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DEVELOPMENT OF A NOVEL DC CURRENT MONITOR DEVICE, BASED ON TUNNELLING MAGNETORESISTIVE SENSORS, FOR ION BEAM CURRENT MEASUREMENT

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Abstract

In this work, the development of a non-invasive DC Current Monitor device (DCCM), based on Tunnelling MagnetoResistive (TMR) sensors, is presented. The device is primarily intended for measuring the current intensity of an ion beam without the need of intercepting it (therefore not altering its characteristics), making it suitable for online current monitoring. Details are given about the design of the device and its performance assessment, namely the linearity of its static response and its frequency-domain behavior.

INTRODUCTION

The first concept of a non-invasive device for measuring ion beam currents appeared in 1969 thanks to the work of Unser at CERN [1]. The device, known in the literature as DC Current Transformer (DCCT), was based on the use of a pair of "twin" ferromagnetic cores driven by a modulating current $I_{modulation}$ at a given frequency f which, without ion beam, would induce, inside the cores, magnetic fluxes of equal amplitudes but opposite phases, thanks to a proper connection of the two coils (see Fig. 1).

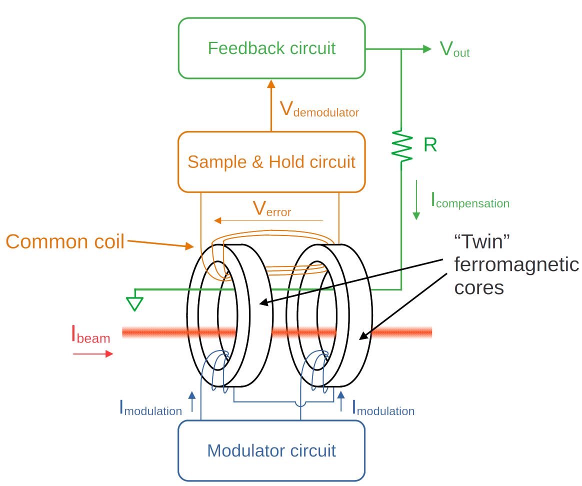

Figure 1: Classical DCCT scheme.

In the presence of an ion beam current passing through the cores, a small asymmetry in the magnetic fluxes arises, generating a V_{error} signal on the common coil, having a dominant frequency component equal to $2f$. This signal is then used to derive a DC voltage signal $V_{demodulator}$ by means, e.g., of a synchronized Sample & Hold circuit, referred in [1] as "demodulator". $V_{demodulator}$ is then used, by means of a feedback circuit, to produce a DC current $I_{compensation}$ which, passing through the cores in opposite direction to the ion beam, cancels out the asymmetry in the fluxes introduced by the ion beam current, bringing V_{error} to zero and thus creating a zero-flux condition. The amplitude of V_{out} is $V_{out} = R \cdot I_{compensation}$ and it is then used as an indirect measure of the ion beam current. The design of such a device is ingenious but quite complicated, since it requires the use of different modules (modulator, magnetic flux detector coil, demodulator, feedback circuit) and, mostly critical, the use of perfectly matched "twin" ferromagnetic cores (see also [2, 3]).

Recently, a new class of magnetic sensing devices, based on the Tunnelling MagnetoResistive (TMR) effect, have been introduced in the market and extensively studied in [4–8]; these sensors have a sensitivity in the order of mV/Gs and a noise figure in the order of 250 pT/$\sqrt{\text{Hz}}$ [9]. These sensors, in addition, have a low magnetic saturation level, in the order of few Gauss, and, hence, are well-suited for all those applications where the magnetic field to be measured is very close to zero.

The aim of the work here presented is to explore the use of such sensors for a non-invasive ion beam DC Current Monitor (DCCM) based on zero-flux detection, in view of the characteristics previously discussed. In the following section of this article, the design of a DCCM based on TMR sensors is presented; the main drawbacks related to the use of TMR technology are also discussed. The results of a linearity test and of a frequency-domain characterization on a prototype are included in the last section.

DESIGN OF THE DCCM SYSTEM

Working Principle

The block diagram of the DCCM device here described is shown in Fig. 2.

