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**Metrological Performance of a Ferrimagnetic Resonance Marker
for the Field Control of the CERN Proton Synchrotron**

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Abstract

In particle accelerators, “field markers” provide a digital trigger when the magnetic field crosses a given threshold. In this paper, the metrological characterization of a magnetic field marker, based on a ferrimagnetic resonance transducer referencing the flux sensed by a coil, is reported. The experimental results of a validation test campaign at the European Organization for Nuclear Research (CERN) to test the marker in static as well as fast ramping fields (up to 2.5 T/s) are illustrated. The repeatability of $\pm 4 \mu\text{T}$ attained in the range (60 to 100) mT is very promising to increase the performance of the Proton Synchrotron accelerator at CERN.

This work has been carried out at CERN in the framework of a scientific collaboration with the University of Sannio

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Abstract — In particle accelerators, “field markers” provide a digital trigger when the magnetic field crosses a given threshold. In this paper, the metrological characterization of a magnetic field marker, based on a ferrimagnetic resonance transducer referencing the flux sensed by a coil, is reported. The experimental results of a validation test campaign at the European Organization for Nuclear Research (CERN) to test the marker in static as well as fast ramping fields (up to 2.5 T/s) are illustrated. The repeatability of $\pm 4 \mu\text{T}$ attained in the range (60 to 100) mT is very promising to increase the performance of the Proton Synchrotron accelerator at CERN.

Index Terms—Combined-function accelerator magnets, real-time magnetic field measurement, B-train, ferrimagnetic resonance, dynamic field marker.

I. INTRODUCTION

IN particle accelerators, real-time measurement of the magnetic field used to bend and focus the particle beams is often relevant for operation. Several systems, such as power supplies, RF cavities, and beam monitoring systems, use the field information as the input of feedback loops. The measurement system is sometimes referred to as a “B-train”, from the fact that the field value is broadcast as a train of incremental digital pulses. In other cases, such as the slowly cycled superconducting magnets of the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), models describing the dynamic response of the magnet based on magnetic measurements are accurate enough, because the effects due to eddy currents and iron hysteresis are not influent [1].

Real-time measurements are usually carried out in a reference magnet powered in series with the accelerator magnets. A rotating coil fluxmeter could be in principle a valid choice for these measurements, especially because it provides an absolute value of the field [2]. However, even state-of-the-art rotating coil systems are limited to few Hz bandwidth, which is typically three orders of magnitude lower than what required for accelerator magnets. It is therefore natural to use a static coil fluxmeter, providing a

voltage output proportional to the field rate dB/dt , with sensitivity increasing with the bandwidth. However, an additional measurement is needed to provide the integration constant. This is commonly carried out by a “field marker”, i.e. a device able to provide a digital trigger pulse as the field crosses a given threshold [3].

In the framework of the long-term consolidation and future upgrades of the CERN injector chain, the options to improve the performance and reliability of field markers are currently investigated. The most demanding in terms of precision, long-term stability, and reliability is the system of the Proton Synchrotron (PS). Different field measurement transducers can be adopted as field markers [4]. In combined function units such as the main magnets of the PS, where a large focusing gradient is superposed to the dipole component, peaking strips have been used. A peaking strip is essentially a magnetically bi-stable wire of a high permeability material, such as permalloy, immersed in a bias field. It is able to generate a large flux change when the external field becomes equal and opposite to the bias, causing the magnetization to flip. A mechanical pre-stress is beneficial to create an almost rectangular B-H cycle [4]. The small diameter of the wire makes negligible the errors due to the field gradient. The main limitation of this transducer is the heat dissipation in the biasing coil, making it unsuitable for operation above a few mT.

Commercial solutions based on Hall-effect field sensors have also been used as field markers [5]-[6]. Even if state-of-the-art transducers can have very high metrological performance, the need for sophisticated calibration and temperature drift compensation limits their use in a feedback system that must guarantee reliability and stability over a time span of decades.

