ELENA ORBIT AND SCHOTTKY MEASUREMENT SYSTEM

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Abstract

A new Extra Low ENergy Antiproton ring (ELENA) is under construction at CERN to further decelerate the antiprotons from the existing Antiproton Decelerator (AD) to an energy of just 100 keV. This contribution will describe the beam position system foreseen for ELENA and how it can be adapted for Schottky measurements. The orbit system being developed is based on electrostatic shoebox beam position monitors fitted with Digital Down Converters (DDC). The main requirement is to measure complete orbits every 20ms with a resolution of 0.1mm for intensities in the range of 1-3E7 charges. The pick-up signals will, after amplification with a low noise charge amplifier, be down-mixed to baseband for position computation. In order to provide the longitudinal Schottky diagnostics of un-bunched beams, the 20 BPM sum signals will, after time of flight corrections, be added digitally to give an expected S/N increase of 13dB compared to using a single electrostatic pick-up.

INTRODUCTION

The Extra Low ENergy Antiproton ELENA ring [1] is a new synchrotron with a circumference of 30.4 m that will be commissioned at CERN in 2016. Table 1 provides a summary of ELENA's main parameters, while Fig. 1 gives a schematic view of the ELENA deceleration cycle which is expected to last some 20 seconds.

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	$3 \cdot 10^7$	$1.0 \cdot 10^7$
Number of extracted bunches	4 (operationally)	
Extracted bunches length, m/ns	1.3/300	

The ELENA orbit measurement system will be based on 20 circular, electrostatic Beam Position Monitors (BPMs) made out of stainless steel and mounted inside quadrupoles and dipoles. After amplification of the signals by low noise amplifiers located very near to the BPMs, the difference and sum signals will be transported by ~50m cables to the rack where they will be digitized and processed.

In a second phase it is foreseen to use the same BPM sum signals for longitudinal Schottky measurements of un-bunched beams and intensity measurements for bunched beams.
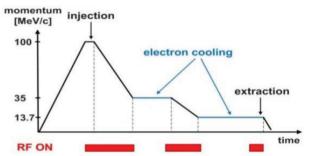

Figure 1: Schematic view of the ELENA cycle.

PICK-UP DESIGN

The proposed design is based on a stainless steel, 100 mm diameter vacuum tank containing two pairs of diagonally cut stainless steel electrodes, one for horizontal and one for vertical measurement. As can be seen in Fig. 2, no separate sum electrode is foreseen, with the sum signal generated by the addition of the electrode signals in the front-end amplifiers. Table 2 summarises the main parameters for the BPM system.
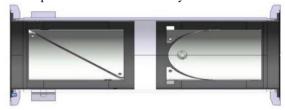

Figure 2: Cross section view of the ELENA Pick-up.

Table 2: Pick-up and Orbit Parameters

Parameter	Value
Resolution, mm	0.1
Accuracy, mm	0.3 – 0.5
Time resolution, ms	20
Electrode inner diameter, mm	66
Electrode length, mm	120
Electrode gap, mm	10
Electrode capacitance, pF	15
Bake out temperature, °C	250
Vacuum, Torr	3E-12

In order to use the BPM electrodes for Schottky measurements, it was necessary to optimize the design for high bandwidth and high sensitivity. To obtain a

sufficiently high time resolution for the intensity measurement of the un-bunched beams, the use of high harmonics is required, since the FFT processing time is inversely proportional to the harmonic number. However, since the signal-to-noise (S/N) ratio is also inversely proportional to the harmonic number, a practical higher limit for the harmonic number is reached when the power spectrum envelope function $\lfloor \sin(\omega(n))/\omega(n)\rfloor^2$ has dropped a factor two [2], where $\omega(n)$ is given by,

$$\omega(n) = \pi n \left(\frac{t_{PU}}{t_{Rev}}\right) = \pi n (L_{Pu}/C_{Circ}). \qquad (1)$$

For ELENA this occurs at harmonic number $n_{3dB} = 111$, for the electrode length of 120 mm.

