INITIAL BEAM RESULTS OF CERN ELENA'S DIGITAL LOW-LEVEL RF SYSTEM

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Abstract

The Extra Low ENergy Antiproton (ELENA) decelerator is under commissioning at CERN. This decelerator is equipped with a new digital low-level RF (LLRF) system, in-house developed and belonging to the LLRF family already deployed in CERN's PS Booster and Low Energy Ion Ring (LEIR) synchrotrons. New features to adapt it to the demanding requirements of ELENA's operation include new, low noise ADC daughtercards and a fixed-frequency clocking scheme. This paper gives an overview of the LLRF system; initial beam results are also shown together with hints on the future system upgrade.

INTRODUCTION

The Extra Low ENergy Antiproton (ELENA) decelerator is under commissioning at CERN [1]. Table 1 shows its main parameters for operation with CERN's Antiproton Decelerator (AD). ELENA will also receive beam from a dedicated H^-/proton source at low (extraction) energy.

Table 1: ELENA Main Parameters for Standard Operation

Parameter	Injection	Extraction
Momentum, MeV/c	100	13.7
Magnetic field, mT	359.8	49.3
Revolution frequency, kHz	1044.3	143
Expected particles number	$3\cdot10^7$	$1\cdot10^7$

ELENA is equipped with the same innovative, in-house developed digital Low-Level RF (LLRF) system already deployed in CERN'S LEIR [2], PS Booster [3] and in the medical accelerator MedAustron [4]. Figure 1 gives a qualitative view of the ELENA commissioning cycle, which last several seconds. Beam is injected from the source and the red segments, referred to as "RF segments", show when the LLRF is expected to act on the beam. Different operational cycles are also envisaged.

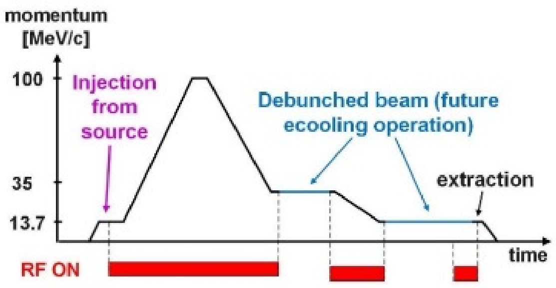

Figure 1: Qualitative view of an ELENA cycle for commissioning when beam is injected from the H^- source. The red RF segments show when the LLRF voltage is active.

LLRF SYSTEM OVERVIEW

Figure 2 shows a schematic view of the ELENA LLRF system. Two boards interact in real time to carry out the requested capabilities. Inputs are taken from the new, high-sensitivity magnetic pick-up, evolution of that used in CERN's AD [5], from a Transverse Pick-up (TPU) as well as from the orbit system [6]. The LLRF receives the measured magnetic field value via optical fiber from the new B-train system. The LLRF interfaces also with the High-Level RF (HLRF) system, as detailed later on.

Hardware and Software

Two main improvements were implemented with respect to a previous description of the main hardware and software blocks [7]. First, a new, low-noise FMC-ADC board with two gain settings was developed. The input signal range permitted varies from 700 mV peak to peak over 50 ohms for the 0 dB gain setting to 300 mV for the 20 dB gain setting. The noise voltage density is 5.8 nV/√Hz for the 20 dB gain setting and 27 nV/√Hz for the 0 dB gain setting. Second, the sweeping clocking scheme is replaced by a 122.7 MHz fixed clock scheme [8]. This allows obtaining optimal signal-to-noise performances by the Analogue-to-Digital and Digital-to-Analogue converters. New sophisticated firmware, resulting from a major theoretical research carried out in-house, deals with the wide revolution frequency sweep.

System Capabilities

Frequency program, beam phase and radial loops are implemented. The radial loop input can be selected from a single TPU or from the mean radial position measured by the beam orbit system. As all ELENA TPUs are in a dispersive region, the latter might reduce the systematic error of the momentum offset measurement caused by the closed orbit. An injection synchronisation loop allows injecting bunched beam from the AD into an ELENA waiting bucket. An extraction synchronisation loop locks the bunches to an external reference, thus improving the reproducibility of the energy for the extracted bunches; the extraction reference is also sent to the experiments. Acceleration/deceleration and shaping capabilities are provided by a double harmonic control of the HLRF system. The LLRF embeds a simulated Btrain generator for hardware tests/commissioning, as this is not yet available from the distributed Btrain system. The LLRF provides 32 observation channels to acquire diagnostics data; each channel includes four, 2048-samples buffers to store the data, minimum, maximum and acquisition time values. Additional buffers are also available. Finally, up to 256 timings and 32 reference functions can also be generated.

