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A HALL PLATE BASED INSTRUMENT TO MEASURE THE SNAPBACK IN THE LARGE HADRON COLLIDER SUPERCONDUCTING DIPOLE MAGNETS

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A Hall Plate Based Instrument to Measure the Snapback in the Large Hadron Collider Superconducting Dipole Magnets

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Abstract – The decay and snapback of the magnetic field multipoles in superconducting particle accelerators like the Large Hadron Collider (LHC) could result in a significant particle beam loss unless adequately compensated. Whilst standard instrumentation used to measure the field quality of the superconducting magnets is good enough to measure the harmonic decay, it is not fast enough to measure the snapback. Therefore, a state of the art instrument was recently developed at CERN to measure the most important harmonics with a high measurement frequency and hence improve the understanding of the snapback phenomenon. In this paper we describe the instrument's principle of operation, its mechanical arrangement, its compensation system and its digital acquisition system. We also compare the performance of two different techniques implemented to achieve the necessary measurement resolution of 6 orders of magnitude lower than the main superimposed dipole field.

Keywords – magnetic measurements, decay and snapback, Hall probe

I. INTRODUCTION

The LHC superconducting magnets [1] need to have a constant magnetic field of 0.537 T for the particles to be injected into the machine and are therefore kept on a constant current plateau of 760 A during the injection phase. Unfortunately, the magnet field multipoles tend to decay when on a constant current plateau causing significant changes in the machine tune and the beam chromaticity [2]. Moreover, during the particle acceleration in the first few seconds of the current ramp, the field multipoles snapback to the original hysteresis curve, hence quickly canceling the decay. In order to avoid particle loss, the field harmonics, particularly the sextupole (b_3) and the decapole (b_5) must be well understood and compensated for with very high accuracy. Unfortunately the so called snapback phenomenon is very fast and the signals from beam diagnostics are too slow to control compensation.

The standard field quality measuring instrument known as the rotating coil system has a maximum acquisition frequency of 0.1 Hz and is well suited to measure the slow decay integrated in sectors of 1.25 m over one entire 15 m superconducting LHC dipole magnet [3]. Unfortunately, even though this system has a relative resolution of 1 ppm of the main field, its measurement accuracy of the dynamics of the snapback is rather limited by its time resolution since the latter occurs in a few tens of seconds.

This limitation motivated the development of the Hall plate based instrument to measure the b_3 and somewhat less critically the b_5 harmonics which affect the first and second order beam chromaticity respectively. The duration of the snapback is around 60s for the standard LHC cycle, so a measurement frequency between 1 Hz and 10 Hz is required to allow adequate understanding and modeling of the phenomena. The b_3 decay amplitude is 200 ± 50 ppm and the b_5 decay amplitude is 34 ± 12 ppm. This effect causes a change of about 60 units of chromaticity which is critical for high intensity beams since they become unstable if not controlled within 2 and 10 units. The decay therefore imposes a required measurement resolution of 15 ppm for a signal to noise ratio of 10 for b_3 and a preferable resolution (though not strictly required) of 2 ppm to have the same signal to noise ratio for b_5. This requirement represents a considerable challenge particularly since 2 ppm is 6 orders of magnitude smaller than the superimposed dipole field of 0.537 T at injection. The instrument also needs to be stable with minimum drift at this resolution at least over one measurement cycle of typically 6000s. It is however not required to have an absolute measurement of the magnetic field harmonics. The absolute value of the field can be obtained by cross calibrating the instrument with the rotating coils. To reduce the complexity and the cost, it is not required to perform an integral measurement of the field over the whole magnetic length of the magnet. The length of the probe can therefore be limited to one twist pitch of the periodic field pattern [4] of the superconducting magnet cable so as to compensate this latter effect. This inherently imposes the assumption that the local dynamics of the snapback do not vary significantly when compared to the dynamics of the integral over the length of the magnet. Having these stringent targets, the design is tackled with two different techniques (analogue technique and digital technique) so as to examine their strengths and weaknesses and finally compare their performance.

