MAGNETIC REQUIREMENTS FOR COMMISSIONING

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INTRODUCTION

The magnet production is approaching the end: between 85% and 95% of the main magnet coils have been assembled. The activities related to the magnet field quality and performances are shifting from the production follow-up to the recovery of all the information that could easy the beam commissioning and the machine operation. Therefore, more time of the test benches is being allocated for special measurements to better understand the behaviour of the orbit correctors (Section 1), of the tune and chromatic correctors (Section 3), and of the dynamic effects and powering history to build a field model of the machine (Section 4). Other relevant issues presented in the session are the estimate of the beta-beating based on the available measurement and taking into account the installation sequence (Section 2), and the evaluation of the magnet training in the tunnel needed to operate at nominal energy (Section 6). Finally, a report on the activities of the Magnet Evaluation Board, focused on the gain obtained through sorting (Section 5) and a discussion on the ongoing estimation of the parasitic fields (Section 7) are given.

1. ORBIT CORRECTION AND FEEDBACK (R. STEINHAGEN)

The orbit correctors, made with the superconducting technology, are expected to undergo many field changes during the same run. For this reason, a pre-cycle is necessary to bring the correctors in the same reproducible state at the beginning of each run.

The behaviour of the MCBH and MCBV orbit correctors has been measured in Block4. These correctors are operated at a maximum current of 55 A, corresponding to a kick of 1.3 mrad at injection, and of 81 μrad at high field. The standard pre-cycle has been defined as 0 A→55A→0A: this gives a remenant field of 8.4 10^{-4} T, with a spread of 0.8 10^{-4} T (one standard deviation). This corresponds to a kick of 0.56±0.05 μrad, which gives a negligible effect on the beam and poses no problem for operation. Therefore, there is no need of a degaussing cycle which would set the systematic part to zero.

The impact of small hysteresis loops on the feedback system has been also analysed, showing that they do not affect the convergence of the correction algorithm. Finally, it has been shown that the measured stability of the power supply meets the requirements.

2. ESTIMATES OF BETA-BEATING (S. SANFILIPPO ET AL.)

The aim of the work is estimating the beta-beating based on the results of the magnetic measurements and on the installation sequence. The budget allocated to the beta-beating (21%) is related to constraints on the mechanical aperture of the machine. The sources are

- the spread in the transfer function of the quadrupoles powered in series;
- the knowledge of the transfer function of the individually powered quadrupoles;
- the uncertainty in the absolute knowledge of the transfer function;
- the systematic and random b2 in the dipoles;
- the dependence on the powering history.

A quadrupole transfer function model is being developed. It relies on the measurements at 1.9 K when available (sampling of ~ 10%), on the room temperature measurements, on the slot allocation and on the uncertainty in the calibration of the measuring systems. In case of missing data (magnets still to be manufactured, or not measured at 1.9 K), values are generated from Gaussian distributions whose parameters are determined on the ground of the acquired experience.

The model predicts a beta-beating of 17%-18%, i.e. within targets. The more relevant contribution comes from the b2 spread in the main quadrupoles, which accounts for 10-12% of beta-beating. Additional work is needed to estimate the dynamic part in the quadrupoles. Moreover, investigations will be carried out to evaluate the contribution given by the feed-down of the sextupole correctors.

3. TUNE AND CHROMATICY CORRECTION (W. VENTURINI)

The tune and chromaticity correction magnets, as the orbit ones, are made with the superconducting technology, and exhibit a significant hysteresis. This can have implications on the reproducibility of the magnet transfer function between different runs, and on the feedback control. Hysteresis heavily depends on the superconducting properties of the cable, and it has been shown that it can vary up to a factor two, depending on the deformation of the Nb-Ti filaments.

Six modules of trimming quadrupoles MQT have been measured. The hysteresis corresponds to a tune shift of 0.005, above the tolerance of 0.003. The nominal value of the trim quadrupoles is zero current, and this is not optimal since around this value the magnetic behaviour is less reproducible. For this reason it is suggested to operate the trim quadrupoles around a nominal current of 6 A, providing a tune shift of 0.2. The decay of b2 in the quadrupoles and the subsequent snap-back (2 units) corresponds to a tune shift of 0.01, and therefore it has to be corrected. If the hysteresis is neglected and a linear model is adopted to determine the current of the correctors, one has a residual uncorrected tuneshift of 0.0014, i.e. within specification. It has been verified that minor hysteresis loops can be easily absorbed by the feedback system.

