Report on the

Workshop on Field Quality Steering of the Dipole Production

Held at CERN, 20-21 March 2003

Organisers: L. Rossi and W. Scandale

A complete collection of the transparencies presented during the workshop is available on the web: http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/fqwrkshp/fqwrkshp.html

Prerequisites and Objectives

The workshop was mainly aimed to harmonics and integrated transfer functions. However, superconductive and cabling effects as well as the issue of the geometry and its stability were discussed, too.

Session 1: Scope

Lucio Rossi opened the workshop with a short welcome in which he pointed out the major goals, namely the discussion and the specification of the parameters for steering the field quality of the LHC main dipoles.

Session 2: Historical Overview and Specifications

Session Chair: Jean-Pierre Riunaud, Scientific Secretary: Massimo Giovannozzi

Jean-Pierre Koutchouk: A Brief Review of the Strategy and Specifications for the LHC MB Field Quality

Jean-Pierre Koutchouk reviewed the different stages in the specification of the field quality of the LHC main dipoles starting from a beam dynamics point of view. In late eighties, beam dynamics was dominated by the b_3 (random and systematic) multipole. The dynamic aperture was computed mainly by using fast indicators (smear and amplitude detuning) due to a limitation in computing resources. Also, experiments performed on existing machines (e.g. Tevatron) were used as guidelines in the design of the LHC. In early nineties, error tables (issued from numerical simulations of LHC dipoles, scaling from HERA dipoles etc.) started to be available, thus requiring the computation of the corresponding dynamic aperture. The simulations were performed based on simplified assumptions, e.g. all the dipoles follow the same Gaussian distribution (as long as systematic effects from different manufacturers can be neglected) and the lattice is super-symmetric. The target dynamic aperture is between 6-8.5 σ. As a result of these studies, the cell length was set to the maximum allowed value and b_3, b_5 correctors were introduced at each dipole end. In addition, the inner coil aperture was increased from 50 mm to 56 mm. In the late nineties, the value of the target dynamic aperture was increased to 12 σ to allow for a safety margin of a factor of two. This safety margin was deduced from the analysis of the limits of the tracking model as well as the experience of HERA, were simulated results showed the dynamic aperture being twice as large as the measured one. The increased computer power allowed to improve the computation of the dynamic aperture: additional criteria, such as nonlinear resonances, chromatic coupling, chromo-geometric detuning terms etc., were introduced. Error distributions which differ for each octant, non super-symmetric lattice, tune split to help the correction of coupling effects, additional a_3 and b_4 correctors, and a reduction in the number of b_5 spool pieces by a factor of two, were the new ingredients in the numerical simulations. An important achievement is the definition of a target error table (always for injection energy) for both the main dipoles and the main quadrupoles producing a target dynamic aperture. Presently, the actual reference is the LHC Project Report 501, in which the values of the normal and skew harmonics for the main dipole are derived based on criteria such as the control of the mechanical aperture and the preservation of the dynamic aperture. With respect to the error table 9901, the new target values represent a consolidation. The influence of the multipoles a_1 and B_1 is considered for the first time, including an impact on the closed-orbit correction system. For some harmonics, the tolerances were relaxed (a_1, a_2, a_3, b_4, b_5, b_7), while for others (B_1, b_2) they were tightened. Finally, b_3, a_4, and a_{11} are unchanged. The requirement on the b_3 at high field has been stable (with one exception), namely it should be positive and as large as is allowed by the b_3-correction system of the dipoles. In this way, the b_3 at injection is minimized. It is stressed that the impact of the increase of b_5 tolerances on off-momentum dynamic aperture should be carefully studied. No clear mechanism has been proposed to explain the asymmetry in the tolerance bands for b_7, which might be worth testing against small variations of the parameters used in numerical simulations.

Stephan Russenschuck: Evolution of the dipole cross-section from the "Yellow Book" to the pre-series design

Stephan Russenschuck reviewed the evolution of the design of the cross-section of the LHC main dipole. Starting from the Yellow Book design (1995) that featured a five-block coil design, a beam separation distance of 194 mm, and combined aluminium collars with a ferromagnetic insert (MBP1), the design of the main dipole for the LHC has undergone a considerable evolution. The five-block coil was originally designed for a magnet with separated collars and a beam separation distance of 180 mm. The main advantage of the five-block coil is that it provides the highest possible average quench margin (of both inner and outer layer). Design changes on the five-block coil, which were carried out in 1996, made it very inflexible to even small adjustments. These changes were motivated mainly by a request from SL-AP for a partial compensation of the persistent currents, namely a reduction of multipole b_3 at injection field from -4.8 to -4.0 units, calculated at 10 mm, which is equivalent to Δb_3 of 2.3 units computed at 17 mm. Additionally, the thickness of the ground plane insulation, the conductor insulation, adjustments at the cable's narrow edge, and the ferromagnetic insert in the combined collars had made the five-block coil very inflexible. However, flexibility is needed to compensate the lower order (odd) field harmonics that arise due to deformations during manufacturing and cool-down.

