CHARACTERIZATION OF A MEASUREMENT SYSTEM FOR DYNAMIC EFFECTS IN LARGE-APERTURE SC QUADRUPOLE MAGNETS

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Abstract

A new measurement system, based on a large-diameter search-coil rotating in the superfluid helium, a fast digital integrator, a motor drive unit with slip rings, and a flexible software environment was developed at CERN for the measurement of dynamic effects in superconducting magnets. This system has made it possible the measure, with a resolution of up to 1 Hz, the multipole field errors due to superconductor magnetization and interstrand coupling currents. In this paper we present the development and calibration of the measurement system, its installation in the vertical cryostat of CERN's recently refurbished test station, and its application to the US-LARP built, 120-mm aperture Nb_3Sn quadrupole magnet (HQ01e) for the upgrade of the LHC insertion regions.

THE FAME MEASUREMENT SYSTEM

The system used for the magnetic measurements of the 120-mm-aperture Nb_3Sn quadrupole magnet (HQ01e) [3] is based on the FAME (FAst Measurement Equipment) system developed at CERN [2]. The system was adapted for the vertical test cryostat and equipped with a purpose-built, large-diameter search coil. The FAME system is composed furthermore of a GPS timing board (NI-6682), a motor drive (Micro Rotating Unit), a custom encoder board, ten Fast Digital Integrators, and a computer with a data acquisition software (FFMM).

The rotating shaft was developed at CERN. It is composed of five, 255-mm-long segments and an outer diameter of 92 mm. Each segment encloses five rectangular coils with a surface of about 0.36 m^2. Fig. 1 (left) shows the cross section of this shaft segment. The external coils are positioned at a radius of 43.62 mm and the intermediate coils at 21.81 mm. The central coil is centered with respect to the shaft rotation axis. The shaft is fixed at the bottom and the top of the magnet by means of a stainless steel support and a spherical, sliding gasket made from Teflon. The shaft is aligned at ambient temperature inside the magnet by the lower and upper supports, which cannot be modified after cooldown. Only four of the five segments are completely in the magnet aperture; the second segment counted from the bottom is the closest one to the magnet center.

In rotating coil measurement systems the main and the lower-order harmonic components must be removed from the absolute signal in order to produce a compensated signal, a technique known as bucking. The compensation of the main quadrupole component is obtained by series connecting the external (main) coil with the two intermediate (compensation) coils with suitable polarity. The dipole component, arising from the offset of the shaft-rotation axis and the magnetic axis (an effect known as feed-down), is compensated for by adding the signal of the central coil, connected with opposite polarity. The standard bucking scheme for quadrupoles, with coil polarities [+1; -1; -1; +1] respectively, is exploited. The compensation coils must be designed to have in combination the same sensitivity coefficient (K-value) as the main coil for the quadrupole field component. The compensation coils of our system have the same surface as the main coil, but they are placed on the shaft at a smaller distance from the rotation axis. Due to an error in the shaft layout, the residual quadrupole component in the compensated signal turned out to be only about ten times smaller than in the absolute signal and is still hundred times larger than the higher-order harmonic components. For this reason, an electronic card with an adjustable voltage divider (Fig. 1, right) was introduced to improve the compensation. The compensated signal is given by

$$U_{cmp} = (U_{abs} - U_{dc})\frac{R_2}{R_1+R_2} - (U_{qc1} - U_{qc2}), \quad (1)$$

where U_{abs} is the main-coil voltage, U_{dc} the central coil voltage, and U_{qc1};U_{qc2} are the intermediate coil voltages. The measuring shaft can be rotated with revolution frequencies of up to 8 Hz by the motor/encoder Micro Rotating Unit (MRU). This unit is equipped with a speed-controlled DC motor and equipped with slip rings for electrically connecting the rotating coils to the integrators.

A misalignment of the MRU with respect to the shaft axis of the order of approximately 1 mm is unavoidable due to the mechanical tolerances of the vertical cryostat insert and lambda plate. This results in precession movement of the connecting shaft and vibrations in the measurement shaft. A frequency of 1 Hz was used for all the measurement as compromise of low vibration level on the shaft and a good time resolution.

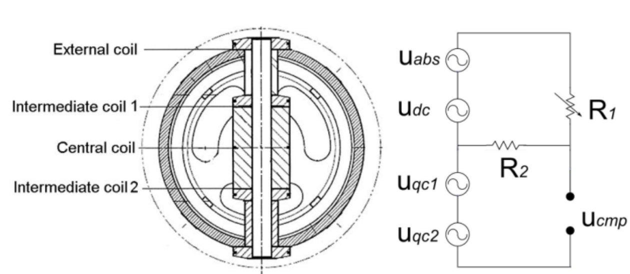

Figure 1: Left: Coss-section of the measurement shaft with search coils. Right: Compensation scheme for the induced voltages in the search coils.

