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# OPERATION AND NEW CAPABILITIES OF CERN'S DIGITAL LLRF FAMILY FOR INJECTORS

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*Abstract*

CERN's digital Low-Level RF (LLRF) family for injectors is deployed on CERN's PS Booster (PSB), Low Energy Ion Ring (LEIR), Extra Low ENergy Antiproton (ELENA) ring and Antiproton Decelerator (AD). It implements multiple capabilities, including beam and cavity feedback loops, bunch shaping, longitudinal blowup, bunch splitting and longitudinal diagnostics.

New capabilities are now available and the LLRF family is soon going to be deployed for tests also in CERN's Proton Synchrotron (PS). This paper provides details on the operation and on the new capabilities of this LLRF family. Hints on future evolution are also given.

## DIGITAL LLRF FAMILY OVERVIEW

CERN's injectors digital LLRF family [1] has been instrumental for the success of the upgraded LHC injectors [2, 3]. This is the second generation LLRF for small synchrotrons developed at CERN and is currently deployed on CERN's PS Booster (PSB), Low Energy Ion Ring (LEIR), Extra Low ENergy Antiproton (ELENA) ring and Antiproton Decelerator (AD) [4−7]. Hardware from this family will soon be deployed on CERN's Proton Synchrotron (PS) for tests, as outlined later in this paper. The synchrotron of the MedAustron complex for hadron therapy [8] is also operated by a LLRF system from this family.

This family exploits, on a more powerful hardware, concepts devised and validated in the first generation LLRF, deployed in 2005 in LEIR [9, 10], used for over ten years for PSB machine tests [11] and now obsolete. Based upon modular building blocks at hardware, firmware, software and Graphical User Interface (GUI) levels, it allows better spares management and common maintenance.

Capabilities implemented include cavity phase/amplitude as well as frequency program generation from a magnetic field information and beam phase, radial and injection/extraction synchronisation loops. Both ferrite-based and wide-band, Finemet based High-Level RF (HLRF) systems have been operationally controlled by this LLRF family [12,13], even in the same machine [14].

Initially based upon a sweeping clock, the family now operates mostly on a fixed-clock scheme. This allows seamless handling of the frequency swing and improves the signal-to-noise ratio in the analogue-to-digital and in the digital-to-analogue conversion.

The LLRF family can now interface with the ObsBox, an RF building block initially developed [15] for CERN's Large Hadron Collider (LHC), as outlined later.

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The digital LLRF family has also been adopted by CERN's Beam Instrumentation group to implement the orbit systems for LEIR, AD [16] and ELENA [17].

This allowed two useful developments. First, the LLRF capabilities permit aligning I,Q data from different Transverse pick-ups (TPU) via a frequency-dependent rotation. The aligned I,Q vectors can then be summed to obtain a total vector with higher signal-to-noise ratio. This method was successfully used for calculating Schottky spectra in ELENA [18] as originally planned [19]. Second, the hardware common to orbit and LLRF systems allows real-time data exchange. An example is the orbit measurement digital values received by the LLRF and used as input to the radial loop, as outlined later in this paper.

Table 1 summarizes the main deployment milestones for CERN's digital LLRF family for injectors). The teams in charge of the deployments are also shown, together with the clocking scheme (fixed vs. sweeping) used.

Figure 1 gives an overview of the ELENA LLRF system as an example of some LLRF characteristics, such as multiharmonics operation, integration of the ObsBox system and interfacing via optical fibre with the orbit system.