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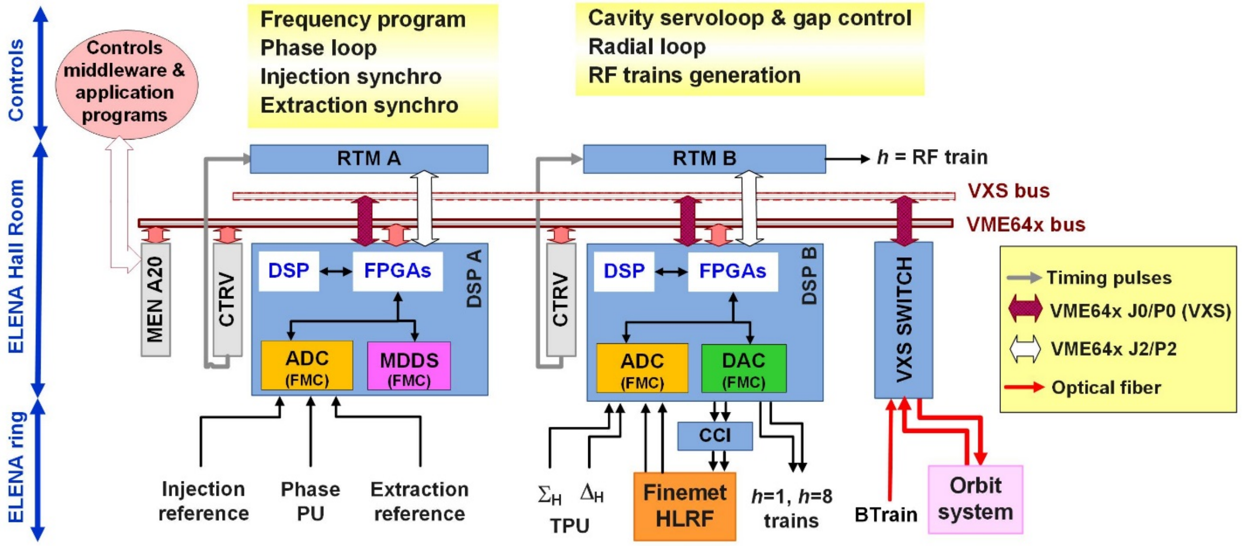


Figure 2: ELENA LLRF schematic view. Keys: MDDS – Master Direct Digital Synthesiser; ADC – Analogue-to-Digital Converter; DAC – Digital-to-Analogue Converted; TPU – Transverse Pick-up; CTRV – Timing Receiver Module; MEN A20 – Master VME board; RTM – Rear Transition Module; CCI – Cavity Control Interface.

System Operation

The ELENA cycle is very different from that of the other machines equipped with the same LLRF, hence upgrades were needed. The cycle is tens of seconds long thus diagnostics data must be available during the cycle and not only after its end. The cycle duration and composition can be changed and the main LLRF parameters are automatically re-calculated by the ELENA RF cycle manager. Finally, “PAUSES” where the execution of the magnetic cycle is stopped, can be added; during “PAUSES” the LLRF internal timing as well as functions are frozen but the LLRF keeps operating as before the “PAUSE” was started.

Operation of ELENA’s HLRF System

A double-harmonic control of the HLRF voltage is required to provide acceleration/deceleration and shaping capabilities. The harmonic numbers are the same for a RF segment but can be changed in different segments. The shaping capabilities are needed by the extraction process. The wide-band, non-tuneable HLRF system is based on a Finemet magnetic alloy. Table 2 shows the available voltage as a function of frequency.

Table 2: HLRF voltage as a function of frequency.

Frequency range [kHz]	Max voltage [V]
143 – 500	100
500 – 2300	500
Outside above ranges	0

Voltage and phase loops are implemented by the LLRF in Cartesian [I,Q] coordinates. A sophisticated mechanism to measure in the LLRF the HLRF transfer function and compensate for it has been implemented in the firmware to cope with the HLRF transfer function and with the huge sweep in revolution frequency. Figure 3 shows the detected vs. programmed voltage for a feedback (upper plot) and a feedforward (lower plot) operation.

