MAGNETIC MEASUREMENT SYSTEMS FOR FUTURE HIGH PERFORMANCE MAGNETS

M. Buzio, R. Beltron, L. Bottura, D. Cote, G. Deferne, O. Dunkel, L. Gaborit,
J. Garcia Perez, D. Giloteaux, L. Walckiers, CERN, Geneva, Switzerland
P. Arpaia, G. Golluccio, V. Inglese, G. Montenero, G. Spiezia, Università del Sannio, Italy

Abstract

This paper describes CERN's current capabilities and plans concerning the measurement of accelerator magnets, focusing on the challenge represented by upcoming projects featuring high-field, high-ramp rate dipoles and quadrupoles. After a brief overview of the existing instrument park we discuss the main future requirements, the issues they raise and the solutions we propose. In particular we describe three ongoing projects based on high-performance digital integrators (FDI), a related C++ software framework (FFMM) and a fast harmonic measurement system (FAME). Finally, we solicit timely input from the magnet community concerning key design parameters and we summarize our conclusions.

INTRODUCTION

As of 2007, magnetic measurement services at CERN are centralized in two work units: one (PH-DT-M1 [1]) is concerned with experimental magnets, while the other (AT-MEI-MM [2]), to which the authors belong, is responsible of all accelerator magnets, i.e., either permanent, resistive or superconducting, excluding only very fast-pulsed kickers (their dynamics fall partially in the RF domain and have traditionally been dealt with by specialists).

Our service has accumulated equipment and know-how from many projects and groups over the whole of CERN's lifetime. As most instruments were originally optimized for a specific application or magnet family, adaptations to new demands are often necessary even if not always practical. While the variety leads to a high maintenance cost, as well as some duplication of functionality and a few inconsistencies among hardware and software platforms, on the whole our park has been proven capable to fulfil very satisfactorily all past and current needs.

Today, at the start of the LHC exploitation phase, we are able to test magnetically all repaired or replacement magnets for any of the accelerators in operation, with the same or better accuracy than the original measurements. In order to improve the performance of the LHC magnetic model (the "FiDeL" project [3]) we are already started work aimed at extending our instruments' capabilities. To cope with the forthcoming high-field, high-performance magnets, however, we must continue in this direction to rebuild the hardware and software foundations of our systems.

CURRENT CAPABILITIES AND LIMITATIONS

Our current capabilities, in terms of what can be measured as a function of the type of magnet, are summarized in Table 1. For each of our instruments, grouped by sensor principle, we list first the typical physical parameters of the compatible magnets (aperture, maximum length, field, ramp rate and temperature), then the quantities that can be measured (field strength, harmonics, axis and direction) and finally the space and time resolution. Bibliographical references are also given where available.

Measurement accuracies are not reported in the table because the end results depend on a variety of additional factors such as field strength, frequency of calibration, accessibility of the volume to be tested, environmental and test conditions. In general, we find that the relative uncertainty of field strength measurements is of the order of a few 10^{-4} for dipoles and about 10^{-3} for quadrupoles; the relative uncertainty of harmonics is about 10^{-5}; the absolute precision of magnetic axis measurements is around 0.1~0.2 mm [11][12]. The main limitations to the accuracy are found to be the bit resolution of the converters, the precision of machined parts and positioning tools, as well as thermal, mechanical and electrical perturbations during calibration and test.

As it can be seen, most devices are designed for (quasi) steady-state conditions, the main limitation being output bandwidth. This is generally due to the combination of different factors such as the mechanical speed of moving parts (e.g. rotating coil, translating stretched wire), the throughput of electronic components (such as the VFC-based digital integrators currently in operation, discussed further on) and the response time of old digital interfaces like RS-232 or VME-MXI. In case of time-varying field, fluxmeter-based instruments (i.e. search coils and stretched wires) are further limited by the total surface area of the coil, which determines the output voltage $V= -\partial\Phi/\partial t$. Standard integrators and voltmeters accept normally inputs up to ±10 V; even if voltage dividers can be implemented, the accuracy of the end result will suffer. A harder constraint comes from the insulation of the coil wire, which is usually very thin and cannot withstand more than a few ~100 V.

Another major limitation is represented by the size of the magnet aperture, most instruments being adapted for typical diameters between 10 and 70 mm. While today we

Table 1: Current magnetic measurement capabilities of the AT-MEI Group. A measurand marked as "±" denotes a potential capability yet to be fully validated developed. “W” and “C” denote respectively room-temperature and cryogenic conditions. Where the field bound limit is marked as *n.a.*, it means that the actual limitation comes from the total magnetic flux rather than the field strength. Note that scanning probes are not limited (within reason) by magnet length, and that certain kinds of fluxmeters such as Stretched Wire systems cannot detect only integral fields.

