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FIRST OPERATIONAL RESULTS OF NEW REAL-TIME MAGNETIC MEASUREMENT SYSTEMS FOR ACCELERATOR CONTROL

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Abstract

A new real-time measurement system for accelerator control to measure the integrated bending field, called FIRESTORM (Field In Real-time Streaming from Online Reference Magnets), has been recently deployed and commissioned in six synchrotron rings at CERN. We present the operational experience during the preparation phase and the restart of the accelerator complex for Run 3, focusing on the metrological performance of the new sensors and electronics, and on the lessons learned during commissioning. We also discuss the prospects for the evolution of the system.

INTRODUCTION

In synchrotrons, accurate knowledge of the bending field in dipole magnets is crucial for controlling the transverse and longitudinal position of beams [1]. At CERN, six synchrotrons use a so-called B-train system to measure in real-time the average bending dipole field and distribute it to different sub-systems, for the purposes of feedback control or beam diagnostics. The RF system is the most critical user, as the instantaneous magnetic field must be known precisely to lock the RF frequency to the particle energy, keeping the beam centered in the vacuum chamber [2,3].

The reason for requiring a real-time measurement system is due to the challenge of predicting accurately the average field, due to the non-linear effects of eddy currents, saturation, and hysteresis. These effects are intrinsic to iron-dominated magnets and depend upon the magnetic characteristics of the iron core, as well as the excitation current history. Similar real-time systems are also used in ion therapy centers, such as the National Centre of Oncological Hadrontherapy (CNAO) [4], MedAustron [5], and Heidelberg Ion-Beam Therapy Centre (HIT) [6].

Six new B-train systems called Field In REal-time STreaming from Online Reference Magnets (FIRESTORM) have been deployed and commissioned with excellent results during the Long Shutdown 2 in the LEIR, PSB, PS, SPS, AD, and ELENA rings at CERN. The FIRESTORM B-train systems have been developed in the context of a site-wide, long-term consolidation project [7,8] to replace the existing ones and are designed to handle the High-Luminosity Large Hadron Collider upgrade. The upgrade necessitates greater beam intensity and more sophisticated beam control across the entire injector chain [9].

This paper presents the newly commissioned systems. We discuss first their measurement principle and overall architecture, then their metrological performance and some of the challenges encountered during the restart of the accelerator complex. We conclude with some prospects for the evolution of the system.

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SYSTEM ARCHITECTURE

The main requirement for the new system, besides phasing out obsolete hardware and software components, was to improve the performance in terms of accuracy and bandwidth of the measured field [3, 10, 11]. Typically a resolution of 5 µT and an absolute reproducibility of 100 µT were required, along with a sampling rate of 250 kHz and a maximum latency of 30 µs. This was achieved by means of high-resolution integrators and new field sensors, such as FerriMagnetic Resonance-based field markers [12] and integral flux loops to capture magnet end effects such as saturation, hysteresis, and eddy currents [7].

The design aims at a uniform design across the whole complex, with full integration with the CERN machine control system and CERN central timing. The system is based on CERN standard components, such as the Linux front-end computers, the FPGA Mezzanine Cards (FMC) [13], and the FESA C++ software framework. This is to allow a common spare pool, improved remote configuration capabilities, and diagnostic capabilities.

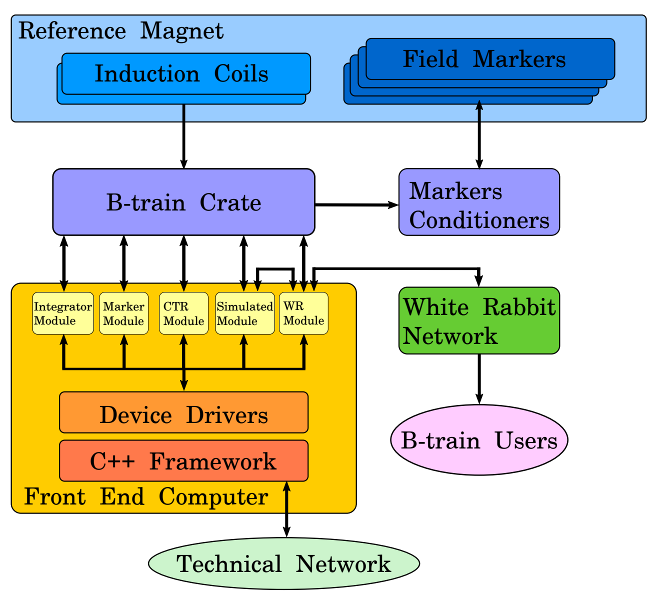

Figure 1: FIRESTORM B-train block diagram.

