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# PSB LLRF: NEW FEATURES FOR MACHINE STUDIES AND OPERATION IN THE PSB 2016 RUN

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*Abstract*

A new digital Low-Level RF (LLRF) system has been successfully deployed on the four PS Booster (PSB) rings in June 2014, after the Long-Shutdown 1 (LS1). Although only recently deployed, several new features for machine studies and operation have already been required and implemented. This note provides an overview of the main features deployed for the 2016 PSB run and of their results.

## SYSTEM OVERVIEW

### *Introduction*

A new digital PSB LLRF system has been successfully deployed in June 2014 in the four PSB Booster rings. The system represents the new standard foreseen for many machines in CERN's Meyrin site and it has already been deployed in CERN's Low Energy Ion Ring (LEIR) and Extra Low ENergy Antiproton Ring (ELENA) machines. It is also operational in the medical machine MedAustron [1].

Four separate LLRF systems control respectively PSB Rings 1 to 4. A fifth LLRF system, called "Ring 0" LLRF, allows to control the beam of the physical PSB Ring 4 in PPM with its operational LLRF system. The Ring 0 LLRF system is dedicated to machine studies and in particular it controls the Finemet-based High-Level RF (HLRF) system installed for test purposes in PSB Ring 0. To do this it includes additional hardware and software with respect to the operational rings.

Figure 1 shows the four operational LLRF systems for the PSB rings together with the "Ring 0" LLRF system.

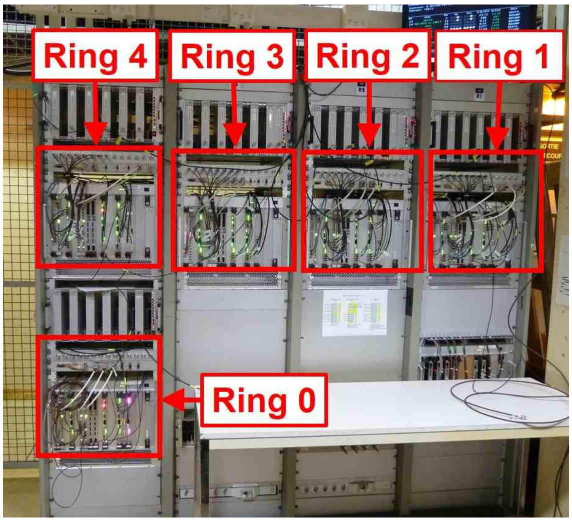


Figure 1: The PSB LLRF systems.

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The total PSB downtime due to LLRF faults in the 39 week long 2016 run was of 34 minutes, thus proving the high reliability of the LLRF system and its positive impact on the machine operation. The system provides additional diagnostics as well as PPM controls with respect to previous PSB LLRF systems, in particular for the synchronisation at extraction process. Last but not least, the system is very powerful and flexible, and can be upgraded to new features often with a reasonable effort. More on this last point is detailed in the next section.

### *New Features*

The PSB LLRF systems are under exploitation, fully operational and satisfied the current PSB operational needs. However, new features have been required in the past and are required to:

a) Study and understand old problems. An example of this is the effect of the extraction bump on the synchronisation process, observed since 2008 in PSB Ring 4 by using a first generation LLRF system [2], at that time deployed operationally in LEIR.

b) Implement new capabilities and allow studies for future beams/operational modes. An example of this are the features required for generating hollow bunches: this was done sporadically in the past but it was much more complex than with the new, powerful LLRF. Another example is the novel scheme of beam blowup at $h$=1 that will be studied within the framework of the PSB LIU project. Finally, interfacing with the new, white-rabbit based B-train distribution scheme will have to be validated.

c) Validate implementations and prepare for the HLRF renovation which will take place after the injectors' Long Shutdown 2 (LS2). In particular, suitable schemes to control the Finemet voltage on several (10 or more) harmonics per HLRF system, to split the voltage at a certain harmonic amongst different cavities and to align these components over the PSB cycle will be devised and if possible partially validated. Furthermore, features required for future beams, such as the phase noise at harmonic $h$ = 1, should be validated for Finemet operation, too. Finally, inputs for simulations will be provided, and simulation results will be validated against beam and system measurements.

As a summary, after LS2 the PSB will restart with substantial changes, such as: new HLRF, adapted LLRF, new B-train system, new injection scheme and new extraction energy. To have a smooth (or at least not too complex) restart after LS2, it is therefore essential to profit from the beam on the two last proton runs, in 2017 and in 2018, for schemes/approaches development and validation.