		magnet parameters					**measurand**					**performance**	
									axis		**field dir.**	**resolution**	
	System	**T**	**Field [T]**	**dB/dt [T/s]**	$\mathbf{L_{MAX}}$ **[m]**	**Gap/Φ [mm]**	**∫BdL ∫GdL**	$\mathbf{b_n}$ $\mathbf{a_n}$	**magn**	**mech**		**time [s]**	**length [mm]**
harmonic coil	15m shaft ("TRU") [4]	W/C	0.01 - 10	0.007	15	40	✓	✓				10	1150
	Shafts for vertical cryostats [5]	W	0.05 - 10	0.007	3	50-70	✓	✓	✓			10	1000
	Industry dipole moles DIMM [6]	W	0.01 - 0.05	*steady-state*	*any (scan)*	50	✓	✓			✓	*steady-state*	200-750
	Industry quad moles QIMM [6]	W	0.01 - 0.05	*steady-state*	*any (scan)*	45-70	✓	✓			✓	*steady-state*	750
	AC mole [7]	W/C	10^{-5}	*steady-state*	*any (scan)*	40-50		±	✓	✓	±	*steady-state*	100-200
	Linac 2 bench	W	0.001-1	*steady-state*	0.2	20-30	✓	✓	✓		✓	*steady-state*	*integral*
fixed coil	Fluxmeter + digital integrator	W	*n.a.*	$f(N_{TURNS}A_{COIL})$	2	> 20	✓	±				10^{-2}	*integral*
	Fluxmeter + digital integrator SPS	W	*n.a.*	2	8	> 20						10^{-2}	*integral*
	Fluxmeter + fast ADC	W	*n.a.*	$f(N_{TURNS}A_{COIL})$	2	> 20						10^{-5}	*integral*
	PS ("Huron") bench	W	*n.a.*	1	1.5	> 20	✓		✓		✓	10^{-2}	30-1000
	Linac 2 bench	W	*n.a.*	300	0.2	20-30	✓	✓	✓		✓	*n.a.*	*integral*
S.W.	Single Stretched Wire [8]	W/C	0.01 - 10	*steady-state*	20	> 10	✓	±	✓		✓	*steady-state*	*integral*
	Double Stretched Wire	W/C	*n.a.*	$f(L_{MAGNET})$	20	> 10	✓					*steady-state*	*integral*
Hall	3-axis Hall probe scanner	W	30	*steady-state*	1.5	> 30	✓	✓				*steady-state*	2
	B3-B5 Hall probe ring [9]	C	10	0.007	*any (scan)*	40		✓				10^{-3}	2
	Polarity checker [10]	W	0.1	*steady-state*	*any (scan)*	50	±					*steady-state*	2

cannot measure at all magnets substantially smaller than that, in case of larger aperture one can always use a smaller coil and extrapolate field harmonics according to the standard power series law; however, errors increase exponentially with harmonic order and this method is unusable when the outer coil diameter is smaller than, typically, $^2/_3$ or the region of interest.

Many other tradeoffs are unavoidable when choosing the best instrument for a given magnet. Longitudinal scanning probes (“moles”) are practical and versatile, but cannot be easily moved transversally and take a long time to integrate the field of long magnets. Hall probes provide a fast response, but give only point-like measurements with poor long-term stability. Motors and inclinometers installed in instruments conceived for room-temperature tests of superconducting magnets, where the field is of the order of a few millitesla, are usually not compatible with high fields. In practice, a combination of multiple tests with different instruments and techniques is often necessary to completely characterize a magnet.

Manufacturing capabilities

The measurement of the field of accelerator magnets requires specifically designed instrumentation that, with the exception of point-like NMR and Hall sensor teslameters, cannot be generally found in the commerce. CERN is equipped from the beginning with the tools and the expertise needed to manufacture the specialized components needed, primarily search coils, and to design and assemble complete systems.

Our group today has state-of-the-art facilities for winding a wide range of coils, either toroidal or rectangular, straight or curved, from a few mm to about 2 m long, which may include up to a few thousand turns making use of mono- or multi-filamentary wires (these, in particular, guarantee a very uniform cross-section geometry and a higher accuracy of the results). Different ceramic or composite supports and different kinds of glue can be used according to the conditions of utilisation [13].

The coils are normally sorted for optimal bucking, pre-assembled in arrays or sandwiches and then mounted in the finished instrument. Sophisticated skills in micro-welding and micro-connectors have been developed to ensure reliable operations. At multiple stages of this process mechanical, electrical and magnetic tests are carried out to assess the quality of the product and to obtain harmonic calibration coefficients.

For what concerns the manufacturing of acquisition electronics, our group has a strong expertise in the fields of designing and testing computer-controlled analogue and digital cards compatible with various industry standards. For all but the simplest cases, the actual assembly of the components is carried out by CERN’s centralized service or subcontracted (the same philosophy applies to high precision mechanical work).

REQUIREMENTS AND ISSUES

We shall now briefly outline the upcoming requirements in terms of magnet parameters and measurement objectives. We consider the LHC, along with the four nearest CERN upgrade projects, that is: Linac 4 (construction already started), LHC IR Upgrade Phase I and II and the superferric proposal for PS2. The orders of magnitude of the relative field and geometric parameters are given in Table 2.

Not surprisingly, one can observe a trend towards extreme apertures (consider also a machine like the future CLIC or ILC, with apertures down to few millimetres), higher fields and ramp rates and as a consequence higher eddy current forces, which scale as B·dB/dt and might have consequences for both magnets and probes.

