validated, warm-cold correlations are being established, and the field quality is being steered toward the beam dynamics targets [4]. In this paper we give an overview of the expected field quality of the machine versus the beam dynamic requirements [5]. The work is focussed on the main dipoles and quadrupoles composing the arcs of the machine, and on the special quadrupoles composing the insertion regions. Special emphasis is given to critical points and open problems both for the production and for the circulating beams.

THE DASHBOARD

In Fig. 1 we summarize the data relative to the production of 5 types of superconducting magnets that compose the Large Hadron Collider [6].

The first (black) column represents the percentage of superconducting coils that have been already wound, cured, and clamped in the collars. This is the earliest stage of the production where all the features of the magnetic field are fixed, namely the geometric component (i.e. the position of the coil with respect to the aperture) and its superconducting properties (determined by the conductor type and treatment). After the coil is assembled in the collars, a set of magnetic measurements at room temperature is performed. This measurement gives a precise estimate of the geometric component, and obviously no indication of the superconducting behaviour.

The second (blue) column represents the percentage of cold masses that have been completed, i.e. the collared coil inside the iron yoke, surrounded by the welding cylinder. The object is called cold mass since it is the part of the magnet that is at 1.9 or 4.5 K in operational conditions. This column roughly corresponds to the number of magnets received at CERN.

The third (yellow) column is the percentage of the magnets that have been tested at CERN either at SM18 or at Block4 at 1.9 or 4.5 K.

The fourth (red) column represents the percentage of magnets whose magnetic field has been measured in operational conditions at CERN.

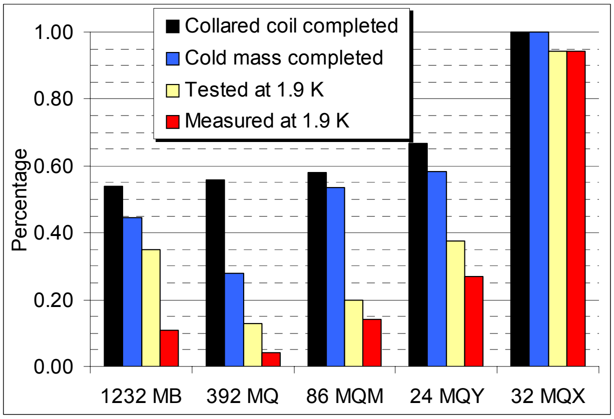

Figure 1: Fraction of coils manufactured, cold mass completed, tested in operational conditions and magnetically measured in operational conditions.

The production of the final focus quadrupoles MQX is completed. For the MB, MQ, and MQM, MQY, one can make the following remarks.

- 55% to 65% of the coils have been completed and measured at room temperature.
- In the case of the MQ, we have a significant difference between the number of collared coils and the number of cold mass. This situation is risky since many coils are being manufactured before having a feedback from cold tests.
- There is some delay between the cold masses produced at the manufacturer and the test in operational conditions at CERN; therefore, a backlog of untested magnets is being created.
- Only a fraction of MB and MQ are expected to be magnetically measured at 1.9 K (around 20%) [3,7]. Whereas for the MB a relevant fraction of magnets has been already measured (10% of total), for the MQ we are below 5%, and more data are needed to establish the warm-cold correlations.
- Data about measurements at 1.9 K for MQM and MQY refer to what has been done in Block4, where the cold masses (bare magnets) are measured in vertical cryostat. Magnetic

measurements give for the time being field harmonics only in the central part, and not the whole integral as seen from the beam. The test program at SM18 of the cryostated magnet has not yet started, and has been recently reviewed in [7].

MAIN DIPOLES

The main LHC dipoles (MB) are needed to bend the particles along the reference orbit, and give the most important contribution to the optics in terms of field errors. 1232 MB are needed for the machine, 1104 in the regular lattice corresponding to 8 arcs, each made up of 23 cells, each one containing 6 dipoles. Moreover, one has 16 MB for each of the 8 insertion regions. The magnets provide a nominal magnetic field of 8.3 T at 11.8 KA with an operational temperature of 1.9 K, over an aperture of 56 mm.