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## NEW FEATURES DEPLOYED IN THE 2016 RUN

This section details new PSB LLRF features partially commissioned or deployed in the 2016 run. They are the following:

a) Improved extraction synchronisation process.
b) Improved longitudinal beam blowup with the C16 HLRF system.
c) B-train and frequency program studies.
d) Operation with Linac4.
e) Finemet operation.

### *Improved extraction synchronisation process*

The synchronisation process is a very delicate and crucial RF gymnastic. Its aim is to modify the frequency and phase of the bunch(es) to be extracted in order to match an external reference, whose frequency and phase might vary during the extraction process itself. Jitters in the position of the extracted bunch(es) are present if the extraction synchronisation process does not perform well. If the process is too violent or fast, a beam carefully crafted with the RF gymnastics carried out during the cycle will be ruined.

The synchronisation algorithm implemented by the new PSB LLRF system has been from the very beginning much more performant than what was previously available. All control parameters such as gain, loop correctors transfer function, beating frequency etc. can be changed as PPM, thus allowing to adapt the extraction process to the beam characteristics. More diagnostics signals are available, such as the beam-to-extraction reference phase which has allowed to spot the effect of the extraction bump described below. These diagnostic signals are visible remotely on a standard Oasis Virtual Scope and can be saved for reference.

This section describes further improvements to the extraction synchronisation process carried out and deployed during the 2016 PSB run.

#### ***Optimised extraction synchronisation algorithm***

The synchronisation process has been upgraded in November 2015 [3] to a new algorithm which minimises beam shaking and its potential blowup. The upgraded process was then deployed on all users in 2016.

Figure 2 shows the beam-to-extraction reference phase for the optimised (blue trace, Ring 4) and non-optimised (pink trace, Ring 3) algorithms, after reaching a beating relation.

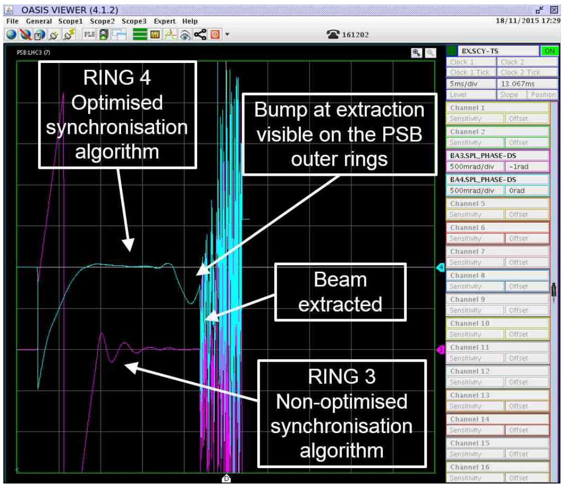


Figure 2: Beam-to-extraction reference phase signals during the extraction synchronisation phase loop. Violet trace: non-optimised algorithm in Ring 3. Blue trace: optimised algorithm in Ring 4. The perturbation on the Ring 4 phase signal is also visible.

Figure 3 shows the waterfall plot of the beam during the extraction synchronisation process, before (left picture) and after (right picture) the algorithm optimisation. The perturbation on the beam given by the non-optimised algorithm on the left hand-side is visible.

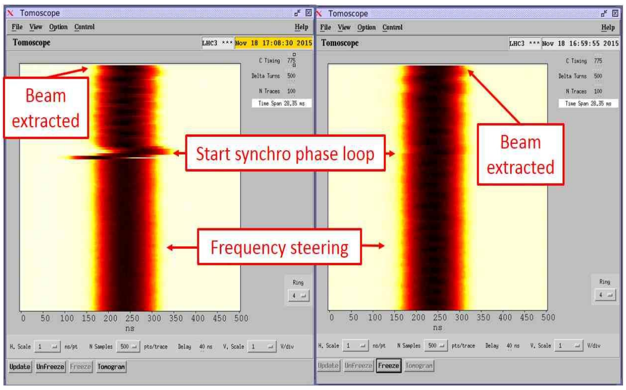


Figure 3: Waterfall plot of the beam during the extraction synchronisation process, before (left picture) and after (right picture) the algorithm optimisation.

