DEVELOPMENT OF UPGRADED MAGNETIC INSTRUMENTATION FOR CERN REAL-TIME REFERENCE FIELD MEASUREMENT SYSTEMS

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Abstract

The control of five of the accelerators in the CERN injector chain (PS, PS Booster, SPS, LEIR and AD) is based upon real-time measurements in a reference magnet. These so-called "B-train" systems include a field marker to signal the achievement of a given field value, complemented by one or more pick-up coils to integrate flux changes. Recently, some concerns were raised about long-term reliability and performance improvements, in terms of both resolution and operational flexibility, for these systems. This paper reports the status of three related R&D activities, namely: the development of a novel dynamic NMR field marker for the PS; a campaign aimed at the detailed measurement of the magnetic state of a PS main magnet; and the design of a standardized electronic signal acquisition and conditioning system.

INTRODUCTION

Precise knowledge of the instantaneous total bending field in a synchrotron is essential for the control of the RF system and is often important for other applications, e.g. power converter control, beam diagnostics, operator feedback etc. This information can be typically obtained from a closed-loop measurement system, which generates and distributes a train of impulsions ("B-train") representing the field in a reference unit powered in series with the machine, or by a mathematical field model ("synthetic B-train") possibly supplemented by off-line measurements.

In a superconducting machine like LHC the off-line approach was the only practical choice. The current semi-empirical model ("FiDeL" [1]) has an adequate performance thanks to the vast database of test results, including all magnetic elements, which has been statistically analysed to extract model parameters. An accurate mathematical simulation is seemingly more difficult to obtain for CERN injectors, which are based on resistive magnets and adopt the real-time measurement approach. Several major uncertainty sources apply in these cases, namely: temperature drifts, hysteresis behaviour in the iron, eddy current effects, material ageing etc. Other relevant factors are extent and precision of the measurement database and real-time number-crunching power, both of which were hardly available in the past.

The five B-train systems at CERN have been in operation for several decades. Therefore, despite their successful track record, concerns over their long-term reliability are legitimate. In certain cases, performance improvements such as an increase of resolution by factor 2 from 0.1 to 0.05 G are necessary to meet future demands. For these reasons, we have recently launched a program of upgrade and standardization of the sensors and of the related electronic cards. In this paper we shall describe some of the related R&D activities, focusing in particular our attention on the case of the Proton Synchrotron (PS) which is at the same time the oldest, most critical and most demanding of the five systems.

THE PS B-TRAIN

The PS ring, which began operation in 1959, includes 100 combined-function magnets with poles shaped to provide a focusing (F) or defocusing (D) quadrupole component in each half. A set of correction coils, the so-called Pole Face Windings (PFW) and Figure-of Eight Loop (I8), provides additional degrees of freedom for the control of beam tune and chromaticity via the quadrupole and sextupole field components [2].

The PS B-train system is based upon a set of search coils which allow the measurement of the instantaneous field from the coil output voltage:

$$\mathrm{B}(t) = B_0 + \frac{1}{A_{coil}} \int_{t_0}^{t} V_{coil} dt \qquad (1)$$

The initial value is provided by a field marker that outputs a trigger pulse when the field reaches the preset level B_0=49.8 G during the pre-injection ramp, thus signaling the start of the integration.

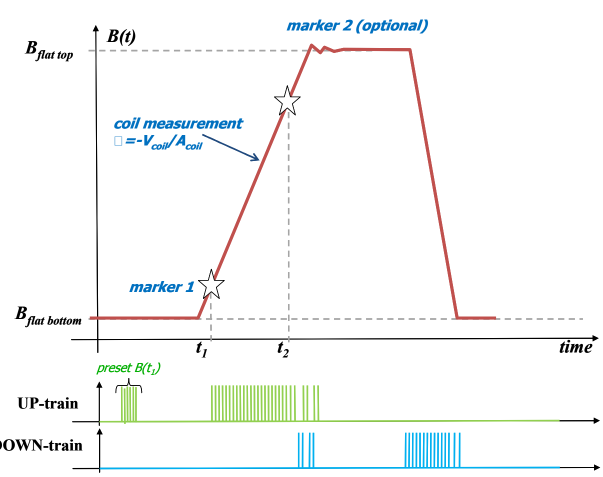

Figure 1: Magnetic cycle with two field markers for the recovery of offset and (optionally) gain errors. A pulse on each one of the two trains represents a ±0.1 G field increment respectively.

