LONGITUDINAL BEAM DIAGNOSTIC FROM A DISTRIBUTED ELECTROSTATIC PICK-UP IN CERN'S ELENA RING

M. E. Angoletta, F. Caspers. S. Federmann, J. Molendijk, J. Sanchez-Quesada, P. J. Secouet, L. Søby, F. Pedersen, M. Timmins, CERN, Geneva, Switzerland

Abstract

The CERN Extra Low ENergy Antiproton (ELENA) Ring is a new synchrotron that will be commissioned in 2016 to further decelerate the antiprotons coming from CERN's Antiproton Decelerator (AD). Required longitudinal diagnostics include the intensity measurement for bunched and debunched beam and the measurement of Dp/p to assess the electron cooling performance.

A novel method for the calculation of these parameters is proposed for ELENA, where signals from the twenty electrostatic Pick-Ups (PU) used for orbit measurements will be combined to improve the signal-to-noise ratio. This requires that the signals be digitally down-converted, rotated and summed so that the many electrostatic PUs will function as a single, distributed PU from the processing system viewpoint. This method includes some challenges and will not be used as the baseline longitudinal diagnostics for the initial ELENA operation. This paper gives an overview of the hardware and digital signal processing involved, as well as of the challenges that will have to be faced.

INTRODUCTION

CERN's Extra Low ENergy Antiproton (ELENA) ring [1] is a new synchrotron with a circumference of 30.4 m that will be commissioned in 2016 to further decelerate the antiprotons coming from CERN's Antiproton Decelerator (AD). Table 1 provides a summary of ELENA's main parameters.

Table 1: ELENA Ring Main Parameters

Parameter	Injection	Extraction
Momentum, MeV/c	100	13.7
Kinetic Energy, MeV	5.3	0.1
Revolution frequency, MHz	1.06	0.145
Expected number of particles	$3{\cdot}10^7$	$1.8{\cdot}10^7$
Number of extracted bunches	4 (operationally)	
Extracted bunches length, m/ns	1.3/300	

ELENA's main task is to increase the number of antiprotons available to the experiments by reducing the particles lost during the post-AD deceleration. Furthermore, the beam emittances will be reduced by an electron cooler. Figure 1 gives a schematic view of the ELENA cycle. Its duration is expected to be of at least 20 seconds. The main actions performed in the cycle, namely bunched beam for deceleration when RF is ON and electron cooling on two plateaus, are also indicated.

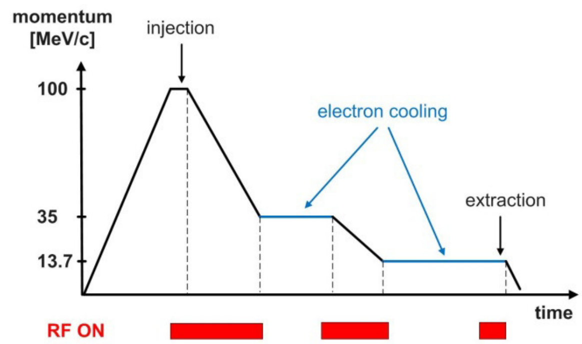

Figure 1: Schematic view of the ELENA cycle.

The DC beam currents in ELENA are very low, between a few µA and down to 0.23 µA, which e.g. rules out to measure the intensity with a conventional DC beam current transformer. Essential longitudinal diagnostics required for commissioning and operation includes the intensity measurement for bunched and debunched beams and the measurement of *Δp/p* for debunched beams to assess the electron cooling performance.

This paper describes a novel method for the calculation of these parameters in the ELENA ring, based on combining signals from the twenty electrostatic pick-ups (PUs) used for orbit measurements to improve the Signal-to-Noise Ratio (SNR). This is not the baseline solution chosen for ELENA, which is described elsewhere [2].