#### ***Study of extraction bump effect on the synchronisation process***

The measurement of beam-to-extraction reference phase showed a perturbation of the extraction process linked to the extraction bump fired during the last 5 ms of each cycle. The perturbation affected only the PSB outer rings. This bump was visible also in measurements carried out in 2008 with the prototype LLRF system on PSB Ring 4, as showed in Figure 4 and detailed elsewhere [2].

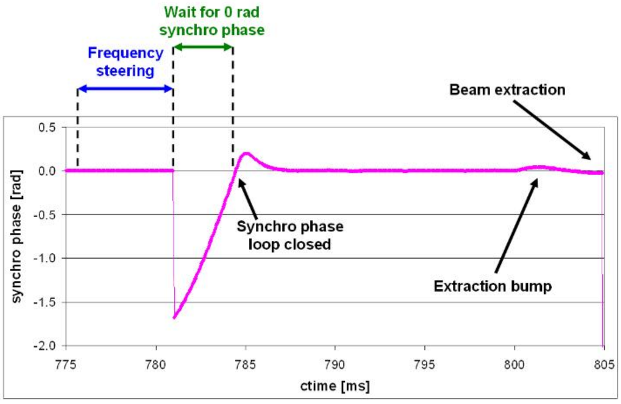


Figure 4: Plot of the beam-to-extraction reference signal phase measured in 2008 by the prototype LLRF system on PSB Ring 4 [2].

The improvements gained with the optimised algorithm described in the previous section were partially lost on the outer rings owing to the extraction bump-related perturbation. As shown in Figure 3, the perturbation shifted the beam radially; moreover, the amount of this shift varied from shot to shot, thus the beam was deposited at different radial positions at extraction.

Several debug features were then added to the LLRF in order to understand the source of the problem.

A measurement & logging of the beam-to-extraction reference phase synchro phase at a user-selectable time (snapshot feature) was deployed in April 2016 [4]. Figure 5 shows the operational knob used to enable the measurement, to decide its ctime and to read the measured phase.

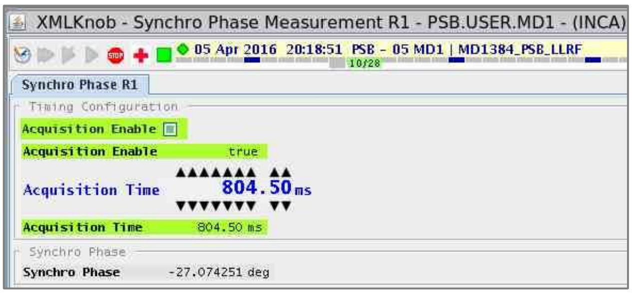


Figure 5: Operational knob allowing to measure and log the extraction reference-to-beam phase during the extraction synchronisation loop.

The capability to freeze the synchronisation loop operation or to end/freeze the phase & radial loops was also implemented [5].

The capability to use in PPM the LLRF input normally dedicated to the injection synchronisation reference for acquiring the signal from a second phase pick-up was deployed in March 2016. This feature was used later on in the year to operate the phase loop with the spare pick-ups located in sections 5L1 and 8L1, which are located far from the BSW. It was observed that the synchronisation response was not perturbed when these phase pick-ups. This prompted the installation of magnetic shielding plates in Ring 1 around the operational phase PU, which cured the problem for that ring. The same shielding will be installed on the Ring4 phase pick-up during the 2017 run.

### *Improved longitudinal blowup by using the C16 HLRF system*

Several improvements were devised, implemented and deployed in the 2016 PSB run.

First, a lack of phase lock between the C16 and the C02 HLRF drive signals was identified and a fix was deployed [6] in April 2016.

An improved version of the C16 blowup firmware was then deployed on all rings in June 2016 [7]. This not only definitely fixed the lock between the C16 and the C02 HLRF systems, but also insured a reproducible (although still harmonic-dependent) phase in the C16 HLRF system after the harmonic change ramp.

Finally, in September 2016 a new firmware was deployed in the Ring 0 LLRF system for tests and validation [8]. This included an automatic delay compensation after the harmonic change ramp, thus allowing changing the operational harmonics (as required for instance for the hollow-bunches operation) whilst obtaining the same phase at the end of the process. This firmware required a re-setup of the blowup parameters on all users and was not deployed on operational rings owing to the pressure to deliver the beams after the technical stop.

