OPERATIONAL EXPERIENCE WITH THE NEW DIGITAL LOW-LEVEL RF SYSTEM FOR CERN'S PS BOOSTER

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Abstract

The four rings of CERN's PS Booster have been equipped in 2014 with a new digital low-level RF (LLRF) system based upon a new, in-house developed LLRF family. This is a second-generation LLRF family that has been since then deployed on other synchrotrons. The paper provides an overview of the system's commissioning and first years of operation. In particular, an overview is given of the main system features and capabilities, such as beam loops and longitudinal beam blowup implementation. Operational improvements with respect to the previous, analogue digital LLRF are also mentioned, together with the planned system evolution to satisfy new requirements.

INTRODUCTION

The PS Booster (PSB) is a proton-accelerator in the LHC proton injection chain. It is made of four superposed rings with 25 m radius, receives debunched beam from CERN's Linac2 and provides beams to CERN's PS and to the Isolde experimental zone. Table 1 shows the PSB main parameters. The synchrotron frequency can reach up to 2 kHz, at injection. A wide range of beams is produced and beam intensities at extraction span four orders of magnitude, from $5{\cdot}10^9$ protons in a single bunch for the LHCPILOT cycle to $3.9{\cdot}10^{13}$ protons from the four combined rings for Isolde. Longitudinal emittances are in the 0.1 to 2.8 eVs range and transverse normalised emittances in the 1 to 20 $\pi{\cdot}$mm·rad range. Variants (intensity and emittance) of each beam are required. A cycle lasts 1.2 s of which 0.5 s is for acceleration with a maximum *dB/dt* of 2.2 T/s. Cycles are executed in user-selectable order and beams with very different characteristics may be required sequentially.

Table 1: PSB Main Parameters

Parameter	Capture	Extraction
Energy	50 MeV	1.4 GeV
Frequency	597 kHz	1.746 MHz

LLRF SYSTEM OVERVIEW

Each physical PSB ring is controlled by a dedicated LLRF system whose operation is currently independent from that of the other rings. Figure 1 shows the building blocks, their functions and the input/output signals for one such LLRF system. Three independent high-level RF (HLRF) systems called C02, C04 and C16 [1] are installed in each ring. These narrow-band, ferrite-based HLRF systems implement voltage and tuning loops, too. The LLRF for each ring generates the RF-modulated cavity drive signal for the three HLRF systems of that ring. The amplitude input is given separately and is summed to the RF-modulated drive by the HLRF.

Hardware and Software

The LLRF Analogue-to-Digital and Digital-to-Analogue converters are clocked with a sweeping clock signal set to harmonic 64 of the revolution frequency. FPGA firmware, DSP code and real-time software running in the frontend collaborate to implement housekeeping, extensive diagnostics and control features. The system can be fully re-configured on a per-cycle basis and provides full archiving capabilities. More details are given elsewhere [2].

System Capabilities

The LLRF implements a frequency program derived from a measured magnetic field. Beam phase and radial loops are implemented, as well as an extraction synchronisation loop to lock in frequency and in phase the circulating bunch(es) to an external reference. The LLRF generates the drive signal for all three HLRF systems in a ring. The phase of the C04 system is controlled by feedback with respect the C02 phase and follows a predetermined phase function to shape the bunches. A powerful phase modulation method is implemented in firmware and applied to the C16 cavity drive, to allow controlled longitudinal emittance blowup. Beam results are show later in this document.

Interfaces with Other Systems

The LLRF sends an h=8 train to the tune measurement system through the output of a DAC channel. The h=64 train, generated by the MDDS and used to clock the system, is sent to the transverse feedback system. The revolution frequency f_{REV} and the RF frequency f_{RF} trains are obtained by the C02 and C04 drive signals respectively.

System Commissioning

The four operational PSB LLRF systems were commissioned in June 2014, after the PSB 16-months long shutdown period 1 (LS1). By the third day of commissioning the beam was captured, accelerated (with operational radial and phase loops) and synchronised at extraction for Ring 3. The same features were deployed on the remaining three LLRF systems by day six of beam commissioning. Additional features such as bunch splitting and

