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BEAM INTENSITY MEASUREMENT IN ELENA USING RING PICK-UPs

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Abstract

A bunched beam intensity measurement system for the CERN Extra Low ENergy Antiproton (ELENA) ring, using a cylindrical shoe-box electrostatic pick-up from the existing orbit system, is presented. The system has been developed to measure very challenging beam currents, as low as 200 nA corresponding to intensities of the order of 10^7 antiprotons circulating with a relativistic beta of the order of 10^{-2}.

In this work we derive and show that the turn-by-turn beam intensity is proportional to the baseline of the sum signal and that, despite the AC-coupling of the system, the installed front-end electronics, based on a charge amplifier, not only guarantees the preservation of the bunch shape (up to a few tens of MHz), but also allows for an absolute calibration of the system. In addition, the linearity of the intensity measurements and their independence with respect to average beam position is evaluated using a standard electromagnetic simulation tool. Finally, experimental measurements throughout typical antiproton deceleration cycles are presented and their accuracy and precision are discussed.

THE MEASUREMENT SYSTEM

This newly developed intensity measurement system is an add-on to the Extra Low ENergy Antiproton (ELENA) ring orbit system [1], using the already available sum signal from one ring Pick-Up (PU). In terms of hardware, the add-on consists of an Analog to Digital Converter (ADC) mounted on a PCIExpress bus [2] integrated in a front-end computer installed in the CERN control system, in order to digitise the PU sum signal.

ELECTROSTATIC PICK-UP AS A CHARGE MONITOR

As an alternative, or a complement, to the standard beam current transformers, an electrostatic orbit PU can be used to measure the intensity of bunched beams, either in a beam line or in a ring.

The Charge Found from the Output Voltage

The beam intensity can be found from the integrated output voltage from an electrostatic PU:

The charge Q, induced in the inner surface of a cylindrical PU is given by

$$Q = Q_b = \rho V \tag{1}$$

where ρ is the beam charge density [charge/m^3], V is the volume enclosed by the PU and Q_b is the portion of the beam charge contained in this volume.

The current density, J is given by

$$J = \frac{i}{A} = \rho\beta c \tag{2}$$

where i is the beam current, A its transverse area and βc its speed. Combining Eq. (1) and Eq. (2) we get

$$Q = \frac{i}{\beta c A} V = \frac{L}{\beta c} i \tag{3}$$

where L is the length of the PU.

The current i_z, drawn from the PU (as shown in Fig. 1), can be written as

$$i_z = \frac{dQ_b}{dt} = \frac{1}{\beta c} \cdot L \cdot \frac{di_b}{dt} \tag{4}$$

This current is split in two in the load impedance, Z, which is assumed to consist of a resistor, R, in parallel with a capacitor, C_L. C_L is in parallel with the pick-up capacitance, C_{pu}, and can be combined into a single capacitance, C, thus including both the PU and the load.

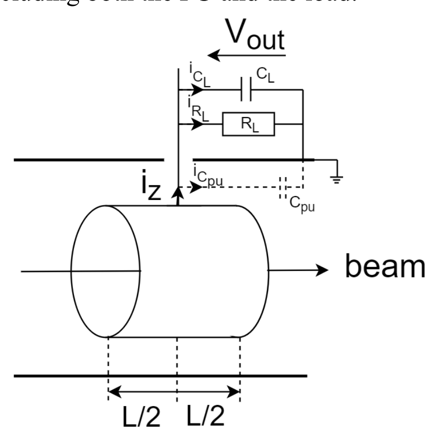

Figure 1: A circular electrostatic pick-up.

Ohm's law is used to get the voltage on the output, V_{out}:

$$i_z = i_R + i_C \tag{5}$$

where:

$$i_R = \frac{V_{out}}{R} \quad \text{and} \quad i_C = \frac{dQ_c}{dt} = C\frac{dV_{out}}{dt} = RC\frac{di_R}{dt}$$

The transfer function can be calculated by combining Eqs. (4) and (5) and differentiating assuming sinusoidal inputs to obtain:

$$\frac{i_R}{i_b} = \frac{L}{\beta c} \cdot \frac{j\omega}{1+j\omega RC} \tag{6}$$

The V_{out} on the load is found by multiplying the current, i_R, with the resistance, R (Ohm's law):

$$V_{out} = R \cdot i_R = \frac{L}{\beta c C} \cdot \frac{j\omega RC}{1+j\omega RC} \cdot i_b \tag{7}$$

Equation (7) is a standard first order high pass transfer function.