Additional objectives that were taken into account for the coil re-optimisation included a lower b_{11} field component, an increase in the quench margin (inner layer coil), a better mechanical support (conductors placed as radial as possible) and lower sensitivity with respect to manufacturing tolerances. The coil design was found by using genetic optimization algorithms and a detailed study of three different design options. This led to the so-called V6-1 coil design (six-block coil with 40 turns; one turn less than the original five-block coil version). The V6-1 coil remained unchanged since autumn 1998 and a final adjustment was foreseen, as soon as sufficient data from the prototype phase would have been gained.
A re-design of the iron yoke was triggered in 1999 from mechanical considerations, for example, manufacturing difficulties concerning the ferromagnetic insert part. Additional objectives were a lower variation of the b_2 and b_3 field components versus excitation and a reduction of the b_3 component at injection field level. The MBP2 yoke design had subsequently undergone engineering changes to improve tooling and manufacturing and to enhance the rigidity of the structure. A re-optimisation of the shape of the iron yoke or the coil block configuration was not performed. Changes include an increased "nose" in the insert, cut-offs for the compensation of b_2 and b_4 drifts due to this nose, and the change of collar material to stainless steel with a relative permeability of 1.0022. As the design of the magnets is now frozen and the computational tool allows the modelling of very fine geometrical details, a refined numerical ROXIE model was created taking into account the modified shape of the iron yoke and the stainless steel collars. Also, the influence of the beam screen is now considered. Detailed analysis and comparison between simulation of beam screen effect and direct measurements showed a good agreement. Although the integrated design process is well established, it was not really used during the various iterations. This resulted in a field quality of the pre-series magnets that do not meet the SL-AP target error tables.

Michele Modena: Final Design of the LHC Dipole for Pre-series and Series Contracts

Michele Modena first described the process of the main dipoles production, the different components participating to the field quality achievement, their tolerances, and the specifications given to the manufacturers. On the individual components, he pointed out how CERN has delivered both the end-spacers and the inter-layers directly to the companies only for the "Pre-Series" Contract. He emphasised that the magnetic length should be controlled within a range of ± 15 mm according to the specifications, thus resulting in a stacking factor in the range of 98.5 % ± 0.25 %. Concerning the acceptance tests, it should be noted that "CERN takes full responsibility for the magnet field quality…", this means that a control of the multipoles is not foreseen as a measure to reject a magnet, provided all the assembly procedures are correctly followed by the manufacturers. During the production, two warm magnetic measurements will be performed on the collared coils and after yoke assembly on the cold mass. The first measurement is an official holding point on the production. It is expected that out of tolerance components or incorrect assembly will be revealed by these measurements (the latter being already occurred twice up to now). Fine-tuning of the magnetic length will be carried out symmetrically, by adding or subtracting special laminations to both ends. This is to avoid any movement of the magnetic centre of the main dipole. It should be noted that the magnet end effects would be different if the end-packs length change. Tests have been carried out introducing more iron-lamination in the end-packs and the results are in agreement with the expectations. It seems that the systematic differences between factories are mainly due to production tooling, rather than due to a variation of the materials.

Oliver Brüning: Criteria Used for Field Error Specifications

Oliver Brüning reviewed the criteria that are used to define the target field quality of the LHC magnets. The mechanical aperture should be enough to accommodate closed-orbit distortion plus ten times the beam size. This condition imposes constraints on the closed orbit, parasitic dispersion, momentum spread, momentum offset, and β-beating, both at injection and at high energy and hence on multiple errors responsible for these effects. Alignment errors should be controlled so that the feed down errors from the short straight sections and the spool piece alignment should be smaller than the corresponding errors in the main dipoles. The correctors strength should allow correcting the various errors under most stringent conditions, i.e. top energy for both injection and collision optics, as well as for ultimate performance. Concerning the beam dynamics, it is said that upper and lower bounds on detuning as a function of the amplitude and/or the momentum offset and momentum spread are required to avoid resonance crossing (or at least to avoid low-order resonances). The target value of the dynamic aperture is 12 σ. Tolerance bands are computed by varying the strength of each multipole until the dynamic aperture is reduced by 0.5 σ (estimated accuracy of the numerical simulations). As a result, the target values for B_1 and a_1 are determined by the strength of the orbit correctors, b_2 is bounded by β–beating, a_2 by the correctors' strength (skew quadrupoles); b_3 and a_3 are limited by correctors' strength; b_4, a_4, b_5 are limited by detuning considerations and dynamic aperture; b_7 and the higher-order components are limited by the dynamic aperture.

