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Improvements on rotating coil systems at CERN

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Abstract – **A large variety of magnetic measurement requirements arises from the multiple accelerator projects at CERN, such as MedAustron, SESAME, HIE-ISOLDE, ELENA, and Linac4. Limited resources and a narrow time scale impose optimized procedures and instrumentations. Standardization of measurement equipment becomes essential in order to increase efficiency in terms of installation time and workflow. This paper gives an overview of the ongoing effort to optimize CERN measurement resources by keeping a suitable measurement quality. A flexible control and acquisition software, a standard drive unit, rotating coil systems with standard assembly of tangential search coils, and multipurpose measurement benches are described as main elements of an optimized development of high-precision magnetic measurement systems.**

I. INTRODUCTION

Quality assurance of magnets is an important task in the development and installation process of an accelerator machine. In general, the beam characteristics of an accelerator are closely related to the field quality and the tuning of the magnet system. The requirements for the magnetic measurements are often determined by a conservative approach rather than the effective needs.

In the design phase of a new accelerator machine, beam dynamic experts and magnet designers must agree on the magnet system requirements. Beam physics experts base their request on past experience and on simulation tools. On the other hand, magnet designers are interested in a deep knowledge of the magnet performances to improve their design tools. Therefore high-precision measurements are constantly on demand and, as a consequence, a continuous development of the measurement techniques is required.

At present, a large variety of projects is underway at CERN.

The MedAustron project is an ion-therapy and research center, based on a synchrotron accelerator complex, located in Austria.

The Synchrotron light for Experimental Science and Applications in the Middle East (SESAME) is a joint project launched in 2003 by countries in the Eastern Mediterranean and Middle East to build a synchrotron light source in Jordan.

The HIE-ISOLDE project aims at greatly expanding the physics programme compared to that of the already existing REX-ISOLDE at CERN. HIE-ISOLDE forms part of the European nuclear physics strategy and its science case covers the majority of the key questions in nuclear structure pursued by the scientific community.

ELENA is a compact ring for cooling and further deceleration of 5.3 MeV antiprotons delivered by the CERN Antiproton Decelerator (AD). The AD physics program is focused on trapping antiprotons and producing antihydrogen after recombination with positrons. The ultimate physics goal is to perform spectroscopy on anti-hydrogen atoms at rest and to investigate the effect of the gravitational force on matter and antimatter.

The Linac4 project is a 160 MeV H- linear accelerator replacing Linac2 as injector to the PS Booster (PSB). The new linac is expected to increase the beam brightness of the PSB by a factor of 2, making possible an upgrade of the LHC injectors for higher intensity and eventually an increase of the LHC luminosity.

Table 1 gives a summary of the magnets, more than 230 in total, to be measured with the rotating coil systems.

Quadrupoles, sextupoles, as well as the corrector magnets for these projects have a magnetic length of up to 80 cm and straight aperture bores. The required measurement relative precision depends on the magnet type and its final use in the machine. In general it ranges from 10^{-3} for correctors to 10^{-5} for lattice quadrupoles. Rotating coil technique is the most suitable method for measuring such magnets [1].

A large number of magnets for different projects (Figure 1) requires a strong synergy in the development of the measurement tools. Highly efficient test equipment and procedures have to be devised to accomplish the measurement task within the given time. User-friendliness, robustness and reliability are additional characteristics required for such systems. Based on the experience gained previously during the LHC development, an R&D program was launched to construct standard rotating coils benches for a full characterization (field strength, filed angle, magnetic center, and field quality) of relatively short magnets by reducing the measurement time.

II. THE BENCH DESIGN

A *bench* for rotating coil measurements is composed of four main elements: the magnetic-measurement shaft, a

Table 1. Magnets requiring rotating coil measurements.