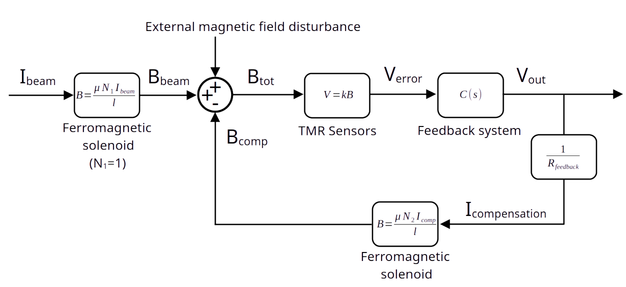

Figure 2: DCCM block diagram.

The current to be measured (referred in the block as I_{beam}) induces a magnetic field B_{beam} inside a ferromagnetic core

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when it goes through it. This magnetic field is detected by the TMR sensor, the output of which, V_{error}, is sent to a feedback system. A compensating current is then generated by means of a resistor $R_{feedback}$ by the feedback system and sent through the core in the opposite direction to that of the ion beam in order that the magnetic fields induced by the two currents inside the core cancel each other: as long as this condition is met, the compensating current would equate the ion beam current and thus it is an indirect measurement of the latter. Any deviation from this equilibrium condition would be detected by the TMR sensor, the output of which is thus an error signal for the feedback system. The feedback scheme allows for a linear response of the device over its entire measurement range. The TMR sensor measures the magnetic field in just one point in the core, therefore making it very sensitive to the position of the ion beam with respect to the ferromagnetic core.

Rejection To External Magnetic Fields

The device previously described would perform well in ideally shielded environment where no external magnetic field is present: actually, many disturbs degenerate the performance of any real device. In this case, an external magnetic field would be detected by the TMR sensor and erroneously regarded as generated by the current to be measured. In fact, the total magnetic field to be compensated by the feedback circuit is $B_{beam} + B_{external}$. To mitigate this problem, the use of two TMR sensors is mandatory. With reference to Fig. 3, two diametrically-opposed TMR sensors would sense both the external magnetic field and the one generated by the ion beam but, if for one sensor the two magnetic field components add up, for the other sensor they subtract: $B_{TMR1} = B_{beam}+B_{external}$ and $B_{TMR2} = B_{beam}-B_{external}$. To obtain a rejection of the external magnetic field, it is sufficient to take as error signal the sum between the signals from the two sensors, so that the signal components related to the "ion beam" magnetic field add and those related to the external magnetic field subtract. To this purpose, however, it is important that the two TMR sensors are selected to be matched in sensitivity.

Feedback System

The feedback system shown in Fig. 2 acquires the voltage error signals provided by the TMR sensors and outputs a compensating current, as previously described. Its main component is an integrator circuit (Fig. 4) which accumulates the error and stops integrating when the error is zero, thus providing a DC voltage at its output; this voltage is applied at a ground-terminated resistance and producing the compensating DC current so that: $V_{out} = R_{feedback} \cdot I_{compensation}$.

As can be clearly seen, the integrator output voltage is proportional to the compensating current and therefore it is used as the indirect measurement of the ion beam current (after performing some sort of calibration). The TMR sensors output voltage is on the level of the mV and their

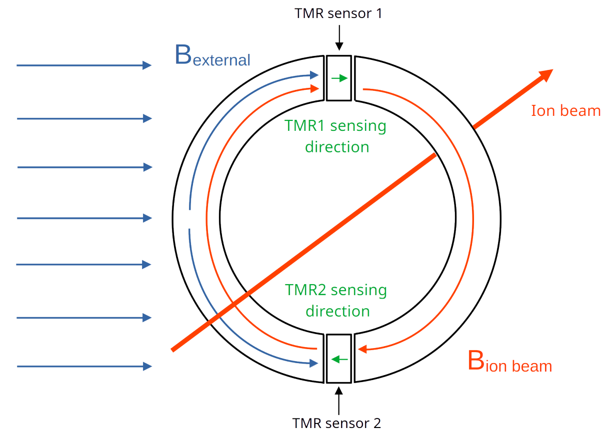

Figure 3: Configuration with two TMR sensors.

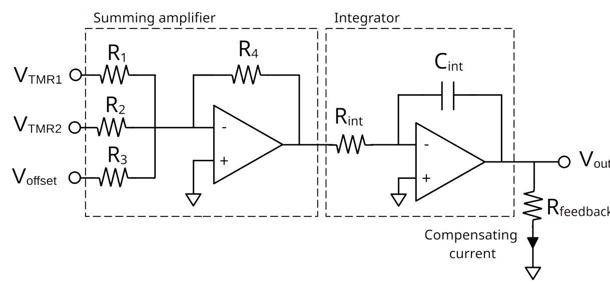

Figure 4: Integrator circuit scheme.

output offset voltage in the same order of magnitude. Therefore, a summing chopper-stabilized amplifier with proper offset correction should be used in order to minimize all the errors related to the offset. This architecture allows to measure both positive and negative current and its measurement range depends on the output current characteristics of the integrator.

