Electrical Quality Assurance in the LHC Tunnel (ELQA) and Magnet Polarity Coordination (Mr. Polarity)

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Abstract

The paper describes the methods and tools for the Electrical Quality Assurance in the LHC tunnel which have recently been validated by finding two non-conformities at installed magnet components. In the second part, the coherence between the magnet construction and measurement on one side, and the magnet interconnection and the Electrical Quality Assurance (ELQA) on the other side is discussed. This activity is known as magnet polarity coordination. Some detected incoherences are reported.

INTRODUCTION

Electrical Quality Assurance and magnet polarity coordination are two sides of the same medal. Electrical Quality Assurance under the responsibility of AT-MEL-EM with the collaboration of HNINP is performed in order to ensure the integrity of the electrical circuits during machine assembly and commissioning and to guarantee that the electrical interconnections correspond to the LHC powering layout. A further objective is to ensure traceability of checks while considering all electrical non-conformities. However, ELQA is not (and cannot) be concerned with the qualification of individual components which includes polarity, continuity, labeling, electrical integrity, voltage taps, magnet type and position. It has to be assumed that the individual magnet components are conform before the tunnel installation. The two reported cases show, however, that this is not always the case.

Magnet Polarity Coordination that we call in chest “Mr. Polarity”, on the other hand is concerned with the coherence between magnet construction and measurement on one side, and the magnet interconnection according to the layout database and the hard and software for ELQA on the other side. The same understanding and application of the engineering specification for LHC magnet polarities by all teams involved has to be ensured. We will report incoherences resulting from permutations in the magnet polarity due to the position of the connection terminals of the installed magnet components.

ELECTRICAL QUALITY ASSURANCE

The parameters to be verified in the framework of the ELQA during machine assembly include:

1. continuity of bus-bars and magnet interconnections,
2. authentication of the magnet type by means of its measured ohmic resistance,
3. magnet polarity check using the voltage taps on the A terminal, and
4. insulation to ground and to other circuits.

The methodology applied to the continuity verification has been described in various papers and at previous LHC performance meetings [1]. It consists of feeding a stable DC current into a branch of the tested circuit. Voltage drops across precision resistors, connected in series at both extremities of the branch, confirm its continuity. The authentication and polarity of magnets connected in series within the branch are verified by measuring differential voltage drops between voltage taps at the magnet’s A terminal and the source or sink of the branch. The voltage measurements are compared to known parameters stored in a database. In order to define a systematic approach for the verification of the about 70000 splices, all different electrical interconnection types and corresponding configurations have been determined by analyzing the data in the LHC reference database. This analysis resulted in the definition of 5 interconnection types in the N-line circuits, 6 types for the circuits of the spool-pieces in the arc zone, and 6 types for the circuits of the spool-pieces in the dispersion suppressor region.

For the verification of the 42 auxiliary bus-bars in the N-line, the access to three successive interconnection planes is required at the level of the N-line interconnection board, see Fig. 1. It has to be stressed that the smallest section of the ARC that can be verified is composed of two half-cells. The two associated auxiliary N-line cables must be installed. Thus the smallest “seed crystal” for two advancing fronts is composed of at least 5 fully equipped half cells. As of the verification of the 6^{th} half cell, the first interconnect can be released and welding operations can be completed.

Fig. 2 shows the scheme for the verification of a magnet powered from the 42 auxiliary N-line cable. First the continuity of the circuit is assured by measuring voltage drops across the current reading resistors. Measured voltage drops between the allocated wire slots on the central interconnection board and the source and sink ends indicate the correct distribution of the wires. Finally the polarity and the type of the connected magnet are checked by measuring the expected voltage between the voltage tap attached to the magnet and the sink end. The verification of the auxiliary spool-piece bus-bars only requires the access to the extremities of a cell [2].

Arc Interconnection Verification

The Arc Interconnection Verification (AIV) is an ELQA application allowing the above mentioned verifications using an automated mobile system with the following characteristics:

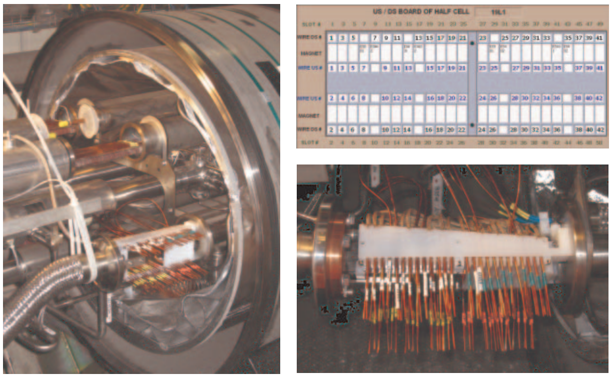

Figure 1: Left: Position of the interconnection board in the interconnection region between SSS and MB. Bottom right: Interconnection board assembled and awaiting test before ultrasonic welding. Top right: Slot assignment on the interconnection board.