First of all, the move towards high fields will raise the problem of finding adequate measurement references to calibrate the sensors and characterize materials and devices; consider, for example, that the common Metrolab NMR Teslameter PT2025 is limited at 14 T. Moreover, different machines pose specific challenges:

- LHC: history-dependent dynamic superconductor effects such as the decay and snapback of the sextupole, which affects directly the chromaticity, might if uncontrolled destroy the beam. To model and control adequately these effects it is desirable to increase the bandwidth of harmonic measurements from about 0.03 to 3 Hz, and to improve their accuracy from about 0.4 to 0.05 units [14].
- Linac4: this machine includes quadrupoles with an aperture as narrow as 20 mm, both resistive (ramped up in as little as 500 μs) and permanent. The challenge here is represented by the limited size of the coil and the high bandwidth necessary for the integration. In addition, it might become necessary to measure the magnetic axis of all individual permanent quadrupoles after installation in a drift tube module (20~30 magnets over a total length of about 1.5 m).
- LHC IR Upgrades: field integral, harmonics and magnetic axis will have to be measured inside apertures up to about three times larger than installed magnets.
- PS2: in this case, similar to that of all other fast-cycled magnets, a high-resolution measurement of eddy current transients will be paramount to understand and control the dynamics of the field. It is also possible that real-time measurements on a reference magnet in parallel with the machine ("B-train") shall be needed, as is the case today in the PS and in other machines, to stabilize quickly the field at the end of ramp-up.

Main problems

Measurements are certainly facilitated by higher field, higher ramp rates and larger apertures, which allow for bigger probes and result in stronger signals. However, there are also difficulties. Considering in particular harmonic coil systems, in order to maintain a reasonable dynamic range the coil surface cannot be reduced too much; thus, we must modulate either the rotation speed (better accuracy) and/or the amplifier gain (more practical). This problem is exacerbated by the need to increase the rotation speed when high bandwidth is desired (e.g. during ramps or snapback transients). In any case, for all the applications considered the existing integrators are inadequate in terms of both bandwidth and signal resolution.

As for the aperture sizes, the figures for Linac4 magnets are quite close to the smallest quadrupole-compensated coils that can be built using current technology. At the other extreme, large coils are undoubtedly easier to build and provide plenty of room to insert, for example, optical targets; however, existing ceramic- or fibreglass-based designs cannot be scaled up for reasons of weight and cost, so new technical solutions must be sought. Finally, let us remark that coils larger than ~100 mm cannot be calibrated in the reference magnets available at CERN and some alternative must be found.

Table 2 – Order-of-magnitude parameters for some of the future high-performance magnets, compared to a main LHC dipole. The dΦ/dt is referred to the whole aperture, while BdB/dt is calculated where the field peaks.

	L [m]	$\varnothing_{ap}$ [mm]	B [T]	dB/dt [T/s]	dΦ/dt [V]	BdB/dt [T/s]
LHC	14	40-70	9	0.007	0.007	0.06
Linac 4	0.3	20-70	1	700	4.200	700
Phase I	10	110-130	10	0.007	0.009	0.07
Phase II	10	130-150	15	0.007	0.011	0.11
PS2 (SF)	3	70	1.8	2	0.420	3.60

CURRENT AND FUTURE PROJECTS

The issues discussed above are long known and, since about three years, our group has already taken some initiatives to tackle the main problems, especially in view of the demands expected from the LHC. We started from the basic infrastructure of our measurement systems by launching some R&D on new acquisition electronics (integrators) and related software. These activities are well advanced and are already deployed, in prototype form, as the base for a fast magnetic measurement system for main LHC dipoles and quadrupoles. All three projects are described more in detail in the sections below.

Considering future accelerators, the project making fastest progress concerns the measurement of permanent and resistive quadrupoles for Linac4. The existing Linac2 bench is being modified to accommodate new mechanics, harmonic coils (see Fig. 1) and motorization to enable accurate measurements of assembled drift tubes and fast-pulsed magnets in stepwise rotating mode. Integration with the new acquisition electronics and software is under way and we expect to be ready to start measurements upon arrival of the first series magnets in 2009.

Figure 1: Prototype quadrupole-compensated harmonic coil for Linac4 permanent magnets.

As for the next machines, here follows a list of the activities planned:

- LHC IR Upgrades: the main R&D effort will be directed towards large diameter harmonic coils for which suitable materials, geometries and calibration procedures have yet to be identified. As it emerged clearly during recent tests of LARP/CERN $NbSn_3$ models, the most urgent need concerns short coil shafts for vertical cryostats in CERN's Bloc4 test station. By 2010, we shall also need long coil shafts, adapted to work at room-temperature inside an anticryostat, to measure series cryoassemblies in SM18 test station. The possible need for adapted short scanning probes, providing the opportunity to carry out local magnetic axis measurements, should also be assessed. It must be stressed that the lead times for some mechanical components (e.g. coil supports, anticryostat tubes) can be quite long and it is very important to know the cold bore geometry in due time for prototyping. In addition, other parameters such as the cable twist pitch length and the position of magnets in a cryoassembly are fundamental to fix the geometry of a coil shaft (coil length and gap between coils must be a multiple of the twist pitch in order to obtain an accurate field integral by canceling out the effect of periodical oscillations).
- Fast-cycled, high-field magnets: the preparation for this class of magnets requires, as a start, testing the compatibility of material and components such as motors, inclinometers and encoders. Moreover, recent eddy current measurements of quadrupoles and octupoles for the PS, with peak dB/dt up to about 60 T/s, have shown that our instrumentation is not completely adequate to detect subtle and rapid transients (below, say, a few 10^{-4} of relative amplitude and ~0.1 ms). More work is needed in this area to ensure better electromagnetic compatibility, finer control of power supplies and elimination of transmission line artifacts.
- “SuperMole”: our park currently includes more than 40 scanning probes of 8 different types, based either on search coils or Hall plates, each one optimized for a particular application. To get ready for the next generations of magnets, avoiding at the same time onerous maintenance and training with ever reducing staff, we must streamline this assortment and combine the different functionalities as much as possible. The outline of a modular design is gradually emerging, making use of the techniques that have been proved more accurate and reliable on the field. These include: tangential coil arrays, able to operate in harmonic or stationary (AC) mode; tracking via centrally placed retro-reflectors; high-field compatible piezoelectric motors; additional Hall plates for the measurement of local fields and the disambiguation of polarities.
- Unified magnetic measurement station: to date, our activities for magnet testing and equipment manufacturing and calibration are carried out in six different laboratories scattered all around CERN sites (bldg. 30, 230, 373 (ISR tunnel – I8), 867, 892 (Bloc4), 2173 (SM18)). This situation, which leads to a waste of time and duplication of equipment, will become unsustainable in a few years considering the expected reduction in staff numbers. A proposal concerning a unified laboratory for all room-temperature activities, ideally situated in proximity of the cryogenic test stations for maximum efficiency, is currently being prepared.
- Coil manufacturing and calibration: while the technology to obtain conventional harmonic coils is firmly established, new needs are emerging. In this area we plan to initiate developments along different lines, including: streamlining and automation of existing procedures; investigation of new coil support materials and techniques, such as multi-layer printed circuit coils; improvement of the accuracy of the calibration, e.g. by testing bucked arrays in known multipole magnets; extension of metrology and calibration procedures to new classes of coils, such as large ones or strongly curved ones.

FAST DIGITAL INTEGRATORS

The workhorse of our existing harmonic coil systems is a VME Precision Digital Integrator (PDI) board, having the general function of deriving magnetic flux increments from an induced voltage signal [15]. Several hundred units have been in operation during the two last decades at CERN where, among the rest, they have been instrumental to measure all ~10000 of LHC magnets. However, the current architecture is starting to show its age. The PDI is based on a Voltage-to-Frequency converter working typically at 50 kHz/V, which actually represent a hard limit to the resolution in case of weak signal or short integration times. An additional bottleneck