Figure 1 shows the system architecture. From the top, we have the reference magnet, ideally installed in a separate

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room and connected in series with the bending dipoles in the ring. In some special cases, when no spare unit is available, a magnet in the accelerator is directly used for the field measurement(e.g. in LEIR). Inside the magnet, there are a variable number of magnetic sensors represented by pairs of induction coils, used to capture the time-changing flux, and field markers providing the integration constant. Each functionally separate magnetic element, such as the two halves of the PS main units, is instrumented individually. Sensors and acquisition chains are also duplicated to provide hot-spare capabilities. All the output signals are conditioned and collected in the B-train crate, to be distributed to the FMC hardware modules hosted in the Front-End Computer (FEC) in charge of the integration and marker detection. The FEC is connected to the CERN technical network in order to load the configuration from a database and share and store the data acquired from the hardware for offline analysis.

Each FMC module is hosted on a Simple PCIexpress Carrier (SPEC) [14]. These modules interact with the FEC via the PCIe bus using custom Linux device drivers. The drivers expose the hardware to the high-level C++ based FESA classes. These can read and write in their physical registers to check and change configuration parameters, and use DMA to exchange large amounts of data.

The FEC also hosts an additional module providing the so-called simulated B-train, obtained by interpolating a compact vector representation of the magnetic cycle, stored in the LSA cycle database, to the desired resolution of 4 µs. Under certain circumstances magnetic field measurement is not the best option for feedback to the RF system: for example, when installing physical sensors is extremely difficult, like in the AD; or, more in general, when machine operators prefer a perfectly reproducible magnetic field for diagnostic purposes.

For both the measured and simulated versions of the B-train, synchronization with the CERN central timing is guaranteed by a dedicated module in the FEC. The field values are distributed to the clients over a dedicated optic fiber network based on White Rabbit (WR) [15]. This is an open hardware and software protocol, developed at CERN together with other international organizations and industry to synchronize with nanosecond accuracy thousands of nodes which can be located up to 10 km far from each other.

METROLOGICAL PERFORMANCE

An accurate metrological characterization of the new B-train systems is not only important to ensure that the design requirements have been met, but also to gain the trust of its end users. This last point is particularly relevant in synchrotrons, where the magnetic field plays a crucial role. For example, when any anomaly of the radial position of the beam is observed, a quantitative assessment of the B-train uncertainty is essential to direct the investigation towards magnetic instrumentation errors, current cycling, or power converter-related issues (e.g. magnetic hysteresis effects or current ripple), or possible malfunctions of other subsystems.

The new B-train systems were characterized by means of measurements carried out with the beam as a reference. In particular, we were looking at the open loop revolution frequency, the mean radial position, and the magnetic field to assess the reproducibility and stability of the system over time. In this paper, we focus on the study carried out at the beginning of the run in the PS, where the B field measurements are used for the regulation of both excitation current and RF cavities.

The resolution of the B-train measurement has been evaluated from the RMS amplitude of the noise, as also reported in Ref. [3], and it is about 1 µT, well below the required value. The other measurement results are listed in Table 1 and Table 2. The average ($\overline{B}$) and standard deviation (σ_B) of the field, Mean Radial beam Position (MRP), and open loop revolution frequency (FOL, measured before the radial loop is closed on the acceleration ramp) were calculated for different proton cycles (LHCIND, TOF, EAST, and SFT-PRO) over 9000 repetitions. All quantities were evaluated at the time t_E from the cycle start, i.e. on the intermediate plateau prior to the acceleration ramp, which has a duration Δt. The field on EAST and STFPRO is reproducible with a standard deviation of about 7 µT, one order of magnitude better than required. In LHCIND and TOF cycles this is as low as 1 µT and within the noise floor of the system. The difference between these cycles can be ascribed to hysteresis effects linked to the composition of the supercycle, which the B-train can capture reliably.

The measured scatter of the revolution frequency σ_{FOL} can be compared to the value σ_f that could be expected on the basis of the observed scatter of the field, via the frequency program for the reference orbit. In the LHCIND, EAST, and STFPRO cycles at t_E we have $\partial f/\partial B \approx 0.1$ Hz/µT, so we find respectively $\sigma_f \approx 0.1$, 0.7 and 0.7 Hz, which are roughly comparable to σ_{FOL}. In the TOF cycle, instead, $\partial f/\partial B \approx 0.25$ Hz/µT, leading to a $\sigma_f \approx 0.3$ Hz $\ll \sigma_{FOL}$. In this case, the much larger measured frequency scatter might be attributed to nonlinear effects in the magnet ends, which are magnified at lower field but cannot be captured by the short induction loops installed in the PS reference unit.

Similarly, the observed scatter of the MRP can also be compared with the value σ_R derived by assuming constant RF frequency and considering that in the PS $\partial B/\partial R \approx$ 100 µT/mm. For EAST and SFTPRO cycles we find that $\sigma_R \approx 0.07$ mm, which is roughly comparable with σ_{MRP}, whereas for LHCIND and TOF cycles σ_{MRP} is two orders of magnitude higher. This seems to indicate that other sources of error affect strongly the radial position of the beam.