Session 3: Procedures to Follow-up Production and Checkpoints

Session Chair: Louis Walckiers, Scientific Secretary: Christine Vollinger

Luc Oberli: Follow-up and Checkpoints of Cable Properties

Luc Oberli gave a presentation on the relevant cable properties with respect to field quality issues namely the cable dimensions, the cable magnetization and the inter-strand cross-contact resistance. Further, he showed and explained the existing four holding-points, which are set during the follow-up of the cable production. From the measurements taken at CERN in the framework of the cable follow-up, the main parameters of the cable dimensions, the magnetization values and the inter-strand cross-section resistance are all within tolerances and the control of these values is well covered by means of the existing holding points.

Elena Wildner: Follow-up and Checkpoints of Harmonics in the Collared Coils and Cold Masses

Elena Wildner presented the holding points for the control of the field quality for the LHC main dipoles during production. These are warm magnetic field measurements carried out at the three manufacturers that are analysed at CERN to steer the field quality towards the beam dynamics limit at an early stage of production. Two holding points exist, the first one for the collared coil assembly and the second one for the cold mass assembly. The analysed results are stored in an

ORACLE database and the original Excel file is kept in a repository to be accessed on the web. The resulting multipole curves are collected in a bimonthly report. All data goes into MTF when the magnet arrives at CERN.
So far, 100 % of the collared coils and 98 % of the cold masses have been measured. The performed analysis allowed the detection of both measurement and assembly problems and seems to be a suitable tool for the control and the steering of the field quality of the dipole production.

Laurent Deniau: Follow-up and Checkpoints for LHC Cryomagnets

Laurent Deniau showed the follow-up and checkpoints, which are carried out on the LHC cryomagnets in order to control their field quality. The talk started by a reminder of the standard magnetic measurement test program performed by the MTM group which is composed of the current cycles so called "full loadline", "ramp" and "machine cycle". The analysis of the 15000 measurements that are performed during these cycles provides a good knowledge of the field quality under different conditions, including the machine operation. Among others, the processed data deliver the local and integral field harmonics, the field angle, and the transfer function, as well as the static field errors induced by geometric contribution, persistent currents, and iron saturation augmented by the dynamic field errors which result from the cable coupling currents during the ramping of the current. From these parameters, different data representation and plots may be built to summarize the field quality of both a single magnet or a sequence of magnets. This includes warm-cold correlation for quality control cross check. A synthesis of these views is put into the cryomagnet Id Card used by the Magnet Evaluation Board for magnet acceptance.
As a conclusion, it was underlined that neither conformity nor non-conformity can be triggered from magnet field quality measured in cold conditions. Moreover, at present the expected delay between warm and cold testing is of the order of few months. Therefore, the feedback for the production cannot come directly from cold measurements. Cold measurements are hence mainly aimed at quantifying and identifying drifts in error sources that cannot be monitored in warm conditions (like persistent currents, iron saturation, cable eddy currents, decay and snap-back and changes of the geometry under Lorentz forces) and provide the basis for extrapolation as well as quality control through warm/cold correlation.