Using the warm magnetic measurements of more than half of the production, and correlations to operational conditions established for 134 equivalent magnets, we make an educated guess of the expected values of the systematic at the end of the production. Warm-cold correlations are well-established, showing no critical points, and we refer to the literature [8] for details. The beam screen impact on field shape (non-negligible on b3, b5, b7) is taken from simulations since no measurements of the final beam screen are available.

Systematic components

In Figure 2 we give a comparison between measured values at room temperature of not allowed field harmonics versus the allowed target range extrapolated at room temperature using warm-cold correlations. All values are within targets.

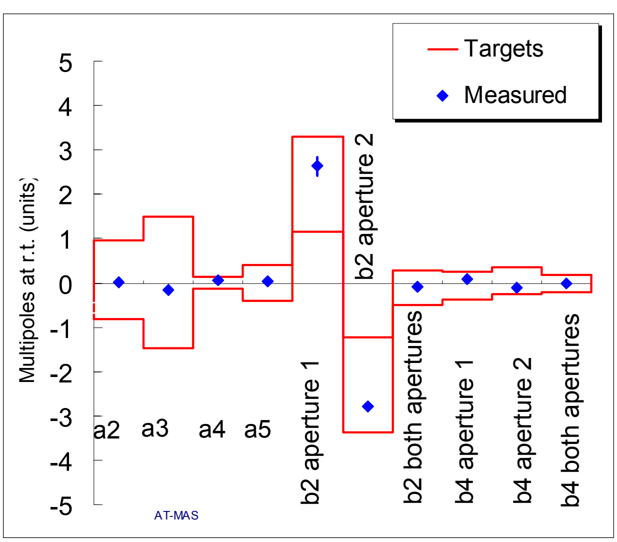

Figure 2: Best estimate of the systematic not allowed multipoles in the MB versus beam dynamics targets extrapolated at room temperature.

For the allowed harmonics the situation is more complicated since three different cross-sections [4] have been used (see Figure 3, left). Therefore when giving the best estimate of the systematic, we have to take into account of the final repartition of cross-sections in the machine. We assume that the cross-section 3 will be kept up to the end of the production, and that will give the same values of allowed multipoles that have been measured up to now.

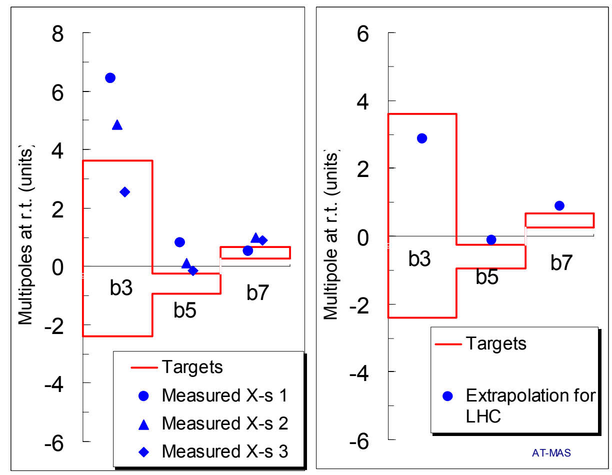

Figure 3: Measured values of the systematic allowed multipoles in the MB for each cross-section type (left) and extrapolation for the final value in the machine (right) versus beam dynamics targets extrapolated at room temperature.