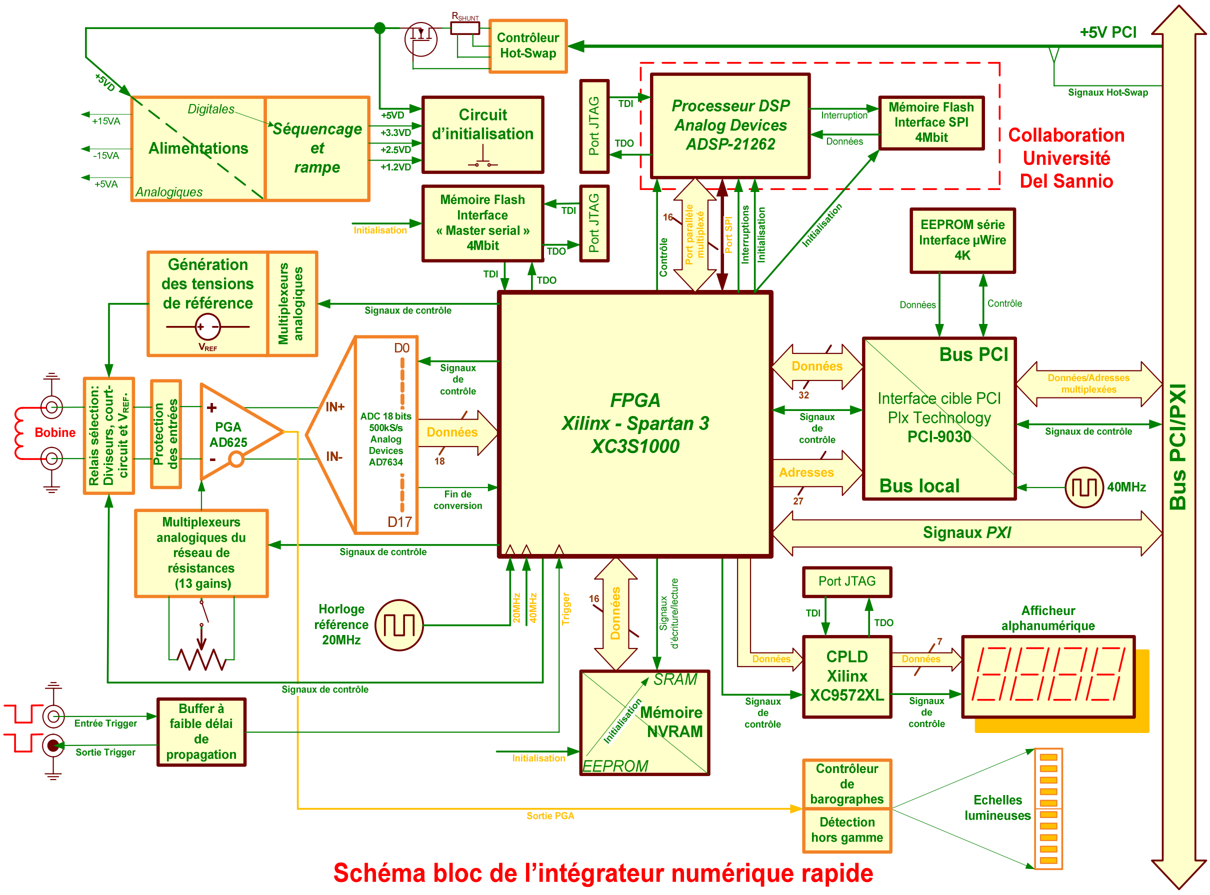

Figure 2: Schematic layout of the PXI Fast Digital Integrator board

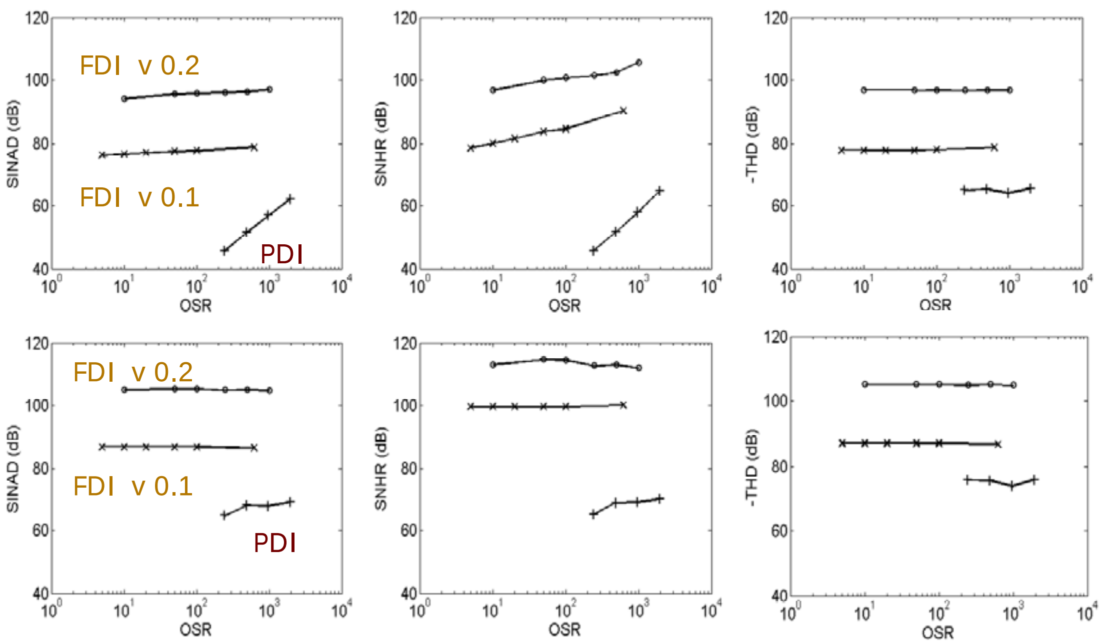

Figure 3: Three different Signal-to-Noise performance metrics to compare the new Fast Digital Integrators against the Precision Digital Integrators as a function of the oversampling ratio. The top row of plots represents the performance as a simple digitizer, while the bottom row as an integrator.

is represented by the VME/MXI interface to the host workstation, which is already strained near its maximum doing standard measurements of LHC cryodipoles with 24 rotating coils in parallel.

For these reasons a new project was started in 2004 to design a new Fast Digital Integrator (FDI) making full use of contemporary electronics and able to cope with future demands in terms of bandwidth and accuracy [16]. The board (whose layout is shown in Fig. 2) is based on the industry-standard PXI architecture and includes an analogue front-end, a fast-switchable, programmable divider/amplifier, a 18-bit, 500 kHz ADC and a DSP carrying out the numerical integration. A reference voltage source with a precision resistor network provides the facility of automatic self-calibration, while an FPGA binds logically the components and drives the external interface. The flexibility of this design is enhanced by the possibility to upgrade the DSP with new integration, filtering, FFT or any other signal processing algorithms. The firmware has been developed in close collaboration with the Università del Sannio, Italy and is tightly integrated with the FFMM C++ framework (see next section).

The performance advantage of the FDI w.r.t. the old PDIs is apparent in Fig. 3, which shows the results of different standard Signal-to-Noise (S/N) tests as a function of the oversampling ratio (i.e. the ratio between ADC sampling rate and integrator trigger rate). As it can be seen the S/N is improved from about 70 dB to more than 110 dB (equivalent to a resolution of 0.5 nVs), which importantly remains constant even at very low oversampling ratios. As a digitizer, as expected, the S/N of the FDI is slightly lower at around 100 dB, however it remains competitive with commercial acquisition boards. The bandwidth of a single card can reach up to 250 kS/s, vs. about 1 kS/s for the PDI, thus enabling an entirely new range of applications (it should be noted that in the current version the bandwidth is limited by the bus interface and therefore is shared between all cards in the same chassis).

