

THE ORBIT MEASUREMENT SYSTEM FOR THE CERN EXTRA LOW ENERGY ANTIPROTON RING

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Abstract

The CERN Extra Low ENergy Antiproton ring (ELENA), intended to further decelerate anti-protons coming from the CERN Antiproton Decelerator (AD) from a momentum of 100 MeV/c to 13.7 MeV/c, has been equipped with an orbit measurement system consisting of 10 horizontal and 10 vertical electrostatic pick-ups. Using charge amplifiers the signals are converted into sum and difference signals that, once digitized, are down converted to baseband and used to calculate intensity independent beam positions. The system is implemented on seven VME switched serial based (VXS) FPGA / DSP boards carrying direct digital synthesisers and analogue to digital converters on standard FPGA mezzanine cards. The switched serial high-speed bus allows intercommunication between DSPs and thus averaging of the signals from all pick-ups in real-time to be used either in the RF radial feedback system or for longitudinal Schottky diagnostics. The system implementation and initial orbit measurements with the H⁻ beam used for ELENA commissioning will be presented, as well as future upgrades for trajectory and longitudinal Schottky measurements.

INTRODUCTION

An overview of the ELENA Orbit system is given in [1]. The system is being implemented in steps; the closed orbit measurement, the trajectory measurement and the longitudinal Schottky measurement. The analogue and digitization electronics are common to all measurements, the difference coming from the subsequent treatment of this data in the Field Programmable Gate Array (FPGA) and Digital Signal Processing (DSP) code. The orbit measurement is already operational and is being used for the ELENA commissioning, with first measurements presented here. Trajectory and longitudinal Schottky measurements will follow in the future.

The ELENA orbit system is built with the same VXS-DSP-FMC-carriers and FMC boards as the CERN AD orbit system [2] and the Firmware, DSP code and real-time software share a common base.

ELENA is CERN's Extra Low ENergy Antiproton ring intended to decelerate antiprotons injected at an energy of 5.3 MeV from the CERN AD to 100 keV. To minimize impact on the CERN AD physics program the ELENA ring is initially being commissioned using H⁻ ions injected at the intended antiproton extraction energy. Due to problems with the H⁻ source the achieved energy has only reached 85 keV, challenging the low energy end of the RF system, and

forcing the system to run at the second RF harmonic (2·132 kHz). The orbit measurement system, measuring the beam position from a signal down mixed to baseband, has been designed to follow this.

The system

The orbit system consists of electrostatic pick-ups equipped with charge amplifiers, preamplifiers and VXS-DSP-FMC-Carriers [3]. The charge amplifiers send sum and difference signals from the pick-ups, via preamplifiers to ADCs placed on FMC boards. The ELENA RF system sends the actual revolution frequency as an integer value via an optical gigabit link, from which the orbit system will generate its own local oscillator frequency on the wanted harmonic used for digital down mixing of the sum and difference signals. Position calculations are performed in DSP modules and the results are sent to the real-time software that makes the data available to the control room. The orbit system also computes a real-time mean radial horizontal position for the RF radial feedback. The system is only capable of producing beam position data during the times when the beam is bunched.

INITIAL MEASUREMENTS

All pick-up signals after the charge and pre-amplifier are also made available to the CERN Oasis system (an online oscilloscope) allowing operators to plot the beam sum or difference signal from any pick-up. During commissioning of ELENA the H⁻ beam is injected using a 700 ns kicker pulse, which for a revolution frequency of 132 kHz (energy 85 keV) results in a bunch like structure even before RF is applied (Figure 1). The number of charges, N_q Eq (1) has been estimated, knowing the charge amplifier feedback capacitance and following amplifier gains. The voltage integrated over the bunch length is divided by the time where a single charge is contributing to the voltage i.e. the effective length of the pick-up divided by the particle speed. The effective length of the pick-up is obtained from the shape of the image charge for a given relativistic β , assuming a centred beam [4].

$$N_q = \frac{C_{feedback} \int V(t) dt}{e \cdot Gain \cdot \frac{l_{PU_eff}}{v}} \quad (1)$$

Where $C_{feedback}$ is the feedback capacitance in the charge amplifier, $\int V(t) dt$ the voltage integrated over the bunch length at the output of the amplifier (Figure 1, trace 2), e the electric charge, l_{PU_eff} the effective length of the pick-up, and v the speed of the particle. The effective length of the pick-up is given by

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$$l_{PU_eff} = l_{PU_real} + \frac{r_{PU}}{\gamma\sqrt{2}} \quad (2)$$

Where l_{PU_real} is the physical pick-up length, r_{PU} is the pick-up radius and γ the Lorentz factor.