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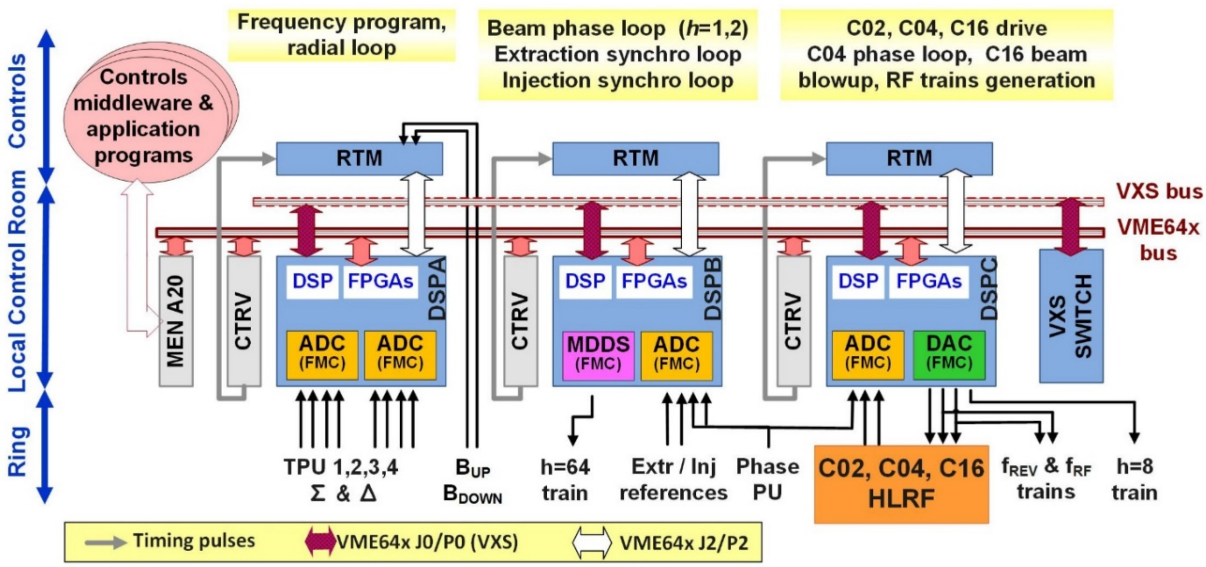

Figure 1: PSB LLRF for one ring. Keys: MDDS – Master Direct Digital Synthesiser; ADC – Analogue-to-Digital Converter; DAC – Digital-to-Analogue Converted; TPU – Transverse Pick-up; CTRV – Timing Receiver Module; MEN A20 – Master VME board; RTM – Rear Transition Module.

further integration within the controls infrastructure were carried out in the following weeks. This rapid commissioning was due to previous tests carried out in the PSB [3] as well as to the experience gained in the MedAustron [4] medical accelerator, where the same LLRF system is deployed.

OPERATIONAL EXPERIENCE

A description of some LLRF capabilities and corresponding beam results, obtained with a prototype digital system, can be found elsewhere [3]. A selection of new or previously unmentioned features is included here.

Frequency Program

The PSB receives a debunched beam from Linac2 on a rising (0.5 T/s) magnetic field. The injection frequency from start-cycle to beam capture does not follow the magnetic field but is kept constant, as shown in Fig. 2, to facilitate the capture process. This cannot be fully adiabatic to avoid the beam spiralling into the vacuum chamber.

In the 2016 run an optimised transition algorithm from fixed frequency to frequency derived from the magnetic field has been implemented. This minimises the beam phase oscillations due to the transition in the frequency source, thus avoiding keeping an artificially high phase loop gain.

Beam Phase and Radial Loops

Phase and radial loops are enabled soon after the voltage starts rising and are typically kept enabled until the beam is extracted. The loops bandwidth can reach 10 kHz

The phase loop corrector is a first-order, high-pass IIR filter with a 10 Hz low cut-off frequency. The phase loop is AC-coupled thus reducing the static frequency errors. The input to the phase loop is signal (b) in Fig. 2. The radial loop corrector is a proportional-integration corrector with its zero programmed to cancel the phase loop low-frequency pole. The input to the radial loop is the average of the radial positions measured from four TPUs located in dispersion regions. The same corrector settings are used in a cycle and can be changed in subsequent cycles.

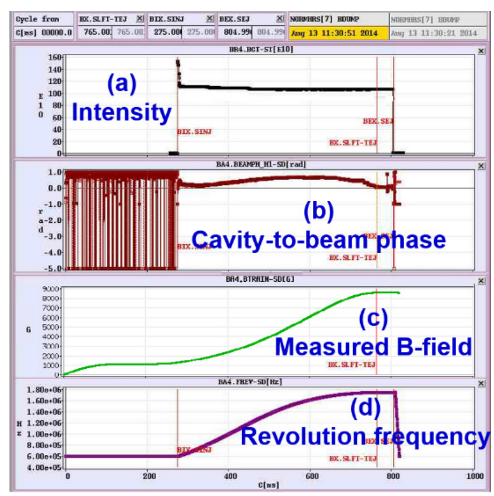

Figure 2: Beam intensity (a), cavity-to-beam phase (b), measured B-field (c) and revolution frequency (d) as a function of the cycle time for a high-intensity NORMGPS cycle on PSB Ring 4.

Extraction Synchronisation Loop

An optimised extraction synchronisation algorithm minimising beam shaking was commissioned in the 2015 run and applied to all beams in 2016. Figure 3 shows the beam-to-extraction reference phase for the optimised and non-optimised algorithm, after reaching a beating relation.