Main Drawbacks

There are two main drawbacks related to the use of TMR technology sensors:

- the magnetic field is measured point-wise as opposed to the classical DCCT, where the magnetic field is sensed along the whole perimeter of the core, thus performing a sort of distributed measure;
- the measured value of the current depends on the position of the ion beam inside the core, since the magnetic field intensity depends on the radial distance from the source that generated it and, as previously remarked, in the DCCM the magnetic field is sensed point-wise.

These disadvantages make the benefits offered by the use of these sensors unworthy, considering that other architectures used for the same purpose are able to perform fine.

PERFORMANCE TESTS

The DCCM device has been built and a test bench has been arranged to evaluate its performance.

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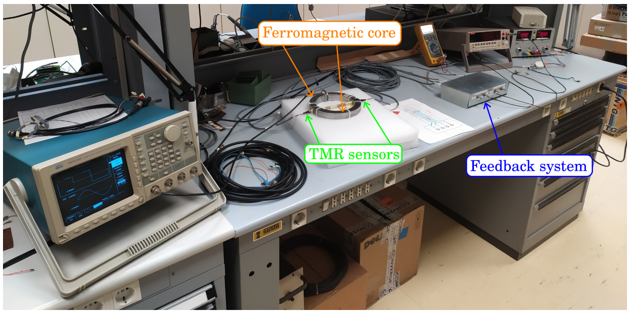

Figure 5: Setup for testing DCCM performances.

In Fig. 5, the ferromagnetic core can be seen together with the two TMR sensors positioned as per Fig. 3 and connected to the feedback system. A linearity test and a frequency-domain characterization have been carried out. Their details are given in the following.

Linearity Test

The setup for the linearity test is schematized in Fig. 6. A DC voltage generator supplies a reference DC current which flows on an electric wire passing through the DCCM. The reference current, given by $I_{ref} = \frac{V_{dc}}{100\Omega}$, is measured by an ammeter in order to have an accurate value, while the voltage output of the feedback system (V_{out}) is measured by a voltmeter. Figure 7 shows a plot of the voltage output with respect to the reference current, showing good linearity. Before acquiring the values of the voltage, a hardware offset correction has been performed in order to obtain a curve passing through the zero. This implementation of the DCCM is capable of measuring currents up to ±50 mA.

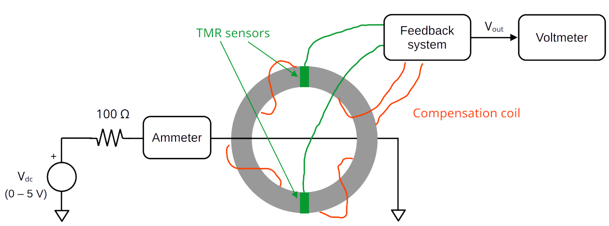

Figure 6: Linearity test setup.

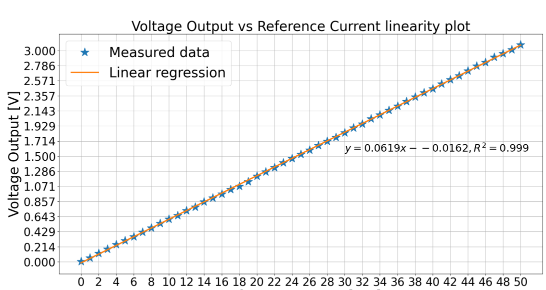

Figure 7: Linearity plot.

Frequency-Domain Characterization

The frequency response has been obtained using the setup schematized in Fig. 8.

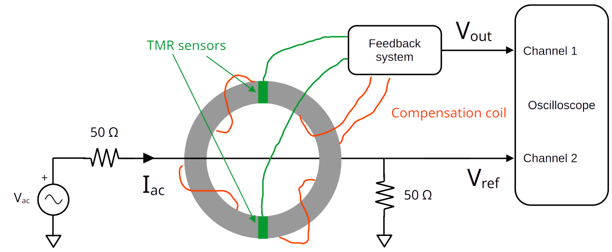

Figure 8: Frequency-domain test setup.

