Experimental qualification of the platform for magnetic measurements at CERN

P. Arpaia[1,2], M. Buzio[2], V. Inglese[2,3], G. Spiezia[2,3]

[1] Department of Engineering, University of Sannio, Corso Garibaldi 107, 82100 Benevento, Italy. Ph : +39 0824 305804-17, Fax: +39 0824 305840, E-mail: arpaia@unisannio.it
[2] CERN, Dept. of Accelerator Technology, Magnet Electrical Systems & Instruments, CH 1211, Genève 23, Switzerland. Ph : +41 22 76 76635, Fax: +41 22 76 76230, E-mail: Marco.Buzio@cern.ch
[3] Department of Engineering, University of Naples - Federico II, Via Claudio 21, 80125 Napoli, Italy; E-mail: {Vitaliano.Inglese-Giovanni.Spiezia}@cern.ch

Abstract **-** The experimental qualification of a new platform for magnetic measurements at the European Organization for Nuclear Research (CERN) is presented. The platform was validated in comparison with the CERN standard test magnet system at warm conditions using the rotating coil method on a superconducting dipole of the Large Hadron Collider. Further characterization tests were carried out at cryogenic temperature (1.9 K) in order to analyze dynamic phenomena of superconducting magnets with a time resolution never reached before.

I. Introduction

The particle accelerator Large Hadron Collider (LHC), under construction at the European Organization for Nuclear Research (CERN), has pushed technological efforts in many areas of engineering. In particular, the series test of LHC superconducting magnets required the development of a new platform for the magnetic measurements [1].

The novelties of such a platform are mainly represented by (i) the Micro Rotating Unit (MRU) [2], a new generation of fast transducers, mainly based on rotating coil, (ii) the new Fast Digital Integrator (FDI) [3]-[4], a PXI-based acquisition card with a DSP on board for signal processing, and (iii) the Flexible Framework for Magnetic Measurements (FFMM) [5], a software framework for managing various tests on magnets.

Conceived to turn continuously and faster than the previous Twin Rotating Unit (TRU) [6], the MRU allows the field harmonics to be evaluated at an higher rate in order to better analyze dynamic effects in superconducting magnets.

FDI answers to the need for a higher-bandwidth and higher-accuracy integrator, arisen from the development of. several fast transducers [2], [7]. As a matter of fact, the Portable Digital Integrator (PDI) [8], the standard de facto integrator in most sub-nuclear research centers, cannot fulfill the new test requirements in terms of resolution and bandwidth [2]. Other solutions were developed worldwide [9]-[10], however, they are mainly prototypes, not fully finalized and characterized.

FFMM has been developed to accomplish the requirements of flexibility and reusability arisen after the series production of the LHC magnets. The magnet tests become more and more specialized and highly variegate, thus a framework is required to develop easily new measurement programs [11]. The state-of-art solutions in industrial [12] and research environments [13]-[16], either do not fully accomplish the above-described requirements in terms of reusability and flexibility, either are still under development and not yet worldwide accessible. FFMM provides a robust library to control remotely the instrumentation involved in the tests, as well as the tools to help the user in the design of new measurement algorithms.

This paper reports about the on-field test campaign carried out at CERN for the qualification of the new platform with twofold main aims of proving that the MRU and FDI overcomes state-of-the-art measurement solutions, and the FFMM provides an infrastructure for designing easily different magnetic tests. In the following Sections, the test plan and the experimental results of such an on-field qualification are detailed.

II. The test plan

The above platform was qualified on field at CERN on LHC superconducting magnets by carrying out different specific tests. In particular, the qualification plan was organized in validation and characterization tests. In the