II. PRINCIPLE OF OPERATION

Considering that the field is two dimensional in the magnet cross section and ignoring the field component along the magnet length we can expand the radial component as [5]:

$$\boldsymbol{B}_r = 10^{-4} \boldsymbol{B}_1 \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}} \right)^{n-1} \left(b_n Sin(n\theta) + a_n Cos(n\theta) \right) \qquad (1)$$

where b_n and a_n are the normalized normal and skew multipoles of order n, r and θ the polar coordinates of a generic point in the magnet bore section and R_{ref} is the reference radius (17 mm in the case of the LHC magnets). A sensor that measures high order harmonics must be capable of strongly suppressing the dipole component. As explained in [6] and as shown in Fig. 1 the compensation of the dipole field and the measurement of the *n-th* order harmonic can be performed using an appropriate arrangement of *n* Hall plates.

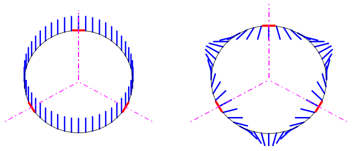

Fig. 1: (left) In a dipole field: Sum $\propto B_1 - B_1/2 - B_1/2 = 0 \therefore$ The dipole field contribution is cancelled.
(right) In a sextupole field: Sum $\propto -B_3 - B_3 - B_3 = -3B_3 \therefore$ Sextupole field is isolated.

With this ideal geometry, the total signal, S_n, from the Hall plates is given to first order by:

$$S_3 \approx 3\boldsymbol{B}_1 10^{-4} \left(\frac{r}{R_{ref}} \right)^2 b_3 ;\; S_5 \approx 5\boldsymbol{B}_1 10^{-4} \left(\frac{r}{R_{ref}} \right)^4 b_5 \qquad (3)$$

This means that in the first approximation, the signals coming from the ideal arrangement of the sensors in the rings are proportional to the normal sextupole and decapole harmonic respectively. The dipole field component is completely compensated by the symmetry. Note that b_3 is also compensated in the decapole arrangement.

III. PROBE MECHANICAL ARRANGEMENT

The Hall plate based probe consists of six rings each supporting 3 sensors for the sextupole measurements and two rings each supporting 5 sensors for the decapole. The support shaft is designed to provide good mechanical stability for the sensors. It is made of Ti_6Al_4V alloy purposely chosen for its relatively high electrical resistivity ($\rho \approx 1.7$ μΩm), its adequate thermal conductivity ($k \approx 7$ W/mK) and its weak paramagnetic behaviour ($\mu_r \approx 1.0002$). The support shaft is 300 mm long with a diameter of 33 mm and has a hole of 15 mm diameter carved inside it in order to minimize the quantity of Ti_6Al_4V. The front end of the shaft is equipped with ball bearings and rollers to insert and rotate the device inside the anti-cryostat of the magnet. The six b_3 rings are placed at a distance of 19.17 mm from each other in order to cover the average wavelength of the cable twist pitch (115 mm) in the superconducting magnets. The two b_5 rings are spaced by half a pattern wavelength (57.5 mm). This spacing is purposely intended to compensate for the periodic field pattern inherent in the superconducting magnets by taking the average value of the six b_3 rings and the average value of the two b_5 rings to compute the harmonics. Apart from the ring supports, the support shaft has two flat surfaces: one for the electrical connection card and one for the inclinometer.

The inclinometer built by Spectron® (New York) provides an absolute reference for the angular position of the shaft with respect to gravity. It is hermetically sealed with a resolution of 30 arc seconds, a sensitivity of 0.1V/degree a linearity half scale of 0.3° and a nominal range of ± 60°. The sensor has a signal conditioner provided by Spectron®.

The Hall plates are mounted into grooves at a radius *r* of 14.9 ± 0.02 mm on the rings at an angular spacing of 120° and 72° for the sextupole and the decapole respectively. They are provided by AREPOC® (Bratislava) and are of the unpackaged type made of InSb with a size of 3.3×6×0.8 mm. The Hall plates have a typical sensitivity of 220 mV/T at an excitation current of 50 mA. The Hall plates are connected in series and are supplied with a common current source having a maximum drift of 100 nA. The Hall plate wires have a diameter of 0.1 mm and are soldered to the electronic connection card.