A bunched beam in a circular accelerator will have a periodic spectrum consisting of all harmonics (H) of the revolution frequency, where the amplitude ratio between harmonics will be dependent upon bunch shape as indicated in Fig. 2.

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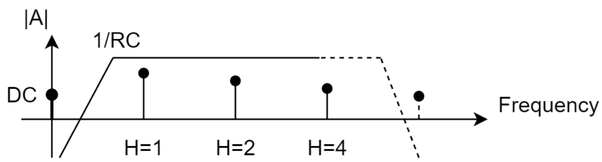

Figure 2: The high pass transfer function of the system.

Ensuring in the design, by appropriately choosing R and C, that all beam harmonics are inside the passband, will preserve the shape of the bunches [3]. Care should also be taken as to ensure that the upper cut off frequency is high enough to include all harmonics with relevant power. The revolution frequency in ELENA changes during deceleration from 1.056 MHz to 144 kHz. The low cut off frequency, $\omega_0 = 1/RC$, will determine the so-called droop time for the cancellation of the DC component. By controlling the low cut off frequency one can also ensure that $1 \ll j\omega RC$, in which case the system will work in a regime where Eq. (7) reduces to

$$V_{out} = R \cdot i_R = \frac{L}{\beta c} \cdot \frac{1}{C} \cdot i_b \tag{8}$$

The total beam charge, Q_{beam}, can be calculated by integrating the beam current, i_b, over one revolution period, T_0, to give

$$Q_{beam} = \int_o^{T_0} (i_b - i_{baseline}) dt =$$
$$= C \cdot \frac{\beta c}{L} \int_0^{T_0} (V_{out} - V_{baseline})\, dt \tag{9}$$

The baseline subtraction is needed otherwise the integral will be zero as the PU is not sensitive to the DC component of the beam spectrum. One can see from Eq. (9) that the knowledge of the beam speed, PU length and total capacitance is needed to get an absolute measurement.

Charge Amplifier

By using a charge (transimpedance) amplifier, see Fig. 3, the sensitivity of measurement can be increased as the total capacitance, C (normally the sum of the PU capacity and the load impedance capacity), becomes essentially $C_{feedback}$:

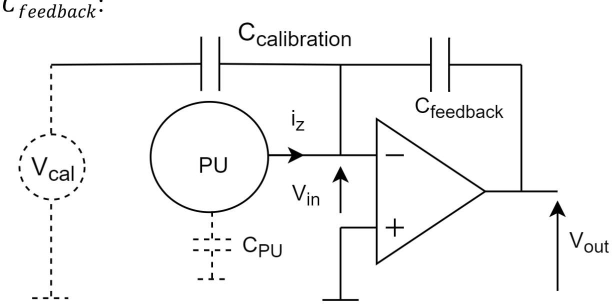

Figure 3: Ideal charge (transimpedance) amplifier, connected to PU and calibration signal input.

Ideally (i.e. for infinite open-loop gain), the feedback around the amplifier will ensure zero voltage at the input terminal, i.e. V_{in} vanishes on the PU. The PU capacitance, C_{PU} is therefore not charged and will not influence the sensitivity. In the ELENA system, a $C_{feedback}$ of 1 pF is used and the ideal operational amplifier shown in Fig. 3 is made up using a discrete input stage of JFETs and a feedback resistor to control the low pass frequency cut-off (~200 Hz) [4]. The open loop gain of this amplifier, in the pass band, is 70 dB, thus ensuring essentially a zero voltage on the input (V_{in} = 0 V).