Using these formulae, the measured intensity at injection was estimated to be 1×10^7 H⁻ particles. ELENA is designed to work with $1 \cdot 10^7$ - $4 \cdot 10^7$ antiprotons. No other measurement of intensity is yet available in ELENA.

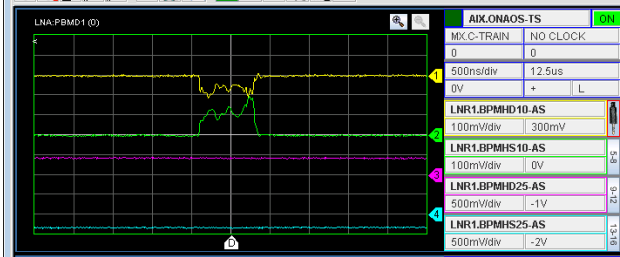


Figure 1: Difference (1) and Sum (2) signals from a pick-up as it enters the ADC after the charge amplifier and pre-amplifier.

Beam Position

To obtain the beam position, both sum and difference signals are sampled and down-converted to baseband in the FPGA, before being further processed in the DSP to produce the final position (difference/sum). The DSP performs a position calculation every 10 μ s (100 kHz) using the most recent data from the down converter. The read out of position data is made via four 2k buffers, with individual start time and sampling rates (lower than 100 kHz), allowing the user to both cover long cycles and look at details. Figure 2 shows the read out at 1 ks/s rate starting a few milliseconds before injection, showing the position from all available horizontal pick-ups versus time. When decimating (here 100 kHz to 1 kHz) average values are used.

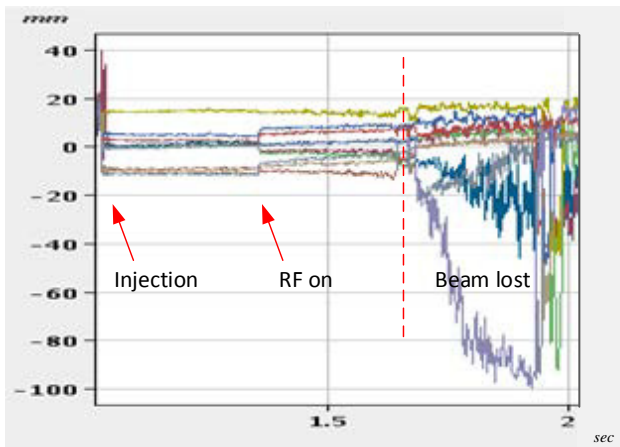


Figure 2: Beam position measurement from 10 horizontal PUs in ELENA. Data rate of 1 kHz. Only the first 1k values of 2k buffer values are shown.

The first part (after injection) is with no RF, with RF applied at approximate 1.35 s (the time is relative to the start of the magnetic cycle, not injection). The beam is captured

and remains in the machine for around 0.35 s (corresponding to 1.7 s in Figure 2). The system “as is” (summer 2017) will present data making no decision on whether to discard data due to too low intensity. This means that if the sum signal (i.e. the denominator in the Difference/Sum calculation) becomes too small the DSP will output a non-physical position of -100 mm for the relevant samples. These values are (for now) filtered together with valid data, resulting in the “towards -100 mm” behaviour observed for some pick-ups in Figure 2, as the beam is being lost.