The maximum width of the hysteresis loop for the MS (lattice sextupoles) and MCS (spool pieces) corresponds to 18 and 6 units of chromaticity respectively, i.e. well above the tolerance of ±2 units. For the MCS, if a linear model is assumed to correct the decay of b3 in the dipoles, an uncorrected chromaticity of up to ±3 units is found. This is not critical for the early phase of commissioning, but should be worked out to obtain the final chromaticity tolerance of ±2 units.

The residual field of Landau octopuses is critical, since it is above the specified value imposed by beam dynamics. For this reason a degaussing cycle has been proposed and successfully tested in one magnet.

4. FIELD MODEL DELIVERABLES (M. LAMONT)

The aim of the field model is to provide a first estimate of the optimal values of the magnet currents to be used in the machine cycle, based on the knowledge acquired with magnetic measurements.

Both for the dipoles and for the quadrupoles, the transfer function in its dependence on the current can be evaluated for a set of magnets connected to the same power supply. The model estimates the field by splitting the different contributions in static components (geometric, magnetization, saturation and residual) and dynamic components (decay, snapback and coupling currents). The second ones also depend on the powering history and on the ramp rate. The same approach is used for estimating the field harmonics.

Implementation in a code (FiDeL) is ongoing and a first version should be available for the sector test, which would allow a first relevant validation of some of the machine settings based on magnetic measurements. It is foreseen to have the code on-line, so to provide the optimal current settings at each fill of the machine, and allowing to take into account of the powering history.

5. WHAT WE GAINED WITH SORTING (L. BOTTURA)

The Magnet Evaluation Board (MEB) has the mandate of assigning the magnets to optimal positions in the lattice to maximize the machine performances. This activity has to satisfy the stringent installation schedule. Nearly half of the main dipoles and one third of the main quadrupoles have been allocated in January 2006.

Since very small systematic differences between dipole manufacturers have been found at the beginning of the production, it has been decided to give up the initial baseline of installing the same dipole manufacturer in the same sector. The only constraint which is still retained is to avoid mixing the inner cable manufacturer in the same sector.

For the main dipoles, the criteria used for allocating slots are 1) maximizing the physical aperture of the machine by allocating magnets with the worse geometry in the slots which require less aperture; 2) minimizing the spread in the transfer function to insure that the closed orbit can be corrected with less than 30% of the corrector strength; 3) minimizing the driving term of the 3rd order resonance by reducing the effective spread of b3; 4) controlling the coupling resonance and vertical dispersion through an appropriate compensation of the a2 components. The obtained results are the following ones.

1. The allocation to specific slots taking into account of the actual size of the beam has allowed to install magnets with a shape out of tolerances, without affecting the physical aperture of the machine.
2. A sorting to minimize the spread of the transfer function has been used for the very early phase of the production, when this parameter was above the target.
3. The initial phase of the production, characterized by high values of the systematic b3 due to the geometry of the coil lay-out, has been assigned to the first two sectors. For these two sectors the spread of b3 is 15% larger than target: local compensation and pairing at 180° or 360° of phase advance has allowed to reduce it by a factor three. Even though the spread of b3 in the rest of the production is from 5% to 30% below target, these sorting algorithms have been used to further reduce the driving term of the 3rd order resonance.

For the main quadrupoles, one has less freedom in the installation due to the different types, and the batch selection is made before the cold test to fit the schedule. The two criteria use for allocating slot are 1) maximizing the physical aperture of the machine and 2) minimizing the beta-beating by reducing the effective spread of the quadrupole transfer function.

1. For the quadrupoles, the aperture requirements are the same for all positions. Therefore, in case of out of geometry out of specifications, a special installation with shift and rolls has been adopted to avoid the loss of physical aperture.
2. The expected beta-beating from the quadrupoles, within targets for each sector, has been further minimized by an appropriate pairing of magnets with large b2 spread, gaining a factor 2 to 3.

6. EXPECTED QUENCH LEVEL WITHOUT BEAM (P. PUGNAT)

An estimate of the number of quenches necessary to have the LHC working at the nominal energy of 7 TeV has been carried out. The analysis presented at the workshop is restricted to the main dipoles and quadrupoles.