The aluminium connector shaft is fixed to the support shaft and houses the 64-pin cable connector. It too is equipped with ball bearings and rollers to make the installation of the probe in the anti-cryostat easier. Four extension shafts of 1 m each are added to the connector shaft so as to extend the probe into the superconducting magnet and allow it to measure the field harmonics in the straight part of the magnet. An angular encoder with a manually adjustable coarse and fine tuning is attached to the end of the extension shafts to allow angular positioning during installation. A shielded twisted pair cable is passed through the hollow interior of the extension shafts to connect the 64-pin connector to the analogue and digital compensation systems.

A complete characterisation of the Hall Probe is necessary in order to quantify all the uncertainty sources and to help the implementation of strategies to minimize them. Knowledge of all these individual uncertainty sources gives an estimate of the uncertainty of the final measurement. The sources of these uncertainties are:

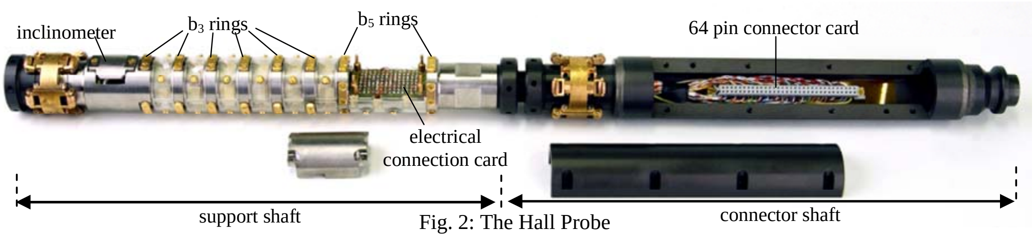

Fig. 2: The Hall Probe

a. geometrical uncertainties inherent in the Hall probe due to manufacturing tolerances assuming that the geometric axis of the instrument coincides with that of the superconducting magnet to be measured.

b. noise inherent in the probe due to electromagnetic interference and thermocouple effects

c. errors due to drifts and noise inherent in the electronics

d. variations in the supply current, errors in the Hall plate sensitivity determination and the Hall generator offset.

Tab. 1: The tolerances to remain within
a total accuracy of 3% for b_3 and 10% for b_5.

Error Parameter	**Error**	**b_3 tolerance**	**b_5 tolerance**
$\delta\alpha$	pitch angle error	0.108 rad	0.229 rad
$\delta\beta$	roll angle error	0.108 rad	0.229 rad
δr	radius error	44 μm	98 μm
$\delta\theta$	Disp. in θ	0.027 rad	0.059 rad
δz_j	Hall plate disp. along magnet axis	72 μm	321 μm
$\delta(L_{pp}-L_{hp})$	difference between probe length and magnet cable twist pitch	0.373 mm	3.59 mm
δz_k	ring disp. along magnet axis	124 μm	717 μm
δI_{cs}	Drift in supply current	100 nA	100 nA
$\delta\gamma_j(B)$	error in Hall plate sensitivity determination	0.164 μV/T max deviation	0.108μV/T max deviation

An analytical formulation of the main uncertainty contributions can be found in [7]. So as to calculate the contribution of each individual uncertainty source to the final measurement uncertainty of the instrument, we assume that all uncertainty sources are mutually independent. Table 1 shows the tolerances for the case that the uncertainty is distributed equally. Notice that the geometrical tolerances are very tight but can be approached during manufacturing. Also, the uncertainty sources compensate for each other statistically in practice. In addition, as will be explained later, some geometrical uncertainty sources are compensated in the calibration procedures. This is performed when setting the front end gain in the case of the analogue compensation and when determining the transfer function in the case of the digital compensation procedure.

IV. ANALOGUE COMPENSATION SYSTEM

The accuracy required from the acquisition electronics is particularly high and can only be approached by using the analogue compensation system. The uncertainty sources in this case include the DAQ drift, the PGA offset, the error due to the settling time in the ADC and noise inherent in the electronics and cabling. The accuracy of each uncertainty source needs to be of 0.03 μV and 0.13 μV for b_3 and b_5 respectively on each channel.