Under these hypotheses, we can give the best estimates of the systematics (See Figure 3, right):

- The normal sextupole b3 is in the upper part of the target range, which is the optimal one from the point of view of beam dynamics. This corresponds to +1.8 units at high field, i.e. well within the 3 units target given by the strength of the correctors for chromaticity. This also corresponds to –5.4 units at injection field, well within the maximal target of 10.5 units.
- The normal decapole b5 is just above the beam dynamics targets, corresponding to 1.2 units at injection field against a maximal target of 1.1 units. This value of b5 gives a 0.5 to 1 sigma reduction of dynamic aperture in the hypothesis of a 20% mismatch in the strength of the b5 correctors. The systematic at high field is of 0.0 units, i.e. within the maximal targets of 0.8 units.
- The normal 14-th pole b7 is above the beam dynamics targets (0.1 units), corresponding to 0.33 units at injection. Also in this case, this gives a small reduction of the dynamic aperture (less than one sigma) according to simulations.

Random components

The variation of main field and multipoles from magnet to magnet must not exceed the budget allocated for the so-called random components. For the integrated transfer function, i.e. the main field component, the closed orbit created by its spread can be corrected at the level of the lattice cell. On the other hand, since each sector is powered separately, and has independent corrector circuits, the budget for the random multipoles is expressed as the maximum tolerable standard deviation (one sigma) over one sector. The best estimate of the spread of the multipoles in operational conditions is given by the sum in quadrature of the spreads measured at room temperature and the warm-cold correlations.

Using this estimate, one finds that the integrated transfer function spread is within targets also if a complete mixing of the cold mass manufacturers is made along the sectors. This has allowed to relaxing the original baseline of installing the same manufacturer in the same octant.

One the other hand, the rule of installing the same cable manufacturer in the same octant has been kept for the inner cable, based on the analysis of the different dynamic behaviour of cables 01B and 01E [8].

The second relevant quantity is the spread of the first allowed harmonic, i.e. the normal sextupole. According to simulations, when this component is increased from the target value of 1.4 units to 2.4 units, a loss of 2 σ in dynamic aperture at injection field is observed.

The delay in the installation has allowed the accumulation of a large stock of dipoles, thus implying that a complete sorting over several sectors of the machine is possible. It has been decided to use this additional degree of freedom to further reduce the random b3, i.e., by installing magnets with 'high b3' and 'low b3' in separate sectors. In Figure 4 we give a tentative estimate of the random components for the first four sectors. Here,

- Sector 7-8 is made up of magnets of type R, mostly with inner cable 01B, and contains the early part of the production, mostly with a mix of cross-section 1 and 2 (only exceptions are 10 magnets from Firm3 with cable 01E, and 4 cross-section 3 magnets).
- Sector 8-1 is made up of magnets of type L, with inner cable 01B, mostly of cross-section 3, with high b3.
- Sector III is made up of magnets of type L, with inner cable 01B, all of them with cross-section 3, with low b3.
- Sector IV is made up of magnets of type L, with inner cable 01E, all of them with cross-section 3.

The estimates of Figure 4 show that all spreads are within targets, with the exception of b3 for Sector 7-8, which is affected by the beginning of the production, mainly by the mix of different cross-section aiming at reducing the high systematic b3. The spread of the integrated transfer function is within the 8 units target in all cases. The spread of b3 is below 1.4 units, and far away from the 2.4 units that start showing strong impact on dynamic aperture according to simulations.

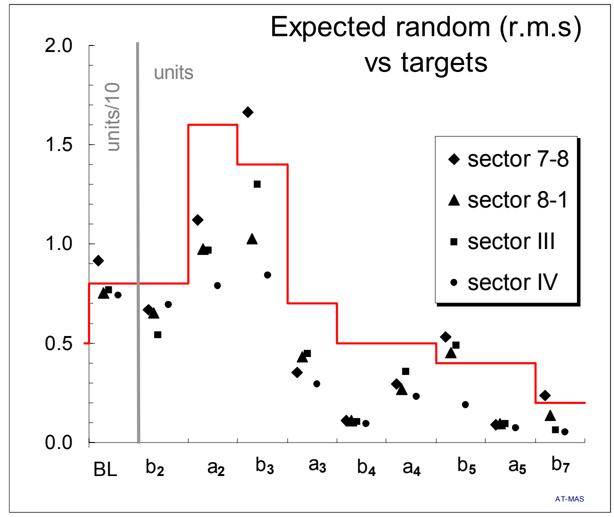

Figure 4: Expected random components in the MB for the first four sectors (one sigma, in units), versus beam dynamics targets.