1. Verification of a full cell,
2. qualification of all types of interconnections with a single tool, which can be independently operated by two persons,
3. hardware optimized for tunnel dimensions and storage underneath the cryo-magnets,
4. fast connection of cables and connectors, and
5. software for the automatic validation of measured data with respect to the LHC reference database.

The mobile system is composed of a central unit to be placed at the center of the cell and includes a portable computer running the software application, two de-multiplexers positioned at the extremities of the cell, and the connectors and cables for pick-up, routing and dispatching of measurement and control signals.

The required signals are picked-up by connectors especially developed to ensure a fast plug-in and a reliable electrical contact. At the extremities of the cell two relay-based de-multiplexers allow the selection of a subset of signals. The selection of the required channel is done via 6 digital lines driven from the central unit. The signals coming from the central N-line interconnection board are directly routed to the connection box of the central unit. The voltage tap signals needed for the polarity checks are routed from each cryo-magnet instrumentation interface box to the connection box via four dedicated cables, see Fig. 3.

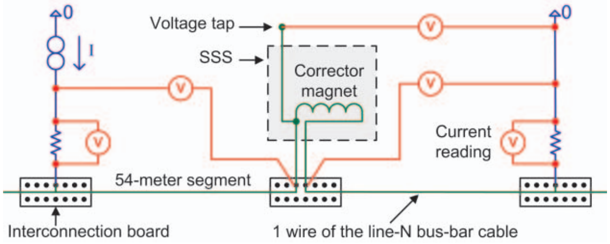

Figure 2: Scheme for the verification of a magnet powered from the 42 auxiliary N-lines cable.

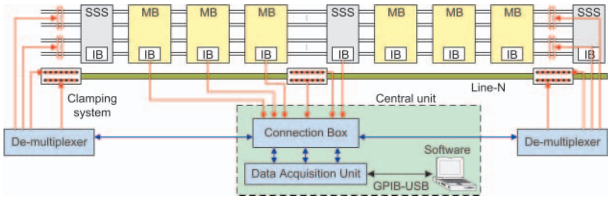

Figure 3: Scheme of the mobile test system.

The central unit contains a data acquisition system, including a high precision digital multimeter, two switching matrices allowing the independent reading of the 3160 possible voltage combinations generated from the 217 signals gathered along the cell, and an I/O card for the control of the whole system. In total, sixteen digital output lines are used in a sink mode to provide the control of the two de-multiplexers. Five analog channels are used. Four provide the current reading and the fifth allows for the differential voltage reading of two signals out of the 3160 possible combinations. The system is controlled by a LabVIEW based program with a GPIB Universal Serial Bus (USB) interface using the standard protocol IEEE 488.2. The system allows fully automatic verification and it is adapted to any configuration of the electrical circuit under test.

The control of the system is based on the LabVIEW application and an Oracle database containing the information needed to perform the electrical qualification and allowing the storage of the test results. The ELQA-DB database contains two parts, one containing the test tables and one containing the results tables. The tests tables have been automatically generated by applying a package of PL/SQL scripts to the LHC reference database. This ensures that the latest version of the LHC machine parameters is used. The generated database contains all electrical interconnection data necessary to perform and validate the electrical verification. The Oracle database is duplicated into a MS-Access format which can be exploited on portable computers, in order to have a self-sufficient test system in the LHC tunnel.

Validation of the procedures and equipment

The ELQA methodology as well as the hard and software applications were successfully validated in September 2005 by finding a non-conformity at a SSS cryomagnet installed in the LHC tunnel. Powering the adjacent orbit corrector in Aperture 1, a voltage drop on the voltage tap of the orbit corrector in Aperture 2 was detected. As the conformity of magnet elements cannot be taken for granted, three different errors could lead to the observations, see Fig. 4: 1) wrong voltage tap labeling, 2) wrong labeling of the bus-bars, 3) internal connection error of magnet elements. By opening the beam tube of Aperture 1 and by insertion of a hall-probe it was found that indeed the first error was present.