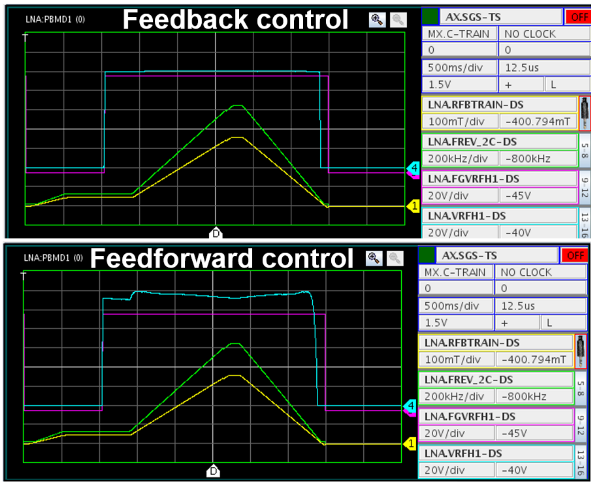


Figure 3: HLRF voltage feedback (upper plot) vs. feedforward (lower plot) control. Traces: measured magnetic field (yellow); revolution frequency (green); programmed voltage (pink); detected voltage (blue).

The feedback operation used both amplitude and phase compensation tables, whilst the feedforward operation shown in Fig. 3 used the phase compensation table only, hence the discrepancy between programmed and detected values.

Interface with Other Systems

The LLRF system provides the revolution frequency value in real-time to the orbit system, and receives from it the measured mean radial position. The h=1 train is sent to the analogue data acquisition and to the tomoscope [9] systems. An h=RF train is sent to the timing and an h=8 train is sent to the tune measurement systems.

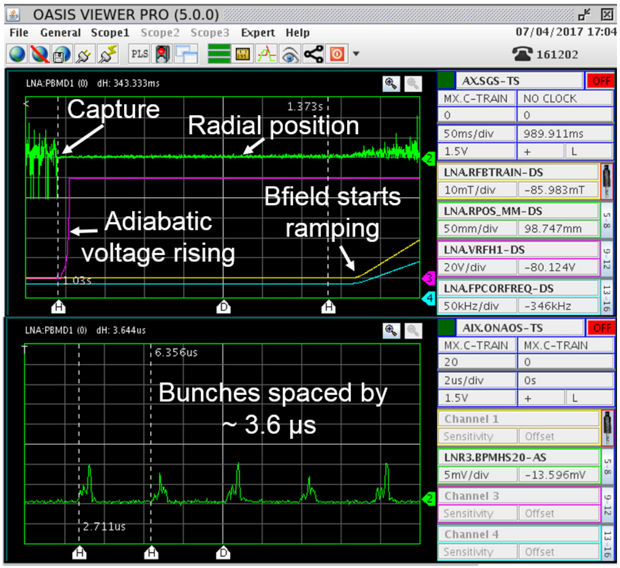
The LLRF makes available to the tomoscope application the acceleration harmonic number and the voltage at both harmonics, acquired when the tomoscope measurement is started.

INITIAL BEAM RESULTS

Beam results are somehow scarce as the ELENA beam commissioning was delayed for various reasons.

Current operation is done with beam injected at a momentum of 12.6 MeV/c, lower than its nominal value. This corresponds to a revolution frequency of 130.7 kHz, outside the cavity operational range, hence the beam is captured at h=2. Furthermore, the new magnetic measurement system is not yet fully calibrated and provides a measurement at injection which is offset by 1 mT with respect to what the beam experiences. Successful beam capture was nevertheless achieved by adding 2100 Hz to the frequency program value at capture, thanks to the frequency offset function embedded within the LLRF system. A pseudo-adiabatic voltage program was implemented, ramping the voltage from 0 V to 100 V in about 10 ms; this was however applied before the injected beam could fully debunch. Future LLRF setting up tasks will include adjusting the adiabatic voltage ramp duration, once the momentum spread of the incoming beam is known.