The charge amplifier will charge the input current onto the capacitor, $C_{feedback}$, and output the integral of i_z as V_{out}. Substituting i_b from Eq. (4) into Eq. (8), we get

$$V_{out} = -\frac{1}{C_{feedback}} \int i_z\, dt = -\frac{1}{C_{feedback}} \cdot \frac{L}{\beta c} \cdot i_b \tag{10}$$

i.e. using a charge amplifier the total capacitance, C in Eq. (9), reduces to $C_{feedback}$ = 1 pF. The capacitance, C_{PU}, for an ELENA orbit PU is ~25 pF. If one assumes 5 pF on the amplifier input, then C would be ~30 pF. The use of charge amplifiers can therefore increase the sensitivity by ~30 dB. For 10^7 charges V_{out} is ~6 mV with the charge amplifier, as opposed to ~210 µV if a voltage amplifier was used.

Integrating the Signal from a PU

As previously stated, for a system where all relevant beam harmonics are within the passband and only the DC part is filtered out, the bunch shape is conserved. With the bunch shape conserved, the intensity can be obtained for a single passage of the beam, using Eq. (9). The area to be found by integration is marked as A1 in Fig. 4. The baseline is the voltage drop marked as $V_{baseline}$ in Fig. 4. If the measurement system has a DC offset, this can be accounted for by measuring the baseline with no beam.

For a circulating beam, after the droop time has passed, no DC is left and the base line is flat (assuming only small and/or slow beam losses when compared to the revolution period). With reference to Fig. 4, this means that the area A2 + A3 = A4. What is needed is A1, which is equal to A4 + A5 so, substituting A4 by A2 + A3, we can see that A1 = A2 + A3 + A5 = A6:

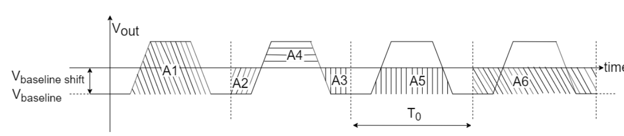

Figure 4: Circulating bunched beam example.

The integral of the output voltage can thus be found as the baseline shift multiplied by the revolution period to give

$$\int V_{out} dt = V_{baseline} \cdot \frac{L_{ELENA}}{\beta c} \tag{11}$$

where L_{ELENA} is the circumference of the machine. By using this baseline shift to calculate the integral of V_{out} in Eq. (9) the beam intensity, Q_{beam} can be found:

$$Q_{beam} = C \cdot \frac{\beta c}{L} \int V_{out} dt =$$
$$= C_{feedback} \cdot V_{baseline} \cdot \frac{L_{ELENA}}{L} \tag{12}$$

Equation (12) shows that the intensity measurement conveniently becomes independent of the beam energy and only depends on known constants.

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Finding the Base Line

In the ELENA system, the baseline shift is found in software after signal digitalisation. Both the baseline without beam and the baseline with beam, i.e. the baseline shift, can be derived by taking the average of all time samples within a percentile interval. This percentile interval should ideally be set so that only the digitised samples with a signal level corresponding to the baseline (i.e. approximately around -1000 as can be seen in the left plot of Fig. 5) is included in the averaging. The settings for the percentile interval are empirically tuned and may depend on the bunch shape. A measurement of the PU sum signal and its cumulative distribution is shown in Fig. 5. Typically, only the data samples over the 1% percentile and below the 25 to 50% percentiles are taken and averaged to find the baseline.

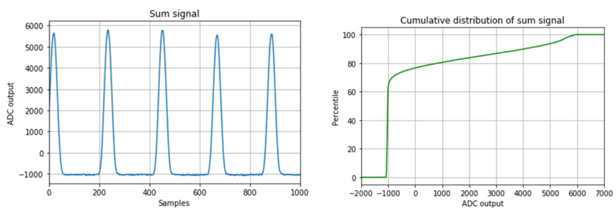

Figure 5: Left the time sampled sum signal. Right the corresponding cumulative distribution.

The typically used sampling rate of the system is set to 125MSPS. The sum signal, shown in Fig. 5, was obtained with a beam of approximately $3{\cdot}10^7$ anti-protons decelerated to 100 keV (kinetic energy). The revolution frequency at this final stage of the ELENA cycle is of 144 kHz and the beam was bunched at RF harmonic 4 in this 30.4 m long ring.

