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Checking the Polarity of Superconducting Multipole LHC Magnets

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Abstract

This paper describes the design and operation of the “Polarity Checker”, a scanning probe designed to check multipole field order, type and polarity of superconducting LHC magnets. First we introduce the measurement method, based on the harmonic analysis of the radial field component picked up by a rotating Hall sensor at different current levels. Then we describe the hardware and the software of the system, which features automatic powering, data acquisition and treatment, discussing the achieved sensitivity and performance. Finally we provide a summary of the test results on the first 505 cryoassemblies, showing how the system was usefully employed to detect some potentially harmful connection errors.

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***Index Terms*—Large Hadron Collider, Hall sensor, magnetic field polarity, magnetic field measurements, superconducting accelerator magnets.**

I. Introduction

THE Large Hadron Collider (LHC) will include about 1750 cryomagnet assemblies, up to almost 16 m long, housing a total of about 10000 superconducting magnets connected in 1612 electrical circuits [1]-[3]. Any construction error leading to an incorrect multipole type or polarity, such as e.g. those due to busbar inversion, connection of a magnet to the wrong circuit or mistakes in the mechanical installation, may seriously compromise LHC operation. To detect this kind of errors all magnets must be checked carefully, which is not easy as in these superconducting accelerator magnets the field can be measured only from the outside via cold bore tubes with 50 mm aperture. To correct such faults after the machine has been built could require warming up to room temperature an entire LHC sector.

The measurement of field polarity is only apparently trivial. For instance, the harmonic coil systems routinely used provide indeed polarities as a free by-product; however, the number of parameters involved is so high (to wit: direction of coil rotation, sense of insertion into the magnet, polarity of dozens of cables and connectors, sign conventions used in various coefficients and subroutines within the analysis software) that the reliability of the result is in practice very poor.

For this reason, we have developed a dedicated probe called "Polarity Checker" to verify harmonic order, type (normal or skew) and polarity of all multipole magnets. As the system had to be portable, self-contained and independent from the rest of the test infrastructure we decided to base it on a Hall sensor, which is the accepted industry standard for this kind of measurements.

Our system is built upon a concept originally devised at BNL to check RHIC magnets, were it has proved to be very useful [4]. At CERN we carry out the checks at room temperature during and/or at the end of the assembly stage, in order to identify and correct polarity as early as possible. In some cases, e.g. for the corrector spool pieces in the main cryodipole, the polarity check must be deferred to the end of the cold tests, when all connections are finalized. The probe must thus be able to measure reliably very low fields, typically a fraction of a millitesla for high-order correctors, as shown in Table I.

TABLE I
Main Parameters of Typical LHC Magnets

Magnet Type	T.F. [mT/A]	I_{max} [A]	B_{max} [mT]	Diode
Main Dipole (MB)	0.66	5.0	3.32	Y
B1 arc Orbit Corrector (MCBV/H)	52.70	0.1	2.64	
B1 IP Orbit Corrector (MCBXH/V)	6.09	2.4	14.62	
Main Quadrupole (MQ)	0.29	3.0	0.88	Y
Tuning Quadrupole (MQT)	0.10	3.0	0.31	
B3 Multipole Corrector (MCS)	0.05	3.0	0.15	Y
B3 Lattice Corrector (MS)	0.02	3.0	0.07	
B4 Multipole Corrector (MCO)	0.40	3.0	1.20	Y
B4 Lattice Corrector (MO)	0.56	1.0	0.56	
B5 Multipole Corrector (MCD)	0.18	3.0	0.55	Y
B6 Multipole Corrector (MCTX)	0.13	0.5	0.06	

NB: the transfer function (T.F.) given here is the one expected taking into account parallel protection resistors where applicable. The maximum field is given at r_{ref}. The maximum current quoted takes into account also power supply limitations and Hall sensor range. Magnets protected with a diode can be powered only at the nominal polarity, while the others can be powered at both polarities (which improves accuracy).

