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COMMISSIONING THE NEW LLRF SYSTEM OF THE CERN PS BOOSTER

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Abstract

The Proton Synchrotron Booster (PSB) is the first synchrotron in the LHC injection chain and produces beams covering a large parameter space for the LHC and various fixed target experiments. Over Long Shutdown 2 (LS2), the Proton Synchrotron Booster was heavily upgraded as part of the LHC Injectors Upgrade (LIU) project. For the LLRF, the most significant changes are the new Finemet loaded cavities, the new injection mechanism, and the increased injection and extraction energies. The Finemet cavities provide exceptional flexibility, allowing an arbitrary distribution of voltage between harmonics, but at the cost of significant broadband impedance. The new injection mechanism allows bunch-to-bucket multi-turn injection, which significantly reduces the amount of beam loss at the start of the cycle. The longitudinal beam production schema for each beam-type was developed over LS2, and then modified during commissioning to suit the final operational configuration of the machine. This paper discusses the commissioning of the new LLRF, and the consequences of the LIU upgrades on the production of various beams.

INTRODUCTION

Over Long Shutdown 2 (LS2), the CERN PS Booster was heavily upgraded as part of the LHC Injectors Upgrade (LIU) project. The upgrades include a new Finemet based high-level RF system, which provide significant flexibility. To mitigate the effects of the higher cavity impedance, servoloops have been implemented in the Low-Level RF (LLRF) system to suppress the induced voltage, effectively reducing the impedance as seen by the beam.

Despite the impedance reduction provided by the servoloops, the impedance of the cavities at higher frequencies could still have an impact on the beam. Over LS2, new beam production schema were designed for each operational beam, which would utilise the flexibility of the new RF system. These beam production schema are discussed in [1], and they were implemented during beam commissioning in 2021.

NEW HARDWARE AND FUNCTIONALITY

New LLRF Carrier Boards

The PSB LLRF is implemented with Field Programmable Gate Arrays (FPGA) and Digital Signal Processors (DSP) on common carrier boards. For each Finemet cavity a dedicated carrier board is required to control the cavity and implement the servoloops. For each sector, the DSP requests the high-level RF amplifier to switch on, and aborts the cycle if the correct response is not received within a pre-defined timeout. One of the new DSPs receives the phase noise information and propagates it to the other boards for the controlled longitudinal emittance blow-up. Extensive diagnostics on voltage programs at each harmonic as well as detected and drive voltages are also available. A detailed description of the full LLRF system can be found in [2].

Servoloops

Due to the large bandwidth of the new Finemet cavities, significant induced voltage will occur over a large frequency range without feedback. This voltage would both limit the beam stability and significantly distort the driven RF voltage. Therefore, 16 cartesian feedback servoloops are used at revolution frequency harmonics to detect and suppress the induced voltage up to the maximum frequency allowed by the amplifiers (18.5 MHz).

At most harmonics, these servoloops act to force the detected voltage to remain as close to zero as possible. For specified harmonics, typically $h = 1$, $h = 2$ and $h = 10$, the servoloops control the detected voltage in amplitude and phase to follow the programmed values. A detailed description of the implementation and servoloops operation can be found in [3].

Phase noise

Controlled longitudinal emittance blow-up is a vital part of PSB operation both for longitudinal stability and to ensure the required longitudinal emittance at extraction. Prior to LS2, emittance blow-up was achieved with single-tone modulation of a high-harmonic RF system. Equivalent functionality to this has been maintained in the new RF system, however the use of bandwidth-limited phase noise is intended to be the primary operational method.

The suitability of phase noise for PSB operation was demonstrated in [4]. The LLRF system includes a noise buffer, which is populated with a given phase noise function to be applied to the beam. The noise is directly applied to the cavity drive signal in a way that is transparent to the beam phase loop.

Multi-Harmonic Operation

Since the beam in the PSB is space-charge dominated at the start of the cycle [1], it is beneficial to provide the lowest possible line density. Typically, two ($h = 1$ and $h = 2$) harmonics are operated in counter-phase (bunch lengthening mode), which gives a significant reduction in the line density. Thanks to the broadband impedance of the

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Finemet cavities, they can sustain RF voltage at arbitrary combinations of harmonic and amplitude, within the limits of available RF power. Therefore, the RF voltage can be smoothly varied between large $h = 2$ to $h = 1$ ratios at the start of the cycle to much smaller ratios later where space charge is less of a concern. Further, it is possible to linearly change the voltage ratio from pure $h = 1$ to pure (or almost pure) $h = 2$ for longitudinal splitting, as originally proposed in [1], or to accelerate with three harmonics simultaneously for additional space charge reduction.