Two analogue cards for the sextupole rings and another card for the decapole rings perform the summation of the data as explained in Section II. This compensation system hence amplifies the signal in proportion to the harmonic of interest to obtain better resolution. The cards consist of the following two stages:

a. *The buffer stage:* the Hall plates are connected to zero-drift chopper-stabilized instrumentation amplifiers to have a dedicated voltage reference regulating the offset voltage. The connection is implemented in differential mode hence erasing common mode noise coming from the Hall probe itself. The amplifiers have a maximum nonlinearity of 20 ppm, a maximum offset voltage of 10 μV and a gain of about 10 at this stage.

b. *The mixer stage:* the summation of the signals is performed at this stage (3 input signals for the sextupole rings and 5 input signals for the decapole rings) using the same zero-drift chopper-stabilized instrumentation amplifiers mentioned above. The non-inverted output signal is an analogue scaled sum of the inputs and has a gain of 10. The output of this stage is then connected to the data acquisition system.

Previous experience on similar compensation cards showed a critical short term output offset variation which represented one of the main uncertainty sources of the analogue compensation approach. Three countermeasures were implemented to minimize this drift:

a. The use of chopped amplifiers characterized by a very low offset, low offset drift (10nV/°C), small low-frequency noise and very high gain. Their trade off is however their limited bandwidth and the filtering required to remove the large ripple voltages generated by chopping. The final configuration therefore uses chopper stabilized amplifiers which combine the chopper amplifier with a conventional wideband amplifier that is kept in the signal path.

b. The use of resistors characterized by a high stability factor of 1 ppm/°C.

c. The use of a metallic enclosure over the circuits acting as a faraday cage to shield against electromagnetic perturbations. The enclosure is also kept at a constant temperature of 20°C by means of thermostatically controlled heaters supplied with a pulse width modulation current generator.

d. All the offset and gain settings as well as the measurement points are placed on the front end electronic rack for easy calibration.

The first order calibration of the compensation cards is carried out inside a reference resistive dipole magnet (Alstom - Belfort) which is continuously checked by a Nuclear Magnetic Resonance (NMR) teslameter (Metrolab® - Geneva) having an accuracy of 10^{-7} T. The voltages on the board test points are measured using a 7½ digits integrating Schlumberger multimeter with an estimated accuracy of ±1μV. The calibration is carried out in the following steps:

a. Hall plates offset correction: this is carried out by placing the probe into a high permeability chamber (mumetal; nickel alloy). In this way the effect of the earth's magnetic field is removed and only the intrinsic offset of the Hall plate is taken into account. The offset is removed at the buffer stage by varying the dedicated voltage reference.

b. Hall plates sensitivity and angular misalignment correction: The probe is inserted into the resistive reference magnet and a field of 0.537 T (which corresponds to the

LHC magnetic field at injection conditions) is applied. It is oriented at 0° with respect to gravity by using the tilt sensor and the gain of the buffer stage is adjusted to have the expected output voltage according to the field applied. Of course the output voltage of each plate depends on the position of the Hall plate on the ring. By keeping the instrument at 0°, the whole assembly is calibrated and errors due to angular misalignment are also compensated for.

c. Dipole component compensation: Since the dipole field should be totally compensated, once the buffer stage is totally calibrated the mixer offset is adjusted to zero by keeping the probe oriented at an angle of 0° in the reference dipole field of 0.537 T. (Note that the gain at the mixer stage is kept fixed to a value of 10 for all mixer amplifiers).

Even after performing this calibration sequence, residual offsets between rings can still be detected. These are mostly due to the imperfections in the reference dipole and can be corrected by a simple but effective calibration procedure which is implemented directly in the LHC dipole during each measurement. A special calibration cycle is performed consisting of an LHC cycle with a current injection plateau of 6000s so as to ensure that the drift due to the decay is negligible. The hall probe is then shifted by 115mm/6 = 19.17 mm six times, parallel to the magnet axis with data being acquired at each step. The probe is aligned with respect to gravity each time using the inclinometer. The average value of all the six shifts for each ring is computed and the difference between each ring average and the first ring is hence obtained. In this way, the readings of each ring can be compared with respect to the reading of all other rings and hence the relative offset can be adjusted off-line for each measurement. The error in the shift as well as the error due to angle misalignment are ignored.

