

# MAGNETIC MEASUREMENT SYSTEMS FOR THE LHC DIPOLE ASSEMBLY COMPANIES

A. Rijllart, J. Billan, J. Garcia-Perez, D. Giloteaux, A. Raimondo, V. Remondino, H. Reymond, CERN, Geneva, Switzerland

## Abstract

The LHC superconducting lattice dipole magnets are presently under construction in three European industries. Due to the stringent magnet performance required for the LHC, these magnets have to be built with high accuracy during all the steps of their assembly. In order to detect defects in the earliest industrial production phases and to ensure the quality of the magnetic field as specified by the CERN contracts, dedicated measurement benches have been built and installed in each assembly company to validate the magnetic field quality at two important production stages: the collared coils and the final cold mass. This paper describes the initial requirements and the implementation of the magnetic measurement systems. Details on the technical solutions, the present status and measurement results are presented.

## INTRODUCTION

The Dipole Industry Magnetic Measurement (DIMM) benches operating at room temperature in each assembly company are essential for acceptance tests, based on the quality of the integrated field and the field harmonics of the cold mass. These systems are also useful for field measurements of collared coils, to evaluate possible deviations from the expected harmonics at the earliest production phases [1].

The same results are also used for a more detailed analysis at a later stage [2] at CERN. A good correlation has been found between cold and warm magnetic measurements, consequently only one third of the dipoles are measured at cold at CERN [3]. This allows significant cost reduction and important gain in time.

## DESCRIPTION OF DIMM

The DIMMs adopt the method of DC excitation current and rotating search coils instead of the classical AC approach. The DC method was first used for the measurement of LHC dipoles at room temperature in 1995 and it has proven [1] to be adequate for dipoles.

To reduce noise, three sets of clockwise and anti-clockwise rotations of search coils are performed in sequence at a current of 10 A. Then the set is repeated at -10 A, in order to minimise iron and earth field effects. The harmonic coefficients can be reconstructed applying the Discrete Fourier Transform (DFT). A complete review of the theory can be found in [4][5].

Initially, the harmonics computed at each position are normalized with respect to the nominal current and the gravity. Then the computed harmonics for the whole magnet are obtained by summing the harmonics at each longitudinal position multiplied by the length of the

measuring search coils. Finally, the harmonics are normalised with respect to the magnetic centre of the magnet. For consistency with cold measurements, the magnetic axes are computed cancelling harmonics 10.

## The Hardware

Each DIMM bench consists of a data acquisition system, an on-line analysis program and two sensitive field-measuring probes that rotate inside the apertures of the dipole and move longitudinally along the magnet [Figure 1].

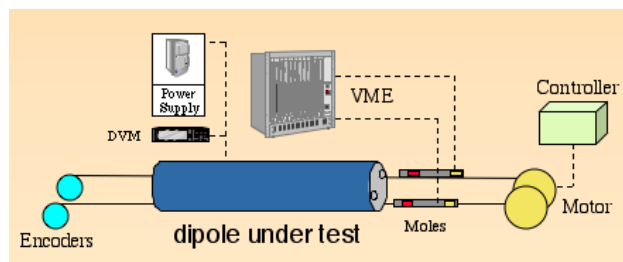


Figure 1: A simplified diagram of the DIMM system.

The core of the system is the magnetic field probe (mole), a very sensitive device as magnets are measured at low field. Moles must be built accurately and carefully calibrated [6], as final results depend on the precision of its components. The main components of the mole are three rotating search coils, an incremental encoder, an electronic gravity sensor and a pneumatic brake.

At each given longitudinal position, the mole rotates to adjust the reference axis of the coils with respect to the gravity. A precision of  $\pm 50 \mu\text{rad}$  is obtained using an electronic gravity sensor. The levelling process is implemented entirely by hardware.

The mole is held in position during measurement by the pneumatic brake. Then, being inside the magnetic field of the dipole under test, a motor rotates the search coils, which produces a voltage proportional to the flux and to the rotation speed. The rotation speed is carefully controlled by software in order to obtain an acceleration phase, followed by a complete revolution at constant speed for data acquisition and then the final deceleration phase.