The marker used is a peaking strip, i.e. a magnetically bi-stable permalloy needle immersed in a $-B_0$ bias field, which generates a detectable voltage pulse when the the external field reaches B_0 and the magnetization flips. The fabrication technique developed in the '50s was very sophisticated and reproducing it today would be very costly, it being based on knowledge no more available. The need to generate a bias field in a small volume without excessive heating constrains the marked field to its current, very low level. Each channel of the system includes one strip and one coil in either half of the magnet; three channels are available for redundancy.

While the B-train has been performing stably for more than 40 years, a number of issues have been raised recently concerning its reliability and performance:

- Possibility of commercially available alternative markers working at higher field and/or for diagnostic purposes
- More flexible diagnostic tools to assess rapidly suspected faults, as needed for minimal downtime
- Better train resolution (0.05 G) for improved RF and magnet current control

In the following sections we shall discuss briefly the related activities.

NMR FIELD MARKER

An alternative field marker based on ferromagnetic resonance (FMR) has long been installed in the reference unit [3]. This sensor was never integrated into the system, supposedly due to the relatively spread-out resonance peak (typically ~200 µs i.e. 4 G) which makes it difficult to generate electronically a trigger pulse with the required precision (0.1 G).

For this reason we have focused our efforts onto commercial NMR teslameters, featuring a reproducibility of the order of 10^{-7} T and therefore very attractive [4]. The sensor used can work only above 430 G, which gives the opportunity to mark at higher fields (just below injection, which is ~1012 G), obviating the need to descend close to zero and thus saving time and improving the magnetic reproducibility. Unfortunately, the S/N ratio and the width of the resonance signal are degraded by the large space (1700 $\mathrm{Gm^{-1}}$ @ 450 G) and time (23000 $\mathrm{Gs^{-1}}$) field gradients in the PS magnets. A specific R&D campaign was started in 2008 to circumvent these limitations.

The method chosen is based on passive gradient compensation by means of a pair of ferrite slabs enclosing the NMR sensor (Fig. 2). Geometrical errors of the order of 0.2-1.0 mm do not affect appreciably the results, except for the parallelism of the inner surfaces which has to be ≤ 5 µm. This has been achieved by mounting the blocks on a high-precision ceramic spacer and embedding the assembly within a resin mould. The choice of high-resistivity, low-saturation (0.6 T) MnZn ferrite ensures that a) no eddy current artefacts are introduced, and b) all standard PS operation cycles bring the material well into the saturation zone, effectively reducing memory effects due to hysteresis.

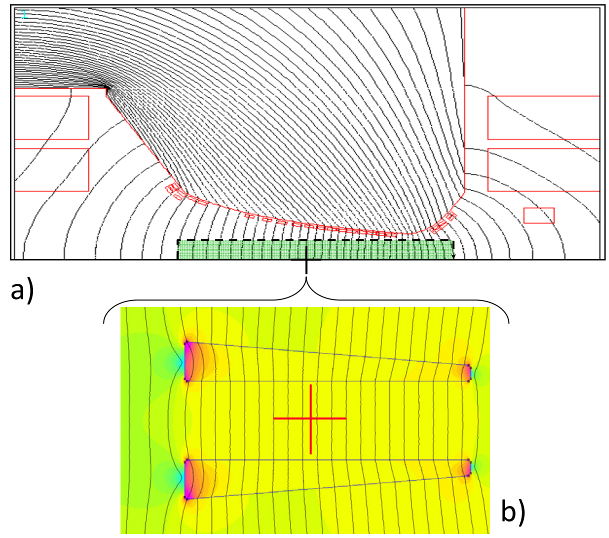

Figure 2: a) cross-section of the PS combined-function magnet showing the 2D region used for detailed FE calculation; b) zoom-in of the straight field lines between two trapezoidal ferrite slabs. The cross marks the beam position, which coincides with the NMR probe.

A series of experimental campaigns were carried out to characterize the probe with the following results:

- The optimal NMR response occurs at 250 G/s, which implies a momentary slow-down of the ramp
- The probe as built is able to measure reliably in the combined field, causing a global field perturbation of the order of 1 ppm (in terms of stored energy)
- The repeatability of the NMR pulse w.r.t. peaking strip trigger is about 0.05G for cycles exceeding the ferrite's saturation, degrades to 0.40 otherwise.

IMPROVED SYSTEM DIAGNOSTICS

Occasionally, beam control malfunctions related to the B-train system trigger a maintenance intervention of the mandated on-call team. Even if these events are often benign and can be ascribed to e.g. timing signals getting out of synch, electronics power supply failures etc., the investigation can still take hours or days of very valuable operation time. For this reason, an effort to improve the diagnostic capabilities for both the acquisition system and the reference magnet has been recently undertaken.

