MAGNET ACCEPTANCE AND ALLOCATION AT THE LHC MAGNET EVALUATION BOARD

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Abstract

The normal and superconducting magnets for the LHC ring have been carefully examined to insure that each of about 1900 assemblies is suitable for the operation in the accelerator. Hardware experts and accelerator physicists have contributed to this work that consisted in magnet acceptance, and sorting according to geometry, field quality and quench level. This paper gives a description of the magnet approval mechanism that has been running since four years, reporting in a concise summary the main results achieved.

THE MAGNET EVALUATION BOARD

A total of 1900 magnet assemblies, mostly superconducting, have been produced, tested and installed during the construction of the Large Hadron Collider (LHC) at CERN. Once the magnet production and delivery started gaining pace, the magnet acceptance and the decision on the optimal tunnel location, based on the result of electrical performance tests as well as the measurement of magnetic field and geometry, became a critical step in the life-cycle of a magnet. A *Magnet Evaluation Board* (MEB) was established in May 2002, charged of magnet acceptance and sorting for the whole ring. The MEB consists of members from accelerator beam physics (*ABP*), the engineers in charge of the magnet assembly and installation activities (called here *magnet coordinators*) and experts in various magnet-specific topics such as electrical performance, magnet protection, field quality and magnet alignment. In practice, the mission of the MEB has been to find suitable tunnel locations (also called *slots*) for the available magnets, preserving and (if possible) optimizing the machine performance. This was done following the planned installation schedule, and including provisions to face day-to-day requirements, such as non-conformities or faults discovered during the preparation of the magnets for installation. One of the first difficulties with which we were confronted was the methods and tools to be adopted for this sizeable work. In addition, it was difficult to find information on the practicalities of accepting and optimizing the location of *real-life* magnets, each with different specific manufacturing features, geometry and, in the case of superconducting magnets, training. The only well-documented procedure available to us was the one for RHIC [1] which provided much of the inspiration behind the MEB.

The definition of working tools and procedures together with the following implementation was a major milestone in understanding what are the important features for magnet installation and operation. This process was mainly tailored for the main bending magnets (MB) available in appreciable quantity at that time. However, we took care to maintain the tools and procedure as general as possible so that they could be applied, with minor adjustments, to the whole magnet population. Figure 1 describes schematically the workflow of the magnet proposal, discussion and approval process. The preparatory work that took place before the meeting represented a large effort, and was necessary to make the discussion of the magnets as efficient as possible.

The magnets to be discussed at a Board meeting were selected by the magnet coordinators and the ABP team, based on the availability (delivery schedule or stock of magnets ready for discussion), on anticipated sorting performed by the ABP team using magnet data from industry, and on specific requests for installation. Prior to the meeting the magnet coordinator prepared the magnet documentation consisting mainly in an *ID card* that contained a summary of the magnet characteristics, a synthesis of magnetic and geometric measurement data, quench levels (relevant for superconducting magnets only) and a list of the main non-conformities encountered in the magnet production and test process. The ID card was complemented by a *performance assent* (only relevant for superconducting magnets, summarising the quench and electrical performance), a *geometric report* (with details of the magnet geometry and magnetic alignment), and a *non-conformity report* (with details of the most critical non-conformities). The above mentioned

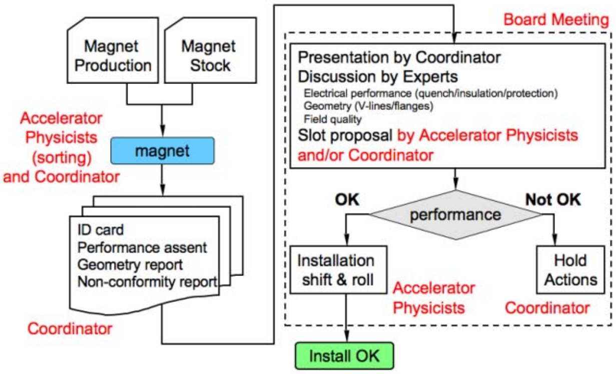

Figure 1. Workflow diagram for the meeting preparation and operation of the Magnet Evaluation Board.

documentation formed the basis of the magnet discussion at the Board meeting, and was presented and commented by the coordinator and the magnet experts.