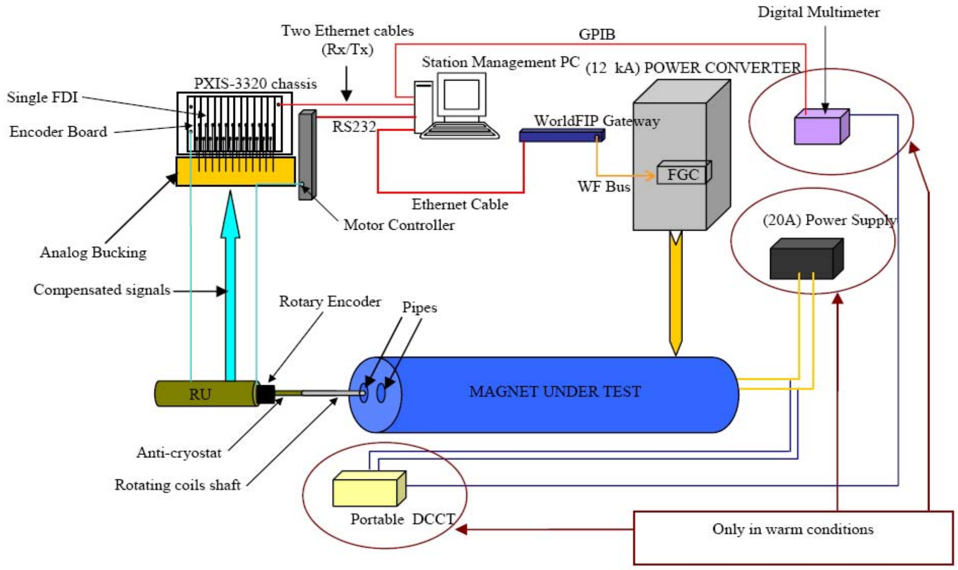


Figure 1. Test station for the platform on-field characterization.

following, (i) the *measurement method*, (ii) the *test station*, (iii) the *validation procedure*, and (iv) the *characterization procedure* are detailed.

The *measurement method* is based on the “rotating coil” [1]: A set of coil-based transducers are placed in the magnet bores, supported by a shaft turning coaxially inside the magnet. The coil signal is integrated according to the Faraday’s law in the angular domain, by exploiting the pulses of an encoder mounted on the shaft, in order to get the induction field. Several coil segments are placed on the shaft by covering the length of the magnet. Each segment, in turn, is made up by three overlapped coils: the external one measures the mean field (absolute signal), while the series connection of the external and the central coils in opposition of phase allows the main field to be deleted in order to measure the field harmonics only (compensated signal).

The *test station* is depicted in Fig. 1. The coil shaft inside the magnet is turned by the Rotating Unit (RU) whose motor is driven by a controller. The magnet under test is supplied by power converters with digital control, with very different capacity depending on the test conditions: tests are carried out at cold (up to 1.9 K) and warm (room temperature) conditions by using a 14 kA 15 V and a 20 A, 135 V power converter, respectively. The current is read by a high-accuracy Direct Current-Current Transformer (DCCT). The coil signals are integrated in the angular domain by six FDI boards, by exploiting the trigger pulses coming out from a conditioning board, suitably processing the output of the encoder mounted on the RU. The FDI boards, the encoder conditioning board, and the motor controller are remotely controlled by a PC running the test program output by FFMM, produced according to a suitable script [5]. The tests were carried out on the LHC dipole MBBR 2427 at the CERN magnet facility SM18.

The *validation procedure* is aimed at verifying that the new hardware, namely the FDI, as well as the new software, FFMM, provide results compatible with the previous PDI-based system, using the previous MMP software [13], on the same LHC dipole in the same measurement conditions. While the new platform is conceived to measure the magnet by continuously turning the shaft in the same direction through the MRU in order to increase the bandwidth, the previous system exploits the “washing machine algorithm” using the standard TRU [6]. The field harmonics are evaluated as average of two measurements carried out by turning the shaft first in one direction (clockwise), and then in the opposite one (contra clockwise), in order to delete the offset and compensate possible mechanical play. Thus, the dipole magnet supplied by ±10 A at a temperature of 152 K, was measured with the same shaft and TRU with both FDI- and PDI- based systems, according to the washing machine algorithm. Tests at room temperature are considered as more severe for the measurement set up, owing to the critical values of signal-to-noise ratio arising from the relatively low values of the field to be measured.