FRONT-END ELECTRONICS

Front-End Amplifier

The input stage of the front-end electronics is a charge amplifier, as shown in Fig. 3. For a given input charge the output voltage is inversely proportional to the feedback capacitance. Two low noise JFET transistors are placed in parallel to form a folded cascode in combination with a pair of PNP/NPN bipolar junction transistors. An emitter-follower isolates the cascode output node from the load capacity of the non-inverting current feedback amplifier (AD811).
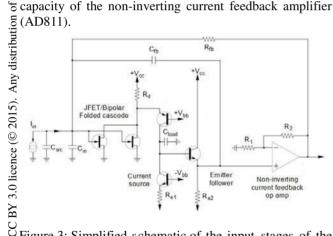

Figure 3: Simplified schematic of the input stages of the ELENA front-end amplifier.

The total input capacitance is minimized to 50 pF to reduce the voltage noise gain. The Johnson thermal noise generated by the GΩ feedback resistor (R_{fb}), which determines the low frequency cut-off of the amplifier, is lowered a factor of five by inserting a voltage amplifier with a gain of five [3]. The gain calibration will be performed by injecting a known charge into each input through a low value calibration capacitor (1pF).

After charge amplification, sum and difference amplifier stages are implemented to generate the sigma and delta signals respectively. Low noise differential amplifiers (AD8129) are used to provide high common-mode rejection within the measurement bandwidth. These are followed by two output cable drivers (LMH6321). The total gain foreseen is 46dB in a 100 Hz-40MHz bandwidth.

Input and Output Analogue Transmission

In order to keep input capacitances low short 90 ohm coaxial cables (10 cm) will be used to connect the BPM electrodes to the amplifier inputs. These cables will be loaded with ferrites and shielded with a metallic screen to obtain a common-mode magnetic shielding of 40 dB against conducted interference from the bunching cavity of ELENA. Low transfer impedance cables will be used to connect the outputs to the digital acquisition system.

DIGITAL ACQUISITION SYSTEM

System Layout

The digital acquisition system is based on the same hardware as the ELENA Low Level RF (LLRF) system [4]. It follows the VME Switched Serial (VXS) [5] enhancement of the VME64x standard as well as using VITA57 standard FPGA Mezzanine Card (FMC) [6].
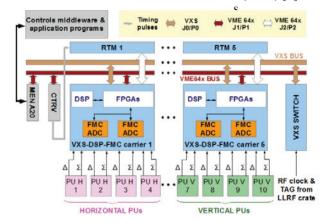

Figure 4: Digital acquisition system block diagram. ADC: Analogue-to-Digital FMC board. RTM: Rear Transition Module. CTRV: Timing Receiver Module. Men A20: master VME board. PU H: Horizontal transverse Pick-Up. PU V: Vertical transverse Pick-Up.

Five VXS-DSP-FMC carriers, holding two, 4 channel FMC-ADC boards will digitize and process the sum and difference signals from the 20 BPMs (Fig. 4). A timing module (CTRV) will provide all the triggers related to the ELENA cycle.

The signal acquisition and processing will use a common RF clock, which is a programmable high harmonic (h_{MDDS}) of the revolution frequency (f_{REV}). A TAG pulsed signal marks the revolution frequency and synchronises all boards in the system. The LLRF crate will provide the RF clock and the TAG signal through optical fibres. Two VXS Switch boards will interconnect the five VXS-DSP-FMC carriers via full-duplex Giga-bit serial links (2 Gbit/s). A rear transition module (RTM) connected to each VXS-DSP-FMC carrier provides general purpose digital inputs and outputs.

Each VXS-DSP-FMC carrier accommodates a DSP (ADSP-21368) and two FPGAs. The Main FPGA (XC5VLX110T) implements the essential infrastructure for the system communication and data exchange. The

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FMC FPGA (XC5VSX95T) performs data processing such as the Digital Down Conversion (FMC-DDC) for the FMC-ADC. The DSP implements the core data treatment and overall system control.

