

WHITE-RABBIT BASED REVOLUTION FREQUENCY PROGRAM FOR THE LONGITUDINAL BEAM CONTROL OF THE CERN PS

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Abstract

The measured bending field of the CERN Proton Synchrotron (PS) is received in real-time by the longitudinal beam control system and converted into the revolution frequency used as set-point for beam phase and radial loops. With the renovation of the bending field measurement system the transmission technique is changed from a differential sequence of pulses, the so-called B-train, to a stream of Ethernet frames based on the White Rabbit protocol. The packets contain field, its derivative and auxiliary information. A new frequency program for the conversion of the bending field into the revolution frequency, depending also on parameters like radius of the accelerator and the particle type, has been developed. Instead of storing large conversion tables from field to frequency for fixed parameters, the frequencies are directly calculated in programmable logic (FPGA). To reduce development time and keep flexibility, the conversion is processed in real-time in the FPGA using Xilinx floating-point primitives mapped by a higher level tool, Simulink System Generator. Commissioning with beam of the new frequency program in the PS is progressing.

INTRODUCTION

The CERN PS accelerates protons and ions [1] for fixed target experiments and as part of the LHC injector chain. For protons, its kinetic range covers 1.4 GeV at injection to 26 GeV total energy. The longitudinal beam control system drives in total 25 cavities in a wide frequency range (2.8-10, 20, 40, 80 and 200 MHz). It requires the so-called open-loop revolution frequency to be derived from the bending field of the main dipole magnets which serves as a reference for the feedback loops closed around the beam. In addition to protons from the PS Booster (PSB) the PS accelerates a large variety of heavy and light ions such as ²⁰⁸Pb⁵⁴⁺ [2,3,4] or ⁴⁰Ar¹¹⁺ injected from LEIR.

Motivated by the renovation of the present measurement system of the magnetic field, its distribution in the form of asynchronous pulses (so-called B-train) [5, 6] has been upgraded [7] to a stream of Ethernet frames based on the White Rabbit (WR) protocol. The reception of the magnetic field information for the longitudinal beam-control and its conversion into the open-loop revolution frequency has been redeveloped and commissioned with beam.

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FIELD MEASUREMENT

The existing system uses a peaking-strip (PKS) marker at 49.8 Gauss as an absolute reference at the start of each cycle. This implies to ramp down to a low field between cycles to reset the integration process, consuming time and power. Moreover, the B_{up}/B_{down} pulses distribution scheme triggered by 0.1 G changes in B at a maximum rate of 500 kHz is at the limit for ions in terms of resolution and also in case of flat zones.

In the new system, the measurement setup is referenced at each cycle by a Ferromagnetic Resonance (FMR) tunable marker and integrates a flux coil voltage, meaning the derivative of B . This kind of marker has a working point closer to the injection field, thus reducing the ramp down constraint besides improving the injection accuracy. The regulation done in B , has to cover the range from 600 G to 13000 G with a maximum changing rate of ~ 30 kG/s.

Following the acquisition process, the magnetic field and its derivative are transported via Ethernet frames using the White Rabbit protocol over optical fibres [8]. At the reception side, B is extracted and then converted into the open-loop revolution frequency.

Transmission side:

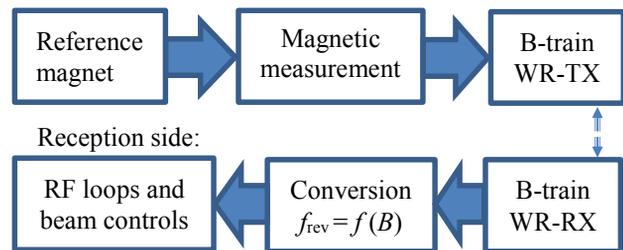


Figure 1: Overview of the whole system and its connection between reference magnet and longitudinal beam control.