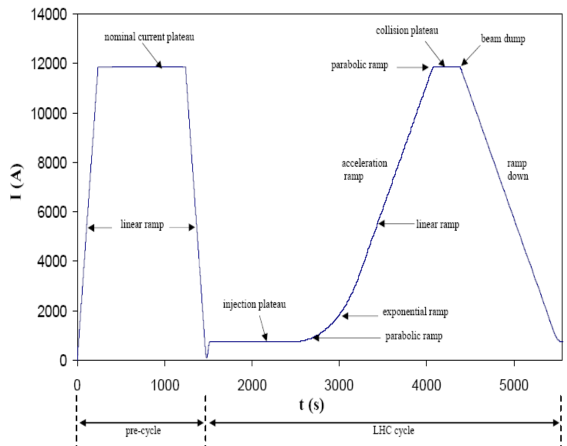
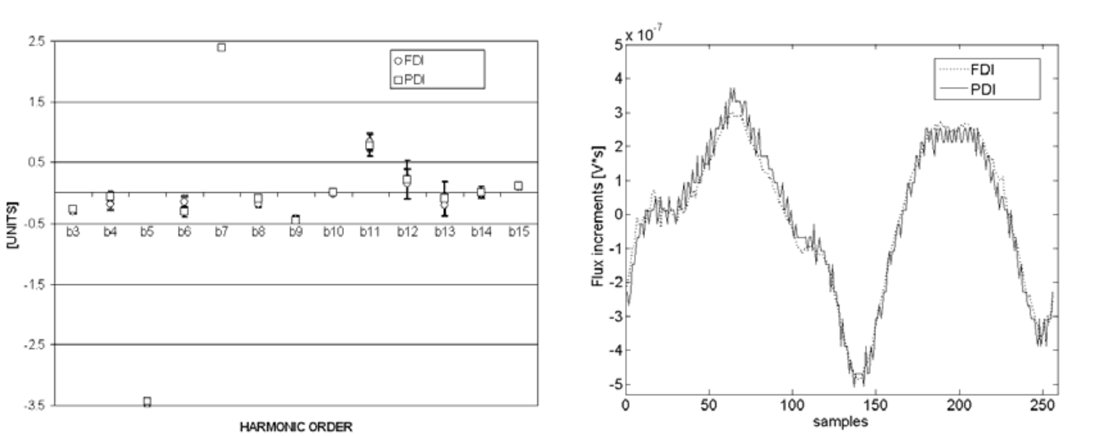


Figure 2 . LHC current cycle.

The *characterization procedure* is based on tests in static and dynamic standard working conditions of the measurement platform. In static tests, the magnet (an LHC dipole) is supplied at constant current by verifying the measurement repeatability. 30 singles turns were acquired along a time interval of 0.125 s, rotating in the same direction at a speed of 8 rps. This test proves also the suitability of the new measurement algorithm. The measurements were carried out at two different gains to study the eventual effects of the ADC quantization noise. In dynamic tests, decay and snapback phenomena of the 3rd and 5th harmonics are analyzed [1] by supplying the magnet with the profile current of the standard LHC cycle (Fig. 2). The new platform can deliver the flux harmonics at a rate of 8 Hz, the maximum rotation speed, allowing the decay and snapback phenomena to be analyzed with a good time resolution and a high accuracy. The dynamic phenomena of decay and snapback, arising after the injection phase (Fig. 2), where the ramp current follows a Parabolic-Exponential-Linear-Parabolic (PELP) profile, were measured by four FDIs fed up by the two central shaft segments. One more FDI was used to acquire the analog signal of the DCCT transducer at the same trigger frequency as the flux.

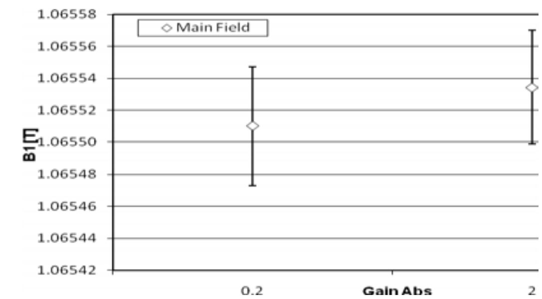
III. Experimental results

In the following, the results of the on-field tests for (i) *validation*, (ii) *static characterization*, and (iv) *dynamic characterization* are reported.

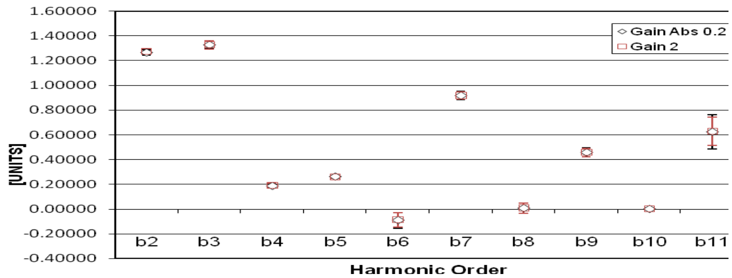


(a) (b)

Figure 3. Average magnetic flux harmonics with 3-σ bar (a), and compensated flux increments (b)at warm conditions, measured by the new FDI-based and the old PDI-based platforms.



(a)



(b)

Figure 4. B_1 mean (a) and high-order harmonics mean (b) with 3-σ bar for two different FDI gains.