Project	Quadruples	Sextupoles	H/V dipoles
MedAustron	-	9	64
SESAME	25	35	-
HIE-ISOLDE	24	-	13
ELENA	16	5	11
Linac4	2	-	27

Fig. 1. Some examples of different types of magnets being measured.

motor drive unit, the support structure, and the data acquisition system. A brief description of each component will be given in this section.

A.   The magnetic-measurement shaft

Magnetic-measurement shafts with a standard length of 1.20 m and different diameters have been designed on the basis of a standardized cross-section (Figure 2)[2]. For the accurate measurement of the multipole field errors it is common practice to suppress the contribution of some field components from the signal of the main measurement coil. In the proposed design, five rectangular sensing coils with an equal surface are used. Two external coils are positioned on the opposite sides of the shaft at a radius maximised with respect to the aperture diameter of the magnet. The intermediate coils, used for compensating (bucking) the signal, are placed at half distance and are centered with respect to the rotation axis. The compensation coils are maintained in position by the same centering pins that fix the external coils. This setup allows for the bucking of the quadrupole component, by connecting in series the external coil with the two intermediate coils with the proper polarity. The residual dipole component can be bucked by further connecting the central coil with inverse polarity.

Ease of manufacturing, stiffness requirements, and cost issues have driven the selection of glass-reinforced epoxy (EPGM 203) as material for tube support and coil core [3]. In addition, glass-fibre epoxy is completely nonmagnetic and nonconducting.

The coils are wound on supports by hand. Each coil is then calibrated individually and matched to other coils of the same assembly to achieve the highest possible compensation ratio. The external coils are mounted onto reference surfaces machined along the outside of the shaft support tube and fixed to it with precise dowel pins. Flatness and parallelism of this fitting is the range of $\pm 20\,\mu m$.

The sensitivity factors of a tangential coil (intercepting the radial component of the magnetic flux density) to a multipole error of order n depend on the opening angle of 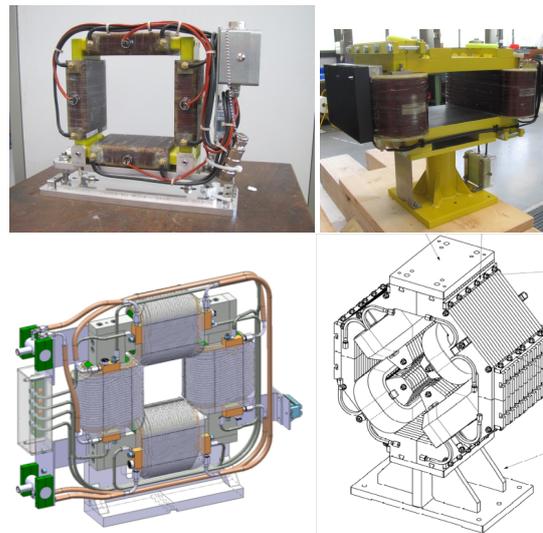the coil. A nominal opening angle of 28.8 degrees was selected in order to have zero sensitivity to the harmonic order between 12 and 13. The shaft thus allows to measure, with a good sensitivity, low order multipoles for $n < 10$ and the "allowed" multipoles ($n = 6, 10, 14$) in quadrupoles.

The shaft is equipped with a specific mechanical connector to adapt it to the drive unit and to allow a suitable angular stiffness. The mechanical connector includes the electrical connections for signals of coils and tilt sensor in order to facilitate the operations of assembling/disassembling of the shaft from the motor unit. Two ceramic ball bearings are placed on the ends of shaft and are held by aluminium cylinders; see Figure 3.

B.   The drive unit

The magnetic-measurement shaft is driven by a compact motor drive, referred to as the Micro Rotating Unit (MRU). The unit includes a DC motor with 15:1 reduction gearbox, able to achieve a maximum rotation speed of 8 turns per second with variations smaller than 3%. The power driver for the motor is shielded from the signal cables, so that the coil signal is not affected by noise. The operation of the unit is remotely controlled by the acquisition software.