Table 1: Deployment Milestones for CERN's Second Generation Digital LLRF Family for Injectors. Keys: MA – MedAustron; RF/BI– Radiofrequency/Beam Instrumentation Group; SC/FFC – Sweeping/Fixed Frequency Clock

| When | What | Who |
|---|---|---|
| **2014** | MedAustron LLRF (SC) | MA, RF |
| | PSB 4 rings LLRF (SC) | RF |
| **2016** | AD orbit (SC) | BI |
| | LEIR LLRF upgrade to 2nd generation LLRF (SC) | RF |
| **2017** | ELENA orbit (SC) | BI |
| | ELENA LLRF (FFC) | RF |
| **2018** | LEIR orbit (SC) | BI |
| | LEIR LLRF upgrade to FFC | RF |
| | ELENA LLRF upgrade to in-frequency longitudinal diagnostics | RF |
| **2019** | CERN Long Shutdown 2 | |
| **2020** | PSB LLRF upgrade to all-Finemet HLRF and Linac4 (FFC) | RF |
| **2021** | AD LLRF with in-frequency longitudinal diagnostics | RF |
| **2022** | AD/ELENA LLRF upgrade to ObsBox longitudinal diagnostics | RF |
| **2023** | Beam loops tests in PS (SC) | RF |

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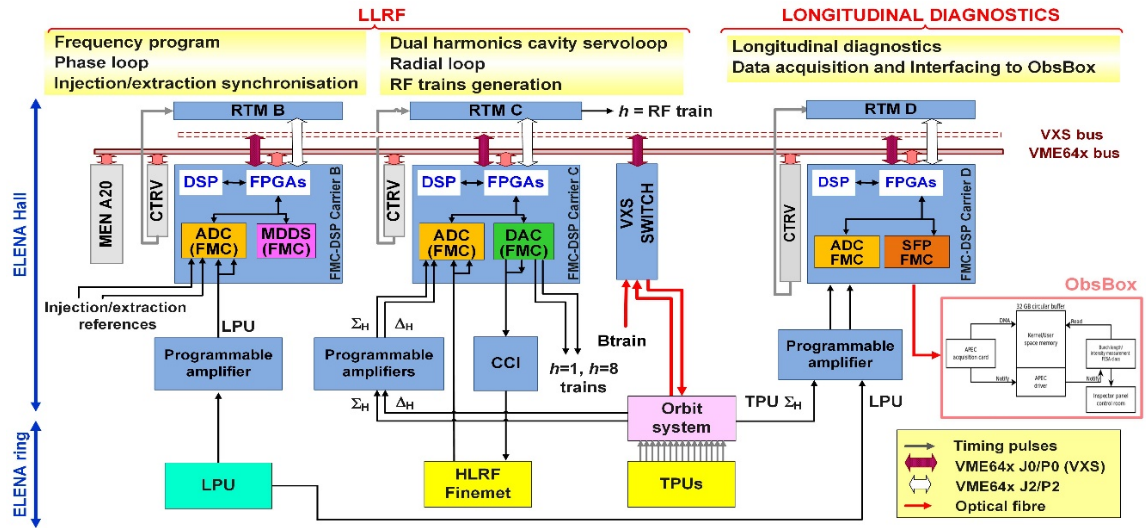


Figure 1: ELENA LLRF and longitudinal diagnostic system. Keys: FMC – FPGA Mezzanine Card, MDDS – Master Direct Digital Synthesiser, ADC – Analogue-to-Digital Converter, DAC – Digital-to-Analogue Converter, CCI – Cavity Control Interface, SFP – Small Form-factor Pluggable Transceiver, CTRV – Timing Receiver Module, MEN A20 – Master VME board, RTM – Rear Transition Module, TPU – Transvers Pick-Up, LPU – Longitudinal Pick-up, Btrain – real-time information on machine magnetic field, ObsBox –CERN RF building block for data processing.

## OPERATION AND NEW CAPABILITIES

The philosophy behind CERN's digital LLRF family for injectors has always been to provide common solutions and approaches for the many accelerators the family operates. Automation in different forms has been introduced over the past few years. All this has allowed easing the maintenance and operational efforts, for stand-by services as well as for experts. This paragraph gives an overview of some common approaches and of recently developed capabilities.