Field sensors based on Nuclear Magnetic Resonance (NMR) are currently the “golden” metrological standard, providing the best absolute accuracy in a wide field range [8]. However, NMR sensors require a homogeneous magnetic field across the probe volume in order to obtain a response from all nuclei at the same frequency, excluding in principle their application in the PS. This drawback could be overcome in principle by special arrangements of compensation coils or ferromagnetic plates homogenizing the field, but these options are impractical [9]. Moreover, in dynamic conditions, the NMR is limited by maximum relative ramp rates of about 0.05 T/s, two orders of magnitude lower than the desired target.

A sensor, based on commercially available filters using the FerriMagnetic Resonance (FMR) effect, has been

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already experimented at CERN as an auxiliary field marker during the last decade [10], [12]. FMR is based on a slight imbalance of the energy emitted and absorbed by electrons flipping between opposite spin states under the influence of incident electromagnetic radiation in crystals with anisotropic characteristics. It has found widespread applications in microwave equipment such as tuneable oscillators and electronically tuneable filters [11]. Preliminary tests have shown the feasibility and the reliability to use a commercial filter as field sensor [12] in static magnetic field conditions. New requests arising from machine operation, along with the availability of improved commercial units, have recently provided the motivation for further investigations [12].

In this paper, the experimental characterization of the field marker based on the FMR is presented. In particular, first the requirements of the real-time system for PS at CERN are described. Then, the design of a transducer, based on a single-crystal FMR sensor, is illustrated. In the last part, the experimental results of the metrological characterization, including the analysis of temperature and field ramp rate, are reported.

II. REAL-TIME SYSTEM REQUIREMENTS

At CERN, the PS is used to accelerate proton and ion beams up to 26 GeV in the injection chain of the LHC. During operation, it exploits a B-train for real-time measurements of the main magnetic field [9]. The PS includes 100 combined function magnets providing a maximum field of 1.2 T and a gradient of 4.8 T/m, ramping up to 2.3 T/s.

The PS B-train is based on three redundant sets of peaking strips and fixed coils. The system carries out the time integration of the coil voltage V_c proportional to the rate of change dB/dt , to measure the field averaged over the coil equivalent surface A_c :

$$B(t) = B_m(t_i) + \frac{1}{A_c} \int_{t_i}^t V_c dt \quad (1)$$

where B_m is the marked value of 4.98 mT given by the peaking strip at $t=t_i$ well below the injection plateau. Each digital pulse in the train represents a change of 10 μ T for $B(t)$, with two parallel channels for broadcasting increments and decrements.

Current and future beam quality requirements for the LHC, especially in terms of limiting the emittance upstream in the injector chain, have a direct impact on the performance of the marker. The challenge for the system currently under development is to achieve a linearity of 50 μ T and resolution of 5 μ T on the measured value of the field, while maintaining the very high long-term reliability shown by the current peaking strips.

In a synchrotron, the absolute accuracy is relatively unimportant in order to control the integrated dipole field, because all the magnets are powered in series and average closed-orbit errors of few 10^{-3} can be trimmed easily. The most critical issue is the long-term stability of the field measurements, which in the PS must be of the order of 3×10^{-5} relative to the peak field of 1.2 T for a reliable machine operation.

A recent campaign of measurements has shown that the accuracy of the field measurement, $B_m(t_i)$, can be poor. This is due to a combination of effects, mainly including hysteresis (as a function of the excitation history) and

temperature, leading in some cases to unacceptable radial oscillations of the beam. Magnetic stability would be greatly enhanced by increasing the current flat-bottom level of around 0 T to 60 T, value lower than the injection field variable according to all the machine conditions. The available peaking strips are in practice limited to 5 mT, thus a new marker such as the FMR is the only viable option.

III. THE FMR FIELD MARKER

In this Section, the (i) *filter* and the (ii) *transducer* circuit of the field marker based on the FMR are detailed.