SYSTEM OVERVIEW

The implementation of the novel method for the longitudinal beam parameters calculation is done in the same crate as the ELENA orbit system. This paper focuses on the longitudinal beam parameters calculation and does not describe the orbit measurement capabilities.

Figure 2 shows a block diagram for the system. Ten horizontal and ten vertical PUs, optimised for high bandwidth and high sensitivity are installed in the ELENA ring and mounted inside quadrupoles and dipoles. The sum (Σ) and difference (Δ) signals from each PU are amplified by low noise amplifiers located very near the PUs, then transported by ~50m cables to the digitization and processing system.

Both Σ and difference Δ signals are needed for the orbit measurement, whilst only the Σ signals are required for the longitudinal parameters. The Σ signals are combined by digital down-conversion, rotation and sum to improve the debunched beam SNR. Calculations on Schottky signal levels show that the SNR from a single PU of ~12 dB can be improved by 13dB by adding the twenty sum signals from all PUs. In doing so the many electrostatic

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PUs function as a single, distributed PU from the processing system viewpoint.

The advantage of this approach is that it provides the sensitivity that could be obtained by a long electrostatic PU as well as the high bandwidth that can be obtained only with short electrodes [3]. However, electrostatic PUs with slow time constants are known to be very sensitive to charging from secondary emission of lost particles. Recovery is slow due to a very large bias resistor. This drawback as well as the need for significant efforts for study and development prevents using the system described in this paper as the baseline solution for ELENA commissioning and initial operation.

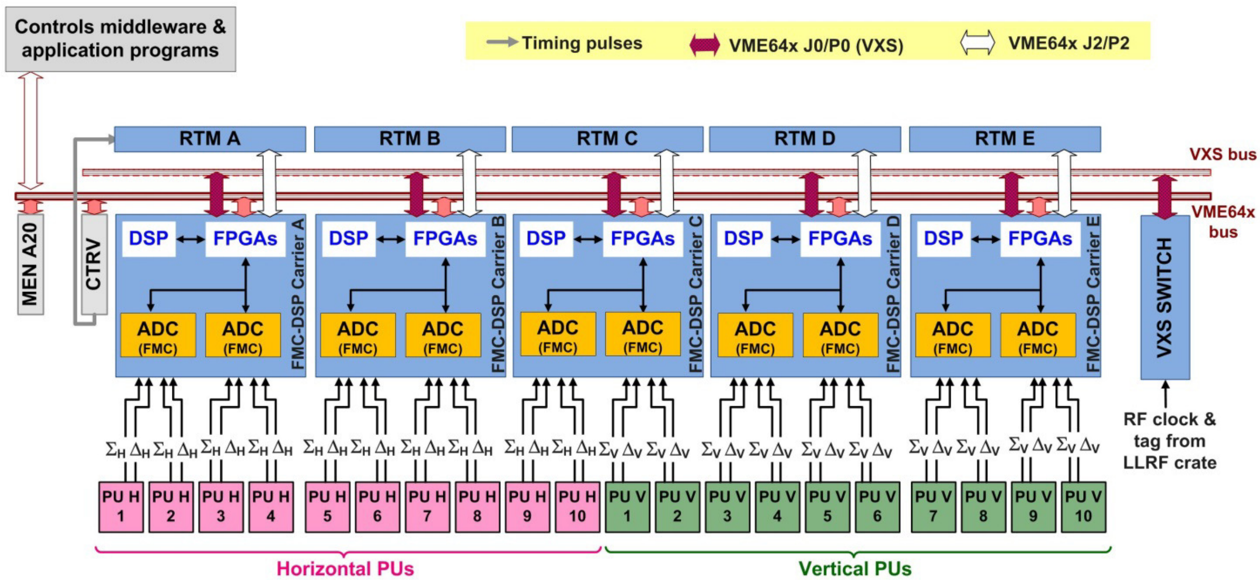

Figure 2: Beam orbit and longitudinal parameters measurement system. Keys: **ADC -** Analogue-to-Digital FMC board; **RTM -** Rear Transition Module; **CTRV -** Timing Receiver Module; **Men A20 –** master VME board; **PU H** – Horizontal transverse Pick-Up; **PU V** – Vertical transverse Pick-Up.