Session 4: Procedures to Follow-up Production and Preliminary Analysis

Session Chair: Jean-Bernard Jeanneret, Scientific Secretary: Massimo Giovannozzi

Marta Bajko: Assembly Procedures and Follow-up of Dipole Shape at 300 K

Marta Bajko discussed the assembly procedures and follow up of the dipole shape at warm conditions. Constraints derived from beam dynamics considerations impose limits to the mechanical tolerance of the order of 2 mm. Furthermore, to minimise feed down error generated by spool pieces, admissible alignment errors are defined to be ± 0.3 mm systematic and 0.5 mm random in both horizontal and vertical planes. Cylinders are bent (one half) to with approximately 9 mm sagitta. The whole magnet is bent under the press, during welding. About 23 % of its curvature is lost due to elastic energy. Therefore, a slightly higher sagitta has to be generated to compensate for the spring back. Each manufacturer follows the same procedure. An iterative procedure was applied at CERN until the value of 9 mm for the sagitta was achieved. After several attempts it was found that a sagitta of about 12 mm during the welding combined with half cylinders of the same sagitta gives the right final value. Re-shaping was applied in the industry on several magnets during the optimisation of the initial parameters to correct out of tolerance sagitta after the welding process in the press. The re-shaped magnets show signs of instability, i.e. their shape tends to go back to the initial state that it had before re-shaping. Presently, six out of eleven considered dipoles show such an unstable behaviour. There are ten more dipoles with high probability of this type of behaviour. For these magnets spool pieces might be displaced transversally by as much as 1-1.5 mm. Concerning this point, it was mentioned that, from beam dynamics considerations, horizontal or vertical misalignment of the spool pieces are not equivalent. In fact, vertical misalignment of a decapole spool piece generates skew components (e.g. a_4) for which no corrector is available. No indications concerning the stability over longer periods (LHC lifetime) are available. Following also a suggestion endorsed by the Machine Advisory Committee, no more dipoles will be re-shaped, while waiting for a better solution to this problem.

Juan Garcia: Follow-up and Checkpoints of Magnetic Axis at 300 and 1.9 K

Juan Garcia presented measurements of the magnetic axis that are carried out both at warm and at cold conditions. These measurements are performed with different instrumentations at CERN and at manufacturers premises. A comparison between the results taken with the two systems could be observed and is currently investigated. Concerning the magnetic axis, a deviation of the horizontal and vertical offsets with respect to the theoretical geometry could be observed before and after cold tests. Measurement examples were shown for different manufacturers illustrating this problem. Further tests on the warm-cold correlation are planned to start in May 2003. Then, measurements of the magnetic axis compared to the theoretical geometry axis for both apertures are presented, showing a fair agreement. A detailed analysis on the mechanical stability of the dipole shape before and after cold test is in progress and results are expected in the next months.

Walter Scandale: Geometry: Analysis and Trend

Walter Scandale reviewed the present status and trends of dipole geometry. The spread in dipole shape, for the set of magnets under consideration, is rather large, certainly out of the mechanical tolerances. Three situations were considered, i.e. after welding, after manufacturing, and after cold test. The spread is minimum after manufacturing, while it goes back to its initial state after cold test. It is confirmed that re-shaping is not a stable solution to cure problems related with dipole shape. The goal now is to find better solutions within the first six months of the year 2003, and then to take a final decision concerning the strategy to follow. Another crucial point is that rather large movements are observed on the magnet ends, which might be a critical issue for the positioning of spool pieces. Four out of six dipoles follow this behaviour: intermediate stages show certain variability, not the initial and final stages. One dipole shows a different behaviour, i.e. after cold test it goes back to its state after re-shaping. Presently, no measurements have been performed to check whether the magnet continues moving after each cool-down: this might be worth investigating. However, it is already clear that quenches do not seem to have a significant impact on shape.

Session 5: Components Properties and Construction Processes

Session Chair: Tom Taylor, Scientific Secretary: Christine Vollinger

Francesco Bertinelli: Status and Trends of the Various Components Affecting the Field Quality

Francesco Bertinelli gave a presentation about the current status and the observed trends of the various components and their effect on field quality. The status of the copper wedges and the stainless steel collars were presented in detail.
An increase of 0.02 mm in the spread of copper wedges dimensions was first observed in September 2002. This could be traced back to tooling wear. All extrusion and drawing dyes have since been replaced. Measurements of wedge geometry carried out by manufacturer and CERN are in very good agreement. The geometrical precision of the new wedges is significantly improved in both spread and average values. Concerning the stainless steel collars, CERN has recently started a campaign to crosscheck measurements between the two suppliers. Measurements of the same collar performed by the two suppliers show differences typically up to 0.04 mm. The reasons are being investigated, but probably originate from the different probe geometry used and different positions along the collar thickness where the measurement is taken. Emphasis is therefore on the quality of the cut (angle and torn area), which may vary within the same collar. A further effect under investigation is the relaxation of the collar after fine-blanking with a possible geometric effect typically up to 0.04 mm. On the basis of the existing data, both production processes appear under control, with the collar dimensions within tolerances: evidence from one of the two suppliers is however less solid. Following recent improvements and with additional work from CERN, the coming results should be more significant.
The question is asked whether further efforts are justified to improve the confidence level of the measurements from 0.04 mm down to 0.02 mm: the Component Centre is waiting for an answer. Additional measurements to define better the geometry could be taken on a few collars with the Smartscope machine, using the 3D method as now to ensure reproducibility.