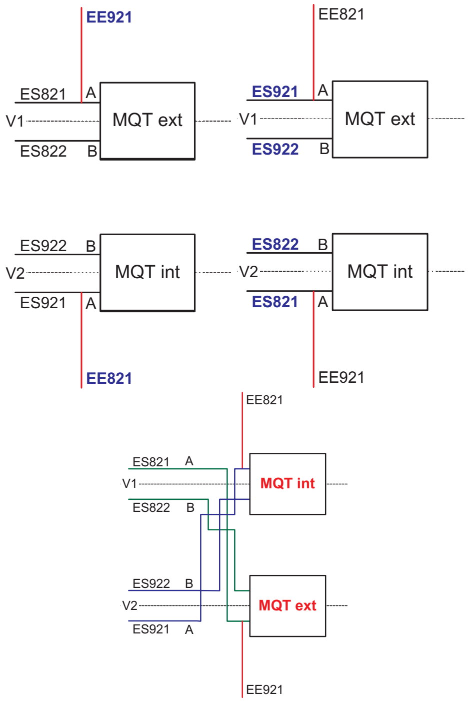

Figure 4: Non-conformity found during first equipment test in the LHC tunnel: Powering the orbit corrector in Aperture 1 a voltage drop on the tap of the orbit corrector in Aperture 2 was detected. If the conformity of magnet elements cannot be taken for granted, then three different errors can lead to the observations. Top left: Wrong voltage tap labeling. Top right: Wrong labeling of the bus-bars. Bottom) Internal connection error of magnet elements. By opening the main line of Aperture 1 and by insertion of a hall-probe it was found that indeed the first error was present.

It is interesting to trace the reason why the non-conformity was not found during the various electrical test during magnet reception, cryostat integration, cold-test, "stripping" and preparation for the installation in the tunnel. The following *scenario* is very likely. It is summarized in Fig. 5: 1) During the integration of the cover flange and interface box, the voltage taps were correctly mounted. 2) The magnet was then (wrongly) prepared for cold test, and the incoherence between the voltage drops on the taps and the powering scheme was detected. This was "corrected" by swapping the voltage taps on the cover flange. 3) The magnet was then cold-tested in SM18 where all the electrical tests passed. 4) After stripping of the wrong bus bar connections, the voltage tap labeling remained in the inverse (wrong) state. As a consequence it has been decided to repeat the voltage tap measurements at the same time with the magnet polarity measurements during the cryo-magnet preparation in SMI2.

Partial Assembly Qualification

The Partial Assembly Qualification (PAQ) is an ELQA application allowing the optimization of mechanical interconnection work in case of missing elements such as the SSS with jumpers and plugs in Sector 8-1. The request for this activity was filed in April 2005; the first system test was successfully performed in August 2005. PAQ does not verify the polarity of the spool correctors. This check will be done later with the Arc Interconnection Verification (AIV). While AIV is limited to 50 V insulation test, PAQ allows a test at 500 V due to the limited number of tested magnets. The PAQ also allows to close the M1, M2, M3, lines at the MB-MB interconnection plane and at the downstream SSS-MB interconnection plane where no N-line interconnection board is present. The system was successfully qualified with a tunnel intervention where the crossing of spool piece bus bars inside a SSS was discovered (EDMS 696203).

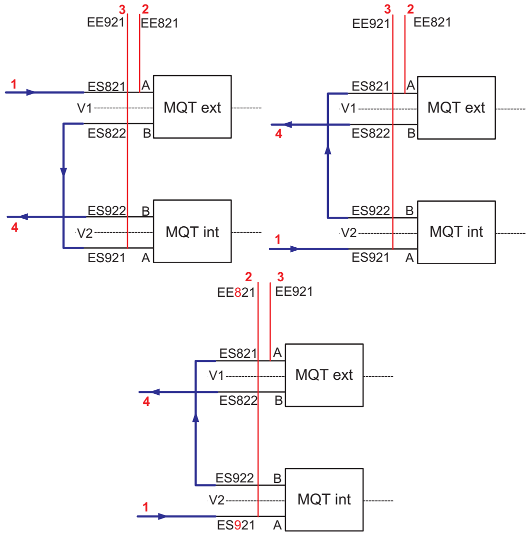

Figure 5: Top left: Baseline prepartion of the SSS for cold test in SM18. Top right: During the integration of the cover flange and interface box, the voltage taps were correctly mounted. The magnet was then (wrongly) prepared for cold test, and the incoherence between the voltage drops on the taps and the powering scheme was detected. This was "corrected" by swapping the voltage taps on the cover flange. Bottom: The magnet was then cold-tested in SM18 where all the electrical tests were conform. After stripping of the wrong bus bar connections the voltage tap labeling remained in the inverse (wrong) state.

MAGNET POLARITY COORDINATION

The coherence between the CERN-EDMS document 90042, [3] defining the magnet polarities and the definitions in the magnetic measurement and beam physics reference frame was discussed in the LHC performance meeting 2005. In this section we discuss incoherences in the magnet polarities that stem from permutations due to the final position of the connection terminals in the LHC tunnel.

Position of the connection terminals

The position of the external connection terminals of magnets or magnet assemblies defines the *normal* installation direction in the tunnel, e.g., with the external connection terminals upstream or downstream of Beam 1. In particular multipole correctors within the magnet assembly might have their connection terminals facing downstream of Beam 1, e.g., MCB in the SSS, MCS in the MB, ref. Table 1 (column D).

The magnet's optical function may change depending on the multipole order, i.e.,

$$B_n^{\rm up} = (-1)^{n-1} B_n^{\rm down}\,, \quad (1)$$
$$A_n^{\rm up} = (-1)^{n} A_n^{\rm down}\,. \quad (2)$$

The terminals are (re)-labeled such that if the current enters the A terminal the field is indeed positive in the sense of the polarity conventions.