HARDWARE

Electrostatic PU Design

The design is based upon a stainless steel body containing two diagonal cut PUs. Two such elements will be inserted into a vacuum tank with a diameter of 100 mm, in order to provide a position measurement in both planes. The sigma signal will be generated in the head amplifier hence no sigma electrode is foreseen.

The design has been optimised for high bandwidth and sensitivity. High Schottky harmonics should to be used to obtain a better time-resolution of the intensity measurement, since the acquisition time is inversely proportional to the harmonic number. The SNR is also inversely proportional to the harmonic number n, hence a practical higher limit for the harmonic number is reached when the power spectra envelope function expressed by (1) has dropped by a factor two.

$$\left[\frac{\sin(\omega(n))}{\omega(n)}\right]^2 \qquad (1)$$

where $\omega(n) = \pi \cdot n \cdot \frac{l_{PU}}{L_{Circonf}}$,

with l_{PU} the PU length and $L_{Circonf}$ the ring circumference.

For ELENA this will occur at n_{3dB} = 111 if considering an electrode length off 120 mm. A 120 mm electrode length has thus been chosen for the PU, with an electrode-to-ground distance of 10 mm. The PUs are located inside quadrupoles and corrector dipoles to gain longitudinal space in the ring, as shown in Figure 3 and Figure 4.

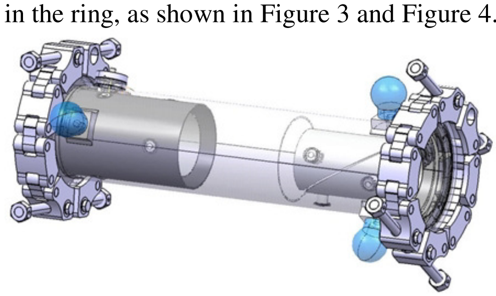

Figure 3: PU assembly inside a dipole.

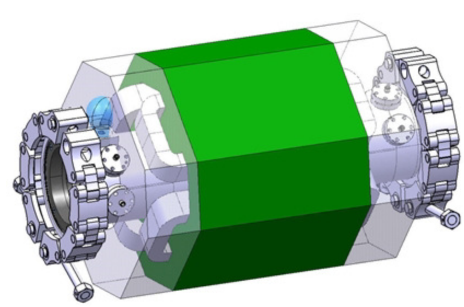

Figure 4: PU assembly inside a quadrupole.

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The whole PU assembly will be bakeable to 250 degrees and NEG coating applied to electrodes, support tubes and vacuum chamber.

Analogue Acquisition System

The signal level V_{Peak} measured in Volts expected from the PU electrodes beams is given by (2):

$$V_{Peak} = \frac{N \cdot q}{C_{tot}} \cdot \frac{l_{PU}}{L_{Circomf}} \cdot \frac{\pi}{2} \cdot B_f \tag{2}$$

where N is the number of particles, C_{tot} the total capacitance, q the elementary charge, $\pi/2$ the PU peak amplitude form factor and B_f the bunching factor.

The requirements for the front-end electronics are driven by the need to use the PUs for longitudinal Schottky measurements on un-bunched beams as well as intensity and position on bunched beams. A bandwidth of forty MHz allows measuring Schottky signals up to the 110th harmonic as from 35 MeV/c.

The maximum gain is given by the signal induced by the shortest possible bunch length of 1.5 m and with 10^7 particles, which should not saturate the system. The highest possible signal amplitude at $\beta = 0.1$ is 3 mV, which gives a maximum gain of 62dB, assuming ± 4V output amplitude.

The minimum gain is determined by the head amplifier output noise which must be 12 dB higher than the ADC input noise not to decrease the SNR. A minimum gain of 58 dB is required when considering an ADC noise of 80 nV/sqrt (Hz) and a head amplifier input noise of 0.4 nV/sqrt (Hz).