Paolo Fessia: Into the Galaxy of Winding Curing and Collaring

Paolo Fessia presented the production process of cold masses with special emphasis on feedback time, which has to be considered after any corrective action is decided on winding, curing, or collaring process. Firstly, individual components, tooling, and assembly process in the three manufacturers were presented. Then, the production time needed by the manufacturers for the assembly of the collared coils was discussed. The necessary time for the coil winding and the collaring is decreasing with the total number of manufactured coils for all three firms. The estimate of the total time for a change of a single component was presented. Clearly, this depends on various factors, such as the production rate (one or three collared coils per week), and on the specific component to be modified. Different examples were given, namely

- A change of polar shims requires a delay of about 1-4 weeks and an estimated cost of about 1500 CHF for each set of shims that cannot be used any more.
- A change in the mid-plane insulation requires about 1.5-2 months delay. Taking into account the cost of the ground insulation (about 9000 CHF per collared coil), it is possible to estimate an extra cost for supply between 1 % and 20 % (from 100.000 CHF

till 2.000.000 CHF) Furthermore, one has to consider that 15 min. of extra work for each coil corresponds to 300.000 CHF.

- A change of copper wedges could be realized with a delay of about 14 weeks for the extrusion of the pieces. In this case, not only the copper wedges but also the end spacers and the end spacer chips and wedge tips have to be modified. A rough estimate of costs, based on former experience, gives about 7000 CHF/dye for the new copper wedges tooling and about 150.000 CHF for the end spacer production. No reusable material has to be taken into account corresponding, presently, to the largest part of costs.
- The costs for a correction of the magnetic length by changing the number of end laminations are estimated to be about 200.000 CHF per manufacturer if the additional nested laminations have to be produced. In this case, a cheaper solution would be to transfer nested laminations between the different cold mass manufacturers.

Iouri Vanenkov: Analysis of the Coil Shape: Trends and Correlation with Magnetic Measurements

Iouri Vanenkov gave a presentation about the trends, which can be observed in the measurements of the coil shapes and showed the correlation between the overall coil shapes and the magnetic measurements. The general objectives of coil shape measurements are the validation of the tooling and the manufacturing method as well as the control of the geometrical tolerances of the coil size and the coil components. Furthermore, the measurements can be used to minimize the random part of the field errors by sorting the poles individually.
The measured parameters to assess the coil size were explained and examples of tooling imperfections and their influence on the longitudinal profile were given. Typically, both the individual layer size and the pole size are measured. The shape of the curing mold gives a typical pattern to the longitudinal coil profile clearly seen in the measurement data. This way, large tolerances on the curing mold result in an increase of the coil waviness. The trends in the size of the assembled and measured poles show an impact on the variation of the measured pre-stress in a magnet. A significant non-systematic variation of the coil size data could be observed for each company. A reduction of this variation was successfully tried in one company by a change of the curing shim. A sorting of the coils is possible but limited due to the cable mixing restrictions. By means of sorting, the random parts of field errors, especially on the a_2 multipole, could be reduced easily.
Finally, an analysis of the geometrical measurements on the outer shape of the collared coils has been carried out which showed a good correlation with the measured multipoles, especially b_2.

Session 6: Present Status: Measurements Versus Targets and Corrective Action

Session Chair: Francesco Ruggiero, Scientific Secretary: Massimo Giovannozzi

Arjan Verweij: Present Status and Trends of Cable Properties and Impact on Field Quality

Arjan Verweij presented the status and trends of cable properties. Filament magnetisation affects field quality by inducing persistent currents. According to specifications, magnetisation should be less than 30 mT (for cable 01 at B = 0.5 T and T = 1.9 K) and less than 23 mT (for cable 02 at B = 0.5 T and T = 1.9 K). Different averages between manufacturers are allowed, but the

spread is fixed (±4.5 %) for all. Although specifications are not met for single strands, the cable, made by many strands, shows much better performance. Using cables from the same manufacturer for the 4 inner and 4 outer coils of each dipole makes it possible to meet specifications given in LHC Project Report 501 for both the systematic and the random part of the dipole field errors.
It is stressed that if the same cable has to be used for each octant, the issue of difference in dipole integrated strength is important.
Inter-strand resistance (R_c) is responsible for eddy currents between the strands, induced by a field variation. The target value for R_c is > 20 μΩ (inner cable) and > 40 μΩ (outer cable). Higher contact resistance could be tolerable, but then the magnet quench performance could become more sensitive to local strand defects or non-uniform joints. Errors induced by contact resistance are higher than target values when using a linear ramp at 10 A/s: they will be reduced by about a factor of five when using the planned exponential ramp. Therefore, the present value of R_c is adequate for reaching the target values of ramp-induced field errors.
Snap-back is due to boundary-induced coupling currents as well as redistribution of transport current. The maximum decay depends of magnetization. No specifications exist for the reproducibility of b_3 during snap-back (in fact, no clear physical explanation was available at the time orders were prepared). Spread among the magnets is large and is expected to continue for the rest of the magnet production, since no clear correlation with R_c is observed. It is requested that a clear decision be taken concerning the distribution of magnets and cables form the various manufacturers over the octants.