OPEN-LOOP REVOLUTION FREQUENCY

In a synchrotron, the orbit of the particles can be controlled by changing the bending field in the dipole magnets or the RF frequency. A theoretical relationship between magnetic field and revolution frequency can be derived from machine parameters [9,10]. According to

$$f_{rev}(B, b) = \frac{c}{2\pi R_{nom}} \frac{1}{\sqrt{1 + \left(\frac{E_0}{b \cdot B \cdot c \cdot \rho_{nom}}\right)^2}} \quad (1)$$

with the velocity of light in vacuum c , the mean radius R_{nom}

of the vacuum chamber and the bending radius of the bending magnet ρ_{nom} to end with the relation Eq. (1) describing the revolution frequency f_{rev} as a function of the magnetic field B . For ions, a charge-over-mass scaling factor b relative to protons ($b=1.0$) is introduced

$$b = Z_{ion} \frac{E_{0,proton}}{E_{0,ion}} \quad (2)$$

requiring only the charge Z_{ion} of the species and its rest mass energy $E_{0,ion}$. This scaling factor is then directly applied as a factor to the magnetic field B . Figure 2 shows

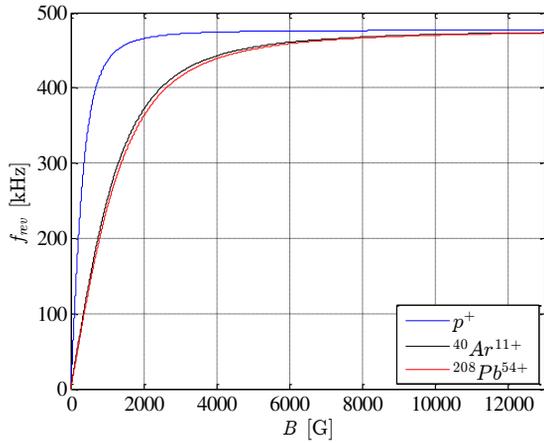


Figure 2: Revolution frequency function of B .

frequency swing for different particle accelerated in the PS.

Table 1: $f_{rev}=f(B_{inj}, B_{ej}, \text{particle type})$

Species	Region	B [G]	f_{rev} [kHz]
p^+	Injection	1013	436
	Ejection	12550	477
$^{208}\text{Pb}^{54+}$	Injection	685	178
	Ejection	12550	473
$^{40}\text{Ar}^{11+}$	Injection	685	187
	Ejection	12550	473

Equation (1) shows that the frequency sensitivity is greater for ions than for protons and in particular at low energy.

Table 2: Δf_{rev} and ΔR for a ΔB of 0.1 G at Injection

species	b	Δf [Hz]	ΔR [mm]
p^+	1	7.0	0.32
$^{208}\text{Pb}^{54+}$	0.261571	22.3	0.40
$^{40}\text{Ar}^{11+}$	0.277303	23.1	0.40

The simple theoretical relationship (1) is not sufficiently precise, mainly due to saturation effect in the main magnet and hypothetically due to uncertainties and dispersion in the magnetic length of the magnets, non-linearities and other errors in addition to the fact that the beam over its path sees the integrated B and not exactly the measured B_{ref} at a specific location in the magnet).

Therefore a fit-based frequency model [11] has been implemented for the PS to reduce the action of the radial loop of the beam control. The polynomial coefficients are extracted using beam-based measurements of the radial loop error to perform a fit optimization of the low energy part of (Eq. 1) in order to minimize the radial loop correction. The fit-based revolution frequency model becomes

$$f_{rev}(x) = \frac{c}{2\pi R_{nom}} \frac{1}{\sqrt{1 + \frac{N}{P(x)}}} \quad (3)$$

with $x=b \cdot B$ and

$$P = \left(x(1 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5) \right)^2 \quad (4)$$

TRANSMISSION/RECEPTION

The WR technology [8] developed at CERN as an extension of the IEEE 1588 protocol, a time precise Ethernet, has been chosen as a transmission standard to distribute the magnetic information in the accelerator complex. There are two ways of using it, the pulse mode where the reference timing is given by the grand master and all slaves align to it allowing generation of grouped precise pulses or simply in Ethernet packet streaming mode, the one currently used.