The charge amplifier concept has been adopted for the noise-optimized JFET input low noise head amplifiers [4]. This has several advantages compared with classical voltage amplifiers. First, gain calibration can be made without relays at the inputs, as the calibration signal can be capacitively injected into a virtual ground. This reduces cable lengths and parasitic capacities improving the SNR. Secondly, a better stability is achieved as the effective charge amplifier gain only depends on few passive components in the feedback paths.

All components will be made of non-magnetic material, since the amplifier box will be mounted very close to the feedthroughs and thus close to the windings of the magnets. The amplifier shielding box will include a tri-axial connection between PU and amplifier to bypass ground loop currents away from the input connectors.

Analogue Transmission

The analogue transmissions between feed-through and head amplifier as well as on the long cable between head amplifier and digitizers located outside the ring are crucial for the performance of the system.

Two main sources of EMI are expected, namely: a) interference from the ELENA bunching. Signals on the amplifier inputs develop due to the SMA connector contact resistance which get amplified together with the wanted beam signals; b) interference from medium wave radio stations induced on output cables.

Several solutions for an analogue transmission that minimises the two above-mentioned EMI sources have been considered. One solution was to use optical fiber cables. This would require two separate cables and gains for each sum signal since the combined dynamic range of bunched and Schottky signals is higher than the 110 dB available with a fiber optic. The optical fiber transmission was discarded due to its cost; it might be considered in a second noise reduction phase if necessary.

The solution retained for ELENA is the same used in the AD for its AC-coupled low-noise beam transformer. It includes: a) common mode magnetic shielding between PU and amplifier using ferrite-loaded coaxial cable and a tri-axial screen; b) low transfer impedance cables between the head amplifier and the digitising system. This solution will be tested in a laboratory setup, where RF currents will be applied to measure the total transfer impedance of connectors and cables.

Digital Acquisition and Processing System

The digital acquisition and signal processing will be carried out with the leading-edge hardware family planned for ELENA's LLRF system. Figure 2 shows the main building blocks, which are detailed elsewhere [5]. The five FMC-DSP-Carrier boards will co-operate to carry out longitudinal measurements and will exchange data in real time via dedicated full-duplex VXS channels with transfer rate 2 Gbit/s.

The beam orbit and longitudinal diagnostics crate will be connected to that of the LLRF system via fiber optic. The LLRF will distribute a revolution "tag" signal and the RF clock. The former marks each revolution turn and is a common revolution phase reference synchronizing in phase all numerically-controlled oscillators implemented in the FPGA code attached to each ADC. The latter is a signal at a high harmonic of the revolution frequency which clocks the ADCs and corresponding FPGA. Additional information received from the LLRF system via the optical fiber includes the current revolution frequency value and the harmonic h_{MDDS} of the RF clock to calculate the signals rotation. The harmonic h_{MDDS} will change during the cycle and its value will be needed to update the hardware setup.

Different types of digitizing hardware could be used if only orbits were to be measured. However, the flight time and cable length correction needed for summing of the sigma signals (see next section) requires the "tag" signal, hence the choice of the hardware.

SOFTWARE

The FPGAs and the DSP hosted by each DSP-FMC-Carrier board will share the digital signal processing tasks. Measuring the beam orbit is a relatively simple task, as each radial position involves dealing with only the Σ and Δ signals from the same PU.

The digital signal processing for the longitudinal diagnostics task is identical to that implemented in the

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baseline solution [2] once the sum signals coming from the various PUs have been combined. This will consist of spectral analysis at a programmable Schottky harmonic for debunched beams. For bunched beams it is planned to integrate many bunches in the time domain, subtract the signal baseline and averaging the result.