COMMISSIONING

The hardware and beam commissioning was mostly completed at the end of 2020 and during the first half of 2021. This section describes the current state of the system, and some of the ongoing work to realise its full potential.

Injection

As described in [2], an injection synchronisation loop required for bunch-to-bucket injection from Linac4 has been introduced. During the injection, the RF remains phase locked to a reference clock at 994 kHz via the injection synchro loop. Once injection is complete, this loop is opened and the beam based feedbacks are enabled.

Without the action of any LLRF loops, the RF frequency is calculated based on either the measured or programmed magnetic field, this will be referred to as the design RF frequency. Under the action of feedback loops, the RF frequency will deviate from the design value, this will be referred to as the closed-loop RF frequency. Figure 1 shows the design RF frequency (black), closed-loop RF frequency (blue), and frequency contributions from the beam phase loop (purple) and radial loop (orange) to the closed-loop RF frequency. The vertical black line indicates the end of injection at fixed frequency. At this point, the gain of the phase and radial loops are linearly increased over a few hundred s. Once the phase and radial loop are active, they add a contribution to the RF frequency, and the closed-loop frequency starts to deviate from the design frequency.

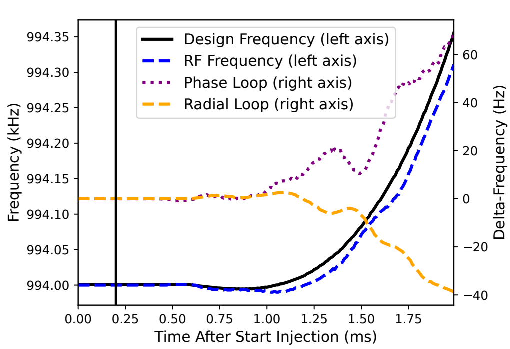

Figure 1: Design RF frequency, real RF frequency, and phase and radial loop corrections during the first 2 ms of a PSB cycle.

The difference between design and closed-loop frequencies is due to imperfections in the accelerator such as differences between the programmed magnetic field and the field integral sampled by the beam. As part of ongoing optimisation of beam operation, the transition from design to closed-loop RF frequency will be adjusted with the duration of injection.

Servoloop Gain Optimisation

During commissioning of the LLRF servoloops, which act to suppress the induced volage, it was found that the non-linearity in the amplifier response was greater than predicted [5]. As a result, the corresponding loop gains had to be lower than anticipated.

After a modification to the amplifiers, it was possible to increase the gain. Over the coming years, all of the amplifiers will be modified, and with each upgraded cavity the servoloop gains will be optimised to suit the final operational configuration.

Cavity Phasing

For each cavity, the cables were installed with similar lengths to minimise the differences in the return paths. The remaining phase offset was then corrected during commissioning with a digital delay, without which there would have been a few percent reduction in the voltage vector sum.

To correct the alignment of the RF phases, one cavity (sector 13) was defined as the reference. Then, with only one of the three cavities used to accelerate the beam, the beam-to-RF phase for each cavity was measured individually. By computing the phase shift relative to the reference cavity, the residual phase error could be corrected. Figure 2 shows the phase shift when accelerating with cavities in sector 13, 7 and 5 compared to the phase in sector 13, before and after compensation.

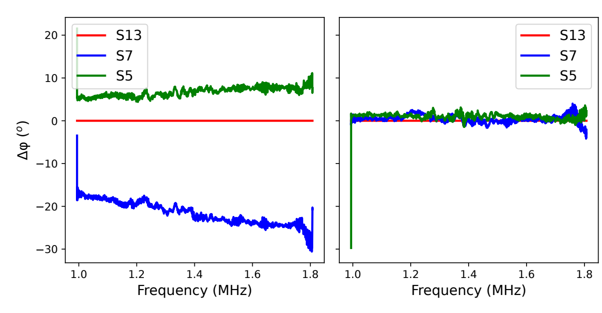

Figure 2: The change in measured beam phase when accelerating with a single cavity using Sector 13 as a reference.