Remark: It has to be noted that the field quality of the magnet modules is always measured in the magnet frame and consequently the **relative** higher order field harmonics may change sign in the magnet assembly depending on the multipole order, i.e., for the relative multipoles of a normal magnet:

$$b_n^{\rm up} = (-1)^{n-N} b_n^{\rm down}\,, \quad (3)$$
$$a_n^{\rm up} = (-1)^{n-N+1} a_n^{\rm down}\,, \quad (4)$$

and for a skew magnet:

$$b_n^{\rm up} = (-1)^{n-N+1} b_n^{\rm down}\,, \quad (5)$$
$$a_n^{\rm up} = (-1)^{n-N} a_n^{\rm down}\,. \quad (6)$$

□

The normal installation direction of the magnets is given in Table 1 in the Appendix together with the number of magnets, the operation temperature and current, the magnetic length, the inductance and the resistance at room temperature. The kickers and experimental magnets are excluded.

Colums A and C give the number of apertures and the number of connection terminals, correspondingly. Four different types of magnets can be identified.

- Single aperture magnets, e.g., MQY with one aperture and one pair of terminals (A=1,C=1).
- Two-in-one magnets with one pair of connection terminals, e.g., MB (A=2,C=1).
- Two-in-one magnets with two pairs of connection terminals for individual powering of the apertures, e.g., MQ (A=2,C=2).
- Magnet modules (individually powered) assembled in twin aperture sub-assemblies, e.g., MO, MQS, MQTL (A=2,C=2).

This classification scheme avoids having to distinguish between two-in-one magnets with a common iron yoke (more or less magnetically coupled) and magnet modules in a common (twin aperture) support structure (magnetically decoupled), which in some cases also allow an individual cold testing of the modules. These technicalities are not important for polarity issues.

The following magnet assemblies are found in the LHC machine:

- MCBCA (35): Superconducting twin-aperture dipole corrector magnet assembly in a MQM-type common support structure. In the MCBCA, the modules are arranged with MCBCV in the internal aperture, i.e, the magnetic field is horizontal, while MCBH is mounted in the external aperture, i.e, the magnetic field is vertical.
- MCBCB (33): Superconducting twin-aperture dipole corrector magnet assembly in a MQM-type common support structure. In the MCBCB, the modules are arranged with MCBCH in the internal aperture, i.e, the magnetic field is vertical, while MCBV is mounted in the external aperture, i.e, the magnetic field is horizontal.
- MCBCC (8): Superconducting twin-aperture dipole corrector magnet assembly in a MSCB-type common support structure. In the MCBCC, the modules are arranged with MCBCV in the internal aperture, i.e, the magnetic field is horizontal, while MCBH is mounted in the external aperture, i.e, the magnetic field is vertical.
- MCBCD (8): Superconducting twin-aperture dipole corrector magnet assembly in a MSCB-type common support structure. In the MCBCD, the modules are arranged with MCBCH in the internal aperture, i.e, the magnetic field is vertical, while MCBV is mounted in the external aperture, i.e, the magnetic field is horizontal.
- MCBX (16): Concentrically nested single aperture dipole correctors, one horizontal MCBXH (inside) and one vertical MCBXV (outside) associated to Q1 (between Q1 and Q2) and to Q2 (between the two Q2 modules).
- MCBXA (8): Nested single aperture horizontal and vertical dipole correctors identical to MCBX with additional concentrically nested multipole correctors MCSX (B_3) inside, and MCTX (B_6) outside. Assembly associated to Q3 (between Q3 and D1).
- MCBYA (18): Superconducting twin wide-aperture dipole corrector magnet assembly in a MQM-type common support structure. In the MCBYA, the modules are arranged such that the field in the internal aperture is horizonal, while the external is vertical.
- MCBYB (20): Superconducting twin wide-aperture dipole corrector magnet assembly in a MQM-type common support structure. In the MCBYB, the modules are arranged such that the field in the internal aperture is vertical, while the external is horizontal.
- MCDO (1232): Nested multipole spool correctors MCD (B_5) and MCO (B_4) inside, mounted on each beam on the MBA dipoles.