Davide Tommasini: Constraints on Sorting: Types of Magnets and Interchangeability

Davide Tommasini presented the key issues that might constrain magnets sorting. The total number of dipole types is 27 (A, B type, diode polarity, interconnections). However, only four types will be present until storage. At this stage a decision on sorting should be taken, as the choice of interconnection will be practically irreversible.
Magnet Evaluation Board will take the decision on magnet approval between WP08 and WP09. At this stage a flag will be defined for each magnet to distinguish among various installation constraints (this point will be further discussed by the Magnet Evaluation Board). The maximum storage capacity for green-type magnets, i.e. those that can be installed everywhere in the ring, is of about 120 dipoles. Up to 60-70 can be stored being accessible individually.
There will be more freedom for tackling the installation of the first octant, thus allowing more experience to be gained for next ones.
An important point is raised, i.e. in case magnets from different manufacturers have to be installed in the same octant (7-8), a decision has to be taken within two, three weeks (maximum) concerning a possible change of diode polarity.

Ezio Todesco: Status and Trends of Field Quality at 300 K and Possible Corrective Actions

Ezio Todesco presented the status and trends of field quality at warm with a proposal for possible corrective actions. Field quality steering is primarily limited by predictivity of the magnet model. Accurate comparisons between measurements and numerical simulations show an agreement for differential effects within 20 %. Another issue is the reproducibility of collared coils. Systematic

effects were observed for pre-series magnets that were re-collared, maybe due to the virgin state. Additional experience is expected based on a third de-collaring of dipole 2002.
It is generally agreed that field quality steering should be based on collared coils, as the delay between collared coils and cold measurements is too long (about seven months now, but it is expected to reduce to two-three months). Therefore, warm/cold correlations become a critical issue in field quality steering. Present data show that correlations allow to steering the production for all multipoles and integrated transfer function, with the exception of the a4.
Presently, the situation of field quality is as follows:

- Non-allowed systematics: within specifications (a_4 is a bit tight).
- Allowed systematics: b_3, b_5, b_7 are out of specification but by less than one unit (this is an improvement with respect to previous cross-section). With this situation the machine could work. However, a drift in the production could be dangerous.
- Randoms: b_3, b_5, are out of specs, but improvements are expected thanks to a more stable production.

Two field quality issues are under considerations, i.e. dipole integrated strength (BdL) and odd multipoles (b_3, b_5, b_7). The first point can be tackled using the magnetic length as steering knob. There is a difference of 20 units in BdL between Firm 3 and Firm 1-2 collared coils. Data should be confirmed by measurements at cold – only two cryomagnets have been tested (see talk by Sthephane Sanfilippo). Laminations redistribution between the three firms might be the appropriate solution. The only drawback is the reduction of margin for further corrections.
Different strategies could be envisaged to tackle the second point. Polar shims could be used to have a limited action on b_3, the critical point being the coupling between b_3 and b_5. In principle it allows very fast action on magnet production. Mid-plane insulation is very efficient, and could push b_3 b_5 and b_7 towards the targets. Copper wedges change is still under study, but the feedback is very slow (see presentation by Paolo Fessia).

Stephane Sanfilippo: Status of Field Quality and First Trends at 1.9 K

Stephane Sanfilippo presented the status of field quality and preliminary trends at cold. Cold measurements are performed without beam screen and its effect on odd multipoles (b_3, b_5, b_7) is deduced from simulations. Nearly all the magnets measured at cold had the first cross section. Results coming from only three magnets displaying the corrected b_3 and b_5 cross-section were presented.
The first item concerns the dipole integrated strength. Two magnets from Firm 3 are clearly above the average of other Firms. However the following magnet measured i.e. 3009 did not confirm this trend. This subject needs further investigations. On the other hand, magnetic length seems to be really stable (apart for a couple of cases that are well understood), thus making it a good candidate for field quality steering handle.
Field direction is another important quantity. Several measurement systems (including long rotating coils and single stretched wire) are being crosschecked. For some magnets the data obtained with long rotating coil give the field direction out of tolerances, while measurements performed by stretched wire system display results within the specifications. Further analysis is ongoing to reduce the uncertainty related to rotating coil results.
Measurements of the multipole components at injection field reveal that b_5 and b_7 are outside the tolerance bands. The random component of b_3 is also not acceptable, but the spread is due to non-nominal shims used for the first pre-series dipoles and to the different cross-sections