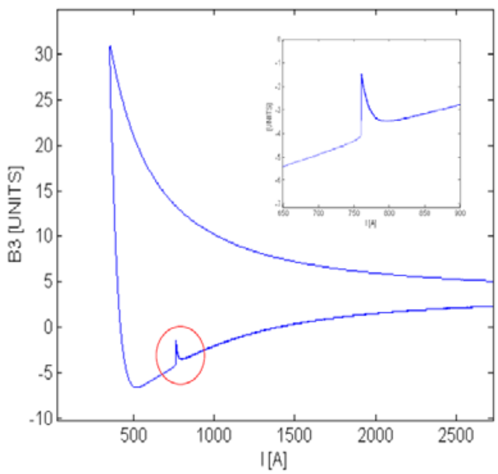
An example of *validation* test results is shown in Fig. 3a. The average of the harmonics over 30 measurements are reported with a bar of $\pm 3\sigma$. The harmonics are much lower than the main field, thus they are expressed as "unit" [1], i.e. the value of the harmonic normalized by the main field and multiplied by a factor 10^4. The measurement results of both the new and the old platforms are compatible, with differences within 0.1 units or less. The difference in the average harmonics is smaller than the uncertainty associated with the dispersion of the single results from one system, and the dispersion on each of the harmonics is similar, proving that the old and new system deliver the same results. In Fig. 3b, the compensated flux increments are shown. The signal comparison demonstrates that the signal-to-noise ratio of the measurement is critical, but also highlights how the new FDI-based platform allows the flux increments to be measured with a higher resolution.

An example of the results of the *static characterization* tests aimed at verifying the repeatability of the new platform using the MRU, is reported in Figs. 4. In Fig. 4a, the mean of B_1 is plotted versus two FDI gains: the values are compatible and the repeatability is about 2.2 μT. The effect of the ADC quantization noise resulted not relevant for such a repeatability test. In Fig. 4b, the mean of the high order harmonics of the LHC dipole are shown with a 3σ bar. The overall repeatability results to be about 0.03 unit.

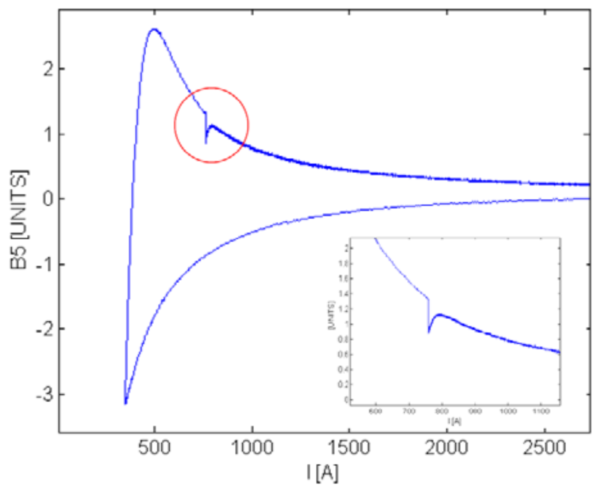
Finally, an example of the results of the *dynamic characterization* tests aimed at verifying the decay and the snapback phenomena of the sextupole and decapole components of the LHC dipole by using the rotating coils. The measurement results are reported in Fig. 5. In particular, the sextupole (Fig. 5a) and the decapole (Fig. 5b) components are depicted as function of the magnet current, highlighting the decay and snapback phenomena. The standard procedure analysis extracts the decay and the snapback profile such as shown in Fig. 5c for the sextupole component. As final result, the new platform highlights the dynamic phenomena with a time resolution never reached before by using the rotating coil method.

IV. Conclusions

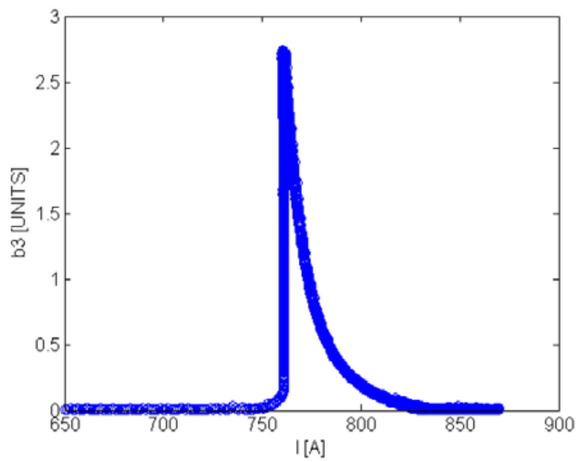
A new flexible platform for magnetic measurements is presented. Such a platform was validated and characterized by analyzing a LHC superconducting dipole magnet, using rotating coils in order to show experimentally on the field how



(a)



(b)



(c)

Figure 5. b3 (a) and b5 (b) decay and snapback; b3 snapback (c) after the data processing.

different magnetic measurement applications can be managed. Besides, the achieved results confirm the improved resolution of the new instrumentation (specifically the FDI) with respect to the existing standard (the PDI) and show the possibility of investigating dynamic effects of superconducting magnets in a larger bandwidth, so far not reachable with state-of-art systems.

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