The order, type and polarity of a given magnetic field follow straightforwardly from the knowledge of the coefficients of the series expansion of the magnetic induction in the complex plane $\mathbf{z}=x+iy$:

$$\mathbf{B} = B_y + iB_x = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{z}}{r_{ref}}\right)^{n-1} = \sum_{n=1}^{\infty} \left(A_n + iB_n\right) \left(\frac{\mathbf{z}}{r_{ref}}\right)^{n-1} \qquad (1)$$

where the reference radius r_{ref} is 17 mm. The sign convention is fixed by the assumption that the x axis is horizontal and points to the right when seen from the

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connection end, while y is vertical, as illustrated in Fig. 1. The origin is taken at the connection end of each cold mass or cryomagnet assembly.

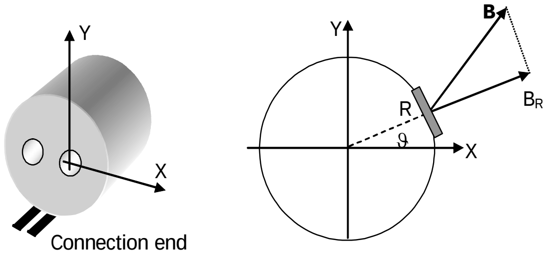

Fig. 1. Frame of reference for the magnetic measurements

II. Measurement Method

The Hall plate is mounted tangentially at a radius R on a rotating support, so that it measures the radial component of the field:

$$B_R(\vartheta) = \vec{B}\cdot\vec{u}_r = \Im\left(\mathbf{B}e^{i\vartheta}\right) \tag{2}$$

The knowledge of this component on the closed boundary of a domain free of currents and of magnetized material is sufficient to find a unique solution for the field inside the domain, as this is equivalent to a classical Neumann boundary value problem for Laplace’s equation resulting from a scalar magnetic potential formulation.

Briefly, the measurement technique can be described as follows: first the magnet is powered and then the probe is manually introduced in its centre. A motor turns the sensor anticlockwise (as seen from the connection end of the probe) to measure the field at N uniformly spaced angular positions, where typically N=32, 64 or 128, obtaining a vector of sampled values:

$$B_{R_j} = B_{R_j}(\vartheta_j),\ \vartheta_j = \frac{2\pi}{N}\,j,\quad \text{j} = 0 \text{ to N - 1} \tag{3}$$

(in our system rotation actually starts from $\vartheta_0=\pi/2$, however the array can be trivially rearranged for reconstitution of the case $\vartheta_0=0$). This can be written in full, truncating the series with negligible error:

$$B_{R_j} = \sum_{n=1}^{N-1}\left(\frac{R}{r_{ref}}\right)^{n-1}\left(A_n\cos\frac{2\pi}{N}jn + B_n\sin\frac{2\pi}{N}jn\right) \tag{4}$$

The coefficients of the DFT of the B_{Rj} vector, defined by:

$$\boldsymbol{\beta}_\mathbf{k} = \frac{1}{N}\sum_{j=0}^{N-1} B_{R_j}\, e^{\frac{2\pi}{N}ijk} \tag{5}$$

may be shown to be proportional to the field coefficients of the same order by first inverting (5):

$$B_{R_j} = \sum_{k=0}^{N-1}\boldsymbol{\beta}_\mathbf{k}\, e^{-\frac{2\pi}{N}ijk} \in \Re \tag{6}$$

and then equating term by term (6) to (4), obtaining finally:

$$\mathbf{C_n} = i\left(\frac{r_{ref}}{R}\right)^{n-1}\beta_n^* \tag{7}$$

where * denotes complex conjugation. The knowledge of the $\mathbf{C}_n$ at just one current level, however, may not be sufficient to derive the correct results as the residual field in the iron yoke, which can reach in some cases a few millitesla, might mask completely the main harmonic. We shall in most cases take at least two measurements at different currents and fit them with a linear regression to compute the transfer functions $\partial\mathbf{C}_n/\partial I$, representing the field produced by the coils (geometric component) from which one can easily derive:

- magnet order and type, as the order of the dominant term in the arrays $\partial B_n/\partial I$, $\partial A_n/\partial I$.
- magnet polarity, as the sign of the dominant term.

