THE NEW LEIR DIGITAL LOW-LEVEL RF SYSTEM

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Abstract

CERN's Low Energy Ion Ring (LEIR) low-level RF (LLRF) system has been successfully upgraded in 2016 to the new digital, LLRF family for frequency-sweeping synchrotrons developed at CERN. For LEIR it implements not only beam loops but also the voltage and phase loops required for the control of two Finemet-based High-Level RF (HLRF) systems. This paper gives an overview of the system and of new requirements implemented, such as the parallel operation of two HLRF systems. Beam results for the 2016 lead ions run are also shown.

INTRODUCTION

LEIR is a 78 m long ion accumulation and acceleration ring in the CERN accelerator complex. Since its commissioning in 2005, O^{4+}, Pb^{54+} and Ar^{11+} ions have been accelerated and extracted; Xe^{39+} will be used for the 2017 run. Table 1 shows the main parameters for Pb^{54+} operation.

Table 1: LEIR Main Parameters for Pb^{54+} Operation

Parameter	Capture	Extraction
Energy	4.2 MeV/u	72 MeV/u
Frequency	361 kHz	1.423 MHz

LEIR has been equipped with an innovative, digital low-level RF (LLRF) system [1] since 2005.

An upgrade to the second generation LLRF family already successfully deployed in CERN's PS Booster [2], in the medical machine MedAustron [3] and in CERN's Extra Low Energy Antiproton Ring (ELENA) [4] was carried out in 2016 for technical and for functional reasons.

Technically, the RIO3 Master VME board failed repeatedly, thus hindering a reliable system operation.

Functionally, parallel control of the two, identical High-level RF (HLRF) systems [5] installed in the ring was required, within the scope of the LHC injectors upgrade project [6] and hoping to increase the beam transmission thanks to a larger bucket. This was not a request for the previous LLRF specifications due to water cooling flow limitations preventing the two HLRF systems from operating at the same time. The cooling limitation was removed in 2010 but the available LLRF processing power did not allow controlling two harmonics on two HLRF systems in parallel without substantially increasing the loop sampling period thus reducing the loops bandwidth.

LLRF SYSTEM OVERVIEW

The LEIR LLRF system is based on the new digital LLRF family for frequency-sweeping synchrotrons developed at CERN [7]. Figure 1 shows the LLRF building blocks, their functions and the input/output signals.

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System Capabilities

These LLRF capabilities encompass those deployed in the previous system. The loops sampling period is decreased from 15 µs to 12.5 µs, thus allowing higher loop bandwidth. The sweeping-clock harmonic is now constant throughout the cycle thanks to the larger sampling window of the analogue-to-digital and digital-to-analogue converters, thus avoiding any phase discontinuity. More (48 vs. 12), parallel, configurable and higher-depth acquisition channels are available as well as additional channels with fixed configuration settings for monitoring. The generation of a simulated magnetic field as a function is also available.

Interface with HLRF

The HLRF systems are short-circuited by mechanical gap relays when no voltage is applied to them to avoid perturbing the accumulated beam. A handshaking protocol is implemented: the LLRF requires the HLRF to open its gap relay and aborts the cycle if a "READY" signal is not obtained within a user-defined timeout of typically 30 ms. A dedicated, custom module (Cavity Control Interface) automatically removes a cavity drive if the corresponding "READY" signal becomes false. The LLRF ramps down the drive signal with a 10 ms ramp before asking the gap relay to close, to avoid fast current transients exciting anode oscillations due to the RF choke.

The HLRF systems can be switched ON/OFF separately at any point in a cycle. The LLRF system carries out the switch-off protocol at the end of the cycle if a HLRF system is not switched OFF or the cycle is aborted. The LLRF implements voltage/phase loops in Cartesian coordinates.

Interface with Other Systems

The LLRF sends an h=1 train to the analogue observation, to the tomoscope [8] and to the transverse feedback systems; an h=8 train is sent to the tune measurement system.

The LLRF makes available to the tomoscope application the acceleration harmonic number and the total voltages at both harmonics when the measurement is triggered. An array with the measured revolution frequency values is given to the chromaticity measurement program. Finally, the revolution frequency value on the injection plateau is given to the new LEIR Schottky system.

System Commissioning

The LEIR LLRF commissioning was divided into two phases. In Phase 1 the LLRF had to provide the same functionality as the previous LLRF. In Phase 2 the LLRF had to implement the parallel control of the two HLRF systems and a method to align their driving signals. Both phases were successfully delivered by July 2016.