The angular position of the shaft is given by an angular encoder with 16384 counts per revolution plus an index pulse on a separate channel.

For the connection of the signal cables a multichannel slipring is used. This configuration allows measurements with a continuous rotation of the shaft at maximum speed.
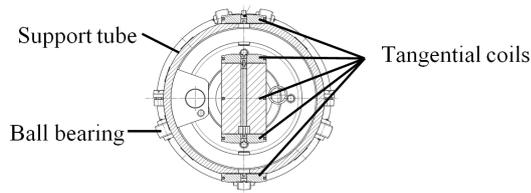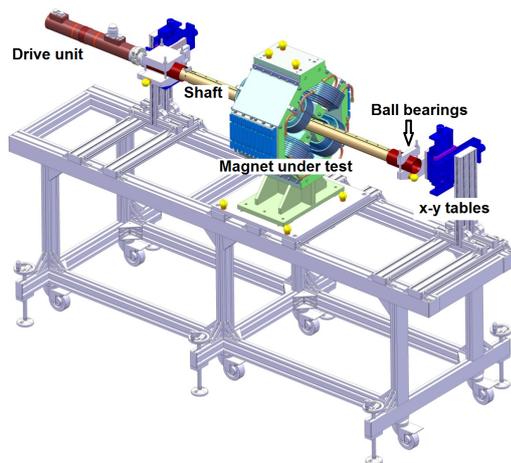
Fig. 2. Cross section of the tangential coil shaft.

Fig. 3. Standard bench for measuring corrector magnets.

C. The support structure

The requirements of the support structure are mainly related to the mechanical stability under the stress of the magnet weight, the adjustable shaft position to fit the magnet dimensions, and the absence of magnetic material, which could disturb the magnetic measurement. The adopted solution is a modular aluminium frame (Figure 4). It is sustained by six adjustable feet allowing the leveling of the magnet under test up to 1200 kg. The drive unit and shaft are held by two x-y adjustable tables. The repeatability of the shaft positioning is assured by two v-shaped supports for the cylinders housing the shaft ball bearings.

D. The acquisition system

The acquisition system is based on a PXI crate with a blade computer, an encoder interface, two integrator cards (Fast Digital Integrator [4]), and a standard acquisition card.

The software application is generated by the Software Framework for Measurement Applications (SFMA) [5] and a test-specific script. An on-line data processing contributes to the reduction of the measurement time.

The integrators are triggered by the angular encoders connected to the shaft through the encoder interface. The integrated voltage signals delivered by the integrators are equal to the flux changes between two adjacent angular

Fig. 4. The bench used for the MedAustron project.

steps. This re-parametrization of the signal (with respect to the angular position) makes the signal (flux) independent of time and variations in the rotation velocity.

The current is measured by using a DC Current Transformer (DCCT) and acquired by the acquisition card synchronously with the flux increments.

III. MEASUREMENT RESULTS

Four benches have been produced and are operational. About 50 magnets have been already measured for the MedAustron project, 10 for Linac4, together with preseries and prototype magnets for other projects. Results obtained for a HIE-ISOLDE preseries quadrupole are given as an example.

Table 2. Measurement results on main field.

System	$\int Gdl$ (Tm/m)	σ
Single Stretched Wire	5.37076	$2 \cdot 10^{-5}$
Rotating coils	5.37435	$5 \cdot 10^{-5}$
Relative difference	$-7 \cdot 10^{-4}$	

