CERN'S PS BOOSTER LLRF RENOVATION: PLANS AND INITIAL BEAM TESTS

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Abstract

In 2008 a project was started to renovate the CERN's PS Booster (PSB) Low-Level RF (LLRF). Required LLRF capabilities include frequency program, beam phase, radial and synchronization loops. The new LLRF will control the signals feeding the three RF cavities present in each ring; it will also shape the beam in a dual harmonic mode, operate a bunch splitting and create a longitudinal blow-up. The main benefits of this new LLRF are its full remote and cycle-to-cycle controllability, built-in observation capability and flexibility. The overall aim is to improve the robustness, maintainability and reliability of PSB operation and to make it compatible with the injection from the future Linac4. This paper outlines the main characteristics of the software and hardware building blocks. Initial beam test results and hints on the main milestones and future work are also given.

INTRODUCTION

The PS Booster (PSB) is a proton-accelerator in the LHC proton injection chain. It is made of four superimposed rings with 25 m radius and provides beams to CERN's PS and to the Isolde experimental zone.

Current PSB operation

PSB receives a proton beam from CERN's Linac2 at the kinetic energy T_I of 50 MeV, injected over a selectable number of revolution periods. The beam is accelerated to a nominal extraction energy T_E of 1.4 GeV, although a cycle at T_E = 1 GeV is also available. The revolution frequency (f_{REV}) ranges from 0.599 MHz (capture) to 1.7458 MHz (extraction at 1.4 GeV). The synchrotron frequency (f_S) range is 2 kHz (injection) to 470 Hz (extraction). The PSB cycle lasts 1.2 s of which 0.5 s is used for acceleration with a maximum *dB/dt* of 2.2 T/s; different cycles are executed in a selectable order. Three independent high-level RF (HLRF) systems, namely C02, C04 and C16 [1], are present in each ring and are operated by the ring's specific LLRF system. Many beams with different specifications are produced. Beam intensities cover four orders of magnitude, from $5 \cdot 10^9$ protons in a single bunch for the LHCPILOT cycle to $3.84 \cdot 10^{13}$ protons from the four combined rings for Isolde. Required emittances also vary considerably: longitudinal emittances can be in the 0.2 to 2.3 eVs range and transverse normalised emittances can vary from less than 1 to more than 20 π·mm·rad.

Future PSB operation

Linac4 [2] will replace Linac2 as PSB injector in 2015; T_I will be 160 MeV, thus increasing the injected beam energy and reducing the current space-charge tune-shift limitations. A sophisticated longitudinal painting scheme will be implemented. An increase of T_E to 2 GeV is under study, to improve the injection into the PS. An extensive PSB consolidation plan, including the HLRF systems, is under way.

RF OPERATIONAL CHALLENGES

The transverse space charge tune shift near the peak of the bunch current is a fundamental limitation with proton synchrotrons at low energies, as it is in the PSB. A second harmonic system is thus required to improve the bunching factor. Longitudinal blow-up is needed to satisfy the required emittance specifications. The rather high f_S calls for a high beam phase loop bandwidth; the wide f_{REV} sweep requires a special sampling frequency treatment. The complexity due to the variety of beams specified is compounded by the many variants of each beam required, in terms of intensity (10% to 90% of the nominal value) or emittance. Beams with very different characteristics are required in subsequent cycles. This calls for high system flexibility and full, cycle-to-cycle parameter control capabilities. Cavity beam loading is also an issue for intense beams. New capabilities will be required in the future: for example, operation with Linac4 will impose the four rings to be synchronized at injection. Additional requirements might stem from possible HLRF upgrades or consolidation.

The current PSB LLRF was installed in the mid-'90s; its parameters are not fully controllable on a cycle-to-cycle basis, and cannot be optimized on each cycle. The system requires a considerable effort to satisfy current operational requirements. A project was started in 2008 to implement a new LLRF satisfying present and future needs, improving robustness, maintainability and reliability of the PSB LLRF operation.

DIGITAL SYSTEM OVERVIEW

The new PSB LLRF system is the evolution of the one successfully deployed in LEIR [3]. The building blocks are conceptually the same, but differences exist in the actual hardware and software implementation.

System capabilities

One new LLRF system for each ring will replace the current one. By controlling the three HLRF systems in each ring, the LLRF will accelerate the beam at harmonic one and two, shape the beam in a dual harmonic mode, perform a bunch splitting and create a controlled longitudinal blow-up. The C04 RF signal will be phase-locked to the fundamental according to a pre-defined reference function to shape the bunch. A synchronisation in frequency and phase of all rings at injection will satisfy the Linac4 injection requirements. The new LLRF will also receive and generate interlocks. Currently the cavities' voltage and tuning loops are implemented in the HLRF; a second stage in the renovation project might include moving these loops to the LLRF, to optimize their performance. HLRF renovation schemes including Finemet-based cavities are under discussion and could generate additional LLRF requirements.

The main benefits of the new LLRF are its full, remote and cycle-to-cycle controllability; built-in diagnostics and extensive signal observation capabilities are also important characteristics. Its digital nature grants an excellent repeatability as well as the implementation of extensive archiving capabilities; this will allow recalling previously-validated sets of control parameters.