Absolute Calibration

The accuracy of the beam intensity calculated using Eq. (12) will depend on how accurately $C_{feedback}$ and $V_{baseline}$ are known, assuming we know L and L_{ELENA} with infinite precision. As the baseline shift is measured using an ADC, it is required to know the voltage gain in between the charge amplifier output and the ADC input, as well as the voltage to bit conversion factor of the ADC. The amplifier gain and ADC parameters are straightforward to know and can be measured to sufficient precision using a standard network analyser. In the case of ELENA, the feedback capacitor, $C_{feedback}$ in Eq. (12), is a high precision capacitor, mounted inside the charge amplifier. The value of this capacitor was estimated by applying a calibration signal (V_{cal} in Fig. 3) via another high precision capacitor, $C_{calibration}$ = 1 pF. In this configuration, the circuit can be seen as a standard inverting operational amplifier with a gain, A_v given by

$$A_v = -\frac{Z_{feedback}}{Z_{source}} = -\frac{\frac{1}{j\omega C_{feedback}}}{\frac{1}{j\omega C_{calibration}}} = -\frac{C_{calibration}}{C_{feedback}} \quad (13)$$

Since both the source impedance, $C_{calibration}$ and $C_{feedback}$, suffer from stray capacity, this limits the precision of this measurement. The measurement precision of $C_{feedback}$ is currently deemed to be the dominant error source in the system. At present, there are no alternative instruments capable of measuring the absolute beam intensity in the ELENA ring, thus making it impossible to perform a cross-calibration.

BEAM POSITION SENSITIVITY

To evaluate the intensity measurements sensitivity to beam position, simulations have been performed in CST Studio Suite [5]. Two models have been evaluated: Model 1: One metal cylinder 1 mm thick, 120 mm long, 66 mm diameter inside an 80 mm diameter metal beam pipe. Model 2: (see Fig. 6) as model 1, but with a 2 mm linear cut in the ring to make it position sensitive. The model 2 is similar to the actual orbit PUs in ELENA [6, page 4].

Simulations have been performed at beam speeds corresponding to β = 1 and β = 0.6, and with 10^7 charges in an approximately 5 m long (measured at 50% of the maximum amplitude) Gaussian bunch. The output is monitored using the voltage probes (the small grey arrows) shown at the top and bottom of Fig. 6.

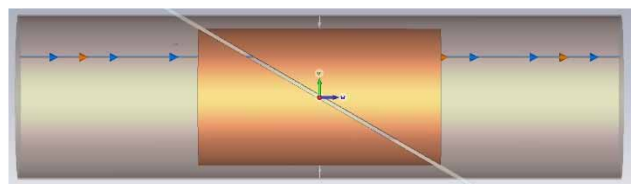

Figure 6: The 3D model of ELENA PU.

Circular PU

For model 1 the beam position is simulated at the PU centre, and moved transversally in 5 mm steps, to 25 mm off centre. The integral over time of the output voltage for each beam offset position and β value is also calculated in the simulation. A negligible (< 0.1%) change in the integrated output voltage is observed with respect to changes in the beam position. The ratio between the time integrated output voltage for the different β values is the ratio of β values themselves, as expected from Eq. (9).

Sweeping the number of charges or sweeping the bunch length reveals no non-linearities. These simulations do not include the front-end electronics.

Linear Cut Circular PU

For model 2 the beam position is simulated at the PU centre, in one case with a 20 mm offset in the horizontal plane, with the same offset in the vertical plane and finally with the same offset simultaneously in both planes. In Fig. 7 the blue curves correspond to centred beams and to vertical offset beams for both β = 1 (leftmost set of curves) and β = 0.6 (rightmost set of curves). The red curves correspond to the output signal from the PU plate towards which the beam is offset and the green curves correspond to the opposite PU plate for both β = 1 and β = 0.6. For a centred beam, and as expected, the integrated output voltage is unchanged when the beam is moved in the vertical plane. A difference in the two signals is seen when the beam is moved in the horizontal plane, as expected for a horizontal PU. When moved in the horizontal plane, the sum of the

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integrals of the output voltages of each plate is the same as the sum of integrals of the same plates when the beam is centred, as one would expect. The ratios for the sum of the integrated output signals for the two different energies is, as expected from Eq. (9), β. This means that the increased bending of the field lines in the case of low beta does not affect the measured output or its integral.