The general policy adopted was that non-conformities, mostly related to mechanical out-of-tolerance, geometry (alignment) and electrical performance had to be resolved prior to the presentation at MEB, so that they would be either closed at the moment of discussion, or a resolving action could be defined following a known and validated procedure. Under all circumstances, non-conformities critical for magnet performance remained under the responsibility of the magnet coordinators and were not resolved by sorting in the tunnel. The only exceptions were cold bore geometry and quench performance of corrector magnets. Specifically, the quench level of a superconducting magnet is one of the few parameters that result in a direct accept/reject decision, and can only be determined with a cryogenic test. Because of this, all superconducting magnets had to be tested in nominal cryogenic conditions before they would be eligible for the discussion at the Board, thus eliminating the uncertainty on the cold magnet performance.

The discussion at the Board focussed on whether the magnet performance was suitable for the proposed slot (provided either by the ABP sorting, or by hardware constraints). In case of positive outcome, the magnet was allocated to the proposed slot, and released for installation. The position of each magnet in the tunnel was further optimized by defining *installation shifts* and *installation rolls* that maximise the aperture and minimise magnetic feed-down and rotation. In few cases, missing information at the time of the meeting, or unsatisfactory performance, resulted in a "hold" decision that was followed-up by the magnet coordinator in collaboration with the ABP team who would then either resolve the issue or find a substitute in the pool of available magnets. Thanks to the preparatory work, however, this branch of the workflow diagram was very rarely reached (typically less than 5 % of the magnets).

A key element to the whole process was the rapid availability of the relevant information to the whole Board. We made extensive use of the Manufacturing and Test Folder (MTF) containing components identification, manufacturing data, and all non-conformities reports, as well as dedicated databases (for geometry and field measurements). Specialized software was developed to produce the data extraction and reports (such as the ID card or the Non-Conformity report) allowing a fast turnover in the preparation and sharing of the information required for the magnet qualification and sorting.

RESULTS

Arc Dipoles

A large part of the work of the MEB has focussed on the 1232 MB's, because of their importance in achieving the LHC performance (energy, aperture, field quality). We could make use of the accumulated production stock to sort batches of magnets pre-selected to form a whole LHC sector (154 MB's). Geometry was the main concern in allocating a magnet to a slot. The MB's were classified according to their geometry (see [2]-[5]), and assigned to tunnel slots following the installation algorithm defined in [3]. The main result is that we do not expect aperture limitations in the arc dipoles. Magnetic sorting was aimed at reducing the random variation of the integral transfer function (b_1), skew quadrupole (a_2) and normal sextupole (b_3) with respect to the average values of each sector. The sorted sequence is expected to be significantly better than a random installation, with a gain of the order of a factor 2 to 3 on the required orbit corrector strength, coupling resonance and vertical dispersion, and third order resonance driving terms.

Arc Quadrupoles

The second class of magnets, in terms of quantity, is that of arc quadrupoles, assembled with a pair of dipole orbit correctors and a corrector package in one of the 360 arc Short Straight Section (SSS) [6]. The situation for SSS's was rather different when compared to the dipoles. Each SSS was built in industry with a much larger number of variants (60) than for the dipoles. Furthermore, all the arc quadrupole locations are equivalent in terms of optical conditions, and the mechanical aperture could not be improved by changing the location of a given SSS. Sorting of the integral transfer function, described in [6], [7], was used to reduce the beta-beating associated with the deviation of the quadrupole strength from the average of a sector. This required early interaction with the magnet manufacturer, and was based on warm magnetic measurements taken on the collared coils [6]. The beta-beating contribution of the optimized sequence of arc quadrupoles is expected to be well within the allocated budget (8.1 % peak and approximately 2.5 % r.m.s. for both planes and beams, over the whole LHC) in spite of a b_2 r.m.s. of 12 units, for the whole quadrupole production, which is 20 % above the specification. The constraints on aperture are tight at the arc quadrupoles, and a significant number of SSS's were found to be outside the specified aperture targets. Optimized installations shifts were specified, ranging from 0.1 to 0.3 mm, and rolls, in the range of -1 to 1 mrad [8]. Thanks to these, most SSS's return within the tolerance bounds, and the maximum residual aperture loss is estimated at 0.1 σ, which is small.