- MCSOX (8): Set of nested multipole correctors MCSSX (A_3), MCOSX (A_4) and MCOX (B_4) close to Q3 (between Q3 and DFBX).
- MSCBA (158): Superconducting twin-aperture sextupole-, dipole corrector magnet-assembly. The external aperture is composed of a sextupole MS and a vertical field dipole (horizontal orbit-corrector) MCBH. The internal aperture is composed of a sextupole MS and a horizontal field dipole (vertical orbit-corrector) MCBV.
- MSCBB (154): Superconducting twin-aperture sextupole-, dipole corrector magnet-assembly. The external aperture is composed of a sextupole MS and a horizontal field dipole (vertical orbit-corrector) MCBV. The internal aperture is composed of a sextupole MS and a vertical field dipole (horizontal orbit-corrector) MCBH.
- MSCBC (32): Superconducting twin-aperture sextupole-, dipole corrector magnet-assembly. The external aperture is composed of a skew sextupole MSS and a vertical field dipole (horizontal orbit-corrector) MCBH. The internal aperture is composed of a normal sextupole MS and a horizontal field dipole (vertical orbit-corrector) MCBV.
- MSCBD (32): Superconducting twin-aperture sextupole-, dipole corrector magnet-assembly. The external aperture is composed of a normal sextupole MS and a horizontal field dipole (vertical orbit-corrector) MCBV. The internal aperture is composed of a skew sextupole MSS and a vertical field dipole (horizontal orbit-corrector) MCBH.

The arrangements of the magnet assemblies with the position of the connection terminals, are sketched in Figs. 6 - 9. The figures define the *normal* position of the connection terminals.

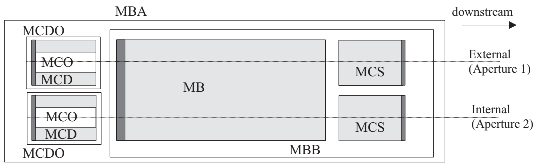

Figure 6: Arrangement of the magnet assemblies in the MBA and MBB dipole cryomagnets.

If the magnets, or magnet assemblies, are installed in the LHC tunnel with the connection terminals pointing into opposite direction, the assembly is marked with a star in the electrical layout database and layout drawings, see Section .

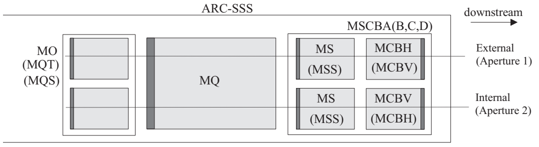

Figure 7: Arrangement of the magnet assemblies in the arc short straight sections (SSS). Different combinations of magnets, polarities, and the presence (or not) of jumper connections to the cryogenic transfer line and of pressure plugs result in 40 variants.

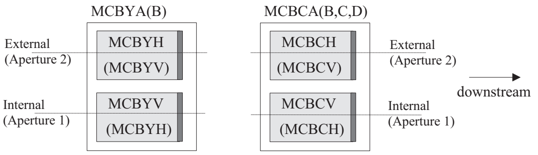

Figure 8: Arrangement of the magnet assemblies MCBYA(B) and MCBCA(B,C,D). Notice that the normal position of the connection terminals is downstream of Beam 1 so that Aperture 2 is on the right seen from the connection end of the magnet (with the connections at the bottom), i.e, on the external side.

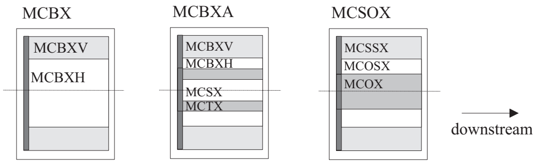

Figure 9: Arrangement of the magnet assemblies MCBX, MCBXA, and MCSOX.

Turned magnets and magnet assemblies

For various reasons, e.g., space available for connections and vacuum equipment, a magnet or an entire magnet assembly may be installed in the LHC tunnel in a reversed sense with respect to the normal direction, i.e., turned by π around the vertical axis. The construction and internal connections of these magnets (assemblies) are not changed. Also the naming of the connection terminals A and B are not changed. However, the magnet's optical function may change depending on the multipole order,

$$B_n^{\mathrm{turn}} = (-1)^{n-1} B_n^{\mathrm{norm}}\,, \tag{7}$$

$$A_n^{\mathrm{turn}} = (-1)^{n} A_n^{\mathrm{norm}}\,. \tag{8}$$

In this case the polarity is changed on the warm side of the magnet which is reflected in the electrical layout database and layout drawing, where the magnet is marked with a star.

The relative higher order field harmonics may change sign in the magnet assembly depending on the multipole order, i.e., for the relative multipoles of a normal magnet:

$$b_n^{\mathrm{turn}} = (-1)^{n-N} b_n^{\mathrm{norm}}\,, \tag{9}$$

$$a_n^{\mathrm{turn}} = (-1)^{n-N+1} a_n^{\mathrm{norm}}\,, \tag{10}$$

and for a skew magnet:

$$\begin{aligned} b_n^{\text{turn}} &= (-1)^{n-N+1} b_n^{\text{norm}}, \quad &(11) \\ a_n^{\text{turn}} &= (-1)^{n-N} a_n^{\text{norm}}. \quad &(12) \end{aligned}$$

Example 1: Compensators in IR2 and IR8

As an example, the electrical layouts of the spectrometer dipole magnet compensations in IR2 and IR8 are shown in Fig. 10. The experiments in these insertion points use spectrometer (dipole) magnets which distort the beam trajectories. This effect is locally compensated with three orbit correctors placed in the straight sections between the interaction point and the final focusing triplet. The compensators are powered according to the rules for the orbit correctors in the arc, i.e., a positive kick (upwards or outwards) on Beam 1 is obtained by a positive setting on the bi-polar power supply and the current entering the B terminal of the compensators. Notice the change of polarity for the turned, vertically deflecting magnet MBXWT in IR2 while the turned, horizontally deflecting magnet MBXWS keeps its optical function.

