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THE NEW DIGITAL LOW-LEVEL RF SYSTEM FOR CERN'S EXTRA LOW ENERGY ANTIPROTON MACHINE

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Abstract

CERN's new Extra Low ENergy Antiproton accelerator/decelerator (ELENA) completed its initial commissioning in 2018. This machine is equipped with a new digital Low-Level RF (LLRF) system that implements beam and cavity loops as well as longitudinal diagnostics. ELENA's LLRF was instrumental for machine commissioning by decelerating some 1 E7 antiprotons from 5.3 MeV to 100 keV. Commissioning with H^- ions took also place. Challenges faced included coping with low beam intensity and the wide frequency swing. This paper gives an overview of the LLRF system capabilities and operation. Beam results achieved with both H^- ions and antiprotons are also shown.

INTRODUCTION

CERN's Extra Low ENergy Antiproton (ELENA) ring underwent its second full year of beam commissioning in 2018. Table 1 shows ELENA's main parameters for operation with antiprotons taken from the Antiproton Decelerator (AD). Figure 1 shows the corresponding cycle, including the segments where the RF is active and the beam is bunched. ELENA can also take beam from an ion source capable of generating H^- ions as well as protons.

Table 1: ELENA Parameters for Antiprotons Operation

Parameter	Injection	Extraction
Energy, MeV	5.3	0.1
Magnetic field, mT	359.8	49.3
Revolution frequency, kHz	1044.9	144
Number of particles	$3 \cdot 10^7$	$1.8 \cdot 10^7$

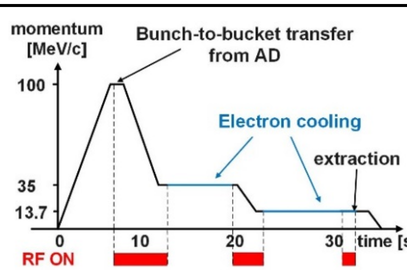

Figure 1: ELENA cycle for antiprotons operation.

The 2018 ELENA's commissioning was successful, despite a lack of beam availability. In particular, the ion source stopped operating in September 2018. It was also powered by its spare insulation transformer thus providing ions at the lower-than-nominal energy of 85 keV. The AD suffered from faults that caused several weeks of downtime. Major progress includes the electron cooler commissioning and the extraction of antiprotons/H- ions to the GBAR experiment [1]. ELENA's in-house developed Low-Level RF (LLRF) was instrumental in enabling both tasks.

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LLRF SYSTEM OVERVIEW

Figure 2 shows a schematic view of the ELENA LLRF system. With respect to a previous description [2], programmable amplifiers are added to better match the input signal level to the analogue-to-digital converters in the LLRF acquisition path. Two external reference signals are sent to the LLRF system to carry out the injection and the extraction synchronisation loops, used for bunch-to-bucket transfer into ELENA from AD and for beam extraction towards the experiments, respectively.

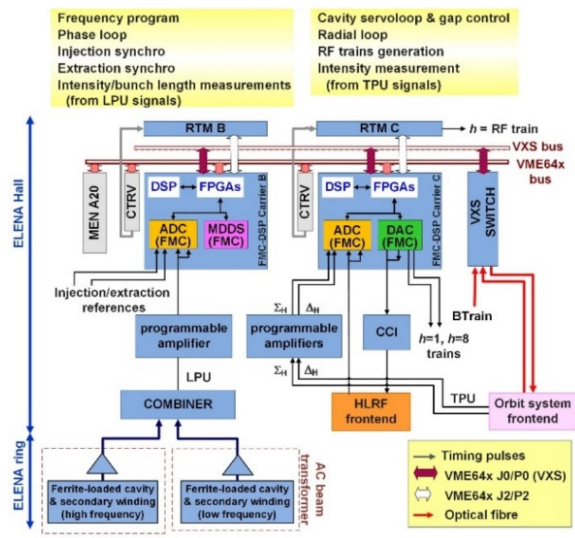

Figure 2: LLRF layout. Keys: MDDS – Master Direct Digital Synthesiser, ADC – Analogue-to-Digital Converter, DAC – Digital-to-Analogue Converter, CTRV – Timing Receiver Module, MEN A20 – Master VME board, RTM – Rear Transition Module, CCI – Cavity Control Interface, LPU/TPU – Longitudinal/Transverse Pick-Up.