Hardware

The VME Switched Serial (VXS) enhancement of the VME64x standard will be used. This supports switched serial fabrics over a new, high-speed P0 connector. It will allow keeping the LEIR system architecture but with more flexible high-speed digital links between VME boards. The VITA57 standard FPGA Mezzanine Card (FMC) will be used for the daughtercards; the signal processing capabilities will then be moved to a powerful FPGA located on the VME motherboard. Many of the selected components, such as the motherboard's Virtex 6 FPGA and the daughtercards' 16-bit ADCs and DACs, are amongst the most advanced units available on the market.

Software

A sharing of the processing tasks between DSP and FPGA different from that implemented in LEIR will be adopted. In particular, the FPGA processing load will be increased to allow a loop sampling period as low as 5 μs. VisualElite tools will be used for the FPGA VHDL code development, to improve code reusability.

INITIAL LLRF BEAM TESTS

A series of beam tests to validate PSB-specific operations was carried out in 2008 as the first step of the PSB LLRF renovation project. A dedicated cycle was allocated and a beam of typically $3 \cdot 10^{12}$ protons was controlled in PSB ring 4 with the same hardware deployed in LEIR. Figure 1 shows the system building blocks, their functionalities and input/output signals; more details on each block are given elsewhere [3]. The LLRF system captured, accelerated and synchronized the beam by controlling the C02 and C04 HLRF systems only. Bunch shaping and splitting were carried out; beam phase loop as well as extraction synchronisation at harmonics h=1 and h=2 were successfully implemented with beam. Parasitic tests with a prototype system on low-intensity beams were previously carried out [4] within the scope of the LEIR LLRF development. Similar results were obtained again in 2008 and the newly deployed features are detailed in the following.

C04 phase loop

The C04 phase was controlled by feedback with respect to either the C02 or the beam phase signals, with equally good results. Figure 2 shows a mountain range plot of 60 profiles of the same bunch, each profile being taken every 1450 turns. The vertical axis shows the time in the cycle, starting immediately after the capture at 276 ms (bottom of the axis) and ending at 388.23 ms. The C04 phase was locked to the C02 phase. The bunches have the typical "flat" shape associated to an improved bunching factor; this proves that the C04 phase loop works as expected.

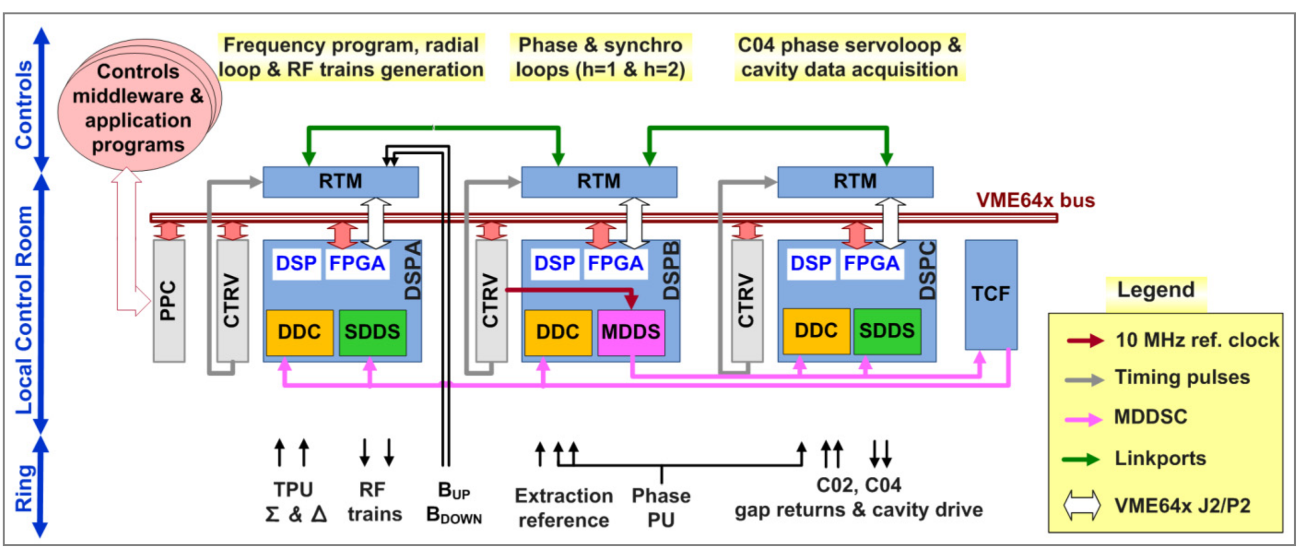

Figure 1: PSB test LLRF - schematic view [3]. Keys: MDDS – Master Direct Digital Synthesiser (DDS); SDDS - Slave DDS; DDC – Digital Down Converter; MDDSC – Tagged Clock; TCF – Tagged Clock Fanout; TPU –Transverse Pick-Up; CTRV – Timing Receiver Module; PPC – Power PC; B_{up}, B_{down} – measured magnetic field.