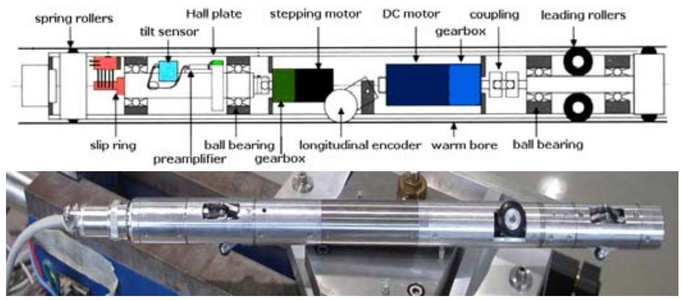

Fig. 2. Internal layout and external view of the Polarity Checker probe.

III. Implementation and Operation

A. Hardware components

The Polarity Checker system, of which 5 units have been built to deal with the series test workload, is composed of a cylindrical probe linked to an electronic rack with a 25m long cable. The main design parameters are given in Table II. The probe, shown in Fig 2, includes:

- a tangential Hall plate with an on-board preamplifier;
- an electrolytic tilt sensor;
- a slip ring to transfer sensor output to the cable;
- a 24×256-stage stepping motor with a 22:1 reduction gearbox to drive the rotation;
- rollers that can be adapted to different pipe diameters.

A longitudinal transport system including an on-board DC motor has also been built in, but as the precision of the movement was found to be inadequate this method was dropped in favor of simple manual positioning, aided by markings on the cable. It should be noted that the range of the Hall plate, the stepping motor and the electrolytic tilt sensor

TABLE II
Main Hardware Parameters of The Polarity Checker

Parameter	Value
Probe length (mm)	768
Probe external diameter (mm)	∅40
Tube internal diameter (mm)	∅40 to ∅73
Tilt sensor range	±45°
Tilt sensor resolution (mrad)	0.1
Hall plate current (mA)	50
Hall plate sensitivity (mV/T)	233.8
Hall plate radius (mm)	11
Hall plate azimuthal offset (mrad)	10.5
Hall plate max. field (mT)	30
Hall plate min. field (mT)	0.01
On-board Preamplifier gain	500
Azimuthal resolution (mrad)	0.047

Note: the parameters listed refer to the first probe of the series built.

are not compatible with high field levels.

The rack houses the following components:

- a high-precision Hall current source;
- the stepping motor driver;
- the tilt sensor conditioning module;
- a NI-6230 16-bit, 200 kHz DAC card to read in Hall voltage and tilt sensor output;
- a bipolar Kepco power supply for magnet excitation;
- a custom-built data switching unit based on a computer-controlled Keithley 2001 multiplexer to route the input current through up to 9 channels in each of 6 different cables (equipped with ad-hoc connectors) to the appropriate magnets in the cryoassemblies;
- a PC that runs the control and analysis software, hosts the DAC card and controls power supply, multiplexer and stepping motor via RS-232.

B. *Software components*

The Polarity Checker software is a collection of LabView modules that perform two basic tasks: a) execute a field measurement and return an array of coefficients $\{\mathbf{C}_n\}$, and b) guide smoothly the operator through the full test of a given assembly, returning a conformity report. Operation is supported by an Excel configuration file that lists the existing types of cryomagnet assembly and their composition, the geometrical and physical properties of the various magnets in the cold mass, as well as their nominal transfer function, multipole type and polarity. The expected results depend on the presence of a parallel protection resistor, on the polarity of the power supply (which may be constrained due to a protection diode) and on the side from which the probe is inserted (the polarity of even normal and odd skew multipole fields changes with a 180° rotation around the *y* axis).