NEW LLRF CAPABILITIES

Frequency Program Calculation

In 2017 we found the frequency program not to follow the Btrain continuously but to show a step-like behaviour. The step amplitude depended on the Btrain and could reach 40 Hz at low energy. The reason was the limited processing resolution of single-precision floating point arithmetic when applied to very low Bfield values. The solution required optimising the numerical implementation of the frequency program and provided sub-Hz resolution also at low energy. This new frequency program showed fluctuations caused by oscillations in the acquired Btrain. The previous frequency program masked such oscillations which still cannot be eliminated. ELENA operations required minimising the fluctuations passed to the beam by adding a smoothing filter to the frequency program.

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Injection Synchronisation Loop

A bunch-to-bucket transfer is implemented to inject a single antiproton bunch from AD to ELENA. The ELENA bucket is synchronised to the same reference given to the AD extraction synchronisation loop. Phase and radial loop are enabled a few ms after the bunch is transferred into ELENA's waiting bucket. A dedicated timing allows leaving the fixed synchronised frequency and moving adiabatically to the frequency program, calculated in real-time from the measured magnetic field.

Extraction Synchronisation Loop

The extraction synchronisation loop, deployed in July 2018, allows extracting H^- ions or antiproton bunches to GBAR in a repeatable way. The basic mechanism consists of frequency steering followed by a synchronisation phase loop; it is already operational in other CERN machines equipped with the same LLRF [3, 4]. The beam harmonic number h is user-selectable and takes on the values 1, 2 or 4. The reference signal for 2018 has $h = 1$, although other options exist. Figure 3 shows the extraction synchronisation process for an antiproton beam at $h = 4$ and a reference at $h = 1$. The measured beam-to-extraction reference phase is remarkably smooth, thus preserving the quality of the beam obtained previously in the cycle.

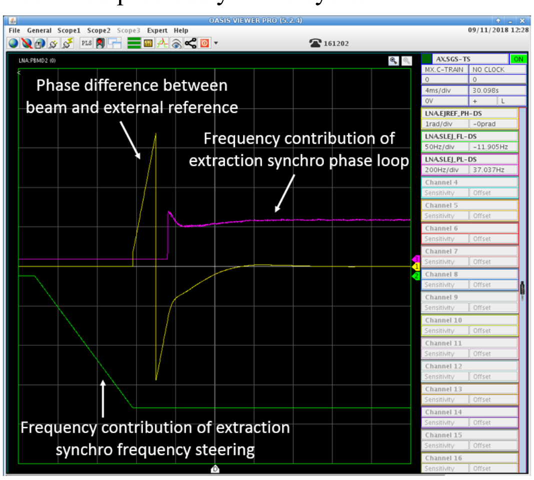

Figure 3: Extraction synchronisation process for an antiproton beam at $h = 4$ and a reference at $h = 1$.

Operation with RF Segments

ELENA requires portions of the cycle where the RF is active, called RF segments, interleaved with portions when the RF is inactive where other actions (such as the electron cooling) take place. Typically an RF segment includes a ramp preceded and followed by some small portions of flat frequency. Up to eight segments can be programmed in a cycle, each with different parameters, such as the RF harmonic number. Figure 4 shows a typical operational antiproton cycle including three RF segments operated at h = 1, 4 and 2, respectively. The harmonics commissioned with beam are shown at the bottom of the plot. A Matlab script allowed adapting the LLRF settings to a change of cycle length, whilst waiting for integration with the future ELENA RF cycle editor.

