Field Decay and Snapback Measurements Using a Fast Hall Plate Detector

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Abstract—In superconducting particle accelerators significant changes occur in tune and chromaticity during the injection of particles and their subsequent acceleration. This behavior is caused by the decay of magnetic field components in the superconducting accelerator magnets during injection and their so-called “snapback” to the original hysteresis curve during the first few seconds after the start of the energy ramp. The two effects are closely related to a spatially periodic modulation of all field components along the magnet axis. In order to avoid a loss of particles the sextupole component in the dipoles has to be compensated with a very high accuracy. Standard magnetic measurements using rotating coils do not have the time resolution required to completely resolve the snapback. For this reason we have developed a fast system for sextupole measurements consisting of three Hall plates mounted on a ring. A new calibration procedure for the first time allows quantitative results. The detector is used to measure decay and snapback as a function of several parameters in the operation cycle. The results obtained help to better understand the interaction between current distribution and magnetization in the coil.

Index Terms—Decay, snapback, superconducting magnets.

I. INTRODUCTION

IN SUPERCONDUCTING accelerator magnets field errors are caused by the coil geometry, the iron yoke saturation, persistent currents and eddy currents [1]. During long periods of constant current excitation, especially during injection, all components of the magnetic field show a decay behavior. The prevailing mechanism contributing to this decay is thought to be the interaction between current distribution and filament magnetization. Current imbalances in the Rutherford cable follow a zigzag path along the strands and can be observed as a spatially periodic pattern in all field harmonics. The wavelength of this spatial modulation is equal to the cable twist pitch. During periods of constant magnetic field the current imbalances diffuse into the whole magnet and generate a periodic change of the internal field along the cable. This periodic field change interacts with the magnetization of the superconducting filaments, resulting in a net decrease of the cable magnetization. As soon as, after the end of injection, the external field is ramped up

again, the magnetization *snaps back* to the original hysteresis curve [2].

In this paper we examine the effect of magnetization decay and snapback on the normal sextupole b_3 . This component is most critical for accelerator operation. We will show that the spatially periodic field pattern is not affected by the magnetization, but that the temporal decays of field pattern and magnetization during injection are correlated. Measurements are performed using a fast detector based on Hall plates.

II. THE DETECTOR

In accelerator magnets field harmonics are usually measured with rotating coils, where all components are obtained in a single measurement cycle [3]. The typical bandwidth of rotating coil measurements is in the range of 0.1 Hz. In order to accurately resolve the snapback a system with an acquisition rate of 1 to 5 Hz is needed. On the other hand, in rotating coil measurements the field components are spatially integrated over the length of the coil. In order to allow both, higher sampling rates and a better spatial resolution, Hall plates can be used for magnetic measurements [4], [5]. A fast sextupole probe with a data acquisition rate of about 3.3 Hz was developed at CERN. The device allows an accurate resolution of the sextupole field during the snapback. Three Hall generators are mounted onto the surface of a ring with an angular spacing of 120° . Each plate measures the projection of the field onto a vector perpendicular to its surface. In an ideal arrangement the sum signal S of the three plates compensates the dipole and only normal multipoles of order $3(2k-1)$ (i.e., $B_3, B_9, B_{15}, \dots$) and skew harmonics of order $6k$ (i.e., $A_6, A_{12}, A_{18}, \dots$) contribute according to:

$$S = \sum_{k=1}^{\infty} 3 \left(\frac{R}{R_{ref}} \right)^{3(2k-1)-1} B_{3(2k-1)} + \sum_{k=1}^{\infty} (-1)^k 3 \left(\frac{R}{R_{ref}} \right)^{6k-1} A_{6k}. \quad (1)$$

For the LHC the reference radius R_{ref} is 17 mm. R is the radial distance of the active area in the Hall plates from the center of the ring. The details on the detector are discussed in [4]. Sensors with similar properties have already been constructed at HERA [6], [7] and BNL [8]. At CERN a first prototype [9] has been further developed. In the improved device Hall generators with *uncovered electric systems* and a new fixation method are used to decrease the angular misalignment of the plates. Shielding the cables and distribution boxes considerably reduces electronic noise. The Hall plate signals are measured simultaneously with nanovoltmeters at a digital resolution of 100 nV and read out by

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Fig. 1. Example for a calibration of the Hall detector performed on the magnet MBP2O1. The normal sextupole component b_3 is plotted as a function of the excitation current in the magnet. Hysteresis cycles measured with rotating coils (points) and Hall detector (lines) are shown in comparison.

a data acquisition software on a workstation. The Hall plate sensitivities of about 220 mV/T thus lead to a resolution of $0.7 \mu\text{T}$ in the B_3 component. Along the detector two sextupole rings are placed at a distance of half a wavelength along the spatially periodic pattern in a magnet. The sum S of the two rings contains information about the magnetization, whereas the difference is proportional to the local amplitude of the field modulation.