It should be underlined that most of the work invested on the C16 blowup improvement was addressed to cope with the C16 operational frequency range limitations, namely the need to change operational harmonics during the cycle. Whilst this is essential for the pre-LS2 operation, it will not profit the future (post-LS2) operation as the new Finemet-based HLRF system does not present the same frequency limitations.

### *B-train and frequency program studies*

Two kinds of studies related to the B-train and to the generation of the frequency program have been carried out in 2016. More studies are planned for the 2017 run.

#### ***New transition method from fixed to B-train derived frequency***

A new transition method from fixed injection frequency to B-train has been implemented in May 2016 [9]. The new algorithm, provided by S. Hancock, minimises the beam phase oscillations due to the transition, thus avoiding keeping an artificially high phase loop gain. Figure 6 shows the frequency program behaviour before (left picture) and after (right picture) the deployment of the new transition method. The phase loop contribution measured in Hertz is also shown for the two cases.

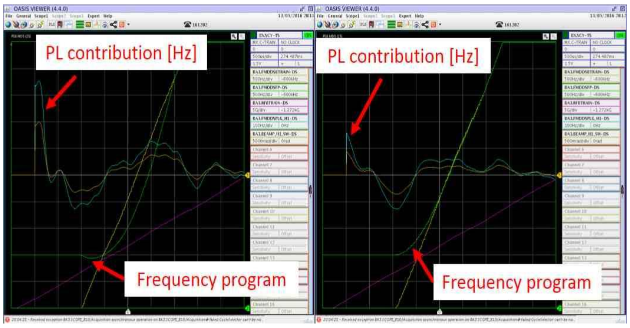


Figure 6: Transition from fixed injection frequency to B-train with the old (left picture) and with the new (right picture) transition methods. The contribution of the beam phase loop measured in Hz is also shown.

***Programmable delay to simulate the effects of new B-train distribution scheme***

After LS2 the B-train information will be generated and distributed digitally. This will present several advantages but will include an additional delay with respect to the current implementation. A programmable delay to the B-train value received by the LLRF was then added to evaluate the effect of this delay on the beam and how the LLRF would correct for it with its beam-related loops.

Initial tests [10] carried out in May 2016 have shown that the radial loop still manages to compensate for the incorrect frequency program generated from a strongly delayed B-train. Figure 7 shows the comparison in the radial loop contribution for an operational cycle and for a cycle where the B-train information is delayed by 100 µs. The maximum contribution of the radial loop is increased by 450 Hz and no substantial beam losses were observed, although no specific observation on the longitudinal plane were done.

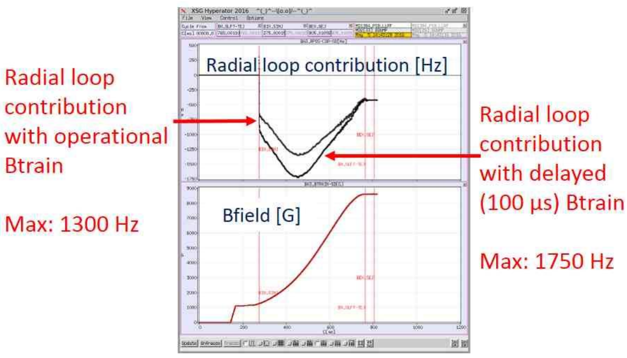


Figure 7: Upper window: radial loop contributions for operation with the operational B-train and with a B-train delayed by 100 µs. Lower window: PSB measured magnetic field.

## *Operation with Linac4*

Upgrades are needed in the PSB LLRF system to receive beam from Linac4. In particular, three tasks have to be deployed and commissioned. First, all rings must be synchronised in frequency and phase to an external injection reference shared with Linac4. Second, the RF interlock system must be commissioned with the PSB LLRF systems. Finally, the longitudinal paining scheme must be overall finalised, which represents a common effort of the ABP, OP and RF groups.

Good progress was made in 2016 on all these tasks, which are however not yet completed. The plan is to have the rings synchronisation commissioned and validated in 2017, as well as the RF interlock system operation with the LLRF. An application is needed to control the RF interlock system, and discussions on its specifications and development steps are under way.

## *Finemet operation*

The month of September 2016 was devoted to restart the Finemet operation in view of the reliability run (6 to 29 September [11]). During this time the Ring 0 LLRF code was upgraded to the various improvements deployed on other rings in 2016. Once done that however the DSP code had to be optimised to allow a reliable operation with beam. In fact, the additional processing time required to deal with the fourth HLRF system (Finemet-based) in PSB Ring 4 was too long and did not allow to complete the synchronisation process.