V. DIGITAL COMPENSATION AND DAQ SYSTEM

Even though it is kept to a minimum, the main limitation of the analogue compensation system is the drift in the output signal particularly that due to the offset and gain setting components. Another limitation is that the calibration of the cards only permits a first order nonlinearity compensation of the Hall plates.

These limitations can be solved by employing a digital compensation approach. The idea is to acquire the voltages directly from the Hall plates using a high resolution ADC. The transfer function of each Hall plate is then applied in real time to compensate for the Hall plate non-linearity error. This subtle yet crucial difference in the design allows a second order non-linearity compensation of the Hall plates. Of course, this approach places exceedingly high demands on the data acquisition, demands that go beyond the guaranteed resolution and stability specifications of the manufacturer. However, these demands can be met rather well by employing several techniques highlighted below.

The hardware used for the data acquisition system consists of a PXI RT platform equipped with 3 data acquisition NI6289 cards based on an SAR 18-bit ADC with 32 single ended multiplexed input channels (or 16 differential multiplexed input channels). In multiplexed mode, the maximum sampling frequency possible is 500kS/s which corresponds to 15kS/s on each channel assuring an over-sampling factor of 1500 when the signal bandwidth is 10Hz. Since the signals that need to be acquired are at a low frequency, the inter-channel delay can be considered to be negligible. The input gain is set to a ± 200 mV input range which according to the supplier's specifications corresponds to a sensitivity of 3.6 μV, a random noise of 9 μV rms and an absolute accuracy of 43 μV. A calibration guaranteed for two years contributes to the system stability. Note that with the required resolution of 2 ppm to resolve b_5, the resolution to be reached by the DAQ should be of 0.2μV. This is an order of magnitude less than the guaranteed sensitivity and random noise of the system.

Tests on the overall performance of the instrument without filtering show a random noise on the channels of around 300 μV rms. This noise is reduced to 12 μV rms as follows: by using shielded twisted pair cabling connected to differential input channels; by implementing shielded terminal blocks; by employing adequate grounding techniques; by installing two power supply filters and introducing a single pole 250Hz cut-off low pass filter. In

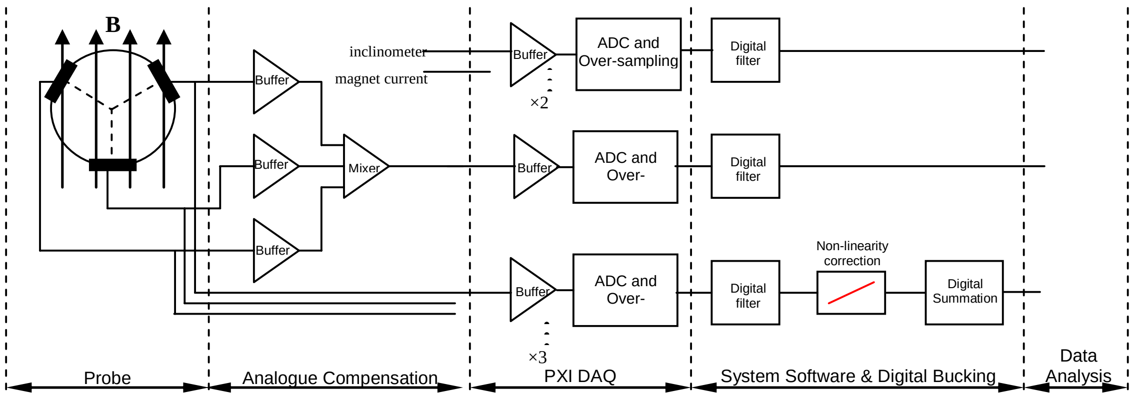

Fig. 3: The Hall plate measuring system. The above diagram is applied to every sextupole ring. The decapole rings are similar but with 5 Hall plates. There is only one inclinometer signal, one magnet current signal, one Hall current signal and one Hall voltage signal for the whole measuring system. Notice that the digital main field cancellation and harmonic isolation option is also included in this schematic.