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The signals from the coil shaft are acquired by means of ten FDIs (5 for the absolute signals and for 5 compensated signals). The pulses from the angular encoder are acquired by a custom made electronic board that provides the trigger signals to the digital integrators. For all the measurements, the encoder card is set to provide 512 trigger pulses at each turn of the shaft. A high-current power converter provides the excitation of the magnet, which is equipped with a high precision current controller. The control system measures the current and sends the measured points and their absolute timestamp to the magnetic measurement system by means of a specific Ethernet connection. The current data points are acquired at the fixed rate of 50 Hz. The GPS timing board provides the absolute time of the trigger pulses. Therefore the measured flux increments and the current can be synchronized during the data post-processing stage. The software application for the data acquisition is based on the Flexible Framework for Magnetic Measurements (FFMM) described in reference [1]. A schematic of the complete system is shown in Fig. 2.

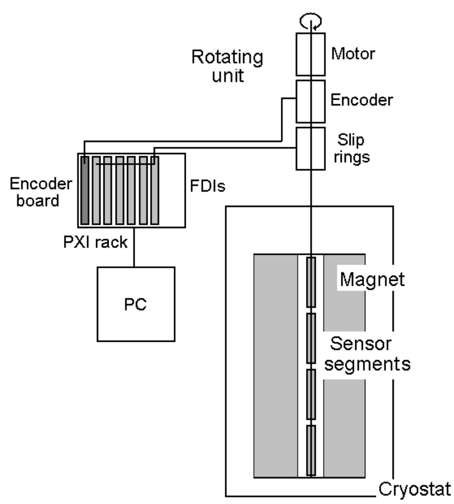

Figure 2: Schematic of the measurement system.

An important source of measurement error in rotating coil systems is related to the ramping of the magnetic field during a complete turn. While the continuous measurement during the ramp yields an improvement in the characterization of the dynamic effects in the magnet, the harmonic coefficients computed by means of the discrete Fourier transform are affected by an error. Technically speaking we measure an amplitude-modulated signal, i.e., a product of space and time-harmonic signals. In the compensated signal, the amplitude modulation is strongly attenuated because the main harmonic component is removed. If this is not true, the error will propagate into the measurement of the higher order multipoles. This is shown in Fig. 3. In any case, the error must be corrected in the absolute signal of the main field when computing the transfer function. The relative error is at its maximum at the onset of the ramp.

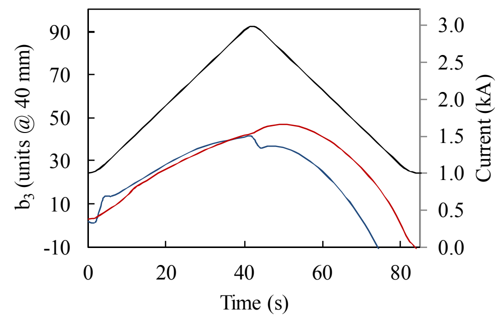

Figure 3: Black: Current cycle. Blue: Measured b_3 component for the search coil configuration with low compensation ratio. Red: Measured b_3 component for the search coil configuration with compensation ratio improved by the voltage divider described in Fig. 1 (right).

The change in amplitude over one coil turn can be compensated for by estimating the field variation and subsequently weighing the flux samples. If the rotation speed of the shaft is high enough, the field variation of the main field can be considered linear and only the current values at the beginning and at the end of each turn are required.

MEASUREMENT RESULTS

Several measurements were carried out with the aim of studying (i) the superconducting filament magnetization around the injection field level expected for the LHC inner triplets, (ii) the dynamic behaviour during ramps and plateaus, and (iii) the static field errors. The requirements for the field measurements are demanding in term of accuracy (0.1 units) and time resolution (1 s).

The results obtained in the test campaign on the HQ01e validated the system as suitable for field quality testing on superconducting magnets. In particular, the precision achieved in the measurement of the transfer function is in the order of ± 0.5 units (Fig. 4). The harmonic field components are measured with a precision of ± 0.03 units at a reference radius of 40 mm. In Fig. 5, the spread of the results for b_6 is reported as multipole measurement example.

The fast acquisition rate of up to 1 Hz yields valuable results for the ramp-induced field errors as well as other the dynamic effect of superconducting magnets.