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The optimised algorithm highlighted a perturbation of the synchronisation loop on the PSB outer rings 1 and 4, as shown in Fig. 3 for ring 1 (blue trace). Modifications of the Ring 1 and Ring 4 LLRF systems to take inputs from a different phase pick-up (PU) traced the perturbation to a magnetic field influence on the PU head amplifier. A shielding installed around the phase PU for Ring 1 solved the problem for that ring. The operational phase PU for Ring 4 was changed to a different one not affected by the external magnetic field; in addition, shielding will be installed in the 2017 run.

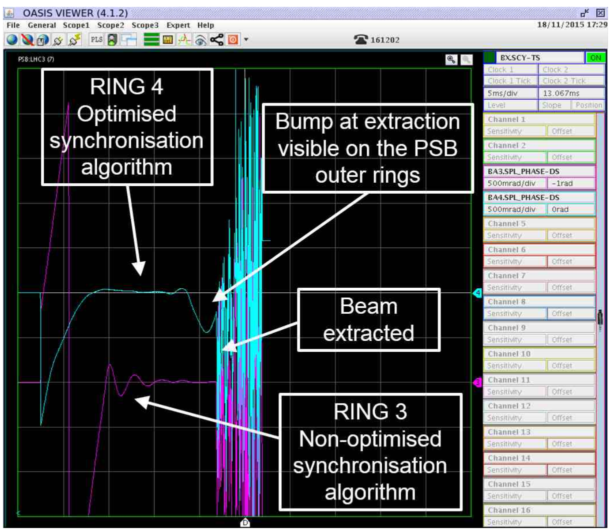

Figure 3: Beam-to-extraction reference phase signals during the extraction synchronisation phase loop. Violet trace: non-optimised algorithm. Blue trace: optimised algorithm. The perturbation on the Ring 4 signal is also visible.

Longitudinal Emittance Blowup

Longitudinal beam blowup is currently obtained via the C16 HLRF system. The drive signal harmonic must be changed during the cycle, as shown in Fig. 4 owing to the increasing revolution frequency and to remain within the operational limits of the HLRF system

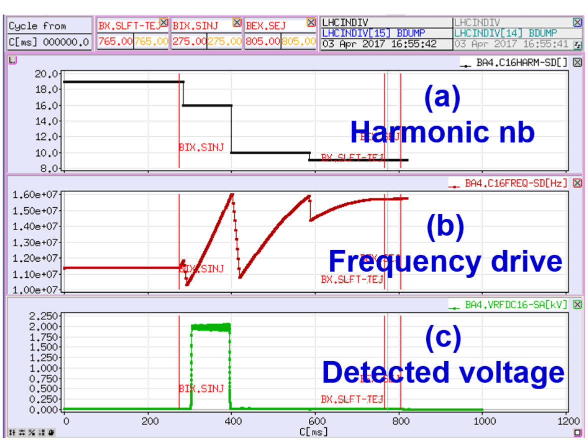

Figure 4: Harmonic number (a), frequency of the drive signal (b) and detected voltage (c) for the C16 HLRF system in a LHCINDIV cycle.

The controlled longitudinal blowup is achieved by phase-modulating the cavity drive with an integer multiple of the synchrotron frequency f_S. This is obtained via a programmed function that follows the expected f_S evolution throughout the PSB cycle. Figure 5 shows the tomogram of a bunch near extraction with a longitudinal emittance of nearly 3 eVs achieved by phase modulation.

System Reliability

The PSB downtime due to LLRF faults in the 39 week long 2016 run was 34 minutes, thus demonstrating the excellent reliability of the LLRF system.

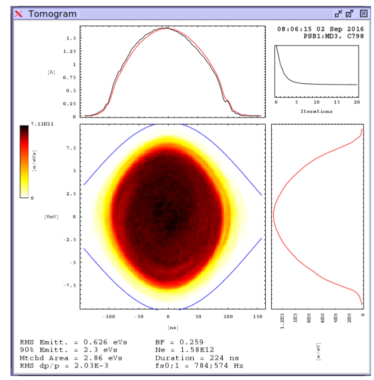

Figure 5: Tomogram at extraction showing a longitudinal emittance of 2.8 eVs obtained via C16 phase modulation.

PLANNED SYSTEM EVOLUTION

The PSB LLRF system is very powerful and flexible: additional features for studies or operation were requested since the end of its commissioning and within the scope pf the LHC injectors upgrade project [5].

Upgrades planned for the 2017 run include a synchronisation between the four operational rings before injection to prepare for future Linac4 operation. A new longitudinal emittance blowup scheme which uses band limited phase noise at the accelerating harmonic [6] will be implemented. The LLRF will interface to the new B-train system, with different electrical distribution format and resolution.

Longer-term upgrades include the complete replacement of the ferrite-based HLRF systems with Finemet-based systems [7] in 2020; studies on how the LLRF will operate them are ongoing [8]. A fixed-frequency clocking scheme will also be used, as for ELENA's LLRF [9].

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