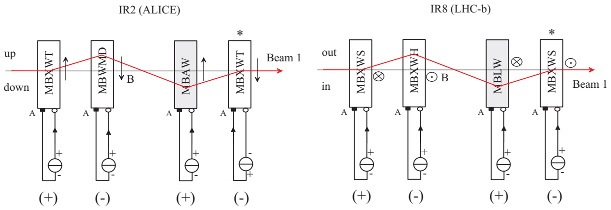

Figure 10: Electrical layouts of the spectrometer dipole magnet compensation scheme in IR2 (left) and IR8 (right). Notice the change of polarity for the turned, vertically deflecting magnet MBXWT in IR2 while the turned, horizontally deflecting magnet MBXWS keeps its optical function. Symbol for the ideal current source according to IEC-60617-2: Graphical symbols for diagrams.

Example 2: Inner triplets in IR2,8 and IR1,5

The electrical layouts of the inner triplet quadrupoles with their adjacent lattice correctors are shown in Fig. 11.

The inner triplets in IR2,8 are shown on the bottom and IR1,5 are shown on the top. For each magnet element the following information is provided. Optical function of the quadrupoles, multipole order of the magnet element, stars indicating turned magnet (sub-assemblies), an indication whether or not the polarity changes when the magnet is turned, the position of the connection terminal (ref. CDD document LHCLSX__%), the terminal in which the current enters, and the magnet polarity (according to the EDMS 90042 document) when the bipolar power supply has a positive setting.

The triplet corrector elements are **not** powered like spool piece circuits as these magnets do not provide a magnet by magnet correction but and overall kick minimization, taking into account all triplet quadrupoles Q1,Q2,Q3, the D1 and D2 dipole and the Q4 quadrupole magnets left and right from the IP. The magnets thus follow the convention that a positive current entering the A terminal implies a positive field independent of the polarity of the quadrupole magnet they are attached to.

The inversion of magnet polarities due to the final position of the magnet terminals (depending on the multipole order) led to polarity errors some of the magnet elements. The electrical layout scheme and the reference database were thus updated accordingly.

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[3] Proudlock P., Russenschuck, S., Zerlauth, M.: LHC Magnet Polarities, Engineering Specification, EDMS Document Nr. 90041, CERN, 2004

[4] Wolf, R.: Field error naming conventions for LHC magnets, Engineering Specification, EDMS document No. 90250, CERN, 2001.