Procedure a) is fully automated and consists of these steps, taking about 2 min. for N=64:

a.1) level the Hall plate within ±1 mrad using feedback from the tilt sensor, allowing a 750 ms delay between steps to allow the output to stabilize;

a.2) set the power supply to the specified current I_K;

a.3) turn the motor by the necessary number of steps to obtain a $2\pi/N$ rotation and then switch it off, to avoid an unacceptably high level of electrical noise;

a.4) acquire 1000 samples at 10 kHz, then low-pass filter at 20 Hz cutoff to obtain an average value of $B_{Rj}^{\,k}$ at the end of the transient;

a.5) repeat N times steps a.3) and a.4) to complete a full revolution;

a.6) compute the harmonic coefficients β_n using the FFT;

a.7) compute the field coefficients $\mathbf{C}_n^{\,k}$ using (7);

a.8) repeat steps a.2) to a.7) for k going from 1 to the prescribed number of current steps;

a.9) compute a linear regression through each set $\{\mathbf{C}_n^{\,k}, I_k\}$ to finally obtain the transfer functions $\partial\mathbf{C}_n/\partial I$.

A low-level validation is carried out at this stage, when the measurement can be rejected and automatically repeated if the estimated noise level or the standard deviation of the best fit exceed a given tolerance.

Procedure b) represents the front-end of the program and is designed to have a wizard-style interface that guides the operator through the test preventing omissions and mistakes. The following steps are carried out:

b.1) input the name and type of the cryomagnet assembly (or of the individual magnet) to be measured;

b.2) push by hand the probe to the center of the magnet to be measured first (for the shorter magnets, an accuracy of the order of 10 mm is sufficient);

b.3) run procedure a);

b.4) compare the measured transfer function and the main harmonic's order, type and polarity with the expected values, issuing a warning in case of non-conformity;

b.5) write a PDF report file with the results;

b.6) repeat steps b.2) to b.5) for all magnets to be measured in both cold bore tubes of the cryoassembly.

Typically, a whole test takes less than one hour. The operator must interpret the results to understand the problem in case of non-conformity. Most commonly, a wrong transfer function indicates that the longitudinal positioning or the current level is incorrect; if the problem cannot be fixed, the magnet is then set aside for further checks.

IV. System Qualification and Performance

A. *Calibration and validation*

The calibration of the probe, carried out in a reference dipole, consists in finding the field-to-Hall voltage transfer function and the azimuthal offset between the tilt sensor and the Hall plate, which are given in Table II. The transfer function, including the effects of the preamplifier, is found by measuring a loadline with the sensor at rest and by cross-checking the results with a NMR teslameter. The offset angle is found as the half-difference of the field directions obtained by taking two harmonic measurements, inserting the probe from opposite ends.

The validation has been done by testing reference magnets of order 1 to 5, for which the polarity was checked using a commercial Hall teslameter placed directly in front of the poles (actual iron poles for the dipole and quadrupole, superconducting coils otherwise). A suitable magnet of order 6 (dodecapole) was not available at the time of the test, however the field parameters are very similar to those of sextupole multipole correctors (MCS) and the final results are reasonably expected to be similar. The magnets were first positioned to yield a positive normal field component, then a positive skew one; tests were then repeated inserting the probe from both ends and inverting the current. In all cases, results were conforming to expectations.

B. *Characterization of performance*

The overall system performance is summarized in Table III. First, the repeatability of the measurements was tested by running 60 consecutive measurements in the reference magnets. The results, given in Table IV, show that the standard deviation of the main field, which represents random measurement errors, is on average about 10^{-3} of the measured value. This is well below the maximum linearity error, which has been estimated from the calibration measurement, which also provided the resolution of the Hall sensor. In the end, we see that even in the worst case (dodecapole) the field amplitude to be measured is 6 times higher than the resolution. Since in LHC magnets all higher order multipole errors are at least two orders of magnitude below the main harmonic, we conclude that the identification of the main harmonic order and polarity is virtually error-free (at least, for the field range in Table I).