COMMISSIONING CHALLENGES

The commissioning of the system after the Long Shutdown 2 was completed successfully but presented many challenges, of which we provide below two representative examples concerning the PSB ring.

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Table 1: PS B-train Performance Statistics on the First Intermediate Plateau for LHCIND and TOF Cycles

	Unit	LCHIND	TOF
Δt	(ms)	400	50
t_E	(ms)	360	280
$\overline{B}$	(mT)	185.99	155.49
σ_B	(μT)	0.86	1.14
$\overline{FOL}$	(kHz)	463.98	458.68
σ_{FOL}	(Hz)	0.30	18.69
$\overline{MRP}$	(mm)	2.20	-0.71
σ_{MRP}	(mm)	0.55	0.69

Table 2: PS B-train Performance Statistics of the First Intermediate Plateau for EAST and SFTPRO Cycles

	Unit	EAST	SFTPRO
Δt	(ms)	30	50
t_E	(ms)	270	280
$\overline{B}$	(mT)	185.86	186.03
σ_B	(μT)	6.97	7.22
$\overline{FOL}$	(kHz)	464.02	464.10
σ_{FOL}	(Hz)	1.15	0.98
$\overline{MRP}$	(mm)	1.73	2.95
σ_{MRP}	(mm)	0.13	0.06

In 2021, at the beginning of beam commissioning, strong phase oscillations at 1.0 and 1.2 kHz were observed throughout the cycle. These oscillations were found to correlate with a ripple in the field measured by the B-train at the same frequencies, with an amplitude of 56.7 μT and 113.5 μT respectively. The B-train system, however, has no known failure mode which can lead to such oscillations: typical measurement errors show up as linear gain errors, low-frequency integrator drift, high-frequency noise, or abrupt jumps linked to missing or untimely field marker triggers. Ultimately, the field ripple was traced back to a hard-to-remove excitation current ripple of amplitude 265 mA and 530 mA respectively, which is roughly consistent with the linear transfer function of the magnet being 215 μT/A. Among the first mitigating measure proposed, digital notch filtering of the B-train output was rejected as it would add an unacceptable delay of 31 ms at 80 dB attenuation. The solution adopted was then to run the power converter in closed loop with the measured B-train and provide the simulated B-train to the RF, which is how the PSB operates to date, until a permanent fix is found. Foregoing the measured feedback has proven surprisingly effective, even if a number of ad-hoc cycle and settings adjustments are necessary and the operational flexibility linked to the measurement is lost. Continuous operation using the simulated B-train represents a severe and unanticipated stress test, which has however permitted a few subtle, intermittent software and firmware bugs to manifest, to be then painstakingly identified and corrected.

In 2022, during the first summer of Run 3, the air conditioning system in the B-train reference magnet room shut down unexpectedly and undetected. Ambient temperature increased from the usual constant value of 23° C up to 36° C, while the temperature in the racks exceeded 45° C. This affected the accuracy of the electronic devices, especially the conditioning electronics of the field marker, which stopped to provide the periodic trigger needed to reset the integration at the start of every machine cycle. As a result, the typical observed integrator drift of about 10 μT/s started to accumulate as a measurement error, leading to a *MRP* drift of the order of 6 mm/min, which prompted the machine operators to launch an investigation which took about one day. Once the air conditioning unit was restored and the temperature fell back to its previous level, the B-Train behavior returned to normal. Suitable mitigating measures to prevent such an incident are currently being defined.

CONCLUSIONS AND OUTLOOK

After a decade of development following an AGILE workflow, the new FIRESTORM B-train systems meet all requirements, as they were initially formulated, and then progressively refined to respond to early user feedback and ever-evolving operating scenarios. The built-in design flexibility will be key to keep the systems functional and accurate in view of the upcoming challenges, starting from the operation of the HL-LHC injector chain and beyond.

A detailed medium-term consolidation plan is currently under discussion, in preparation for a long list of mandatory upgrades. These include periodic updates to the hardware (SPEC cards, White Rabbit network) and software (FESA classes and the underlying FEC operating system) infrastructure, as well as specific demands such as introduction of new ion species, elimination of zero cycles (necessary for period recalibration of the integrators) and extension of the duration of cycle plateaus. At the same time, operational experience confirms the importance of integral induction coils to capture dynamic effects, in addition to early warning systems for typical fault conditions. To solve these problems, we propose to implement suitably adapted sensors (such as the PS integral coil prototype currently under test), to improve integrator drift correction according to novel algorithms already tested off-line, and to automatize software remote diagnostics and alarms in FESA.

In addition, we will soon deploy a prototype version of a so-called predicted B-train module, which computes on the basis of mathematical models the magnetic field in real-time as a function of the excitation current. This includes a very promising deep-learning neural network approach that, in recent off-line tests, appears to handle magnetic hysteresis with high accuracy. In the long term, we are confident that such a radical shift of strategic approach will be able to effectively complement, or possibly even replace, the traditional reliance on measurement feedback.

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