APPENDIX

Magnet	E		Description	N	T	I_{nom}	l_{m}	L	R	A	C	D
Units					K	A	m	H	Ω			
MB	1	B_1	Main dipole coldmass	1232	1.9	11850	14.3	0.102		2	1	u
MBRB	2	B_1	Twin apert. sep. dipole (194 mm) D4	2	4.5	5520	9.45	0.052		2	1	u
MBRC	2	B_1	Twin apert. sep. dipole (188 mm) D2	8	4.5	6000	9.45	0.052		2	1	u
MBRS	2	B_1	Single apert. sep. dipole D3	4	4.5	5520	9.45	0.026		1	1	u
MBW	2	B_1	Twin apert. dipole D3,D4 in IR3,7	20	NC	720	3.4	0.18	0.055	2	1	u
MBWMD	8	A_1	Dipole compensator for ALICE, IR2	1	NC	550	2.62	0.639	0.172	1	1	u
MBX	2	B_1	Single apert. sep. dipole D1	4	1.9	5800	9.45	0.026		1	1	u
MBXW	2	B_1	D1 dipole in IR1,5	24	NC	750	3.4	0.145	0.06	1	1	u
MBXWH	8	B_1	Dipole compensator for LHC-b, IR8	1	NC	750	3.4	0.145	0.04	1	1	u
MBXWS	8	B_1	Dipole compensator for LHC-b, IR8	2	NC	780	0.78	0.04	0.05	1	1	u
MBXWT	8	A_1	Dipole compensator for ALICE, IR2	2	NC	600	1.53	0.08		1	1	u
MCBCH	7	B_1	Orbit corr. in MCBCA(B,C,D)	84	1.9/4.5	100^+	0.904	2.84		1	1	d
MCBCV	7	A_1	Orbit corr. in MCBCA(B,C,D)	84	1.9/4.5	100^+	0.904	2.84		1	1	d
MCBH	7	B_1	Arc orbit corr. in MSCBA(B,C,D), hor.	376	1.9	55	0.647	6.02		1	1	d
MCBV	7	A_1	Arc orbit corr. in MSCBA(B,C,D), vert.	376	1.9	55	0.647	6.02		1	1	d
MCBWH	7	B_1	Single apert. orbit corr., hor.	8	NC	550	1.7	0.05	0.043	1	1	u
MCBWV	7	A_1	Single apert. orbit corr., vert.	8	NC	550	1.7	0.05	0.043	1	1	u
MCBXH	7	B_1	Horizontal orbit corr. in MCBX(A)	24	1.9	550	0.45	0.287		1	1	u
MCBXV	7	A_1	Vertical orbit corr. in MCBX(A)	24	1.9	550	0.48	0.175		1	1	u
MCBYH	7	B_1	Orbit corr. in MCBYA(B)	38	4.5	72	0.899	5.27		1	1	d
MCBYV	7	A_1	Orbit corr. in MCBYA(B)	38	4.5	72	0.899	5.27		1	1	d
MCD	6	B_5	Decapole corr. in MCDO	1232	1.9	550	0.066	0.0004	1.34	1	1	u
MCO	6	B_4	Octupole corr. in MCDO	1232	1.9	100	0.066	0.0004	3.11	1	1	u
MCOSX	6	A_4	Skew octupole in MCSOX	8	1.9	100	0.138	0.0032	12.1	1	1	u
MCOX	6	B_4	Octupole associated to MCSOX	8	1.9	100	0.137	0.0044	13.0	1	1	u
MCS	6	B_3	Sextupole corr.	2464	1.9	550	0.11	0.0008	0.1	1	1	d
MCSSX	6	A_3	Skew sextupole in MCSOX	8	1.9	100	0.132	0.0078	13.7	1	1	u
MCSX	6	B_3	Sextupole in MCBXA	8	1.9	100	0.576	0.0047		1	1	u
MCTX	6	B_6	Dodecapole in MCBXA	8	1.9	80	0.615	0.0292		1	1	u
MO	5	B_4	Octupole lattice corr. in arc SSS	168	1.9	550	0.32	0.00015	4.5	2	2	u
MQ	3	B_2	Lattice quadrupole in the arc	392	1.9	11870	3.1	0.0056	0.87	2	2	u
MQM	4	B_2	Insertion region quad. 3.4 m	38	1.9/4.5	5390^*	3.4	0.0151		2	2	u
MQMC	4	B_2	Insertion region quad. 2.4m	12	1.9/4.5	5390^*	2.4	0.0107		2	2	u
MQML	4	B_2	Insertion region quad. 4.8 m	36	1.9/4.5	5390^*	4.8	0.0213		2	2	u
MQS	5	A_2	Skew quad. lattice corr. in arc SSS	32	1.9	550	0.32	0.031	$0.33^!$	2	2	u
MQSX	6	A_2	Skew quadrupole Q3	8	1.9	550	0.223	0.014	8.02	1	1	u
MQT	5	B_2	Tuning quad. in arc SSS	160	1.9	550	0.32	0.031	$0.33^!$	2	2	u
MQTLH	5	B_2	MQTL (Half Shell Type)	24	4.5	400	1.3	0.120	1.49	2	2	d
MQTLI	5	B_2	MQTL (Inertia Tube Type)	36	1.9	550	1.3	0.120		2	2	d
MQWA	4	B_2	Twin apert. quad. in IR3,7. FD or DF	40	NC	710	3.108	0.028	0.037	2	1	u
MQWB	4	B_2	Twin apert. quad. in IR3,7. FF or DD	8	NC	600	3.108	0.028	0.037	2	1	u
MQXA	4	B_2	Single apert. triplet quad. Q1, Q3	16	1.9	6450	6.37	0.090		1	1	u
MQXB	4	B_2	Single apert. triplet quad. Q2	16	1.9	11950	5.5	0.019		1	1	u
MQY	4	B_2	Insertion wide apert. quad. 3.4 m	24	4.5	3610	3.4	0.074		2	2	u
MS	5	B_3	Arc sext. corr. next to MCBH, MCBV	688	1.9	550	0.369	0.036	$0.21^!$	1	1	u
MSDA	9	A_1	Ejection dump septum, module A	10	NC	880	4.088	0.036	0.027	1	1	u
MSDB	9	A_1	Ejection dump septum, module B	10	NC	880	4.088	0.056	0.034	1	1	u
MSDC	9	A_1	Ejection dump septum, module C	10	NC	880	4.088	0.079	0.041	1	1	u
MSIA	9	B_1	Injection septum, module A	4	NC	950	3.73	0.010	0.011	1	1	u
MSIB	9	B_1	Injection septum, module B	6	NC	950	3.73	0.024	0.0164	1	1	u
MSS	5	A_3	Arc skew sextupole corr. in MCBH	64	1.9	550	0.369	0.036		1	1	u

Table 1: LHC magnet equipment names. Kickers and experimental magnets are excluded. E = Type (see text). N = Number of magnets, T = operation temperature, I = nominal current, l_{m} = magnetic length, L = self inductance R = ohmic resistance at room temperature (if apertures are individually powered then R and L are given for one aperture), A = number of apertures, C = number of pairs of connection terminals, D = Normal position of the connection terminals, u: upstream, d: downstream of Beam 1. NC = Normal conducting. (*) 4310 A at 4.5 K. (+) 80 A at 4.5 K. (!) Protection resistor in parallel. Reference: LHC functional layout database.