III. CALIBRATION

In order to accurately measure a sextupole component in the range of a few units, the dipole component has to be compensated with an accuracy of about 10^{-6} . For the calibration it is difficult to find a reference magnet, which is homogeneous and accurate in the μT range. In addition, also imperfections in the positioning of the plates and the detector disturb a perfect compensation. However, already a rough calibration allows to qualitatively reconstruct hysteresis curves. In order to optimize the calibration we use rotating coils as a standard. In the easiest case three parameters (A , B , C) in the Hall detector measurements can be fitted to the b_3 measured by the rotating coils: The amplitude of the hysteresis curve, a linear term and an offset:

$$b_3 = A \cdot (U_{H1} + U_{H2} + U_{H3}) / I + B \cdot I + C. \quad (2)$$

U_{it} are the signals of the plates on a ring and I is the current in the magnet. Non-linear sensitivities of the Hall plates (up to 0.2% below 1 T) can lead to deviations in the curves. In order to compensate for this effect the Hall plate signals U_{it} in (2) can be replaced by low order polynomials:

$$U_{it} \rightarrow a_{it}U_{it}^3 + b_{it}U_{it}^2 + c_{it}U_{it} + d_{it}. \quad (3)$$

The adaptation to the rotating coil measurements becomes less reproducible as the number of unknown parameters increases. Computer simulations have shown that better Hall plate linearities can considerably improve the detector performance. In most magnets a substantial value of b_9 disturbs the sextupole signal. For example, at injection, a b_9 of 0.23 units causes an error of about 8%. Higher harmonics partially compensate each other.

Fig. 2. Standard current cycle for snapback measurements. The magnet excitation current is sketched as a function of time.

For $b_{15} = 0.06$ units, $a_6 = 0.08$ units and $a_{12} = -0.0007$ units the total error is 2.6%. This contribution varies with the background field and has a maximum of up to 7% in the interval $[0.4 \text{ T} < B_0 < 0.8 \text{ T}]$. The noise in the measurement usually has an amplitude in the range of 0.05 units. Over a limited range around the injection plateau $[0.4 \text{ T} < B_0 < 0.8 \text{ T}]$ the snapback can be measured with a reproducibility of about 0.15 units and an accuracy of about 0.3 units. An example for the calibration on the magnet MBP2O1 is shown in Fig. 1. The points indicate rotating coils and the full lines show the average signal of the two rings in the Hall plate detector.

IV. EXPERIMENTS

Measurements were performed on 3 different 15-m long magnets, the two 3rd generation LHC prototype dipoles MBP2O1 (version 1, aperture 2), MBP2O2 (version 1, aperture 1) and the pre-series magnet HCLBB_001-CR001 001 (aperture 2), referred to as MBPSO1, which represents the closest match to the actual design of the LHC. A standardized operation cycle has been used as a reference for all snapback measurements (Fig. 2). An initial quench erases the persistent currents, the following precycle moves the operating point away from the virgin curve onto a reproducible hysteresis curve. Afterwards the current is ramped up to injection, following the up-ramp branch of the hysteresis curve. The injection of particles at a constant field is simulated for typically 17 min. Afterwards, the current is ramped up again, simulating the acceleration of particles. We performed variations of single parameters in the current cycle, with the scope of detecting a more or less sensitive snapback response.

A. Measurements and Results

In a first series of measurements the ramp-rate after injection was varied between 1, 2, 5 and 7 A/s. Here, the precycle flat top current was 11 500 A. The measured average signal of the two rings during snapback is shown in Fig. 3. Within the accuracy of the measurements, the snapback does not change with the ramp-rate. The difference between the signals of the rings is a measure for the amplitude of the periodic pattern inside the magnet. In Fig. 4 this parameter is traced for a complete operation cycle. The bumps in some parts of the curve are due to the very high ramp-rate (50 A/s) in the precycle. During injection the pattern amplitude changes. However, after injection,

Fig. 3. The decay and snapback of the normal sextupole b_3 in MBP2O1 are measured for different ramp rates of 1, 2, 5 and 7 A/s after injection. The average signal of the two rings in the Hall detector is shown as a function of the excitation current flowing in the magnet.

Fig. 4. The periodic pattern amplitude A_{PP} is shown as a function of the excitation current for a standard snapback cycle on MBP2O1.

the spatial modulation is not influenced by the snapback. The same behavior was verified also on other magnets and for different injection currents. This shows that the spatially periodic modulation in the magnets is not significantly influenced by the magnetization and only caused by the current imbalances in the coil.