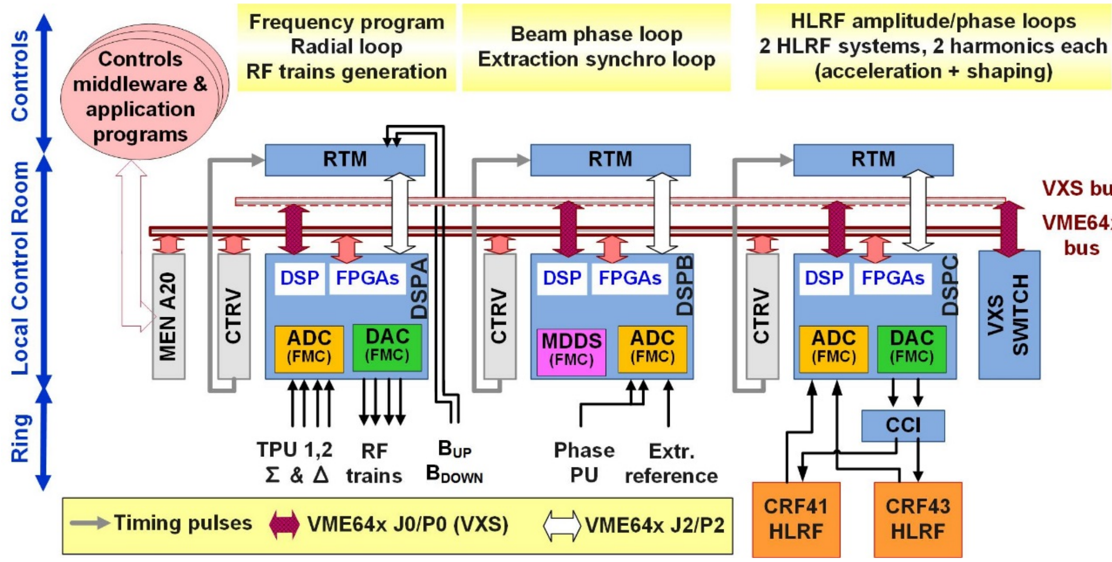

Figure 1: LEIR LLRF schematic view. Keys: MDDS – Master Direct Digital Synthesiser; ADC – Analogue-to-Digital Converter; DAC – Digital-to-Analogue Converted; TPU – Transverse Pick-up; CTRV – Timing Receiver Module; MEN A20 – Master VME board; RTM – Rear Transition Module; CCI – Cavity Control Interface.

BEAM OPERATION

This section includes a selection of capabilities and corresponding beam results. Additional beam results, obtained with the previous LEIR LLRF system and available also with the current one, are found elsewhere [1].

Capture, Frequency Program and Beam Loops

Differently from CERN's PS Booster [2], the LEIR cycle features an injection plateau allowing an iso-adiabatic capture to be programmed. The voltage is ramped to its desired final value in about 60 ms which gives an adiabaticity coefficient of about 0.1. The frequency follows the magnetic field from the beginning of the cycle. The beam phase and the radial loop are enabled soon after the capture has started. An extraction synchronisation loop which locks in frequency and in phase the circulating bunch(es) to an external reference is enabled 30 ms prior to extraction. Figure 2 shows the frequency contributions measured in Hz from the frequency program (green trace) and from the various loops for a Pb^{54+} NOMINAL cycle.

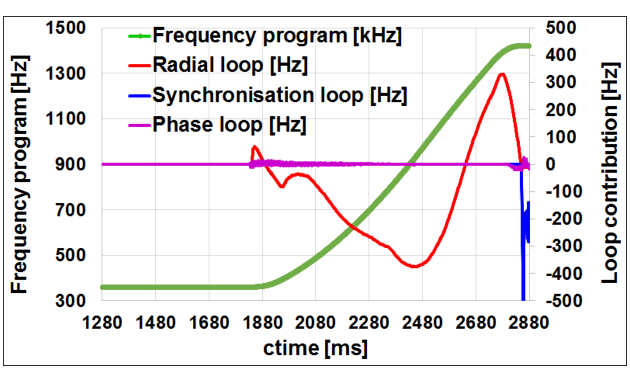

Figure 2: Frequency program (left axis) and loop contributions (right axis) for a Pb^{54+} NOMINAL cycle.

Extraction Synchronisation Loop

The LEIR LLRF system profits from the same optimised extraction synchronisation algorithm already deployed in CERN's PS Booster [2]. Figure 3 shows the evolution of the beam-to-extraction reference phase for the optimised (yellow trace) vs. non-optimised (white trace) algorithms, after the two signals have reached a beating relation. The phase (hence the frequency) overshoot at the synchronisation phase loop closure is clearly minimised, thus avoiding a potential beam blowup.

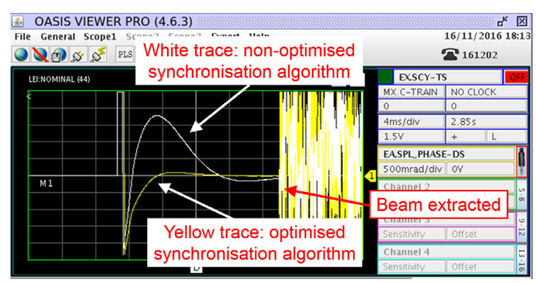

Figure 3: Beam-to-extraction reference phase signals during the extraction synchronisation loop. White trace: non-optimised algorithm. Yellow trace: optimised algorithm.