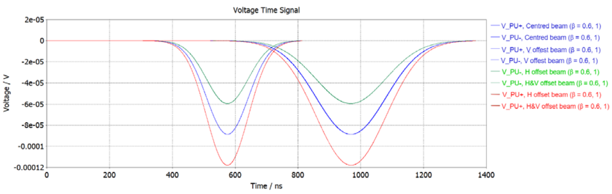

Figure 7: Beam position and β sweep for linear cut PU.

MEASUREMENTS

This system, installed in ELENA, uses Eq. (12) to provide an intensity measurement, every 1 ms, during the ELENA deceleration cycle. A typical output is shown in Fig. 8 where injection occurs at approximately 2.8 s, when the beam coming from the CERN Antiproton Decelerator (AD) is injected. Due to the high pass characteristic of the system, this approach is only valid while the beam is bunched. Therefore, the “zero-intensity” intervals which appear between 4.5 s to 6.8 s and 8.8 s to 11 s occur exactly when the beam is de-bunched and cooled.

Also due to the high pass characteristic of the PU together with the charge amplifier, the droop time is, in the current setup, of the order of a few hundreds of µs, i.e. less than one measurement period.

An overshoot consisting of the first two points of the measurement at injection is observed. This overshoot, which normally would indicate beam loss at injection is *not* believed to be real by the ELENA operators. Further studies are required to understand whether it is indeed so.

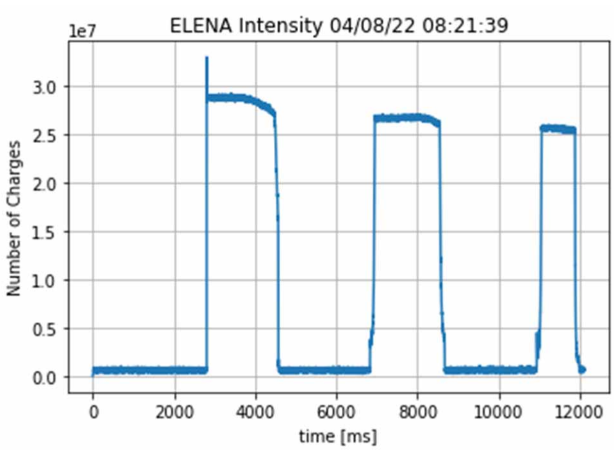

Figure 8: The Intensity as measured in the bunched periods of the ELENA deceleration cycle.

The number of charges was compared to that of the Cryogenic Current Comparator (CCC) [3], installed in the AD ring. Not considering the overshoot at injection, the proposed method measures approximately 85% of the intensity measured by the CCC.

CONCLUSIONS

A system capable of measuring low intensity (few 10^7 charges) antiproton beams, when bunched during the CERN ELENA deceleration cycle, was presented. The system is based on the sum signal from a circular linearly cut electrostatic PU also used by the ELENA orbit system. It has been shown that the baseline shift, caused by the high pass transfer function of the PU can be used to measure the absolute intensity, provided that the system bandwidth covers all relevant harmonics of the bunched beam spectrum. The baseline shift method does not seem to be affected by relativistic effects, as indicated by the CST simulations (only $\beta = 1$ and $\beta = 0.6$ evaluated). When compared to voltage amplifiers, the use of charge amplifiers as the first amplifier in the chain gives an advantage in terms of sensitivity, though stray capacitance sets a limit to the absolute accuracy of the intensity measurement if the feedback capacitor is taken to very low values. In this system the feedback capacitor is approximately 1 pF and the estimated sensitivity gain 30 dB.

It has been shown, via simulations, that the position sensitivity of the sum signal is negligible, making an electrostatic PU an interesting intensity sensor.

Measurements from the ELENA system were presented. Since no alternative reliable intensity measurement exists in ELENA, it is challenging to validate the accuracy of this measurement. By design, the absolute accuracy of the system is currently limited by the accuracy of the knowledge of the feedback capacitor capacitance, including its stray capacitance once mounted and used in the charge amplifier configuration. At present, this system provides successfully relative intensity measurements during the ELENA cycle. Further studies will be continued with the goal of providing more accurate absolute intensity measurements.

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