measured. At collision, magnets with cross-section 1 have b_3 and b_5 outside tolerances. The sextupole stands also above the critical limit defined by the sextupole correction capability. The corrective action taken on the coil cross section led to an improved situation for b_3 and b_5, standing at the limits of the window (for the dipoles measured so far at cold). However for magnets with the second cross section, b_7 was found to be outside specifications.
For geometric components correlation between warm and cold measurements is rather good. However the distribution of the scatter is not a Gaussian but a multi modal one. More statistics are needed to assess the warm/cold correlation.
High-field behaviour of transfer function is well described by the iron saturation and in general there is a good agreement between estimates and measurements for the multipoles. Detailed studies of the harmonics behaviour at high-field show a good agreement between model and measurements for even multipoles (b_2, b_4) but not for odd multipoles (b_3, b_5). The source seems to be coils motion under electromagnetic forces.
Persistent current errors measured at injection are in line with the expected values for series-production apart from the effect observed on the main dipole that is not fully understood.
Ramp rate effects on B_1 and on the harmonics at 10 A/s were found to be smaller than expected thanks to the effective production control of the inter-strand resistance.
The decay of the magnetization is responsible for a significant spread on low order multipoles and in particular on B_1 and a_1. A possible explanation could be a difference in the decay properties of the inner and outer coils. In this case a_1 would stem from left/right asymmetry. Due to the relevance of this subject, further investigations are foreseen.

Stephane Fartoukh: Magnetic Measurements Compared to Specifications and Updated Consequences on Beam Dynamics

Stephane Fartoukh discussed consequences on beam dynamics of the magnetic measurements results starting from low-order harmonics. The dipoles produced by Firm 3 show a B_1 component systematically higher than the others. The impact on the closed-orbit correctors is non negligible. The best solution would be to act directly on the magnet laminations. In this case it is mentioned that measurements of the longitudinal magnetic centre at cold should be foreseen at least for few dipoles. This represents an extra measurement: a formal request to Magnet Evaluation Board will be issued. On the other hand, partial solutions could be envisaged too, such as a careful mixing of the magnets at the level of single cell (two per each Firm with Firm 3 dipoles near the cell centre). Indeed, if few arc cells will be equipped with only Firm 3 magnets, the safety margin available for the closed-orbit correctors will be drastically reduced.
Another important issue is the field direction. Presently, a discrepancy between the two measurements technique is observed: provided the single stretched wire proves to be the correct one, all the dipoles are within tolerance. It is also mentioned that large values of the local field direction could be an issue.
Beta-beating and linear coupling are well under control and correctable, as, according to the running average, b_2 and a_2 are within tolerances.
Dynamic aperture computations for field errors at injection show a mild (almost negligible) dependence on b_7, b_9, while the random part of b_3 is the real limiting factor. However, mixing of the two cross-section types as well as other non-standard components (shims) make the present estimate of b_3 random rather pessimistic. With the dipole cross-section 2, the value of the dynamic aperture is 11.2 σ - instead of $(12 \pm 0.5)\ \sigma$ - due to the b_7 component. Finally, a detailed

analysis of different installation scenarios for the pre-series magnets shows no sizeable impact on dynamic aperture.

As far as dynamical effects are concerned, the large random decay of B_1 and a_1 might have a strong impact on closed-orbit feedback system. The average effect of b_3 is still large, but less critical than expected, due to a reduction of a factor between two to three.

All the harmonics specified are within tolerances at high-energy. Only the systematic b_3 is too large, leaving only 0.6 units of safety margin in nominal operation conditions. Of course, the operating current could be slightly increased, but this will prevent future upgrades, such as 9 T operation.

Finally, it is mentioned that all these conclusions should be confirmed by including feed-down effects induced by misalignment errors.

Session 7: Open discussion: what are the guideline to steer the production and actions to be taken, as emerged from the workshop?

Session Chair: O. Brüning, L. Rossi, Scientific Secretaries: Massimo Giovannozzi, Christine Vollinger

1. Topic: values and steering of the magnetic length

   Concerning the value of the magnetic length and its variation, there is an agreement that the magnetic length has to be in tight control with little variation. In order to steer the dipole integrated strength, the following suggestions were made:

   Change the end laminations (as presented in the talk by **Paolo Fessia**).