Beam Stability

The beam production schema developed over LS2 [1] were implemented during beam commissioning 2021. For very low intensity beams, this worked as predicted. However, at intermediate to high intensity, the beam stability did not match prediction. Most notably, it was found that the 2_{nd} RF harmonic in bunch lengthening mode was required for

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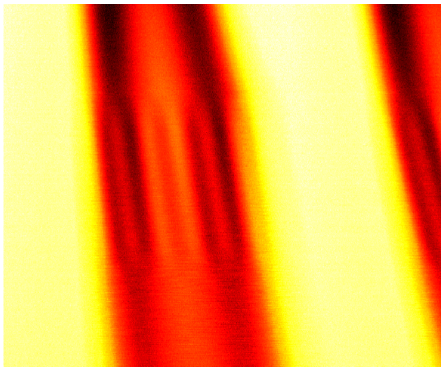
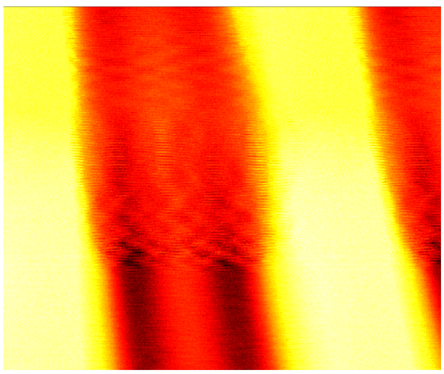


(a) Modulation off



(b) Modulation on

Figure 3: Waterfall plots of beam profiles measured with a pulse of high harmonic without (a) phase modulation and with (b) phase modulation.

beam stability through most of the cycle. Therefore, the beam production was adapted from initial designs to allow beams to be delivered within specification.

Controlled Longitudinal Emittance Blow-up

Along with the functionality for phase noise, the previous method of using single-tone modulation of a high harmonic has been retained.

In the PSB, high-harmonic blow-up currently uses the 10th RF harmonic, but any harmonic with an active servoloop could be used. Figure 3 shows a waterfall plot of the bunch profiles with the $h = 10$ active, but not modulated (Fig 3a) and then with the modulation active to increase the emittance (Fig 3b). This method of blow-up is relatively fast, compared with phase noise, however as it requires additional RF voltage there are more restrictions on its application.

To apply phase noise to the beam, the noise buffer is populated with a given noise function. When this is applied to the RF, particles with synchrotron frequencies within the noise frequency band will be excited to larger synchrotron oscillation amplitudes. Figure 4 shows a waterfall plot of the bunch profiles under the application of phase noise. The commissioning of this method of blow-up is still being finalised.

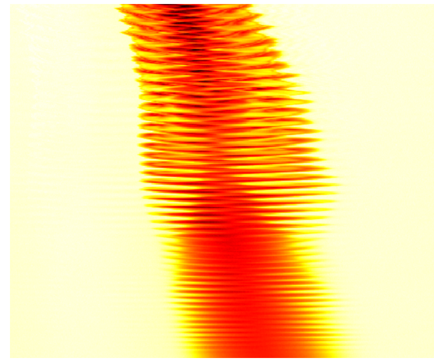


Figure 4: Longitudinal profile evolution during phase noise blow-up.

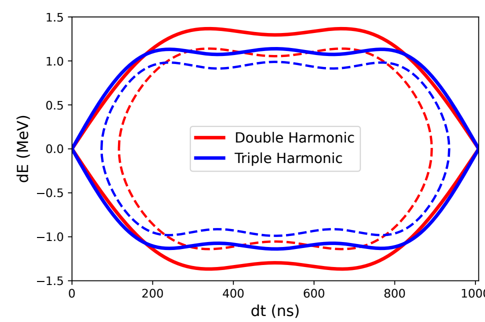


Figure 5: A comparison of the RF bucket shape (solid line) and bunch outline (dashed line) during double (red) and triple (blue) harmonic operation.

Triple Harmonic Operation

As the PSB is space-charge dominated at the start of the cycle, it is operated with the 2nd RF harmonic in bunch lengthening mode to reduce space charge effects in most cases [1]. However, thanks to the flexibility of the new RF systems, it is possible to include the 3rd harmonic as well to further lengthen the bunch. After preliminary experiments before LS2 with a test cavity, this is now being explored as a future operational configuration for high brightness and high intensity beams.

Figure 5 sketches a comparison of the separatrix and bunch outlines at injection for double- and triple-harmonic operation. As can be seen, the addition of a third harmonic gives a slight increase in the bunch length, and therefore a beneficial reduction in the longitudinal line density.

CONCLUSION

The major upgrades made to the PSB as part of the LIU project included new HLRF systems and heavily modified LLRF systems. The hardware and beam commissioning with the LLRF started in late 2020 and continued through the first half of 2021. Most functionalities are operational and all beams for physics users are produced with required specifications. Over the coming years, the remaining features will be brought into operation to continue improving longitudinal beam quality.

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