For this application, a dedicated frame (Fig. 3) with specific type (0x42, ASCII code of 'B' for B_{field} measurement frame) and content has been defined as a standard to transmit magnetic information. The latency of the link is monitored by extracting and differentiating the time included in each frame. To guarantee a transmission rate of the existing B -train, the frame rate is constant and currently set to 250 kHz, with a maximum rate defined by the size of the payload and number of users in a standard Ethernet 1 Gbps network.

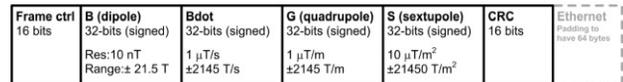


Figure 3: Layout of B field frame.

IMPLEMENTATION (CORE)

The new frequency program uses mainly standard hardware as open hardware designs (SPEC and SVEC) [8,12] related to the WR project. New FMC daughter boards hardware designs (ADC, CVORB, SERIAL40M)

[10] and specific firmware to adapt the data format from the WR core to the transmission standard of the RF beam control have been developed. A new approach has been explored and validated for the conversion of B to f_{rev} implemented in the FPGA of the SVEC board. The conventional way might have been to pass through the development of a fixed-point implementation and iterative algorithms to perform elaborated mathematics like the reciprocal square root or via huge and static conversions tables present in the existing system to implement Eq. (3). The approach chosen was to calculate the revolution frequency on the fly in floating point algorithms in the FPGA. The calculated f_{rev} digital word is serially Manchester encoded for being finally distributed through the daughter board FMC-DTX-4CHA as a reference revolution frequency to the beam control. This so-called open-loop revolution frequency is then multiplied by the harmonic number. Some corrections such as a frequency steering offset and weighted radial and phase loop errors are applied to finally become the closed loop revolution frequency. The better the frequency program quality, the smaller is the difference between open and closed loop, which translates in a well centered orbit in the machine and less action of the radial loop.

To reduce the floating point development time, Matlab System Generator associated with the ISE Xilinx Primitives library has been used. The library contains optimized versions of advanced mathematic operations whereas the simulation and verification process is convenient and simple. Then the generation process ends up with a mapped and configured netlist directly targeting the project FPGA. These generated files have to be included in the Register Transfer to Logic design entry tools or directly in ISE where it is simply interfaced by port mapping to the main part of the design. This way of designing gives a higher abstraction level to the FPGA and allows to build complex blocks more rapidly. However the commercial tool is vendor specific and requires a license.

The complete project is a versatile assembly of different languages (VHDL2008, Verilog2010 and native C) and philosophy (generic code and use of specific IP cores). In the WR Core, an instantiated LatticeMico32 soft core processor described in Verilog is initialized by a compiled and linked C code. After the compilation and generation processes, a unique file is given to the final tool Xilinx ISE to perform the fitting for the Spartan6 FGPA.

EXPERIMENTAL RESULTS AND COMMISSIONING

The transmission and reception of magnetic bending field frames over WR has been validated and commissioned with beam on operational cycles without a significant or notable difference on the radial loop signal (Fig. 6), confirming as well that the conversion part is fulfilling the requirements. This is a trustable indication about the whole chain validity from this complete new setup. The small difference between both systems is explained by the two independent measurement setups of

the magnetic field which slightly deviate from each other. In both sides of the WR link, relevant signals are directly stored in the DDR memories (Fig. 7-9), remotely available for acquisition and diagnostic. On top of this, drivers and FESA classes have been developed and deployed for the integration in the CERN infrastructure.