MAIN QUADRUPOLES

The main LHC quadrupoles (MQ) are needed to focus the particle beams along the machine. 392 MQ are used in the machine; among them, 360 are in the arcs, thus corresponding to 8 arcs, each made up of 22.5 cells, containing 2 quadrupoles each. Moreover, one has 2 MQ for each of the 8 insertion regions, and 8 more in IR3 and in IR7 (cleaning insertions), for a total of 32 MQ in the interaction regions. The main quadrupoles provide a nominal field gradient of 220 T/m at 11.8 KA with an operational temperature of 1.9 K over an aperture of 56 mm.

The MQ are ~ 1/3 of the MB, have a length of ~1/5 of the MB (3.15 m against 14.3 m), and their field at the reference radius of 17 mm is ~1/2 (3.7 T against 8.3 T). This gives a factor 30 in the impact of a field imperfection in the MQ with respect to the MB, the factor being slightly lowered due to the higher beta function in the MQ. Due to this large factor, the beam dynamic targets on the MQ field imperfections are set in order to keep them 'in the shadow' on the MB, and therefore it is very unlikely that they can become critical for the machine. A separate argument is used for the spread of the integrated field gradient, which induces beta-beating that can reduce the physical aperture of the machine. This is by far the more critical issue of the MQ field quality [10].

Warm magnetic measurements of more than half of the production are available. Correlations to operational conditions have been established for 16 magnets for the more critical components (field gradient, b6), but for some low order not allowed multipoles are not yet assessed. In the followings, we will extrapolate the warm data to operational conditions under the following simplifying assumptions.

- The spread in operational conditions is equal to the spread measured at room temperature.

- The only offset between operational conditions and room temperature measurements is in b6 at injection field, and is assumed to be equal to –4 units as evaluated through measurements.
- The beam screen impact on field shape (non-negligible on b4, b6, b8 and b10) is taken from simulations since no measurements are available.

Issues specific to the warm-cold correlations will be analysed in a separate subsection.

Systematic components

Not allowed normal systematic components are close to zero as expected by symmetry (see Figure 5). The systematic component of b6 measured at the beginning of the production (cross-section 1) is 1.5 units larger than target. Such values of b6 lead to losses of dynamic aperture at injection; for this reason a second cross-section has been issued after the completion of two sectors (i.e. approximately 90 quadrupoles). This revised baseline has a 2.5 units lower b6, thus matching well the beam dynamic targets (see Figure 5). The measured value is given by ~100 magnets with cross-section 1 and ~100 with cross-section 2. Assuming that the rest of the production will have cross-section 2, the tentative estimate for the final value shown that systematic b6 will be within targets. The systematic skew components are also within targets (see Figure 6).

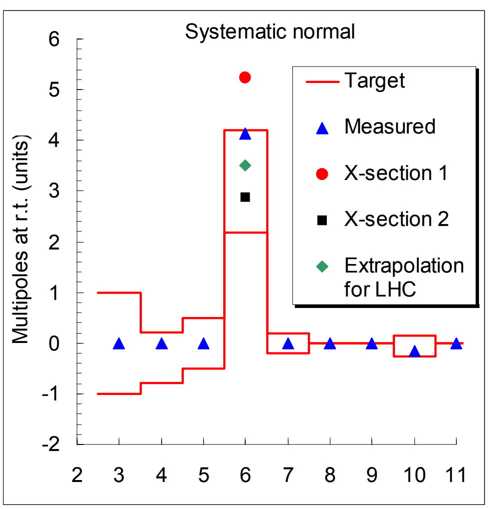

Figure 5: Expected systematic components in the MQ for the normal multipoles measured at room temperature versus beam dynamics targets extrapolated at room temperature

Random components

The most critical random component is the spread of the integrated field gradient. Its budget (10 units for one sigma) is determined by the beta-beating budget (14% for the on-momentum case, plus 7% for the off-momentum, for a total of 21% budget, corresponding to 10% beam size blow-up). The spread of the field gradient in the room temperature measurements is 12 units, i.e. 20% more than the target (see Figure 7). According to the experience acquired during the production, and to the results given by simulations, it will be hard to reduce this spread. On the top of this spread, one has to add the warm-cold correlation, which for the present set of data is about 5 units. A sorting strategy is being applied to reduce the integrated field gradient spread.