The accuracy of field direction measurements is limited by the open-loop motor control, which causes random errors around 2 mrad as was found by taking the difference of the tilt sensor readings at the beginning and at the end of a revolution. Additional phase errors up to 1/6 rad for a dodecapole may arise due to the inaccuracy of field measurement, consistently with the results of the repeatability test. While the accuracy is inadequate for field direction measurements in LHC magnets, it is nevertheless well below the threshold necessary to correctly attribute normal or skew field type, i.e. at least $\pi/12 \approx 262$ mrad.

TABLE III
ESTIMATED ACCURACY

Measured quantity	Value
Field resolution (mT)	0.02
Field linearity	3%
Main harmonic order	error-free
Main harmonic polarity	error-free
Main harmonic type	error-free
Field direction (mrad)	10.0

TABLE IV
REPEATABILITY TEST RESULTS

Magnet Order	Main Field (mT)		Field direction (mrad)
(1=dipole)	Avg.	Std. Dev.	Std. Dev.
1	-25.58	0.024	1.79
2	8.60	0.010	1.70
3	0.10	0.001	4.19
4	-0.85	0.001	7.55
5	0.42	0.001	2.04

V. LHC MAGNET TEST RESULTS

To date, a total of 505 cryomagnet assemblies have been checked at CERN, where all faults could also be corrected. Predictably, the fault rate was much higher in 2003 and 2004 than it is today. A summary of results is given in Table V.

About 3% of all corrector magnets were found to have polarity or aperture inversions. This fault rate, if undetected, would have lead to a loss of correcting capability, which could be acceptable in some cases (e.g. for the dipole spool pieces), recoverable in others (e.g. the dipole correctors, which are individually powered) but catastrophic for some (e.g. main dipoles and quadrupoles, skew and tuning quadrupoles).

A. *Polarity checks in cryodipoles*

In cryodipoles only three faults, i.e. about 1%, were discovered in 2004. In all three cases the 600 A superconducting busbars of one corrector spool piece had been crossed, leading to a polarity inversion. This has been rectified by crossing and re-labeling the busbars at the connection end of the cryomagnet. No errors were found in the main dipoles.

B. *Polarity checks in Short Straight Sections*

The fault rate in arc Short Straight Sections is much higher (about 20%), no doubt due to the variety and complexity of these assemblies (a total of 61 different types can be found in the arcs, with 13 more types with up to 9 magnets per aperture in the insertion regions). A total of 13 polarity errors and 58 aperture inversions have been identified so far, all of them in the dipole, sextupole and octupole correctors (no error in the main, tuning and skew quadrupoles). Aperture inversions of MS and MCB correctors are always coupled, since the magnets are included in the same subassembly.

TABLE V
SUMMARY OF POLARITY CHECK RESULTS

Magnet Type	Tested	Faults	Type
Cryodipoles	330	3	Any
- Main dipoles (MB)	330	0	-
- Spool piece correctors	990	3	Polarity
Short Straight Sections	175	34	Any
- Main Quadrupoles (MQ)	175	0	-
- Dipole Correctors (MCB)	175	3 28	Polarity Aperture
- Tuning Quadrupoles (MQT)	71	0	-
- Skew Quadrupoles (MQS)	1	0	-
- Sextupole Correctors (MS)	175	8 28	Polarity Aperture
- Octupole Correctors (MO)	103	2 2	Polarity Aperture
Total Cryoassemblies	505	37	Any
Total magnets	2020	61	Any

All magnets are of 2-in-1 type, except the spool piece sextupole, octupole and decapole correctors in cryodipoles which are individually mounted at the ends of each dipole.

VI. CONCLUSIONS

The Polarity Checker has been proved to be a fast, easy to use and reliable instrument which has helped to identify a large number of connection errors, detrimental although not critical, in the LHC magnets. At the moment, its capabilities are being extended to cope with the complex Short Straight Sections in the Insertion Regions.

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