An additional feature added in September 2016 to the Ring 0 LLRF system was the possibility to control in voltage and phase the third harmonic of the Finemet system [12], rather than simply servoing it to zero voltage to counteract the effects of the beam loading. This capability was required to contribute to future longitudinal painting and allows operation with harmonics $h$=1+2+3 [13].

# PLANS FOR THE 2017 RUN

This sections gives an overview of the upgrades planned for the PSB LLRF in 2017. The new features should be deployed before the PSB spring startup if possible. Unfortunately, the PSB restart has been very demanding owing to several hardware- and cables-related problems originated by works around the rings, and in particular the switchboard installation. Figure 8 shows some of the hardware damages suffered by the PSB LLRF systems, which took a sizeable amount of time to be discovered.

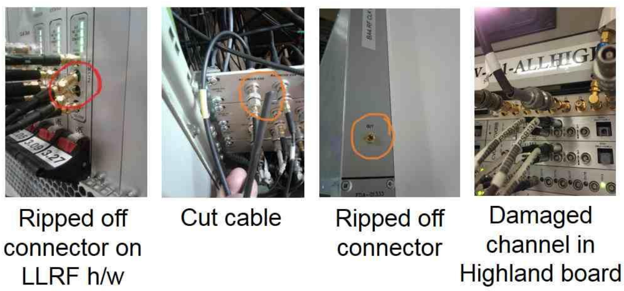


Figure 8: Some hardware damages collateral to the switchboard installation.

The main features to be deployed in the operational rings are the following:

a) To deploy on all rings the firmware for improved beam blowup with the C16 HLRF system.
b) To develop, deploy and commission the noise generation at the $h$=1 harmonic. This noise will be inserted in

the phase loop as well as in the C02 HLRF drive in order to study the replacement of the C16 blowup at a much lower frequency. An initial scheme will be deployed and additional improvements might be needed.

c) To finalise and validate the tasks needed for injection from Linac4 and described by the "Operation with Linac4" section of this note.

d) To prepare for tests with the White Rabbit-based distribution of the B-train values. If possible the tests will be carried out in late 2017. Upgrades of the firmware as well as of the DSP code and FESA classes are needed to acquire the B-train value from the new distribution medium. Comparison with the performance of the current B-train distribution scheme should be done, thus expanding the tests shown in the "Programmable delay to simulate the effects of new B-train distribution scheme" section of this document. The experience gained with the ELENA LLRF and machine, where the LLRF already received the B-train value via White Rabbit, will therefore be extremely useful.

e) To upgrade a certain number of FESA classes to the FESA3 version.

The main features to be deployed in the Ring 0 LLRF are the following:

a) To develop, deploy and commission the noise generation at the $h$=1 harmonic. This noise will be inserted in the phase loop as well as in the Finemet HLRF servoloop at $h$=1. Further improvements of this scheme might be needed, depending on the experimental results obtained.

b) To upgrade the whole Ring 0 LLRF from the current sweeping to a fixed-frequency clock operation. This operational mode is already deployed in ELENA and will be the operational one for all CERN machines equipped with the same LLRF after LS2. From a beam performance viewpoint this upgrade will be transparent, i.e. it will bring no new capabilities apart from a better signal-to-noise ratio. It will be however an important step allowing the beam validation of existing features with the new scheme.

c) To provide the "Beams and RF Studies" section of the RF group with data on LLRF and HLRF behaviours for studies. An example is the phase measurement of the Finemet HLRF when the LLRF servoloops are active.

## CONCLUSION

The PSB LLRF systems are fully operational, provide a higher performance than ever before as well as a very high reliability. New features are however required for beam studies and to prepare for operating the future PSB HLRF and with injection from Linac4.

After LS2 the PSB will restart as a very different machine, equipped with a new, H- injection scheme, HLRF, LLRF, extraction energy, B-train system. Moreover, some key people in the LLRF, HLRF and studies sections will likely have retired by then.

It is therefore essential that we profit as much as possible from the beam before LS2 to validate new approaches and to define the future LLRF system.

## ACKNOWLEDGEMENTS

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All these colleagues of mine were instrumental in the development of the features described in this note as well as for the results obtained.

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