The random b6 is much larger than target due to the large impact of the cross-section change on b6; this out-of-target is not critical. For the skew components, everything is within targets (see Figure 8).

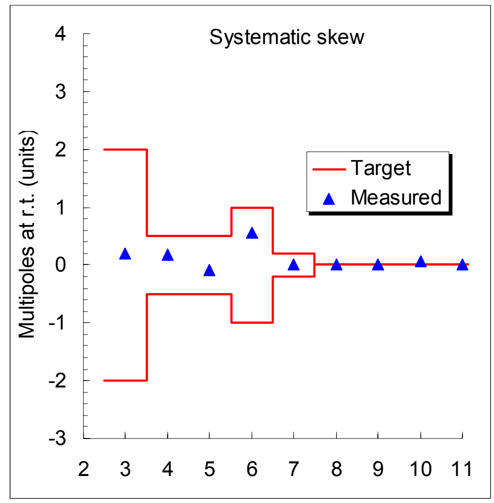

Figure 6: Expected systematic components in the MQ for the skew multipoles measured at room temperature versus beam dynamics targets extrapolated at room temperature.

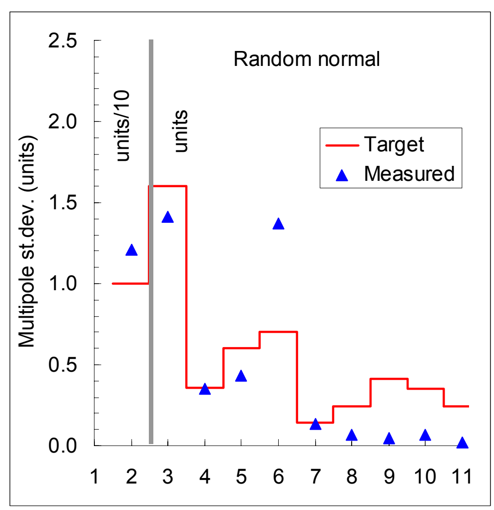

Figure 7: Expected random components (one sigma) in the MQ for the normal multipoles versus beam dynamics targets.

Critical issues: collar permeability

After producing more than two octants of collared coils, high values of the magnetic permeability (up to 1.04, against a tolerance of 1.005) have been observed in some batches of the stainless steel collars. According to simulations, an additional 0.01 in permeability gives rise to 30 units of b2 and -2.5 units of b6, i.e. it can spoil both the uniformity of the field gradient and the systematic b6.

Magnets produced with these collars have shown in room temperature magnetic measurements high values of integrated field and low values of b6 (see Figure 9), below the limit for the systematic. The origin of the problem has been traced back to the steel producer, and steps are being taken to solve the problem. At least 40 magnets are being affected by this feature. One of these magnets has been measured at 1.9 K, and has shown no anomaly: therefore, for this magnet warm-cold offset do not fit with the previously established values. For the b6 offset between room temperature measurements and injection field, the measured offset is 1.5 units instead of -4 units (see Figure 10). A similar loss of correlations is seen in the integrated field gradient. A special program of measurements is being done to verify this effect and to check if the model to extrapolate warm data to operational conditions can include these anomalous permeabilities.