A. FMR filter

Ferrimagnetic resonance occurs in certain ferrites, which are electrical insulators and thus well suited to high-frequency operation. Unlike NMR, electron resonance phenomena are affected by a number of environmental and chemical factors, including the temperature. The material used as sensor for the FMR field marker is the Yttrium Iron Garnet (YIG), with a nominal gyromagnetic ratio of 28.026 GHz/T. The selected unit, manufactured and customized to our specifications by OmniYig[®] Inc., Santa Clara, CA, is made by two semi-circular RF loops, coupled via a 0.3 mm single-crystal YIG sphere. Resonance conditions correspond to the maximum of the energy transmission between the two loops.

The quality of the field measurement strongly depends on the Q-factor of the YIG filter. It improves when losses are low, i.e. the coupling is weak [10]. Single-crystal YIG filters can reach high Q values close to 10^4 , although their response to external field depends on the temperature and on their alignment in the resonator, owing to the anisotropy of the crystal [13]. The YIG filter of OmniYig[®] reaches a Q of about 1000. Polycrystalline spheres, such as used so far at CERN, have better stability in the temperature range of 25 to 55 °C, although with a Q lower by about one order of magnitude. The temperature excursion in PS application is relatively low, about $\pm 2^\circ\text{C}$, thus a properly aligned single crystal sphere is deemed as the best candidate solution. The orientation of the sphere was optimized by the manufacturer in order to achieve the best stability in the desired field range.

The ferrite must be magnetized beyond saturation to guarantee both a high Q-value [12-14] and minimal hysteresis effects in the material itself. Typical values for the saturation magnetization of YIG are between 30 and 100 mT. These values also define the lower limit of the measurement range.

B. The FMR transducer

To work as a field marker, the YIG filter needs for a conditioning circuit to pass signals from RF to the frequency band of the standard electronics in the B-Train. A signal synthesizer sends an RF wave to the YIG filter through an RF coaxial cable at a given frequency. The 5-dB attenuators at the YIG ports are necessary to reduce the multiple wave reflections, due to impedance mismatch between the source output and YIG filter input, as well as between the filter output and the amplifier. The signal is amplified before the RF detector diode to provide a final output containing essentially its amplitude envelope.

Such as standard NMR equipment, the FMR transducer can operate in two basic modes:

a) *Marker mode*, i.e. the input frequency is fixed and the field changes, meaning that the response shows a resonance

peak when the field reaches the corresponding value. The peak is then processed to generate a digital trigger pulse.

b) *Teslameter mode*, i.e. the field is fixed while the input frequency is swept across a given range, generating a resonance curve. This mode might be of interest for future applications.

IV. CALIBRATION RESULTS

In the following, the calibration set up and the results of the static and dynamic tests are reported.

Fig. 1: Schematic layout of the calibration system.

A. The calibration set up

In Fig. 1, the set up for the metrological characterization of the FMR transducer is illustrated. The field reference is given by an NMR probe, working in a DC field only, supplemented by a fixed coil to provide the field change during ramps. These probes are stacked with the FMR under test as closely as possible in an epoxy-impregnated glass fiber support mounted in an H-type dipole magnet. This magnet has been chosen for its good field homogeneity in the central part and its low inductance in order to ramp the field up to 3 T/s. Systematic field differences between the positions of the probes have been evaluated first by NMR-mapping and by exchanging the respective locations during the tests.

The RF chain is computer-controlled to sweep the input signal in the range from 1 to 3 GHz, corresponding roughly to a field from 50 to 110 mT. The power converter of the magnet is controlled through a WorldFIP bus to generate arbitrarily complex excitation cycles. All the measurements have to be carried out on a stable hysteresis cycle of the magnet in order to compare the results obtained over several current cycles. The stabilization can be obtained simply by pre-cycling the magnet for at least five times.