The repeatability of the measurements is also compatible with the requirements. The spread of the transfer function (Fig. 6), measured on the nominal current plateau in four different cycles, is in the order of ± 2 units. For the multipoles the repeatability (Fig. 7), evaluated in the same conditions as the transfer function, is in the range of ± 0.05 units.

Toward the end of the measurement campaign a mechanical degradation occurred in the measurement system. During a test of the field repeatability, the noise in the absolute signal started to grow and large oscillations appeared in the main field component. The noise is less pronounced at low field but increases as the field rises. The estimated noise on the high-field plateau is on the order of 0.2%. Further tests show that the noise depends on the direction of rotation of the shaft and it is not completely repeatable. The cause of this problem must be studied once the magnet and the measurements system will be extracted from the cryostat.

Nevertheless, because to the high compensation factor (bucking ratio) of the search coil system, the effect of vibrations is less evident on the compensated signal and the noise on the measured multipole remains at the same level as before.

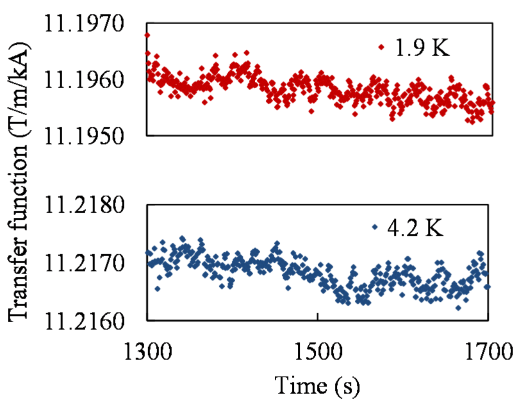

Figure 4: Precision of transfer function measurements during a plateau at nominal current level. Both for operation at 1.9 (red) and 4.2 K (blue).

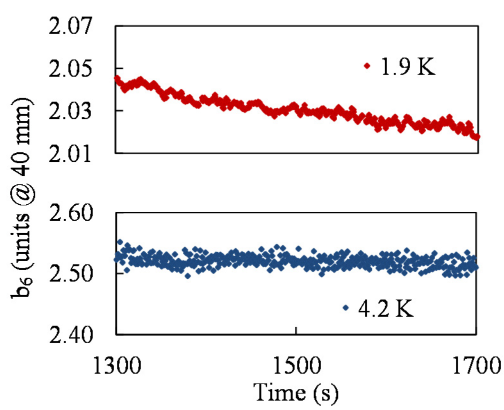

Figure 5: Precision of b_6 measurements during a plateau at nominal current level. Both for operation at 1.9 (red) and 4.2 K (blue).

CONCLUSION

This first application of the FAME magnetic measurement system to a model magnet, cold-tested in a vertical cryostat, was not free of technical challenges. These included vibrations due to the misalignment of the shaft and the motor-drive unit, sub-optimal compensation ratios, and ramp-rate dependent effects on the continuous field measurements. Nevertheless, the improved acquisition rate of up to 1 Hz yielded valuable results for the ramp-induced field errors as well as the decay and snapback of superconducting filament magnetization. In particular, the effect of fast transient instabilities at 4.5 K on the transfer function and multipole field errors could be resolved with unprecedented resolution.

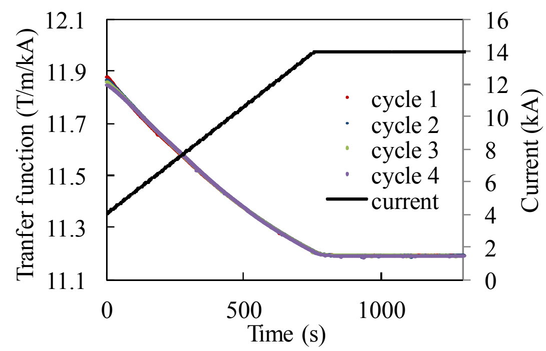

Figure 6: Repeatability of transfer function measurements in four excitation cycles.

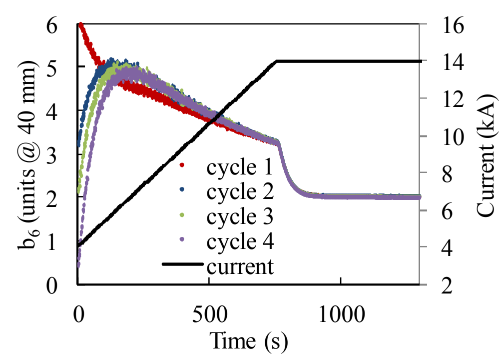

Figure 7: Repeatability of b_6 measurements in four excitation cycles. The multipole depends on the pre-cycling conditions at low field but it is repeatable at nominal field.

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