To date, a prototype run of a few dozen units is being manufactured and a few FDIs are already employed at CERN for magnetic measurements. The whole project is the object of a Technology Transfer agreement between CERN and Metrolab, Geneva, which will eventually result in the industrial commercialization of the board, including CERN-developed industry-standard LabView drivers. The practical advantage for our group lies obviously in the availability of low-cost hardware and dedicated support. Pending the results from the current testing and validation campaign, a number of hardware, firmware and driver software improvements are already planned:

- DMA-based bus interface to increase aggregated throughput by up to two orders of magnitude.
- Nanosecond-accuracy synchronization of the time-base of the integrators in the same chassis.
- Software-controlled internal generation of triggers, also necessary for the card to function more flexibly in pure ADC mode.
- Generation of reference voltages for self-calibration via a programmable 18-bit DAC, providing more accuracy, flexibility and the additional possibility for the card to work as a signal generator.
- Different compression algorithms to reduce bus traffic and output file size (e.g. adaptive sampling rate modulation for arbitrary signals and FFT-based filtering for harmonic measurements).
- Development of a stand-alone unit with USB connectivity.

FLEXIBLE FRAMEWORK FOR MAGNETIC MEASUREMENTS

Throughout the long LHC design and construction phase most of the software infrastructure at the heart of our instrumentation has been based on a vast collection of LabView modules, developed upon our specification by CERN's Control Systems Group (AB/CO) and utilised in a number of specialised versions of the Magnetic Measurement Program [17]. As such, this complex software solution is not compatible with our new integrator's architecture, and no resources are available to adapt it readily. As a consequence, new software is being developed to control the integrators and solve the general problem of carrying out the measurement, analyse and store the results.

Since we are now in a phase of prototyping new instruments, it is very important to shorten the cycle going from the specification of new functionality to its implementation, testing and debugging. An object-oriented C++ class framework called FFMM (Flexible Framework for Magnetic Measurements) has been chosen as the most efficient solution, and the development has been internalized as of 2005 via a fruitful collaboration accord with the Università del Sannio, Italy [18].

The framework includes at present several dozen classes to drive, besides the integrators, a variety of instruments such as sensors, motors, encoders and power supplies, and the library is foreseen to expand to cover almost the totality of our equipment. At the core of the project is the capability to specify the test logic via a simplified script, containing the necessary magnet and test parameters alongside the sequence of operations to be performed. In perspective, the framework will decouple the definition of the measurement algorithm and all technical parameters, which are in the domain of the test engineer, from the complexities of the underlying C++ machinery. In this way, even non-software specialists shall be able to make full use of the system.

To date, a stable prototype version of the framework is already being used to measure LHC cryodipoles, as described in the next section. A long list of essential improvements is planned for the next three years covered by the collaboration accord. Among these:

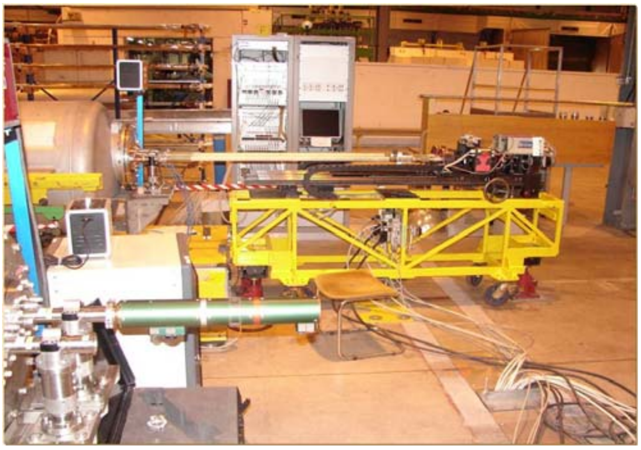

Figure 4: A visual comparison between the Twin Rotating Units, which can be seen in the background while driving two coil shafts inserted in a LHC cryodipoles, and the new Mobile Rotating Unit (in the foreground), directly attached to the anticryostat.

- Close integration with the development of the FDI cards, including specifically in the drivers efficient simultaneous management of large numbers of cards acquiring at full speed.
- Implementation of additional features in the framework, such as data logging, fault detection, debugging facilities and automatic scheduling and synchronization of events and algorithms. The underlying theme is to increase the level of abstraction of the test script w.r.t. C++ programming aspects.
- In the longer term, development of user-friendly graphical interfaces for script programmers and end users.

On a parallel path, the framework is also gradually encompassing different data analysis and post-processing tasks. Most data reduction algorithms are in fact closely related to the procedure followed and to the test conditions, which are inherently known to the acquisition software. From this reason, programming both within the same context can lead to improved consistency and efficiency. Taking also into account that the existing web-based facilities used for the analysis of LHC data are being phased out, we plan the following developments:

- On-line calculation of test results (field strengths, harmonics, statistical indicators etc.) to provide real-time feedback to the test operator and facilitate system diagnostics.
- Off-line data reduction tasks such as the automatic calculation of field harmonics, various types of integrals or feature extraction. Of particular importance (and sophistication) is the detection of invalid or unrealistic measurements and the subsequent recalculation of final results taking into account missing data points.
- Network connection with online repositories (typically CERN-standard Oracle databases) to obtain input test data, such as magnet parameters or harmonic coil geometry data, and to store raw or processed test results.

FAST MEASUREMENT SYSTEM

As recalled above, the exploitation of LHC is likely to require integral measurement of field strength and harmonics in main dipoles and quadrupoles with a higher bandwidth and precision than those obtained during series tests. With this aim in mind, the development of a FAst MEasurement system (FAME) has been launched in 2006 and today the first prototype unit is operation to measure LHC cryodipoles SM18 [19].