addition to these precautions, the tilt sensor is switched off every time a measurement is performed since it is supplied with a pulse width modulated signal which introduces noise along the cable. Hence, practically all the noise of the system is reduced to the noise inherent in the DAQ. The design resolution and stability of the DAQ are improved by employing several techniques which are the result of an in-depth system characterization:

a. Over-sampling and decimating: this is a well known technique largely used in sigma delta modulators. After over-sampling, an average of the 1500 over-sampled points is taken to establish the frequency resolution of 10Hz. From an implementation point of view, this is equivalent to performing a moving average. This type of filter is known to be a very poor low pass filter in the frequency domain but the best smoothing filter in the time domain which is our domain of interest.

b. Using redundant channels: as expected, during the characterization procedure, a short term drift of about 3 μV peak-to-peak is seen on the DAQ channels even when they are short circuited. For b_3, such a drift would be equivalent to 9 μV (90 ppm) and 15 μV (150 ppm) for b_5. This drift is the same for all channels of one card but differs between the cards. It can hence be deduced that this drift is inherent to the programmable gain amplifier (PGA). By simply short circuiting one of the channels to ground, removing its inherent ADC offset, smoothing it with a moving average window of 10 samples and subtracting it from the other channels, this drift is practically eliminated.

c. Using a continuous transfer function for the Hall plates calibration: The calibration procedure of the digital system is performed using the dipole Alstom HB436/MCB22 in the same arrangement described in section IV. A 40 point transfer function is obtained for each Hall plate at each polarity to obtain the transfer function over the range of operation of the instrument (0.3 T to 0.8 T). The initial implementation of using a linear interpolation between calibration points of the Hall plates transfer function introduced an equivalent drift of about 10 μv every time there was a crossing between one interpolation line and the other. By using a continuous polynomial interpolation of all the calibration points, this sporadic drift is eliminated.

d. Settling error: During the characterization procedure, a catastrophic inter-channel interference of about 2000 ppm of the signal step size can be detected on the neighboring channels. Inter-channel cross-talk was immediately dismissed since: the voltage signals have a very low frequency; twisted pair cables were used; the effect is limited to the downstream channel in the acquisition card. This effect was hence considered to be due to the settling time of the ADC. The settling time limits the acquisition frequency and the settling error measured in ppm of step size is a function of the source impedance. Since the Hall plates have a very low resistance (a few ohms) the large settling error was primarily due to the large impedance of the single pole low pass filter. Two measures were taken to reduce this effect:

i. By choosing a low resistance at each input (around 68 Ω) and a high capacitance (around 4.7 μF) for the low pass filter, the source impedance is reduced to yield a settling error of only 30 ppm of the signal step size but still keeping the same cut-off frequency.

ii. By grouping the channels with voltage signals of the same magnitude and placing them one after the other, large step size differences between channels can be reduced to a minimum. For example, a group consists of all the top Hall plates. The different groups can also be isolated by using redundant channels between them and shorting these channels to the first signal channel of the group. In this way all the groups are shielded from each other reducing further the risk of suffering from inter-channel interference.

e. Offset minimization: since the absolute accuracy of the system is of 43 μV, a sporadic offset of the ADC in the order of 20 μV can be measured when the DAQ is restarted. This offset is compensated for after the measurement by measuring a short circuit to ground and subtracting it from each channel during the analysis procedure.

Note that having an absolute accuracy of 46 μV represents a decisive limitation in obtaining an absolute measurement using the instrument. The instrument is hence cross-calibrated during each measurement with the rotating coils to obtain an absolute measurement.

VI. DATA ANALYSIS PROCEDURE

The existence of residual errors in the Hall probe sensor read-out can be observed when comparing the hysteresis curves obtained from the Hall probe sensor to the ones obtained using the rotating coils. These signals include all the errors not corrected so far. In the case of the analogue compensation these errors include:

a. Non-linear sensitivity of the Hall plates (since the calibration is limited to a first order correction)

b. Hall plates and amplifier voltage offsets dependent on temperature

c. b_3 components inherently present as errors in the field of the reference magnet dipole.

In the case of the digital compensation these errors include:

a. Errors in the determination of the Hall plate transfer functions

b. The variation of the ADC offset in time.