An AC voltage generator supplies a reference AC current which flows on an electric wire passing through the DCCM. The reference current, given now by $I_{ref} = \frac{V_{ref}}{50\Omega}$, and the voltage output of the DCCM have been acquired by means of an oscilloscope.

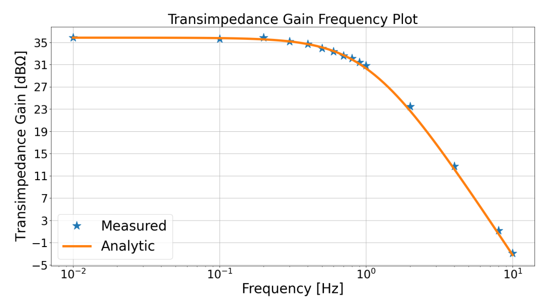

Figure 9: Frequency-domain amplitude plot.

Using these data, a frequency-domain model has been obtained with the following transfer function:

$$G(s) = \frac{V_{out}}{I_{ref}} = \frac{61.9\Omega}{(1 + 0.15s)^2}. \quad (1)$$

Figure 9 shows the comparison between the analytical model (Eq. (1)) transimpedance gain plot and the measured one. The bandwidth of the device is, therefore, approximatively 1 Hz. This result is in accordance with the specifications chosen during the design phase, since the DCCM is required to measure DC currents. Furthermore, the bandwidth was limited as much as possible to minimize the noise.

CONCLUSIONS

A device (DCCM), based on Tunnelling MagnetoResistance sensors, has been realized in order to measure DC currents and to be immune from external magnetic fields. A zero-flux feedback system has been implemented to provide a linear response of the device over its entire measurement range. A frequency-domain characterization has been performed and an analytical model of the DCCM has been obtained. The present architecture of the DCCM (using only two measuring points on the entire perimeter of the core) allows for an accurate current measurement provided that the ion beam passes at the center of the device.

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REFERENCES

[1] K. Unser, "Beam Current Transformer with D. C. to 200 MHz Range", *IEEE Trans. Nucl. Sci.*, vol. 16, no. 3, pp. 934–938, Jun. 1969. doi:10.1109/tns.1969.4325406

[2] P. Odier, "DCCT technology review", in *Proc. 2nd CARE-HHH-ABI networking meeting*, Lyon, France, Dec. 2004. doi:10.13140/2.1.4385.9846

[3] M. C. Bastos *et al.*, "High accuracy current measurement in the main power converters of the large hadron collider: tutorial 53", *IEEE Instrum. Meas. Mag.*, vol. 17, no. 1, pp. 66-73, Feb. 2014. doi:10.1109/MIM.2014.6783001

[4] E. Azab, Y. G. Hegazy, H. Reeg, M. Schwickert, and K. Hofmann, "Tunneling Magnetoresistance DC Current Transformer for Ion Beam Diagnostics", *ACS Sens.*, vol. 21, no. 9, p. 3043, Apr. 2021. doi:10.3390/s21093043

[5] E. Soliman, K. Hofmann, H. Reeg, and M. Schwickert, "Sensor Studies for DC Current Transformer Application", in *Proc. IBIC'14*, Monterey, CA, USA, Sep. 2014, paper WEPF31, pp. 624–628.

[6] E. Soliman, K. Hofmann, H. Reeg, and M. Schwickert, "Noise study of open-loop direct current-current transformer using magneto-resistance sensors", in *IEEE SAS'16*, Catania, Italy, Apr. 2016, pp. 1-5. doi:10.1109/sas.2016.7479631

[7] Y. Zhao, Y. Du, L. Wang, and J. Cao, "Development of new beam current transformer based on TMR", *Radiat. Detect. Technol. Methods*, vol. 3, no. 3, Jun. 2019. doi:10.1007/s41605-019-0131-1

[8] Crocus Technology, "Non-intrusive current-sensing using TMR: a comparison between TMR sensors, sense resistors, Hall-effect sensors and current transformers", 2019 https://www.mouser.com/pdfDocs/AN118-Non-intrusive-Current-Sensing-Using-CT100-TMR-Linear-Sensor-Rev00.pdf

[9] MultiDimension Technology Co. Ltd., "TMR9082 datasheet", https://www.alldatasheet.com/datasheet-pdf/pdf/1705381/MULTIDIMENSION/TMR9082.html