The system, which is depicted in Fig. 4, is based on the following components:

- A modified version of the long ceramic coil shafts with 12 dipole-compensated coil sectors (1/6 of the turns of a standard system), better mass balancing and sturdier connectors.
- A novel Mobile Rotating Unit (MRU), including 54-channel slip rings for continuous unidirectional rotation up to 8 Hz. This attaches directly to the anticryostat and replaces the previous bulky Twin Rotating Units [3].
- A patch panel at the output allows one to make arbitrary series connection of the available coils, thus permitting changes in the compensation schemes or combination of several coils in a single "supersector", which can be used to measure the integral saving on the number of integrators.
- A rack of FDI integrators, necessary to cope with the increased bandwidth
- A host PC running the FFMM software to control the hardware and perform the acquisition.

It must be noted that the convenience of the MRU comes at the price of fixing rigidly the longitudinal position of the coils, which usually should be symmetrical w.r.t. magnet end fields; moving the coils at a new position requires the insertion of apposite spacers.

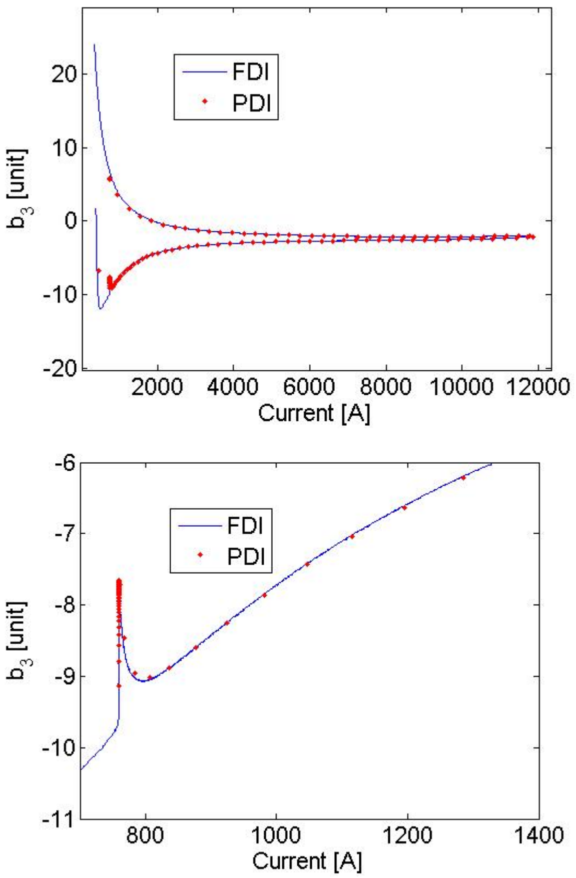

Figure 5: Two consecutive hysteresis curves of the normal sextupole in MBA 2551 taken with old and new integrators at the center of the dipole. The expanded view of the decay and snapback phase (bottom graph) gives an indication of the improvement of the precision that can be attained.

At present, the existing prototype system is being metrologically characterized and the results obtained on spare LHC main dipoles are being compared to those issued from the old acquisition system. As an example, in Fig. 5 we can consider the hysteresis curve of the sextupole component measured at the centre of a dipole, obtained during two consecutive LHC cycles with the two systems. The improvement in the precision of the measurement is striking.

Our plans for the further development of the FAME system cover the following points:

- Finalization of the design of the MRUs and of the spacers (needed for longitudinal centering on the corrector magnets installed in different cryoassemblies).
- Production of one more system for dipole and one for quadrupole cryoassemblies, in prevision of further tests for LHC in the framework of FiDeL activities (tracking tests, investigation of new machine cycles, characterization of poorly-known magnet types).
- Further development of control and analysis software, including more robust and user-friendly operation, as well as improved data reduction algorithms (e.g. more accurate harmonic analysis when the field is changing, if necessary with high-speed progressive update during coil rotation).
- Adaptation of the MRUs to other test benches, namely vertical cryostats for short models and upcoming large diameter coil system.

CONCLUSIONS

CERN historical experience shows that targeting measurement systems at individual magnet classes, as it was possible when adequate resources were available, produces optimized results but may lead to subsequent waste and difficulties. Today, we are in a position to compact and rationalize the existing instrument park and, at the same time, plan to meet future requirements. By pursuing the lines of development discussed above, we believe that it shall be possible to get equipped to respond efficiently to all these challenges.

To reach this goal, we would like to call attention to the importance of receiving in due time certain key bits of information, taking into account the delays associated with the subcontracting of critical components (primarily high precision mechanics, but, recently, also some electronic parts due to the global industry changeover to lead-free technologies).

In particular:

- The size of the magnet bore, if outside the popular 40-70 mm range, is the most urgent parameter to be known (long lead times for harmonic coil shafts and anticryostats).
- The cable twist pitch and the longitudinal position of magnets are also very important in the case of long coil shafts for cryoassemblies.
- Other parameters driving instrument design include the ranges of B and dB/dt, length and radius of curvature of the magnet, shape and size of the good field region, nature and position of optical or mechanical references.
- Realistic accuracy requirements from beam optics are also welcome.

To conclude, let us recall our need for appropriate high-performance magnets to be used to qualify materials and components, calibrate coils and cross-check instruments. Such magnets, perhaps, could be included in the planning for the construction of models and prototypes for future machines.

