A Fast Sextupole Probe for Snapback Measurement in the LHC Dipoles

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***Abstract*—In superconducting particle accelerators a fast change of the magnetic field occurs during the first few seconds after the start of an energy ramp. Standard magnetic measurements using a coil rotating at 1 Hz do not have the time resolution required to completely resolve this phase, usually called *snapback*. For this reason we have developed a new and fast system dedicated to sextupole measurements. The basic component consists of three Hall plates mounted on a ring. In an ideal case this arrangement compensates the main dipole field and produces a signal proportional to the sextupole only. Mechanical tolerances and differences in the sensitivity of the Hall plates are compensated by instrumentation amplifiers and an in situ fine adjustment of the probe orientation. Using this hybrid compensation technique we have measured sextupole variations in an LHC dipole prototype during snapback at a rate of 5 Hz. In this paper we present details on the device and the results of our measurements.**

I. INTRODUCTION

One of the characteristics of superconducting accelerator magnets is a relatively large magnetic field drift during periods of constant excitation current [1]. This drift has a time constant in the order of some hundreds of seconds, depends on the powering history of the magnet (memory effect) and is caused by an interaction between the current distribution in the cables and the magnetization of the superconducting filaments [2]. The field returns rapidly to the original hysteresis curve as soon as the magnet is ramped. In the case of LHC dipoles this so-called *snapback* phase takes place within some seconds [1]. Hence, for an adequate measurement of the snapback we need a measurement system with an acquisition rate in the range of 5 to 10 Hz. The standard equipment for magnetic measurements in accelerator magnets are rotating coils [3], slender pick-ups that turn inside the bore of the magnet and produce a signal proportional to the harmonics of the field. The typical bandwidth of measurements with rotating coils is in the range 0.1 to 1 Hz. This rate is therefore not sufficient to accurately resolve the evolution of the sextupole during snapback. For this reason we started the development of a fast sextupole detector capable of providing the required bandwidth. Fast measurements during snapback could reveal fine details and help to understand this phenomenon for which we have so far only a qualitative explanation and no quantitative model. Note that similar sensors were already built by measurement groups at HERA [4] and BNL [5]. However, they are only sparingly documented in the literature.

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II. WORKING PRINCIPLE OF THE PROBE

We follow standard practice for accelerator magnets and we consider that the field **B** is two dimensional in the magnet cross section, ignoring the field component along the magnet length. For convenience we choose a cylindrical coordinate system with the z axis along the magnet length. Every point in the magnet cross section can be identified by a radius r and an angle θ (measured starting from the horizontal axis). Inside the magnet bore we expand the radial and tangential components in series [6]:

$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}} \right)^{n-1} \left[B_n \sin(n\theta) + A_n \cos(n\theta) \right] \tag{1}$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}} \right)^{n-1} \left[B_n \cos(n\theta) - A_n \sin(n\theta) \right] \tag{2}$$

Here, B_n and A_n are the normal and skew multipoles of order n. The first coefficient B_1 is the *normal dipole* and is equal to the main field generated by a bending accelerator magnet. In a symmetric dipole magnet only the odd order normal multipole components, the so-called allowed multipoles, are different from zero. We are particularly interested in the behaviour of the first allowed multipole, the *normal sextupole* coefficient B_3. In a well-designed dipole magnet the higher order multipoles are small, in the range of 10^{-4} relative to the main field. Thus, a sensor that measures higher order harmonics must be capable of strongly suppressing the dipole component. The necessary compensation can be achieved using the periodic properties of the magnetic field associated with each multipole. We consider a circle of radius R, centered in the origin of the cylindrical coordinate system. From Eqs. (1) and (2) we see that on this circle the magnetic field associated with a multipole of order n is a rotating vector of constant module.

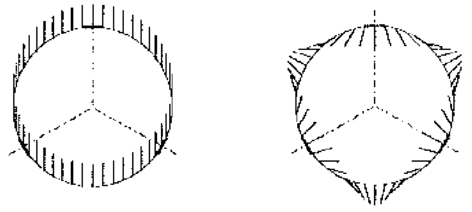

Fig. 1. Working principle of the sextupole probe. Three field sensors are placed onto the surface of a circle at 90°, 210°, and 330°. They measure the projections of the field onto the three axes starting from the center of the circle. The field vectors are shown for a dipole (left) and for a sextupole (right) (lines originating on the circle).