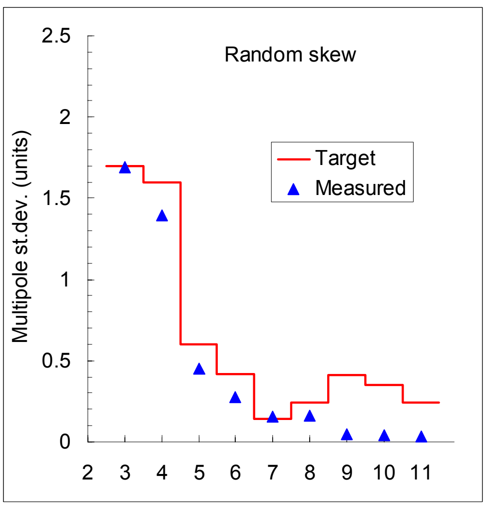

Figure 8: Expected random components (one sigma) in the MQ for the skew multipoles versus beam dynamics targets.

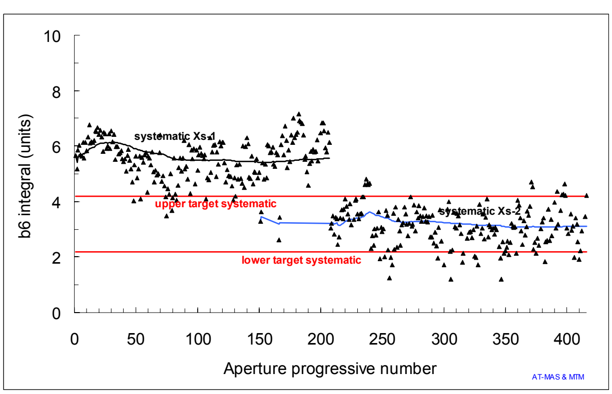

Figure 9: Measured b6 (dots) versus collared coil progressive number, and limits for the systematic (solid lines).

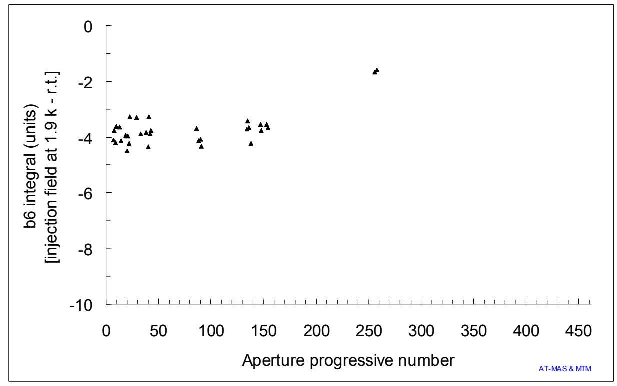

Figure 10: Measured offset in b6 between injection field and room temperature measurements (dots), and anomalous correlation (around number 250).

MQM QUADRUPOLES

The MQM are quadrupoles with an aperture of 56 mm, to be placed in the Dispersion Suppressors (48), and in the Matching Sections (38). Their main feature is that they are independently powered, and their function is to make the transition of the optics functions from the regular cells to the interaction regions. They are produced with three different lengths (MQM, MQMC and MQML) and are assembled in cryostats labelled by Q5 to Q10 (the so-called Special Short Straight Sections) that can contain more than one unit of these magnets, plus the correctors. The MQM provide a nominal field gradient of 160 to 200 T/m at 4.3 or 5.4 KA with an operational temperature of 1.9 or 4.5 K, and a magnetic length of 2.4 to 4.8 m [11].

The field quality is expected to be at the same level as in the MQ, since they have similar features (but different coil layout). Indeed, these magnets operate at different currents, whereas the compensation of the persistent current contribution with the geometric component can be done only for one value of the injection field. Therefore, several units of b6 can be expected, depending on what is the lower value of the current that is used for each magnet. The second order allowed field harmonic b10 is also affected by this feature. A first estimate of this effect on dynamic aperture shows a visible effect on high amplitudes (larger than 12 sigma) [12].