REFERENCES

[1] http://ph-dep-dt.web.cern.ch/ph-dep-dt
[2] http://at-dep-mei.web.cern.ch/at-dep-mei
[3] M. Di Castro, D. Sernelius, L. Bottura, L. Deniau, N. Sammut, S. Sanfilippo, W. Venturini Delsolaro, “Parametric field modelling for the LHC main magnets in operating conditions”, PAC 2007,

Albuquerque, NM, 25-29 June 2007, p. 1586-1588 (2007)

[4] J. Billan, L. Bottura, M. Buzio, G. D'Angelo, G. Deferne, O. Dunkel, P. Legrand, A. Rijllart, A. Siemko, P. Sievers, S. Schloss, L. Walckiers, “Twin rotating coils for cold magnetic measurements of 15 m long LHCdipoles”, IEEE Trans. Appl. Supercond., Vol. 10, Mar. 2000, pp. 1422-1426

[5] J. Billan, C.R. Gregory, P. Legrand, L. Oberli, A.P. Verweij, L. Walckiers, “Test of 1 m long model magnets for LHC”, IEEE Transactions on Magnetics, Vol. 28, Jan. 1992, pp. 362-365

[6] J.G. Perez, J.Billan, M. Buzio; P. Galbraith, D. Giloteaux, V. Remondino, "Performance of the Room Temperature Systems for Magnetic Field Measurements of the LHC Superconducting Magnets", IEEE Transactions on Applied Superconductivity, Volume 16, Issue 2, June 2006 Page(s): 269 – 272

[7] M. Buzio, P. Galbraith, J. Garcia Perez , E. Laface, S. Pauletta, “A Device to Measure Magnetic and Mechanical Axis of Superconducting Magnets for the Large Hadron Collider at CERN”, Proceedings of the IEEE Instrumentation and Measurement Technology Conference, Sorrento, Italy, 2006.

[8] J. Di Marco *et al.*, “Field alignment of quadrupole magnets for the LHC interaction regions”, IEEE Trans. Appl. Supercond, vol. 10, Jan. 2000, pp.127-130

[9] N.J. Sammut, E. Benedico-Mora, L. Bottura, P. Galbraith, D. Giloteaux, G. Greco, M. Haverkamp, M. Marchesotti, A. Masi, J. Micallef, T. Pieloni, N. Smirnov, A. Tikhov, “A Hall Plate Based Instrument to Measure the Snapback in the Large Hadron Collider Superconducting Dipole Magnets”, Proceedings of the IEEE Instrumentation and Measurement Technology Conference IMTC 2006, 24-27 Apr 2006, pp. 61-66.

[10] M. Buzio, L. Bottura, G. Brun, G. Fievez, P. Galbraith, J. Garcia Perez, R. Lopez, A. Masi, S. Russenschuck, N. Smirnov, A. Tikhov, L. Walckiers, “Checking the Polarity of Superconducting Multipole LHC Magnets”, IEEE Transactions on Applied Superconductivity, June 2006, Volume: 16, Issue: 2, pp. 1391- 1394

[11] L. Walckiers, L. Bottura, M. Buzio, P. Schnizer, N. Smirnov, “Sensitivity and accuracy of the systems for the magnetic measurements of the LHC magnets at CERN”, Proceedings of EPAC 2000, Vienna, 26-30 June 2000, pp 2184-2187 (2000)

[12] L. Bottura, M. Buzio, S. Pauletta, N. Smirnov, “Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments”, Proceedings of the IEEE Instrumentation and Measurement Technology Conference IMTC 2006, pp. 765-770 (2006)

[13] O. Dunkel *et al.*, “Magnetic Calibration System for Rotating-Coil-Based Measurement Instrumentation at CERN”, Proceedings of the International Workshop on Magnetic Measurments IMMW 15, Fermilab, Batavia, IL, 21-24 Aug. 2007

[14] L. Bottura, “RMS status report”, LTC meeting, 23 June 2004

[15] http://www.metrolab.com/index.php?id=24#par104

[16] P. Arpaia, L. Bottura, P. Cimmino, D. Giloteaux, A. Masi, J. Garcia Perez, G. Spiezia, L. Walckiers, “A Fast Digital Integrator for Magnetic Field Measurements at Cern”, Proceedings of the IEEE Instrumentation and Measurement Technology Conference IMTC 2006, 24-27 April 2006, pp. 67-71

[17] H. Reymond, “Experience with configurable acquisition software”, Proceedings of the 14th International Magnetic Measurement Workshop, CERN, Geneva, 26-29 Sept. 2005

[18] P. Arpaia, M. L. Bernardi, L. Bottura, M. Buzio, L. Deniau, G. Di Lucca, V. Inglese, J. Garcia Perez, G. Spiezia, L. Walckiers,, “Kernel Design of a Flexible Software Framework for Magnetic Measurements at CERN”, IEEE Instrumentation and Measurement Technology Conference Proceedings IMTC 2008, 12-15 May 2008, pp. 607-611

[19] L. Bottura, N. Brooks, M. Buzio, D. Cote, O. Dunkel, P. Galbraith, D. Giloteaux, J. García Perez, A. Masi, “Fast Magnetic Measurement Equipment”, 15th International Magnetic Measurement Workshop, Fermilab, Batavia, IL, August 21-24, 2007