In a second experiment on MBP2O2 snapback cycles were performed with precycle flat top currents of 0, 1000, 2000, 4000, 8000 and 11 850 A. In order to find the expected minimum snapback amplitude, we reduced the flat top time to 5 minutes. The snapback curves shown in Fig. 5 are affected by current overshoots of the magnet power supply. These overshoots have a similar magnitude and represent a systematic error in the range of about 0.2 units. For the same measurements in Fig. 6 the magnetization decay Δb_3 during injection is plotted as a function of the measured pattern decay ΔA_{PP} . A cycle with a 5 min precycle at 11 850 A and an injection duration of 10 000 s is also shown. The spread in the data is mostly due to noise in the power

Fig. 5. The decay and snapback of the normal sextupole component b_3 is shown as a function of the excitation current for several cycles with different precycle flat top currents measured on MBP2O2.

Fig. 6. For the current cycles on MBP2O2 the magnetization decay Δb_3 during injection is plotted as a function of the pattern decay ΔA_{PP} .

supply. Within the accuracy of the measurement all plots describe the same linear and possibly also symmetric correlation between Δb_3 and ΔA_{PP} :

$$\Delta b_3 = a |\Delta A_{PP}| + c. \quad (4)$$

a is a proportionality factor and c a constant offset which is in the same range as the current overshoots. After a long time at injection the 10 000 s measurement shows a certain reversal of the pattern decay at a constant magnetization, thus, indicating the existence of current redistributions with long time constants competing with the original decay. (The effect of successive current redistributions with alternating directions on the filament magnetization was analyzed in [2]). In Fig. 7 the change in pattern amplitude during injection and the snapback amplitude are plotted as functions of the precycle flat top current. Within the accuracy of the measurements the change of the periodic pattern amplitude indicates a linear behavior and a change in sign at a flat top current close to 2000 A. The snapback amplitude indicates a minimum close to 2000 A. For high and for low flat-top

Fig. 7. For the cycles measured on MBP2O2 the snapback amplitude Δb_3 and the periodic pattern decay ΔA_{PP} are shown as functions of the precycle flat top current.

Fig. 8. On MBPSO1 the nonnormalized snapback amplitude ΔB_3 was measured for several cycles with different injection currents. The time between the precycle and the injection plateau was held constant.

Fig. 9. For the measurements at different injection currents performed on MBPSO1 the magnetization decay Δb_3 during injection is plotted as a function of the pattern decay ΔA_{PP} .

currents linear extrapolations of the snapback data are shown in the figure. Both straight lines cross at a point, which is still inside the error bars and which has an offset comparable to c .

A third run was performed on the magnet MBPSO1 with injection currents of 300, 550, 800 and 1050 A. In this case a 30 min flat top in the precycle was used and the time between precycle and injection was left constant. The amplitude of the non-normalized snapback ΔB_3 remains constant (Fig. 8). In Fig. 9 for the same data the magnetization decay during injection is plotted as a function of the pattern decay. In this experiment the detector rings had a different position with respect to the phase of the periodic pattern. For this reason the sign and magnitude of ΔA_{PP} differ from Fig. 6. During the measurements on MBPSO1 the magnet was powered by an improved power supply. No significant overshoots were observed and the noise remained small. Also here the linear behavior of (4) is confirmed. The measurements at different injection currents have slightly different small offsets (e.g., ~ 0.05 units @ 800 A), which mainly appear during the first 10 s of the decay. Flux creep is a possible explanation for this effect. Apart from that, within the accuracy of the measurements, no other significant indication toward flux creep was found.

V. CONCLUSION

A new prototype of Hall detector, together with an improved calibration procedure allows measurements with a significantly increased precision. At 0.5 T the device attains a resolution of 0.015 units, a reproducibility of 0.15 units, an accuracy of 0.3 units and a bandwidth of 3.3 Hz. The observation that the pattern amplitude does not show a snapback indicates that the spatially periodic pattern in the magnets is not significantly influenced by the magnetization. However, a correlation is found between the pattern decay and magnetization decay during injection. For measurements with different precycle currents the decay of the pattern amplitude indicates a change in sign at a flat-top current close to 2000 A, thus, suggesting current redistributions with opposite directions. Measurements with different ramp-rates after injection show the snapback to be independent of the ramp rate. For measurements at different injection currents we find a constant nonnormalized snapback amplitude ΔB_3 . Both results very well correspond to the linear correlation described above, since the induction of currents during ramps before and after injection is relatively small in comparison to the currents induced during the precycle.

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