Combining the sigma signals from horizontal and vertical PUs positioned all around the ELENA ring is a somewhat laborious task. In fact, the location of the revolution tag associated with the RF clock received from the LLRF varies with respect to the acquired Σ signals (for bunched beams) or phase of single turn Schottky signal (for debunched beam) due to the beam time-of-flight and cable length. The time-of-flight difference is due to the ring azimuthal position $\varphi_{z,N}$ of the nth PU. The total cable delay $\Delta t_{cab,N}$ for the nth PU comes from several contributions, such as a) cable delay differences between head amplifiers and digital receivers; b) cable delay differences in tag distribution to cavity gap receiver and each PU-station receiver.

For Schottky measurements, the phase rotation $\varphi_{Sch,N}$ required to bring the nth single turn Schottky (I, Q) couple in phase is given in equation (3):

$$\varphi_{\mathrm{Sch,N}}[rad] = h_{Sch} \cdot (\varphi_{z,N} + 2\pi \cdot f_{rev} \cdot \Delta t_{cab,N}). \tag{3}$$

where h_{Sch} is the selected Schottky harmonic and f_{rev} is the current revolution frequency value distributed from the LLRF system.

For the bunched beam intensity, the RF clock offset corresponding to the start of the integration window $n_{bc,N}$ is given in equation (4):

$$n_{\mathrm{bc,N}} = h_{MDDS} \cdot \left(\frac{\varphi_{z,N}}{2\pi} + f_{rev} \cdot \Delta t_{cab,N} \right). \tag{4}$$

A table containing the $\varphi_{z,N}$ and $\Delta t_{cab,N}$ values for each PU will be calculated as a one-time setup operation. This will be done by plotting the phase of each bunched-beam {I,Q} vector as a function of frequency for a chosen harmonic. When the PU azimuth phases are set to their correct values, the remaining phase shift measured will have a linear phase shift versus frequency equal to the total cable delay $\Delta t_{cab,N}$. Measurement of cable lengths will give a first approximation of the delay differences.

Similar rotations are routinely done on the same hardware in the LLRF system to implement the low-level RF loops.

MEASURED INTENSITY CALIBRATION

Three methods are available to obtain an absolute intensity calibration.

First, the gains of the ADC and of the *ensemble* pick-up and head amplifier charge gain can be calibrated in the laboratory via a pick-up test stand with an inner coaxial electrode simulating the beam. The induced charge on the electrodes is fully defined by the pick-up length, the capacity-per-unit-length associated with the coaxial structure and the voltage applied to the coaxial electrode.

Second, the bunched beam intensity can be compared to that obtained via Schottky signals, as it is done for the ELENA baseline method. Since the former scales linearly with the gain and the latter scales with the gain squared, the gain will be valid if the two measurements coincide.

Finally, the beam intensity can be compared with that obtained via the baseline system [2] in the ring. The bunched beam intensity measurement right before extraction can be compared to that obtained with the baseline system in the extraction lines.

STAGED IMPLEMENTATION

The novel intensity measurement method described in this paper will not be available for the ELENA commissioning, owing to limited manpower and to the risk of saturation in the PU electronics from lost antiprotons. Software measures to exclude the saturated pick-ups from the sum will be devised, if required, once the severity of this saturation is better known. The intensity measurement method described in this paper will then be implemented and deployed.

If the migration is successful, the system here described could take the place of the baseline system for longitudinal parameters measurement in the ring. The space occupied by the ring AC beam transformer would then be liberated and used to install a superconducting DCCT, currently under study at CERN. This will provide easier absolute intensity calibration and better time and intensity resolution for de-bunched beam measurements.

CONCLUSIONS

A novel method for the calculation of longitudinal beam parameters from a distributed electrostatic PU will be implemented in ELENA. This method will not be the baseline solution for ELENA owing to the possible saturation of the electrostatic PUs from lost particles. If successfully deployed it could however become the workhorse for longitudinal diagnostics at a later stage, thus allowing to remove the AC beam transformer and to install a superconducting DCCT.

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