The beam is kept bunched for about 400 ms, until the magnetic ramp starts. The upper plot in Fig. 4 shows the LLRF diagnostics signals on the initial plateau, and in particular the radial position (green trace), the voltage program (pink trace) and the magnetic field (green trace). The lower plot shows a zoom on the bunches as seen from the sigma signal of a TPU. The measured bunch spacing of about 3.6 µs corresponds to an h=2 capture. An offline analysis of the measured bunch profiles hints a tentative number of up to $1.5 \cdot 10^6$ captured H^- charges.

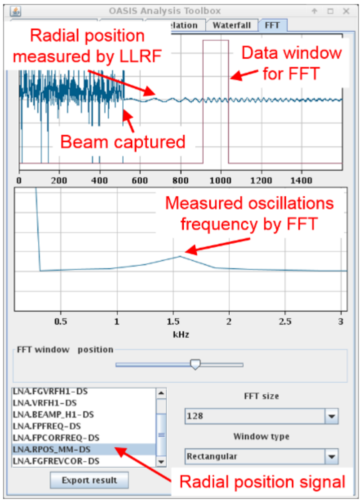


AX.SGS-TS
MX.C-TRAIN | NO CLOCK
0 | 0
50ms/div | 989.911ms
1.5V | + | L
LNA.RFBTRAIN-DS
10mT/div | -85.983mT
LNA.RPOS_MM-DS
50mm/div | 98.747mm
LNA.VRFH1-DS
20V/div | -80.124V
LNA.FPCORFREQ-DS
50kHz/div | -346kHz

AIX.ONAOS-TS
MX.C-TRAIN | MX.C-TRAIN
20 | 0
2us/div | 0s
1.5V | + | L
Channel 1
Sensitivity | Offset
LNR3.BPMHS20-AS
5mV/div | -13.596mV
Channel 3
Sensitivity | Offset
Channel 4
Sensitivity | Offset

Figure 4: Upper plot: LLRF signals on injection plateau. Traces: magnetic field (yellow); measured radial position (green); detected HLRF voltage (pink); frequency program (blue). Lower plot: bunched beam on a shorter timescale.

A synchrotron frequency f_S of ~1.5 kHz could be derived by the radial oscillation FFT analysis. Figure 5 shows the radial position measured by the LLRF system without radial and phase loops, the data window selected for the FFT and the resulting f_S value.



LNA.FGVRFH1-DS
LNA.VRFH1-DS
LNA.BEAMP_H1-DS
LNA.FPFREQ-DS
LNA.FPCORFREQ-DS
LNA.RPOS_MM-DS
LNA.FGFREVCOR-DS

FFT size: 128
Window type: Rectangular

Figure 5: Synchrotron frequency obtained by FFT of radial position oscillations as measured by the LLRF system.

OUTLOOK AND FUTURE WORK

The LLRF commissioning will continue in 2017 and additional capabilities will be deployed. These include injection and extraction loops to receive beam via a bunch-to-bucket transfer from the AD and to extract beam to the GBAR experiment.

A new digital processing system to measure the beam intensity and to analyse Schottky signals will be implemented as an add-on to the LLRF. This system will process the signal coming from the newly designed high-sensitivity magnetic PU, as it is now done in the AD [10]. The data processing developed for this purpose will also be the key ingredient to implement the same diagnostics via an innovative, distributed electrostatic pick-up scheme [11].

Many new concepts deployed in ELENA will be exported to the other CERN machines equipped with the same LLRF. The decoding of the new Btrain format will be used in CERN's PSB [12] and LEIR [3] for tests before Long Shutdown 2 (LS2) and will become the new standard. The fiber optic–based interface with the orbit system will be deployed in LEIR in 2017 to interface with LEIR's new orbit system. The compensation table scheme used in the ELENA HLRF servoloops will be deployed in CERN's PSB and LEIR to increase their loop stability margins. The fixed clocking scheme will be deployed in all machines after LS2 and will become the new LLRF clocking standard.

Finally, within the scope of the AD consolidation program [13], the AD HLRF will be upgraded to a Finemet-based system in LS2. The ELENA LLRF and longitudinal diagnostics systems will then be exported to the AD, too, in preparation for its restart in 2020.

ACKNOWLEDGMENTS

The long lasting collaboration between CERN, KEK and J-PARC on wideband, MA loaded cavities studies as well as the various Japanese contributions (MA cores, amplifiers, radiation testing, etc.) played a very important role for this project. They have been sincerely appreciated and are gratefully acknowledged.

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