FMC-ADC

The FMC-ADC board (Fig. 5) has four independent channels (±1V range) with digitalization performed using two dual ADCs (AD9286) of 16-bits and a sampling rate up to 125 MSPS. The input bandwidth is limited to 40 MHz. Each channel has two possible gains, 0 dB or 18 dB.

The DDC firmware converts the selected beam revolution harmonic into a baseband I/Q signal. The ADC sampling clock and the local oscillator are locked to the RF clock. Low pass filtering and decimation is carried out with a configurable first order Cascaded Integrator Comb (CIC) filter. The phase of the down-converted I/Q signal can be varied to compensate the beam time of flight and cable delay differences of each input channel.
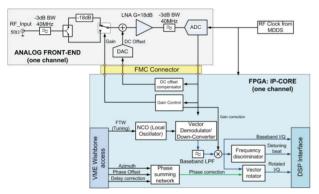

Figure 5: FMC-ADC board hardware and DDC firmware.

ORBIT MEASUREMENTS

The analogue front-ends will deliver RF difference and a sum signal for each BPM, i.e. 40 signals, which must be digitized and down converted to baseband for position calculations. Depending on the level of RF induced EMI, the measurements will be carried out using the first or second harmonic of the beam signal. Digital down conversion using the selected harmonic as local oscillator permits continuous position measurements during the whole deceleration cycle, whenever the beam is bunched. After low pass filtering and decimation of the complex I/Q data the positions are calculated according to equation (2).

$$\Delta x(t) = K_{PU} \cdot \frac{\Delta}{\Sigma}(t) = K_{PU} \cdot Re\left\{\frac{I_\Delta(t) + jQ_\Delta(t)}{I_\Sigma(t) + jQ_\Sigma(t)}\right\} \qquad (2)$$

BUNCHED BEAM INTENSITY MEASUREMENTS

The beam intensity will be calculated from the time domain signal of each BPM sum signal by digital integration after baseline subtraction (Fig. 6). The baseline value is determined by sampling and averaging

in a small region in between the bunches. The TAG signal and the revolution frequency value will be used to determine the start of the baseline integration window. The intensity value will be obtained by averaging the mean value of all sum signals in a user-selectable number of revolutions. The number of samples to the beam base line centre varies for each BPM according to,

$$N_{ADC} = h_{MDDS} \cdot \left(\frac{\varphi_{BPM}}{2\pi} + \Delta tcable_{BPM} \cdot f_{rev}\right). \qquad (3)$$

Where φ_{BPM} is the azimuthal position of the BPM, and $\Delta tcable_{BPM}$ is the total cable delay.
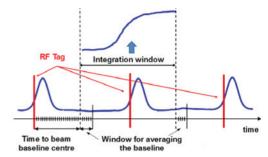

Figure 6: Integration window for bunched intensity measurements.

LONGITUDINAL SCHOTTKY MEASUREMENTS

De-bunched beam intensity and longitudinal parameters will be calculated from Schottky spectra. The sum of all 20 BPM sigma signals will be used, after time of flight compensation (phase rotation of the complex I/Q data), and should theoretically improve the signal-to-noise ratio compared to a single BPM signal by 13dB.

The complex FFT of consecutive I/Q samples, using windowing and programmable overlap, will be calculated and further averaged to produce one measurement per second. A high Schottky harmonic should be selected whenever the SNR allows it, so as to improve the statistics, since the acquisition duration of the required input record for the FFT processing is inversely proportional to the harmonic number. The system will be able to measure up to the 111th harmonic of f_{REV}. The averaged FFT will then be used to estimate the total intensity, mean momentum and momentum spread.

CONCLUSION

The idea of using the summed, time of flight corrected digital signals from the 20 electrostatic BPMs to provide longitudinal Schottky data is both novel and challenging. The BPMs and front-end electronics have therefore been optimized for this longitudinal Schottky measurement, with the choice of the VXS standard allowing direct inter module communication for the sum-signal addition.

The orbit measurement is foreseen to be operational for the first-phase of ELENA commissioning in 2016, after which the bunched intensity measurement and Schottky measurements will be commissioned.

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