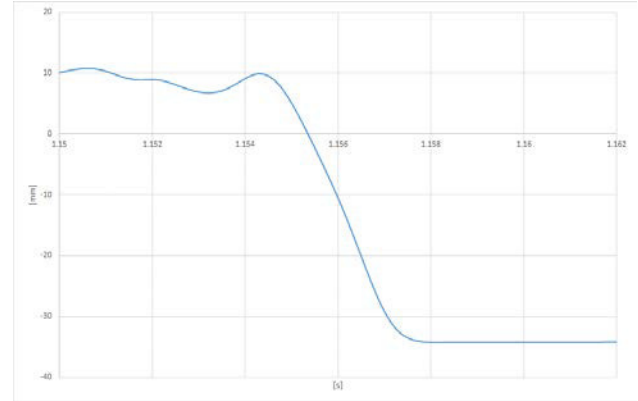


Figure 3: Step response from one ELENA pick-up after application of a calibration signal at 1.145 s. Data rate of 10 kHz.

The measured step response of the system is shown in Figure 3 where the output position signal of a single pick-up is shown; at 1.15 s to 1.154 s no signal nor beam is present, the calibration signal is then switched on and shows the step response of the system, which is critically damped with a time constant of approximate 2 ms. The step time is given by intern filtering and can therefore be changed. The calibration signal is a sinusoidal signal generated (DDS on FMC) at the actual revolution frequency injected on the “negative” PU plate, resulting in a position matching the maximum negative -35 mm displacement.

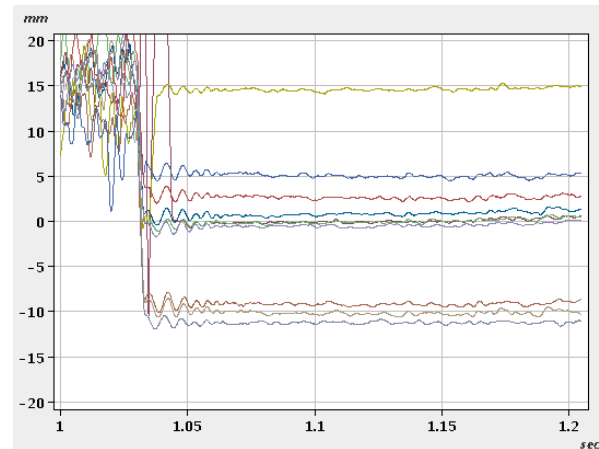


Figure 4: Beam position measurement in ELENA with H⁻ injected at 1.03 sec. Data rate of 10 kHz.

Shown in Figure 4 is the beam position at injection with a 10 kHz sampling rate. Once the beam position is stable, an upper limit on the resolution of the system can be estimated as the standard deviation from measurement to

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measurement, calculated to be 0.1 mm, matching the requirement.

The closed orbit can be plotted for any time in the acceleration cycle (where position data is available i.e. when the beam is bunched). The orbit can then be entered into the standard CERN orbit correction application. Figure 5 shows one of the very first times this was successful performed in ELENA; in pink the initial orbit, and in green the corrected orbit. Only horizontal correction was performed, with the vertical measurement showing good reproducibility of both the machine and the measurement.

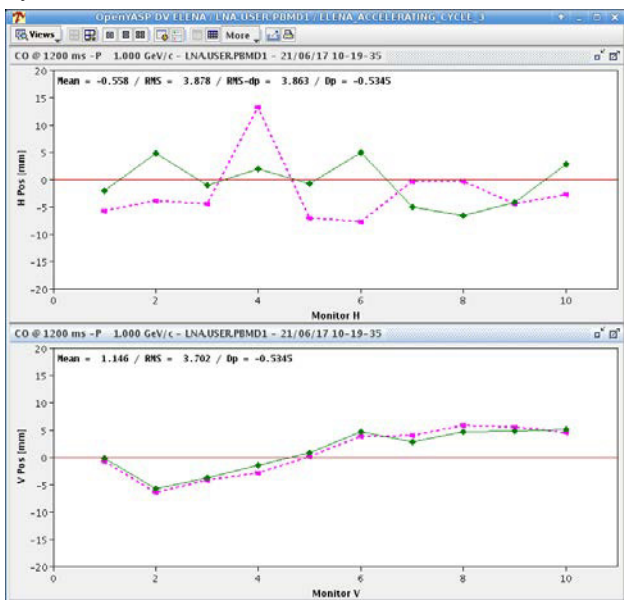


Figure 5: Orbit measurement (x-axis is the 10 pick-ups in each plane for which the position is given in mm) before (pink) and after (green) a horizontal orbit correction in ELENA.