### *Graphical User Interfaces*

Synoptics are used to show the processing flow of each LLRF loop or capability as well as names of diagnostic signals. They also allow setting the corresponding parameters and reading back specific measurements. Figure 2 shows the synoptic for the PSB Btrain filtering, a new capability deployed in the 2023 run and mentioned later in this paper.

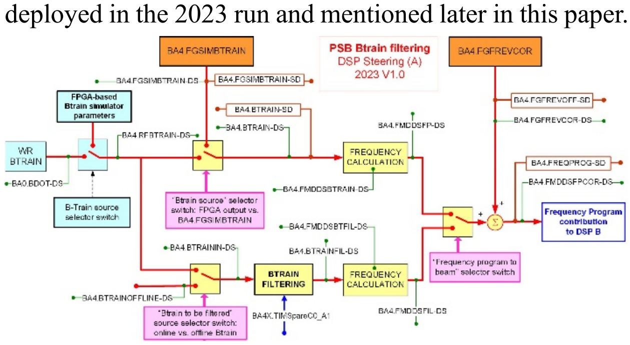


Figure 2: Example of LLRF GUI for PSB Ring4.

Orange boxes are reference functions that can be accessed via double-clicking them. Yellow boxes indicate DSP data processing and light blue boxes are for FPGAs.

Names on green lines are digital diagnostics signals that can be displayed on a virtual scope as a function of time. Signals in brown-outlined boxes are digital signals with a fixed sampling frequency and covering the whole cycle. Signal names are the same across accelerators and their prefix refers to the machine they belong to. In Figure 2, the prefix "BA4" refers to Ring 4 in the PSB.

### *Setup of LLRF Parameters*

Experts setup manually the LLRF parameters for operational cycles in the PSB. New cycles for studies are created by cloning existing, operational ones.

In AD, ELENA and LEIR new cycles are automatically generated from pre-defined values stored in the central database and propagated to all firmware and software modules by dedicated procedures called "RF cycle editors".

In 2023 LEIR has adopted the same LLRF timing structure as AD and ELENA, that is described elsewhere [7].

### *Cavity Voltage Control*

The PSB reference voltage functions are handled by a software layer interfacing the user voltage request for total voltage per harmonic and the servoloops controlling each of the three HLRF systems in a PSB ring. The software layer distributes the total requested voltage per harmonic in a PSB Ring to the three HLRF systems in that ring according to their respective active cells number. It scales down the voltage request for a HLRF system if the vector sum of all programmed harmonic exceeds predefined limits. These limits are now conservatively checked by assuming all voltage functions in the same HLRF system are in phase and using a frequency independent maximum level. More information is available elsewhere [5, 20].

In AD and ELENA the generation of the voltage program and of its many adiabatic captures/debunching during a cycle is handled by the RF cycle editor depending on user parameters. Since 2022 also LEIR is equipped with similar voltage generation facilities.

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### *Firmware and DSP Software Management*

An automatic FPGA firmware and DSP software updating system is available for all modules in the LLRF family. This guarantees that any module replaced in a system is automatically flashed with the firmware and software for the insertion slot. The system also verifies that the installed hardware configuration matches that expected for the slot.

The firmware/software management system is based on a python script, executed in the front-end computer boot sequence or triggered manually for a system maintenance. This automatic method allows saving time and avoiding mistakes for instance for stand-by service interventions.

### *ObsBox*

The ObsBox processing system is now a favourite companion for CERN's digital LLRF family for injectors. Based on a fast computer, fully integrated in CERN's controls infrastructure, it possesses a high processing power and hosts a Linux server running real-time software for online data analysis. It receives via optical fibre data in the time domain sampled and averaged by the LLRF system. Figure 3 shows bunched beam profiles in ELENA acquired in the 2023 run. More details are available elsewhere [21].