All these residual errors result in an insufficient compensation of the main dipole field and limit the possibility of measuring the absolute value of the harmonics of interest. A cross calibration with the rotating coils is therefore necessary to compensate for these errors. As described in [8] the Hall plate data is reduced to fit the rotating coil hysteresis curve using a second order conversion formula. The snapback curve is then isolated from the hysteresis curve by subtracting the interpolated rotating coils data from the Hall probe data.

VII. RESULTS

Fig. 4 shows the measurement results for b_3 and b_5 respectively. As expected, the analogue compensation system performs very well in terms of resolution but is relatively weak in stability. Conversely, the digital compensation system has a larger random error but is very stable over the whole measurement. In the case of the analogue compensation the random noise is reduced to 0.09 μV (0.9 ppm) for b_3 and 0.24 μV (2.4 ppm) for b_5. However, the drift over the whole cycle is of 430 ppm for b_3 and 200 ppm for b_5 and is prohibitive when cross-calibrating with the rotating coils. Such a large drift is probably due to the gain setting components which are inherently mechanical and hence have a weaker performance when compared to the rest of the electronics. By using noise and drift reduction techniques in the digital compensation system, the random noise is reduced to 0.22 μV (2.2 ppm) for b_3 and 0.76 μV (7.6 ppm) for b_5. The drift over the whole cycle of 6000s was reduced to 12 ppm for b_3 and 20 ppm for b_5. Such a drift at this resolution is acceptable particularly since the cross calibration is done over 1300 s. After comparing these two systems and testing their performance, it is apparent that the digital compensation system is much more promising. The digital compensation system will therefore be used for series measurements and the analogue cards will be kept as prototypes for further research and development. The measurements will consequently be used to model the snapback phenomenon and establish the correlation between the decay amplitude and the snapback current constant as described in [9].

VIII. CONCLUSION

A robust instrument has been developed to measure the hysteresis behaviour at 10Hz so as to model the snapback phenomena in superconducting magnets. The resolution achieved was very close to the ambitious target of 2 ppm and the targeted stability over the snapback interval was also reached. A metrological characterisation was performed and a calibration procedure was implemented in order to compensate for the largest errors inherent in the system. The innovative digital compensation approach was proven to work better than the analogue approach and was chosen as the platform on which to perform series measurements.

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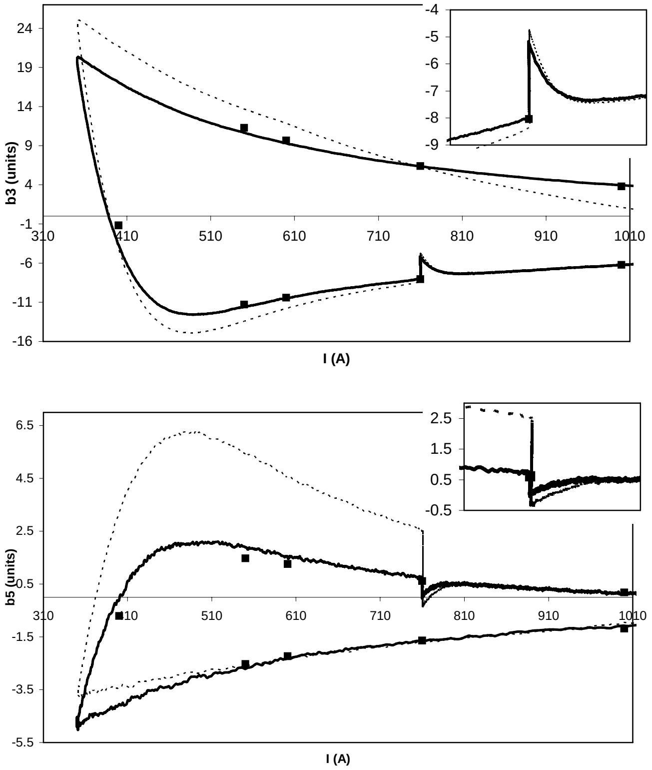

Fig. 4: The b_3 (top) and the b_5 (bottom) hysteresis curve measured with the Hall plate based instrument using analogue compensation (dotted line) and digital compensation (continuous line). The large points show the measurements achieved with the rotating coils. Top right of each graph depicts a close-up of the snapback phenomenon.

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