The spread of the integrated field gradient is of the same order as in the MQ. Indeed, the situation is different since the MQM are individually powered. On the one hand, if all MQM are measured in operational conditions, one can accept any spread in the integrated transfer function, and recover the different gradients with the powering current. On the other hand, if only a fraction is measured and one has to rely on warm-cold correlations, their gradients are not exactly known and therefore they can give additional beta-beating that is not included in the present budget. This constitutes a strong argument for having all the special short straight sections measured at 1.9 K. The alternative is to measure them with the beam during the commissioning, which is very time-consuming.

MQY QUADRUPOLES

The MQY are large aperture quadrupoles (70 mm), to be placed in the Matching Sections (24). As the MQM's, they are independently powered, and their function is to make the transition of the optics functions from the regular cells to the interaction regions. There are assembled in cryostats labelled by Q4 to Q6 (the so-called Special Short Straight Sections) that can contain more than one unit of these magnets, plus the correctors. The MQY provide a nominal field gradient of 160 T/m at 3.6 KA with an operational temperature of 4.5 K, and a magnetic length of 3.6 m.

The field quality is comparable to what expected for the final focus quadrupoles MQX, which have the same aperture. We pin out the following critical issues.

- As for the MQM, the geometric value of b6 can compensate the persistent current only for a given value of the injection field, which is indeed a free parameter; indeed, the problem is less serious than for the MQM due to the larger aperture.
- Due to the high value of the beta functions inside these quadrupoles, a very good level of field uniformity is required. Simulations using measured errors show that a reduction of up to one sigma is observed in the critical region below 11 sigmas.
- As for the MQM, the knowledge of the transfer function would allow any spread in the field gradient. On the other hand, if no measurements are available, a large contribution to beta-beating, beyond the allocated budget, is given.
- More than 40% of the production is affected by a magnetic permeability of collars beyond tolerance, leading to similar effects to what observed in the MQ (loss of correlation, higher transfer function and lower b6 measured at room temperature).

MQX QUADRUPOLES

The MQX are large aperture quadrupoles (70 mm), to be placed in the Interaction Regions (4 MQXA and 4 MQXB per interaction region, for a total of 16+16 quadrupoles). Each MQXA is placed in the cryostats labelled Q1 and Q3, whereas two MQXB are placed in the cryostat labelled Q2, plus corrector magnets. Their function is to provide the final squeeze of the optic at the interaction point. The MQX provide a nominal field gradient of 215 T/m at 7.1 or 11.9 KA with an operational temperature of 1.9 K, and a magnetic length of 5.5 to 6.5 m.

All magnets have been measured at room temperature, and most of them at 1.9 K; results have been presented in [13,14]. Field quality of these magnets is extremely good, being below one unit for all multipoles. The only exception is a systematic component of b4 in the MQXB of around 1.2 units, most probably due to a systematic ovalization of the coil. This component can be corrected by b4 correctors; this need all the force of the b4 correctors for a complete correction but the effect does not needs to be corrected at 100%. This out of tolerance is therefore considered as not critical.

CONCLUSIONS

We have given an overview of the expected field quality of the machine, based on the numerous set of measurements available at this advanced stage of the production. Tentative conclusions about the critical points are the followings.

- For the main dipoles, the systematic values of b5 and b7 will be marginal, leading to a loss of up to 1 sigma in the dynamic aperture at injection, which is considered as non critical.
- For the main quadrupoles the budget allocated for the spread of the integrated field gradient is tight, and is already 20% more than target at half of the production, in the data at room temperature. A sorting procedure is being used to reduce the impact on the beta-beating.
- For the main quadrupoles correlations are not yet completely assessed for some multipoles.
- For the MQ and for the MQY the use of collars whose magnetic permeability is out of tolerance is endangering the reliability of warm-cold correlations.
- For the MQM and for the MQY it is instrumental to have measurements at 1.9 K of the integrated field gradient to avoid a cumbersome beam-based measurement during the commissioning. Measurements of field harmonics are also mandatory to estimate the impact on dynamic aperture at injection energy.

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