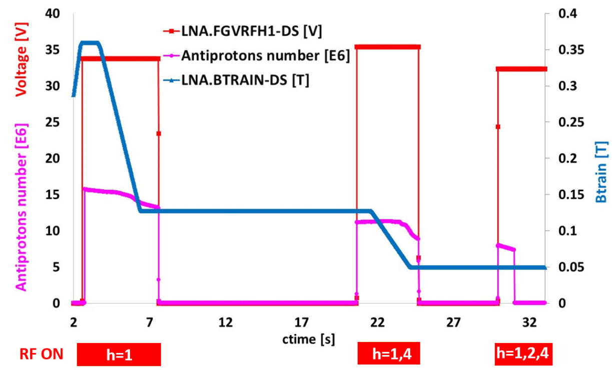

Figure 4: Antiproton cycle with three RF segments and h = 1, 4, 2. Traces: Btrain [blue], voltage program [red], bunched beam intensity [pink].

Extended Cavity Limits

The LLRF implements the cavity servoloops at each operational harmonic and enforces limits on the reference voltage as a function of frequency. The aim is to avoid overdriving the High Level RF (HLRF) system.

The voltage limits are given by HLRF experts. Those imposed in 2017 [2] require operating at $h = 2$ with the source powered by the spare insulation transformer. In fact, no voltage is allowed at the injection frequency of 132 kHz, corresponding to an energy of 85 keV. To keep operating at the same h value used with the nominal source energy, extended cavity limits were deployed after a series of HLRF tests. Table 2 shows the limits implemented in the LLRF, including transition between two voltage levels; this enables the servoloop to smoothly follow its voltage program.

At the end of the 2018 run the HLRF was modified to provide a maximum voltage of 100 V, in an effort to reduce noise transferred to the beam. The cavity voltage limits were scaled down accordingly.

Table 2: Extended Cavity Voltage Limits in the 2018 Run

Frequency range [kHz]	**Max Voltage [Vpeak]**
120 - 140	Linear interpolation, 30 V to 100 V
140 - 500	100 V
500 – 600	Linear interpolation, 100 V to 500 V
600 – 2300	500 V
Elsewhere	0 V

Longitudinal Diagnostics

Traditional DC beam transformers do not work at ELENA's low intensity hence alternative measurements were developed. Longitudinal diagnostic capabilities are included in the LLRF. Bunched-beam intensity and bunch length are obtained by measuring the first Fourier components of downconverted data. Input signals come from both Longitudinal Pick-Up (LPU) and Transverse Pick-Up, shown in Figure 1. For LPU signals, an analysis based upon two RF harmonics is also available, similarly to what was implemented for the AD [5]. A drawback of this method is that the measured intensity depends on the bunch shape;

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improvements to remove this dependence are planned. Figures 4 and 5 show examples of intensity measurements obtained during the 2018 ELENA run.

An empirical intensity calibration was done by equating the value measured at injection into ELENA to that measured with a different system at extraction from the AD. This calibration is optimistic as it does not account for losses in the ELENA injection line; new methods are under study. Nevertheless, the intensity measurements provided by the LLRF system were instrumental to verify machine efficiency progress.

LLRF OPERATION WITH H- IONS

The ion source is synchronised with the LLRF by receiving the revolution frequency train. A single RF segment is used as no cooling is carried out before extracting beam to GBAR. Figure 5 shows the H- operational cycle for the 2018 run. The H- beam at 85 keV energy is transferred into an ELENA waiting bucket. Phase and radial loops are enabled, then the energy is ramped from injection to nominal extraction at 100 keV. Here the extraction synchronisation loop is started and the beam is extracted.

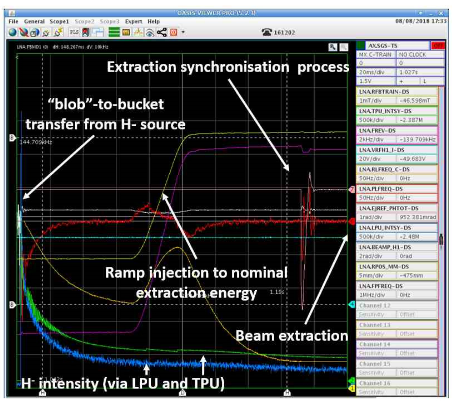

Figure 5: Typical H- production cycle in 2018.