The frequency of its angular rotation is equal to the multipole order. Now we suppose to sample the radial component of the field at points placed on the circle at equispaced angular intervals, and to sum over all of the sampled values. Choosing an angular spacing of 120° between sampling points we obtain the following sum signal S:

$$S=\sum_{n=1}^{\infty}\left\{B_n\left(\frac{R}{R_{ref}}\right)^{n-1}\sin(n\varphi)\left[1+2\cos\left(\frac{2n\pi}{3}\right)\right]+ \right. \\ \left. +A_n\left(\frac{R}{R_{ref}}\right)^{n-1}\cos(n\varphi)\left[1+2\cos\left(\frac{2n\pi}{3}\right)\right]\right\}. \tag{3}$$

Here, φ is the angular position of the first sampling point on the circle. It is easy to verify that:

$$1+2\cos\left(\frac{2n\pi}{3}\right)=\begin{cases}3 \text{ for } n=3k\\ 0 \text{ for } n\neq 3k\end{cases} \tag{4}$$

where k is an arbitrary integer number. Therefore the sum signal contains contributions only from the normal and skew multipoles of order $3k$, i.e. the multipoles of order 3, 6, 9, etc. Thus with this configuration we can achieve the desired suppression of the dipole field. Furthermore, the signal generated by the normal sextupole can be maximized if we choose to place the first sampling point at an angle $\varphi = 90°$ (as in Fig. 1). In this particular case we obtain that:

$$\sin\left(\frac{3k\pi}{2}\right)=\begin{cases}1 \text{ for } k \text{ odd}\\ 0 \text{ for } k \text{ even}\end{cases} \\ \cos\left(\frac{3k\pi}{2}\right)=\begin{cases}0 & \text{for } k \text{ odd}\\ (-1)^{k/2} & \text{for } k \text{ even}\end{cases} \tag{5}$$

The consequence is that only the normal multipoles of order 3(2k-1) (i.e. B_3, B_9, B_{15}, ...) and the skew multipoles of order $6k$ (i.e. A_6, A_{12}, A_{18}, ...) contribute to the total sum S. The sum signal of our device is then given by:

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

Now we recall that in a dipole the normal multipoles of order 3(2k-1) are allowed by symmetry. With increasing order, however, they strongly decrease in amplitude. On the other hand the skew multipoles of the order $6k$ are not allowed by symmetry. Thus, in a *good* magnet they are close to zero. For this reason we can simplify Eq. (6) as follows:

$$S \approx 3\left(\frac{R}{R_{ref}}\right)^{2}B_3 \tag{7}$$

The sum signal of this ideal sensor is proportional to the normal sextupole only, as desired. Note finally that multipoles of different orders could be measured with similar sensors, using a different spacing among the sampling points.

III. REALIZATION OF THE DETECTOR

A. *Error Analysis*

The sensor discussed above requires the local measurement of a single (radial) field component, which slowly varies in time. The most suitable devices for such a measurement are Hall plates. In a first approximation Hall plates provide a voltage signal proportional to the field normal to their active surface and proportional to the excitation current. Therefore the principle of the sensor discussed in the previous section can be put into practice mounting three Hall plates with identical sensitivities on the triangular arrangement shown in Fig. 1. In practice different Hall plates have different sensitivities to the field, in addition to a small offset signal. Both, sensitivity and offset are functions of the temperature. Finally mechanical tolerances affect the precision, especially due to inaccuracies in the placement of the plates. These are the largest sources of measurement errors. For the typical snapback of LHC dipoles we would like to achieve an accuracy of 3 %, corresponding to a sextupole resolution of 3 µT at 17 mm in a background dipole field of 0.5 T. Using the above values as target specifications, we have estimated the maximum tolerable inaccuracies in the Hall plate sensitivity, mechanical tolerances, temperature gradient and electronic noise in the range of 1 to 10 Hz. The results of this error estimate are summarized in Table I. From the values shown in the table it is evident that the most critical parameters are the Hall plate sensitivities and their tilt around the center. These requirements cannot be achieved in practice. Therefore, as discussed in the next sections, we have chosen a hybrid technique for the adjustment and compensation in order to suppress the dipole contribution and achieve the target resolution.