At present, the tool being used is a relatively simple PC-based acquisition system including two National Instruments M-series cards, allowing the simultaneous measurement of up to two digital channels at 10 MHz along with up to 16 analog channels at an aggregated sampling rate of 1.2 MHz. The digital inputs are used to acquire the TTL triggers from two peaking strips (F and D) and to time stamp them with 0.1 µs resolution (i.e. ~0.002 G), while the analog inputs are used to acquire two coils (F and D) and two current signals (DCCT outputs) at 200 kHz (i.e. 0.2 G resolution).

Figures 3, 4, and 5 show the results of an ongoing test campaign aimed at understanding the source of an apparent discrepancy of a few Gauss between beam control parameters, B-train and FMR measurements leading to cycling-dependent radial position errors. In particular, we have tracked for the first time the field in the F and D halves of the reference magnet, showing how powering the I8 coil alone between cycles (Fig. 5) imbalances the remanent field, possibly explaining the discrepancy observed in the subsequent LHC cycle.

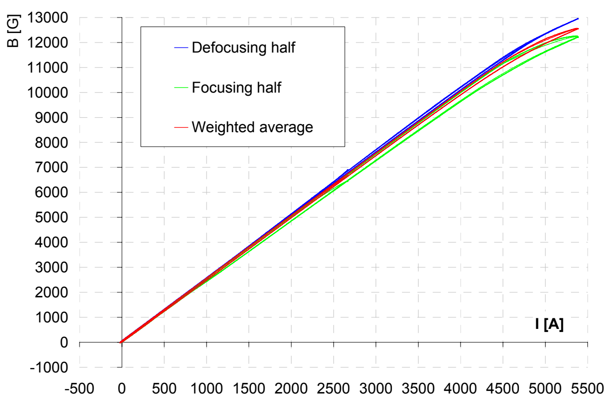

Figure 3: Typical hysteresis cycles of the vertical field vs. excitation current in the F and D halves along the reference closed orbit.

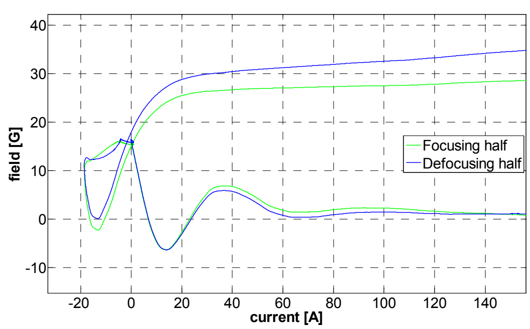

Figure 4: Zoom of the hysteresis loops in a typical case (linear part B=2.5 G/A subtracted).

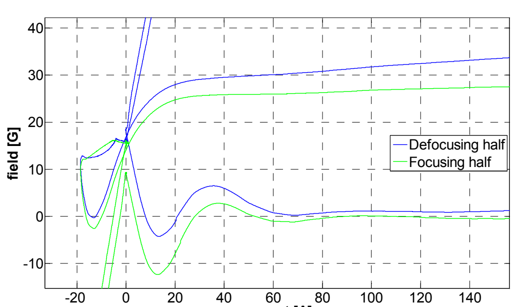

Figure 5: As in Fig. 4 for a cycle exhibiting radial position errors, just after an isolated I8 powering cycle.

The acquisition system is currently being upgraded to a more performing PXI architecture, including all relevant sensor and current signals.

NEW STANDARDIZED ELECTRONICS

The development of upgraded B-train electronics, standardized for all existing systems, has been recently launched to guarantee the long-term reliability of CERN injector chain. The goal, besides the streamlining of all maintenance and calibration procedures, includes the incorporation of all improvements requested by the users in the last decade, such as: incremented train resolution, possibly with additional high-speed digital B(t) distribution channels; possibility of switching remotely between redundant chains; improved synthetic B-train; on-line measurement of field harmonics, etc.

While hardware standards (VME) and input/output signals must remain rigorously compatible with the existing infrastructure, a more general and flexible field marking logic based on multiple points/multiple sensors is currently being discussed. The integration of improved diagnostics, like e.g. a full set of post-mortem signals as shown in the previous section, is also planned.

CONCLUSIONS

B-trains are complex and vital systems that need an upgrade to ensure smooth injector operation during the LHC exploitation era. Suitable tools are being prepared to obviate the lack of critical sensor spares and to answer the remaining open questions concerning the detailed behaviour of magnets such as the PS main units.

A major electronics upgrade is being developed, and we aim at having the first prototype cards ready for the planned 2012 shutdown. According to the upcoming test results, a new marking system for the PS might enable substantial optimization of the current cycles.

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