   Reduction of the length of the mandrel.

During the discussion **Lyn Evans** pointed out that special efforts were made during construction of the SPS machine to bring BdL within limits. Furthermore, he stated clearly that the mandrel should not be changed. **Lucio Rossi** wanted to have absolute certainty that the field of dipoles from Firm 3 is higher than that in the other manufacturers and suggested to wait for one more measurement before corrective actions are taken. He also explained that as long as the coil sizes are within limits, the company cannot be held responsible for the B_1 value. He then favoured the change in laminations as the easiest solution compared to a reduction of the mandrel size. **Jos Vlogaert** favoured the option of reducing the mandrel since a change of the laminations at the present production phase limits the corrective range of future actions. **Paolo Fessia** remarked that a change of mandrel, if considered, should happen now, since currently a number of mandrels are in production. Concerning the existing mandrel size, he already compared the mandrels of Firm 3 and Firm 2 and could not find any difference in the radii. **Ezio Todesco** pointed out that for the case that all companies show a trend in direction of a low B_1 later on, this might not be recovered, if the laminations are already added today. **Davide Tommasini** remarked that the mandrel should not be touched as long as the source of the high B_1 is not found, however, in case it is proven that the length is wrong, the mandrel has to be corrected.

Conclusion

Agreements were found on the following points:

- The magnetic length of the main dipoles should be corrected by changing the end laminations of the individual magnets. The mandrel will not be touched at the moment.

- From beam dynamics point of view, this adjustment has to be done symmetrically around the magnetic centre of the dipoles.
- In order to keep the costs for the corrective action as low as possible, or even cost-neutral, nested laminations between the different companies should be exchanged in a first step. Furthermore, **Jos Vlogaert** will start the discussions with the companies right now in order to profit from the already ongoing negotiations concerning the coil tolerances.
- A more detailed analysis of the behaviour of the dipole integrated strength at cold should be carried out to obtain a complete picture of this problem. In this respect, additional cold measurements of Firm 3 magnets have the highest priority.

2. Topic: odd order multipoles (b_3, b_5, b_7)

The value of odd order multipoles should be modified to bring them within the beam dynamics limits. Thus, a second correction of the coil cross-section is suggested (see also talks by **Ezio Todesco** and **Stephane Fartoukh**).

Stephane Fartoukh recommended a reduction of multipole b_3 of about 2-3 units on high field level. He insisted that from beam dynamics point of view, b_3 is still considered the most dangerous to control. **Andrzej Siemko** suggested changing only the insulation thickness on the copper wedges, instead of changing the size of the copper wedge, to reduce the costs. **Ezio Todesco** concluded as it was already presented in his talk, i.e. the only way to reduce the three multipoles b_3, b_5 and b_7 with one single correction is a change in the mid-plane thickness. **Davide Tommasini** commented that a change in the mid-plane thickness means little cost involvement as long as a commercially available insulation thickness is chosen. **Jean-Pierre Koutchouk** asked about the requirements by which the accuracy on the b_5 has to be set (answered by **Stephane Fartoukh** to approximately 20 %). **Lucio Rossi** suggested taking solution no. 4 which was proposed in the talk by **Ezio Todesco**. Solution no. 4 suggests an increase of the mid-plane insulation of 0.1 mm. This would still leave the possibility to take an additional correction (e.g. solution no. 1, same talk), if later on necessary. Solution no. 1 foresees a change of the outer polar shim of 0.1 mm. **Lucio Rossi** asked whether the expected values of the multipoles after this correction are satisfactory from beam dynamics point of view, explicitly b_7. **Stephane Fartoukh** could confirm this, also for multipole b_7 that seems to be acceptable, even if it is not within the desired beam dynamics bounds.

Rob Wolf pointed out that a step change on b_3 and b_5 (1 unit and 0.2 unit, respectively) has to be expected due to change in cable. However, this change will mainly affect the persistent currents, which have to be considered at injection only, when the correctors have their maximum power.

Conclusion

Agreements were found on the following points:

- The mid-plane thickness will be changed according to the solution no. 4 being presented in the talk by **Ezio Todesco**.
- In the case that an additional adjustment is necessary, the solution no. 1 from the presentation by **Ezio Todesco**, can be applied to further modify b_3.

- A cost estimate should be given by **Davide Tommasini** as soon as possible and before the meeting of the closed Panel following this workshop.