The signal from the outward coil (absolute signal) is used for the determination of the main component. On the other hand, the field harmonics are computed combining signals coming from different coils (bucking signal). The bucking allows rejecting the main harmonic component, so that errors coming from imperfections of coils rotation are eliminated and a higher amplification of voltage can be applied to the field harmonics detection.

The two voltage signals from the rotating coils are sent to low-noise pre-amplifiers. The outputs of the pre-amplifiers together with the encoder pulses are sent to two integrators in VME crate, based on voltage-to-frequency conversion. Using integrators, field measurements are insensitive to variations of angular velocity of search coils.

A motor mounted in a support placed near the connection side of the magnet moves the moles inside the aperture to the twenty longitudinal positions necessary to measure the entire magnet.

On the other side of the magnet, a commercial encoder, mounted on a second support, measures the actual position of the mole with a precision of  $\pm 0.3$  mm. Such a precision is necessary in order to comply with the given tolerances on magnetic length.

The data acquisition system, based on the VME industrial standard, is connected via a fast connection card (VME-MXI) to a SUN workstation. The VME houses the integrators, an ADC, a DAC, two digital I/O cards and a DAQ processor card.

A LabVIEW® application controls the VME, the motor controller for the longitudinal movement via RS232, the power supplies and the DVMs for the current read-out through GPIB.

Although not used at the moment, a second power supply is available to measure the correctors mounted close to the dipole. In this way, correctors could be measured in the dipole companies any time if required.

### The Software

The control of DIMM benches, the measurement cycle execution and the analysis are performed by the LabVIEW® application. This choice was based on the availability of several thousands of libraries, used to drive external devices via a computer, and on the capability of this language to easily integrate all the needed functions to manage the interaction between hardware and the graphical user interface, as specified in the requirements.

Figure 2 shows the software structure.

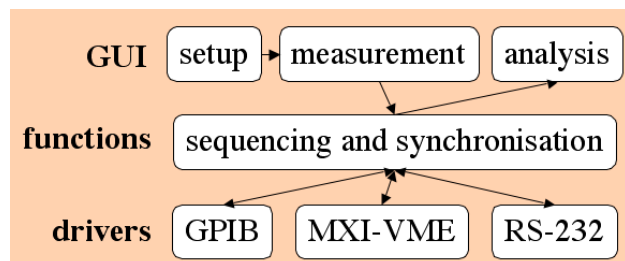


Figure 2: DIMM software structure.

The lowest level of the software is composed of the drivers of the interfaces and equipment used.

The middle level is composed of multi-device sequencing and synchronisation functions using the lower level drivers. This is the core of the software that manages the control and read-out of the devices with the defined measurement procedure and parameters.

The user interface allows the operator to define the measurement parameters and shows the status during the measurement and the final results.

The configuration definition is split into two parts, the first one is used to configure the hardware aspects (VME cards addresses, mole and encoder type, speed of rotation of search coils, integrators parameters, setup of the motor controller, etc.) and the second one defines the software parameters (scale factors for harmonics and limits setup).

Before the start of each measurement the current cycle with the measurements points is shown and during execution the progress of the measurement and its dynamic evolution is shown in graphs.

After the measurement results are displayed in graphical and numerical format. Several analysis tools are available to be applied on the collected data. Facilities are given to export measurement data as flat ASCII files and binary files (raw and results data).

At the end of the analysis, files are sent directly to CERN via the company's own network or via a dedicated ADSL modem.

### DIMM's Features

DIMMs were designed to work in an industrial environment. They are robust and easy to use at the manufacturers' sites by non-specialist personnel, because we have used our experience over many years of measurement systems at CERN that have been optimised for reliability. On-call support from CERN is supplied by CERN personnel. In this context, a procedure for standard measurements was well defined and documented so that the personnel at the company can measure a complete magnet in less than two and a half hours.