B. *Selection of Hall Plates*

We built the sextupole sensor using AREPOC packaged Hall plates of the type HHP-NP. They have a sensitivity around 230 mV/T at an excitation current of 50 mA. In Table II we report the relevant parameters of the plates selected. As we have stated previously, we are interested mainly in a detailed measurement of the snapback phase, which takes place in the LHC dipoles at injection conditions (0.54 T). We have therefore performed an *ad hoc* calibration of the plates using a split solenoid magnet with a main field in the range of 0 to 1 T and a NMR probe as a reference. The

TABLE I

SUMMARY OF MAXIMUM TOLERANCES FOR A 3% RELATIVE ACCURACY IN THE SEXTUPOLE SNAPBACK MEASUREMENT

Tolerance on Hall plate sensitivity	(-)	3×10^{-6}
Maximum error for the center position of each plate		
Radius	(mm)	0.5
Angle	(degrees)	10
Tilt angle of each plate around the center	(degrees)	0.8
Probe positioning angle (rigid rotation)	(degrees)	5
Temperature gradient among plates	(K)	1
Electrical noise level (1-10 Hz)	(µV)	10

probes were sorted in groups of three, so that the sensitivities in each group matched within 5×10^{-3}.

C. Mechanical Arrangement

The choice of material for the support structure is delicate. The material must have non-magnetic properties and a high electrical resistivity in order to avoid perturbations of the magnetic field both in steady state and during ramps. At the same time a good thermal conductivity is desirable in order to accurately stabilize the temperature of the three Hall plates on a ring. We have chosen a titanium alloy (Ti_6Al_4V, Grade 5) as a good compromise between a high electrical resistivity ($\rho \approx 1.7$ [$\mu\Omega$ m]) and adequate thermal conductivity ($k \approx 7$ [W/K m]). In addition, the alloy chosen has a negligible paramagnetic behaviour ($\mu_r \approx 1.0002$).

Two groups of three plates were mounted on the support rings shown in Fig. 2. The plates were glued into the precision machined grooves of the support rings. The reference surface at the bottom of the grooves has a radius of 14.3 mm with respect to the rotation axis. Calibration measurements performed after gluing showed that the sensitive area of the Hall plates is not aligned with the reference surface. The alignment errors among the plates varied between 6 and 10 degrees. We believe that these large errors are due to the gluing technique chosen, and also due to the lack of a reference surface in the packaged Hall plates.

We have assembled two of the rings on a Ti-alloy support shaft. The shaft is equipped with rollers and ball bearings in order to move and rotate the device inside the warm bore of a magnet, see Fig. 3. The two rings have a variable spacing, which can be adjusted on the support shaft. In the LHC magnets the local amplitude of the sextupole can be affected by a periodic pattern, which has a wavelength equal to the twist pitch of the superconducting cable of the inner layer [4]-[5]. Placing the two rings of the detector at a distance of half a twist pitch we can compensate for the influence of the periodic pattern. The support shaft was equipped with two additional Hall plates mounted on two perpendicular surfaces. Their purpose is to measure the two components of the magnetic field on the axis of the detector, thus providing a good approximation of the normal and skew dipole.

Finally the mechanical assembly was wrapped into an adhesive Kapton foil in order to provide a good thermal insulation against the wall of the warm bore. The Ti-alloy used in the rings has a thermal conductivity much larger than Kapton. Thus, in spite of the temperature regulation transients in the warm bore, the temperature gradient in the support rings is negligible. For this reason it was possible to avoid a temperature regulation of the sensor. The outer diameter of the whole probe is 32 mm and its length, including the housing for the connectors, is approximately 250 mm.