B. Static tests

The calibration curve of the bare YIG filter (i.e. without RF chain) has been evaluated in a DC field with respect to NMR, by detecting the transmission coefficient peak with a network analyser [12] (Fig. 2). The calibration of the transducer as a whole (RF chain included) was repeated in the same conditions by sweeping the filter input with the RF synthesizer (Fig. 3). The effective gyromagnetic ratio evaluated from a linear regression is found to be 28.09 GHz/T, with a difference less than 2×10^{-4} with respect to the sensor-only configuration.

The difference with the nominal value for YIG amounts to about 0.2% and is attributed to the presence of material impurities in the YIG filter [15] and to the non perfect orthogonality of the two semi-circular RF antennae [16]. The linear regression has a systematic offset of 0.6 mT, consistent with the field inhomogeneity measured inside the dipole.

The non-linearity behaviour of the FMR as field transducer displays a characteristic parabolic behaviour (black line in Figs. 2a and 3a) with amplitude within $\pm 42 \mu\text{T}$. This non-linearity is below the specifications and acceptable. The most important result is the very low 2- σ uncertainty (Figs. 2,b and 3,b) of this calibration: less than $\pm 8 \mu\text{T}$ in the range of interest.

The most critical potential issue is the temperature dependence of the sensor. The calibration of the transducer was repeated by heating the sensor with hot air between 22 and 35 °C and by measuring its temperature with a thermocouple. In the range between 50 and 100 mT, the temperature stability has been found to be around $\pm 3.6 \mu\text{T}/^\circ\text{C}$, within the specifications.

The FMR transducer is therefore validated as a field marker for the PS B-train.

Fig. 2: Calibration results in static field without RF chain (sensor only): (a) difference between the measurement with the NMR and the bare YIG filter, with a parabolic fit (black line); (b) 2 σ uncertainty.

Fig. 3: Calibration results in static field with RF chain (full transducer): (a) difference between the measurement with the NMR and the FMR transducer (ΔB) with a parabolic fit (black line); (b) 2 σ uncertainty.

C. Dynamic tests

Dynamic behaviour was tested in a ramping field, by comparing the FMR resonance curve with the field value obtained by integrating the output of the flux coil,

previously calibrated using the NMR probe with an uncertainty less than ± 10 ppm.

Fig. 4: Dynamic test procedure: measurement of the reference field by the coil and NMR sensors (top) and simultaneous acquisition of the FMR output (bottom).

In Fig. 4, the dynamic test procedure is highlighted. At the flat bottom, the field is measured by the NMR; then, the field is increased, and the voltage induced on the coil and the RF diode output are acquired simultaneously. The field value measured by the coil when the diode output is minimum, $B(t_1)$, is compared with the field value corresponding to the frequency set at the YIG filter input. The dynamic results show that the uncertainty level is compatible with the static mode (Fig. 5).

Similar tests were performed on the standard commercial version of the filter made with an aluminium casing for noise reduction and thermal stability. A linear dependence with ramp rate of about 0.4-mT for 2.5 T/s was observed (Fig. 5). This effect is attributed to eddy currents with a time constant around 160 μ s, value confirmed analytically.

The measurements, previously quoted, of the new customized filter unit made with a plastic Noryl casing coated with 8 μ m of copper and silver, show indeed no measurable ramp rate dependence.

Fig. 5: Dynamic calibration results for the original aluminium case YIG filter at $B=94.89$ mT: experimental data (*) and simulated field error (continuous line), i.e. the lag due to eddy currents generated on the YIG filter aluminium case.

V. CONCLUSIONS

In this paper, the experimental results of the metrological characterization of a FMR transducer are analysed. This transducer is found to be fully adequate to be used as a high-precision field marker for the real-time field measurement

systems of the PS, as well as other injectors at CERN. In the near future, (i) its long term repeatability and reliability will be assessed on the PS reference magnet in parallel with the existing system, (ii) its thermal stability will be improved, and (iii) automated peak detection electronics will be developed.

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