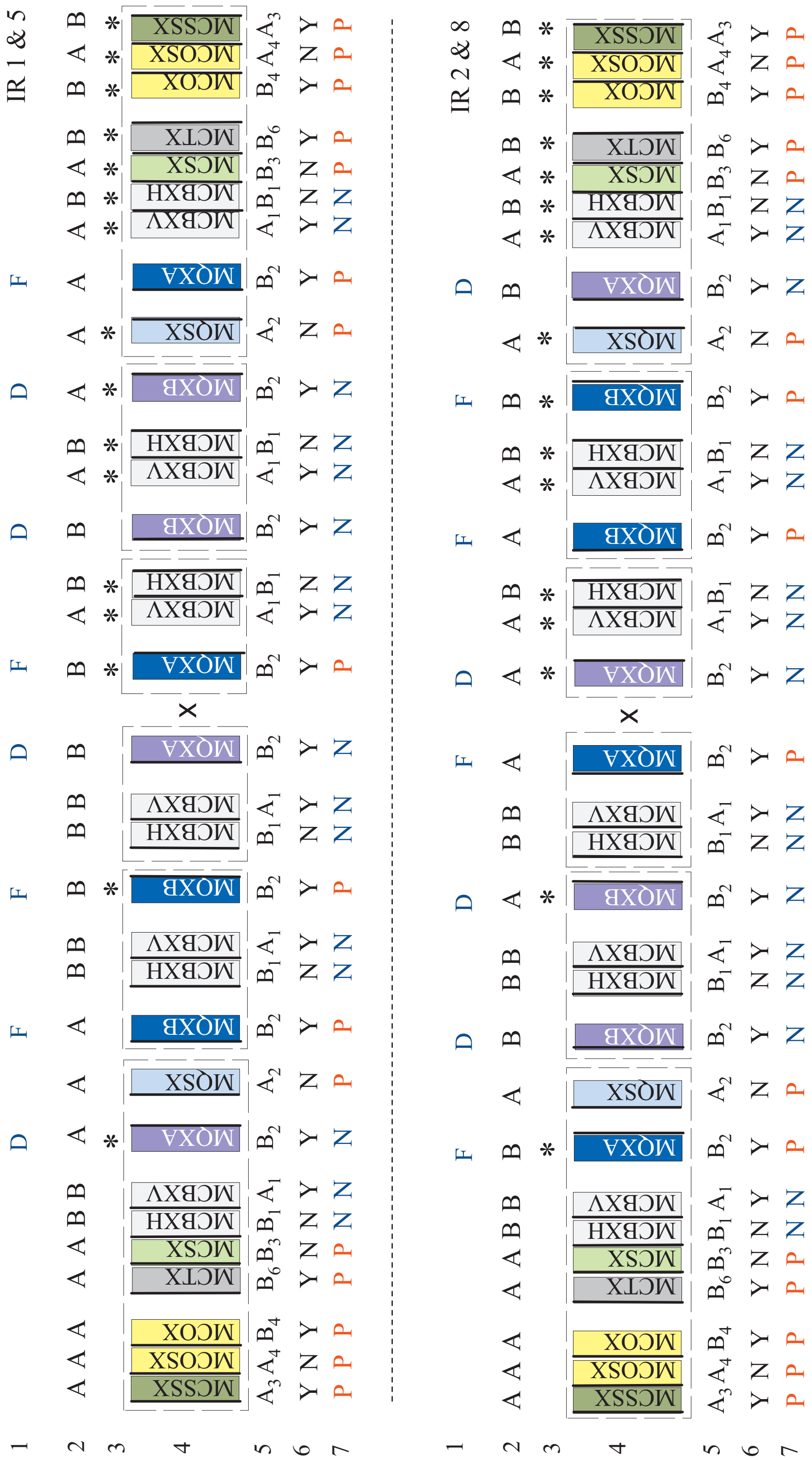

Figure 11: Electrical layout of the inner triplets in IR1,5 (top) and IR2,8 (bottom). Row 1: Optical function of the quadrupole. Row 2: Current entering A or B terminal. Row 3: Stars indicate the turned magnets. Row 4: Name of the magnet element. Notice that MCSSX, MCOSX, and MCOX are nested magnet elements in an assembly called MCSOX. Row 5: Multipole order of the magnet element. Row 6: Polarity changes when the magnet is turned (Y = yes , N = no). Row 7: Polarity of the magnet elements when the bipolar power supply has a positive reading.