Mean radial position

The system has two VXS switch cards allowing high speed serial communication between the VXS-DSP-FMC carriers; this is implemented in a “sushi train style” where blocks of data (32x32 bytes) are passed from all cards both right and left in a circular manner allowing all boards to communicate. Passing one block of data between two neighbouring boards takes approximately 340 ns. In the ELENA setup seven VXS-DSP-FMC-carriers are in use i.e. 1 μ s is needed to pass one block of data to all cards (maximum of 3 transfers required). This carrier intercommunication is used to pass the calculated beam position from each DSP to one central DSP that is used to calculate the mean radial position (from selected pick-ups). The calculated value is updated every 10 μ s and made available via a giga-bit link on optical fiber to the low level RF system for radial feedback.

TRAJECTORY

To enable measurements of the turn by turn trajectory at injection, knowledge of the RF frequency and phase is required. The ELENA low level RF system, in its fixed sample frequency scheme, can provide this via the already

existing gigabit link. Also including the stable phase function giving the relation between RF phase and beam. The FMC-MDDS generating the FMC-ADC sample frequency, can then be omitted in the orbit system. The turn by turn position will be calculated from the difference and sum signal averaged over one bunch length i.e. no inter bunch position.

LONGITUDINAL SCHOTTKY

The longitudinal Schottky signals will be measured using all 20 sum signals (vertical and horizontal), phase compensated and then averaged together to gain signal to noise ratio (a theoretical 13 dB SNR gain is possible). The phase compensation will take into account the physical position of each pick-up as well as cable delays etc. The analogue bandwidth of the system is limited to 40 MHz by the anti-aliasing filters mounted on the FMC-ADCs. With the total power equal in all Schottky harmonics, spectral density will be lower at higher harmonics, as the spectra are wider. However, a wider spectrum makes it faster to get a given relative frequency resolution (FFT frequency resolution is given by the total sampling time) Fast measurement are preferred, i.e. highest possible harmonic will be chosen. Initial calculation [5] indicates SNR will be sufficient for Schottky measurement up to the 110th harmonic. The 40MHz bandwidth will limit this at injection. The FPGA sampling of data can be paused allowing the DSPs to perform the necessary FFTs uninterrupted.

CONCLUSION

The status of the orbit system developed for, and used during, commissioning of the CERN ELENA ring has been presented with measurements showing its capability to measure the closed orbit with a time resolution of 10 μ s, a step response time of approximately 2 ms and a position resolution of 0.1 mm for $1 \cdot 10^7$ H⁺ particles. No measurements are presented with antiprotons as they have not yet been circulating in ELENA. The orbit measurements have been integrated into the CERN control system allowing for automatic orbit correction. The system also makes available the mean radial position to the radial feedback of the RF system. The next step will be to implement the necessary modifications for the addition of trajectory and longitudinal Schottky measurements to the system.

REFERENCES

- [1] L. Søby *et al.*, "ELENA Orbit and Schottky measurement system," in *Proceedings IPAC 2015*, Richmond, VA, USA.
- [2] R. Marco-Hernandez *et al.* A New orbit system for the CERN antiproton decelerator, in *Proceedings IBIC'15* Melbourne, Australia.
- [3] M. E. Angoletta *et al.*, A Leading Edge Hardware Family for Diagnostics Applications and Low Level RF in CERN's ELENA Ring, in *Proceedings IBIC'13*, Oxford, UK.
- [4] Maurice Cohen-Solal, "Design, test and calibration of an electrostatic beam position monitor," *Physical Review*.
- [5] F. Pedersen, "Ideas and choices for low noise longitudinal pick-ups and diagnostics for ELENA", CERN, Switzerland.