The first result of interest is the integrated gradient along the magnet aperture. The integrated gradient is defined as the average field, dived by the measurement radius and multiplied by the effective measurement length of the shaft. The results obtained (see Table 2) by using the new
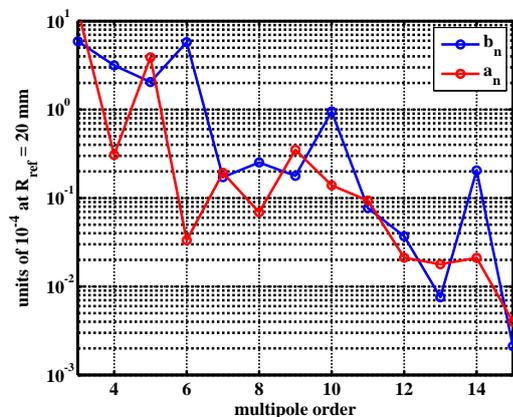
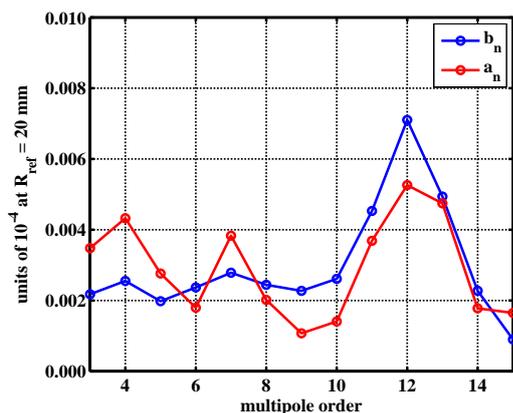*Fig. 5. Measured multipoles on a quadrupole.*

Fig. 6. Standard deviations of measured multipoles computed on ten measurements.

rotating coil bench is analysed in terms of repeatability or relative standard deviation (σ) of ten consecutive measurements, the calibration error, or the difference with respect to the Single Stretched Wire system, which can be taken as a reference [6]. The precision of the system results to be excellent. A residual calibration error is present due to a possible coil nonhomogeneity in longitudinal direction (sausaging). An "in situ" calibration should be able to further improve the results [7].

For the measurement of the magnetic multipoles, the results are reported as relative value to the main field (normalization) and expressed in units of 10^{-4} (0.01%). The reference radius used to express the multipoles is 20 mm. The measured multipoles are only evaluated in terms of repeatability because it is difficult to have a reference for such quantities. In Figure 5, the measured normal and skew normalized multipoles are shown. Their amplitude is

drawn with logarithmic scale in order to make visible the high order multipoles with small amplitude. In this way two important properties of harmonic fields are visualized: The Riemann-Lebesque lemma that states that higher order harmonics in a periodic signal must converge to zero, and the Cauchy estimat for Taylor coefficients, which states that in a conservative field, the multipole field errors must scale with $1/r^n$, where r is the reference radius and n the multipole error. Any obvious deviation of these rules can be attributed to measurement errors.

The multipoles of the qudrupole magnet are well noticeable (b_6, b_{10}, b_{14}). These multipole field errors are due to the finite length of the pole surfaces and are therefore present in the field even if the magnets were built without manufacturing tolerances. These field harmonics are therefore known as the allowed field harmonics, unlike the nonallowed terms which must be attributed to asymmetries resulting from manufacturing tolerances.

The linear decreasing slope proves that the results are not limited by the precision of the measurement system [8]. In Figure 6, the repeatability of the measurements of multipoles is given. It further confirms the very low noise of 0.3 ppm. The multipoles of order 12 and 13 are most affected by noise because the shaft has a low sensitivity this range due to its opening angle.

The repeatability on measurements of the magnetic center has been also investigated. The shaft was first positioned in the magnetic center of the magnet (minimization of feed-down effect), then removed and replaced several times by repeating the measurement. With a certain care during the operations, a repeatability in the range of ± 20 μm has been assessed on the magnetic center coordinates.

IV. CONCLUSIONS

A set of new rotating coil benches has been developed at CERN in order to respond to the measurement needs of the new projects. An effort in terms of standardization ad flexibility of the tools has been made to assure a short development time. New magnetic-measurement shafts and support structures have been designed, produced and tested. The performance in terms of measurement quality has demonstrated to be suitable for the most demanding requirements.

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