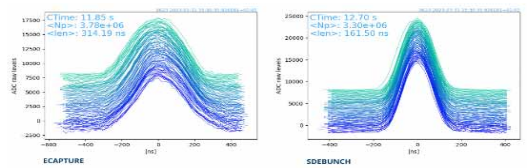


Figure 3: Bunched beam profiles at the start (left) and at the end (right) of a deceleration ramp in ELENA.

### *Orbit Signal as Radial Loop Input*

In AD, ELENA and LEIR the LLRF receives in real time from the orbit system the beam orbit measurement. This can be selected as input to the radial loop instead of the radial position calculated in the LLRF system. In AD and ELENA the radial loop is now routinely closed on the orbit measurement, thus providing a better global correction of the beam position and a smoother radial loop contribution.

### *Frequency Program from Btrain*

The frequency program is derived from magnetic field data, measured or simulated, that the LLRF receives via optical fiber over a White Rabbit (WR) network [22]. Noise in a measured Btrain is transferred to the beam and generates blowup. This was the case for ELENA [6], where workarounds were implemented in the LLRF to reduce the frequency program noise as well as frequency drifts on plateaus. In 2021 the operation team choose to use a simulated Btrain by directly programming a LLRF function.

In AD the frequency program is derived from an imperfectly simulated Btrain and it is several kHz different from the real one. A feedforward frequency correction function and the radial loop compensated for this frequency offset.

In the PSB a new capability was deployed in 2023 to allow filtering the measured Btrain via a 2$^{nd}$ order filter. Figure 2 shows the synoptic depicting this new capability.

### *Beam Control Implementation for CERN's PS*

CERN's PS is currently operated by several LLRF systems, each targeting one or more beams. The plan for its consolidation is to move to a single, flexible LLRF system. This will be achieved by splitting the current systems in two parts: a) a beam control, generating the closed-loop revolution frequency $f_{REV}$ through phase, radial and synchronisation loops and b) several cavity controllers, one per cavity. The beam control part will be implemented by motherboards and FMC modules from the digital LLRF family. It will use a sweeping clock and a modified firmware implementing the loops. Figure 4 shows the final PS LLRF beam control; custom hardware from CERN's digital LLRF family for injectors is shown as blue boxes. In particular, ten motherboards will be used, hosting ADC, SFP or DTX (differential transceiver) FMC modules.

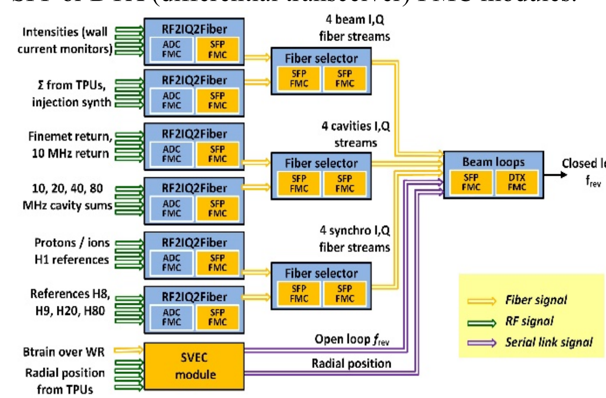


Figure 4: PS LLRF beam control implementation.

Phase and radial loops were developed and partially validated with a laboratory set up. System tests with beam are planned for 2023 and will include a subset of the full system comprising a "Beam loops" and two "RF2IQ2Fiber" boards, hosting the FMC modules shown in Figure 4.

## FUTURE APPLICATIONS

The ObsBox subsystem will be exported to LEIR and the PSB, equipped with the same LLRF, to provide bunched beam measurements. The many LLRF capabilities, packaged in a different form factor, will be used for newly proposed medical machines [23].

## CONCLUSION

Developing the digital LLRF family for injectors was a large RF group manpower investment, well repaid by synergies across the various machines it operates. New applications are under way or planned. A standard RF group building block, the ObsBox, is now interfaced to the LLRF and provides additional diagnostic features.

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