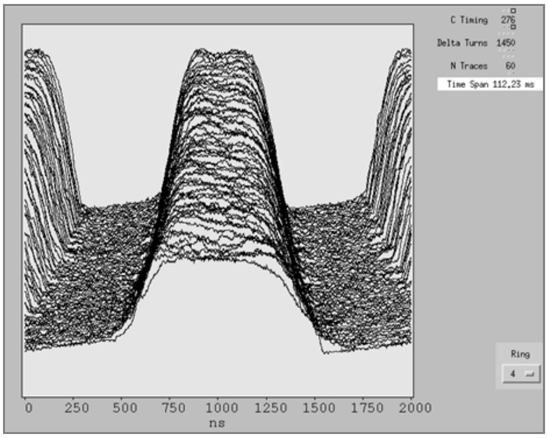

Figure 2: Mountain range plot after beam capture.

Bunch splitting

Bunch splitting is required for some beams in order to meet for instance the longitudinal emittance requirements. Bunch splitting is carried out on the flat-top at a fixed frequency and starts when the C02 voltage V_{C02} is decreased and the C04 voltage V_{C04} increased. For the tests, V_{C02} was 8 kV during the cycle and was decreased to 0.4 kV after the splitting; V_{C04} kept the value of 5 kV during the cycle and was increased to 8 kV for the bunch splitting. Figure 3 shows a mountain range plot of a bunch being split. The observation window covers 8.5 ms, between 756 ms (at the bottom) and 764.5 ms (at the top). It should be noticed that the two bunches after the bunch splitting have the same height, within a small tolerance.

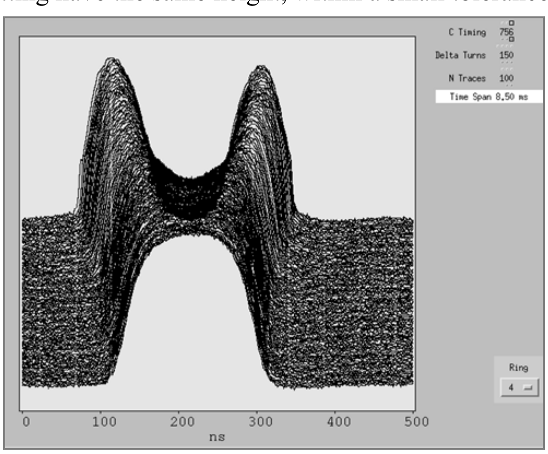

Figure 3: Mountain range plot of the splitting process.

Synchronisation at extraction

Two synchronisation types were considered, with a reference signal at a) $h = 1$ and b) $h = 2$, respectively. For a), only the C02 system was active and V_{C02} was 8 kV at extraction. For b) V_{C02} and V_{C04} were 0.54 kV and 8 kV, respectively, and two bunches were circulating. Figure 4 shows the synchronisation phase loop corrector transfer function; this is a third-order corrector PID^2, implemented by adding a first-order PI section to a second-order D^2 corrector. This was the best choice as the phase loop bandwidth was about twice f_S, hence the transfer function of the beam and phase loop combined system had a double real pole at the frequency f_S.

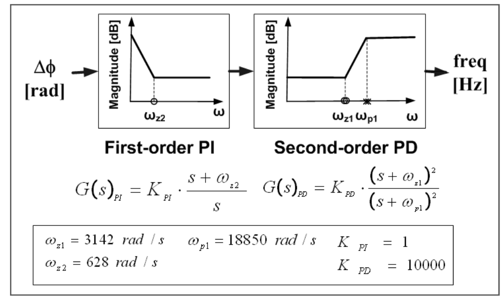

Figure 4: Extraction synchro corrector - transfer function.

Figure 5 shows a Tomogram plot of the two bunches in a single ring just before extraction: these are symmetric and short, owing to the lack of the C16 blow-up.

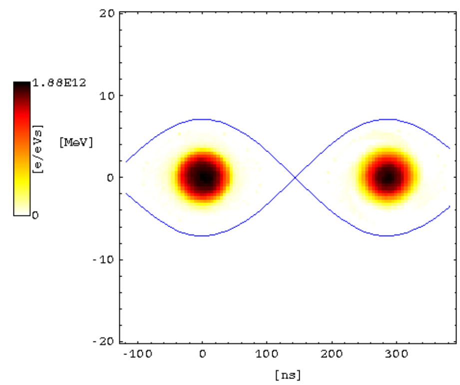

Figure 5: Tomogram plot of an h=2 beam at extraction.

CONCLUSION AND OUTLOOK

A project to renovate CERN's PSB LLRF was started in 2008; it consists of an aggressive hardware development plan and a parallel beam test program. The latter aims at validating the technical choices and will be carried out with the LEIR-style hardware first, then with the new hardware. High-intensity beams tests including the control of all three HLRF systems are planned for 2010-2011. By 2013 all four PSB rings will be equipped with the new LLRF. This will be commissioned to operate with Linac2 prior to its commissioning with Linac4 in 2015. The extension of this technology to other machines, such as CERN's PS, is under study.

REFERENCES

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