Measurements with beam (Fig. 3-6) are made with the operational user for LHC-type beam with 25ns spacing on 4 consecutive cycles with the existing setup and then switched to the new WR system for the 4 next cycles. They shows the existing B-field still measured with the $PKS+B_{up}/B_{down}$ setup available in the samplers, the new Bfield FMR+WR accessed in the DDR memory through the fesa class, the closed loop revolution frequency analogue signal resampled (Fig. 4) and the radial loop with arbitrary units also resampled from the beam analogue signal (Fig. 5) of the LHC beam control. Figure 5 confirms that the cycle is properly accelerated through transition crossing up-to flattop. The only notable difference is during the ejection synchronization process and is visible at the end of the radial loop signal (Fig. 5 and 6). The cycle-to-cycle dependent start of the locking of the loop explain this behavior.

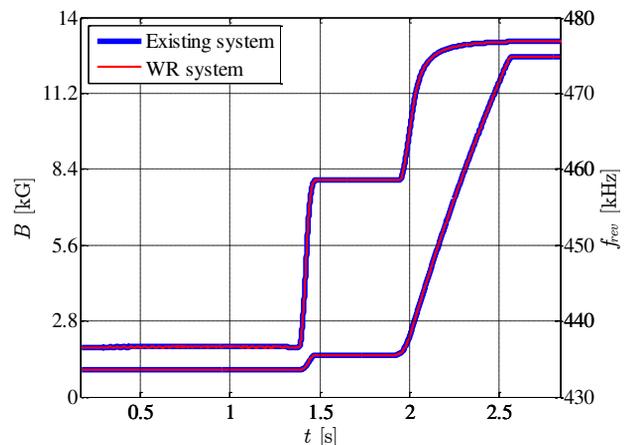


Figure 3: Measured magnetic field and associated closed loop revolution frequency of a LHC-type proton cycle.

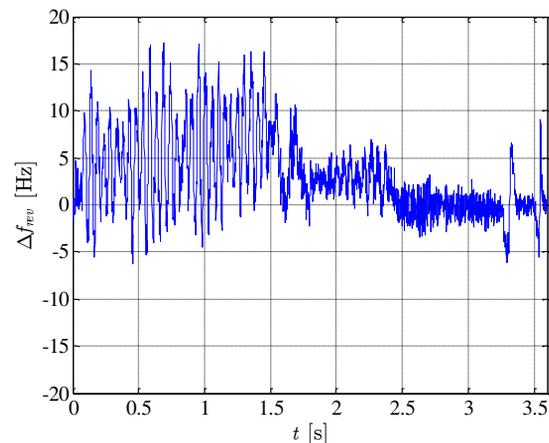


Figure 4: Difference Δf_{rev} between closed loop revolution frequency of existing and WR-system.

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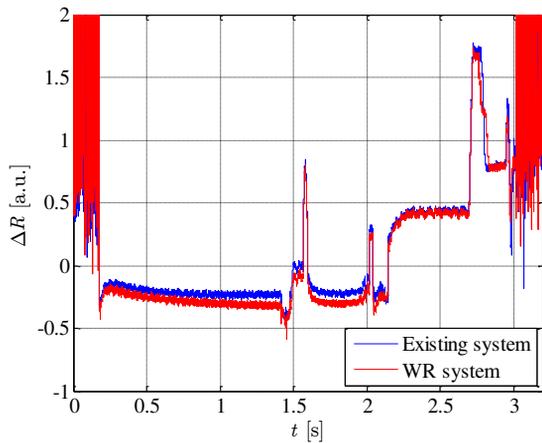


Figure 5: Measurement of the beam control radial loop error signal ΔR averaged on 4 cycles (LHC proton beam).

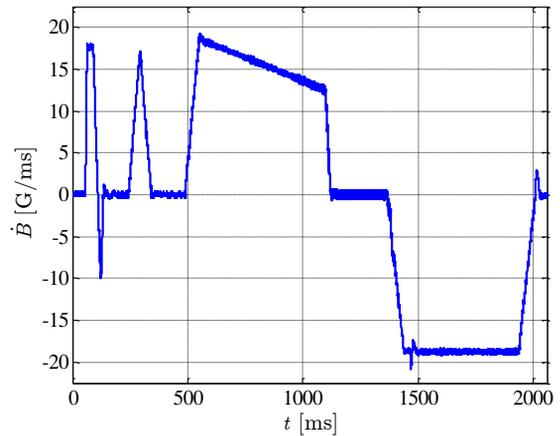


Figure 8: Received magnetic field derivative of ion cycle from Fig. 7.