For the main dipoles, the quench performance of 908 magnets has been evaluated; most of them have been cooled down, tested, and warmed up only once, whereas 115 have been tested a second time after the warm-up (the so-called test after thermal cycle). The data relative to these magnets show that 79% reach the nominal field (8.33 T) without quench, 17% reach after 1 quench, 3% after 2 quenches and 1% after 3 quenches. A plain extrapolation of these results to the 1232 main dipoles of the machine gives a total number of ~300 quenches to reach nominal field, i.e. ~40 per octant. Indeed, only the magnets with the weakest performance underwent this type of test. For this reason, the statistics is probably biased: taking onto account of this effect, a new estimate of 25 quenches per octant is found out. Taking into account the detraining phenomena, one obtains 30 quenches per octant. The error associated to these estimates is 3 to 6 quenches per octant (one standard deviation), depending on the assumed scenario.

For the main quadrupoles, 196 of them have been tested: 55% reached the nominal field gradient (220 T/m) without quench, and 32% after one quench. Only 9 quadrupoles have been tested after a thermal cycle, and 3 of them reached the nominal field gradient without quench. Using the same method applied for the dipoles one obtains a total of 60 quenches for the 392 quadrupoles of the machine, i.e. 8 per octant.

7. CHASING FOR PARASITIC FIELDS (A. DEVRED)

There is a long history of parasitic magnetic field affecting the performances of several accelerator machines. An effort aimed at inventorying potential sources of parasitic magnetic fields and evaluating the impacts on beam dynamics has been launched in February 2005 by the Field Quality Working Group.

The beam screen in the main dipoles produces a systematic effect on the allowed field harmonics, which is not negligible for b5 and b7. Indeed, the coil cross-section of the main dipoles has been designed to include this effect, estimated through numerical codes. To validate the simulations, measurements of beam screen prototypes have been carried in Block4 at the beginning of the production. A final version of the beam screen has been recently measured in the MFISC dipole (used for testing the superconducting cables). Results show that the measured effect is around 1/3 less that what expected; this can be explained by an horizontal misalignment of the beam screen inside the aperture of 1 mm. Unexpected values of a2 and b2 are also observed: they can be interpreted by the b11 shift induced by the beam screen, leading to an offset in the centre estimate based on the feed-down method. A new post-processing of measurement data should clarify if the measured impact of beam screen on field quality agrees with the simulations.

In 2005 it has been discovered that the PbSb plates present in the connection cryostats used at the extremities of the dispersion suppressors can have transitions to the superconductive state. Such transitions would give a kick to the beam of 1.5 to 17 σ, i.e. well above the collimation requirements. To avoid this effect, it has been proposed to add a thermal link from the plates to the 60-65 K thermal shields to ensure that the PbSb plates are always above their critical temperature. This solution will be adopted both for the already built cryostats and for that ones that are still in production.

The stray fields generated by bus-bars in the LHC magnet interconnects are being modelled through EUCLID with ROXIE. The whole 3D geometry must be taken into account, sensitivities matrices have to be evaluated, and the impact on the beam has to be worked out. These activities are expected to be completed within 2006.

OUTLOOK ON CRITICAL ISSUES

We give here our interpretation of the open points and priorities for the next year related to magnetic requirements for the beam commissioning.

- The test activity at CERN should be further shifted from the follow-up of the production to the characterization of the dynamic behaviour of the main magnets and of the hysteretic properties of the correctors.
    - The dynamic behaviour of the main quadrupoles is to be measured.
    - More statistics is needed for the dynamic behaviour of the main dipoles, which dominate the machine beam dynamics at injection energy.
    - The determination of the transfer function for all the correctors and for the expected cycles, including hysteresis when needed, should be completed.
- The model of the machine optics which couples magnetic measurements, geometry, and slot allocation should be continuously updated with the new measurements and with the MEB assignments. Estimates of the beam dynamic parameters such as closed orbit, beta functions, tuneshift, natural chromaticity, resonance strengths, physical and dynamic aperture could be given. Results could be partially benchmarked with the outcome of the sector test with beam.
- An estimate of the difference in main magnets and corrector settings for each octant, based on magnetic measurements and slot allocation, could be provided. The impact of an initial simplified setting (the same in all octants) and the expected performance loss could be evaluated.
- Hardware commissioning could allow to verify the expected quench level of an octant without beam, and the possibility of training in the tunnel.
- The search for parasitic fields should be completed.