TABLE II
NOMINAL PARAMETERS FOR THE HALL PLATES USED

Excitation current	(mA)	50
Typical sensitivity (at 50 mA excitation)	(mV/T)	≈ 230
Active area	(mm^2)	0.5 x 1.25
Non-linearity (0...1T)	(%)	< 0.2
Temperature coefficient of the sensitivity	(1/K)	$\approx 10^{-1}$
Offset	(μV)	< 50
Temperature coefficient of the offset	(μV/K)	< 0.3
Input resistance	(Ω)	≈ 5
Output resistance	(Ω)	≈ 15

D. Cabling and Acquisition

We have connected all the Hall plates in the detector in series with the current source. This ensures that the excitation current is the same for all Hall plates. The excitation current chosen is modest (50 mA) and the input resistance of the Hall plates is small (5 Ω). For this reason also the total voltage on the plates is negligible (in the range of 1.5 V). A 15-m long cable connects the sensor in the magnet to the conditioners and data acquisition system. The voltage signal of each Hall plate in a ring is conditioned by a compensation card, shown schematically in Fig. 4. This card provides an amplifying and summing stage. The instrumentation amplifiers for each channel have an adjustable gain (in the range of 5 to 10) and are used to compensate the expected residual differences in the sensitivities as well as the angular misalignment of the Hall plates on the support ring. The criterion for the fine-adjustment of the gains was to obtain an optimal bucking of the dipole.

The sum signal from the conditioners and also the voltage of the individual Hall plates, are measured with Keithley Mod. 2001 DVM's. The DVM's are controlled with a LabView based software running on a Sun-Ultra workstation. The acquisition system was described in detail in [7]. We used the DVM's as integrating voltmeters, with an integration time of 200 ms. This results in a data acquisition rate of 5 Hz, within the range required. In addition the 50 Hz background from the power network and other electronic noise sources

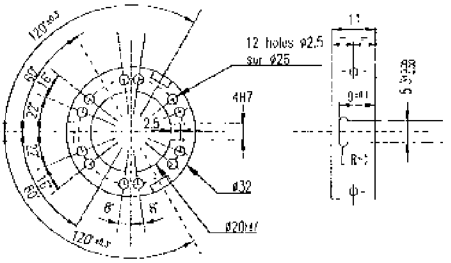

Fig. 2. Ti-alloy support ring with machined grooves for the Hall plates.

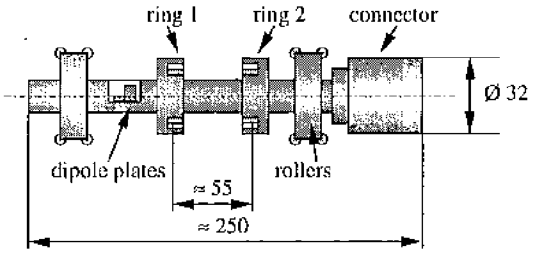

Fig. 3. Schematic assembly of the sextupole rings on the support shaft, showing the rollers that support the probe in the warm bore of the magnet, as well as the signal cable connector.

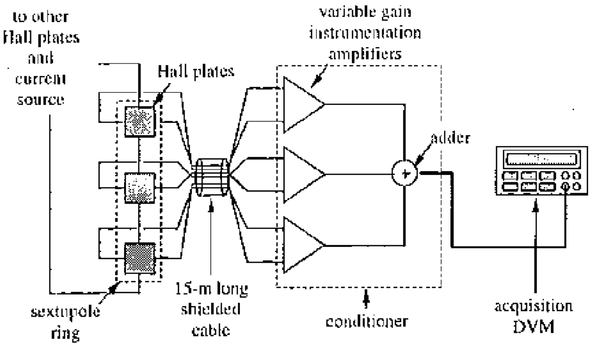

Fig. 4. Schematic cabling scheme, signal conditioning and data acquisition system for the sextupole probe.

are strongly filtered. The typical residual noise was in the 10 μV range. Note that a shorter integration time (e.g. 100 ms, resulting in a 10 Hz acquisition rate) would still provide a satisfactory S/N ratio.

E. Probe Calibration

A first step in the characterization of the sensor was the calibration of the sensitivity to the field and the measurement of the relative alignment of the Hall plates in a reference dipole. As already mentioned, we observed that the plates were tilted around their nominal position by several degrees. The measured sensitivity values and the tilt were used in order to adjust the gains of the input amplifier of the compensation boxes so that the sum signal is zero. At this stage we have calculated the sensitivity of each ring to all multipoles up to order 15. The typical sensitivity to a sextupole field, taking into account the gains of the amplifier stage, is around 3 V/T @ 17 mm. We verified the correctness of our sensitivities by direct measurements in a sextupole. The measurements agree with the computed sensitivity to better than 3 %.