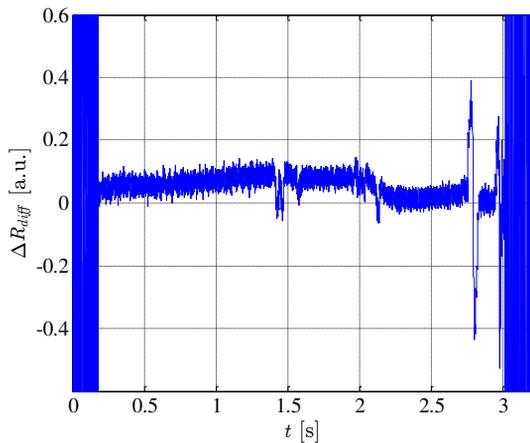


Figure 6: Difference performed on averaged radial loop errors ΔR of figure 5 for existing and WR-system. Spikes show blow-up, then transition crossing and ejection synchronization in the right.

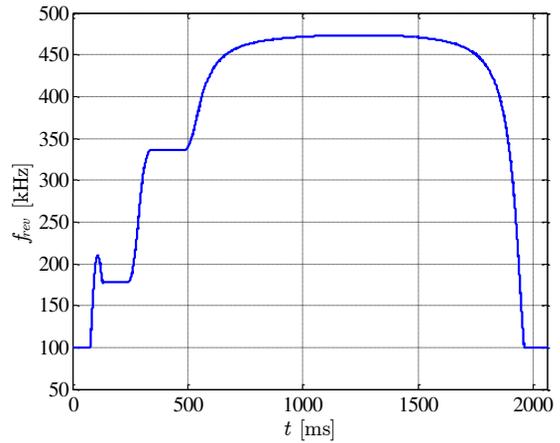


Figure 9: Real-time open-loop revolution frequency f_{rev} converted by WR system using the $^{40}\text{Ar}^{11+}$ scaling factor, $b=0.2773$.

CONCLUSION

New hardware and firmware developments have been completed to adapt the PS frequency program according to this new distribution scheme of the bending field over White Rabbit. Measurements with beam shows a minor difference between the existing and the new WR system (Fig. 4, 5 and 6) essentially because the bending field measurement setups are different and also the regulation is still performed using the existing field measurement setup. The new revolution frequency is real-time processed entirely in the FPGA with a floating-point signal chain giving accurate values.

Furthermore, acceleration of LHC type proton beam has been demonstrated successfully, confirming the functionality and capability of the new system on its own. As a last step, the new system will be put in operation after the completion of its integration in the CERN control system in addition to a dedicated commissioning phase with ions. Finally, some further development work is planned, notably to offer more advanced diagnostics signals in addition to a monitoring of the link status.

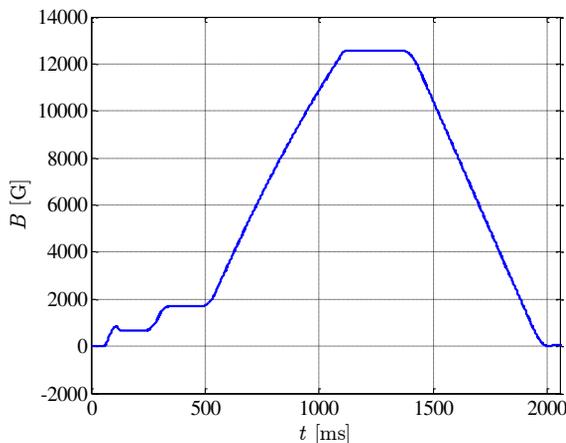


Figure 7: Received magnetic field available from on-board DDR memory of a single bunch ion cycle.

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