DS and MS Straight Sections

The straight sections of the dispersion suppressor (DS, 64 assemblies) and matching sections (MS, 50 assemblies) form the third largest group of magnets in the LHC. These assemblies, containing different types of quadrupoles and orbit correctors, are in reality very inhomogeneous in configuration and size. The majority of DS and MS assemblies is specific to tunnel location. A matter of concern was the long training in the MQTL magnets that are used to match the optics in insertions. The policy adopted was to sort the MQTL magnets so that non-conform magnets would be installed in the vicinity of the cleaning insertions regions (IR3 and IR7), where the current setting is firm due to the tight optical constraints imposed by the collimation system, and below nominal. In all other slots the MQTL have to reach nominal current to guarantee full flexibility in the powering envelope. Once this was done, the DS and MS assemblies were analysed on a one-by-one basis and, when possible, sorted by geometry. It is worth recalling that some field quality sorting was made by the magnet coordinator in case of assemblies containing several quadrupoles, while the specific case of the Q6 assemblies in IR3 and IR7 containing 6 MQTLH magnets in series was made by the ABP team. Thanks to the installation shifts and rolls specified, the final aperture is expected to be broadly preserved, with a modest loss (at most 0.3 σ) at locations where the optical conditions are especially tight (e.g. IR3, IR7 and in the dispersion suppressors) [4], [8]. Optics work is in progress to remove the aperture bottlenecks.

Low Beta Quadrupoles

The superconducting low-beta quadrupoles (optical elements Q1, Q2 and Q3, 24 assemblies), provided within the scope of the US-LHC and Japan-LHC collaborations, are among the most critical elements in the LHC. All delivered magnets performed to specifications, and the field quality was within targets, with good compensation of field errors among the two magnet modules making up a Q2 assembly. Sorting was based on the geometry, in view of maximizing the aperture. The alignment shifts specified for these magnets have been optimized to achieve an aperture of 8.4 σ, with a minimum quadrupole feed-down, so that local orbit corrections should require at most 30 % of the dipole corrector strength [4]. In longitudinal direction, the position has been set within the interconnection range, aiming at a minimum beta-beating within the allocated budget of 7 %, and leaving margin for further longitudinal adjustment if necessary at a later stage.

Cold Separation and Recombination Dipoles

These superconducting magnets (16 assemblies), corresponding to the optical elements D1 (in IR2 and IR8), D2, D3 and D4 (in IR4), were also provided within the scope of the US-LHC collaboration. They were cold tested before shipment to CERN, and, in most cases, already prepared for a specific slot. Field quality was within the specifications, and early interaction with the production team at BNL was beneficial in allocating the best magnets to the most critical slots. The analysis of aperture was done on a one-by-one basis using fiducialisation data taken at CERN after shipment. The main issue was the observed deviations (up to 2 mm) between the expected straightness and the measured shape of the cold bore. Installation shifts were sufficient to recover the specified aperture.

Normal Conducting Magnets

This class comprises several types of dipoles distributed over all long straight sections, namely D1 (in IR1 and IR5), D3 and D4 (in cleaning insertions) and the quadrupoles (MQW's) in the cleaning insertions. The multipole components in most of these magnet types are small and field quality was not a sorting criterion. The magnets were selected to insure that the mechanical aperture is preserved and to minimize the impact of random variation of the transfer function for magnets powered in series. The most critical magnets of this class were found to be the MQW's. These are twin aperture normal conducting quadrupoles whose field quality and bore size is limited by the imposed beam separation. Both magnetic (minimization of the beta-beating) and geometric sorting was applied [4]. The aperture at few locations in these assemblies is expected to be smaller than the specified target (6 to 6.5 σ), which, however, is acceptable as these magnets have specific protections and are normal conducting devices.

CONCLUSIONS

The work of the MEB was formally completed in March 2007 with the acceptance of the last LHC magnet. We have produced a sequence of magnets that is compatible with the expected performance. When compared to a random installation, sorting has guarded against a loss of mechanical aperture estimated at 1.5 mm, a loss of dynamic aperture estimated at 1 σ, and an increase of beta-beating by 5 to 10 % This can be considered as a direct added value of MEB, in addition to the systematic, but much less glamorous work, of making sure that all installed magnets do conform with the hardware specifications that pertain to their function.

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REFERENCES

[1] J. Wei, et al., Proc. of PAC, New York, 3176-3178, 1999.

[2] S. Fartoukh, Proc. of LHC Workshop Chamonix-XIII, pp.148-158, 2004.

[3] S. Fartoukh, Proc. of EPAC, Lucerne, pp. 176-178, 2004.

[4] J.B. Jeanneret, LHC Project Report 1007, June 2007.

[5] E. Wildner, Proc. of LHC Workshop Chamonix-XIII, pp. 127-137, 2004.

[6] T. Tortschanoff, et al., Completion of the Series Fabrication of the Main Superconducting Quadrupole Magnets of LHC, these Proceedings.

[7] A. Lombardi, Y. Papaphilippou, Proc. of EPAC, Edinburgh, pp. 2017-2019, 2006.

[8] D. Missiaen, et al., Geometry of the LHC SSS Before Installation in the Tunnel: Resulting Aperture, Axis and BPM Positioning, these Proceedings.