The system is flexible enough to adapt to non-standard measurements. In this case, the DIMM is operated by CERN personnel.

DIMMs are autonomous: they require simple standard maintenance, which is expected once every 3-5 months (calibration of moles, checks on the integrity of cables, motors, etc.). Results are complete: the entire analysis package is included in the program. This saves time during production, as the factory is able to decide to repeat the measurement in case of doubtful results before dismantling the magnet from the measurement bench. The same results are automatically sent to CERN, immediately after each measurement session, so that an evaluation of field quality can be promptly carried out. These results are stored in an Oracle database. Raw data are also sent to CERN, in case a more detailed analysis is necessary.

Harmonics are indeed a reflection of the coil geometry and of the magnets mechanical structure. A deviation from the nominal values may indicate that a component is out of tolerances or that the coil or the magnets were badly assembled. The presence or absence of certain harmonics is used by the analysis team at CERN to determine the nature, size and localisation of these defects [7]. An example is given in Figure 3 where DIMM pointed out a defect in the middle of the dipole in aperture

1, in the upper left quadrant. After de-assembling of the collared coils, a double protection shim was found at that position.

### Using DIMM in Industries

A well-defined procedure, based on our experience, has been set up for measurements at the factories sites. This method provides precise results in a reasonable measuring time. The personnel at the companies can carry out standard measurements of dipoles after only a one-day training course.

All the operator has to do is entering a few values in the measuring program, such as the magnet number, the operator's name and the temperature in the hall. The program stores a number of default values relevant to standard measurements. Updating these values is necessary only in case of changes in the hardware. Then, the operator can start the measurement, which, from this point on, is completely automatic. The program is user-friendly: at the end of the measurement, the operator has just to launch the analysis routine and send results to CERN using the specific buttons.

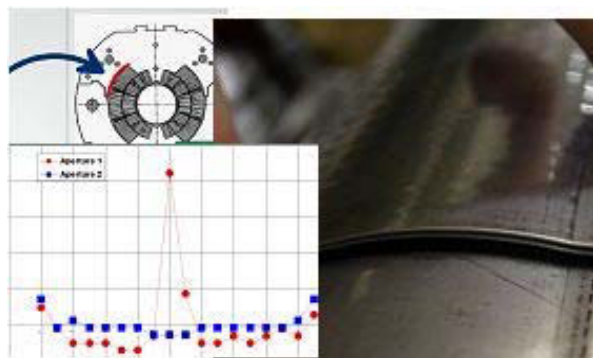


Figure 3: Example of mechanical defect pointed out by DIMM.

### CONCLUSIONS

In order to evaluate the main field, the magnetic length and the field harmonics, the DIMM magnetic measurement system was developed for acceptance tests for the dipole series production at the factories.

It was designed to be robust and to require minimal maintenance, which could be done in parallel with the moles calibration.

The electronic hardware is commonly available on the market and the software was developed using an industrial control system standard.

The complete measurement at each production stage, including the on-line analysis, takes less than 2.5 hours and results are available at CERN immediately after the end of the measurement.

After the initial setting of the moles and motors modules, the measurement is completely automatic, including the final analysis. The system is also flexible to be used for non-standard measurements. In this case, magnets are measured by CERN personnel.

A total of eight DIMMs have been built, six of which have been installed in the three dipole assembly companies between November 2002 and November 2003. Each company is equipped with two DIMMs, one for the measurement of collared coils and one for the final measurement of the cold mass. Two extra devices are kept at CERN as spare systems and for future development.

As of May 2004, about 20 manufactured collared coils have been found out of tolerances thanks to DIMMs. All these coils showed real mechanical defects in the positions expected. The monetary value saved is already more than the whole investment in the warm magnetic measurements for the production so far.

DIMMs have proven to be very precise, provided that the moles are regularly calibrated.

Furthermore, because of the good correlation found between warm and cold measurements, only one third of the dipoles are now measured at cold at CERN [3]. This speeds up the magnets tests and allows significant savings in the construction of the LHC dipoles.

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