HLRF Systems Alignment and Beam Results

The accelerating harmonics of the two LEIR HLRF systems were aligned first by using new dedicated LLRF diagnostics signals, then by observing the beam via the tomoscope application. The high reproducibility of the beam obtained with the frequency offset modulation, described later in this section, was instrumental to enable the fine tuning of the HLRF phasing. Figure 4 shows two almost-identical tomograms for an h=2+4 beam. In the left-hand plot only one HLRF system was used whilst in the right-hand plot both HLRF systems were used and the accelerating voltage was equally split between the two.

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The beam phase loop could be successfully closed by using the gap return signal of either HLRF system.

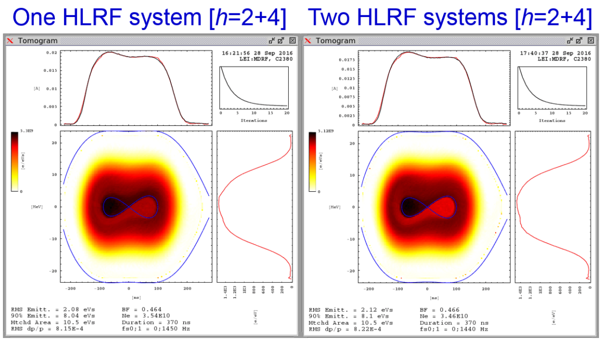

Figure 4: Almost-identical tomograms for an *h*=2+4 beam achieved with one (left) and two (right) HLRF systems.

The expectation was that the transmission could have been improved by the combination of a larger bucket, given by the overall higher available voltage, and of the emittance blowup, resulting from the frequency offset function modulation. However in October 2016 an acceptance limit of about 7 MeV on the injection plateau was demonstrated, which precluded a transmission improvement by double-HLRF operation. This mode remains available for machine studies.

Hollow Bunches Formation

A first attempt to improve the transmission was carried out by optimising the voltage program and frequency offset at capture so as to have the beam smeared around the outer side of the inner seperatrix, as shown in Fig. 5. Maintaining the inner seperatrix through the ramp allowed keeping the flat bunches throughout, thus improving the transmission.

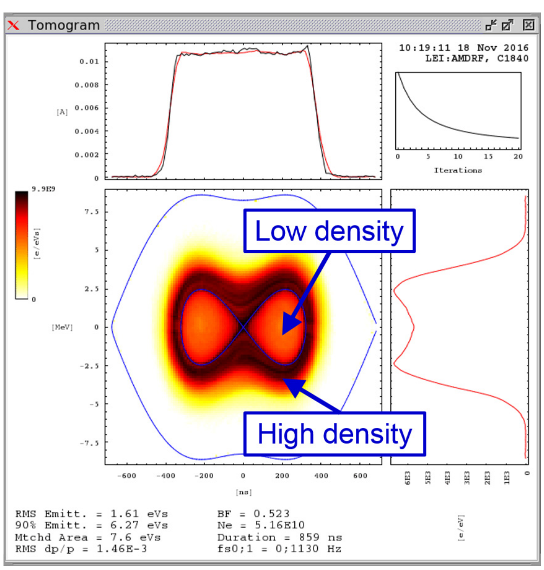

Figure 5: Hollow bunch after capture, showing a remarkably flat profile.

Frequency Offset Function Modulation

The fixed frequency derived from the measured magnetic field was modulated during the capture process by using a dedicated LabView-based application and via a time-dependent function, shown in Fig. 6. An initial frequency of 50 Hz was linearly increased to 450 Hz over a time-span of about 53 ms. This innovative method produced an uniform distribution in phase space with very high reproducibility. This was a key-ingredient of the intensity record of more than 10^{10} charges extracted obtained in LEIR on December 1st 2016.

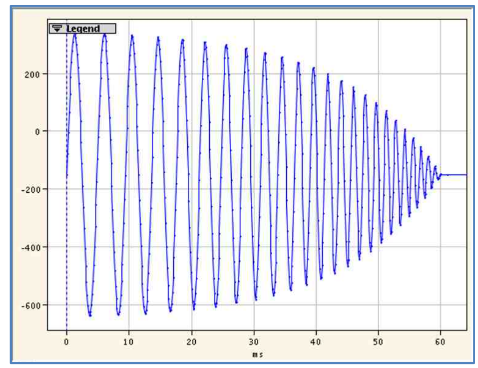

Figure 6: Modulated frequency offset function during the first 60 ms of the beam capture process.

OUTLOOK AND SYSTEM EVOLUTION

No additional LLRF features are required specifically for the 2017 xenon run. However, new features for beam studies and operation are required within the scope of the LHC injectors upgrade, in view of future lead runs. This underlines the importance of having a powerful, flexible and upgradable LLRF to allow the machine optimisation.

For the 2017 run the new LLRF will interface via optical fiber with the new LEIR orbit and turn-by-turn measurement system, built with the same hardware family as the LLRF. In particular, the LLRF will provide the revolution frequency value in real time and will receive the measured mean radial position. An operation at *h*=3+6 will also be attempted, to increase the extracted number of bunches.

In the longer term integration with the new B-train system, presenting different electrical distribution format and resolution, will be carried out. Additional features such as controlling more harmonics per HLRF system could also trickle down to LEIR thanks to synergies with other planned LLRF upgrades [9].

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