LLRF OPERATION WITH ANTIPROTONS

A single bunch extracted from the AD is transferred into an ELENA waiting bucket. Beam is then decelerated at h = 1 and debunched. Phase and radial loops are enabled during the ramp; adiabatic bunching/de-bunching take typically 20 ms. A second deceleration by another RF segment can use a different h. Preliminary tests seem to indicate reduced losses on the second ramp if a higher h is used.

The beam is de-bunched again for electron cooling. Finally, the beam is re-bunched and extracted after synchronising to an external reference, also sent to the extraction kicker and to GBAR. Bunch rotation or bunched beam cooling are performed before extraction to give shorter bunches. The two combined processes were applied to a beam at h = 1; a bunch length of 200 ns was obtained from an initial one of 600 ns, as seen in Figure 6. The bunch rotation, implemented by abruptly changing the voltage amplitude, generated synchrotron oscillations, that will be removed in future runs. Figure 7 shows four bunches synchronised and extracted, as seen on the extraction line. The vertical scale is different for the two plots.

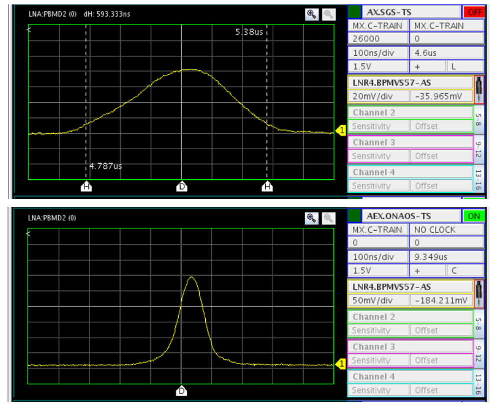

Figure 6: Bunch length before (top) and after (bottom) combined bunch rotation and bunched beam cooling.

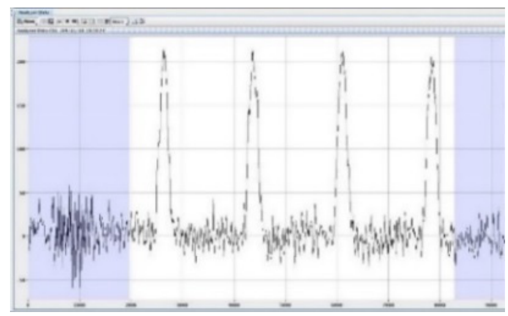

Figure 7: Four synchronised bunches after extraction.

OUTLOOK AND CONCLUSIONS

ELENA will restart beam commissioning with H- ions in 2020 and with antiprotons in 2021. Presently the LLRF includes all needed functionalities; its settings will be integrated in the new ELENA RF cycle editor. Features already present, such as the shaping voltage program, will be commissioned. The remote control of the programmable amplifiers' gain, seen in Figure 1, will be deployed.

The longitudinal diagnostics will be improved by adding a dedicated motherboard, the FMC-DSP-Carrier board D, which will process the downconverted data. Debunched beam data will also be treated and Schottky spectra and $\Delta p/p$ values will be measured. The ObsBox, successfully deployed in other CERN machines [6], will be integrated in the system as a powerful add-on. It will receive, over optical fibre, data digitized by the ADC FMC on the FMC-DSP-Carrier board D and will process in time bunched and de-bunched beam data. The bunched-beam intensity will be obtained by integrating the bunch profile and subtracting its baseline; this removes the dependence on bunch shape. In the longer term, the ObsBox will process also data coming from ELENA's distributed pick-up [7, 8].

In 2021 ELENA's LLRF and longitudinal diagnostics will be customised and exported to CERN's AD [9].

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