IV. MEASUREMENT RESULTS

A snapback measurement with our sensor was performed inside the 15-m long MBP2N1 LHC prototype dipole. The sensor was oriented inside the warm bore of the magnet maximizing the signal of the Hall plate placed at φ = 90°. A subsequent fine adjustment of the angle was done cycling the magnet from low (0.5 T) to high (8 T) field and minimizing the average sum signal of the sensor. This *in situ* adjustment takes into account the angular alignment and increases the dipole bucking ratio, defined as the ratio of the signal of the Hall plate at 90° to the sum signal. Thanks to this fine adjustment we have achieved a bucking ratio in the range of 1000. Afterwards a continuous field ramp was measured without stop at injection current. This curve provided a reference measurement that includes the contribution of the normal sextupole, the un-bucked dipole and, if present, contributions from all other harmonics. Finally we pre-cycled the magnet and we measured the field decay at injection level (0.54 T) followed by the snapback at the start of the ramp (see [1] for details about the snapback phenomenon).

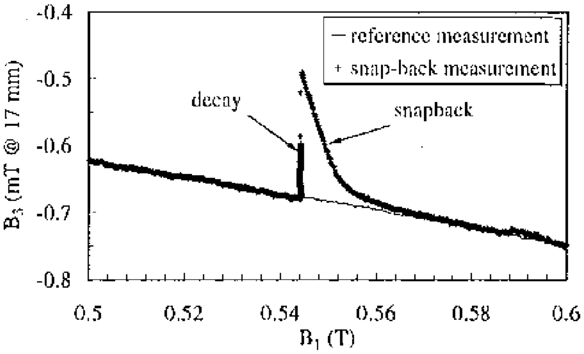

Fig. 5. Snapback measurement at 0.54 T injection field in the 15-m long MBP2N1 LHC prototype dipole.

The main result of our experiment is shown in Fig. 5. The curve has been drift-corrected, so that the measurements taken before the injection decay and after the snapback are coincident with the reference curve. The noise in the signal was less than 10 μT @ 17 mm. Also the resolution of the sextupole change during snapback is excellent.

V. CONCLUSIONS

The sextupole probe satisfies the requirements on the bandwidth (5 Hz) and field resolution (better than 10 μT @ 17 mm) for a fast snapback measurement. At the moment it works in *relative* mode, comparing measurements to a reference curve. We will re-work the present configuration using the experience gained. In particular we plan to use unpackaged Hall plates for a better mechanical alignment. An on-board measurement of the inclination with respect to gravity will be added in order to provide an absolute reference for the angular position. Besides, we have evidence for a change of the periodic pattern during the snapback phase. An array of sextupole sensors will allow simultaneous measurements of sextupole average and variation along the length of the periodic pattern.

REFERENCES

[1] L. Bottura, L. Walckiers, R. Wolf, "Field decay and snap-back in LHC model dipoles", *IEEE Trans. Appl. Sup.*, vol. 7 (2), pp. 602-605, 1997.
[2] R. Wolf, "The decay of the field integral in superconducting accelerator magnets wound with Rutherford cables", Proc. 15th Int. Conf. on Magnet Technology, pp. 238-241, *Science Press*, 1997.
[3] A. Jain, "Harmonic coils", CERN Report 98-05, pp. 175-213, 1998.
[4] H. Brück et al., "Observation of a periodic pattern in the persistent-current fields of the superconducting HERA magnets", Proc. 1991 Part. Acc. Conf., pp. 2149-2151, 1991.
[5] A.K. Ghosh, K.E. Robins, W.B. Sampson, "Axial variation in the magnetic field of superconducting dipoles", Supercollider, vol. 4, pp. 765-772, 1992.
[6] A. Jain, "Basic theory of magnets", CERN Report 98-05, pp. 1-21.
[7] Z. Ang, et al., "Measurement of AC loss and magnetic field during ramps in the LHC model dipoles, *IEEE Trans. Appl. Sup.*, vol. 9 (2), pp. 742-745, 1999.